This book is dedicated to
Robert Jourdain,
John Socha,
Ralf Brown
and Peter Abel

Assembly Language for Beginners

Dennis Yurichev

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Dennis Yurichev
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Text version (July 17, 2018).

The latest version (and Russian edition) of this text is accessible at beginners.re.

The cover was made by Andy Nechaevsky: facebook.

Call for translators!

You may want to help me with translating this work into languages other than English and Russian. Just send me any piece of translated text (no matter how short) and I'll put it into my LaTeX source code.

Read here.

We already have something in German, French, a bit in Italian, Portuguese and Polish.

Speed isn't important, because this is an open-source project, after all. Your name will be mentioned as a project contributor. Korean, Chinese, and Persian languages are reserved by publishers. English and Russian versions I do by myself, but my English is still that horrible, so I'm very grateful for any notes about grammar, etc. Even my Russian is flawed, so I'm grateful for notes about Russian text as well!

So do not hesitate to contact me: `dennis@yurichev.com`.

Abridged contents

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[1] Floating-Point Unit

[2]Redundant Array of Independent Disks

[3]Java Virtual Machine
[4]Pseudorandom Number Generator

[5]Instruction Set Architecture

[6] Initialization Vector

Preface

There are several popular meanings of the term "reverse engineering":

1) The reverse engineering of software; researching compiled programs

2) The scanning of 3D structures and the subsequent digital manipulation required in order to duplicate them

3) Recreating DBMS[7] structure

This book is about the first meaning.

Prerequisites

Basic knowledge of the C PL[8]. Recommended reading: 12.1.3 on page 1012.

Exercises and tasks

...can be found at: `http://challenges.re`.

About the author

Dennis Yurichev is an experienced reverse engineer and programmer. He can be contacted by email: **dennis@yurichev.com**.

Praise for*Assembly Language for Beginners*

- "Now that Dennis Yurichev has made this book free (libre), it is a contribution to the world of free knowledge and free education." Richard M. Stallman, GNU founder, software freedom activist.
- "It's very well done .. and for free .. amazing."[9] Daniel Bilar, Siege Technologies, LLC.
- "... excellent and free"[10] Pete Finnigan, Oracle RDBMS security guru.
- "... [the] book is interesting, great job!" Michael Sikorski, author of *Practical Malware Analysis: The Hands-On Guide to Dissecting Malicious Software*.
- "... my compliments for the very nice tutorial!" Herbert Bos, full professor at the Vrije Universiteit Amsterdam, co-author of *Modern Operating Systems (4th Edition)*.
- "... It is amazing and unbelievable." Luis Rocha, CISSP / ISSAP, Technical Manager, Network & Information Security at Verizon Business.
- "Thanks for the great work and your book." Joris van de Vis, SAP Netweaver & Security specialist.

[7] Database Management Systems
[8] Programming Language
[9] twitter.com/daniel_bilar/status/436578617221742593
[10] twitter.com/petefinnigan/status/400551705797869568

- "... [a] reasonable intro to some of the techniques."[11] Mike Stay, teacher at the Federal Law Enforcement Training Center, Georgia, US.
- "I love this book! I have several students reading it at the moment, [and] plan to use it in graduate course."[12] Sergey Bratus , Research Assistant Professor at the Computer Science Department at Dartmouth College
- "Dennis @Yurichev has published an impressive (and free!) book on reverse engineering"[13] Tanel Poder, Oracle RDBMS performance tuning expert .
- "This book is a kind of Wikipedia to beginners..." Archer, Chinese Translator, IT Security Researcher.
- "[A] first-class reference for people wanting to learn reverse engineering. And it's free for all." Mikko Hyppönen, F-Secure.

Thanks

For patiently answering all my questions: Andrey "herm1t" Baranovich, Slava "Avid" Kazakov, SkullC0DEr.

For sending me notes about mistakes and inaccuracies: Stanislav "Beaver" Bobrytskyy, Alexander Lysenko, Alexander "Solar Designer" Peslyak, Federico Ramondino, Mark Wilson, Xenia Galinskaya, Razikhova Meiramgul Kayratovna, Anatoly Prokofiev, Kostya Begunets, Valentin "netch" Nechayev, Aleksandr Plakhov, Artem Metla, Shell Rocket, Zhu Ruijin, Changmin Heo, Vitor Vidal, Stijn Crevits, Jean-Gregoire Foulon[14], Ben L., Etienne Khan, Norbert Szetei[15], Marc Remy, Michael Hansen, Derk Barten, The Renaissance[16], Hugo Chan.

For helping me in other ways: Andrew Zubinski, Arnaud Patard (rtp on #debian-arm IRC), noshadow on #gcc IRC, Aliaksandr Autayeu, Mohsen Mostafa Jokar.

For translating the book into Simplified Chinese: Antiy Labs (antiy.cn), Archer.

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For translating the book into Portuguese: Thales Stevan de A. Gois, Diogo Mussi.

For translating the book into Italian: Federico Ramondino[17], Paolo Stivanin[18], twyK.

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For translating the book into German: Dennis Siekmeier[23], Julius Angres[24], Dirk Loser[25], Clemens Tamme.

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For translating the book into Japanese: shmz@github[26].

For proofreading: Alexander "Lstar" Chernenkiy, Vladimir Botov, Andrei Brazhuk, Mark "Logxen" Cooper, Yuan Jochen Kang, Mal Malakov, Lewis Porter, Jarle Thorsen, Hong Xie.

Vasil Kolev[27] did a great amount of work in proofreading and correcting many mistakes.

For illustrations and cover art: Andy Nechaevsky.

[11] reddit
[12] twitter.com/sergeybratus/status/505590326560833536
[13] twitter.com/TanelPoder/status/524668104065159169
[14] https://github.com/pixjuan
[15] https://github.com/73696e65
[16] https://github.com/TheRenaissance
[17] https://github.com/pinkrab
[18] https://github.com/paolostivanin
[19] https://github.com/besnardf
[20] https://github.com/mremy
[21] https://github.com/T30rix
[22] https://github.com/BlueSkeye
[23] https://github.com/DSiekmeier
[24] https://github.com/JAngres
[25] https://github.com/PolymathMonkey
[26] https://github.com/shmz
[27] https://vasil.ludost.net/

Thanks also to all the folks on github.com who have contributed notes and corrections[28].

Many LaTeX packages were used: I would like to thank the authors as well.

Donors

Those who supported me during the time when I wrote significant part of the book:

2 * Oleg Vygovsky (50+100 UAH), Daniel Bilar ($50), James Truscott ($4.5), Luis Rocha ($63), Joris van de Vis ($127), Richard S Shultz ($20), Jang Minchang ($20), Shade Atlas (5 AUD), Yao Xiao ($10), Pawel Szczur (40 CHF), Justin Simms ($20), Shawn the R0ck ($27), Ki Chan Ahn ($50), Triop AB (100 SEK), Ange Albertini (€10+50), Sergey Lukianov (300 RUR), Ludvig Gislason (200 SEK), Gérard Labadie (€40), Sergey Volchkov (10 AUD), Vankayala Vigneswararao ($50), Philippe Teuwen ($4), Martin Haeberli ($10), Victor Cazacov (€5), Tobias Sturzenegger (10 CHF), Sonny Thai ($15), Bayna AlZaabi ($75), Redfive B.V. (€25), Joona Oskari Heikkilä (€5), Marshall Bishop ($50), Nicolas Werner (€12), Jeremy Brown ($100), Alexandre Borges ($25), Vladimir Dikovski (€50), Jiarui Hong (100.00 SEK), Jim Di (500 RUR), Tan Vincent ($30), Sri Harsha Kandrakota (10 AUD), Pillay Harish (10 SGD), Timur Valiev (230 RUR), Carlos Garcia Prado (€10), Salikov Alexander (500 RUR), Oliver Whitehouse (30 GBP), Katy Moe ($14), Maxim Dyakonov ($3), Sebastian Aguilera (€20), Hans-Martin Münch (€15), Jarle Thorsen (100 NOK), Vitaly Osipov ($100), Yuri Romanov (1000 RUR), Aliaksandr Autayeu (€10), Tudor Azoitei ($40), Z0vsky (€10), Yu Dai ($10), Anonymous ($15), Vladislav Chelnokov ($25), Nenad Noveljic ($50), Ryan Smith ($25), Andreas Schommer (€5).

Thanks a lot to every donor!

mini-FAQ

Q: What are the prerequisites for reading this book?

A: A basic understanding of C/C++ is desirable.

Q: Should I really learn x86/x64/ARM and MIPS at once? Isn't it too much?

A: Starters can read about just x86/x64, while skipping or skimming the ARM and MIPS parts.

Q: Can I buy a Russian or English hard copy/paper book?

A: Unfortunately, no. No publisher got interested in publishing a Russian or English version so far. Meanwhile, you can ask your favorite copy shop to print and bind it.

Q: Is there an epub or mobi version?

A: No. The book is highly dependent on TeX/LaTeX-specific hacks, so converting to HTML (epub/mobi are a set of HTMLs) would not be easy.

Q: Why should one learn assembly language these days?

A: Unless you are an OS[29] developer, you probably don't need to code in assembly—the latest compilers (2010s) are much better at performing optimizations than humans [30].

Also, the latest CPU[31]s are very complex devices, and assembly knowledge doesn't really help towards understand their internals.

That being said, there are at least two areas where a good understanding of assembly can be helpful: First and foremost, for security/malware research. It is also a good way to gain a better understanding of your compiled code while debugging. This book is therefore intended for those who want to understand assembly language rather than to code in it, which is why there are many examples of compiler output contained within.

Q: I clicked on a hyperlink inside a PDF-document, how do I go back?

A: In Adobe Acrobat Reader click Alt+LeftArrow. In Evince click "<" button.

Q: May I print this book / use it for teaching?

A: Of course! That's why the book is licensed under the Creative Commons license (CC BY-SA 4.0).

Q: Why is this book free? You've done great job. This is suspicious, as with many other free things.

[28] https://github.com/DennisYurichev/RE-for-beginners/graphs/contributors
[29] Operating System
[30] A very good text on this topic: [Agner Fog, *The microarchitecture of Intel, AMD and VIA CPUs*, (2016)]
[31] Central Processing Unit

A: In my own experience, authors of technical literature write mostly for self-advertisement purposes. It's not possible to make any decent money from such work.

Q: How does one get a job in reverse engineering?

A: There are hiring threads that appear from time to time on reddit, devoted to RE[32] (2016). Try looking there.

A somewhat related hiring thread can be found in the "netsec" subreddit: 2016.

Q: How can I learn programming in general?

A: Mastering both C and LISP languages makes programmer's life much, much easier. I would recommend solving exercises from [Brian W. Kernighan, Dennis M. Ritchie, *The C Programming Language*, 2ed, (1988)] and SICP[33].

Q: I have a question...

A: Send it to me by email (dennis@yurichev.com).

How to learn programming

Many people keep asking about it.

There is no "royal road", but there are quite efficient ways.

From my own experience, this is just: solving exercises from:

- Brian W. Kernighan, Dennis M. Ritchie, *The C Programming Language*, 2ed, (1988)
- Harold Abelson, Gerald Jay Sussman, Julie Sussman – Structure and Interpretation of Computer Programs
- Donald E. Knuth, *The Art of Computer Programming*
- Niklaus Wirth's books
- Brian W. Kernighan, Rob Pike, *Practice of Programming*, (1999)

... in pure C and LISP. You may never use these programming languages in future at all. Almost all commercial programmers don't. But C and LISP coding experience will help enormously in long run.

Also, you can skip reading these books itselves, just skim them whenever you feel you need to understand something you missing for the exercise you currently solve.

This may take years at best, or a lifetime, but still this is way faster than to rush between fads.

The success of these books probably related to the fact that their authors are teachers and all this material has been honed on students first.

As of LISP, I personally would recommend Racket (Scheme dialect). But this is matter of taste, anyway.

Some people say assembly language understanding is also very helpful, even if you will never use it. This is true. But this is a way for the most dedicated geeks, and it can be postponed at start.

Also, self-taught people (including author of these lines) often has the problem of trying too hard on hard problems, skipping easy ones. This is a great mistake. Compare to sport or music – no one starts at 100kg weights, or Paganini's Caprices. I would say – you can try to tackle a problem if you can outline its solution in your mind.

> I think the art of doing research consists largely of asking questions, and sometimes answering them. Learn how to repeatedly pose miniquestions that represent special cases of the big questions you are hoping to solve.
>
> When you begin to explore some area, you take baby steps at first, building intuition about that territory. Play with many small examples, trying to get a complete understanding of particular parts of the general situation.
>
> In that way you learn many properties that are true and many properties that are false. That gives guidance about directions that are fruitful versus directions to avoid.
>
> Eventually your brain will have learned how to take larger and larger steps. And shazam, you'll be ready to take some giant steps and solve the big problem.

[32] reddit.com/r/ReverseEngineering/
[33] Structure and Interpretation of Computer Programs

> But don't stop there! At this point you'll be one of very few people in the world who have ever understood your problem area so well. It will therefore be your responsibility to discover what else is true, in the neighborhood of that problem, using the same or similar methods to what your brain can now envision. Take your results to their "natural boundary" (in a sense analogous to the natural boundary where a function of a complex variable ceases to be analytic).
>
> My little book Surreal Numbers provides an authentic example of research as it is happening. The characters in that story make false starts and useful discoveries in exactly the same order as I myself made those false starts and useful discoveries, when I first studied John Conway's fascinating axioms about number systems — his amazingly simple axioms that go significantly beyond real-valued numbers.
>
> (One of the characters in that book tends to succeed or fail by brute force and patience; the other is more introspective, and able to see a bigger picture. Both of them represent aspects of my own activities while doing research. With that book I hoped to teach research skills "by osmosis", as readers observe a detailed case study.)
>
> Surreal Numbers deals with a purely mathematical topic, not especially close to computer science; it features algebra and logic, not algorithms. When algorithms become part of the research, a beautiful new dimension also comes into play: Algorithms can be implemented on computers!
>
> I strongly recommend that you look for every opportunity to write programs that carry out all or a part of whatever algorithms relate to your research. In my experience the very act of writing such a program never fails to deepen my understanding of the problem area.

(Donald E. Knuth – https://theorydish.blog/2018/02/01/donald-knuth-on-doing-research/)

Good luck!

About the Korean translation

In January 2015, the Acorn publishing company (www.acornpub.co.kr) in South Korea did a huge amount of work in translating and publishing this book (as it was in August 2014) into Korean.

It's available now at their website.

The translator is Byungho Min (twitter/tais9). The cover art was done by the artistic Andy Nechaevsky, a friend of the author: facebook/andydinka. Acorn also holds the copyright to the Korean translation.

So, if you want to have a *real* book on your shelf in Korean and want to support this work, it is now available for purchase.

About the Persian/Farsi translation

In 2016 the book was translated by Mohsen Mostafa Jokar (who is also known to Iranian community for his translation of Radare manual[34]). It is available on the publisher's website[35] (Pendare Pars).

Here is a link to a 40-page excerpt: https://beginners.re/farsi.pdf.

National Library of Iran registration information: http://opac.nlai.ir/opac-prod/bibliographic/4473995.

About the Chinese translation

In April 2017, translation to Chinese was completed by Chinese PTPress. They are also the Chinese translation copyright holders.

The Chinese version is available for order here: http://www.epubit.com.cn/book/details/4174. A partial review and history behind the translation can be found here: http://www.cptoday.cn/news/detail/3155.

The principal translator is Archer, to whom the author owes very much. He was extremely meticulous (in a good sense) and reported most of the known mistakes and bugs, which is very important in literature such as this book. The author would recommend his services to any other author!

[34] http://rada.re/get/radare2book-persian.pdf
[35] http://goo.gl/2Tzx0H

The guys from Antiy Labs has also helped with translation. Here is preface written by them.

Chapter 1

Code Patterns

1.1 The method

When the author of this book first started learning C and, later, C++, he used to write small pieces of code, compile them, and then look at the assembly language output. This made it very easy for him to understand what was going on in the code that he had written. [1]. He did this so many times that the relationship between the C/C++ code and what the compiler produced was imprinted deeply in his mind. It's now easy for him to imagine instantly a rough outline of a C code's appearance and function. Perhaps this technique could be helpful for others.

By the way, there is a great website where you can do the same, with various compilers, instead of installing them on your box. You can use it as well: https://godbolt.org/.

Exercises

When the author of this book studied assembly language, he also often compiled small C functions and then rewrote them gradually to assembly, trying to make their code as short as possible. This probably is not worth doing in real-world scenarios today, because it's hard to compete with the latest compilers in terms of efficiency. It is, however, a very good way to gain a better understanding of assembly. Feel free, therefore, to take any assembly code from this book and try to make it shorter. However, don't forget to test what you have written.

Optimization levels and debug information

Source code can be compiled by different compilers with various optimization levels. A typical compiler has about three such levels, where level zero means that optimization is completely disabled. Optimization can also be targeted towards code size or code speed. A non-optimizing compiler is faster and produces more understandable (albeit verbose) code, whereas an optimizing compiler is slower and tries to produce code that runs faster (but is not necessarily more compact). In addition to optimization levels, a compiler can include some debug information in the resulting file, producing code that is easy to debug. One of the important features of the ´debug' code is that it might contain links between each line of the source code and its respective machine code address. Optimizing compilers, on the other hand, tend to produce output where entire lines of source code can be optimized away and thus not even be present in the resulting machine code. Reverse engineers can encounter either version, simply because some developers turn on the compiler's optimization flags and others do not. Because of this, we'll try to work on examples of both debug and release versions of the code featured in this book, wherever possible.

Sometimes some pretty ancient compilers are used in this book, in order to get the shortest (or simplest) possible code snippet.

[1] In fact, he still does this when he can't understand what a particular bit of code does.

1.2 Some basics

1.2.1 A short introduction to the CPU

The CPU is the device that executes the machine code a program consists of.

A short glossary:

Instruction : A primitive CPU command. The simplest examples include: moving data between registers, working with memory, primitive arithmetic operations. As a rule, each CPU has its own instruction set architecture (ISA).

Machine code : Code that the CPU directly processes. Each instruction is usually encoded by several bytes.

Assembly language : Mnemonic code and some extensions, like macros, that are intended to make a programmer's life easier.

CPU register : Each CPU has a fixed set of general purpose registers (GPR[2]). ≈ 8 in x86, ≈ 16 in x86-64, and also ≈ 16 in ARM. The easiest way to understand a register is to think of it as an untyped temporary variable. Imagine if you were working with a high-level PL and could only use eight 32-bit (or 64-bit) variables. Yet a lot can be done using just these!

One might wonder why there needs to be a difference between machine code and a PL. The answer lies in the fact that humans and CPUs are not alike—it is much easier for humans to use a high-level PL like C/C++, Java, or Python, but it is easier for a CPU to use a much lower level of abstraction. Perhaps it would be possible to invent a CPU that can execute high-level PL code, but it would be many times more complex than the CPUs we know of today. In a similar fashion, it is very inconvenient for humans to write in assembly language, due to it being so low-level and difficult to write in without making a huge number of annoying mistakes. The program that converts the high-level PL code into assembly is called a *compiler*. [3].

A couple of words about different ISAs

The x86 ISA has always had variable-length instructions, so when the 64-bit era came, the x64 extensions did not impact the ISA very significantly. In fact, the x86 ISA still contains a lot of instructions that first appeared in 16-bit 8086 CPU, yet are still found in the CPUs of today. ARM is a RISC[4] CPU designed with constant-length instructions in mind, which had some advantages in the past. In the very beginning, all ARM instructions were encoded in 4 bytes[5]. This is now referred to as "ARM mode". Then they realized it wasn't as frugal as they first imagined. In fact, the most common CPU instructions[6] in real world applications can be encoded using less information. They therefore added another ISA, called Thumb, in which each instruction was encoded in just 2 bytes. This is now referred to as "Thumb mode". However, not *all* ARM instructions can be encoded in just 2 bytes, so the Thumb instruction set is somewhat limited. It is worth noting that code compiled for ARM mode and Thumb mode can coexist within one single program. The ARM creators thought Thumb could be extended, giving rise to Thumb-2, which appeared in ARMv7. Thumb-2 still uses 2-byte instructions, but has some new instructions which have the size of 4 bytes. There is a common misconception that Thumb-2 is a mix of ARM and Thumb. This is incorrect. Rather, Thumb-2 was extended to fully support all processor features so it could compete with ARM mode—a goal that was clearly achieved, as the majority of applications for iPod/iPhone/iPad are compiled for the Thumb-2 instruction set. (Though, admittedly, this is largely due to the fact that Xcode does this by default). Later the 64-bit ARM came out. This ISA has 4-byte instructions, and lacked the need of any additional Thumb mode. However, the 64-bit requirements affected the ISA, resulting in us now having three ARM instruction sets: ARM mode, Thumb mode (including Thumb-2) and ARM64. These ISAs intersect partially, but it can be said that they are different ISAs, rather than variations of the same one. Therefore, we will try to add fragments of code in all three ARM ISAs in this book. There are, by the way, many other RISC ISAs with fixed length 32-bit instructions, such as MIPS, PowerPC and Alpha AXP.

[2] General Purpose Registers
[3] Old-school Russian literature also uses the term "translator".
[4] Reduced Instruction Set Computing
[5] Fixed-length instructions are handy because one can calculate the next (or previous) instruction address without effort. This feature will be discussed in the switch() operator (1.15.2 on page 173) section.
[6] e.g. MOV/PUSH/CALL/Jcc

1.2.2 Numeral Systems

Humans have become accustomed to a decimal numeral system, probably because almost everyone has 10 fingers. Nevertheless, the number “10” has no significant meaning in science and mathematics. The natural numeral system in digital electronics is binary: 0 is for an absence of current in the wire, and 1 for presence. 10 in binary is 2 in decimal, 100 in binary is 4 in decimal, and so on.

If the numeral system has 10 digits, it has a *radix* (or *base*) of 10. The binary numeral system has a *radix* of 2.

Important things to recall:

1) A *number* is a number, while a *digit* is a term from writing systems, and is usually one character

2) The value of a number does not change when converted to another radix; only the writing notation for that value has changed (and therefore the way of representing it in RAM[7]).

1.2.3 Converting From One Radix To Another

Positional notation is used almost every numerical system. This means that a digit has weight relative to where it is placed inside of the larger number. If 2 is placed at the rightmost place, it’s 2, but if it’s placed one digit before rightmost, it’s 20.

What does 1234 stand for?

$10^3 \cdot 1 + 10^2 \cdot 2 + 10^1 \cdot 3 + 1 \cdot 4 = 1234$ or $1000 \cdot 1 + 100 \cdot 2 + 10 \cdot 3 + 4 = 1234$

It’s the same story for binary numbers, but the base is 2 instead of 10. What does 0b101011 stand for?

$2^5 \cdot 1 + 2^4 \cdot 0 + 2^3 \cdot 1 + 2^2 \cdot 0 + 2^1 \cdot 1 + 2^0 \cdot 1 = 43$ or $32 \cdot 1 + 16 \cdot 0 + 8 \cdot 1 + 4 \cdot 0 + 2 \cdot 1 + 1 = 43$

There is such a thing as non-positional notation, such as the Roman numeral system. [8]. Perhaps, humankind switched to positional notation because it’s easier to do basic operations (addition, multiplication, etc.) on paper by hand.

Binary numbers can be added, subtracted and so on in the very same as taught in schools, but only 2 digits are available.

Binary numbers are bulky when represented in source code and dumps, so that is where the hexadecimal numeral system can be useful. A hexadecimal radix uses the digits 0..9, and also 6 Latin characters: A..F. Each hexadecimal digit takes 4 bits or 4 binary digits, so it’s very easy to convert from binary number to hexadecimal and back, even manually, in one’s mind.

hexadecimal	binary	decimal
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
A	1010	10
B	1011	11
C	1100	12
D	1101	13
E	1110	14
F	1111	15

How can one tell which radix is being used in a specific instance?

Decimal numbers are usually written as is, i.e., 1234. Some assemblers allow an identifier on decimal

[7] Random-Access Memory
[8] About numeric system evolution, see [Donald E. Knuth, *The Art of Computer Programming*, Volume 2, 3rd ed., (1997), 195–213.]

radix numbers, in which the number would be written with a ”d” suffix: 1234d.

Binary numbers are sometimes prepended with the ”0b” prefix: 0b100110111 (GCC[9] has a non-standard language extension for this[10]). There is also another way: using a ”b” suffix, for example: 100110111b. This book tries to use the ”0b” prefix consistently throughout the book for binary numbers.

Hexadecimal numbers are prepended with ”0x” prefix in C/C++ and other PLs: 0x1234ABCD. Alternatively, they are given a ”h” suffix: 1234ABCDh. This is common way of representing them in assemblers and debuggers. In this convention, if the number is started with a Latin (A..F) digit, a 0 is added at the beginning: 0ABCDEFh. There was also convention that was popular in 8-bit home computers era, using $ prefix, like $ABCD. The book will try to stick to ”0x” prefix throughout the book for hexadecimal numbers.

Should one learn to convert numbers mentally? A table of 1-digit hexadecimal numbers can easily be memorized. As for larger numbers, it’s probably not worth tormenting yourself.

Perhaps the most visible hexadecimal numbers are in URL[11]s. This is the way that non-Latin characters are encoded. For example: `https://en.wiktionary.org/wiki/na%C3%AFvet%C3%A9` is the URL of Wiktionary article about “naïveté” word.

Octal Radix

Another numeral system heavily used in the past of computer programming is octal. In octal there are 8 digits (0..7), and each is mapped to 3 bits, so it’s easy to convert numbers back and forth. It has been superseded by the hexadecimal system almost everywhere, but, surprisingly, there is a *NIX utility, used often by many people, which takes octal numbers as argument: `chmod`.

As many *NIX users know, `chmod` argument can be a number of 3 digits. The first digit represents the rights of the owner of the file (read, write and/or execute), the second is the rights for the group to which the file belongs, and the third is for everyone else. Each digit that `chmod` takes can be represented in binary form:

decimal	binary	meaning
7	111	**rwx**
6	110	**rw-**
5	101	**r-x**
4	100	**r--**
3	011	**-wx**
2	010	**-w-**
1	001	**--x**
0	000	**---**

So each bit is mapped to a flag: read/write/execute.

The importance of `chmod` here is that the whole number in argument can be represented as octal number. Let’s take, for example, 644. When you run `chmod 644 file`, you set read/write permissions for owner, read permissions for group and again, read permissions for everyone else. If we convert the octal number 644 to binary, it would be `110100100`, or, in groups of 3 bits, `110 100 100`.

Now we see that each triplet describe permissions for owner/group/others: first is `rw-`, second is `r--` and third is `r--`.

The octal numeral system was also popular on old computers like PDP-8, because word there could be 12, 24 or 36 bits, and these numbers are all divisible by 3, so the octal system was natural in that environment. Nowadays, all popular computers employ word/address sizes of 16, 32 or 64 bits, and these numbers are all divisible by 4, so the hexadecimal system is more natural there.

The octal numeral system is supported by all standard C/C++ compilers. This is a source of confusion sometimes, because octal numbers are encoded with a zero prepended, for example, 0377 is 255. Sometimes, you might make a typo and write ”09” instead of 9, and the compiler would report an error. GCC might report something like this:
`error: invalid digit "9" in octal constant.`

[9] GNU Compiler Collection
[10] `https://gcc.gnu.org/onlinedocs/gcc/Binary-constants.html`
[11] Uniform Resource Locator

Also, the octal system is somewhat popular in Java. When the IDA shows Java strings with non-printable characters, they are encoded in the octal system instead of hexadecimal. The JAD Java decompiler behaves the same way.

Divisibility

When you see a decimal number like 120, you can quickly deduce that it's divisible by 10, because the last digit is zero. In the same way, 123400 is divisible by 100, because the two last digits are zeros.

Likewise, the hexadecimal number 0x1230 is divisible by 0x10 (or 16), 0x123000 is divisible by 0x1000 (or 4096), etc.

The binary number 0b1000101000 is divisible by 0b1000 (8), etc.

This property can often be used to quickly realize if an address or a size of some block in memory is padded to some boundary. For example, sections in PE[12] files are almost always started at addresses ending with 3 hexadecimal zeros: 0x41000, 0x10001000, etc. The reason behind this is the fact that almost all PE sections are padded to a boundary of 0x1000 (4096) bytes.

Multi-Precision Arithmetic and Radix

Multi-precision arithmetic can use huge numbers, and each one may be stored in several bytes. For example, RSA keys, both public and private, span up to 4096 bits, and maybe even more.

In [Donald E. Knuth, *The Art of Computer Programming*, Volume 2, 3rd ed., (1997), 265] we find the following idea: when you store a multi-precision number in several bytes, the whole number can be represented as having a radix of $2^8 = 256$, and each digit goes to the corresponding byte. Likewise, if you store a multi-precision number in several 32-bit integer values, each digit goes to each 32-bit slot, and you may think about this number as stored in radix of 2^{32}.

How to Pronounce Non-Decimal Numbers

Numbers in a non-decimal base are usually pronounced by digit by digit: "one-zero-zero-one-one-...". Words like "ten" and "thousand" are usually not pronounced, to prevent confusion with the decimal base system.

Floating point numbers

To distinguish floating point numbers from integers, they are usually written with ".0" at the end, like 0.0, 123.0, etc.

1.3 An Empty Function

The simplest possible function is arguably one that does nothing:

Listing 1.1: C/C++ Code

```
void f()
{
        return;
};
```

Let's compile it!

[12] Portable Executable

1.3.1 x86

Here's what both the GCC and MSVC compilers produce on the x86 platform:

Listing 1.2: Optimizing GCC/MSVC (assembly output)

```
f:
        ret
```

There is just one instruction: RET, which returns execution to the caller.

1.3.2 ARM

Listing 1.3: Optimizing Keil 6/2013 (ARM mode) assembly output

```
f       PROC
        BX      lr
        ENDP
```

The return address is not saved on the local stack in the ARM ISA, but rather in the link register, so the BX LR instruction causes execution to jump to that address—effectively returning execution to the caller.

1.3.3 MIPS

There are two naming conventions used in the world of MIPS when naming registers: by number (from $0 to $31) or by pseudo name ($V0, $A0, etc.).

The GCC assembly output below lists registers by number:

Listing 1.4: Optimizing GCC 4.4.5 (assembly output)

```
        j       $31
        nop
```

…while IDA[13] does it by pseudo name:

Listing 1.5: Optimizing GCC 4.4.5 (IDA)

```
        j       $ra
        nop
```

The first instruction is the jump instruction (J or JR) which returns the execution flow to the caller, jumping to the address in the $31 (or $RA) register.

This is the register analogous to LR[14] in ARM.

The second instruction is NOP[15], which does nothing. We can ignore it for now.

A Note About MIPS Instructions and Register Names

Register and instruction names in the world of MIPS are traditionally written in lowercase. However, for the sake of consistency, this book will stick to using uppercase letters, as it is the convention followed by all the other ISAs featured this book.

[13] Interactive Disassembler and Debugger developed by Hex-Rays
[14] Link Register
[15] No Operation

1.3.4 Empty Functions in Practice

Despite the fact empty functions seem useless, they are quite frequent in low-level code.

First of all, they are quite popular in debugging functions, like this one:

Listing 1.6: C/C++ Code

```
void dbg_print (const char *fmt, ...)
{
#ifdef _DEBUG
        // open log file
        // write to log file
        // close log file
#endif
};

void some_function()
{
        ...

        dbg_print ("we did something\n");

        ...
};
```

In a non-debug build (as in a "release"), `_DEBUG` is not defined, so the `dbg_print()` function, despite still being called during execution, will be empty.

Similarly, a popular method of software protection is to make one build for legal customers, and another demo build. A demo build can lack some important functions, as with this example:

Listing 1.7: C/C++ Code

```
void save_file ()
{
#ifndef DEMO
        // actual saving code
#endif
};
```

The `save_file()` function can be called when the user clicks `File->`Save on the menu. The demo version may be delivered with this menu item disabled, but even if a software cracker will enable it, only an empty function with no useful code will be called.

IDA marks such functions with names like `nullsub_00`, `nullsub_01`, etc.

1.4 Returning Values

Another simple function is the one that simply returns a constant value:

Listing 1.8: C/C++ Code

```
int f()
{
        return 123;
};
```

Let's compile it.

1.4.1 x86

Here's what both the GCC and MSVC compilers produce (with optimization) on the x86 platform:

Listing 1.9: Optimizing GCC/MSVC (assembly output)

```
f:
        mov     eax, 123
        ret
```

There are just two instructions: the first places the value 123 into the EAX register, which is used by convention for storing the return value, and the second one is RET, which returns execution to the caller.

The caller will take the result from the EAX register.

1.4.2 ARM

There are a few differences on the ARM platform:

Listing 1.10: Optimizing Keil 6/2013 (ARM mode) ASM Output

```
f       PROC
        MOV      r0,#0x7b ; 123
        BX       lr
        ENDP
```

ARM uses the register R0 for returning the results of functions, so 123 is copied into R0.

It is worth noting that MOV is a misleading name for the instruction in both the x86 and ARM ISAs.

The data is not in fact *moved*, but *copied*.

1.4.3 MIPS

The GCC assembly output below lists registers by number:

Listing 1.11: Optimizing GCC 4.4.5 (assembly output)

```
        j       $31
        li      $2,123                  # 0x7b
```

…while IDA does it by their pseudo names:

Listing 1.12: Optimizing GCC 4.4.5 (IDA)

```
                jr      $ra
                li      $v0, 0x7B
```

The $2 (or $V0) register is used to store the function's return value. LI stands for "Load Immediate" and is the MIPS equivalent to MOV.

The other instruction is the jump instruction (J or JR) which returns the execution flow to the caller.

You might be wondering why the positions of the load instruction (LI) and the jump instruction (J or JR) are swapped. This is due to a RISC feature called "branch delay slot".

The reason this happens is a quirk in the architecture of some RISC ISAs and isn't important for our purposes—we must simply keep in mind that in MIPS, the instruction following a jump or branch instruction is executed *before* the jump/branch instruction itself.

As a consequence, branch instructions always swap places with the instruction executed immediately beforehand.

In practice, functions which merely return 1 (*true*) or 0 (*false*) are very frequent.

The smallest ever of the standard UNIX utilities, */bin/true* and */bin/false* return 0 and 1 respectively, as an exit code. (Zero as an exit code usually means success, non-zero means error.)

1.5 Hello, world!

Let's use the famous example from the book [Brian W. Kernighan, Dennis M. Ritchie, *The C Programming Language*, 2ed, (1988)]:

Listing 1.13: C/C++ Code

```
#include <stdio.h>

int main()
{
    printf("hello, world\n");
    return 0;
}
```

1.5.1 x86

MSVC

Let's compile it in MSVC 2010:

```
cl 1.cpp /Fa1.asm
```

(The /Fa option instructs the compiler to generate an assembly listing file)

Listing 1.14: MSVC 2010

```
CONST   SEGMENT
$SG3830 DB      'hello, world', 0AH, 00H
CONST   ENDS
PUBLIC  _main
EXTRN   _printf:PROC
; Function compile flags: /Odtp
_TEXT   SEGMENT
_main   PROC
        push    ebp
        mov     ebp, esp
        push    OFFSET $SG3830
        call    _printf
        add     esp, 4
        xor     eax, eax
        pop     ebp
        ret     0
_main   ENDP
_TEXT   ENDS
```

MSVC produces assembly listings in Intel-syntax. The differences between Intel-syntax and AT&T-syntax will be discussed in 1.5.1 on page 11.

The compiler generated the file, `1.obj`, which is to be linked into `1.exe`. In our case, the file contains two segments: `CONST` (for data constants) and `_TEXT` (for code).

The string `hello, world` in C/C++ has type `const char[]`[Bjarne Stroustrup, *The C++ Programming Language, 4th Edition*, (2013)p176, 7.3.2], but it does not have its own name. The compiler needs to deal with the string somehow, so it defines the internal name `$SG3830` for it.

That is why the example may be rewritten as follows:

```
#include <stdio.h>

const char $SG3830[]="hello, world\n";

int main()
{
    printf($SG3830);
    return 0;
}
```

Let's go back to the assembly listing. As we can see, the string is terminated by a zero byte, which is standard for C/C++ strings. More about C/C++ strings: 5.4.1 on page 704.

In the code segment, _TEXT, there is only one function so far: `main()`. The function `main()` starts with prologue code and ends with epilogue code (like almost any function) [16].

[16] You can read more about it in the section about function prologues and epilogues (1.6 on page 29).

After the function prologue we see the call to the `printf()` function:
`CALL _printf`. Before the call, a string address (or a pointer to it) containing our greeting is placed on the stack with the help of the PUSH instruction.

When the `printf()` function returns the control to the `main()` function, the string address (or a pointer to it) is still on the stack. Since we do not need it anymore, the stack pointer (the ESP register) needs to be corrected.

`ADD ESP, 4` means add 4 to the ESP register value.

Why 4? Since this is a 32-bit program, we need exactly 4 bytes for address passing through the stack. If it was x64 code we would need 8 bytes. `ADD ESP, 4` is effectively equivalent to `POP register` but without using any register[17].

For the same purpose, some compilers (like the Intel C++ Compiler) may emit `POP ECX` instead of `ADD` (e.g., such a pattern can be observed in the Oracle RDBMS code as it is compiled with the Intel C++ compiler). This instruction has almost the same effect but the ECX register contents will be overwritten. The Intel C++ compiler supposedly uses `POP ECX` since this instruction's opcode is shorter than `ADD ESP, x` (1 byte for `POP` against 3 for `ADD`).

Here is an example of using `POP` instead of `ADD` from Oracle RDBMS:

Listing 1.15: Oracle RDBMS 10.2 Linux (app.o file)

```
.text:0800029A                 push    ebx
.text:0800029B                 call    qksfroChild
.text:080002A0                 pop     ecx
```

After calling `printf()`, the original C/C++ code contains the statement `return 0` —return 0 as the result of the `main()` function.

In the generated code this is implemented by the instruction `XOR EAX, EAX`.

`XOR` is in fact just "eXclusive OR"[18] but the compilers often use it instead of `MOV EAX, 0`—again because it is a slightly shorter opcode (2 bytes for `XOR` against 5 for `MOV`).

Some compilers emit `SUB EAX, EAX`, which means *SUBtract the value in the* EAX *from the value in* EAX. That in any case will results in zero.

The last instruction RET returns the control to the caller. Usually, this is C/C++ CRT[19] code which in turn returns control to the OS.

GCC

Now let's try to compile the same C/C++ code in the GCC 4.4.1 compiler in Linux: `gcc 1.c -o 1`. Next, with the assistance of the IDA disassembler, let's see how the `main()` function was created. IDA, like MSVC, uses Intel-syntax[20].

Listing 1.16: code in IDA

```
main            proc near

var_10          = dword ptr -10h

                push    ebp
                mov     ebp, esp
                and     esp, 0FFFFFFF0h
                sub     esp, 10h
                mov     eax, offset aHelloWorld ; "hello, world\n"
                mov     [esp+10h+var_10], eax
                call    _printf
                mov     eax, 0
                leave
                retn
main            endp
```

[17] CPU flags, however, are modified
[18] Wikipedia
[19] C Runtime library
[20] We could also have GCC produce assembly listings in Intel-syntax by applying the options `-S -masm=intel`.

The result is almost the same. The address of the `hello, world` string (stored in the data segment) is loaded in the EAX register first, and then saved onto the stack.
In addition, the function prologue has `AND ESP, 0FFFFFFF0h` —this instruction aligns the ESP register value on a 16-byte boundary. This results in all values in the stack being aligned the same way (The CPU performs better if the values it is dealing with are located in memory at addresses aligned on a 4-byte or 16-byte boundary)[21].

`SUB ESP, 10h` allocates 16 bytes on the stack. Although, as we can see hereafter, only 4 are necessary here.

This is because the size of the allocated stack is also aligned on a 16-byte boundary.

The string address (or a pointer to the string) is then stored directly onto the stack without using the PUSH instruction. *var_10* —is a local variable and is also an argument for `printf()`. Read about it below.

Then the `printf()` function is called.

Unlike MSVC, when GCC is compiling without optimization turned on, it emits `MOV EAX, 0` instead of a shorter opcode.

The last instruction, LEAVE —is the equivalent of the `MOV ESP, EBP` and `POP EBP` instruction pair —in other words, this instruction sets the stack pointer (ESP) back and restores the EBP register to its initial state. This is necessary since we modified these register values (ESP and EBP) at the beginning of the function (by executing `MOV EBP, ESP` / `AND ESP, …`).

GCC: AT&T syntax

Let's see how this can be represented in assembly language AT&T syntax. This syntax is much more popular in the UNIX-world.

Listing 1.17: let's compile in GCC 4.7.3

```
gcc -S 1_1.c
```

We get this:

Listing 1.18: GCC 4.7.3

```
        .file   "1_1.c"
        .section        .rodata
.LC0:
        .string "hello, world\n"
        .text
        .globl  main
        .type   main, @function
main:
.LFB0:
        .cfi_startproc
        pushl   %ebp
        .cfi_def_cfa_offset 8
        .cfi_offset 5, -8
        movl    %esp, %ebp
        .cfi_def_cfa_register 5
        andl    $-16, %esp
        subl    $16, %esp
        movl    $.LC0, (%esp)
        call    printf
        movl    $0, %eax
        leave
        .cfi_restore 5
        .cfi_def_cfa 4, 4
        ret
        .cfi_endproc
.LFE0:
        .size   main, .-main
        .ident  "GCC: (Ubuntu/Linaro 4.7.3-1ubuntu1) 4.7.3"
        .section        .note.GNU-stack,"",@progbits
```

[21] Wikipedia: Data structure alignment

The listing contains many macros (the parts that begin with a dot). These are not interesting for us at the moment.

For now, for the sake of simplicity, we can ignore them (except the *.string* macro which encodes a null-terminated character sequence just like a C-string). Then we'll see this [22]:

Listing 1.19: GCC 4.7.3

```
.LC0:
        .string "hello, world\n"
main:
        pushl   %ebp
        movl    %esp, %ebp
        andl    $-16, %esp
        subl    $16, %esp
        movl    $.LC0, (%esp)
        call    printf
        movl    $0, %eax
        leave
        ret
```

Some of the major differences between Intel and AT&T syntax are:

- Source and destination operands are written in opposite order.

  In Intel-syntax: <instruction> <destination operand> <source operand>.

  In AT&T syntax: <instruction> <source operand> <destination operand>.

  Here is an easy way to memorize the difference: when you deal with Intel-syntax, you can imagine that there is an equality sign (=) between operands and when you deal with AT&T-syntax imagine there is a right arrow (→) [23].

- AT&T: Before register names, a percent sign must be written (%) and before numbers a dollar sign ($). Parentheses are used instead of brackets.

- AT&T: A suffix is added to instructions to define the operand size:

  - q — quad (64 bits)
  - l — long (32 bits)
  - w — word (16 bits)
  - b — byte (8 bits)

To go back to the compiled result: it is almost identical to what was displayed by IDA. There is one subtle difference: `0FFFFFFF0h` is presented as `$-16`. It's the same thing: `16` in the decimal system is `0x10` in hexadecimal. `-0x10` is equal to `0xFFFFFFF0` (for a 32-bit data type).

One more thing: the return value is set to 0 by using the usual `MOV`, not `XOR`. `MOV` just loads a value to a register. Its name is a misnomer (as the data is not moved but rather copied). In other architectures, this instruction is named "LOAD" or "STORE" or something similar.

String patching (Win32)

We can easily find the "hello, world" string in the executable file using Hiew:

[22] This GCC option can be used to eliminate "unnecessary" macros: *-fno-asynchronous-unwind-tables*

[23] By the way, in some C standard functions (e.g., memcpy(), strcpy()) the arguments are listed in the same way as in Intel-syntax: first the pointer to the destination memory block, and then the pointer to the source memory block.

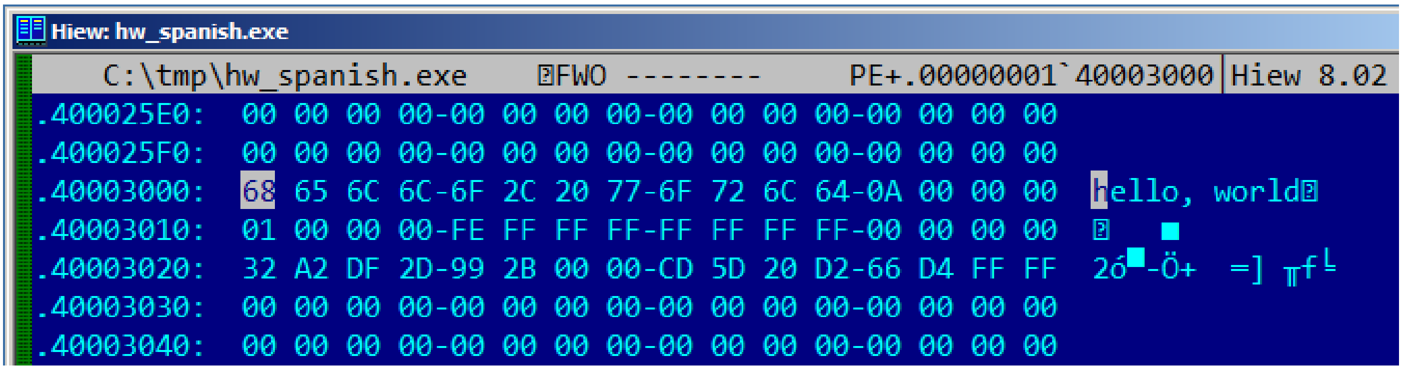


Figure 1.1: Hiew

And we can try to translate our message into Spanish:

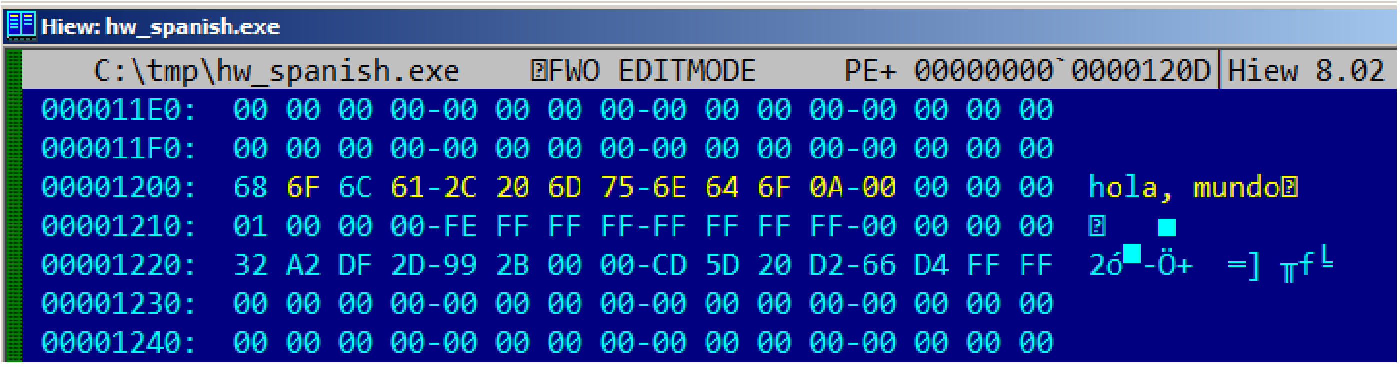


Figure 1.2: Hiew

The Spanish text is one byte shorter than English, so we also added the 0x0A byte at the end (\n) with a zero byte.

It works.

What if we want to insert a longer message? There are some zero bytes after original English text. It's hard to say if they can be overwritten: they may be used somewhere in CRT code, or maybe not. Anyway, only overwrite them if you really know what you're doing.

String patching (Linux x64)

Let's try to patch a Linux x64 executable using rada.re:

Listing 1.20: rada.re session

```
dennis@bigbox ~/tmp % gcc hw.c

dennis@bigbox ~/tmp % radare2 a.out
 -- SHALL WE PLAY A GAME?
[0x00400430]> / hello
Searching 5 bytes from 0x00400000 to 0x00601040: 68 65 6c 6c 6f
Searching 5 bytes in [0x400000-0x601040]
hits: 1
0x004005c4 hit0_0 .HHhello, world;0.

[0x00400430]> s 0x004005c4

[0x004005c4]> px
- offset -   0 1  2 3  4 5  6 7  8 9  A B  C D  E F  0123456789ABCDEF
0x004005c4  6865 6c6c 6f2c 2077 6f72 6c64 0000 0000  hello, world....
0x004005d4  011b 033b 3000 0000 0500 0000 1cfe ffff  ...;0...........
0x004005e4  7c00 0000 5cfe ffff 4c00 0000 52ff ffff  |...\...L...R...
0x004005f4  a400 0000 6cff ffff c400 0000 dcff ffff  ....l...........
```

```
0x00400604  0c01 0000 1400 0000 0000 0000 017a 5200  .............zR.
0x00400614  0178 1001 1b0c 0708 9001 0710 1400 0000  .x..............
0x00400624  1c00 0000 08fe ffff 2a00 0000 0000 0000  ........*.......
0x00400634  0000 0000 1400 0000 0000 0000 017a 5200  .............zR.
0x00400644  0178 1001 1b0c 0708 9001 0000 2400 0000  .x..........$...
0x00400654  1c00 0000 98fd ffff 3000 0000 000e 1046  ........0......F
0x00400664  0e18 4a0f 0b77 0880 003f 1a3b 2a33 2422  ..J..w...?.;*3$"
0x00400674  0000 0000 1c00 0000 4400 0000 a6fe ffff  ........D.......
0x00400684  1500 0000 0041 0e10 8602 430d 0650 0c07  .....A....C..P..
0x00400694  0800 0000 4400 0000 6400 0000 a0fe ffff  ....D...d.......
0x004006a4  6500 0000 0042 0e10 8f02 420e 188e 0345  e....B....B....E
0x004006b4  0e20 8d04 420e 288c 0548 0e30 8606 480e  . ..B.(..H.0..H.

[0x004005c4]> oo+
File a.out reopened in read-write mode

[0x004005c4]> w hola, mundo\x00

[0x004005c4]> q

dennis@bigbox ~/tmp % ./a.out
hola, mundo
```

Here's what's going on: I searched for the "hello" string using the / command, then I set the *cursor* (*seek*, in rada.re terms) to that address. Then I want to be sure that this is really that place: px dumps bytes there. oo+ switches rada.re to *read-write* mode. w writes an ASCII string at the current *seek*. Note the \00 at the end—this is a zero byte. q quits.

Software *localization* of MS-DOS era

This method was a common way to translate MS-DOS software to Russian language back to 1980's and 1990's. Russian words and sentences are usually slightly longer than its English counterparts, so that is why *localized* software has a lot of weird acronyms and hardly readable abbreviations.

Perhaps this also happened to other languages during that era, in other countries.

1.5.2 x86-64

MSVC: x86-64

Let's also try 64-bit MSVC:

Listing 1.21: MSVC 2012 x64

```
$SG2989 DB      'hello, world', 0AH, 00H

main    PROC
        sub     rsp, 40
        lea     rcx, OFFSET FLAT:$SG2989
        call    printf
        xor     eax, eax
        add     rsp, 40
        ret     0
main    ENDP
```

In x86-64, all registers were extended to 64-bit, and now their names have an R- prefix. In order to use the stack less often (in other words, to access external memory/cache less often), there is a popular way to pass function arguments via registers (*fastcall*) 6.1.3 on page 735. I.e., a part of the function's arguments are passed in registers, and the rest—via the stack. In Win64, 4 function arguments are passed in the RCX, RDX, R8, and R9 registers. That is what we see here: a pointer to the string for `printf()` is now passed not in the stack, but rather in the RCX register. The pointers are 64-bit now, so they are passed in the 64-bit registers (which have the R- prefix). However, for backward compatibility, it is still possible to access the 32-bit parts, using the E- prefix. This is how the RAX/EAX/AX/AL register looks like in x86-64:

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RAX[x64]							
				EAX			
						AX	
						AH	AL

The main() function returns an *int*-typed value, which in C/C++ is still 32-bit, for better backward compatibility and portability, so that is why the EAX register is cleared at the function end (i.e., the 32-bit part of the register) instead of with RAX. There are also 40 bytes allocated in the local stack. This is called the “shadow space”, which we’ll talk about later: 1.10.2 on page 100.

GCC: x86-64

Let’s also try GCC in 64-bit Linux:

Listing 1.22: GCC 4.4.6 x64

```
.string "hello, world\n"
main:
        sub     rsp, 8
        mov     edi, OFFSET FLAT:.LC0 ; "hello, world\n"
        xor     eax, eax  ; number of vector registers passed
        call    printf
        xor     eax, eax
        add     rsp, 8
        ret
```

Linux, *BSD and Mac OS X also use a method to pass function arguments in registers. [Michael Matz, Jan Hubicka, Andreas Jaeger, Mark Mitchell, *System V Application Binary Interface. AMD64 Architecture Processor Supplement*, (2013)] [24].

The first 6 arguments are passed in the RDI, RSI, RDX, RCX, R8, and R9 registers, and the rest—via the stack.

So the pointer to the string is passed in EDI (the 32-bit part of the register). Why doesn’t it use the 64-bit part, RDI?

It is important to keep in mind that all MOV instructions in 64-bit mode that write something into the lower 32-bit register part also clear the higher 32-bits (as stated in Intel manuals: 12.1.4 on page 1013).
I.e., the MOV EAX, 011223344h writes a value into RAX correctly, since the higher bits will be cleared.

If we open the compiled object file (.o), we can also see all the instructions’ opcodes [25]:

Listing 1.23: GCC 4.4.6 x64

```
.text:00000000004004D0                  main  proc near
.text:00000000004004D0 48 83 EC 08      sub     rsp, 8
.text:00000000004004D4 BF E8 05 40 00   mov     edi, offset format ; "hello, world\n"
.text:00000000004004D9 31 C0            xor     eax, eax
.text:00000000004004DB E8 D8 FE FF FF   call    _printf
.text:00000000004004E0 31 C0            xor     eax, eax
.text:00000000004004E2 48 83 C4 08      add     rsp, 8
.text:00000000004004E6 C3               retn
.text:00000000004004E6                  main  endp
```

As we can see, the instruction that writes into EDI at 0x4004D4 occupies 5 bytes. The same instruction writing a 64-bit value into RDI occupies 7 bytes. Apparently, GCC is trying to save some space. Besides, it can be sure that the data segment containing the string will not be allocated at the addresses higher than 4GiB.

We also see that the EAX register has been cleared before the printf() function call. This is done because according to ABI[26] standard mentioned above, the number of used vector registers is to be passed in EAX in *NIX systems on x86-64.

[24] Also available as https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf
[25] This must be enabled in **Options → Disassembly → Number of opcode bytes**
[26] Application Binary Interface

Address patching (Win64)

If our example was compiled in MSVC 2013 using \MD switch (meaning a smaller executable due to MSVCR*.DLL file linkage), the main() function comes first, and can be easily found:

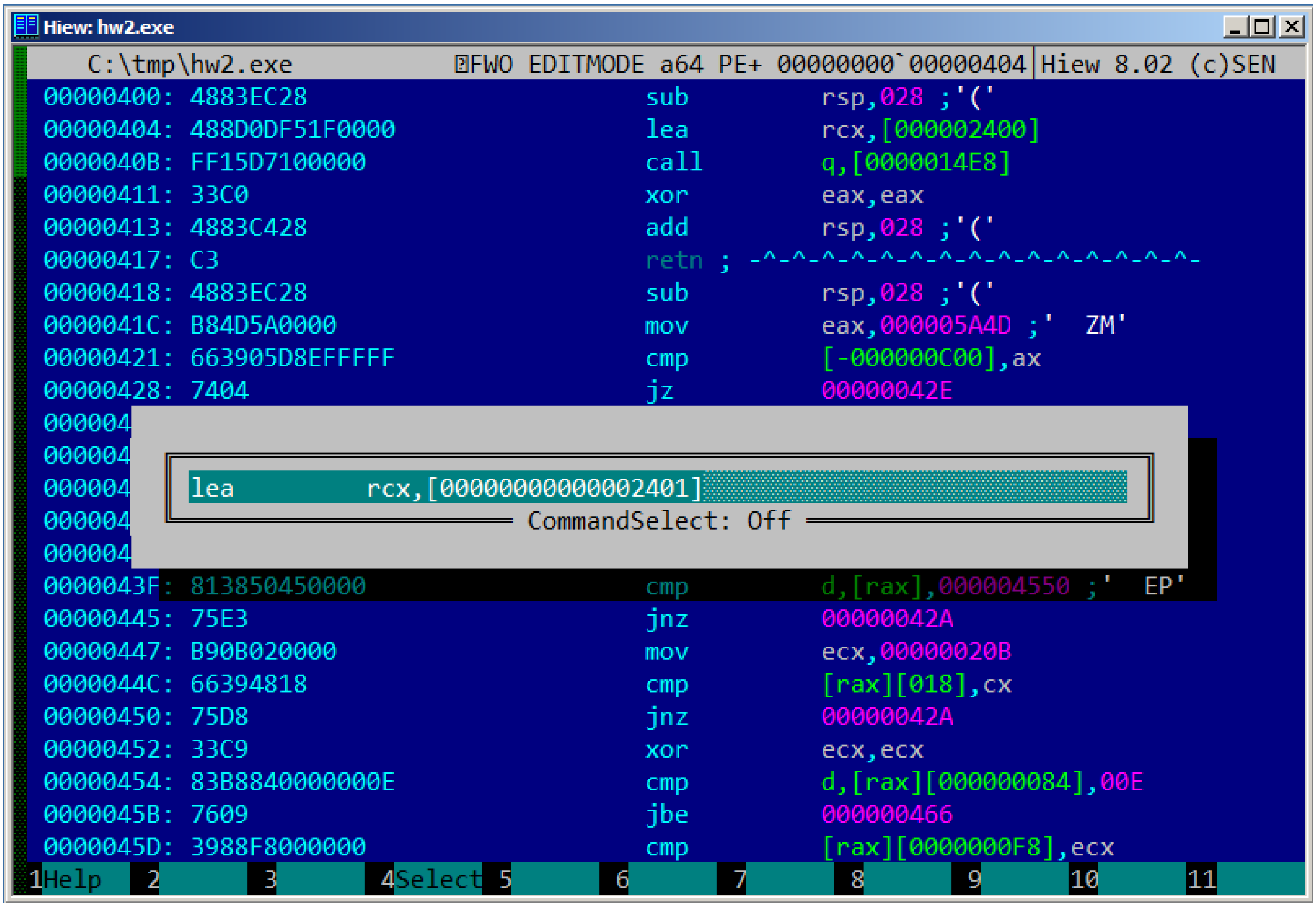


Figure 1.3: Hiew

As an experiment, we can increment address by 1:

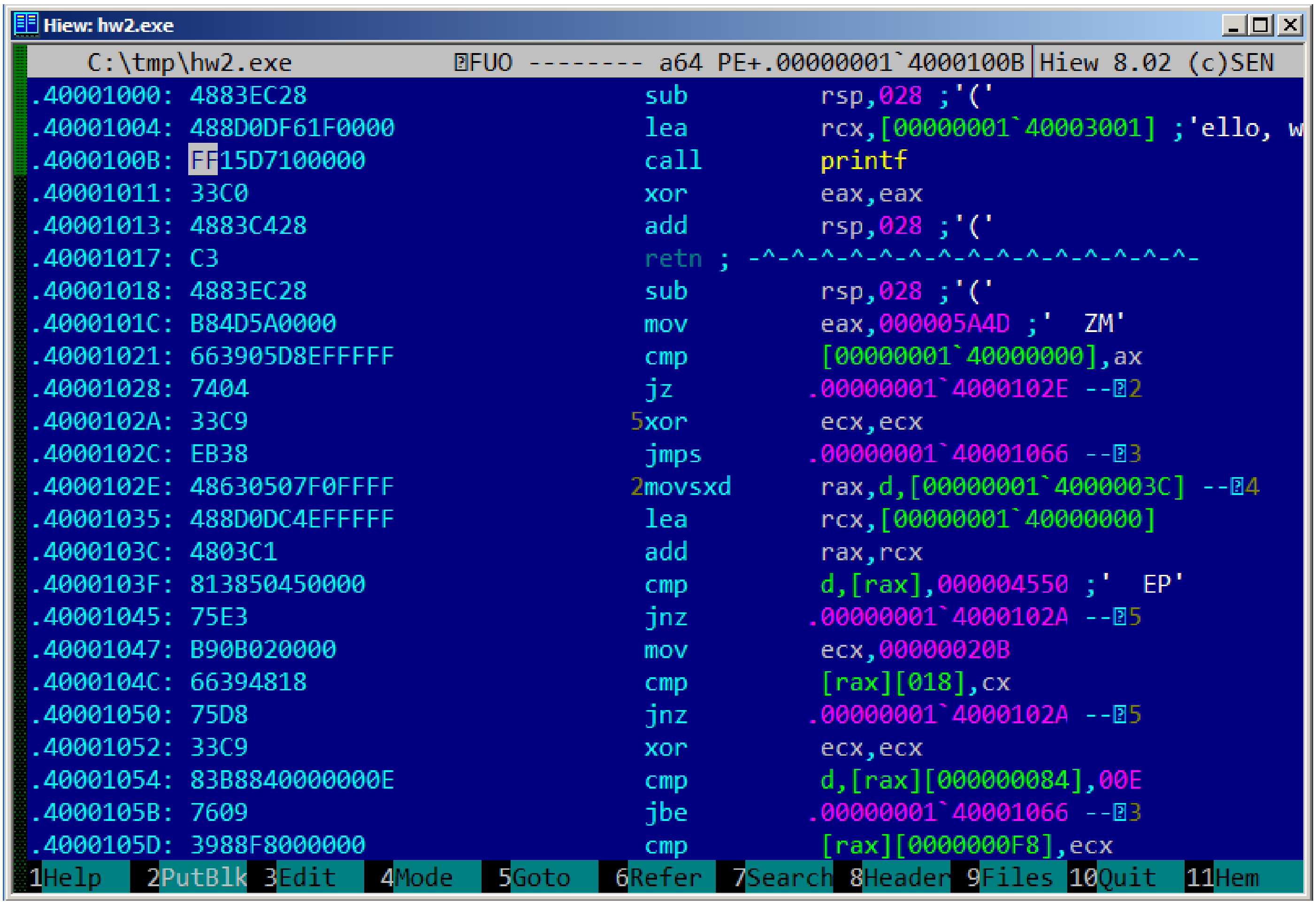


Figure 1.4: Hiew

Hiew shows “ello, world”. And when we run the patched executable, this very string is printed.

Pick another string from binary image (Linux x64)

The binary file I’ve got when I compile our example using GCC 5.4.0 on Linux x64 box has many other text strings. They are mostly imported function names and library names.

Run objdump to get the contents of all sections of the compiled file:

```
$ objdump -s a.out

a.out:     file format elf64-x86-64

Contents of section .interp:
 400238 2f6c6962 36342f6c 642d6c69 6e75782d  /lib64/ld-linux-
 400248 7838362d 36342e73 6f2e3200           x86-64.so.2.
Contents of section .note.ABI-tag:
 400254 04000000 10000000 01000000 474e5500  ............GNU.
 400264 00000000 02000000 06000000 20000000  ............ ...
Contents of section .note.gnu.build-id:
 400274 04000000 14000000 03000000 474e5500  ............GNU.
 400284 fe461178 5bb710b4 bbf2aca8 5ec1ec10  .F.x[.......^...
 400294 cf3f7ae4                             .?z.

...
```

It’s not a problem to pass address of the text string “/lib64/ld-linux-x86-64.so.2” to `printf()`:

```
#include <stdio.h>
```

```
int main()
{
    printf(0x400238);
    return 0;
}
```

It's hard to believe, but this code prints the aforementioned string.

If you would change the address to `0x400260`, the "GNU" string would be printed. This address is true for my specific GCC version, GNU toolset, etc. On your system, the executable may be slightly different, and all addresses will also be different. Also, adding/removing code to/from this source code will probably shift all addresses back or forward.

1.5.3 GCC—one more thing

The fact that an *anonymous* C-string has *const* type (1.5.1 on page 9), and that C-strings allocated in constants segment are guaranteed to be immutable, has an interesting consequence: the compiler may use a specific part of the string.

Let's try this example:

```
#include <stdio.h>

int f1()
{
        printf ("world\n");
}

int f2()
{
        printf ("hello world\n");
}

int main()
{
        f1();
        f2();
}
```

Common C/C++-compilers (including MSVC) allocate two strings, but let's see what GCC 4.8.1 does:

Listing 1.24: GCC 4.8.1 + IDA listing

```
f1              proc near

s               = dword ptr -1Ch

                sub     esp, 1Ch
                mov     [esp+1Ch+s], offset s ; "world\n"
                call    _puts
                add     esp, 1Ch
                retn
f1              endp

f2              proc near

s               = dword ptr -1Ch

                sub     esp, 1Ch
                mov     [esp+1Ch+s], offset aHello ; "hello "
                call    _puts
                add     esp, 1Ch
                retn
f2              endp

aHello          db 'hello '
s               db 'world',0xa,0
```

Indeed: when we print the "hello world" string these two words are positioned in memory adjacently and puts() called from f2() function is not aware that this string is divided. In fact, it's not divided; it's divided only "virtually", in this listing.

When puts() is called from f1(), it uses the "world" string plus a zero byte. puts() is not aware that there is something before this string!

This clever trick is often used by at least GCC and can save some memory. This is close to *string interning*.

Another related example is here: 3.2 on page 469.

1.5.4 ARM

For my experiments with ARM processors, several compilers were used:

- Popular in the embedded area: Keil Release 6/2013.
- Apple Xcode 4.6.3 IDE with the LLVM-GCC 4.2 compiler [27].
- GCC 4.9 (Linaro) (for ARM64), available as win32-executables at http://go.yurichev.com/17325.

32-bit ARM code is used (including Thumb and Thumb-2 modes) in all cases in this book, if not mentioned otherwise. When we talk about 64-bit ARM here, we call it ARM64.

Non-optimizing Keil 6/2013 (ARM mode)

Let's start by compiling our example in Keil:

```
armcc.exe --arm --c90 -O0 1.c
```

The *armcc* compiler produces assembly listings in Intel-syntax, but it has high-level ARM-processor related macros [28], but it is more important for us to see the instructions "as is" so let's see the compiled result in IDA.

Listing 1.25: Non-optimizing Keil 6/2013 (ARM mode) IDA

```
.text:00000000             main
.text:00000000 10 40 2D E9   STMFD   SP!, {R4,LR}
.text:00000004 1E 0E 8F E2   ADR     R0, aHelloWorld ; "hello, world"
.text:00000008 15 19 00 EB   BL      __2printf
.text:0000000C 00 00 A0 E3   MOV     R0, #0
.text:00000010 10 80 BD E8   LDMFD   SP!, {R4,PC}

.text:000001EC 68 65 6C 6C+aHelloWorld  DCB "hello, world",0    ; DATA XREF: main+4
```

In the example, we can easily see each instruction has a size of 4 bytes. Indeed, we compiled our code for ARM mode, not for Thumb.

The very first instruction, STMFD SP!, {R4,LR}[29], works as an x86 PUSH instruction, writing the values of two registers (R4 and LR) into the stack.

Indeed, in the output listing from the *armcc* compiler, for the sake of simplification, actually shows the PUSH {r4,lr} instruction. But that is not quite precise. The PUSH instruction is only available in Thumb mode. So, to make things less confusing, we're doing this in IDA.

This instruction first decrements the SP[31] so it points to the place in the stack that is free for new entries, then it saves the values of the R4 and LR registers at the address stored in the modified SP.

This instruction (like the PUSH instruction in Thumb mode) is able to save several register values at once which can be very useful. By the way, this has no equivalent in x86. It can also be noted that the STMFD instruction is a generalization of the PUSH instruction (extending its features), since it can work with any register, not just with SP. In other words, STMFD may be used for storing a set of registers at the specified memory address.

[27] It is indeed so: Apple Xcode 4.6.3 uses open-source GCC as front-end compiler and LLVM code generator
[28] e.g. ARM mode lacks PUSH/POP instructions
[29] STMFD[30]
[31] stack pointer. SP/ESP/RSP in x86/x64. SP in ARM.

The ADR R0, aHelloWorld instruction adds or subtracts the value in the PC[32] register to the offset where the hello, world string is located. How is the PC register used here, one might ask? This is called "position-independent code"[33].

Such code can be executed at a non-fixed address in memory. In other words, this is PC-relative addressing. The ADR instruction takes into account the difference between the address of this instruction and the address where the string is located. This difference (offset) is always to be the same, no matter at what address our code is loaded by the OS. That's why all we need is to add the address of the current instruction (from PC) in order to get the absolute memory address of our C-string.

BL __2printf[34] instruction calls the printf() function. Here's how this instruction works:

- store the address following the BL instruction (0xC) into the LR;
- then pass the control to printf() by writing its address into the PC register.

When printf() finishes its execution it must have information about where it needs to return the control to. That's why each function passes control to the address stored in the LR register.

That is a difference between "pure" RISC-processors like ARM and CISC[35]-processors like x86, where the return address is usually stored on the stack. Read more about this in next section (1.7 on page 30).

By the way, an absolute 32-bit address or offset cannot be encoded in the 32-bit BL instruction because it only has space for 24 bits. As we may recall, all ARM-mode instructions have a size of 4 bytes (32 bits). Hence, they can only be located on 4-byte boundary addresses. This implies that the last 2 bits of the instruction address (which are always zero bits) may be omitted. In summary, we have 26 bits for offset encoding. This is enough to encode $current\_PC \pm \approx 32M$.

Next, the MOV R0, #0[36] instruction just writes 0 into the R0 register. That's because our C-function returns 0 and the return value is to be placed in the R0 register.

The last instruction LDMFD SP!, R4,PC[37]. It loads values from the stack (or any other memory place) in order to save them into R4 and PC, and increments the stack pointer SP. It works like POP here.
N.B. The very first instruction STMFD saved the R4 and LR registers pair on the stack, but R4 and PC are *restored* during the LDMFD execution.

As we already know, the address of the place where each function must return control to is usually saved in the LR register. The very first instruction saves its value in the stack because the same register will be used by our main() function when calling printf(). In the function's end, this value can be written directly to the PC register, thus passing control to where our function has been called.

Since main() is usually the primary function in C/C++, the control will be returned to the OS loader or to a point in a CRT, or something like that.

All that allows omitting the BX LR instruction at the end of the function.

DCB is an assembly language directive defining an array of bytes or ASCII strings, akin to the DB directive in the x86-assembly language.

Non-optimizing Keil 6/2013 (Thumb mode)

Let's compile the same example using Keil in Thumb mode:

```
armcc.exe --thumb --c90 -O0 1.c
```

We are getting (in IDA):

Listing 1.26: Non-optimizing Keil 6/2013 (Thumb mode) + IDA

```
.text:00000000             main
.text:00000000 10 B5          PUSH    {R4,LR}
.text:00000002 C0 A0          ADR     R0, aHelloWorld ; "hello, world"
.text:00000004 06 F0 2E F9    BL      __2printf
.text:00000008 00 20          MOVS    R0, #0
.text:0000000A 10 BD          POP     {R4,PC}
```

[32] Program Counter. IP/EIP/RIP in x86/64. PC in ARM.
[33] Read more about it in relevant section (6.4.1 on page 748)
[34] Branch with Link
[35] Complex Instruction Set Computing
[36] Meaning MOVe
[37] LDMFD[38] is an inverse instruction of STMFD

```
.text:00000304 68 65 6C 6C+aHelloWorld  DCB "hello, world",0    ; DATA XREF: main+2
```

We can easily spot the 2-byte (16-bit) opcodes. This is, as was already noted, Thumb. The BL instruction, however, consists of two 16-bit instructions. This is because it is impossible to load an offset for the printf() function while using the small space in one 16-bit opcode. Therefore, the first 16-bit instruction loads the higher 10 bits of the offset and the second instruction loads the lower 11 bits of the offset.

As was noted, all instructions in Thumb mode have a size of 2 bytes (or 16 bits). This implies it is impossible for a Thumb-instruction to be at an odd address whatsoever. Given the above, the last address bit may be omitted while encoding instructions.

In summary, the BL Thumb-instruction can encode an address in $current\_PC \pm \approx 2M$.

As for the other instructions in the function: PUSH and POP work here just like the described STMFD/LDMFD only the SP register is not mentioned explicitly here. ADR works just like in the previous example. MOVS writes 0 into the R0 register in order to return zero.

Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Xcode 4.6.3 without optimization turned on produces a lot of redundant code so we'll study optimized output, where the instruction count is as small as possible, setting the compiler switch -O3.

Listing 1.27: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
__text:000028C4             _hello_world
__text:000028C4 80 40 2D E9   STMFD           SP!, {R7,LR}
__text:000028C8 86 06 01 E3   MOV             R0, #0x1686
__text:000028CC 0D 70 A0 E1   MOV             R7, SP
__text:000028D0 00 00 40 E3   MOVT            R0, #0
__text:000028D4 00 00 8F E0   ADD             R0, PC, R0
__text:000028D8 C3 05 00 EB   BL              _puts
__text:000028DC 00 00 A0 E3   MOV             R0, #0
__text:000028E0 80 80 BD E8   LDMFD           SP!, {R7,PC}

__cstring:00003F62 48 65 6C 6C+aHelloWorld_0  DCB "Hello world!",0
```

The instructions STMFD and LDMFD are already familiar to us.

The MOV instruction just writes the number 0x1686 into the R0 register. This is the offset pointing to the "Hello world!" string.

The R7 register (as it is standardized in [*iOS ABI Function Call Guide*, (2010)][39]) is a frame pointer. More on that below.

The MOVT R0, #0 (MOVe Top) instruction writes 0 into higher 16 bits of the register. The issue here is that the generic MOV instruction in ARM mode may write only the lower 16 bits of the register.

Keep in mind, all instruction opcodes in ARM mode are limited in size to 32 bits. Of course, this limitation is not related to moving data between registers. That's why an additional instruction MOVT exists for writing into the higher bits (from 16 to 31 inclusive). Its usage here, however, is redundant because the MOV R0, #0x1686 instruction above cleared the higher part of the register. This is supposedly a shortcoming of the compiler.

The ADD R0, PC, R0 instruction adds the value in the PC to the value in the R0, to calculate the absolute address of the "Hello world!" string. As we already know, it is "position-independent code" so this correction is essential here.

The BL instruction calls the puts() function instead of printf().

GCC replaced the first printf() call with puts(). Indeed: printf() with a sole argument is almost analogous to puts().

Almost, because the two functions are producing the same result only in case the string does not contain printf format identifiers starting with %. In case it does, the effect of these two functions would be different [40].

[39] Also available as http://go.yurichev.com/17276

[40] It has also to be noted the puts() does not require a '\n' new line symbol at the end of a string, so we do not see it here.

Why did the compiler replace the `printf()` with `puts()`? Presumably because `puts()` is faster [41].

Because it just passes characters to stdout without comparing every one of them with the % symbol.

Next, we see the familiar `MOV R0, #0` instruction intended to set the R0 register to 0.

Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

By default Xcode 4.6.3 generates code for Thumb-2 in this manner:

Listing 1.28: Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```
__text:00002B6C                   _hello_world
__text:00002B6C 80 B5          PUSH           {R7,LR}
__text:00002B6E 41 F2 D8 30    MOVW           R0, #0x13D8
__text:00002B72 6F 46          MOV            R7, SP
__text:00002B74 C0 F2 00 00    MOVT.W         R0, #0
__text:00002B78 78 44          ADD            R0, PC
__text:00002B7A 01 F0 38 EA    BLX            _puts
__text:00002B7E 00 20          MOVS           R0, #0
__text:00002B80 80 BD          POP            {R7,PC}

...

__cstring:00003E70 48 65 6C 6C 6F 20+aHelloWorld  DCB "Hello world!",0xA,0
```

The BL and BLX instructions in Thumb mode, as we recall, are encoded as a pair of 16-bit instructions. In Thumb-2 these *surrogate* opcodes are extended in such a way so that new instructions may be encoded here as 32-bit instructions.

That is obvious considering that the opcodes of the Thumb-2 instructions always begin with `0xFx` or `0xEx`.

But in the IDA listing the opcode bytes are swapped because for ARM processor the instructions are encoded as follows: last byte comes first and after that comes the first one (for Thumb and Thumb-2 modes) or for instructions in ARM mode the fourth byte comes first, then the third, then the second and finally the first (due to different endianness).

So that is how bytes are located in IDA listings:

- for ARM and ARM64 modes: 4-3-2-1;
- for Thumb mode: 2-1;
- for 16-bit instructions pair in Thumb-2 mode: 2-1-4-3.

So as we can see, the `MOVW`, `MOVT.W` and `BLX` instructions begin with `0xFx`.

One of the Thumb-2 instructions is `MOVW R0, #0x13D8` —it stores a 16-bit value into the lower part of the `R0` register, clearing the higher bits.

Also, `MOVT.W R0, #0` works just like `MOVT` from the previous example only it works in Thumb-2.

Among the other differences, the BLX instruction is used in this case instead of the BL.

The difference is that, besides saving the RA[42] in the LR register and passing control to the `puts()` function, the processor is also switching from Thumb/Thumb-2 mode to ARM mode (or back).

This instruction is placed here since the instruction to which control is passed looks like (it is encoded in ARM mode):

```
__symbolstub1:00003FEC _puts           ; CODE XREF: _hello_world+E
__symbolstub1:00003FEC 44 F0 9F E5     LDR  PC, =__imp__puts
```

This is essentially a jump to the place where the address of `puts()` is written in the imports' section.

So, the observant reader may ask: why not call `puts()` right at the point in the code where it is needed?

Because it is not very space-efficient.

Almost any program uses external dynamic libraries (like DLL in Windows, .so in *NIX or .dylib in Mac OS X). The dynamic libraries contain frequently used library functions, including the standard C-function `puts()`.

[41] ciselant.de/projects/gcc_printf/gcc_printf.html
[42] Return Address

In an executable binary file (Windows PE .exe, ELF or Mach-O) an import section is present. This is a list of symbols (functions or global variables) imported from external modules along with the names of the modules themselves.

The OS loader loads all modules it needs and, while enumerating import symbols in the primary module, determines the correct addresses of each symbol.

In our case, *__imp__puts* is a 32-bit variable used by the OS loader to store the correct address of the function in an external library. Then the LDR instruction just reads the 32-bit value from this variable and writes it into the PC register, passing control to it.

So, in order to reduce the time the OS loader needs for completing this procedure, it is good idea to write the address of each symbol only once, to a dedicated place.

Besides, as we have already figured out, it is impossible to load a 32-bit value into a register while using only one instruction without a memory access.

Therefore, the optimal solution is to allocate a separate function working in ARM mode with the sole goal of passing control to the dynamic library and then to jump to this short one-instruction function (the so-called thunk function) from the Thumb-code.

By the way, in the previous example (compiled for ARM mode) the control is passed by the BL to the same thunk function. The processor mode, however, is not being switched (hence the absence of an "X" in the instruction mnemonic).

More about thunk-functions

Thunk-functions are hard to understand, apparently, because of a misnomer. The simplest way to understand it as adaptors or convertors of one type of jack to another. For example, an adaptor allowing the insertion of a British power plug into an American wall socket, or vice-versa. Thunk functions are also sometimes called *wrappers*.

Here are a couple more descriptions of these functions:

> "A piece of coding which provides an address:", according to P. Z. Ingerman, who invented thunks in 1961 as a way of binding actual parameters to their formal definitions in Algol-60 procedure calls. If a procedure is called with an expression in the place of a formal parameter, the compiler generates a thunk which computes the expression and leaves the address of the result in some standard location.
>
> …
>
> Microsoft and IBM have both defined, in their Intel-based systems, a "16-bit environment" (with bletcherous segment registers and 64K address limits) and a "32-bit environment" (with flat addressing and semi-real memory management). The two environments can both be running on the same computer and OS (thanks to what is called, in the Microsoft world, WOW which stands for Windows On Windows). MS and IBM have both decided that the process of getting from 16- to 32-bit and vice versa is called a "thunk"; for Windows 95, there is even a tool, THUNK.EXE, called a "thunk compiler".

(The Jargon File)

Another example we can find in LAPACK library—a "Linear Algebra PACKage" written in FORTRAN. C/C++ developers also want to use LAPACK, but it's insane to rewrite it to C/C++ and then maintain several versions. So there are short C functions callable from C/C++ environment, which are, in turn, call FORTRAN functions, and do almost anything else:

```
double Blas_Dot_Prod(const LaVectorDouble &dx, const LaVectorDouble &dy)
{
    assert(dx.size()==dy.size());
    integer n = dx.size();
    integer incx = dx.inc(), incy = dy.inc();

    return F77NAME(ddot)(&n, &dx(0), &incx, &dy(0), &incy);
}
```

Also, functions like that are called "wrappers".

ARM64

GCC

Let's compile the example using GCC 4.8.1 in ARM64:

Listing 1.29: Non-optimizing GCC 4.8.1 + objdump

```
0000000000400590 <main>:
  400590:       a9bf7bfd        stp     x29, x30, [sp,#-16]!
  400594:       910003fd        mov     x29, sp
  400598:       90000000        adrp    x0, 400000 <_init-0x3b8>
  40059c:       91192000        add     x0, x0, #0x648
  4005a0:       97ffffa0        bl      400420 <puts@plt>
  4005a4:       52800000        mov     w0, #0x0                        // #0
  4005a8:       a8c17bfd        ldp     x29, x30, [sp],#16
  4005ac:       d65f03c0        ret

...

Contents of section .rodata:
 400640 01000200 00000000 48656c6c 6f210a00  ........Hello!..
```

There are no Thumb and Thumb-2 modes in ARM64, only ARM, so there are 32-bit instructions only. The Register count is doubled: .2.4 on page 1041. 64-bit registers have X- prefixes, while its 32-bit parts—W-.

The STP instruction (*Store Pair*) saves two registers in the stack simultaneously: X29 and X30.

Of course, this instruction is able to save this pair at an arbitrary place in memory, but the SP register is specified here, so the pair is saved in the stack.

ARM64 registers are 64-bit ones, each has a size of 8 bytes, so one needs 16 bytes for saving two registers.

The exclamation mark ("!") after the operand means that 16 is to be subtracted from SP first, and only then are values from register pair to be written into the stack. This is also called *pre-index*. About the difference between *post-index* and *pre-index* read here: 1.32.2 on page 439.

Hence, in terms of the more familiar x86, the first instruction is just an analogue to a pair of PUSH X29 and PUSH X30. X29 is used as FP[43] in ARM64, and X30 as LR, so that's why they are saved in the function prologue and restored in the function epilogue.

The second instruction copies SP in X29 (or FP). This is made so to set up the function stack frame.

ADRP and ADD instructions are used to fill the address of the string "Hello!" into the X0 register, because the first function argument is passed in this register. There are no instructions, whatsoever, in ARM that can store a large number into a register (because the instruction length is limited to 4 bytes, read more about it here: 1.32.3 on page 440). So several instructions must be utilized. The first instruction (ADRP) writes the address of the 4KiB page, where the string is located, into X0, and the second one (ADD) just adds the remainder to the address. More about that in: 1.32.4 on page 442.

0x400000 + 0x648 = 0x400648, and we see our "Hello!" C-string in the .rodata data segment at this address.

puts() is called afterwards using the BL instruction. This was already discussed: 1.5.4 on page 21.

MOV writes 0 into W0. W0 is the lower 32 bits of the 64-bit X0 register:

High 32-bit part	low 32-bit part
X0	
	W0

The function result is returned via X0 and main() returns 0, so that's how the return result is prepared. But why use the 32-bit part?

Because the *int* data type in ARM64, just like in x86-64, is still 32-bit, for better compatibility.

So if a function returns a 32-bit *int*, only the lower 32 bits of X0 register have to be filled.

In order to verify this, let's change this example slightly and recompile it. Now main() returns a 64-bit value:

[43] Frame Pointer

Listing 1.30: main() returning a value of uint64_t type

```
#include <stdio.h>
#include <stdint.h>

uint64_t main()
{
        printf ("Hello!\n");
        return 0;
}
```

The result is the same, but that's how MOV at that line looks like now:

Listing 1.31: Non-optimizing GCC 4.8.1 + objdump

```
  4005a4:       d2800000        mov     x0, #0x0        // #0
```

LDP (*Load Pair*) then restores the X29 and X30 registers.

There is no exclamation mark after the instruction: this implies that the values are first loaded from the stack, and only then is SP increased by 16. This is called *post-index*.

A new instruction appeared in ARM64: RET. It works just as BX LR, only a special *hint* bit is added, informing the CPU that this is a return from a function, not just another jump instruction, so it can execute it more optimally.

Due to the simplicity of the function, optimizing GCC generates the very same code.

1.5.5 MIPS

A word about the "global pointer"

One important MIPS concept is the "global pointer". As we may already know, each MIPS instruction has a size of 32 bits, so it's impossible to embed a 32-bit address into one instruction: a pair has to be used for this (like GCC did in our example for the text string address loading). It's possible, however, to load data from the address in the range of $register - 32768 ... register + 32767$ using one single instruction (because 16 bits of signed offset could be encoded in a single instruction). So we can allocate some register for this purpose and also allocate a 64KiB area of most used data. This allocated register is called a "global pointer" and it points to the middle of the 64KiB area. This area usually contains global variables and addresses of imported functions like printf(), because the GCC developers decided that getting the address of some function must be as fast as a single instruction execution instead of two. In an ELF file this 64KiB area is located partly in sections .sbss ("small BSS[44]") for uninitialized data and .sdata ("small data") for initialized data. This implies that the programmer may choose what data he/she wants to be accessed fast and place it into .sdata/.sbss. Some old-school programmers may recall the MS-DOS memory model 11.6 on page 1003 or the MS-DOS memory managers like XMS/EMS where all memory was divided in 64KiB blocks.

This concept is not unique to MIPS. At least PowerPC uses this technique as well.

Optimizing GCC

Let's consider the following example, which illustrates the "global pointer" concept.

Listing 1.32: Optimizing GCC 4.4.5 (assembly output)

```
$LC0:
; \000 is zero byte in octal base:
        .ascii  "Hello, world!\012\000"
main:
; function prologue.
; set the GP:
        lui     $28,%hi(__gnu_local_gp)
        addiu   $sp,$sp,-32
        addiu   $28,$28,%lo(__gnu_local_gp)
; save the RA to the local stack:
        sw      $31,28($sp)
```

[44] Block Started by Symbol

```
12 ; load the address of the puts() function from the GP to $25:
13         lw      $25,%call16(puts)($28)
14 ; load the address of the text string to $4 ($a0):
15         lui     $4,%hi($LC0)
16 ; jump to puts(), saving the return address in the link register:
17         jalr    $25
18         addiu   $4,$4,%lo($LC0) ; branch delay slot
19 ; restore the RA:
20         lw      $31,28($sp)
21 ; copy 0 from $zero to $v0:
22         move    $2,$0
23 ; return by jumping to the RA:
24         j       $31
25 ; function epilogue:
26         addiu   $sp,$sp,32 ; branch delay slot + free local stack
```

As we see, the $GP register is set in the function prologue to point to the middle of this area. The RA register is also saved in the local stack. `puts()` is also used here instead of `printf()`. The address of the `puts()` function is loaded into $25 using LW the instruction ("Load Word"). Then the address of the text string is loaded to $4 using LUI ("Load Upper Immediate") and ADDIU ("Add Immediate Unsigned Word") instruction pair. LUI sets the high 16 bits of the register (hence "upper" word in instruction name) and ADDIU adds the lower 16 bits of the address.

ADDIU follows JALR (haven't you forgot *branch delay slots* yet?). The register $4 is also called $A0, which is used for passing the first function argument [45].

JALR ("Jump and Link Register") jumps to the address stored in the $25 register (address of `puts()`) while saving the address of the next instruction (LW) in RA. This is very similar to ARM. Oh, and one important thing is that the address saved in RA is not the address of the next instruction (because it's in a *delay slot* and is executed before the jump instruction), but the address of the instruction after the next one (after the *delay slot*). Hence, $PC+8$ is written to RA during the execution of JALR, in our case, this is the address of the LW instruction next to ADDIU.

LW ("Load Word") at line 20 restores RA from the local stack (this instruction is actually part of the function epilogue).

MOVE at line 22 copies the value from the $0 ($ZERO) register to $2 ($V0).

MIPS has a *constant* register, which always holds zero. Apparently, the MIPS developers came up with the idea that zero is in fact the busiest constant in the computer programming, so let's just use the $0 register every time zero is needed.

Another interesting fact is that MIPS lacks an instruction that transfers data between registers. In fact, `MOVE DST, SRC` is `ADD DST, SRC, $ZERO` ($DST = SRC + 0$), which does the same. Apparently, the MIPS developers wanted to have a compact opcode table. This does not mean an actual addition happens at each MOVE instruction. Most likely, the CPU optimizes these pseudo instructions and the ALU[46] is never used.

J at line 24 jumps to the address in RA, which is effectively performing a return from the function. ADDIU after J is in fact executed before J (remember *branch delay slots*?) and is part of the function epilogue. Here is also a listing generated by IDA. Each register here has its own pseudo name:

Listing 1.33: Optimizing GCC 4.4.5 (IDA)

```
.text:00000000 main:
.text:00000000
.text:00000000 var_10          = -0x10
.text:00000000 var_4           = -4
.text:00000000
; function prologue.
; set the GP:
.text:00000000                 lui     $gp, (__gnu_local_gp >> 16)
.text:00000004                 addiu   $sp, -0x20
.text:00000008                 la      $gp, (__gnu_local_gp & 0xFFFF)
; save the RA to the local stack:
.text:0000000C                 sw      $ra, 0x20+var_4($sp)
; save the GP to the local stack:
; for some reason, this instruction is missing in the GCC assembly output:
```

[45]The MIPS registers table is available in appendix .3.1 on page 1042

[46]Arithmetic Logic Unit

```
15 .text:00000010                 sw      $gp, 0x20+var_10($sp)
16 ; load the address of the puts() function from the GP to $t9:
17 .text:00000014                 lw      $t9, (puts & 0xFFFF)($gp)
18 ; form the address of the text string in $a0:
19 .text:00000018                 lui     $a0, ($LC0 >> 16)  # "Hello, world!"
20 ; jump to puts(), saving the return address in the link register:
21 .text:0000001C                 jalr    $t9
22 .text:00000020                 la      $a0, ($LC0 & 0xFFFF)  # "Hello, world!"
23 ; restore the RA:
24 .text:00000024                 lw      $ra, 0x20+var_4($sp)
25 ; copy 0 from $zero to $v0:
26 .text:00000028                 move    $v0, $zero
27 ; return by jumping to the RA:
28 .text:0000002C                 jr      $ra
29 ; function epilogue:
30 .text:00000030                 addiu   $sp, 0x20
```

The instruction at line 15 saves the GP value into the local stack, and this instruction is missing mysteriously from the GCC output listing, maybe by a GCC error [47]. The GP value has to be saved indeed, because each function can use its own 64KiB data window. The register containing the `puts()` address is called $T9, because registers prefixed with T- are called "temporaries" and their contents may not be preserved.

Non-optimizing GCC

Non-optimizing GCC is more verbose.

Listing 1.34: Non-optimizing GCC 4.4.5 (assembly output)

```
$LC0:
        .ascii  "Hello, world!\012\000"
main:
; function prologue.
; save the RA ($31) and FP in the stack:
        addiu   $sp,$sp,-32
        sw      $31,28($sp)
        sw      $fp,24($sp)
; set the FP (stack frame pointer):
        move    $fp,$sp
; set the GP:
        lui     $28,%hi(__gnu_local_gp)
        addiu   $28,$28,%lo(__gnu_local_gp)
; load the address of the text string:
        lui     $2,%hi($LC0)
        addiu   $4,$2,%lo($LC0)
; load the address of puts() using the GP:
        lw      $2,%call16(puts)($28)
        nop
; call puts():
        move    $25,$2
        jalr    $25
        nop  ; branch delay slot

; restore the GP from the local stack:
        lw      $28,16($fp)
; set register $2 ($V0) to zero:
        move    $2,$0
; function epilogue.
; restore the SP:
        move    $sp,$fp
; restore the RA:
        lw      $31,28($sp)
; restore the FP:
        lw      $fp,24($sp)
        addiu   $sp,$sp,32
; jump to the RA:
        j       $31
        nop  ; branch delay slot
```

[47] Apparently, functions generating listings are not so critical to GCC users, so some unfixed errors may still exist.

We see here that register FP is used as a pointer to the stack frame. We also see 3 NOPs. The second and third of which follow the branch instructions. Perhaps the GCC compiler always adds NOPs (because of *branch delay slots*) after branch instructions and then, if optimization is turned on, maybe eliminates them. So in this case they are left here.

Here is also IDA listing:

Listing 1.35: Non-optimizing GCC 4.4.5 (IDA)

```
1  .text:00000000 main:
2  .text:00000000
3  .text:00000000 var_10          = -0x10
4  .text:00000000 var_8           = -8
5  .text:00000000 var_4           = -4
6  .text:00000000
7  ; function prologue.
8  ; save the RA and FP in the stack:
9  .text:00000000                 addiu   $sp, -0x20
10 .text:00000004                 sw      $ra, 0x20+var_4($sp)
11 .text:00000008                 sw      $fp, 0x20+var_8($sp)
12 ; set the FP (stack frame pointer):
13 .text:0000000C                 move    $fp, $sp
14 ; set the GP:
15 .text:00000010                 la      $gp, __gnu_local_gp
16 .text:00000018                 sw      $gp, 0x20+var_10($sp)
17 ; load the address of the text string:
18 .text:0000001C                 lui     $v0, (aHelloWorld >> 16)  # "Hello, world!"
19 .text:00000020                 addiu   $a0, $v0, (aHelloWorld & 0xFFFF)  # "Hello, world!"
20 ; load the address of puts() using the GP:
21 .text:00000024                 lw      $v0, (puts & 0xFFFF)($gp)
22 .text:00000028                 or      $at, $zero ; NOP
23 ; call puts():
24 .text:0000002C                 move    $t9, $v0
25 .text:00000030                 jalr    $t9
26 .text:00000034                 or      $at, $zero ; NOP
27 ; restore the GP from local stack:
28 .text:00000038                 lw      $gp, 0x20+var_10($fp)
29 ; set register $2 ($V0) to zero:
30 .text:0000003C                 move    $v0, $zero
31 ; function epilogue.
32 ; restore the SP:
33 .text:00000040                 move    $sp, $fp
34 ; restore the RA:
35 .text:00000044                 lw      $ra, 0x20+var_4($sp)
36 ; restore the FP:
37 .text:00000048                 lw      $fp, 0x20+var_8($sp)
38 .text:0000004C                 addiu   $sp, 0x20
39 ; jump to the RA:
40 .text:00000050                 jr      $ra
41 .text:00000054                 or      $at, $zero ; NOP
```

Interestingly, IDA recognized the `LUI`/`ADDIU` instructions pair and coalesced them into one `LA` ("Load Address") pseudo instruction at line 15. We may also see that this pseudo instruction has a size of 8 bytes! This is a pseudo instruction (or *macro*) because it's not a real MIPS instruction, but rather a handy name for an instruction pair.

Another thing is that IDA doesn't recognize NOP instructions, so here they are at lines 22, 26 and 41. It is `OR $AT, $ZERO`. Essentially, this instruction applies the OR operation to the contents of the $AT register with zero, which is, of course, an idle instruction. MIPS, like many other ISAs, doesn't have a separate NOP instruction.

Role of the stack frame in this example

The address of the text string is passed in the register. Why setup a local stack anyway? The reason for this lies in the fact that the values of registers RA and GP have to be saved somewhere (because `printf()` is called), and the local stack is used for this purpose. If this was a leaf function, it would have been possible to get rid of the function prologue and epilogue, for example: 1.4.3 on page 8.

Optimizing GCC: load it into GDB

Listing 1.36: sample GDB session

```
root@debian-mips:~# gcc hw.c -O3 -o hw

root@debian-mips:~# gdb hw
GNU gdb (GDB) 7.0.1-debian
...
Reading symbols from /root/hw...(no debugging symbols found)...done.
(gdb) b main
Breakpoint 1 at 0x400654
(gdb) run
Starting program: /root/hw

Breakpoint 1, 0x00400654 in main ()
(gdb) set step-mode on
(gdb) disas
Dump of assembler code for function main:
0x00400640 <main+0>:    lui     gp,0x42
0x00400644 <main+4>:    addiu   sp,sp,-32
0x00400648 <main+8>:    addiu   gp,gp,-30624
0x0040064c <main+12>:   sw      ra,28(sp)
0x00400650 <main+16>:   sw      gp,16(sp)
0x00400654 <main+20>:   lw      t9,-32716(gp)
0x00400658 <main+24>:   lui     a0,0x40
0x0040065c <main+28>:   jalr    t9
0x00400660 <main+32>:   addiu   a0,a0,2080
0x00400664 <main+36>:   lw      ra,28(sp)
0x00400668 <main+40>:   move    v0,zero
0x0040066c <main+44>:   jr      ra
0x00400670 <main+48>:   addiu   sp,sp,32
End of assembler dump.
(gdb) s
0x00400658 in main ()
(gdb) s
0x0040065c in main ()
(gdb) s
0x2ab2de60 in printf () from /lib/libc.so.6
(gdb) x/s $a0
0x400820:        "hello, world"
(gdb)
```

1.5.6 Conclusion

The main difference between x86/ARM and x64/ARM64 code is that the pointer to the string is now 64-bits in length. Indeed, modern CPUs are now 64-bit due to both the reduced cost of memory and the greater demand for it by modern applications. We can add much more memory to our computers than 32-bit pointers are able to address. As such, all pointers are now 64-bit.

1.5.7 Exercises

- http://challenges.re/48
- http://challenges.re/49

1.6 Function prologue and epilogue

A function prologue is a sequence of instructions at the start of a function. It often looks something like the following code fragment:

```
    push    ebp
    mov     ebp, esp
    sub     esp, X
```

What these instruction do: save the value in the EBP register, set the value of the EBP register to the value of the ESP and then allocate space on the stack for local variables.

The value in the EBP stays the same over the period of the function execution and is to be used for local variables and arguments access. For the same purpose one can use ESP, but since it changes over time this approach is not too convenient.

The function epilogue frees the allocated space in the stack, returns the value in the EBP register back to its initial state and returns the control flow to the caller:

```
    mov     esp, ebp
    pop     ebp
    ret     0
```

Function prologues and epilogues are usually detected in disassemblers for function delimitation.

1.6.1 Recursion

Epilogues and prologues can negatively affect the recursion performance.

More about recursion in this book: 3.4.3 on page 481.

1.7 Stack

The stack is one of the most fundamental data structures in computer science [48]. AKA[49] LIFO[50].

Technically, it is just a block of memory in process memory along with the ESP or RSP register in x86 or x64, or the SP register in ARM, as a pointer within that block.

The most frequently used stack access instructions are PUSH and POP (in both x86 and ARM Thumb-mode). PUSH subtracts from ESP/RSP/SP 4 in 32-bit mode (or 8 in 64-bit mode) and then writes the contents of its sole operand to the memory address pointed by ESP/RSP/SP.

POP is the reverse operation: retrieve the data from the memory location that SP points to, load it into the instruction operand (often a register) and then add 4 (or 8) to the stack pointer.

After stack allocation, the stack pointer points at the bottom of the stack. PUSH decreases the stack pointer and POP increases it. The bottom of the stack is actually at the beginning of the memory allocated for the stack block. It seems strange, but that's the way it is.

ARM supports both descending and ascending stacks.

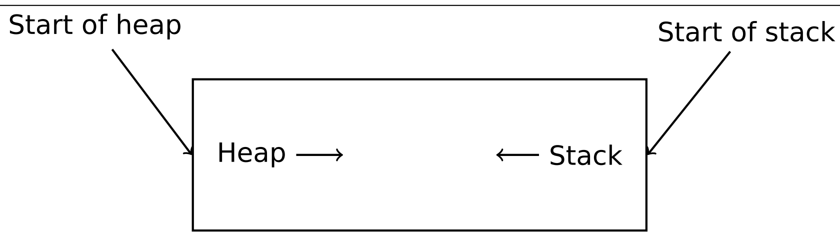
For example the STMFD/LDMFD, STMED[51]/LDMED[52] instructions are intended to deal with a descending stack (grows downwards, starting with a high address and progressing to a lower one). The STMFA[53]/LDMFA[54], STMEA[55]/LDMEA[56] instructions are intended to deal with an ascending stack (grows upwards, starting from a low address and progressing to a higher one).

1.7.1 Why does the stack grow backwards?

Intuitively, we might think that the stack grows upwards, i.e. towards higher addresses, like any other data structure.

The reason that the stack grows backward is probably historical. When the computers were big and occupied a whole room, it was easy to divide memory into two parts, one for the heap and one for the stack. Of course, it was unknown how big the heap and the stack would be during program execution, so this solution was the simplest possible.

[48] wikipedia.org/wiki/Call_stack
[49] Also Known As
[50] Last In First Out
[51] Store Multiple Empty Descending (ARM instruction)
[52] Load Multiple Empty Descending (ARM instruction)
[53] Store Multiple Full Ascending (ARM instruction)
[54] Load Multiple Full Ascending (ARM instruction)
[55] Store Multiple Empty Ascending (ARM instruction)
[56] Load Multiple Empty Ascending (ARM instruction)



In [D. M. Ritchie and K. Thompson, *The UNIX Time Sharing System*, (1974)][57] we can read:

> The user-core part of an image is divided into three logical segments. The program text segment begins at location 0 in the virtual address space. During execution, this segment is write-protected and a single copy of it is shared among all processes executing the same program. At the first 8K byte boundary above the program text segment in the virtual address space begins a nonshared, writable data segment, the size of which may be extended by a system call. Starting at the highest address in the virtual address space is a stack segment, which automatically grows downward as the hardware's stack pointer fluctuates.

This reminds us how some students write two lecture notes using only one notebook: notes for the first lecture are written as usual, and notes for the second one are written from the end of notebook, by flipping it. Notes may meet each other somewhere in between, in case of lack of free space.

1.7.2 What is the stack used for?

Save the function's return address

x86

When calling another function with a CALL instruction, the address of the point exactly after the CALL instruction is saved to the stack and then an unconditional jump to the address in the CALL operand is executed.

The CALL instruction is equivalent to a
`PUSH address_after_call / JMP operand` instruction pair.

RET fetches a value from the stack and jumps to it —that is equivalent to a `POP tmp / JMP tmp` instruction pair.

Overflowing the stack is straightforward. Just run eternal recursion:

```
void f()
{
        f();
};
```

MSVC 2008 reports the problem:

```
c:\tmp6>cl ss.cpp /Fass.asm
Microsoft (R) 32-bit C/C++ Optimizing Compiler Version 15.00.21022.08 for 80x86
Copyright (C) Microsoft Corporation.  All rights reserved.

ss.cpp
c:\tmp6\ss.cpp(4) : warning C4717: 'f' : recursive on all control paths, function will cause ↙
    ↘ runtime stack overflow
```

...but generates the right code anyway:

```
?f@@YAXXZ PROC                    ; f
; File c:\tmp6\ss.cpp
; Line 2
        push    ebp
        mov     ebp, esp
; Line 3
        call    ?f@@YAXXZ         ; f
```

[57] Also available as http://go.yurichev.com/17270

```
; Line 4
        pop     ebp
        ret     0
?f@@YAXXZ ENDP                          ; f
```

...Also if we turn on the compiler optimization (/Ox option) the optimized code will not overflow the stack and will work *correctly*[58] instead:

```
?f@@YAXXZ PROC                          ; f
; File c:\tmp6\ss.cpp
; Line 2
$LL3@f:
; Line 3
        jmp     SHORT $LL3@f
?f@@YAXXZ ENDP                          ; f
```

GCC 4.4.1 generates similar code in both cases without, however, issuing any warning about the problem.

ARM

ARM programs also use the stack for saving return addresses, but differently. As mentioned in "Hello, world!" (1.5.4 on page 19), the RA is saved to the LR (link register). If one needs, however, to call another function and use the LR register one more time, its value has to be saved. Usually it is saved in the function prologue.

Often, we see instructions like `PUSH R4-R7,LR` along with this instruction in epilogue `POP R4-R7,PC`—thus register values to be used in the function are saved in the stack, including LR.

Nevertheless, if a function never calls any other function, in RISC terminology it is called a *leaf function*[59]. As a consequence, leaf functions do not save the LR register (because they don't modify it). If such function is small and uses a small number of registers, it may not use the stack at all. Thus, it is possible to call leaf functions without using the stack, which can be faster than on older x86 machines because external RAM is not used for the stack [60]. This can be also useful for situations when memory for the stack is not yet allocated or not available.

Some examples of leaf functions: 1.10.3 on page 103, 1.10.3 on page 103, 1.278 on page 315, 1.294 on page 333, 1.22.5 on page 333, 1.186 on page 210, 1.184 on page 208, 1.203 on page 226.

Passing function arguments

The most popular way to pass parameters in x86 is called "cdecl":

```
push arg3
push arg2
push arg1
call f
add esp, 12 ; 4*3=12
```

Callee functions get their arguments via the stack pointer.

Therefore, this is how the argument values are located in the stack before the execution of the `f()` function's very first instruction:

ESP	return address
ESP+4	argument#1, marked in IDA as arg_0
ESP+8	argument#2, marked in IDA as arg_4
ESP+0xC	argument#3, marked in IDA as arg_8
...	...

[58] irony here
[59] infocenter.arm.com/help/index.jsp?topic=/com.arm.doc.faqs/ka13785.html
[60] Some time ago, on PDP-11 and VAX, the CALL instruction (calling other functions) was expensive; up to 50% of execution time might be spent on it, so it was considered that having a big number of small functions is an anti-pattern [Eric S. Raymond, *The Art of UNIX Programming*, (2003)Chapter 4, Part II].

For more information on other calling conventions see also section (6.1 on page 734).

By the way, the callee function does not have any information about how many arguments were passed. C functions with a variable number of arguments (like `printf()`) determine their number using format string specifiers (which begin with the % symbol).

If we write something like:

```
printf("%d %d %d", 1234);
```

`printf()` will print 1234, and then two random numbers[61], which were lying next to it in the stack.

That's why it is not very important how we declare the `main()` function: as `main()`, `main(int argc, char *argv[])` or `main(int argc, char *argv[], char *envp[])`.

In fact, the CRT-code is calling `main()` roughly as:

```
push envp
push argv
push argc
call main
...
```

If you declare `main()` as `main()` without arguments, they are, nevertheless, still present in the stack, but are not used. If you declare `main()` as `main(int argc, char *argv[])`, you will be able to use first two arguments, and the third will remain "invisible" for your function. Even more, it is possible to declare `main(int argc)`, and it will work.

Alternative ways of passing arguments

It is worth noting that nothing obliges programmers to pass arguments through the stack. It is not a requirement. One could implement any other method without using the stack at all.

A somewhat popular way among assembly language newbies is to pass arguments via global variables, like:

Listing 1.37: Assembly code

```
        ...

        mov     X, 123
        mov     Y, 456
        call    do_something

        ...

X       dd      ?
Y       dd      ?

do_something proc near
        ; take X
        ; take Y
        ; do something
        retn
do_something endp
```

But this method has obvious drawback: *do_something()* function cannot call itself recursively (or via another function), because it has to zap its own arguments. The same story with local variables: if you hold them in global variables, the function couldn't call itself. And this is also not thread-safe [62]. A method to store such information in stack makes this easier—it can hold as many function arguments and/or values, as much space it has.

[Donald E. Knuth, *The Art of Computer Programming*, Volume 1, 3rd ed., (1997), 189] mentions even weirder schemes particularly convenient on IBM System/360.

MS-DOS had a way of passing all function arguments via registers, for example, this is piece of code for ancient 16-bit MS-DOS prints "Hello, world!":

[61] Not random in strict sense, but rather unpredictable: 1.7.4 on page 37

[62] Correctly implemented, each thread would have its own stack with its own arguments/variables.

```
mov  dx, msg      ; address of message
mov  ah, 9        ; 9 means "print string" function
int  21h          ; DOS "syscall"

mov  ah, 4ch      ; "terminate program" function
int  21h          ; DOS "syscall"

msg  db 'Hello, World!\$'
```

This is quite similar to 6.1.3 on page 735 method. And also it's very similar to calling syscalls in Linux (6.3.1 on page 747) and Windows.

If a MS-DOS function is going to return a boolean value (i.e., single bit, usually indicating error state), CF flag was often used.

For example:

```
mov ah, 3ch       ; create file
lea dx, filename
mov cl, 1
int 21h
jc  error
mov file_handle, ax
...
error:
...
```

In case of error, CF flag is raised. Otherwise, handle of newly created file is returned via AX.

This method is still used by assembly language programmers. In Windows Research Kernel source code (which is quite similar to Windows 2003) we can find something like this (file *base/ntos/ke/i386/cpu.asm*):

```
        public  Get386Stepping
Get386Stepping  proc

        call    MultiplyTest            ; Perform multiplication test
        jnc     short G3s00             ; if nc, muttest is ok
        mov     ax, 0
        ret
G3s00:
        call    Check386B0              ; Check for B0 stepping
        jnc     short G3s05             ; if nc, it's B1/later
        mov     ax, 100h                ; It is B0/earlier stepping
        ret

G3s05:
        call    Check386D1              ; Check for D1 stepping
        jc      short G3s10             ; if c, it is NOT D1
        mov     ax, 301h                ; It is D1/later stepping
        ret

G3s10:
        mov     ax, 101h                ; assume it is B1 stepping
        ret

        ...

MultiplyTest    proc

        xor     cx,cx                   ; 64K times is a nice round number
mlt00:  push    cx
        call    Multiply                ; does this chip's multiply work?
        pop     cx
        jc      short mltx              ; if c, No, exit
        loop    mlt00                   ; if nc, YEs, loop to try again
        clc
mltx:
        ret

MultiplyTest    endp
```

Local variable storage

A function could allocate space in the stack for its local variables just by decreasing the stack pointer towards the stack bottom.

Hence, it's very fast, no matter how many local variables are defined. It is also not a requirement to store local variables in the stack. You could store local variables wherever you like, but traditionally this is how it's done.

x86: alloca() function

It is worth noting the `alloca()` function [63]. This function works like `malloc()`, but allocates memory directly on the stack. The allocated memory chunk does not have to be freed via a `free()` function call, since the function epilogue (1.6 on page 29) returns ESP back to its initial state and the allocated memory is just *dropped*. It is worth noting how `alloca()` is implemented. In simple terms, this function just shifts ESP downwards toward the stack bottom by the number of bytes you need and sets ESP as a pointer to the *allocated* block.

Let's try:

```
#ifdef __GNUC__
#include <alloca.h> // GCC
#else
#include <malloc.h> // MSVC
#endif
#include <stdio.h>

void f()
{
    char *buf=(char*)alloca (600);
#ifdef __GNUC__
    snprintf (buf, 600, "hi! %d, %d, %d\n", 1, 2, 3); // GCC
#else
    _snprintf (buf, 600, "hi! %d, %d, %d\n", 1, 2, 3); // MSVC
#endif

    puts (buf);
};
```

`_snprintf()` function works just like `printf()`, but instead of dumping the result into stdout (e.g., to terminal or console), it writes it to the `buf` buffer. Function `puts()` copies the contents of `buf` to stdout. Of course, these two function calls might be replaced by one `printf()` call, but we have to illustrate small buffer usage.

MSVC

Let's compile (MSVC 2010):

Listing 1.38: MSVC 2010

```
...

    mov     eax, 600  ; 00000258H
    call    __alloca_probe_16
    mov     esi, esp

    push    3
    push    2
    push    1
    push    OFFSET $SG2672
    push    600       ; 00000258H
    push    esi
    call    __snprintf
```

[63] In MSVC, the function implementation can be found in `alloca16.asm` and `chkstk.asm` in `C:\Program Files (x86)\Microsoft Visual Studio 10.0\VC\crt\src\intel`

```
    push   esi
    call   _puts
    add    esp, 28

...
```

The sole `alloca()` argument is passed via EAX (instead of pushing it into the stack) [64].

GCC + Intel syntax

GCC 4.4.1 does the same without calling external functions:

Listing 1.39: GCC 4.7.3

```
.LC0:
        .string "hi! %d, %d, %d\n"
f:
        push    ebp
        mov     ebp, esp
        push    ebx
        sub     esp, 660
        lea     ebx, [esp+39]
        and     ebx, -16                  ; align pointer by 16-bit border
        mov     DWORD PTR [esp], ebx      ; s
        mov     DWORD PTR [esp+20], 3
        mov     DWORD PTR [esp+16], 2
        mov     DWORD PTR [esp+12], 1
        mov     DWORD PTR [esp+8], OFFSET FLAT:.LC0 ; "hi! %d, %d, %d\n"
        mov     DWORD PTR [esp+4], 600    ; maxlen
        call    _snprintf
        mov     DWORD PTR [esp], ebx      ; s
        call    puts
        mov     ebx, DWORD PTR [ebp-4]
        leave
        ret
```

GCC + AT&T syntax

Let's see the same code, but in AT&T syntax:

Listing 1.40: GCC 4.7.3

```
.LC0:
        .string "hi! %d, %d, %d\n"
f:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $660, %esp
        leal    39(%esp), %ebx
        andl    $-16, %ebx
        movl    %ebx, (%esp)
        movl    $3, 20(%esp)
        movl    $2, 16(%esp)
        movl    $1, 12(%esp)
        movl    $.LC0, 8(%esp)
        movl    $600, 4(%esp)
        call    _snprintf
        movl    %ebx, (%esp)
        call    puts
        movl    -4(%ebp), %ebx
        leave
```

[64] It is because alloca() is rather a compiler intrinsic (11.3 on page 999) than a normal function. One of the reasons we need a separate function instead of just a couple of instructions in the code, is because the MSVC[65] alloca() implementation also has code which reads from the memory just allocated, in order to let the OS map physical memory to this VM[66] region. After the `alloca()` call, ESP points to the block of 600 bytes and we can use it as memory for the `buf` array.

```
        ret
```

The code is the same as in the previous listing.

By the way, `movl $3, 20(%esp)` corresponds to `mov DWORD PTR [esp+20], 3` in Intel-syntax. In the AT&T syntax, the register+offset format of addressing memory looks like `offset(%register)`.

(Windows) SEH

SEH[67] records are also stored on the stack (if they are present). Read more about it: (6.5.3 on page 764).

Buffer overflow protection

More about it here (1.20.2 on page 275).

Automatic deallocation of data in stack

Perhaps the reason for storing local variables and SEH records in the stack is that they are freed automatically upon function exit, using just one instruction to correct the stack pointer (it is often ADD). Function arguments, as we could say, are also deallocated automatically at the end of function. In contrast, everything stored in the *heap* must be deallocated explicitly.

1.7.3 A typical stack layout

A typical stack layout in a 32-bit environment at the start of a function, before the first instruction execution looks like this:

...	...
ESP-0xC	local variable#2, marked in IDA as `var_8`
ESP-8	local variable#1, marked in IDA as `var_4`
ESP-4	saved value ofEBP
ESP	Return Address
ESP+4	argument#1, marked in IDA as `arg_0`
ESP+8	argument#2, marked in IDA as `arg_4`
ESP+0xC	argument#3, marked in IDA as `arg_8`
...	...

1.7.4 Noise in stack

> When one says that something seems random, what one usually means in practice is that one cannot see any regularities in it.
>
> Stephen Wolfram, A New Kind of Science.

Often in this book "noise" or "garbage" values in the stack or memory are mentioned. Where do they come from? These are what has been left there after other functions' executions. Short example:

```
#include <stdio.h>

void f1()
{
        int a=1, b=2, c=3;
};

void f2()
{
        int a, b, c;
        printf ("%d, %d, %d\n", a, b, c);
```

[67] Structured Exception Handling

```
};

int main()
{
        f1();
        f2();
};
```

Compiling …

Listing 1.41: Non-optimizing MSVC 2010

```
$SG2752 DB      '%d, %d, %d', 0aH, 00H

_c$ = -12       ; size = 4
_b$ = -8        ; size = 4
_a$ = -4        ; size = 4
_f1     PROC
        push    ebp
        mov     ebp, esp
        sub     esp, 12
        mov     DWORD PTR _a$[ebp], 1
        mov     DWORD PTR _b$[ebp], 2
        mov     DWORD PTR _c$[ebp], 3
        mov     esp, ebp
        pop     ebp
        ret     0
_f1     ENDP

_c$ = -12       ; size = 4
_b$ = -8        ; size = 4
_a$ = -4        ; size = 4
_f2     PROC
        push    ebp
        mov     ebp, esp
        sub     esp, 12
        mov     eax, DWORD PTR _c$[ebp]
        push    eax
        mov     ecx, DWORD PTR _b$[ebp]
        push    ecx
        mov     edx, DWORD PTR _a$[ebp]
        push    edx
        push    OFFSET $SG2752 ; '%d, %d, %d'
        call    DWORD PTR __imp__printf
        add     esp, 16
        mov     esp, ebp
        pop     ebp
        ret     0
_f2     ENDP

_main   PROC
        push    ebp
        mov     ebp, esp
        call    _f1
        call    _f2
        xor     eax, eax
        pop     ebp
        ret     0
_main   ENDP
```

The compiler will grumble a little bit…

```
c:\Polygon\c>cl st.c /Fast.asm /MD
Microsoft (R) 32-bit C/C++ Optimizing Compiler Version 16.00.40219.01 for 80x86
Copyright (C) Microsoft Corporation.  All rights reserved.

st.c
c:\polygon\c\st.c(11) : warning C4700: uninitialized local variable 'c' used
c:\polygon\c\st.c(11) : warning C4700: uninitialized local variable 'b' used
c:\polygon\c\st.c(11) : warning C4700: uninitialized local variable 'a' used
```

```
Microsoft (R) Incremental Linker Version 10.00.40219.01
Copyright (C) Microsoft Corporation.  All rights reserved.

/out:st.exe
st.obj
```

But when we run the compiled program …

```
c:\Polygon\c>st
1, 2, 3
```

Oh, what a weird thing! We did not set any variables in `f2()`. These are “ghosts” values, which are still in the stack.

Let's load the example into OllyDbg:

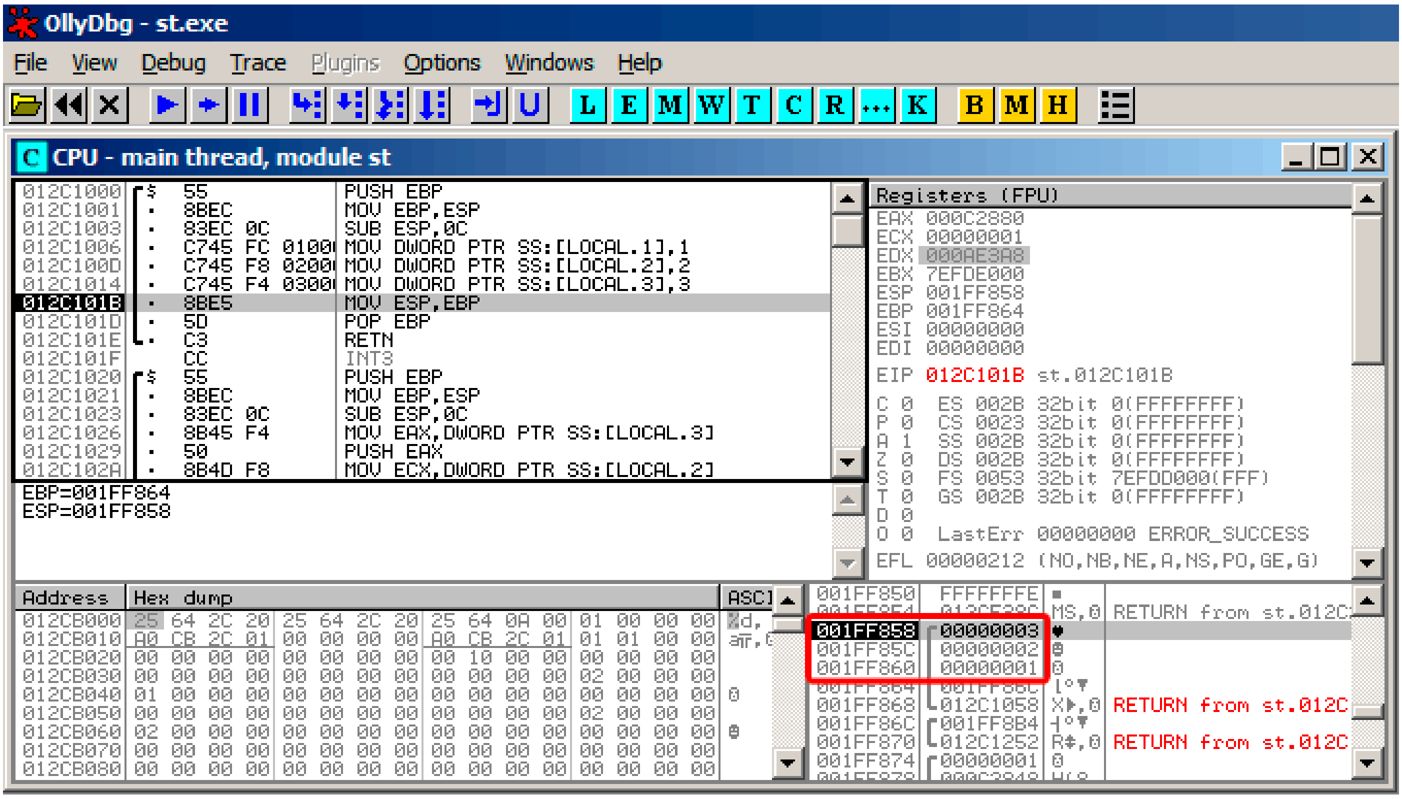


Figure 1.5: OllyDbg: `f1()`

When `f1()` assigns the variables a, b and c, their values are stored at the address `0x1FF860` and so on.

And when f2() executes:

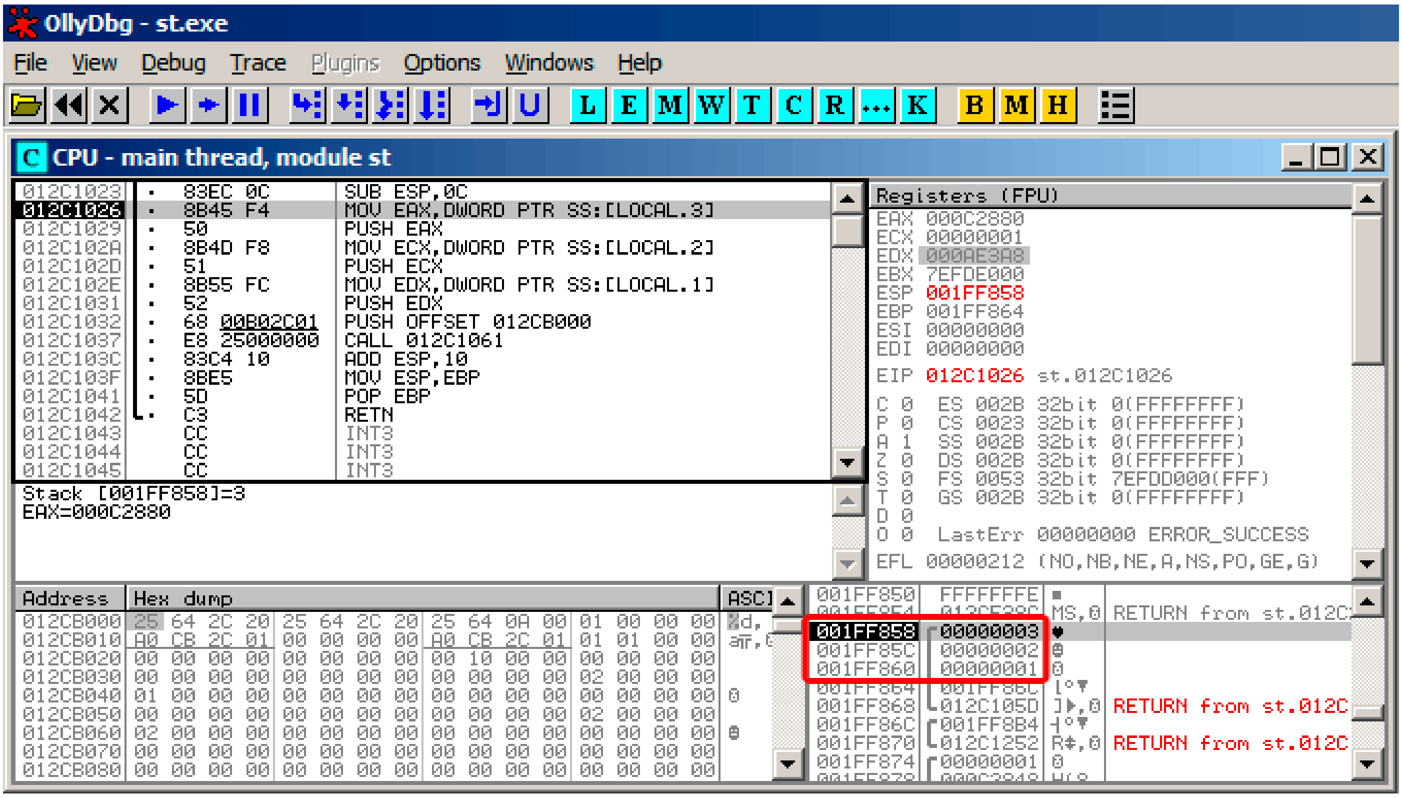


Figure 1.6: OllyDbg: f2()

... a, b and c of f2() are located at the same addresses! No one has overwritten the values yet, so at that point they are still untouched. So, for this weird situation to occur, several functions have to be called one after another and SP has to be the same at each function entry (i.e., they have the same number of arguments). Then the local variables will be located at the same positions in the stack. Summarizing, all values in the stack (and memory cells in general) have values left there from previous function executions. They are not random in the strict sense, but rather have unpredictable values. Is there another option? It would probably be possible to clear portions of the stack before each function execution, but that's too much extra (and unnecessary) work.

MSVC 2013

The example was compiled by MSVC 2010. But the reader of this book made attempt to compile this example in MSVC 2013, ran it, and got all 3 numbers reversed:

```
c:\Polygon\c>st
3, 2, 1
```

Why? I also compiled this example in MSVC 2013 and saw this:

Listing 1.42: MSVC 2013

```
_a$ = -12       ; size = 4
_b$ = -8        ; size = 4
_c$ = -4        ; size = 4
_f2     PROC

...

_f2     ENDP

_c$ = -12       ; size = 4
_b$ = -8        ; size = 4
_a$ = -4        ; size = 4
_f1     PROC
```

```
...

_f1     ENDP
```

Unlike MSVC 2010, MSVC 2013 allocated a/b/c variables in function `f2()` in reverse order.And this is completely correct, because C/C++ standards has no rule, in which order local variables must be allocated in the local stack, if at all. The reason of difference is because MSVC 2010 has one way to do it, and MSVC 2013 has supposedly something changed inside of compiler guts, so it behaves slightly different.

1.7.5 Exercises

- http://challenges.re/51
- http://challenges.re/52

1.8 printf() with several arguments

Now let's extend the *Hello, world!* (1.5 on page 8) example, replacing `printf()` in the `main()` function body with this:

```
#include <stdio.h>

int main()
{
        printf("a=%d; b=%d; c=%d", 1, 2, 3);
        return 0;
};
```

1.8.1 x86

x86: 3 arguments

MSVC

When we compile it with MSVC 2010 Express we get:

```
$SG3830 DB      'a=%d; b=%d; c=%d', 00H

...

        push    3
        push    2
        push    1
        push    OFFSET $SG3830
        call    _printf
        add     esp, 16                                 ; 00000010H
```

Almost the same, but now we can see the `printf()` arguments are pushed onto the stack in reverse order. The first argument is pushed last.

By the way, variables of *int* type in 32-bit environment have 32-bit width, that is 4 bytes.

So, we have 4 arguments here. $4 * 4 = 16$ —they occupy exactly 16 bytes in the stack: a 32-bit pointer to a string and 3 numbers of type *int*.

When the stack pointer (ESP register) has changed back by the
`ADD ESP, X` instruction after a function call, often, the number of function arguments could be deduced by simply dividing X by 4.

Of course, this is specific to the *cdecl* calling convention, and only for 32-bit environment.

See also the calling conventions section (6.1 on page 734).

In certain cases where several functions return right after one another, the compiler could merge multiple “ADD ESP, X” instructions into one, after the last call:

```
push a1
push a2
call ...
...
push a1
call ...
...
push a1
push a2
push a3
call ...
add esp, 24
```

Here is a real-world example:

Listing 1.43: x86

```
.text:100113E7    push    3
.text:100113E9    call    sub_100018B0 ; takes one argument (3)
.text:100113EE    call    sub_100019D0 ; takes no arguments at all
.text:100113F3    call    sub_10006A90 ; takes no arguments at all
.text:100113F8    push    1
.text:100113FA    call    sub_100018B0 ; takes one argument (1)
.text:100113FF    add     esp, 8       ; drops two arguments from stack at once
```

MSVC and OllyDbg

Now let's try to load this example in OllyDbg. It is one of the most popular user-land win32 debuggers. We can compile our example in MSVC 2012 with /MD option, which means to link with MSVCR*.DLL, so we can see the imported functions clearly in the debugger.

Then load the executable in OllyDbg. The very first breakpoint is in ntdll.dll, press F9 (run). The second breakpoint is in CRT-code. Now we have to find the main() function.

Find this code by scrolling the code to the very top (MSVC allocates the main() function at the very beginning of the code section):

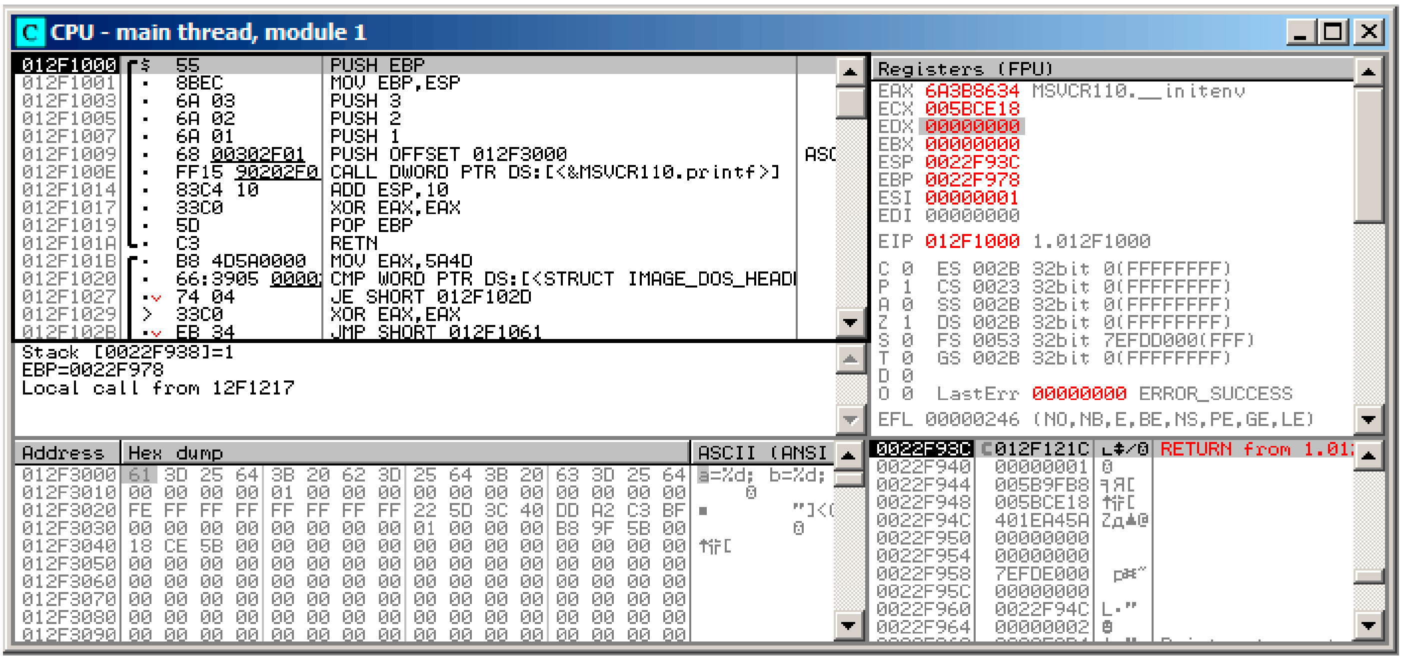


Figure 1.7: OllyDbg: the very start of the main() function

Click on the PUSH EBP instruction, press F2 (set breakpoint) and press F9 (run). We have to perform these actions in order to skip CRT-code, because we aren't really interested in it yet.

Press F8 (step over) 6 times, i.e. skip 6 instructions:

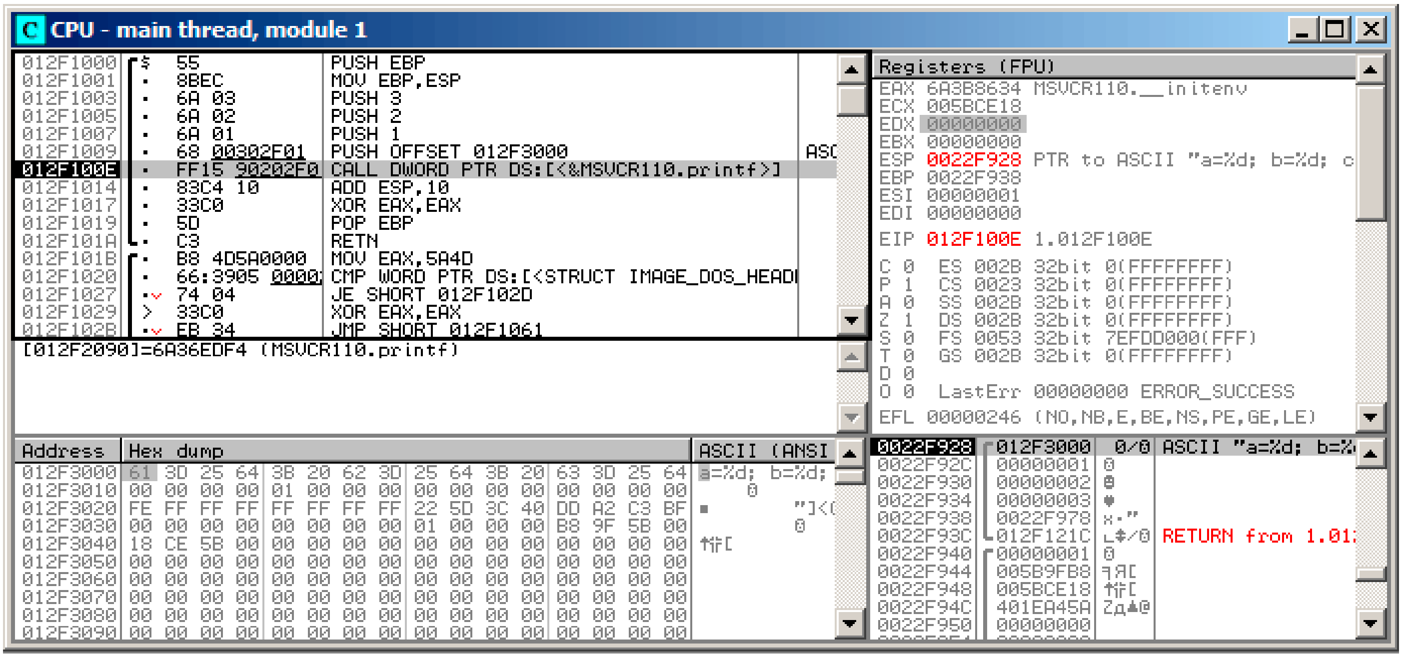


Figure 1.8: OllyDbg: before `printf()` execution

Now the PC points to the CALL `printf` instruction. OllyDbg, like other debuggers, highlights the value of the registers which were changed. So each time you press F8, EIP changes and its value is displayed in red. ESP changes as well, because the arguments values are pushed into the stack.

Where are the values in the stack? Take a look at the right bottom debugger window:

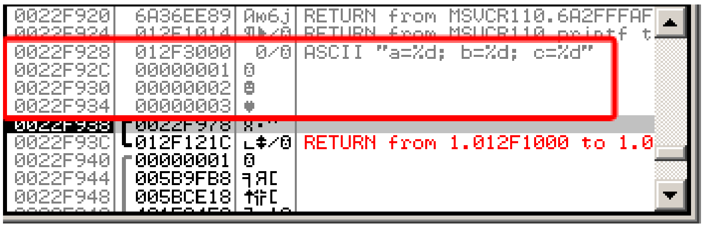


Figure 1.9: OllyDbg: stack after the argument values have been pushed (The red rectangular border was added by the author in a graphics editor)

We can see 3 columns there: address in the stack, value in the stack and some additional OllyDbg comments. OllyDbg understands `printf()`-like strings, so it reports the string here and the 3 values *attached* to it.

It is possible to right-click on the format string, click on "Follow in dump", and the format string will appear in the debugger left-bottom window, which always displays some part of the memory. These memory values can be edited. It is possible to change the format string, in which case the result of our example would be different. It is not very useful in this particular case, but it could be good as an exercise so you start building a feel of how everything works here.

Press F8 (step over).

We see the following output in the console:

```
a=1; b=2; c=3
```

Let's see how the registers and stack state have changed:

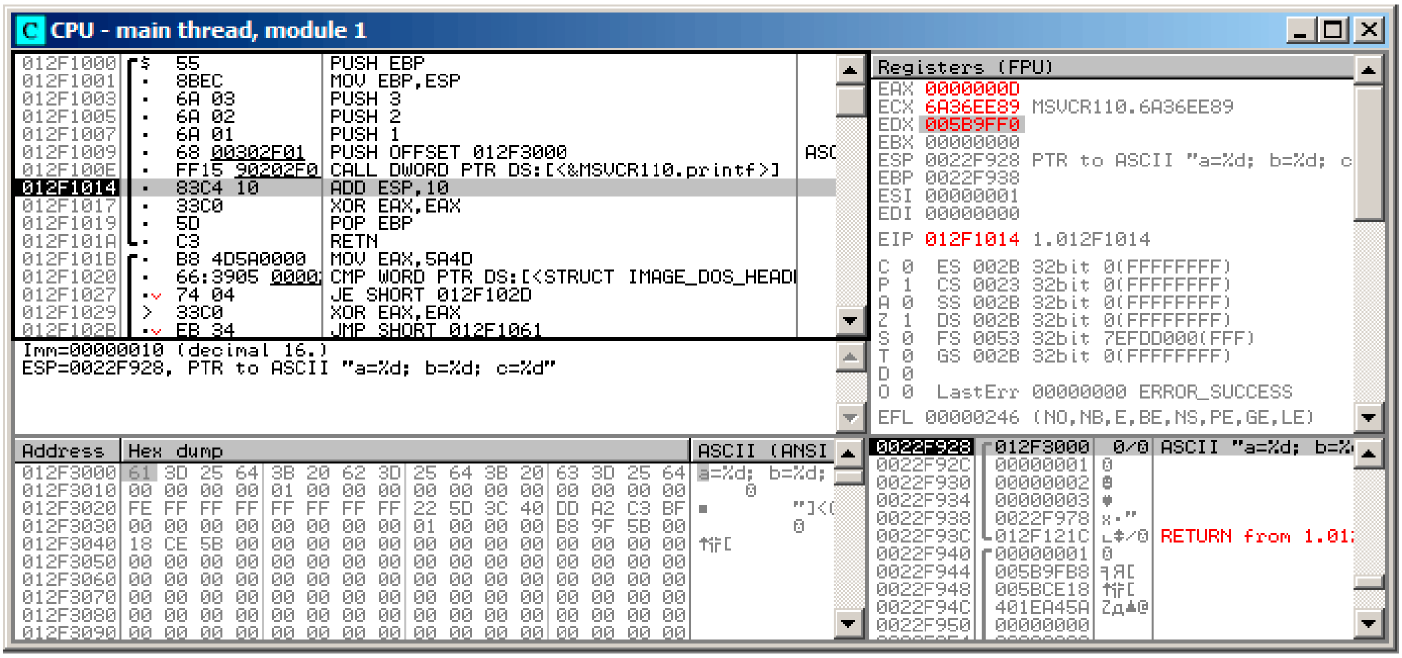


Figure 1.10: OllyDbg after `printf()` execution

Register EAX now contains `0xD` (13). That is correct, since `printf()` returns the number of characters printed. The value of EIP has changed: indeed, now it contains the address of the instruction coming after `CALL printf`. ECX and EDX values have changed as well. Apparently, the `printf()` function's hidden machinery used them for its own needs.

A very important fact is that neither the ESP value, nor the stack state have been changed! We clearly see that the format string and corresponding 3 values are still there. This is indeed the *cdecl* calling convention behavior: callee does not return ESP back to its previous value. The caller is responsible to do so.

Press F8 again to execute ADD ESP, 10 instruction:

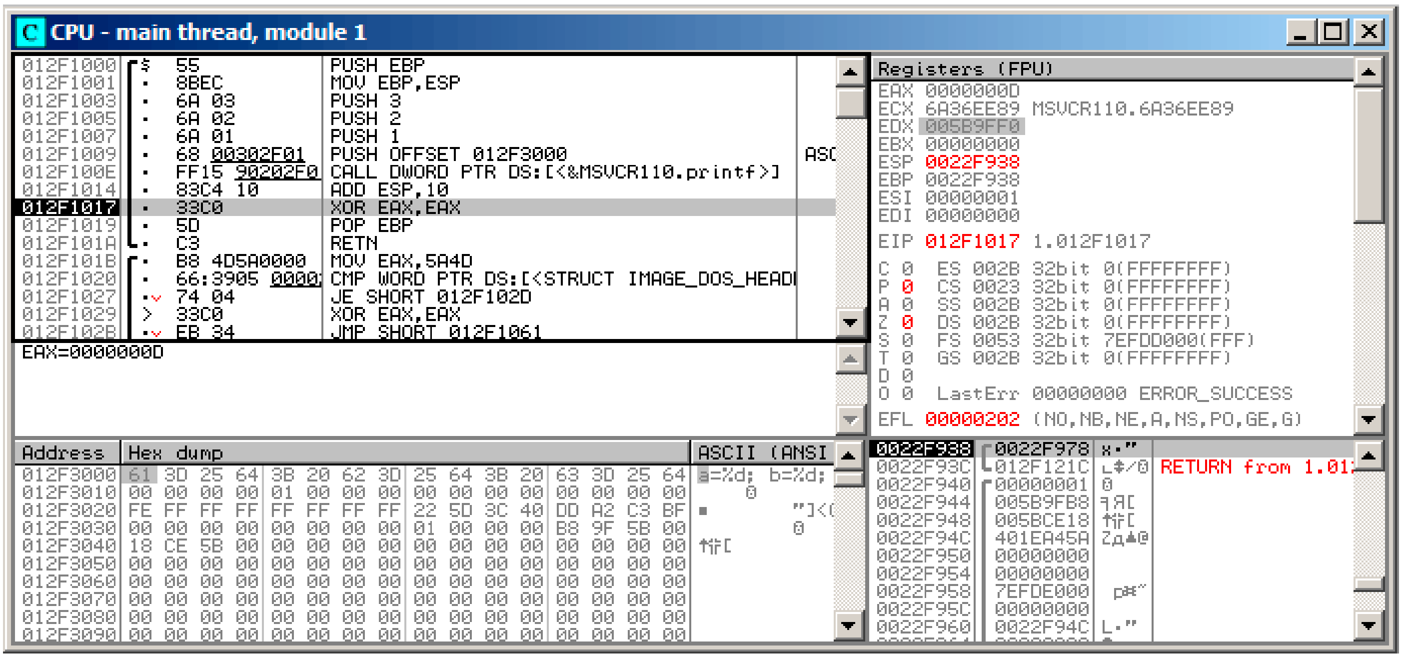


Figure 1.11: OllyDbg: after ADD ESP, 10 instruction execution

ESP has changed, but the values are still in the stack! Yes, of course; no one needs to set these values to zeros or something like that. Everything above the stack pointer (SP) is *noise* or *garbage* and has no meaning at all. It would be time consuming to clear the unused stack entries anyway, and no one really needs to.

GCC

Now let's compile the same program in Linux using GCC 4.4.1 and take a look at what we have got in IDA:

```
main            proc near

var_10          = dword ptr -10h
var_C           = dword ptr -0Ch
var_8           = dword ptr -8
var_4           = dword ptr -4

                push    ebp
                mov     ebp, esp
                and     esp, 0FFFFFFF0h
                sub     esp, 10h
                mov     eax, offset aADBDCD ; "a=%d; b=%d; c=%d"
                mov     [esp+10h+var_4], 3
                mov     [esp+10h+var_8], 2
                mov     [esp+10h+var_C], 1
                mov     [esp+10h+var_10], eax
                call    _printf
                mov     eax, 0
                leave
                retn
main            endp
```

Its noticeable that the difference between the MSVC code and the GCC code is only in the way the arguments are stored on the stack. Here the GCC is working directly with the stack without the use of PUSH/POP.

GCC and GDB

Let's try this example also in GDB[68] in Linux.

-g option instructs the compiler to include debug information in the executable file.

```
$ gcc 1.c -g -o 1
```

```
$ gdb 1
GNU gdb (GDB) 7.6.1-ubuntu
...
Reading symbols from /home/dennis/polygon/1...done.
```

Listing 1.44: let's set breakpoint on `printf()`

```
(gdb) b printf
Breakpoint 1 at 0x80482f0
```

Run. We don't have the `printf()` function source code here, so GDB can't show it, but may do so.

```
(gdb) run
Starting program: /home/dennis/polygon/1

Breakpoint 1, __printf (format=0x80484f0 "a=%d; b=%d; c=%d") at printf.c:29
29      printf.c: No such file or directory.
```

Print 10 stack elements. The most left column contains addresses on the stack.

```
(gdb) x/10w $esp
0xbffff11c:     0x0804844a      0x080484f0      0x00000001      0x00000002
0xbffff12c:     0x00000003      0x08048460      0x00000000      0x00000000
0xbffff13c:     0xb7e29905      0x00000001
```

The very first element is the RA (`0x0804844a`). We can verify this by disassembling the memory at this address:

```
(gdb) x/5i 0x0804844a
   0x804844a <main+45>: mov    $0x0,%eax
   0x804844f <main+50>: leave
   0x8048450 <main+51>: ret
   0x8048451:   xchg   %ax,%ax
   0x8048453:   xchg   %ax,%ax
```

The two XCHG instructions are idle instructions, analogous to NOPs.

The second element (`0x080484f0`) is the format string address:

```
(gdb) x/s 0x080484f0
0x80484f0:      "a=%d; b=%d; c=%d"
```

Next 3 elements (1, 2, 3) are the `printf()` arguments. The rest of the elements could be just "garbage" on the stack, but could also be values from other functions, their local variables, etc. We can ignore them for now.

Run "finish". The command instructs GDB to "execute all instructions until the end of the function". In this case: execute till the end of `printf()`.

```
(gdb) finish
Run till exit from #0  __printf (format=0x80484f0 "a=%d; b=%d; c=%d") at printf.c:29
main () at 1.c:6
6               return 0;
Value returned is $2 = 13
```

GDB shows what `printf()` returned in EAX (13). This is the number of characters printed out, just like in the OllyDbg example.

We also see "return 0;" and the information that this expression is in the `1.c` file at the line 6. Indeed, the `1.c` file is located in the current directory, and GDB finds the string there. How does GDB know which C-code line is being currently executed? This is due to the fact that the compiler, while generating

[68] GNU Debugger

debugging information, also saves a table of relations between source code line numbers and instruction addresses. GDB is a source-level debugger, after all.

Let's examine the registers. 13 in EAX:

```
(gdb) info registers
eax            0xd      13
ecx            0x0      0
edx            0x0      0
ebx            0xb7fc0000       -1208221696
esp            0xbffff120       0xbffff120
ebp            0xbffff138       0xbffff138
esi            0x0      0
edi            0x0      0
eip            0x804844a        0x804844a <main+45>
...
```

Let's disassemble the current instructions. The arrow points to the instruction to be executed next.

```
(gdb) disas
Dump of assembler code for function main:
   0x0804841d <+0>:     push   %ebp
   0x0804841e <+1>:     mov    %esp,%ebp
   0x08048420 <+3>:     and    $0xfffffff0,%esp
   0x08048423 <+6>:     sub    $0x10,%esp
   0x08048426 <+9>:     movl   $0x3,0xc(%esp)
   0x0804842e <+17>:    movl   $0x2,0x8(%esp)
   0x08048436 <+25>:    movl   $0x1,0x4(%esp)
   0x0804843e <+33>:    movl   $0x80484f0,(%esp)
   0x08048445 <+40>:    call   0x80482f0 <printf@plt>
=> 0x0804844a <+45>:    mov    $0x0,%eax
   0x0804844f <+50>:    leave
   0x08048450 <+51>:    ret
End of assembler dump.
```

GDB uses AT&T syntax by default. But it is possible to switch to Intel syntax:

```
(gdb) set disassembly-flavor intel
(gdb) disas
Dump of assembler code for function main:
   0x0804841d <+0>:     push   ebp
   0x0804841e <+1>:     mov    ebp,esp
   0x08048420 <+3>:     and    esp,0xfffffff0
   0x08048423 <+6>:     sub    esp,0x10
   0x08048426 <+9>:     mov    DWORD PTR [esp+0xc],0x3
   0x0804842e <+17>:    mov    DWORD PTR [esp+0x8],0x2
   0x08048436 <+25>:    mov    DWORD PTR [esp+0x4],0x1
   0x0804843e <+33>:    mov    DWORD PTR [esp],0x80484f0
   0x08048445 <+40>:    call   0x80482f0 <printf@plt>
=> 0x0804844a <+45>:    mov    eax,0x0
   0x0804844f <+50>:    leave
   0x08048450 <+51>:    ret
End of assembler dump.
```

Execute next instruction. GDB shows ending bracket, meaning, it ends the block.

```
(gdb) step
7       };
```

Let's examine the registers after the `MOV EAX, 0` instruction execution. Indeed EAX is zero at that point.

```
(gdb) info registers
eax            0x0      0
ecx            0x0      0
edx            0x0      0
ebx            0xb7fc0000       -1208221696
esp            0xbffff120       0xbffff120
ebp            0xbffff138       0xbffff138
esi            0x0      0
edi            0x0      0
```

```
eip            0x804844f        0x804844f <main+50>
...
```

x64: 8 arguments

To see how other arguments are passed via the stack, let's change our example again by increasing the number of arguments to 9 (`printf()` format string + 8 *int* variables):

```
#include <stdio.h>

int main()
{
        printf("a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n", 1, 2, 3, 4, 5, 6, 7, 8);
        return 0;
};
```

MSVC

As it was mentioned earlier, the first 4 arguments has to be passed through the RCX, RDX, R8, R9 registers in Win64, while all the rest—via the stack. That is exactly what we see here. However, the `MOV` instruction, instead of PUSH, is used for preparing the stack, so the values are stored to the stack in a straightforward manner.

Listing 1.45: MSVC 2012 x64

```
$SG2923 DB      'a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d', 0aH, 00H

main    PROC
        sub     rsp, 88

        mov     DWORD PTR [rsp+64], 8
        mov     DWORD PTR [rsp+56], 7
        mov     DWORD PTR [rsp+48], 6
        mov     DWORD PTR [rsp+40], 5
        mov     DWORD PTR [rsp+32], 4
        mov     r9d, 3
        mov     r8d, 2
        mov     edx, 1
        lea     rcx, OFFSET FLAT:$SG2923
        call    printf

        ; return 0
        xor     eax, eax

        add     rsp, 88
        ret     0
main    ENDP
_TEXT   ENDS
END
```

The observant reader may ask why are 8 bytes allocated for *int* values, when 4 is enough? Yes, one has to recall: 8 bytes are allocated for any data type shorter than 64 bits. This is established for the convenience's sake: it makes it easy to calculate the address of arbitrary argument. Besides, they are all located at aligned memory addresses. It is the same in the 32-bit environments: 4 bytes are reserved for all data types.

GCC

The picture is similar for x86-64 *NIX OS-es, except that the first 6 arguments are passed through the RDI, RSI, RDX, RCX, R8, R9 registers. All the rest—via the stack. GCC generates the code storing the string pointer into `EDI` instead of `RDI`—we noted that previously: 1.5.2 on page 15.

We also noted earlier that the EAX register has been cleared before a `printf()` call: 1.5.2 on page 15.

Listing 1.46: Optimizing GCC 4.4.6 x64

```
.LC0:
        .string "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n"

main:
        sub     rsp, 40

        mov     r9d, 5
        mov     r8d, 4
        mov     ecx, 3
        mov     edx, 2
        mov     esi, 1
        mov     edi, OFFSET FLAT:.LC0
        xor     eax, eax ; number of vector registers passed
        mov     DWORD PTR [rsp+16], 8
        mov     DWORD PTR [rsp+8], 7
        mov     DWORD PTR [rsp], 6
        call    printf

        ; return 0

        xor     eax, eax
        add     rsp, 40
        ret
```

GCC + GDB

Let's try this example in GDB.

```
$ gcc -g 2.c -o 2
```

```
$ gdb 2
GNU gdb (GDB) 7.6.1-ubuntu
...
Reading symbols from /home/dennis/polygon/2...done.
```

Listing 1.47: let's set the breakpoint to `printf()`, and run

```
(gdb) b printf
Breakpoint 1 at 0x400410
(gdb) run
Starting program: /home/dennis/polygon/2

Breakpoint 1, __printf (format=0x400628 "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n") at ↙
    ↳ printf.c:29
29      printf.c: No such file or directory.
```

Registers RSI/RDX/RCX/R8/R9 have the expected values. RIP has the address of the very first instruction of the `printf()` function.

```
(gdb) info registers
rax            0x0      0
rbx            0x0      0
rcx            0x3      3
rdx            0x2      2
rsi            0x1      1
rdi            0x400628 4195880
rbp            0x7fffffffdf60   0x7fffffffdf60
rsp            0x7fffffffdf38   0x7fffffffdf38
r8             0x4      4
r9             0x5      5
r10            0x7fffffffdce0   140737488346336
r11            0x7ffff7a65f60   140737348263776
r12            0x400440 4195392
r13            0x7fffffffe040   140737488347200
r14            0x0      0
r15            0x0      0
```

```
rip            0x7ffff7a65f60   0x7ffff7a65f60 <__printf>
...
```

Listing 1.48: let's inspect the format string

```
(gdb) x/s $rdi
0x400628:       "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n"
```

Let's dump the stack with the x/g command this time—*g* stands for *giant words*, i.e., 64-bit words.

```
(gdb) x/10g $rsp
0x7fffffffdf38: 0x0000000000400576      0x0000000000000006
0x7fffffffdf48: 0x0000000000000007      0x00007fff00000008
0x7fffffffdf58: 0x0000000000000000      0x0000000000000000
0x7fffffffdf68: 0x00007ffff7a33de5      0x0000000000000000
0x7fffffffdf78: 0x00007fffffffe048      0x0000000100000000
```

The very first stack element, just like in the previous case, is the RA. 3 values are also passed through the stack: 6, 7, 8. We also see that 8 is passed with the high 32-bits not cleared: `0x00007fff00000008`. That's OK, because the values are of *int* type, which is 32-bit. So, the high register or stack element part may contain "random garbage".

If you take a look at where the control will return after the `printf()` execution, GDB will show the entire `main()` function:

```
(gdb) set disassembly-flavor intel
(gdb) disas 0x0000000000400576
Dump of assembler code for function main:
   0x000000000040052d <+0>:     push   rbp
   0x000000000040052e <+1>:     mov    rbp,rsp
   0x0000000000400531 <+4>:     sub    rsp,0x20
   0x0000000000400535 <+8>:     mov    DWORD PTR [rsp+0x10],0x8
   0x000000000040053d <+16>:    mov    DWORD PTR [rsp+0x8],0x7
   0x0000000000400545 <+24>:    mov    DWORD PTR [rsp],0x6
   0x000000000040054c <+31>:    mov    r9d,0x5
   0x0000000000400552 <+37>:    mov    r8d,0x4
   0x0000000000400558 <+43>:    mov    ecx,0x3
   0x000000000040055d <+48>:    mov    edx,0x2
   0x0000000000400562 <+53>:    mov    esi,0x1
   0x0000000000400567 <+58>:    mov    edi,0x400628
   0x000000000040056c <+63>:    mov    eax,0x0
   0x0000000000400571 <+68>:    call   0x400410 <printf@plt>
   0x0000000000400576 <+73>:    mov    eax,0x0
   0x000000000040057b <+78>:    leave
   0x000000000040057c <+79>:    ret
End of assembler dump.
```

Let's finish executing `printf()`, execute the instruction zeroing EAX, and note that the EAX register has a value of exactly zero. RIP now points to the LEAVE instruction, i.e., the penultimate one in the `main()` function.

```
(gdb) finish
Run till exit from #0  __printf (format=0x400628 "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%↙
    ↳ d\n") at printf.c:29
a=1; b=2; c=3; d=4; e=5; f=6; g=7; h=8
main () at 2.c:6
6               return 0;
Value returned is $1 = 39
(gdb) next
7       };
(gdb) info registers
rax            0x0      0
rbx            0x0      0
rcx            0x26     38
rdx            0x7ffff7dd59f0   140737351866864
rsi            0x7fffffd9       2147483609
rdi            0x0      0
rbp            0x7fffffffdf60   0x7fffffffdf60
rsp            0x7fffffffdf40   0x7fffffffdf40
r8             0x7ffff7dd26a0   140737351853728
```

```
r9             0x7ffff7a60134   140737348239668
r10            0x7fffffffd5b0   140737488344496
r11            0x7ffff7a95900   140737348458752
r12            0x400440 4195392
r13            0x7fffffffe040   140737488347200
r14            0x0      0
r15            0x0      0
rip            0x40057b 0x40057b <main+78>
...
```

1.8.2 ARM

ARM: 3 arguments

ARM's traditional scheme for passing arguments (calling convention) behaves as follows: the first 4 arguments are passed through the R0-R3 registers; the remaining arguments via the stack. This resembles the arguments passing scheme in fastcall (6.1.3 on page 735) or win64 (6.1.5 on page 737).

32-bit ARM

Non-optimizing Keil 6/2013 (ARM mode)

Listing 1.49: Non-optimizing Keil 6/2013 (ARM mode)

```
.text:00000000 main
.text:00000000 10 40 2D E9   STMFD   SP!, {R4,LR}
.text:00000004 03 30 A0 E3   MOV     R3, #3
.text:00000008 02 20 A0 E3   MOV     R2, #2
.text:0000000C 01 10 A0 E3   MOV     R1, #1
.text:00000010 08 00 8F E2   ADR     R0, aADBDCD     ; "a=%d; b=%d; c=%d"
.text:00000014 06 00 00 EB   BL      __2printf
.text:00000018 00 00 A0 E3   MOV     R0, #0          ; return 0
.text:0000001C 10 80 BD E8   LDMFD   SP!, {R4,PC}
```

So, the first 4 arguments are passed via the R0-R3 registers in this order: a pointer to the `printf()` format string in R0, then 1 in R1, 2 in R2 and 3 in R3. The instruction at 0x18 writes 0 to R0—this is *return 0* C-statement. There is nothing unusual so far.

Optimizing Keil 6/2013 generates the same code.

Optimizing Keil 6/2013 (Thumb mode)

Listing 1.50: Optimizing Keil 6/2013 (Thumb mode)

```
.text:00000000 main
.text:00000000 10 B5        PUSH    {R4,LR}
.text:00000002 03 23        MOVS    R3, #3
.text:00000004 02 22        MOVS    R2, #2
.text:00000006 01 21        MOVS    R1, #1
.text:00000008 02 A0        ADR     R0, aADBDCD     ; "a=%d; b=%d; c=%d"
.text:0000000A 00 F0 0D F8  BL      __2printf
.text:0000000E 00 20        MOVS    R0, #0
.text:00000010 10 BD        POP     {R4,PC}
```

There is no significant difference from the non-optimized code for ARM mode.

Optimizing Keil 6/2013 (ARM mode) + let's remove return

Let's rework example slightly by removing *return 0*:

```
#include <stdio.h>

void main()
{
        printf("a=%d; b=%d; c=%d", 1, 2, 3);
};
```

The result is somewhat unusual:

Listing 1.51: Optimizing Keil 6/2013 (ARM mode)

```
.text:00000014 main
.text:00000014 03 30 A0 E3   MOV     R3, #3
.text:00000018 02 20 A0 E3   MOV     R2, #2
.text:0000001C 01 10 A0 E3   MOV     R1, #1
.text:00000020 1E 0E 8F E2   ADR     R0, aADBDCD     ; "a=%d; b=%d; c=%d\n"
.text:00000024 CB 18 00 EA   B       __2printf
```

This is the optimized (-O3) version for ARM mode and this time we see B as the last instruction instead of the familiar BL. Another difference between this optimized version and the previous one (compiled without optimization) is the lack of function prologue and epilogue (instructions preserving the R0 and LR registers values). The B instruction just jumps to another address, without any manipulation of the LR register, similar to JMP in x86. Why does it work? Because this code is, in fact, effectively equivalent to the previous. There are two main reasons: 1) neither the stack nor SP (the stack pointer) is modified; 2) the call to `printf()` is the last instruction, so there is nothing going on afterwards. On completion, the `printf()` function simply returns the control to the address stored in LR. Since the LR currently stores the address of the point from where our function has been called then the control from `printf()` will be returned to that point. Therefore we do not have to save LR because we do not have necessity to modify LR. And we do not have necessity to modify LR because there are no other function calls except `printf()`. Furthermore, after this call we do not to do anything else! That is the reason such optimization is possible.

This optimization is often used in functions where the last statement is a call to another function. A similar example is presented here: 1.15.1 on page 154.

ARM64

Non-optimizing GCC (Linaro) 4.9

Listing 1.52: Non-optimizing GCC (Linaro) 4.9

```
.LC1:
        .string "a=%d; b=%d; c=%d"
f2:
; save FP and LR in stack frame:
        stp     x29, x30, [sp, -16]!
; set stack frame (FP=SP):
        add     x29, sp, 0
        adrp    x0, .LC1
        add     x0, x0, :lo12:.LC1
        mov     w1, 1
        mov     w2, 2
        mov     w3, 3
        bl      printf
        mov     w0, 0
; restore FP and LR
        ldp     x29, x30, [sp], 16
        ret
```

The first instruction STP (*Store Pair*) saves FP (X29) and LR (X30) in the stack. The second `ADD X29, SP, 0` instruction forms the stack frame. It is just writing the value of SP into X29.

Next, we see the familiar ADRP/ADD instruction pair, which forms a pointer to the string. *lo12* meaning low 12 bits, i.e., linker will write low 12 bits of LC1 address into the opcode of ADD instruction. %d in printf() string format is a 32-bit *int*, so the 1, 2 and 3 are loaded into 32-bit register parts.

Optimizing GCC (Linaro) 4.9 generates the same code.

ARM: 8 arguments

Let's use again the example with 9 arguments from the previous section: 1.8.1 on page 50.

```
#include <stdio.h>

int main()
{
        printf("a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n", 1, 2, 3, 4, 5, 6, 7, 8);
        return 0;
};
```

Optimizing Keil 6/2013: ARM mode

```
.text:00000028             main
.text:00000028
.text:00000028             var_18 = -0x18
.text:00000028             var_14 = -0x14
.text:00000028             var_4  = -4
.text:00000028
.text:00000028 04 E0 2D E5  STR    LR, [SP,#var_4]!
.text:0000002C 14 D0 4D E2  SUB    SP, SP, #0x14
.text:00000030 08 30 A0 E3  MOV    R3, #8
.text:00000034 07 20 A0 E3  MOV    R2, #7
.text:00000038 06 10 A0 E3  MOV    R1, #6
.text:0000003C 05 00 A0 E3  MOV    R0, #5
.text:00000040 04 C0 8D E2  ADD    R12, SP, #0x18+var_14
.text:00000044 0F 00 8C E8  STMIA  R12, {R0-R3}
.text:00000048 04 00 A0 E3  MOV    R0, #4
.text:0000004C 00 00 8D E5  STR    R0, [SP,#0x18+var_18]
.text:00000050 03 30 A0 E3  MOV    R3, #3
.text:00000054 02 20 A0 E3  MOV    R2, #2
.text:00000058 01 10 A0 E3  MOV    R1, #1
.text:0000005C 6E 0F 8F E2  ADR    R0, aADBDCDDDEDFDGD ; "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g↙
    ↳ =%"...
.text:00000060 BC 18 00 EB  BL     __2printf
.text:00000064 14 D0 8D E2  ADD    SP, SP, #0x14
.text:00000068 04 F0 9D E4  LDR    PC, [SP+4+var_4],#4
```

This code can be divided into several parts:

- Function prologue:

  The very first STR LR, [SP,#var_4]! instruction saves LR on the stack, because we are going to use this register for the printf() call. Exclamation mark at the end indicates *pre-index*.

  This implies that SP is to be decreased by 4 first, and then LR will be saved at the address stored in SP. This is similar to PUSH in x86. Read more about it at: 1.32.2 on page 439.

  The second SUB SP, SP, #0x14 instruction decreases SP (the stack pointer) in order to allocate 0x14 (20) bytes on the stack. Indeed, we have to pass 5 32-bit values via the stack to the printf() function, and each one occupies 4 bytes, which is exactly $5 * 4 = 20$. The other 4 32-bit values are to be passed through registers.

- Passing 5, 6, 7 and 8 via the stack: they are stored in the R0, R1, R2 and R3 registers respectively. Then, the ADD R12, SP, #0x18+var_14 instruction writes the stack address where these 4 variables are to be stored, into the R12 register. *var_14* is an assembly macro, equal to -0x14, created by IDA to conveniently display the code accessing the stack. The *var_?* macros generated by IDA reflect local variables in the stack.

So, SP+4 is to be stored into the R12 register.

The next `STMIA R12, R0-R3` instruction writes registers R0-R3 contents to the memory pointed by R12. `STMIA` abbreviates *Store Multiple Increment After*. *"Increment After"* implies that R12 is to be increased by 4 after each register value is written.

- Passing 4 via the stack: 4 is stored in `R0` and then this value, with the help of the `STR R0, [SP,#0x18+var_18]` instruction is saved on the stack. *var_18* is -0x18, so the offset is to be 0, thus the value from the `R0` register (4) is to be written to the address written in SP.
- Passing 1, 2 and 3 via registers: The values of the first 3 numbers (a, b, c) (1, 2, 3 respectively) are passed through the R1, R2 and R3 registers right before the `printf()` call, and the other 5 values are passed via the stack:
- `printf()` call.
- Function epilogue:

  The `ADD SP, SP, #0x14` instruction restores the SP pointer back to its former value, thus annulling everything what has been stored on the stack. Of course, what has been stored on the stack will stay there, but it will all be rewritten during the execution of subsequent functions.

  The `LDR PC, [SP+4+var_4],#4` instruction loads the saved LR value from the stack into the PC register, thus causing the function to exit. There is no exclamation mark—indeed, PC is loaded first from the address stored in SP ($4 + var\_4 = 4 + (-4) = 0$, so this instruction is analogous to `LDR PC, [SP],#4`), and then SP is increased by 4. This is referred as *post-index*[69]. Why does IDA display the instruction like that? Because it wants to illustrate the stack layout and the fact that `var_4` is allocated for saving the LR value in the local stack. This instruction is somewhat similar to `POP PC` in x86[70].

Optimizing Keil 6/2013: Thumb mode

```
.text:0000001C             printf_main2
.text:0000001C
.text:0000001C             var_18 = -0x18
.text:0000001C             var_14 = -0x14
.text:0000001C             var_8  = -8
.text:0000001C
.text:0000001C 00 B5        PUSH    {LR}
.text:0000001E 08 23        MOVS    R3, #8
.text:00000020 85 B0        SUB     SP, SP, #0x14
.text:00000022 04 93        STR     R3, [SP,#0x18+var_8]
.text:00000024 07 22        MOVS    R2, #7
.text:00000026 06 21        MOVS    R1, #6
.text:00000028 05 20        MOVS    R0, #5
.text:0000002A 01 AB        ADD     R3, SP, #0x18+var_14
.text:0000002C 07 C3        STMIA   R3!, {R0-R2}
.text:0000002E 04 20        MOVS    R0, #4
.text:00000030 00 90        STR     R0, [SP,#0x18+var_18]
.text:00000032 03 23        MOVS    R3, #3
.text:00000034 02 22        MOVS    R2, #2
.text:00000036 01 21        MOVS    R1, #1
.text:00000038 A0 A0        ADR     R0, aADBDCDDDEDFDGD ; "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; ↙
    ↳ g=%"...
.text:0000003A 06 F0 D9 F8  BL      __2printf
.text:0000003E
.text:0000003E             loc_3E   ; CODE XREF: example13_f+16
.text:0000003E 05 B0        ADD     SP, SP, #0x14
.text:00000040 00 BD        POP     {PC}
```

The output is almost like in the previous example. However, this is Thumb code and the values are packed into stack differently: 8 goes first, then 5, 6, 7, and 4 goes third.

Optimizing Xcode 4.6.3 (LLVM): ARM mode

[69]Read more about it: 1.32.2 on page 439.

[70]It is impossible to set IP/EIP/RIP value using POP in x86, but anyway, you got the analogy right.

```
__text:0000290C             _printf_main2
__text:0000290C
__text:0000290C             var_1C = -0x1C
__text:0000290C             var_C  = -0xC
__text:0000290C
__text:0000290C 80 40 2D E9   STMFD  SP!, {R7,LR}
__text:00002910 0D 70 A0 E1   MOV    R7, SP
__text:00002914 14 D0 4D E2   SUB    SP, SP, #0x14
__text:00002918 70 05 01 E3   MOV    R0, #0x1570
__text:0000291C 07 C0 A0 E3   MOV    R12, #7
__text:00002920 00 00 40 E3   MOVT   R0, #0
__text:00002924 04 20 A0 E3   MOV    R2, #4
__text:00002928 00 00 8F E0   ADD    R0, PC, R0
__text:0000292C 06 30 A0 E3   MOV    R3, #6
__text:00002930 05 10 A0 E3   MOV    R1, #5
__text:00002934 00 20 8D E5   STR    R2, [SP,#0x1C+var_1C]
__text:00002938 0A 10 8D E9   STMFA  SP, {R1,R3,R12}
__text:0000293C 08 90 A0 E3   MOV    R9, #8
__text:00002940 01 10 A0 E3   MOV    R1, #1
__text:00002944 02 20 A0 E3   MOV    R2, #2
__text:00002948 03 30 A0 E3   MOV    R3, #3
__text:0000294C 10 90 8D E5   STR    R9, [SP,#0x1C+var_C]
__text:00002950 A4 05 00 EB   BL     _printf
__text:00002954 07 D0 A0 E1   MOV    SP, R7
__text:00002958 80 80 BD E8   LDMFD  SP!, {R7,PC}
```

Almost the same as what we have already seen, with the exception of STMFA (Store Multiple Full Ascending) instruction, which is a synonym of STMIB (Store Multiple Increment Before) instruction. This instruction increases the value in the SP register and only then writes the next register value into the memory, rather than performing those two actions in the opposite order.

Another thing that catches the eye is that the instructions are arranged seemingly random. For example, the value in the R0 register is manipulated in three places, at addresses 0x2918, 0x2920 and 0x2928, when it would be possible to do it in one point.

However, the optimizing compiler may have its own reasons on how to order the instructions so to achieve higher efficiency during the execution.

Usually, the processor attempts to simultaneously execute instructions located side-by-side.
For example, instructions like MOVT R0, #0 and ADD R0, PC, R0 cannot be executed simultaneously since they both modify the R0 register. On the other hand, MOVT R0, #0 and MOV R2, #4 instructions can be executed simultaneously since the effects of their execution are not conflicting with each other. Presumably, the compiler tries to generate code in such a manner (wherever it is possible).

Optimizing Xcode 4.6.3 (LLVM): Thumb-2 mode

```
__text:00002BA0               _printf_main2
__text:00002BA0
__text:00002BA0               var_1C = -0x1C
__text:00002BA0               var_18 = -0x18
__text:00002BA0               var_C  = -0xC
__text:00002BA0
__text:00002BA0 80 B5          PUSH     {R7,LR}
__text:00002BA2 6F 46          MOV      R7, SP
__text:00002BA4 85 B0          SUB      SP, SP, #0x14
__text:00002BA6 41 F2 D8 20    MOVW     R0, #0x12D8
__text:00002BAA 4F F0 07 0C    MOV.W    R12, #7
__text:00002BAE C0 F2 00 00    MOVT.W   R0, #0
__text:00002BB2 04 22          MOVS     R2, #4
__text:00002BB4 78 44          ADD      R0, PC  ; char *
__text:00002BB6 06 23          MOVS     R3, #6
__text:00002BB8 05 21          MOVS     R1, #5
__text:00002BBA 0D F1 04 0E    ADD.W    LR, SP, #0x1C+var_18
__text:00002BBE 00 92          STR      R2, [SP,#0x1C+var_1C]
__text:00002BC0 4F F0 08 09    MOV.W    R9, #8
__text:00002BC4 8E E8 0A 10    STMIA.W  LR, {R1,R3,R12}
__text:00002BC8 01 21          MOVS     R1, #1
```

```
__text:00002BCA 02 22          MOVS     R2, #2
__text:00002BCC 03 23          MOVS     R3, #3
__text:00002BCE CD F8 10 90    STR.W    R9, [SP,#0x1C+var_C]
__text:00002BD2 01 F0 0A EA    BLX      _printf
__text:00002BD6 05 B0          ADD      SP, SP, #0x14
__text:00002BD8 80 BD          POP      {R7,PC}
```

The output is almost the same as in the previous example, with the exception that Thumb-instructions are used instead.

ARM64

Non-optimizing GCC (Linaro) 4.9

Listing 1.53: Non-optimizing GCC (Linaro) 4.9

```
.LC2:
        .string "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n"
f3:
; grab more space in stack:
        sub     sp, sp, #32
; save FP and LR in stack frame:
        stp     x29, x30, [sp,16]
; set stack frame (FP=SP):
        add     x29, sp, 16
        adrp    x0, .LC2 ; "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n"
        add     x0, x0, :lo12:.LC2
        mov     w1, 8           ; 9th argument
        str     w1, [sp]        ; store 9th argument in the stack
        mov     w1, 1
        mov     w2, 2
        mov     w3, 3
        mov     w4, 4
        mov     w5, 5
        mov     w6, 6
        mov     w7, 7
        bl      printf
        sub     sp, x29, #16
; restore FP and LR
        ldp     x29, x30, [sp,16]
        add     sp, sp, 32
        ret
```

The first 8 arguments are passed in X- or W-registers: [*Procedure Call Standard for the ARM 64-bit Architecture (AArch64)*, (2013)][71]. A string pointer requires a 64-bit register, so it's passed in X0. All other values have a *int* 32-bit type, so they are stored in the 32-bit part of the registers (W-). The 9th argument (8) is passed via the stack. Indeed: it's not possible to pass large number of arguments through registers, because the number of registers is limited.

Optimizing GCC (Linaro) 4.9 generates the same code.

1.8.3 MIPS

3 arguments

Optimizing GCC 4.4.5

The main difference with the "Hello, world!" example is that in this case `printf()` is called instead of `puts()` and 3 more arguments are passed through the registers $5…$7 (or $A0…$A2). That is why these registers are prefixed with A-, which implies they are used for function arguments passing.

[71]Also available as http://go.yurichev.com/17287

Listing 1.54: Optimizing GCC 4.4.5 (assembly output)

```
$LC0:
        .ascii  "a=%d; b=%d; c=%d\000"
main:
; function prologue:
        lui     $28,%hi(__gnu_local_gp)
        addiu   $sp,$sp,-32
        addiu   $28,$28,%lo(__gnu_local_gp)
        sw      $31,28($sp)
; load address of printf():
        lw      $25,%call16(printf)($28)
; load address of the text string and set 1st argument of printf():
        lui     $4,%hi($LC0)
        addiu   $4,$4,%lo($LC0)
; set 2nd argument of printf():
        li      $5,1                    # 0x1
; set 3rd argument of printf():
        li      $6,2                    # 0x2
; call printf():
        jalr    $25
; set 4th argument of printf() (branch delay slot):
        li      $7,3                    # 0x3

; function epilogue:
        lw      $31,28($sp)
; set return value to 0:
        move    $2,$0
; return
        j       $31
        addiu   $sp,$sp,32 ; branch delay slot
```

Listing 1.55: Optimizing GCC 4.4.5 (IDA)

```
.text:00000000 main:
.text:00000000
.text:00000000 var_10          = -0x10
.text:00000000 var_4           = -4
.text:00000000
; function prologue:
.text:00000000                 lui     $gp, (__gnu_local_gp >> 16)
.text:00000004                 addiu   $sp, -0x20
.text:00000008                 la      $gp, (__gnu_local_gp & 0xFFFF)
.text:0000000C                 sw      $ra, 0x20+var_4($sp)
.text:00000010                 sw      $gp, 0x20+var_10($sp)
; load address of printf():
.text:00000014                 lw      $t9, (printf & 0xFFFF)($gp)
; load address of the text string and set 1st argument of printf():
.text:00000018                 la      $a0, $LC0        # "a=%d; b=%d; c=%d"
; set 2nd argument of printf():
.text:00000020                 li      $a1, 1
; set 3rd argument of printf():
.text:00000024                 li      $a2, 2
; call printf():
.text:00000028                 jalr    $t9
; set 4th argument of printf() (branch delay slot):
.text:0000002C                 li      $a3, 3
; function epilogue:
.text:00000030                 lw      $ra, 0x20+var_4($sp)
; set return value to 0:
.text:00000034                 move    $v0, $zero
; return
.text:00000038                 jr      $ra
.text:0000003C                 addiu   $sp, 0x20 ; branch delay slot
```

IDA has coalesced pair of LUI and ADDIU instructions into one LA pseudo instruction. That's why there are no instruction at address 0x1C: because LA *occupies* 8 bytes.

Non-optimizing GCC 4.4.5

Non-optimizing GCC is more verbose:

Listing 1.56: Non-optimizing GCC 4.4.5 (assembly output)

```
$LC0:
        .ascii  "a=%d; b=%d; c=%d\000"
main:
; function prologue:
        addiu   $sp,$sp,-32
        sw      $31,28($sp)
        sw      $fp,24($sp)
        move    $fp,$sp
        lui     $28,%hi(__gnu_local_gp)
        addiu   $28,$28,%lo(__gnu_local_gp)
; load address of the text string:
        lui     $2,%hi($LC0)
        addiu   $2,$2,%lo($LC0)
; set 1st argument of printf():
        move    $4,$2
; set 2nd argument of printf():
        li      $5,1                    # 0x1
; set 3rd argument of printf():
        li      $6,2                    # 0x2
; set 4th argument of printf():
        li      $7,3                    # 0x3
; get address of printf():
        lw      $2,%call16(printf)($28)
        nop
; call printf():
        move    $25,$2
        jalr    $25
        nop

; function epilogue:
        lw      $28,16($fp)
; set return value to 0:
        move    $2,$0
        move    $sp,$fp
        lw      $31,28($sp)
        lw      $fp,24($sp)
        addiu   $sp,$sp,32
; return
        j       $31
        nop
```

Listing 1.57: Non-optimizing GCC 4.4.5 (IDA)

```
.text:00000000 main:
.text:00000000
.text:00000000 var_10          = -0x10
.text:00000000 var_8           = -8
.text:00000000 var_4           = -4
.text:00000000
; function prologue:
.text:00000000                 addiu   $sp, -0x20
.text:00000004                 sw      $ra, 0x20+var_4($sp)
.text:00000008                 sw      $fp, 0x20+var_8($sp)
.text:0000000C                 move    $fp, $sp
.text:00000010                 la      $gp, __gnu_local_gp
.text:00000018                 sw      $gp, 0x20+var_10($sp)
; load address of the text string:
.text:0000001C                 la      $v0, aADBDCD     # "a=%d; b=%d; c=%d"
; set 1st argument of printf():
.text:00000024                 move    $a0, $v0
; set 2nd argument of printf():
.text:00000028                 li      $a1, 1
; set 3rd argument of printf():
.text:0000002C                 li      $a2, 2
```

```
; set 4th argument of printf():
.text:00000030                 li      $a3, 3
; get address of printf():
.text:00000034                 lw      $v0, (printf & 0xFFFF)($gp)
.text:00000038                 or      $at, $zero
; call printf():
.text:0000003C                 move    $t9, $v0
.text:00000040                 jalr    $t9
.text:00000044                 or      $at, $zero ; NOP
; function epilogue:
.text:00000048                 lw      $gp, 0x20+var_10($fp)
; set return value to 0:
.text:0000004C                 move    $v0, $zero
.text:00000050                 move    $sp, $fp
.text:00000054                 lw      $ra, 0x20+var_4($sp)
.text:00000058                 lw      $fp, 0x20+var_8($sp)
.text:0000005C                 addiu   $sp, 0x20
; return
.text:00000060                 jr      $ra
.text:00000064                 or      $at, $zero ; NOP
```

8 arguments

Let's use again the example with 9 arguments from the previous section: 1.8.1 on page 50.

```
#include <stdio.h>

int main()
{
        printf("a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n", 1, 2, 3, 4, 5, 6, 7, 8);
        return 0;
};
```

Optimizing GCC 4.4.5

Only the first 4 arguments are passed in the $A0 …$A3 registers, the rest are passed via the stack.

This is the O32 calling convention (which is the most common one in the MIPS world). Other calling conventions (like N32) may use the registers for different purposes.

SW abbreviates "Store Word" (from register to memory). MIPS lacks instructions for storing a value into memory, so an instruction pair has to be used instead (LI/SW).

Listing 1.58: Optimizing GCC 4.4.5 (assembly output)

```
$LC0:
        .ascii  "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\012\000"
main:
; function prologue:
        lui     $28,%hi(__gnu_local_gp)
        addiu   $sp,$sp,-56
        addiu   $28,$28,%lo(__gnu_local_gp)
        sw      $31,52($sp)
; pass 5th argument in stack:
        li      $2,4                    # 0x4
        sw      $2,16($sp)
; pass 6th argument in stack:
        li      $2,5                    # 0x5
        sw      $2,20($sp)
; pass 7th argument in stack:
        li      $2,6                    # 0x6
        sw      $2,24($sp)
; pass 8th argument in stack:
        li      $2,7                    # 0x7
        lw      $25,%call16(printf)($28)
        sw      $2,28($sp)
```

```
; pass 1st argument in $a0:
        lui     $4,%hi($LC0)
; pass 9th argument in stack:
        li      $2,8                    # 0x8
        sw      $2,32($sp)
        addiu   $4,$4,%lo($LC0)
; pass 2nd argument in $a1:
        li      $5,1                    # 0x1
; pass 3rd argument in $a2:
        li      $6,2                    # 0x2
; call printf():
        jalr    $25
; pass 4th argument in $a3 (branch delay slot):
        li      $7,3                    # 0x3

; function epilogue:
        lw      $31,52($sp)
; set return value to 0:
        move    $2,$0
; return
        j       $31
        addiu   $sp,$sp,56 ; branch delay slot
```

Listing 1.59: Optimizing GCC 4.4.5 (IDA)

```
.text:00000000 main:
.text:00000000
.text:00000000 var_28          = -0x28
.text:00000000 var_24          = -0x24
.text:00000000 var_20          = -0x20
.text:00000000 var_1C          = -0x1C
.text:00000000 var_18          = -0x18
.text:00000000 var_10          = -0x10
.text:00000000 var_4           = -4
.text:00000000
; function prologue:
.text:00000000                 lui     $gp, (__gnu_local_gp >> 16)
.text:00000004                 addiu   $sp, -0x38
.text:00000008                 la      $gp, (__gnu_local_gp & 0xFFFF)
.text:0000000C                 sw      $ra, 0x38+var_4($sp)
.text:00000010                 sw      $gp, 0x38+var_10($sp)
; pass 5th argument in stack:
.text:00000014                 li      $v0, 4
.text:00000018                 sw      $v0, 0x38+var_28($sp)
; pass 6th argument in stack:
.text:0000001C                 li      $v0, 5
.text:00000020                 sw      $v0, 0x38+var_24($sp)
; pass 7th argument in stack:
.text:00000024                 li      $v0, 6
.text:00000028                 sw      $v0, 0x38+var_20($sp)
; pass 8th argument in stack:
.text:0000002C                 li      $v0, 7
.text:00000030                 lw      $t9, (printf & 0xFFFF)($gp)
.text:00000034                 sw      $v0, 0x38+var_1C($sp)
; prepare 1st argument in $a0:
.text:00000038                 lui     $a0, ($LC0 >> 16)  # "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d↙
    ↳ ; g=%"...
; pass 9th argument in stack:
.text:0000003C                 li      $v0, 8
.text:00000040                 sw      $v0, 0x38+var_18($sp)
; pass 1st argument in $a0:
.text:00000044                 la      $a0, ($LC0 & 0xFFFF)  # "a=%d; b=%d; c=%d; d=%d; e=%d; f↙
    ↳ =%d; g=%"...
; pass 2nd argument in $a1:
.text:00000048                 li      $a1, 1
; pass 3rd argument in $a2:
.text:0000004C                 li      $a2, 2
; call printf():
.text:00000050                 jalr    $t9
; pass 4th argument in $a3 (branch delay slot):
```

```
.text:00000054                 li      $a3, 3
; function epilogue:
.text:00000058                 lw      $ra, 0x38+var_4($sp)
; set return value to 0:
.text:0000005C                 move    $v0, $zero
; return
.text:00000060                 jr      $ra
.text:00000064                 addiu   $sp, 0x38 ; branch delay slot
```

Non-optimizing GCC 4.4.5

Non-optimizing GCC is more verbose:

Listing 1.60: Non-optimizing GCC 4.4.5 (assembly output)

```
$LC0:
        .ascii  "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\012\000"
main:
; function prologue:
        addiu   $sp,$sp,-56
        sw      $31,52($sp)
        sw      $fp,48($sp)
        move    $fp,$sp
        lui     $28,%hi(__gnu_local_gp)
        addiu   $28,$28,%lo(__gnu_local_gp)
        lui     $2,%hi($LC0)
        addiu   $2,$2,%lo($LC0)
; pass 5th argument in stack:
        li      $3,4                    # 0x4
        sw      $3,16($sp)
; pass 6th argument in stack:
        li      $3,5                    # 0x5
        sw      $3,20($sp)
; pass 7th argument in stack:
        li      $3,6                    # 0x6
        sw      $3,24($sp)
; pass 8th argument in stack:
        li      $3,7                    # 0x7
        sw      $3,28($sp)
; pass 9th argument in stack:
        li      $3,8                    # 0x8
        sw      $3,32($sp)
; pass 1st argument in $a0:
        move    $4,$2
; pass 2nd argument in $a1:
        li      $5,1                    # 0x1
; pass 3rd argument in $a2:
        li      $6,2                    # 0x2
; pass 4th argument in $a3:
        li      $7,3                    # 0x3
; call printf():
        lw      $2,%call16(printf)($28)
        nop
        move    $25,$2
        jalr    $25
        nop
; function epilogue:
        lw      $28,40($fp)
; set return value to 0:
        move    $2,$0
        move    $sp,$fp
        lw      $31,52($sp)
        lw      $fp,48($sp)
        addiu   $sp,$sp,56
; return
        j       $31
        nop
```

Listing 1.61: Non-optimizing GCC 4.4.5 (IDA)

```
.text:00000000 main:
.text:00000000
.text:00000000 var_28          = -0x28
.text:00000000 var_24          = -0x24
.text:00000000 var_20          = -0x20
.text:00000000 var_1C          = -0x1C
.text:00000000 var_18          = -0x18
.text:00000000 var_10          = -0x10
.text:00000000 var_8           = -8
.text:00000000 var_4           = -4
.text:00000000
; function prologue:
.text:00000000                 addiu   $sp, -0x38
.text:00000004                 sw      $ra, 0x38+var_4($sp)
.text:00000008                 sw      $fp, 0x38+var_8($sp)
.text:0000000C                 move    $fp, $sp
.text:00000010                 la      $gp, __gnu_local_gp
.text:00000018                 sw      $gp, 0x38+var_10($sp)
.text:0000001C                 la      $v0, aADBDCDDDEDFDGD  # "a=%d; b=%d; c=%d; d=%d; e=%d; f↙
    ↳ =%d; g=%"...
; pass 5th argument in stack:
.text:00000024                 li      $v1, 4
.text:00000028                 sw      $v1, 0x38+var_28($sp)
; pass 6th argument in stack:
.text:0000002C                 li      $v1, 5
.text:00000030                 sw      $v1, 0x38+var_24($sp)
; pass 7th argument in stack:
.text:00000034                 li      $v1, 6
.text:00000038                 sw      $v1, 0x38+var_20($sp)
; pass 8th argument in stack:
.text:0000003C                 li      $v1, 7
.text:00000040                 sw      $v1, 0x38+var_1C($sp)
; pass 9th argument in stack:
.text:00000044                 li      $v1, 8
.text:00000048                 sw      $v1, 0x38+var_18($sp)
; pass 1st argument in $a0:
.text:0000004C                 move    $a0, $v0
; pass 2nd argument in $a1:
.text:00000050                 li      $a1, 1
; pass 3rd argument in $a2:
.text:00000054                 li      $a2, 2
; pass 4th argument in $a3:
.text:00000058                 li      $a3, 3
; call printf():
.text:0000005C                 lw      $v0, (printf & 0xFFFF)($gp)
.text:00000060                 or      $at, $zero
.text:00000064                 move    $t9, $v0
.text:00000068                 jalr    $t9
.text:0000006C                 or      $at, $zero ; NOP
; function epilogue:
.text:00000070                 lw      $gp, 0x38+var_10($fp)
; set return value to 0:
.text:00000074                 move    $v0, $zero
.text:00000078                 move    $sp, $fp
.text:0000007C                 lw      $ra, 0x38+var_4($sp)
.text:00000080                 lw      $fp, 0x38+var_8($sp)
.text:00000084                 addiu   $sp, 0x38
; return
.text:00000088                 jr      $ra
.text:0000008C                 or      $at, $zero ; NOP
```

1.8.4 Conclusion

Here is a rough skeleton of the function call:

Listing 1.62: x86

```
...
PUSH 3rd argument
PUSH 2nd argument
PUSH 1st argument
CALL function
; modify stack pointer (if needed)
```

Listing 1.63: x64 (MSVC)

```
MOV RCX, 1st argument
MOV RDX, 2nd argument
MOV R8, 3rd argument
MOV R9, 4th argument
...
PUSH 5th, 6th argument, etc. (if needed)
CALL function
; modify stack pointer (if needed)
```

Listing 1.64: x64 (GCC)

```
MOV RDI, 1st argument
MOV RSI, 2nd argument
MOV RDX, 3rd argument
MOV RCX, 4th argument
MOV R8, 5th argument
MOV R9, 6th argument
...
PUSH 7th, 8th argument, etc. (if needed)
CALL function
; modify stack pointer (if needed)
```

Listing 1.65: ARM

```
MOV R0, 1st argument
MOV R1, 2nd argument
MOV R2, 3rd argument
MOV R3, 4th argument
; pass 5th, 6th argument, etc., in stack (if needed)
BL function
; modify stack pointer (if needed)
```

Listing 1.66: ARM64

```
MOV X0, 1st argument
MOV X1, 2nd argument
MOV X2, 3rd argument
MOV X3, 4th argument
MOV X4, 5th argument
MOV X5, 6th argument
MOV X6, 7th argument
MOV X7, 8th argument
; pass 9th, 10th argument, etc., in stack (if needed)
BL function
; modify stack pointer (if needed)
```

Listing 1.67: MIPS (O32 calling convention)

```
LI $4, 1st argument ; AKA $A0
LI $5, 2nd argument ; AKA $A1
LI $6, 3rd argument ; AKA $A2
LI $7, 4th argument ; AKA $A3
; pass 5th, 6th argument, etc., in stack (if needed)
LW temp_reg, address of function
JALR temp_reg
```

1.8.5 By the way

By the way, this difference between the arguments passing in x86, x64, fastcall, ARM and MIPS is a good illustration of the fact that the CPU is oblivious to how the arguments are passed to functions. It is also possible to create a hypothetical compiler able to pass arguments via a special structure without using stack at all.

MIPS $A0 …$A3 registers are labeled this way only for convenience (that is in the O32 calling convention). Programmers may use any other register (well, maybe except $ZERO) to pass data or use any other calling convention.

The CPU is not aware of calling conventions whatsoever.

We may also recall how new coming assembly language programmers passing arguments into other functions: usually via registers, without any explicit order, or even via global variables. Of course, it works fine.

1.9 scanf()

Now let's use scanf().

1.9.1 Simple example

```
#include <stdio.h>

int main()
{
        int x;
        printf ("Enter X:\n");

        scanf ("%d", &x);

        printf ("You entered %d...\n", x);

        return 0;
};
```

It's not clever to use `scanf()` for user interactions nowadays. But we can, however, illustrate passing a pointer to a variable of type *int*.

About pointers

Pointers are one of the fundamental concepts in computer science. Often, passing a large array, structure or object as an argument to another function is too expensive, while passing their address is much cheaper. For example, if you going to print a text string to console, it's much easier to pass its address into OS kernel.

In addition if the callee function needs to modify something in the large array or structure received as a parameter and return back the entire structure then the situation is close to absurd. So the simplest thing to do is to pass the address of the array or structure to the callee function, and let it change what needs to be changed.

A pointer in C/C++—is simply an address of some memory location.

In x86, the address is represented as a 32-bit number (i.e., it occupies 4 bytes), while in x86-64 it is a 64-bit number (occupying 8 bytes). By the way, that is the reason behind some people's indignation related to switching to x86-64—all pointers in the x64-architecture require twice as much space, including cache memory, which is "expensive" memory.

It is possible to work with untyped pointers only, given some effort; e.g. the standard C function `memcpy()`, that copies a block from one memory location to another, takes 2 pointers of type `void*` as arguments, since it is impossible to predict the type of the data you would like to copy. Data types are not important, only the block size matters.

Pointers are also widely used when a function needs to return more than one value (we are going to get back to this later (3.21 on page 611)).

scanf() function—is such a case.

Besides the fact that the function needs to indicate how many values were successfully read, it also needs to return all these values.

In C/C++ the pointer type is only needed for compile-time type checking.

Internally, in the compiled code there is no information about pointer types at all.

x86

MSVC

Here is what we get after compiling with MSVC 2010:

```
CONST    SEGMENT
$SG3831    DB    'Enter X:', 0aH, 00H
$SG3832    DB    '%d', 00H
$SG3833    DB    'You entered %d...', 0aH, 00H
CONST    ENDS
PUBLIC    _main
EXTRN    _scanf:PROC
EXTRN    _printf:PROC
; Function compile flags: /Odtp
_TEXT    SEGMENT
_x$ = -4                        ; size = 4
_main    PROC
    push   ebp
    mov    ebp, esp
    push   ecx
    push   OFFSET $SG3831 ; 'Enter X:'
    call   _printf
    add    esp, 4
    lea    eax, DWORD PTR _x$[ebp]
    push   eax
    push   OFFSET $SG3832 ; '%d'
    call   _scanf
    add    esp, 8
    mov    ecx, DWORD PTR _x$[ebp]
    push   ecx
    push   OFFSET $SG3833 ; 'You entered %d...'
    call   _printf
    add    esp, 8

    ; return 0
    xor    eax, eax
    mov    esp, ebp
    pop    ebp
    ret    0
_main    ENDP
_TEXT    ENDS
```

x is a local variable.

According to the C/C++ standard it must be visible only in this function and not from any other external scope. Traditionally, local variables are stored on the stack. There are probably other ways to allocate them, but in x86 that is the way it is.

The goal of the instruction following the function prologue, PUSH ECX, is not to save the ECX state (notice the absence of corresponding POP ECX at the function's end).

In fact it allocates 4 bytes on the stack for storing the x variable.

x is to be accessed with the assistance of the _x$ macro (it equals to -4) and the EBP register pointing to the current frame.

Over the span of the function's execution, EBP is pointing to the current stack frame making it possible to access local variables and function arguments via EBP+`offset`.

It is also possible to use ESP for the same purpose, although that is not very convenient since it changes frequently. The value of the EBP could be perceived as a *frozen state* of the value in ESP at the start of the function's execution.

Here is a typical stack frame layout in 32-bit environment:

…	…
EBP-8	local variable #2, marked in IDA as `var_8`
EBP-4	local variable #1, marked in IDA as `var_4`
EBP	saved value of EBP
EBP+4	return address
EBP+8	argument#1, marked in IDA as `arg_0`
EBP+0xC	argument#2, marked in IDA as `arg_4`
EBP+0x10	argument#3, marked in IDA as `arg_8`
…	…

The `scanf()` function in our example has two arguments.

The first one is a pointer to the string containing `%d` and the second is the address of the `x` variable.

First, the `x` variable's address is loaded into the EAX register by the `lea eax, DWORD PTR _x$[ebp]` instruction.

LEA stands for *load effective address*, and is often used for forming an address (.1.6 on page 1028).

We could say that in this case LEA simply stores the sum of the EBP register value and the `_x$` macro in the EAX register.

This is the same as `lea eax, [ebp-4]`.

So, 4 is being subtracted from the EBP register value and the result is loaded in the EAX register. Next the EAX register value is pushed into the stack and `scanf()` is being called.

`printf()` is being called after that with its first argument — a pointer to the string: `You entered %d...\n`.

The second argument is prepared with: `mov ecx, [ebp-4]`. The instruction stores the `x` variable value and not its address, in the ECX register.

Next the value in the ECX is stored on the stack and the last `printf()` is being called.

MSVC + OllyDbg

Let's try this example in OllyDbg. Let's load it and keep pressing F8 (step over) until we reach our executable file instead of `ntdll.dll`. Scroll up until `main()` appears.

Click on the first instruction (PUSH EBP), press F2 (*set a breakpoint*), then F9 (*Run*). The breakpoint will be triggered when `main()` begins.

Let's trace to the point where the address of the variable x is calculated:

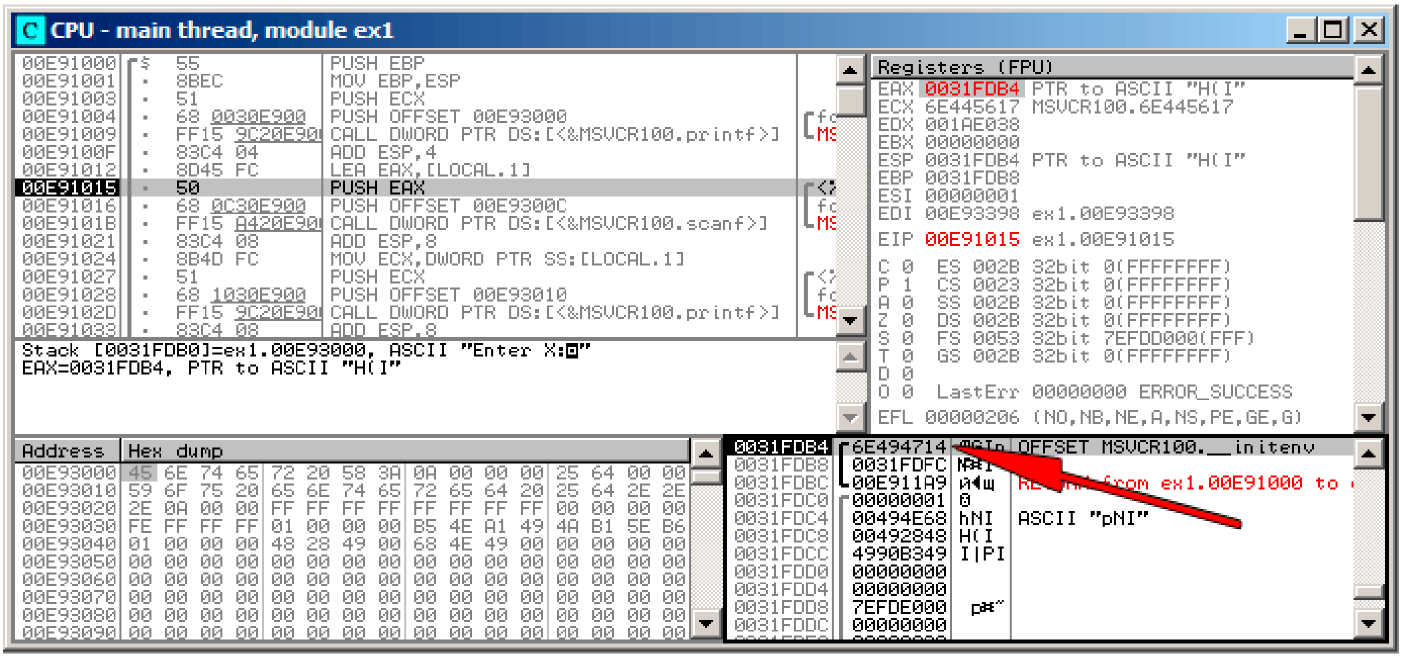


Figure 1.12: OllyDbg: The address of the local variable is calculated

Right-click the EAX in the registers window and then select "Follow in stack".

This address will appear in the stack window. The red arrow has been added, pointing to the variable in the local stack. At that moment this location contains some garbage (0x6E494714). Now with the help of PUSH instruction the address of this stack element is going to be stored to the same stack on the next position. Let's trace with F8 until the `scanf()` execution completes. During the `scanf()` execution, we input, for example, 123, in the console window:

```
Enter X:
123
```

scanf() completed its execution already:

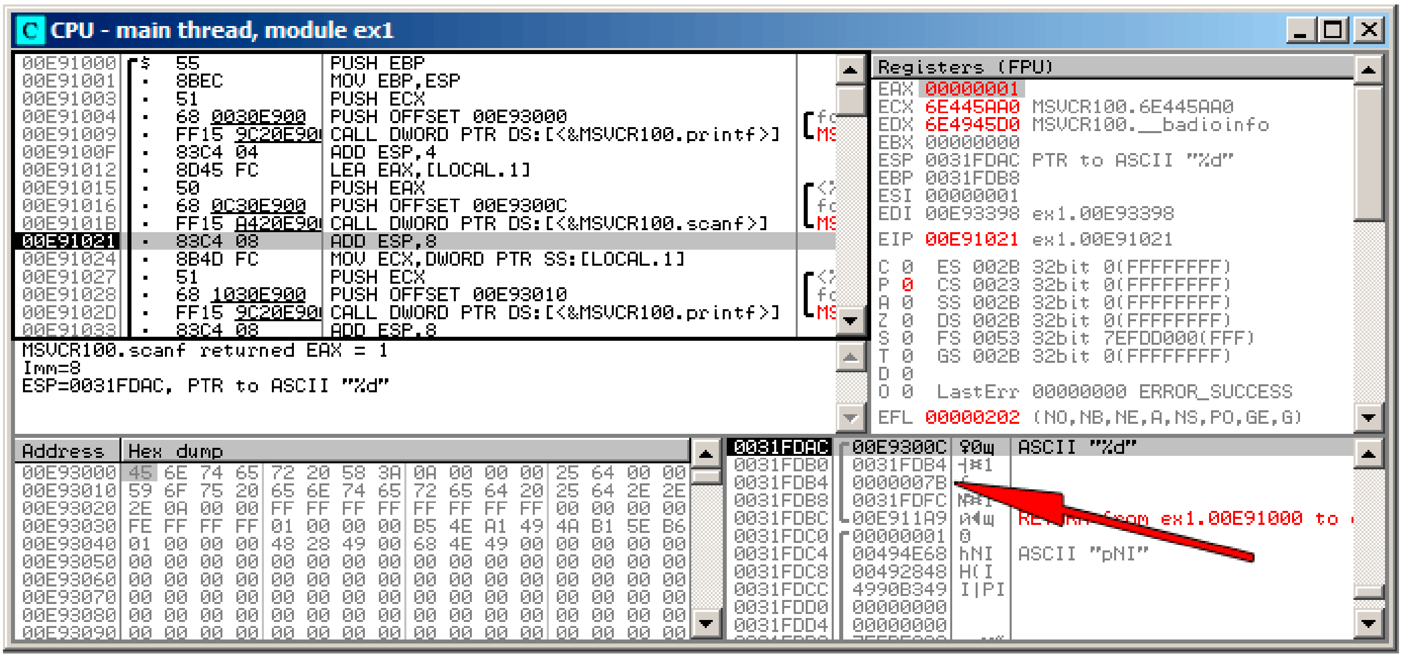


Figure 1.13: OllyDbg: scanf() executed

scanf() returns 1 in EAX, which implies that it has read successfully one value. If we look again at the stack element corresponding to the local variable it now contains 0x7B (123).

Later this value is copied from the stack to the ECX register and passed to `printf()`:

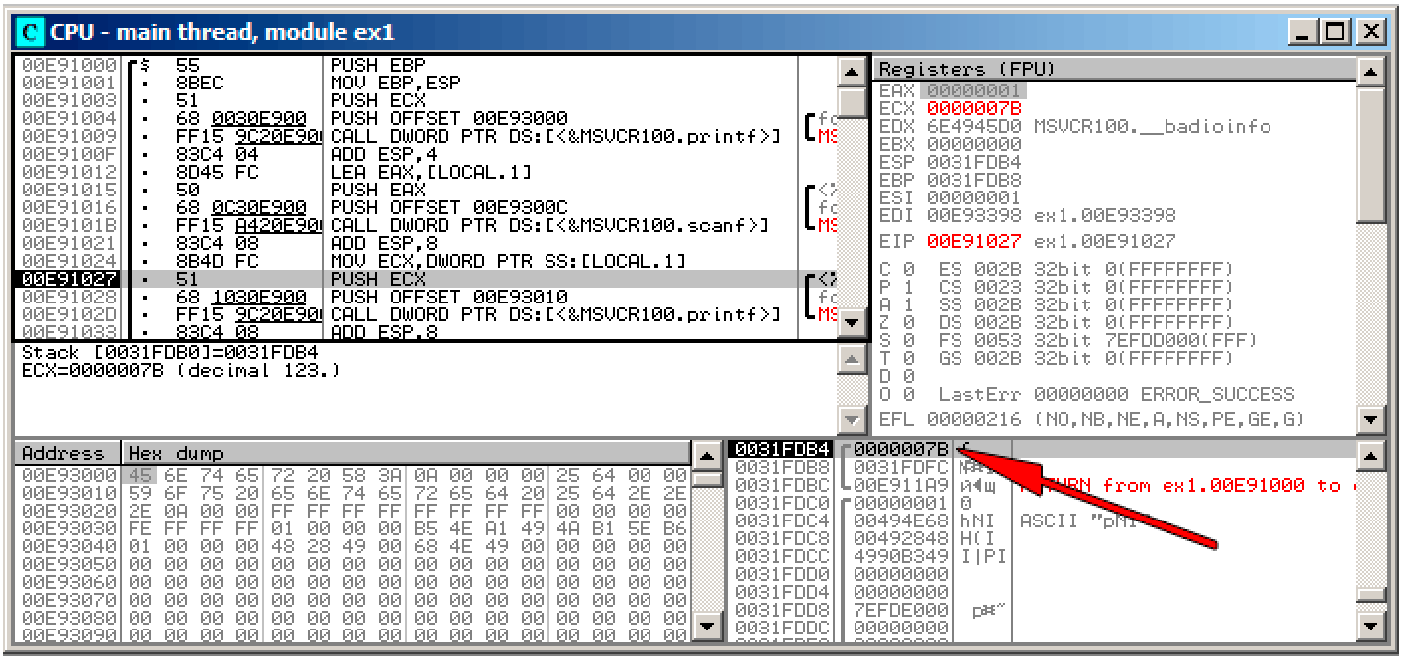


Figure 1.14: OllyDbg: preparing the value for passing to `printf()`

GCC

Let's try to compile this code in GCC 4.4.1 under Linux:

```
main            proc near

var_20          = dword ptr -20h
var_1C          = dword ptr -1Ch
var_4           = dword ptr -4

                push    ebp
                mov     ebp, esp
                and     esp, 0FFFFFFF0h
                sub     esp, 20h
                mov     [esp+20h+var_20], offset aEnterX ; "Enter X:"
                call    _puts
                mov     eax, offset aD  ; "%d"
                lea     edx, [esp+20h+var_4]
                mov     [esp+20h+var_1C], edx
                mov     [esp+20h+var_20], eax
                call    ___isoc99_scanf
                mov     edx, [esp+20h+var_4]
                mov     eax, offset aYouEnteredD___ ; "You entered %d...\n"
                mov     [esp+20h+var_1C], edx
                mov     [esp+20h+var_20], eax
                call    _printf
                mov     eax, 0
                leave
                retn
main            endp
```

GCC replaced the `printf()` call with call to `puts()`. The reason for this was explained in (1.5.4 on page 21).

As in the MSVC example—the arguments are placed on the stack using the `MOV` instruction.

By the way

This simple example is a demonstration of the fact that compiler translates list of expressions in C/C++-block into sequential list of instructions. There are nothing between expressions in C/C++, and so in resulting machine code, there are nothing between, control flow slips from one expression to the next one.

x64

The picture here is similar with the difference that the registers, rather than the stack, are used for arguments passing.

MSVC

Listing 1.68: MSVC 2012 x64

```
_DATA   SEGMENT
$SG1289 DB      'Enter X:', 0aH, 00H
$SG1291 DB      '%d', 00H
$SG1292 DB      'You entered %d...', 0aH, 00H
_DATA   ENDS

_TEXT   SEGMENT
x$ = 32
main    PROC
$LN3:
        sub     rsp, 56
        lea     rcx, OFFSET FLAT:$SG1289 ; 'Enter X:'
        call    printf
        lea     rdx, QWORD PTR x$[rsp]
        lea     rcx, OFFSET FLAT:$SG1291 ; '%d'
        call    scanf
        mov     edx, DWORD PTR x$[rsp]
        lea     rcx, OFFSET FLAT:$SG1292 ; 'You entered %d...'
        call    printf

        ; return 0
        xor     eax, eax
        add     rsp, 56
        ret     0
main    ENDP
_TEXT   ENDS
```

GCC

Listing 1.69: Optimizing GCC 4.4.6 x64

```
.LC0:
        .string "Enter X:"
.LC1:
        .string "%d"
.LC2:
        .string "You entered %d...\n"

main:
        sub     rsp, 24
        mov     edi, OFFSET FLAT:.LC0 ; "Enter X:"
        call    puts
        lea     rsi, [rsp+12]
        mov     edi, OFFSET FLAT:.LC1 ; "%d"
        xor     eax, eax
        call    __isoc99_scanf
        mov     esi, DWORD PTR [rsp+12]
        mov     edi, OFFSET FLAT:.LC2 ; "You entered %d...\n"
        xor     eax, eax
        call    printf
```

```
        ; return 0
        xor     eax, eax
        add     rsp, 24
        ret
```

ARM

Optimizing Keil 6/2013 (Thumb mode)

```
.text:00000042             scanf_main
.text:00000042
.text:00000042             var_8          = -8
.text:00000042
.text:00000042 08 B5        PUSH    {R3,LR}
.text:00000044 A9 A0        ADR     R0, aEnterX  ; "Enter X:\n"
.text:00000046 06 F0 D3 F8  BL      __2printf
.text:0000004A 69 46        MOV     R1, SP
.text:0000004C AA A0        ADR     R0, aD  ; "%d"
.text:0000004E 06 F0 CD F8  BL      __0scanf
.text:00000052 00 99        LDR     R1, [SP,#8+var_8]
.text:00000054 A9 A0        ADR     R0, aYouEnteredD___ ; "You entered %d...\n"
.text:00000056 06 F0 CB F8  BL      __2printf
.text:0000005A 00 20        MOVS    R0, #0
.text:0000005C 08 BD        POP     {R3,PC}
```

In order for `scanf()` to be able to read item it needs a parameter—pointer to an *int*. *int* is 32-bit, so we need 4 bytes to store it somewhere in memory, and it fits exactly in a 32-bit register. A place for the local variable x is allocated in the stack and IDA has named it *var_8*. It is not necessary, however, to allocate a such since SP (stack pointer) is already pointing to that space and it can be used directly.

So, SP's value is copied to the R1 register and, together with the format-string, passed to `scanf()`. Later, with the help of the LDR instruction, this value is moved from the stack to the R1 register in order to be passed to `printf()`.

ARM64

Listing 1.70: Non-optimizing GCC 4.9.1 ARM64

```
.LC0:
        .string "Enter X:"
.LC1:
        .string "%d"
.LC2:
        .string "You entered %d...\n"
scanf_main:
; subtract 32 from SP, then save FP and LR in stack frame:
        stp     x29, x30, [sp, -32]!
; set stack frame (FP=SP)
        add     x29, sp, 0
; load pointer to the "Enter X:" string:
        adrp    x0, .LC0
        add     x0, x0, :lo12:.LC0
; X0=pointer to the "Enter X:" string
; print it:
        bl      puts
; load pointer to the "%d" string:
        adrp    x0, .LC1
        add     x0, x0, :lo12:.LC1
; find a space in stack frame for "x" variable (X1=FP+28):
        add     x1, x29, 28
; X1=address of "x" variable
; pass the address to scanf() and call it:
        bl      __isoc99_scanf
; load 32-bit value from the variable in stack frame:
```

```
27        ldr     w1, [x29,28]
28 ; W1=x
29 ; load pointer to the "You entered %d...\n" string
30 ; printf() will take text string from X0 and "x" variable from X1 (or W1)
31        adrp    x0, .LC2
32        add     x0, x0, :lo12:.LC2
33        bl      printf
34 ; return 0
35        mov     w0, 0
36 ; restore FP and LR, then add 32 to SP:
37        ldp     x29, x30, [sp], 32
38        ret
```

There is 32 bytes are allocated for stack frame, which is bigger than it needed. Perhaps some memory aligning issue? The most interesting part is finding space for the x variable in the stack frame (line 22). Why 28? Somehow, compiler decided to place this variable at the end of stack frame instead of beginning. The address is passed to `scanf()`, which just stores the user input value in the memory at that address. This is 32-bit value of type *int*. The value is fetched at line 27 and then passed to `printf()`.

MIPS

A place in the local stack is allocated for the x variable, and it is to be referred as $\$sp + 24$.

Its address is passed to `scanf()`, and the user input values is loaded using the `LW` ("Load Word") instruction and then passed to `printf()`.

Listing 1.71: Optimizing GCC 4.4.5 (assembly output)

```
$LC0:
        .ascii  "Enter X:\000"
$LC1:
        .ascii  "%d\000"
$LC2:
        .ascii  "You entered %d...\012\000"
main:
; function prologue:
        lui     $28,%hi(__gnu_local_gp)
        addiu   $sp,$sp,-40
        addiu   $28,$28,%lo(__gnu_local_gp)
        sw      $31,36($sp)
; call puts():
        lw      $25,%call16(puts)($28)
        lui     $4,%hi($LC0)
        jalr    $25
        addiu   $4,$4,%lo($LC0) ; branch delay slot
; call scanf():
        lw      $28,16($sp)
        lui     $4,%hi($LC1)
        lw      $25,%call16(__isoc99_scanf)($28)
; set 2nd argument of scanf(), $a1=$sp+24:
        addiu   $5,$sp,24
        jalr    $25
        addiu   $4,$4,%lo($LC1) ; branch delay slot

; call printf():
        lw      $28,16($sp)
; set 2nd argument of printf(),
; load word at address $sp+24:
        lw      $5,24($sp)
        lw      $25,%call16(printf)($28)
        lui     $4,%hi($LC2)
        jalr    $25
        addiu   $4,$4,%lo($LC2) ; branch delay slot

; function epilogue:
        lw      $31,36($sp)
; set return value to 0:
        move    $2,$0
; return:
```

```
        j       $31
        addiu   $sp,$sp,40      ; branch delay slot
```

IDA displays the stack layout as follows:

Listing 1.72: Optimizing GCC 4.4.5 (IDA)

```
.text:00000000 main:
.text:00000000
.text:00000000 var_18   = -0x18
.text:00000000 var_10   = -0x10
.text:00000000 var_4    = -4
.text:00000000
; function prologue:
.text:00000000          lui     $gp, (__gnu_local_gp >> 16)
.text:00000004          addiu   $sp, -0x28
.text:00000008          la      $gp, (__gnu_local_gp & 0xFFFF)
.text:0000000C          sw      $ra, 0x28+var_4($sp)
.text:00000010          sw      $gp, 0x28+var_18($sp)
; call puts():
.text:00000014          lw      $t9, (puts & 0xFFFF)($gp)
.text:00000018          lui     $a0, ($LC0 >> 16)  # "Enter X:"
.text:0000001C          jalr    $t9
.text:00000020          la      $a0, ($LC0 & 0xFFFF)  # "Enter X:" ; branch delay slot
; call scanf():
.text:00000024          lw      $gp, 0x28+var_18($sp)
.text:00000028          lui     $a0, ($LC1 >> 16)  # "%d"
.text:0000002C          lw      $t9, (__isoc99_scanf & 0xFFFF)($gp)
; set 2nd argument of scanf(), $a1=$sp+24:
.text:00000030          addiu   $a1, $sp, 0x28+var_10
.text:00000034          jalr    $t9  ; branch delay slot
.text:00000038          la      $a0, ($LC1 & 0xFFFF)  # "%d"
; call printf():
.text:0000003C          lw      $gp, 0x28+var_18($sp)
; set 2nd argument of printf(),
; load word at address $sp+24:
.text:00000040          lw      $a1, 0x28+var_10($sp)
.text:00000044          lw      $t9, (printf & 0xFFFF)($gp)
.text:00000048          lui     $a0, ($LC2 >> 16)  # "You entered %d...\n"
.text:0000004C          jalr    $t9
.text:00000050          la      $a0, ($LC2 & 0xFFFF)  # "You entered %d...\n" ; branch delay ↙
    ↳ slot
; function epilogue:
.text:00000054          lw      $ra, 0x28+var_4($sp)
; set return value to 0:
.text:00000058          move    $v0, $zero
; return:
.text:0000005C          jr      $ra
.text:00000060          addiu   $sp, 0x28 ; branch delay slot
```

1.9.2 Popular mistake

It's a very popular mistake (and/or typo) to pass value of *x* instead of pointer to *x*:

```
#include <stdio.h>

int main()
{
        int x;
        printf ("Enter X:\n");

        scanf ("%d", x); // BUG

        printf ("You entered %d...\n", x);

        return 0;
};
```

So what happens here? *x* is not uninitialized and contains some random noise from local stack. When `scanf()` called, it takes string from user, parses it into number and tries to write it into *x*, treating it as an address in memory. But there is a random noise, so `scanf()` will try to write at random address. Most likely, the process will crash.

Interestingly enough, some CRT libraries in debug build, put visually distinctive patterns into memory just allocated, like 0xCCCCCCCC or 0x0BADF00D and so on. In this case, *x* may contain 0xCCCCCCCC, and `scanf()` would try to write at address 0xCCCCCCCC. And if you'll notice that something in your process tries to write at address 0xCCCCCCCC, you'll know that uninitialized variable (or pointer) gets used without prior initialization. This is better than as if newly allocated memory is just cleared.

1.9.3 Global variables

What if the x variable from the previous example isn't local but a global one? Then it would have been accessible from any point, not only from the function body. Global variables are considered anti-pattern, but for the sake of the experiment, we could do this.

```
#include <stdio.h>

// now x is global variable
int x;

int main()
{
        printf ("Enter X:\n");

        scanf ("%d", &x);

        printf ("You entered %d...\n", x);

        return 0;
};
```

MSVC: x86

```
_DATA    SEGMENT
COMM    _x:DWORD
$SG2456    DB    'Enter X:', 0aH, 00H
$SG2457    DB    '%d', 00H
$SG2458    DB    'You entered %d...', 0aH, 00H
_DATA    ENDS
PUBLIC    _main
EXTRN    _scanf:PROC
EXTRN    _printf:PROC
; Function compile flags: /Odtp
_TEXT    SEGMENT
_main    PROC
    push   ebp
    mov    ebp, esp
    push   OFFSET $SG2456
    call   _printf
    add    esp, 4
    push   OFFSET _x
    push   OFFSET $SG2457
    call   _scanf
    add    esp, 8
    mov    eax, DWORD PTR _x
    push   eax
    push   OFFSET $SG2458
    call   _printf
    add    esp, 8
    xor    eax, eax
    pop    ebp
    ret    0
_main    ENDP
_TEXT    ENDS
```

In this case the x variable is defined in the _DATA segment and no memory is allocated in the local stack. It is accessed directly, not through the stack. Uninitialized global variables take no space in the executable file (indeed, why one needs to allocate space for variables initially set to zero?), but when someone accesses their address, the OS will allocate a block of zeros there[72].

Now let's explicitly assign a value to the variable:

```
int x=10; // default value
```

We got:

```
_DATA   SEGMENT
_x      DD      0aH

...
```

Here we see a value 0xA of DWORD type (DD stands for DWORD = 32 bit) for this variable.

If you open the compiled .exe in IDA, you can see the *x* variable placed at the beginning of the _DATA segment, and after it you can see text strings.

If you open the compiled .exe from the previous example in IDA, where the value of *x* hasn't been set, you would see something like this:

Listing 1.73: IDA

```
.data:0040FA80 _x              dd ?    ; DATA XREF: _main+10
.data:0040FA80                         ; _main+22
.data:0040FA84 dword_40FA84    dd ?    ; DATA XREF: _memset+1E
.data:0040FA84                         ; unknown_libname_1+28
.data:0040FA88 dword_40FA88    dd ?    ; DATA XREF: ___sbh_find_block+5
.data:0040FA88                         ; ___sbh_free_block+2BC
.data:0040FA8C ; LPVOID lpMem
.data:0040FA8C lpMem           dd ?    ; DATA XREF: ___sbh_find_block+B
.data:0040FA8C                         ; ___sbh_free_block+2CA
.data:0040FA90 dword_40FA90    dd ?    ; DATA XREF: _V6_HeapAlloc+13
.data:0040FA90                         ; __calloc_impl+72
.data:0040FA94 dword_40FA94    dd ?    ; DATA XREF: ___sbh_free_block+2FE
```

_x is marked with ? with the rest of the variables that do not need to be initialized. This implies that after loading the .exe to the memory, a space for all these variables is to be allocated and filled with zeros [*ISO/IEC 9899:TC3 (C C99 standard)*, (2007)6.7.8p10]. But in the .exe file these uninitialized variables do not occupy anything. This is convenient for large arrays, for example.

[72] That is how a VM behaves

MSVC: x86 + OllyDbg

Things are even simpler here:

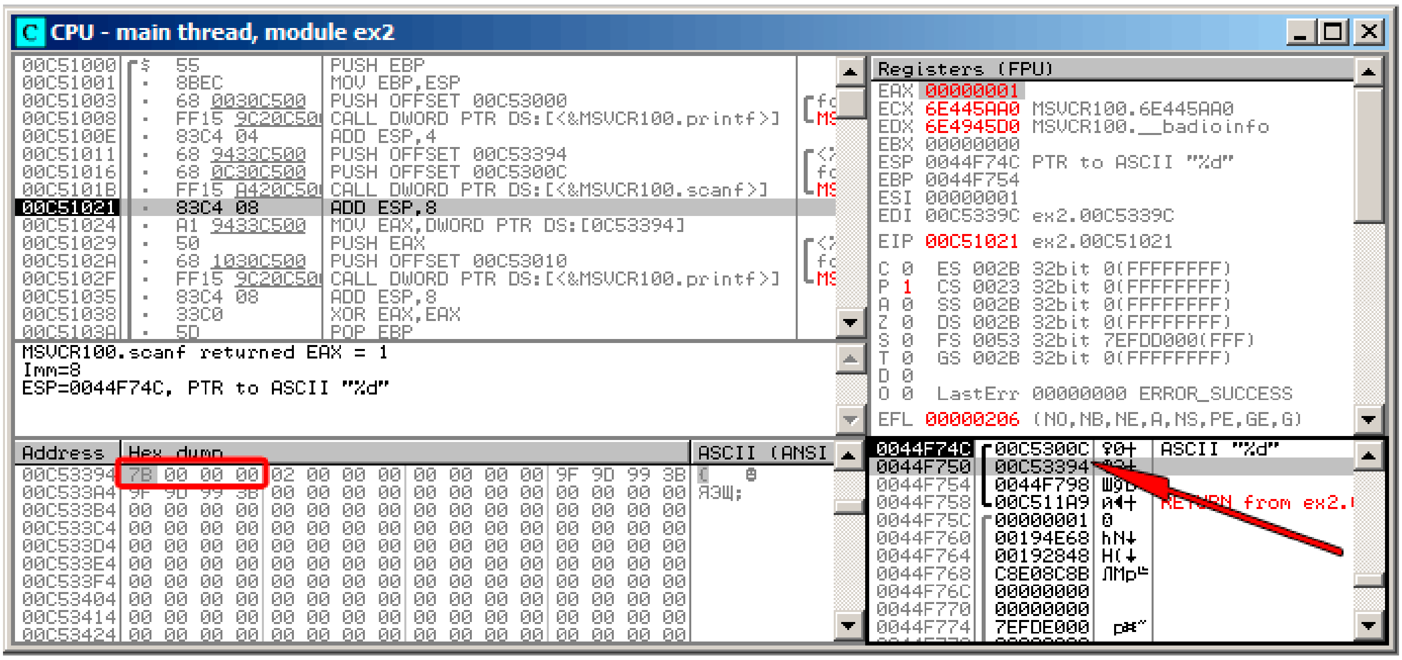


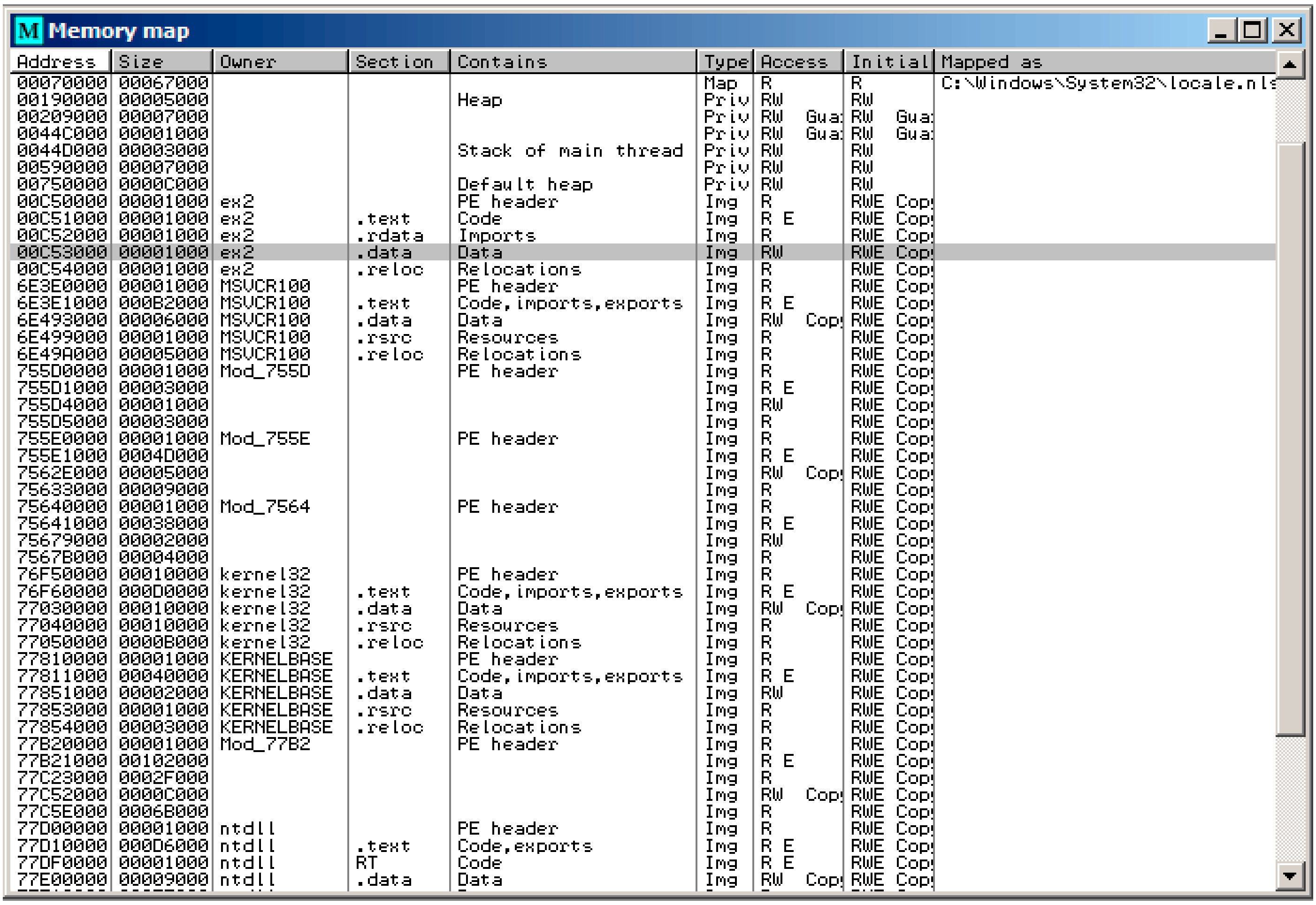
Figure 1.15: OllyDbg: after `scanf()` execution

The variable is located in the data segment. After the PUSH instruction (pushing the address of x) gets executed, the address appears in the stack window. Right-click on that row and select "Follow in dump". The variable will appear in the memory window on the left. After we have entered 123 in the console, `0x7B` appears in the memory window (see the highlighted screenshot regions).

But why is the first byte 7B? Thinking logically, `00 00 00 7B` must be there. The cause for this is referred as endianness, and x86 uses *little-endian*. This implies that the lowest byte is written first, and the highest written last. Read more about it at: 2.8 on page 464. Back to the example, the 32-bit value is loaded from this memory address into EAX and passed to `printf()`.

The memory address of x is `0x00C53394`.

In OllyDbg we can review the process memory map (Alt-M) and we can see that this address is inside the `.data` PE-segment of our program:



Address	Size	Owner	Section	Contains	Type	Access	Initial	Mapped as
00070000	00067000				Map	R	R	C:\Windows\System32\locale.nl
00190000	00005000			Heap	Priv	RW	RW	
00209000	00007000				Priv	RW Gua	RW Gua	
0044C000	00001000				Priv	RW Gua	RW Gua	
0044D000	00003000			Stack of main thread	Priv	RW	RW	
00590000	00007000				Priv	RW	RW	
00750000	0000C000			Default heap	Priv	RW	RW	
00C50000	00001000	ex2		PE header	Img	R	RWE Cop	
00C51000	00001000	ex2	.text	Code	Img	R E	RWE Cop	
00C52000	00001000	ex2	.rdata	Imports	Img	R	RWE Cop	
00C53000	00001000	ex2	.data	Data	Img	RW	RWE Cop	
00C54000	00001000	ex2	.reloc	Relocations	Img	R	RWE Cop	
6E3E0000	00001000	MSVCR100		PE header	Img	R	RWE Cop	
6E3E1000	000B2000	MSVCR100	.text	Code,imports,exports	Img	R E	RWE Cop	
6E493000	00006000	MSVCR100	.data	Data	Img	RW Cop	RWE Cop	
6E499000	00001000	MSVCR100	.rsrc	Resources	Img	R	RWE Cop	
6E49A000	00005000	MSVCR100	.reloc	Relocations	Img	R	RWE Cop	
755D0000	00001000	Mod_755D		PE header	Img	R	RWE Cop	
755D1000	00003000				Img	R E	RWE Cop	
755D4000	00001000				Img	RW	RWE Cop	
755D5000	00003000				Img	R	RWE Cop	
755E0000	00001000	Mod_755E		PE header	Img	R	RWE Cop	
755E1000	0004D000				Img	R E	RWE Cop	
7562E000	00005000				Img	RW Cop	RWE Cop	
75633000	00009000				Img	R	RWE Cop	
75640000	00001000	Mod_7564		PE header	Img	R	RWE Cop	
75641000	00038000				Img	R E	RWE Cop	
75679000	00002000				Img	RW	RWE Cop	
7567B000	00004000				Img	R	RWE Cop	
76F50000	00010000	kernel32		PE header	Img	R	RWE Cop	
76F60000	000D0000	kernel32	.text	Code,imports,exports	Img	R E	RWE Cop	
77030000	00010000	kernel32	.data	Data	Img	RW Cop	RWE Cop	
77040000	00010000	kernel32	.rsrc	Resources	Img	R	RWE Cop	
77050000	0000B000	kernel32	.reloc	Relocations	Img	R	RWE Cop	
77810000	00001000	KERNELBASE		PE header	Img	R	RWE Cop	
77811000	00040000	KERNELBASE	.text	Code,imports,exports	Img	R E	RWE Cop	
77851000	00002000	KERNELBASE	.data	Data	Img	RW	RWE Cop	
77853000	00001000	KERNELBASE	.rsrc	Resources	Img	R	RWE Cop	
77854000	00003000	KERNELBASE	.reloc	Relocations	Img	R	RWE Cop	
77B20000	00001000	Mod_77B2		PE header	Img	R	RWE Cop	
77B21000	00102000				Img	R E	RWE Cop	
77C23000	0002F000				Img	R	RWE Cop	
77C52000	0000C000				Img	RW Cop	RWE Cop	
77C5E000	0006B000				Img	R	RWE Cop	
77D00000	00001000	ntdll		PE header	Img	R	RWE Cop	
77D10000	000D6000	ntdll	.text	Code,exports	Img	R E	RWE Cop	
77DF0000	00001000	ntdll	RT	Code	Img	R E	RWE Cop	
77E00000	00009000	ntdll	.data	Data	Img	RW Cop	RWE Cop	

Figure 1.16: OllyDbg: process memory map

GCC: x86

The picture in Linux is near the same, with the difference that the uninitialized variables are located in the `_bss` segment. In ELF[73] file this segment has the following attributes:

```
; Segment type: Uninitialized
; Segment permissions: Read/Write
```

If you, however, initialize the variable with some value e.g. 10, it is to be placed in the `_data` segment, which has the following attributes:

```
; Segment type: Pure data
; Segment permissions: Read/Write
```

MSVC: x64

Listing 1.74: MSVC 2012 x64

```
_DATA   SEGMENT
COMM    x:DWORD
$SG2924 DB      'Enter X:', 0aH, 00H
$SG2925 DB      '%d', 00H
$SG2926 DB      'You entered %d...', 0aH, 00H
_DATA   ENDS
```

[73] Executable File format widely used in *NIX systems including Linux

```
_TEXT   SEGMENT
main    PROC
$LN3:
        sub     rsp, 40

        lea     rcx, OFFSET FLAT:$SG2924 ; 'Enter X:'
        call    printf
        lea     rdx, OFFSET FLAT:x
        lea     rcx, OFFSET FLAT:$SG2925 ; '%d'
        call    scanf
        mov     edx, DWORD PTR x
        lea     rcx, OFFSET FLAT:$SG2926 ; 'You entered %d...'
        call    printf

        ; return 0
        xor     eax, eax

        add     rsp, 40
        ret     0
main    ENDP
_TEXT   ENDS
```

The code is almost the same as in x86. Please note that the address of the x variable is passed to `scanf()` using a LEA instruction, while the variable's value is passed to the second `printf()` using a MOV instruction. DWORD PTR—is a part of the assembly language (no relation to the machine code), indicating that the variable data size is 32-bit and the MOV instruction has to be encoded accordingly.

ARM: Optimizing Keil 6/2013 (Thumb mode)

Listing 1.75: IDA

```
.text:00000000 ; Segment type: Pure code
.text:00000000         AREA .text, CODE
...
.text:00000000 main
.text:00000000         PUSH    {R4,LR}
.text:00000002         ADR     R0, aEnterX  ; "Enter X:\n"
.text:00000004         BL      __2printf
.text:00000008         LDR     R1, =x
.text:0000000A         ADR     R0, aD       ; "%d"
.text:0000000C         BL      __0scanf
.text:00000010         LDR     R0, =x
.text:00000012         LDR     R1, [R0]
.text:00000014         ADR     R0, aYouEnteredD___ ; "You entered %d...\n"
.text:00000016         BL      __2printf
.text:0000001A         MOVS    R0, #0
.text:0000001C         POP     {R4,PC}
...
.text:00000020 aEnterX DCB "Enter X:",0xA,0 ; DATA XREF: main+2
.text:0000002A         DCB    0
.text:0000002B         DCB    0
.text:0000002C off_2C  DCD x                ; DATA XREF: main+8
.text:0000002C                              ; main+10
.text:00000030 aD      DCB "%d",0           ; DATA XREF: main+A
.text:00000033         DCB    0
.text:00000034 aYouEnteredD___ DCB "You entered %d...",0xA,0 ; DATA XREF: main+14
.text:00000047         DCB 0
.text:00000047 ; .text ends
.text:00000047
...
.data:00000048 ; Segment type: Pure data
.data:00000048         AREA .data, DATA
.data:00000048         ; ORG 0x48
.data:00000048         EXPORT x
.data:00000048 x       DCD 0xA              ; DATA XREF: main+8
.data:00000048                              ; main+10
.data:00000048 ; .data ends
```

So, the x variable is now global and for this reason located in another segment, namely the data segment (*.data*). One could ask, why are the text strings located in the code segment (*.text*) and x is located right here? Because it is a variable and by definition its value could change. Moreover it could possibly change often. While text strings has constant type, they will not be changed, so they are located in the *.text* segment.

The code segment might sometimes be located in a ROM[74] chip (keep in mind, we now deal with embedded microelectronics, and memory scarcity is common here), and changeable variables —in RAM.

It is not very economical to store constant variables in RAM when you have ROM.

Furthermore, constant variables in RAM must be initialized, because after powering on, the RAM, obviously, contains random information.

Moving forward, we see a pointer to the x (`off_2C`) variable in the code segment, and that all operations with the variable occur via this pointer.

That is because the x variable could be located somewhere far from this particular code fragment, so its address must be saved somewhere in close proximity to the code.

The LDR instruction in Thumb mode can only address variables in a range of 1020 bytes from its location,

and in ARM-mode —variables in range of ± 4095 bytes.

And so the address of the x variable must be located somewhere in close proximity, because there is no guarantee that the linker would be able to accommodate the variable somewhere nearby the code, it may well be even in an external memory chip!

One more thing: if a variable is declared as *const*, the Keil compiler allocates it in the `.constdata` segment.

Perhaps thereafter, the linker could place this segment in ROM too, along with the code segment.

ARM64

Listing 1.76: Non-optimizing GCC 4.9.1 ARM64

```
        .comm   x,4,4
.LC0:
        .string "Enter X:"
.LC1:
        .string "%d"
.LC2:
        .string "You entered %d...\n"
f5:
; save FP and LR in stack frame:
        stp     x29, x30, [sp, -16]!
; set stack frame (FP=SP)
        add     x29, sp, 0
; load pointer to the "Enter X:" string:
        adrp    x0, .LC0
        add     x0, x0, :lo12:.LC0
        bl      puts
; load pointer to the "%d" string:
        adrp    x0, .LC1
        add     x0, x0, :lo12:.LC1
; form address of x global variable:
        adrp    x1, x
        add     x1, x1, :lo12:x
        bl      __isoc99_scanf
; form address of x global variable again:
        adrp    x0, x
        add     x0, x0, :lo12:x
; load value from memory at this address:
        ldr     w1, [x0]
; load pointer to the "You entered %d...\n" string:
        adrp    x0, .LC2
        add     x0, x0, :lo12:.LC2
        bl      printf
; return 0
        mov     w0, 0
```

[74] Read-Only Memory

```
35 ; restore FP and LR:
36         ldp     x29, x30, [sp], 16
37         ret
```

In this case the x variable is declared as global and its address is calculated using the ADRP/ADD instruction pair (lines 21 and 25).

MIPS

Uninitialized global variable

So now the x variable is global. Let's compile to executable file rather than object file and load it into IDA. IDA displays the x variable in the .sbss ELF section (remember the "Global Pointer"? 1.5.5 on page 25), since the variable is not initialized at the start.

Listing 1.77: Optimizing GCC 4.4.5 (IDA)

```
.text:004006C0 main:
.text:004006C0
.text:004006C0 var_10          = -0x10
.text:004006C0 var_4           = -4
.text:004006C0
; function prologue:
.text:004006C0                 lui     $gp, 0x42
.text:004006C4                 addiu   $sp, -0x20
.text:004006C8                 li      $gp, 0x418940
.text:004006CC                 sw      $ra, 0x20+var_4($sp)
.text:004006D0                 sw      $gp, 0x20+var_10($sp)
; call puts():
.text:004006D4                 la      $t9, puts
.text:004006D8                 lui     $a0, 0x40
.text:004006DC                 jalr    $t9 ; puts
.text:004006E0                 la      $a0, aEnterX     # "Enter X:" ; branch delay slot
; call scanf():
.text:004006E4                 lw      $gp, 0x20+var_10($sp)
.text:004006E8                 lui     $a0, 0x40
.text:004006EC                 la      $t9, __isoc99_scanf
; prepare address of x:
.text:004006F0                 la      $a1, x
.text:004006F4                 jalr    $t9 ; __isoc99_scanf
.text:004006F8                 la      $a0, aD          # "%d"       ; branch delay slot
; call printf():
.text:004006FC                 lw      $gp, 0x20+var_10($sp)
.text:00400700                 lui     $a0, 0x40
; get address of x:
.text:00400704                 la      $v0, x
.text:00400708                 la      $t9, printf
; load value from "x" variable and pass it to printf() in $a1:
.text:0040070C                 lw      $a1, (x - 0x41099C)($v0)
.text:00400710                 jalr    $t9 ; printf
.text:00400714                 la      $a0, aYouEnteredD___  # "You entered %d...\n" ; branch ↙
    ↘ delay slot
; function epilogue:
.text:00400718                 lw      $ra, 0x20+var_4($sp)
.text:0040071C                 move    $v0, $zero
.text:00400720                 jr      $ra
.text:00400724                 addiu   $sp, 0x20  ; branch delay slot

...

.sbss:0041099C  # Segment type: Uninitialized
.sbss:0041099C                 .sbss
.sbss:0041099C                 .globl x
.sbss:0041099C x:              .space 4
.sbss:0041099C
```

IDA reduces the amount of information, so we'll also do a listing using objdump and comment it:

Listing 1.78: Optimizing GCC 4.4.5 (objdump)

```
1  004006c0 <main>:
2  ; function prologue:
3    4006c0:       3c1c0042        lui     gp,0x42
4    4006c4:       27bdffe0        addiu   sp,sp,-32
5    4006c8:       279c8940        addiu   gp,gp,-30400
6    4006cc:       afbf001c        sw      ra,28(sp)
7    4006d0:       afbc0010        sw      gp,16(sp)
8  ; call puts():
9    4006d4:       8f998034        lw      t9,-32716(gp)
10   4006d8:       3c040040        lui     a0,0x40
11   4006dc:       0320f809        jalr    t9
12   4006e0:       248408f0        addiu   a0,a0,2288 ; branch delay slot
13 ; call scanf():
14   4006e4:       8fbc0010        lw      gp,16(sp)
15   4006e8:       3c040040        lui     a0,0x40
16   4006ec:       8f998038        lw      t9,-32712(gp)
17 ; prepare address of x:
18   4006f0:       8f858044        lw      a1,-32700(gp)
19   4006f4:       0320f809        jalr    t9
20   4006f8:       248408fc        addiu   a0,a0,2300 ; branch delay slot
21 ; call printf():
22   4006fc:       8fbc0010        lw      gp,16(sp)
23   400700:       3c040040        lui     a0,0x40
24 ; get address of x:
25   400704:       8f828044        lw      v0,-32700(gp)
26   400708:       8f99803c        lw      t9,-32708(gp)
27 ; load value from "x" variable and pass it to printf() in $a1:
28   40070c:       8c450000        lw      a1,0(v0)
29   400710:       0320f809        jalr    t9
30   400714:       24840900        addiu   a0,a0,2304 ; branch delay slot
31 ; function epilogue:
32   400718:       8fbf001c        lw      ra,28(sp)
33   40071c:       00001021        move    v0,zero
34   400720:       03e00008        jr      ra
35   400724:       27bd0020        addiu   sp,sp,32   ; branch delay slot
36 ; pack of NOPs used for aligning next function start on 16-byte boundary:
37   400728:       00200825        move    at,at
38   40072c:       00200825        move    at,at
```

Now we see the x variable address is read from a 64KiB data buffer using GP and adding negative offset to it (line 18). More than that, the addresses of the three external functions which are used in our example (`puts()`, `scanf()`, `printf()`), are also read from the 64KiB global data buffer using GP (lines 9, 16 and 26). GP points to the middle of the buffer, and such offset suggests that all three function's addresses, and also the address of the x variable, are all stored somewhere at the beginning of that buffer. That make sense, because our example is tiny.

Another thing worth mentioning is that the function ends with two NOPs (`MOVE $AT,$AT` — an idle instruction), in order to align next function's start on 16-byte boundary.

Initialized global variable

Let's alter our example by giving the x variable a default value:

```
int x=10; // default value
```

Now IDA shows that the x variable is residing in the .data section:

Listing 1.79: Optimizing GCC 4.4.5 (IDA)

```
.text:004006A0 main:
.text:004006A0
.text:004006A0 var_10          = -0x10
.text:004006A0 var_8           = -8
.text:004006A0 var_4           = -4
.text:004006A0
.text:004006A0                 lui     $gp, 0x42
.text:004006A4                 addiu   $sp, -0x20
```

```
.text:004006A8                 li      $gp, 0x418930
.text:004006AC                 sw      $ra, 0x20+var_4($sp)
.text:004006B0                 sw      $s0, 0x20+var_8($sp)
.text:004006B4                 sw      $gp, 0x20+var_10($sp)
.text:004006B8                 la      $t9, puts
.text:004006BC                 lui     $a0, 0x40
.text:004006C0                 jalr    $t9 ; puts
.text:004006C4                 la      $a0, aEnterX     # "Enter X:"
.text:004006C8                 lw      $gp, 0x20+var_10($sp)
; prepare high part of x address:
.text:004006CC                 lui     $s0, 0x41
.text:004006D0                 la      $t9, __isoc99_scanf
.text:004006D4                 lui     $a0, 0x40
; add low part of x address:
.text:004006D8                 addiu   $a1, $s0, (x - 0x410000)
; now address of x is in $a1.
.text:004006DC                 jalr    $t9 ; __isoc99_scanf
.text:004006E0                 la      $a0, aD          # "%d"
.text:004006E4                 lw      $gp, 0x20+var_10($sp)
; get a word from memory:
.text:004006E8                 lw      $a1, x
; value of x is now in $a1.
.text:004006EC                 la      $t9, printf
.text:004006F0                 lui     $a0, 0x40
.text:004006F4                 jalr    $t9 ; printf
.text:004006F8                 la      $a0, aYouEnteredD___  # "You entered %d...\n"
.text:004006FC                 lw      $ra, 0x20+var_4($sp)
.text:00400700                 move    $v0, $zero
.text:00400704                 lw      $s0, 0x20+var_8($sp)
.text:00400708                 jr      $ra
.text:0040070C                 addiu   $sp, 0x20

...

.data:00410920                 .globl x
.data:00410920 x:              .word 0xA
```

Why not .sdata? Perhaps that this depends on some GCC option?

Nevertheless, now x is in .data, which is a general memory area, and we can take a look how to work with variables there.

The variable's address must be formed using a pair of instructions.

In our case those are `LUI` ("Load Upper Immediate") and `ADDIU` ("Add Immediate Unsigned Word").

Here is also the objdump listing for close inspection:

Listing 1.80: Optimizing GCC 4.4.5 (objdump)

```
004006a0 <main>:
  4006a0:       3c1c0042        lui     gp,0x42
  4006a4:       27bdffe0        addiu   sp,sp,-32
  4006a8:       279c8930        addiu   gp,gp,-30416
  4006ac:       afbf001c        sw      ra,28(sp)
  4006b0:       afb00018        sw      s0,24(sp)
  4006b4:       afbc0010        sw      gp,16(sp)
  4006b8:       8f998034        lw      t9,-32716(gp)
  4006bc:       3c040040        lui     a0,0x40
  4006c0:       0320f809        jalr    t9
  4006c4:       248408d0        addiu   a0,a0,2256
  4006c8:       8fbc0010        lw      gp,16(sp)
; prepare high part of x address:
  4006cc:       3c100041        lui     s0,0x41
  4006d0:       8f998038        lw      t9,-32712(gp)
  4006d4:       3c040040        lui     a0,0x40
; add low part of x address:
  4006d8:       26050920        addiu   a1,s0,2336
; now address of x is in $a1.
  4006dc:       0320f809        jalr    t9
  4006e0:       248408dc        addiu   a0,a0,2268
  4006e4:       8fbc0010        lw      gp,16(sp)
```

```
; high part of x address is still in $s0.
; add low part to it and load a word from memory:
  4006e8:       8e050920        lw      a1,2336(s0)
; value of x is now in $a1.
  4006ec:       8f99803c        lw      t9,-32708(gp)
  4006f0:       3c040040        lui     a0,0x40
  4006f4:       0320f809        jalr    t9
  4006f8:       248408e0        addiu   a0,a0,2272
  4006fc:       8fbf001c        lw      ra,28(sp)
  400700:       00001021        move    v0,zero
  400704:       8fb00018        lw      s0,24(sp)
  400708:       03e00008        jr      ra
  40070c:       27bd0020        addiu   sp,sp,32
```

We see that the address is formed using LUI and ADDIU, but the high part of address is still in the $S0 register, and it is possible to encode the offset in a LW ("Load Word") instruction, so one single LW is enough to load a value from the variable and pass it to `printf()`.

Registers holding temporary data are prefixed with T-, but here we also see some prefixed with S-, the contents of which must be preserved before use in other functions (i.e., saved somewhere).

That is why the value of $S0 has been set at address 0x4006cc and has been used again at address 0x4006e8, after the `scanf()` call. The `scanf()` function does not change its value.

1.9.4 scanf()

As was noted before, it is slightly old-fashioned to use `scanf()` today. But if we have to, we have to check if `scanf()` finishes correctly without an error.

```
#include <stdio.h>

int main()
{
        int x;
        printf ("Enter X:\n");

        if (scanf ("%d", &x)==1)
                printf ("You entered %d...\n", x);
        else
                printf ("What you entered? Huh?\n");

        return 0;
};
```

By standard, the `scanf()`[75] function returns the number of fields it has successfully read.

In our case, if everything goes fine and the user enters a number `scanf()` returns 1, or in case of error (or EOF[76]) — 0.

Let's add some C code to check the `scanf()` return value and print error message in case of an error.

This works as expected:

```
C:\...>ex3.exe
Enter X:
123
You entered 123...

C:\...>ex3.exe
Enter X:
ouch
What you entered? Huh?
```

[75] scanf, wscanf: MSDN
[76] End of File

MSVC: x86

Here is what we get in the assembly output (MSVC 2010):

```
        lea     eax, DWORD PTR _x$[ebp]
        push    eax
        push    OFFSET $SG3833 ; '%d', 00H
        call    _scanf
        add     esp, 8
        cmp     eax, 1
        jne     SHORT $LN2@main
        mov     ecx, DWORD PTR _x$[ebp]
        push    ecx
        push    OFFSET $SG3834 ; 'You entered %d...', 0aH, 00H
        call    _printf
        add     esp, 8
        jmp     SHORT $LN1@main
$LN2@main:
        push    OFFSET $SG3836 ; 'What you entered? Huh?', 0aH, 00H
        call    _printf
        add     esp, 4
$LN1@main:
        xor     eax, eax
```

The caller function (`main()`) needs the callee function (`scanf()`) result, so the callee returns it in the EAX register.

We check it with the help of the instruction `CMP EAX, 1` (*CoMPare*). In other words, we compare the value in the EAX register with 1.

A JNE conditional jump follows the CMP instruction. JNE stands for *Jump if Not Equal*.

So, if the value in the EAX register is not equal to 1, the CPU will pass the execution to the address mentioned in the JNE operand, in our case `$LN2@main`. Passing the control to this address results in the CPU executing `printf()` with the argument `What you entered? Huh?`. But if everything is fine, the conditional jump is not be taken, and another `printf()` call is to be executed, with two arguments: `'You entered %d...'` and the value of x.

Since in this case the second `printf()` has not to be executed, there is a JMP preceding it (unconditional jump). It passes the control to the point after the second `printf()` and just before the `XOR EAX, EAX` instruction, which implements `return 0`.

So, it could be said that comparing a value with another is *usually* implemented by CMP/Jcc instruction pair, where *cc* is *condition code*. CMP compares two values and sets processor flags[77]. Jcc checks those flags and decides to either pass the control to the specified address or not.

This could sound paradoxical, but the CMP instruction is in fact SUB (subtract). All arithmetic instructions set processor flags, not just CMP. If we compare 1 and 1, $1-1$ is 0 so the ZF flag would be set (meaning that the last result is 0). In no other circumstances ZF can be set, except when the operands are equal. JNE checks only the ZF flag and jumps only if it is not set. JNE is in fact a synonym for JNZ (*Jump if Not Zero*). Assembler translates both JNE and JNZ instructions into the same opcode. So, the CMP instruction can be replaced with a SUB instruction and almost everything will be fine, with the difference that SUB alters the value of the first operand. CMP is *SUB without saving the result, but affecting flags*.

MSVC: x86: IDA

It is time to run IDA and try to do something in it. By the way, for beginners it is good idea to use /MD option in MSVC, which means that all these standard functions are not be linked with the executable file, but are to be imported from the MSVCR*.DLL file instead. Thus it will be easier to see which standard function are used and where.

While analyzing code in IDA, it is very helpful to leave notes for oneself (and others). In instance, analyzing this example, we see that JNZ is to be triggered in case of an error. So it is possible to move the cursor to the label, press “n” and rename it to “error”. Create another label—into “exit”. Here is my result:

```
.text:00401000 _main proc near
.text:00401000
```

[77] x86 flags, see also: wikipedia.

```
.text:00401000 var_4 = dword ptr -4
.text:00401000 argc  = dword ptr  8
.text:00401000 argv  = dword ptr  0Ch
.text:00401000 envp  = dword ptr  10h
.text:00401000
.text:00401000       push    ebp
.text:00401001       mov     ebp, esp
.text:00401003       push    ecx
.text:00401004       push    offset Format ; "Enter X:\n"
.text:00401009       call    ds:printf
.text:0040100F       add     esp, 4
.text:00401012       lea     eax, [ebp+var_4]
.text:00401015       push    eax
.text:00401016       push    offset aD ; "%d"
.text:0040101B       call    ds:scanf
.text:00401021       add     esp, 8
.text:00401024       cmp     eax, 1
.text:00401027       jnz     short error
.text:00401029       mov     ecx, [ebp+var_4]
.text:0040102C       push    ecx
.text:0040102D       push    offset aYou ; "You entered %d...\n"
.text:00401032       call    ds:printf
.text:00401038       add     esp, 8
.text:0040103B       jmp     short exit
.text:0040103D
.text:0040103D error: ; CODE XREF: _main+27
.text:0040103D       push    offset aWhat ; "What you entered? Huh?\n"
.text:00401042       call    ds:printf
.text:00401048       add     esp, 4
.text:0040104B
.text:0040104B exit: ; CODE XREF: _main+3B
.text:0040104B       xor     eax, eax
.text:0040104D       mov     esp, ebp
.text:0040104F       pop     ebp
.text:00401050       retn
.text:00401050 _main endp
```

Now it is slightly easier to understand the code. However, it is not a good idea to comment on every instruction.

You could also hide(collapse) parts of a function in IDA. To do that mark the block, then press “–” on the numerical pad and enter the text to be displayed instead.

Let’s hide two blocks and give them names:

```
.text:00401000 _text segment para public 'CODE' use32
.text:00401000       assume cs:_text
.text:00401000       ;org 401000h
.text:00401000 ; ask for X
.text:00401012 ; get X
.text:00401024       cmp  eax, 1
.text:00401027       jnz  short error
.text:00401029 ; print result
.text:0040103B       jmp  short exit
.text:0040103D
.text:0040103D error: ; CODE XREF: _main+27
.text:0040103D       push offset aWhat ; "What you entered? Huh?\n"
.text:00401042       call ds:printf
.text:00401048       add  esp, 4
.text:0040104B
.text:0040104B exit: ; CODE XREF: _main+3B
.text:0040104B       xor  eax, eax
.text:0040104D       mov  esp, ebp
.text:0040104F       pop  ebp
.text:00401050       retn
.text:00401050 _main endp
```

To expand previously collapsed parts of the code, use “+” on the numerical pad.

By pressing “space”, we can see how IDA represents a function as a graph:

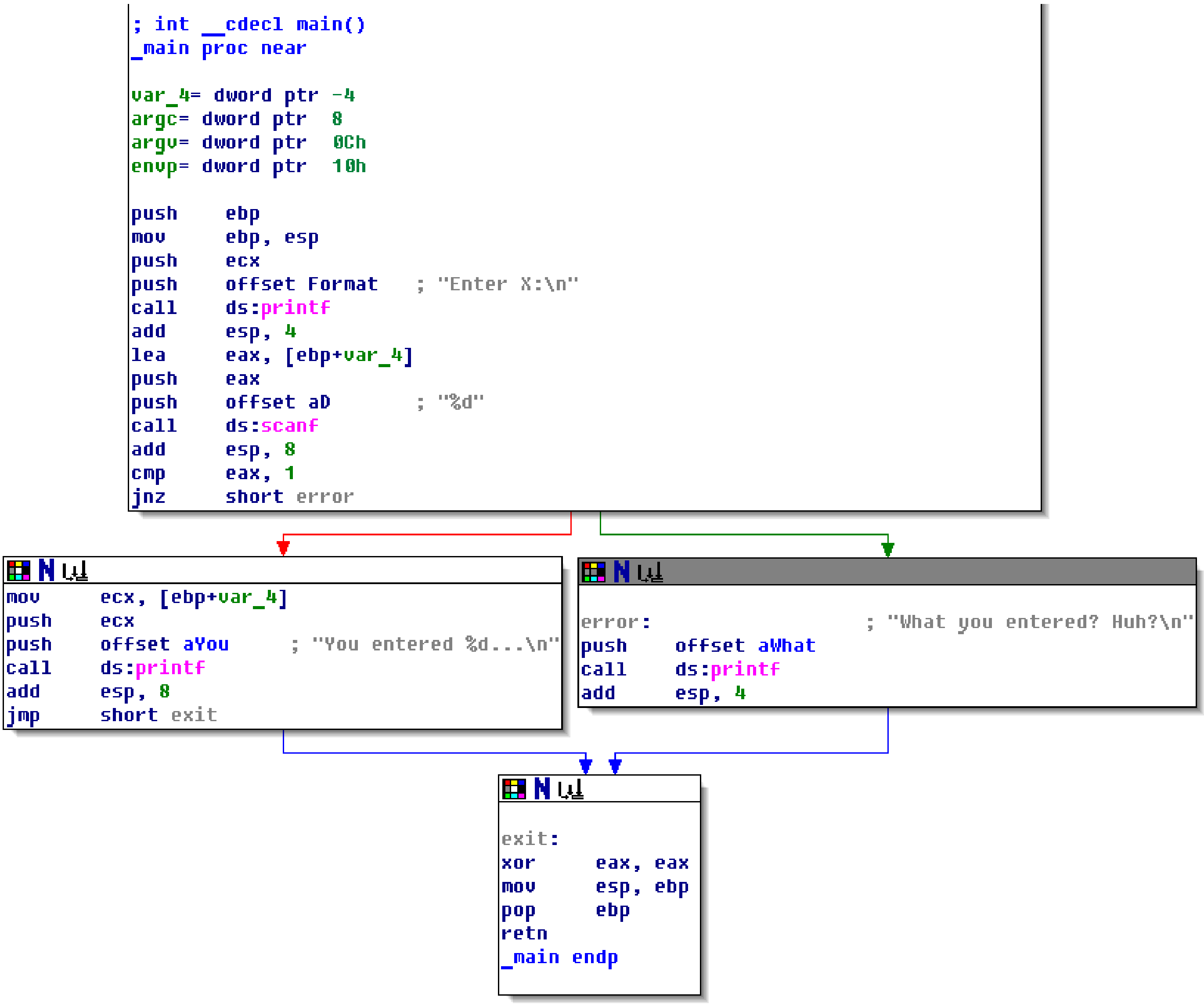


Figure 1.17: Graph mode in IDA

There are two arrows after each conditional jump: green and red. The green arrow points to the block which executes if the jump is triggered, and red if otherwise.

It is possible to fold nodes in this mode and give them names as well ("group nodes"). Let's do it for 3 blocks:

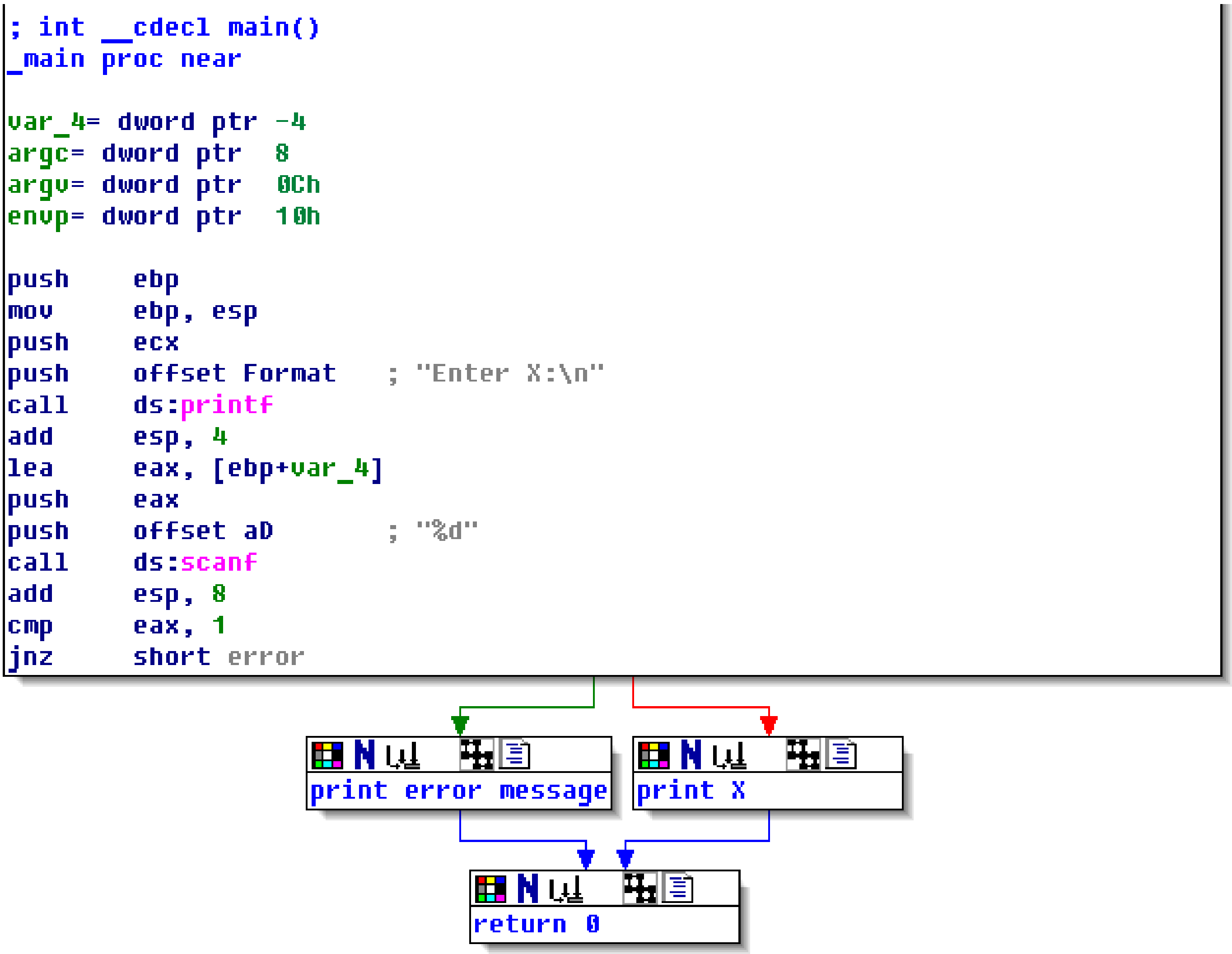


Figure 1.18: Graph mode in IDA with 3 nodes folded

That is very useful. It could be said that a very important part of the reverse engineers' job (and any other researcher as well) is to reduce the amount of information they deal with.

MSVC: x86 + OllyDbg

Let's try to hack our program in OllyDbg, forcing it to think `scanf()` always works without error. When an address of a local variable is passed into `scanf()`, the variable initially contains some random garbage, in this case `0x6E494714`:

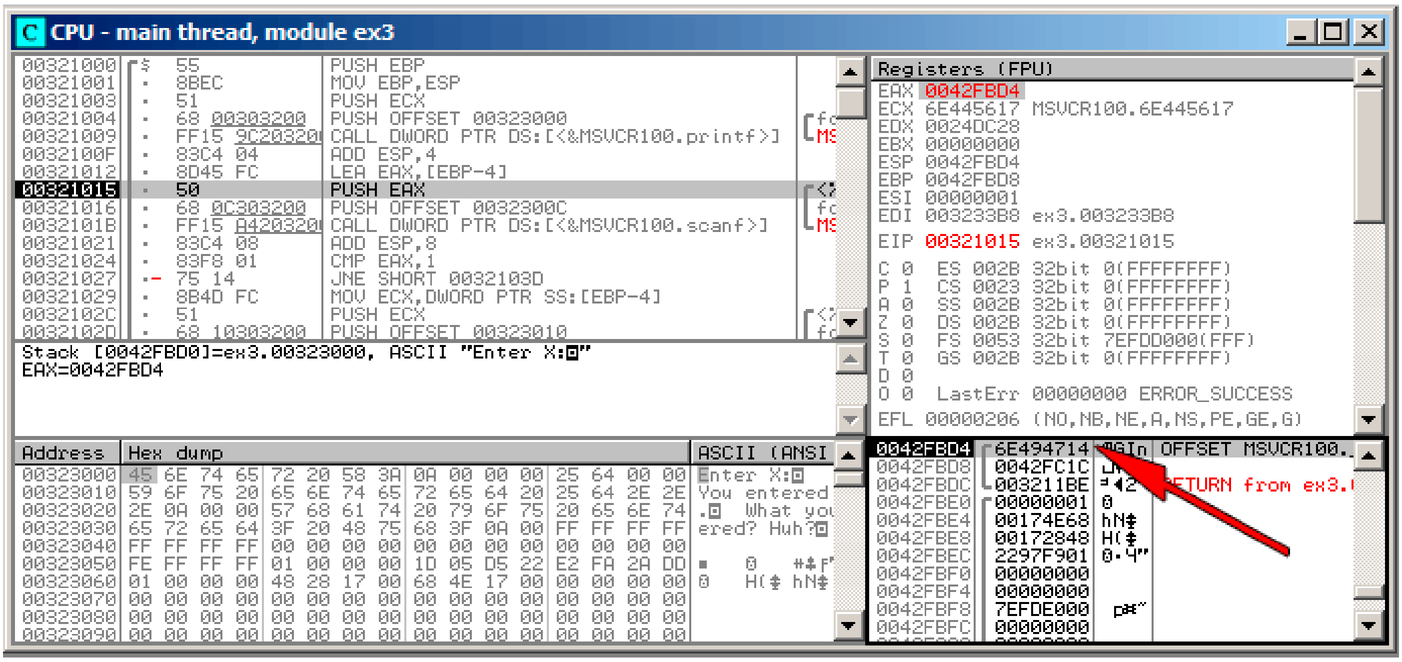


Figure 1.19: OllyDbg: passing variable address into `scanf()`

While `scanf()` executes, in the console we enter something that is definitely not a number, like “asdasd”. `scanf()` finishes with 0 in EAX, which indicates that an error has occurred:

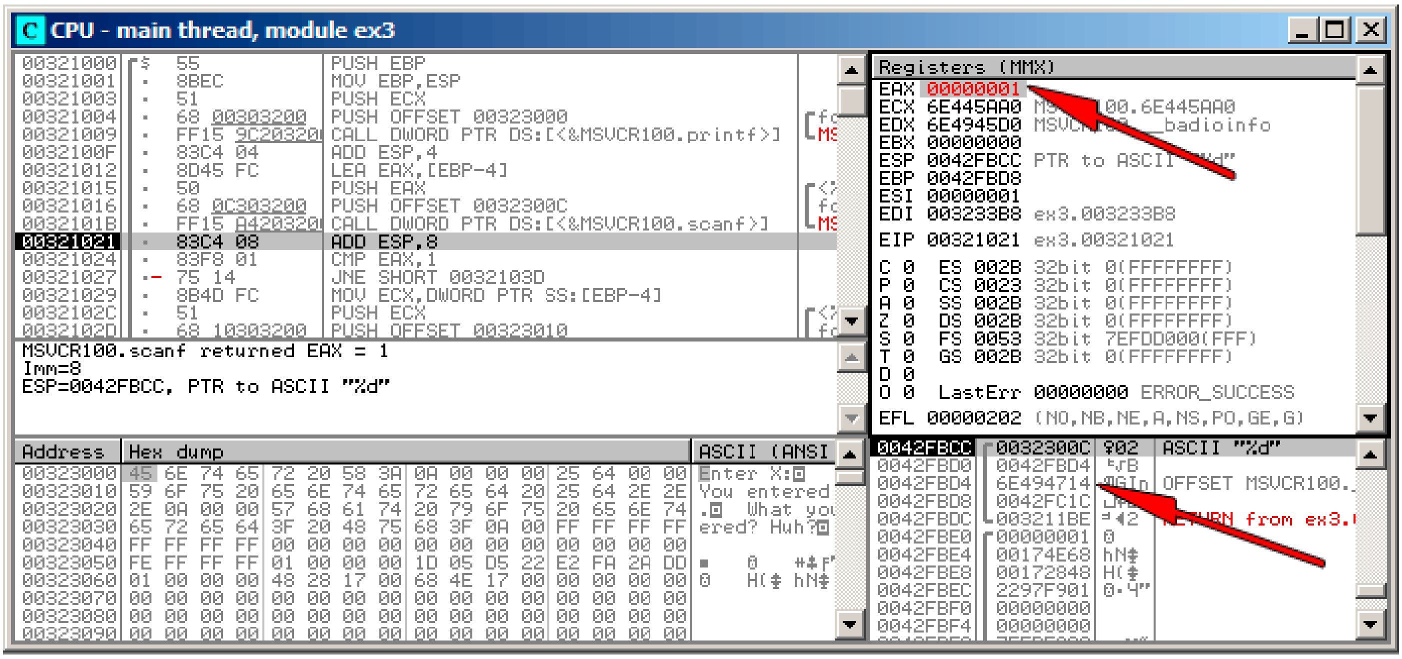


Figure 1.20: OllyDbg: `scanf()` returning error

We can also check the local variable in the stack and note that it has not changed. Indeed, what would `scanf()` write there? It simply did nothing except returning zero.

Let’s try to “hack” our program. Right-click on EAX, Among the options there is “Set to 1”. This is what we need.

We now have 1 in EAX, so the following check is to be executed as intended, and `printf()` will print the value of the variable in the stack.

When we run the program (F9) we can see the following in the console window:

Listing 1.81: console window

```
Enter X:
asdasd
You entered 1850296084...
```

Indeed, 1850296084 is a decimal representation of the number in the stack (0x6E494714)!

MSVC: x86 + Hiew

This can also be used as a simple example of executable file patching. We may try to patch the executable so the program would always print the input, no matter what we enter.

Assuming that the executable is compiled against external `MSVCR*.DLL` (i.e., with `/MD` option) [78], we see the `main()` function at the beginning of the `.text` section. Let's open the executable in Hiew and find the beginning of the `.text` section (Enter, F8, F6, Enter, Enter).

We can see this:

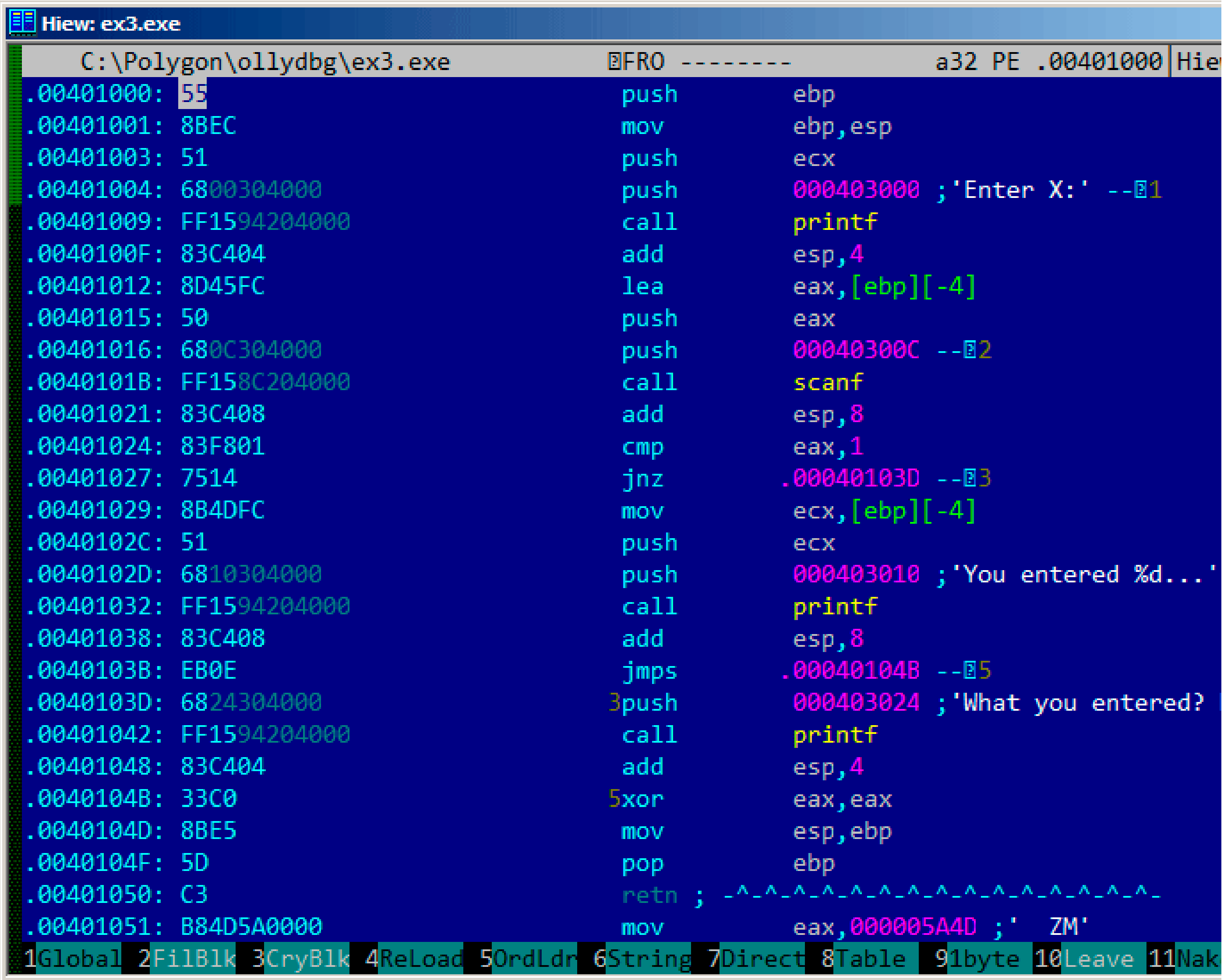


Figure 1.21: Hiew: `main()` function

Hiew finds ASCIIZ[79] strings and displays them, as it does with the imported functions' names.

[78] that's what also called "dynamic linking"

[79] ASCII Zero (null-terminated ASCII string)

Move the cursor to address .00401027 (where the JNZ instruction, we have to bypass, is located), press F3, and then type “9090” (meaning two NOPs):

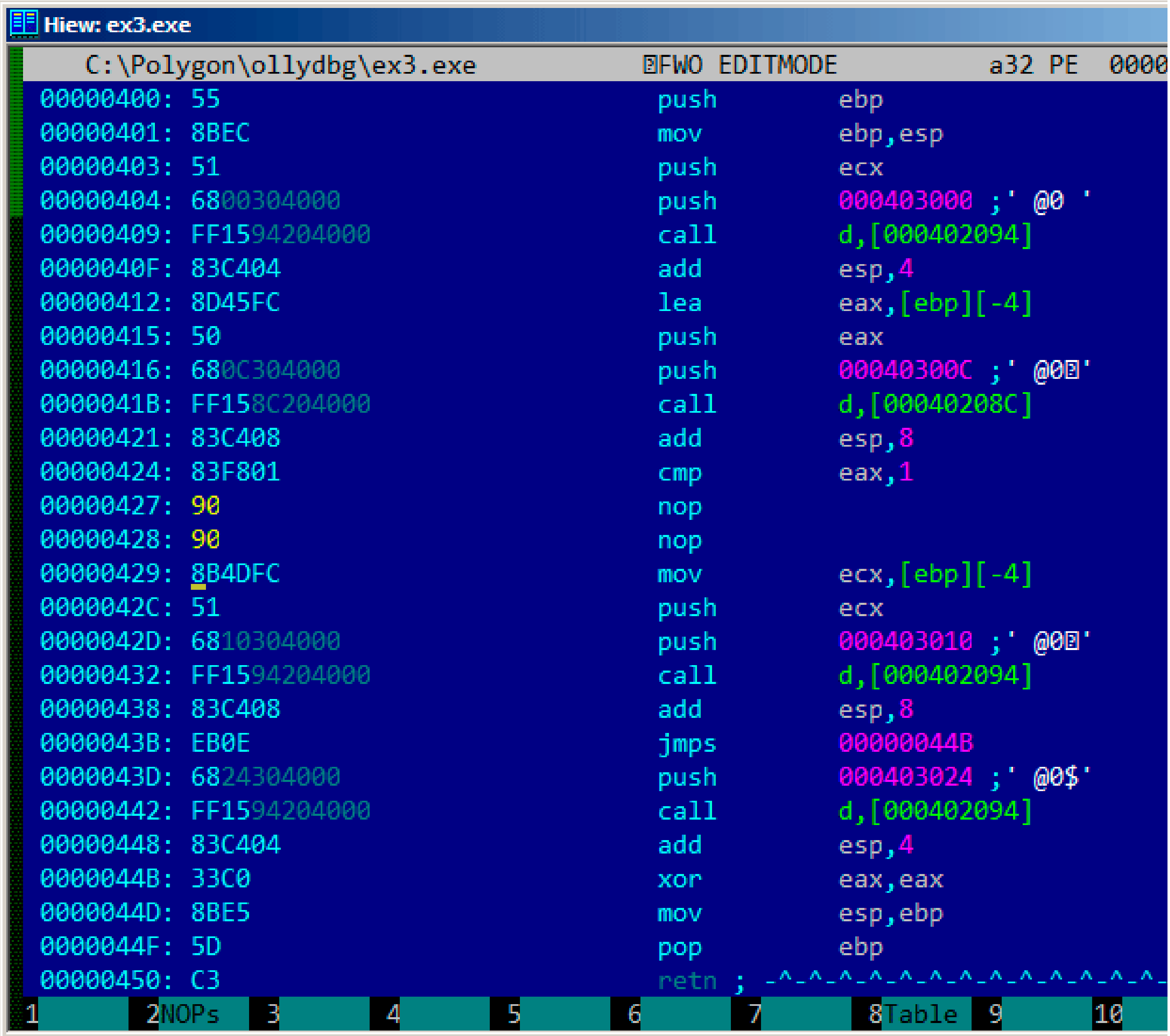


Figure 1.22: Hiew: replacing JNZ with two NOPs

Then press F9 (update). Now the executable is saved to the disk. It will behave as we wanted.

Two NOPs are probably not the most æsthetic approach. Another way to patch this instruction is to write just 0 to the second opcode byte (jump offset), so that JNZ will always jump to the next instruction.

We could also do the opposite: replace first byte with EB while not touching the second byte (jump offset). We would get an unconditional jump that is always triggered. In this case the error message would be printed every time, no matter the input.

MSVC: x64

MSVC: x64

Since we work here with *int*-typed variables, which are still 32-bit in x86-64, we see how the 32-bit part of the registers (prefixed with E-) are used here as well. While working with pointers, however, 64-bit register parts are used, prefixed with R-.

Listing 1.82: MSVC 2012 x64

```
_DATA   SEGMENT
$SG2924 DB      'Enter X:', 0aH, 00H
$SG2926 DB      '%d', 00H
$SG2927 DB      'You entered %d...', 0aH, 00H
$SG2929 DB      'What you entered? Huh?', 0aH, 00H
_DATA   ENDS

_TEXT   SEGMENT
x$ = 32
main    PROC
$LN5:
        sub     rsp, 56
        lea     rcx, OFFSET FLAT:$SG2924 ; 'Enter X:'
        call    printf
        lea     rdx, QWORD PTR x$[rsp]
        lea     rcx, OFFSET FLAT:$SG2926 ; '%d'
        call    scanf
        cmp     eax, 1
        jne     SHORT $LN2@main
        mov     edx, DWORD PTR x$[rsp]
        lea     rcx, OFFSET FLAT:$SG2927 ; 'You entered %d...'
        call    printf
        jmp     SHORT $LN1@main
$LN2@main:
        lea     rcx, OFFSET FLAT:$SG2929 ; 'What you entered? Huh?'
        call    printf
$LN1@main:
        ; return 0
        xor     eax, eax
        add     rsp, 56
        ret     0
main    ENDP
_TEXT   ENDS
END
```

ARM

ARM: Optimizing Keil 6/2013 (Thumb mode)

Listing 1.83: Optimizing Keil 6/2013 (Thumb mode)

```
var_8    = -8

         PUSH    {R3,LR}
         ADR     R0, aEnterX     ; "Enter X:\n"
         BL      __2printf
         MOV     R1, SP
         ADR     R0, aD          ; "%d"
         BL      __0scanf
         CMP     R0, #1
         BEQ     loc_1E
         ADR     R0, aWhatYouEntered ; "What you entered? Huh?\n"
         BL      __2printf

loc_1A                           ; CODE XREF: main+26
         MOVS    R0, #0
         POP     {R3,PC}

loc_1E                           ; CODE XREF: main+12
         LDR     R1, [SP,#8+var_8]
         ADR     R0, aYouEnteredD___ ; "You entered %d...\n"
         BL      __2printf
         B       loc_1A
```

The new instructions here are CMP and BEQ[80].

CMP is analogous to the x86 instruction with the same name, it subtracts one of the arguments from the other and updates the conditional flags if needed.

BEQ jumps to another address if the operands were equal to each other, or, if the result of the last computation has been 0, or if the Z flag is 1. It behaves as JZ in x86.

Everything else is simple: the execution flow forks in two branches, then the branches converge at the point where 0 is written into the R0 as a function return value, and then the function ends.

ARM64

Listing 1.84: Non-optimizing GCC 4.9.1 ARM64

```
.LC0:
        .string "Enter X:"
.LC1:
        .string "%d"
.LC2:
        .string "You entered %d...\n"
.LC3:
        .string "What you entered? Huh?"
f6:
; save FP and LR in stack frame:
        stp     x29, x30, [sp, -32]!
; set stack frame (FP=SP)
        add     x29, sp, 0
; load pointer to the "Enter X:" string:
        adrp    x0, .LC0
        add     x0, x0, :lo12:.LC0
        bl      puts
; load pointer to the "%d" string:
        adrp    x0, .LC1
        add     x0, x0, :lo12:.LC1
; calculate address of x variable in the local stack
        add     x1, x29, 28
        bl      __isoc99_scanf
; scanf() returned result in W0.
; check it:
        cmp     w0, 1
; BNE is Branch if Not Equal
; so if W0<>0, jump to L2 will be occurred
        bne     .L2
; at this moment W0=1, meaning no error
; load x value from the local stack
        ldr     w1, [x29,28]
; load pointer to the "You entered %d...\n" string:
        adrp    x0, .LC2
        add     x0, x0, :lo12:.LC2
        bl      printf
; skip the code, which print the "What you entered? Huh?" string:
        b       .L3
.L2:
; load pointer to the "What you entered? Huh?" string:
        adrp    x0, .LC3
        add     x0, x0, :lo12:.LC3
        bl      puts
.L3:
; return 0
        mov     w0, 0
; restore FP and LR:
        ldp     x29, x30, [sp], 32
        ret
```

Code flow in this case forks with the use of CMP/BNE (Branch if Not Equal) instructions pair.

[80](PowerPC, ARM) Branch if Equal

MIPS

Listing 1.85: Optimizing GCC 4.4.5 (IDA)

```
.text:004006A0 main:
.text:004006A0
.text:004006A0 var_18     = -0x18
.text:004006A0 var_10     = -0x10
.text:004006A0 var_4      = -4
.text:004006A0
.text:004006A0            lui     $gp, 0x42
.text:004006A4            addiu   $sp, -0x28
.text:004006A8            li      $gp, 0x418960
.text:004006AC            sw      $ra, 0x28+var_4($sp)
.text:004006B0            sw      $gp, 0x28+var_18($sp)
.text:004006B4            la      $t9, puts
.text:004006B8            lui     $a0, 0x40
.text:004006BC            jalr    $t9 ; puts
.text:004006C0            la      $a0, aEnterX      # "Enter X:"
.text:004006C4            lw      $gp, 0x28+var_18($sp)
.text:004006C8            lui     $a0, 0x40
.text:004006CC            la      $t9, __isoc99_scanf
.text:004006D0            la      $a0, aD           # "%d"
.text:004006D4            jalr    $t9 ; __isoc99_scanf
.text:004006D8            addiu   $a1, $sp, 0x28+var_10  # branch delay slot
.text:004006DC            li      $v1, 1
.text:004006E0            lw      $gp, 0x28+var_18($sp)
.text:004006E4            beq     $v0, $v1, loc_40070C
.text:004006E8            or      $at, $zero        # branch delay slot, NOP
.text:004006EC            la      $t9, puts
.text:004006F0            lui     $a0, 0x40
.text:004006F4            jalr    $t9 ; puts
.text:004006F8            la      $a0, aWhatYouEntered  # "What you entered? Huh?"
.text:004006FC            lw      $ra, 0x28+var_4($sp)
.text:00400700            move    $v0, $zero
.text:00400704            jr      $ra
.text:00400708            addiu   $sp, 0x28

.text:0040070C loc_40070C:
.text:0040070C            la      $t9, printf
.text:00400710            lw      $a1, 0x28+var_10($sp)
.text:00400714            lui     $a0, 0x40
.text:00400718            jalr    $t9 ; printf
.text:0040071C            la      $a0, aYouEnteredD___  # "You entered %d...\n"
.text:00400720            lw      $ra, 0x28+var_4($sp)
.text:00400724            move    $v0, $zero
.text:00400728            jr      $ra
.text:0040072C            addiu   $sp, 0x28
```

`scanf()` returns the result of its work in register $V0. It is checked at address 0x004006E4 by comparing the values in $V0 with $V1 (1 has been stored in $V1 earlier, at 0x004006DC). BEQ stands for "Branch Equal". If the two values are equal (i.e., success), the execution jumps to address 0x0040070C.

Exercise

As we can see, the JNE/JNZ instruction can be easily replaced by the JE/JZ and vice versa (or BNE by BEQ and vice versa). But then the basic blocks must also be swapped. Try to do this in some of the examples.

1.9.5 Exercise

- http://challenges.re/53

1.10 Accessing passed arguments

Now we figured out that the caller function is passing arguments to the callee via the stack. But how does the callee access them?

Listing 1.86: simple example

```
#include <stdio.h>

int f (int a, int b, int c)
{
        return a*b+c;
};

int main()
{
        printf ("%d\n", f(1, 2, 3));
        return 0;
};
```

1.10.1 x86

MSVC

Here is what we get after compilation (MSVC 2010 Express):

Listing 1.87: MSVC 2010 Express

```
_TEXT   SEGMENT
_a$ = 8         ; size = 4
_b$ = 12        ; size = 4
_c$ = 16        ; size = 4
_f      PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _a$[ebp]
        imul    eax, DWORD PTR _b$[ebp]
        add     eax, DWORD PTR _c$[ebp]
        pop     ebp
        ret     0
_f      ENDP

_main   PROC
        push    ebp
        mov     ebp, esp
        push    3 ; 3rd argument
        push    2 ; 2nd argument
        push    1 ; 1st argument
        call    _f
        add     esp, 12
        push    eax
        push    OFFSET $SG2463 ; '%d', 0aH, 00H
        call    _printf
        add     esp, 8
        ; return 0
        xor     eax, eax
        pop     ebp
        ret     0
_main   ENDP
```

What we see is that the `main()` function pushes 3 numbers onto the stack and calls `f(int,int,int)`.

Argument access inside `f()` is organized with the help of macros like:
`_a$ = 8`, in the same way as local variables, but with positive offsets (addressed with *plus*). So, we are addressing the *outer* side of the stack frame by adding the `_a$` macro to the value in the EBP register.

Then the value of a is stored into EAX. After IMUL instruction execution, the value in EAX is a product of the value in EAX and the content of _b.

After that, ADD adds the value in _c to EAX.

The value in EAX does not need to be moved: it is already where it must be. On returning to caller, it takes the EAX value and use it as an argument to printf().

MSVC + OllyDbg

Let's illustrate this in OllyDbg. When we trace to the first instruction in f() that uses one of the arguments (first one), we see that EBP is pointing to the stack frame, which is marked with a red rectangle.

The first element of the stack frame is the saved value of EBP, the second one is RA, the third is the first function argument, then the second and third ones.

To access the first function argument, one needs to add exactly 8 (2 32-bit words) to EBP.

OllyDbg is aware about this, so it has added comments to the stack elements like

"RETURN from" and "Arg1 = …", etc.

N.B.: Function arguments are not members of the function's stack frame, they are rather members of the stack frame of the caller function.

Hence, OllyDbg marked "Arg" elements as members of another stack frame.

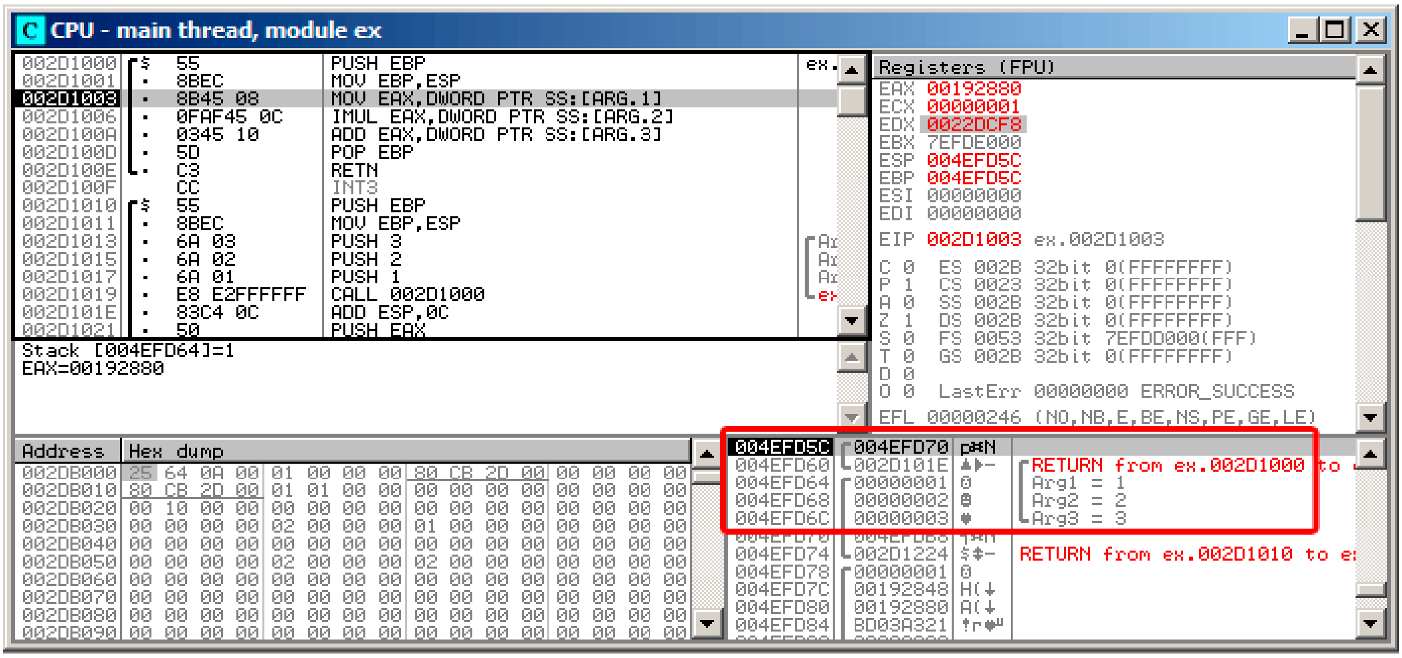


Figure 1.23: OllyDbg: inside of f() function

GCC

Let's compile the same in GCC 4.4.1 and see the results in IDA:

Listing 1.88: GCC 4.4.1

```
        public f
f       proc near

arg_0   = dword ptr  8
arg_4   = dword ptr  0Ch
arg_8   = dword ptr  10h

        push    ebp
        mov     ebp, esp
        mov     eax, [ebp+arg_0] ; 1st argument
        imul    eax, [ebp+arg_4] ; 2nd argument
        add     eax, [ebp+arg_8] ; 3rd argument
        pop     ebp
```

```
        retn
f       endp

        public main
main    proc near

var_10  = dword ptr -10h
var_C   = dword ptr -0Ch
var_8   = dword ptr -8

        push    ebp
        mov     ebp, esp
        and     esp, 0FFFFFFF0h
        sub     esp, 10h
        mov     [esp+10h+var_8], 3 ; 3rd argument
        mov     [esp+10h+var_C], 2 ; 2nd argument
        mov     [esp+10h+var_10], 1 ; 1st argument
        call    f
        mov     edx, offset aD  ; "%d\n"
        mov     [esp+10h+var_C], eax
        mov     [esp+10h+var_10], edx
        call    _printf
        mov     eax, 0
        leave
        retn
main    endp
```

The result is almost the same with some minor differences discussed earlier.

The stack pointer is not set back after the two function calls(f and printf), because the penultimate LEAVE (.1.6 on page 1028) instruction takes care of this at the end.

1.10.2 x64

The story is a bit different in x86-64. Function arguments (first 4 or first 6 of them) are passed in registers i.e. the callee reads them from registers instead of reading them from the stack.

MSVC

Optimizing MSVC:

Listing 1.89: Optimizing MSVC 2012 x64

```
$SG2997 DB      '%d', 0aH, 00H

main    PROC
        sub     rsp, 40
        mov     edx, 2
        lea     r8d, QWORD PTR [rdx+1] ; R8D=3
        lea     ecx, QWORD PTR [rdx-1] ; ECX=1
        call    f
        lea     rcx, OFFSET FLAT:$SG2997 ; '%d'
        mov     edx, eax
        call    printf
        xor     eax, eax
        add     rsp, 40
        ret     0
main    ENDP

f       PROC
        ; ECX - 1st argument
        ; EDX - 2nd argument
        ; R8D - 3rd argument
        imul    ecx, edx
        lea     eax, DWORD PTR [r8+rcx]
        ret     0
f       ENDP
```

As we can see, the compact function f() takes all its arguments from the registers.

The LEA instruction here is used for addition, apparently the compiler considered it faster than ADD.

LEA is also used in the main() function to prepare the first and third f() arguments. The compiler must have decided that this would work faster than the usual way of loading values into a register using MOV instruction.

Let's take a look at the non-optimizing MSVC output:

Listing 1.90: MSVC 2012 x64

```
f               proc near

; shadow space:
arg_0           = dword ptr  8
arg_8           = dword ptr  10h
arg_10          = dword ptr  18h

                ; ECX - 1st argument
                ; EDX - 2nd argument
                ; R8D - 3rd argument
                mov     [rsp+arg_10], r8d
                mov     [rsp+arg_8], edx
                mov     [rsp+arg_0], ecx
                mov     eax, [rsp+arg_0]
                imul    eax, [rsp+arg_8]
                add     eax, [rsp+arg_10]
                retn
f               endp

main            proc near
                sub     rsp, 28h
                mov     r8d, 3 ; 3rd argument
                mov     edx, 2 ; 2nd argument
                mov     ecx, 1 ; 1st argument
                call    f
                mov     edx, eax
                lea     rcx, $SG2931    ; "%d\n"
                call    printf

                ; return 0
                xor     eax, eax
                add     rsp, 28h
                retn
main            endp
```

It looks somewhat puzzling because all 3 arguments from the registers are saved to the stack for some reason. This is called "shadow space" [81]: every Win64 may (but is not required to) save all 4 register values there. This is done for two reasons: 1) it is too lavish to allocate a whole register (or even 4 registers) for an input argument, so it will be accessed via stack; 2) the debugger is always aware where to find the function arguments at a break [82].

So, some large functions can save their input arguments in the "shadows space" if they want to use them during execution, but some small functions (like ours) may not do this.

It is a caller responsibility to allocate "shadow space" in the stack.

GCC

Optimizing GCC generates more or less understandable code:

Listing 1.91: Optimizing GCC 4.4.6 x64

```
f:
        ; EDI - 1st argument
        ; ESI - 2nd argument
        ; EDX - 3rd argument
```

[81] MSDN
[82] MSDN

```
        imul    esi, edi
        lea     eax, [rdx+rsi]
        ret

main:
        sub     rsp, 8
        mov     edx, 3
        mov     esi, 2
        mov     edi, 1
        call    f
        mov     edi, OFFSET FLAT:.LC0 ; "%d\n"
        mov     esi, eax
        xor     eax, eax  ; number of vector registers passed
        call    printf
        xor     eax, eax
        add     rsp, 8
        ret
```

Non-optimizing GCC:

Listing 1.92: GCC 4.4.6 x64

```
f:
        ; EDI - 1st argument
        ; ESI - 2nd argument
        ; EDX - 3rd argument
        push    rbp
        mov     rbp, rsp
        mov     DWORD PTR [rbp-4], edi
        mov     DWORD PTR [rbp-8], esi
        mov     DWORD PTR [rbp-12], edx
        mov     eax, DWORD PTR [rbp-4]
        imul    eax, DWORD PTR [rbp-8]
        add     eax, DWORD PTR [rbp-12]
        leave
        ret
main:
        push    rbp
        mov     rbp, rsp
        mov     edx, 3
        mov     esi, 2
        mov     edi, 1
        call    f
        mov     edx, eax
        mov     eax, OFFSET FLAT:.LC0 ; "%d\n"
        mov     esi, edx
        mov     rdi, rax
        mov     eax, 0  ; number of vector registers passed
        call    printf
        mov     eax, 0
        leave
        ret
```

There are no "shadow space" requirements in System V *NIX ([Michael Matz, Jan Hubicka, Andreas Jaeger, Mark Mitchell, *System V Application Binary Interface. AMD64 Architecture Processor Supplement*, (2013)] [83]), but the callee may want to save its arguments somewhere in case of registers shortage.

GCC: uint64_t instead of int

Our example works with 32-bit *int*, that is why 32-bit register parts are used (prefixed by E-).

It can be altered slightly in order to use 64-bit values:

```
#include <stdio.h>
#include <stdint.h>

uint64_t f (uint64_t a, uint64_t b, uint64_t c)
```

[83] Also available as https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf

```
{
        return a*b+c;
};

int main()
{
        printf ("%lld\n", f(0x1122334455667788,
                            0x1111111122222222,
                            0x3333333344444444));
        return 0;
};
```

Listing 1.93: Optimizing GCC 4.4.6 x64

```
f       proc near
        imul    rsi, rdi
        lea     rax, [rdx+rsi]
        retn
f       endp

main    proc near
        sub     rsp, 8
        mov     rdx, 3333333344444444h ; 3rd argument
        mov     rsi, 1111111122222222h ; 2nd argument
        mov     rdi, 1122334455667788h ; 1st argument
        call    f
        mov     edi, offset format ; "%lld\n"
        mov     rsi, rax
        xor     eax, eax ; number of vector registers passed
        call    _printf
        xor     eax, eax
        add     rsp, 8
        retn
main    endp
```

The code is the same, but this time the *full size* registers (prefixed by R-) are used.

1.10.3 ARM

Non-optimizing Keil 6/2013 (ARM mode)

```
.text:000000A4 00 30 A0 E1      MOV     R3, R0
.text:000000A8 93 21 20 E0      MLA     R0, R3, R1, R2
.text:000000AC 1E FF 2F E1      BX      LR
...
.text:000000B0              main
.text:000000B0 10 40 2D E9      STMFD   SP!, {R4,LR}
.text:000000B4 03 20 A0 E3      MOV     R2, #3
.text:000000B8 02 10 A0 E3      MOV     R1, #2
.text:000000BC 01 00 A0 E3      MOV     R0, #1
.text:000000C0 F7 FF FF EB      BL      f
.text:000000C4 00 40 A0 E1      MOV     R4, R0
.text:000000C8 04 10 A0 E1      MOV     R1, R4
.text:000000CC 5A 0F 8F E2      ADR     R0, aD_0        ; "%d\n"
.text:000000D0 E3 18 00 EB      BL      __2printf
.text:000000D4 00 00 A0 E3      MOV     R0, #0
.text:000000D8 10 80 BD E8      LDMFD   SP!, {R4,PC}
```

The `main()` function simply calls two other functions, with three values passed to the first one —(`f()`).

As was noted before, in ARM the first 4 values are usually passed in the first 4 registers (R0-R3).

The `f()` function, as it seems, uses the first 3 registers (R0-R2) as arguments.

The MLA (*Multiply Accumulate*) instruction multiplies its first two operands (R3 and R1), adds the third operand (R2) to the product and stores the result into the zeroth register (R0), via which, by standard, functions return values.

Multiplication and addition at once (*Fused multiply–add*) is a very useful operation. By the way, there was no such instruction in x86 before FMA-instructions appeared in SIMD [84].

The very first `MOV R3, R0`, instruction is, apparently, redundant (a single `MLA` instruction could be used here instead). The compiler has not optimized it, since this is non-optimizing compilation.

The `BX` instruction returns the control to the address stored in the LR register and, if necessary, switches the processor mode from Thumb to ARM or vice versa. This can be necessary since, as we can see, function `f()` is not aware from what kind of code it may be called, ARM or Thumb. Thus, if it gets called from Thumb code, `BX` is not only returns control to the calling function, but also switches the processor mode to Thumb. Or not switch, if the function has been called from ARM code [*ARM(R) Architecture Reference Manual, ARMv7-A and ARMv7-R edition*, (2012)A2.3.2].

Optimizing Keil 6/2013 (ARM mode)

```
.text:00000098             f
.text:00000098 91 20 20 E0       MLA     R0, R1, R0, R2
.text:0000009C 1E FF 2F E1       BX      LR
```

And here is the `f()` function compiled by the Keil compiler in full optimization mode (`-O3`).

The `MOV` instruction was optimized out (or reduced) and now `MLA` uses all input registers and also places the result right into `R0`, exactly where the calling function will read and use it.

Optimizing Keil 6/2013 (Thumb mode)

```
.text:0000005E 48 43          MULS    R0, R1
.text:00000060 80 18          ADDS    R0, R0, R2
.text:00000062 70 47          BX      LR
```

The `MLA` instruction is not available in Thumb mode, so the compiler generates the code doing these two operations (multiplication and addition) separately.

First the `MULS` instruction multiplies `R0` by `R1`, leaving the result in register `R0`. The second instruction (`ADDS`) adds the result and `R2` leaving the result in register `R0`.

ARM64

Optimizing GCC (Linaro) 4.9

Everything here is simple. `MADD` is just an instruction doing fused multiply/add (similar to the `MLA` we already saw). All 3 arguments are passed in the 32-bit parts of X-registers. Indeed, the argument types are 32-bit *int*'s. The result is returned in `W0`.

Listing 1.94: Optimizing GCC (Linaro) 4.9

```
f:
        madd    w0, w0, w1, w2
        ret

main:
; save FP and LR to stack frame:
        stp     x29, x30, [sp, -16]!
        mov     w2, 3
        mov     w1, 2
        add     x29, sp, 0
        mov     w0, 1
        bl      f
        mov     w1, w0
        adrp    x0, .LC7
        add     x0, x0, :lo12:.LC7
        bl      printf
; return 0
```

[84] wikipedia

```
        mov     w0, 0
; restore FP and LR
        ldp     x29, x30, [sp], 16
        ret

.LC7:
        .string "%d\n"
```

Let's also extend all data types to 64-bit `uint64_t` and test:

```
#include <stdio.h>
#include <stdint.h>

uint64_t f (uint64_t a, uint64_t b, uint64_t c)
{
        return a*b+c;
};

int main()
{
        printf ("%lld\n", f(0x1122334455667788,
                                0x1111111122222222,
                                0x3333333344444444));
        return 0;
};
```

```
f:
        madd    x0, x0, x1, x2
        ret
main:
        mov     x1, 13396
        adrp    x0, .LC8
        stp     x29, x30, [sp, -16]!
        movk    x1, 0x27d0, lsl 16
        add     x0, x0, :lo12:.LC8
        movk    x1, 0x122, lsl 32
        add     x29, sp, 0
        movk    x1, 0x58be, lsl 48
        bl      printf
        mov     w0, 0
        ldp     x29, x30, [sp], 16
        ret

.LC8:
        .string "%lld\n"
```

The `f()` function is the same, only the whole 64-bit X-registers are now used. Long 64-bit values are loaded into the registers by parts, this is also described here: 1.32.3 on page 440.

Non-optimizing GCC (Linaro) 4.9

The non-optimizing compiler is more redundant:

```
f:
        sub     sp, sp, #16
        str     w0, [sp,12]
        str     w1, [sp,8]
        str     w2, [sp,4]
        ldr     w1, [sp,12]
        ldr     w0, [sp,8]
        mul     w1, w1, w0
        ldr     w0, [sp,4]
        add     w0, w1, w0
        add     sp, sp, 16
        ret
```

The code saves its input arguments in the local stack, in case someone (or something) in this function needs using the W0...W2 registers. This prevents overwriting the original function arguments, which may be needed again in the future.

This is called *Register Save Area.* ([*Procedure Call Standard for the ARM 64-bit Architecture (AArch64)*, (2013)][85]). The callee, however, is not obliged to save them. This is somewhat similar to "Shadow Space": 1.10.2 on page 100.

Why did the optimizing GCC 4.9 drop this argument saving code? Because it did some additional optimizing work and concluded that the function arguments will not be needed in the future and also that the registers W0...W2 will not be used.

We also see a MUL/ADD instruction pair instead of single a MADD.

1.10.4 MIPS

Listing 1.95: Optimizing GCC 4.4.5

```
.text:00000000 f:
; $a0=a
; $a1=b
; $a2=c
.text:00000000         mult    $a1, $a0
.text:00000004         mflo    $v0
.text:00000008         jr      $ra
.text:0000000C         addu    $v0, $a2, $v0     ; branch delay slot
; result is in $v0 upon return
.text:00000010 main:
.text:00000010
.text:00000010 var_10 = -0x10
.text:00000010 var_4  = -4
.text:00000010
.text:00000010         lui     $gp, (__gnu_local_gp >> 16)
.text:00000014         addiu   $sp, -0x20
.text:00000018         la      $gp, (__gnu_local_gp & 0xFFFF)
.text:0000001C         sw      $ra, 0x20+var_4($sp)
.text:00000020         sw      $gp, 0x20+var_10($sp)
; set c:
.text:00000024         li      $a2, 3
; set a:
.text:00000028         li      $a0, 1
.text:0000002C         jal     f
; set b:
.text:00000030         li      $a1, 2            ; branch delay slot
; result in $v0 now
.text:00000034         lw      $gp, 0x20+var_10($sp)
.text:00000038         lui     $a0, ($LC0 >> 16)
.text:0000003C         lw      $t9, (printf & 0xFFFF)($gp)
.text:00000040         la      $a0, ($LC0 & 0xFFFF)
.text:00000044         jalr    $t9
; take result of f() function and pass it as a second argument to printf():
.text:00000048         move    $a1, $v0          ; branch delay slot
.text:0000004C         lw      $ra, 0x20+var_4($sp)
.text:00000050         move    $v0, $zero
.text:00000054         jr      $ra
.text:00000058         addiu   $sp, 0x20 ; branch delay slot
```

The first four function arguments are passed in four registers prefixed by A-.

There are two special registers in MIPS: HI and LO which are filled with the 64-bit result of the multiplication during the execution of the MULT instruction.

These registers are accessible only by using the MFLO and MFHI instructions. MFLO here takes the low-part of the multiplication result and stores it into $V0. So the high 32-bit part of the multiplication result is dropped (the HI register content is not used). Indeed: we work with 32-bit *int* data types here.

Finally, ADDU ("Add Unsigned") adds the value of the third argument to the result.

[85]Also available as http://go.yurichev.com/17287

There are two different addition instructions in MIPS: ADD and ADDU. The difference between them is not related to signedness, but to exceptions. ADD can raise an exception on overflow, which is sometimes useful[86] and supported in Ada PL, for instance. ADDU does not raise exceptions on overflow.

Since C/C++ does not support this, in our example we see ADDU instead of ADD.

The 32-bit result is left in $V0.

There is a new instruction for us in main(): JAL ("Jump and Link").

The difference between JAL and JALR is that a relative offset is encoded in the first instruction, while JALR jumps to the absolute address stored in a register ("Jump and Link Register").

Both f() and main() functions are located in the same object file, so the relative address of f() is known and fixed.

1.11 More about results returning

In x86, the result of function execution is usually returned [87] in the EAX register. If it is byte type or a character (*char*), then the lowest part of register EAX (AL) is used. If a function returns a *float* number, the FPU register ST(0) is used instead. In ARM, the result is usually returned in the R0 register.

1.11.1 Attempt to use the result of a function returning *void*

So, what if the main() function return value was declared of type *void* and not *int*? The so-called startup-code is calling main() roughly as follows:

```
push envp
push argv
push argc
call main
push eax
call exit
```

In other words:

```
exit(main(argc,argv,envp));
```

If you declare main() as *void*, nothing is to be returned explicitly (using the *return* statement), then something random, that has been stored in the EAX register at the end of main() becomes the sole argument of the exit() function. Most likely, there will be a random value, left from your function execution, so the exit code of program is pseudorandom.

We can illustrate this fact. Please note that here the main() function has a *void* return type:

```
#include <stdio.h>

void main()
{
        printf ("Hello, world!\n");
};
```

Let's compile it in Linux.

GCC 4.8.1 replaced printf() with puts() (we have seen this before: 1.5.4 on page 21), but that's OK, since puts() returns the number of characters printed out, just like printf(). Please notice that EAX is not zeroed before main()'s end.

This implies that the value of EAX at the end of main() contains what puts() has left there.

Listing 1.96: GCC 4.8.1

```
.LC0:
        .string "Hello, world!"
main:
```

[86] http://go.yurichev.com/17326

[87] See also: MSDN: Return Values (C++): MSDN

```
        push    ebp
        mov     ebp, esp
        and     esp, -16
        sub     esp, 16
        mov     DWORD PTR [esp], OFFSET FLAT:.LC0
        call    puts
        leave
        ret
```

Let’ s write a bash script that shows the exit status:

Listing 1.97: tst.sh

```
#!/bin/sh
./hello_world
echo $?
```

And run it:

```
$ tst.sh
Hello, world!
14
```

14 is the number of characters printed. The number of characters printed is *slips* from `printf()` through EAX/RAX into “exit code”.

By the way, when we decompile C++ in Hex-Rays, we can often encounter a function which terminated with destructor of some class:

```
...

call    ??1CString@@QAE@XZ ; CString::~CString(void)
mov     ecx, [esp+30h+var_C]
pop     edi
pop     ebx
mov     large fs:0, ecx
add     esp, 28h
retn
```

By C++ standard, destructor doesn’t return anything, but when Hex-Rays don’t know about it, and thinks that both destructor and this function returns *int*, we can see something like that in output:

```
...

        return CString::~CString(&Str);
}
```

1.11.2 What if we do not use the function result?

`printf()` returns the count of characters successfully output, but the result of this function is rarely used in practice.

It is also possible to call a function whose essence is in returning a value, and not use it:

```
int f()
{
    // skip first 3 random values:
    rand();
    rand();
    rand();
    // and use 4th:
    return rand();
};
```

The result of the rand() function is left in EAX, in all four cases.

But in the first 3 cases, the value in EAX is just not used.

1.11.3 Returning a structure

Let's go back to the fact that the return value is left in the EAX register.

That is why old C compilers cannot create functions capable of returning something that does not fit in one register (usually *int*), but if one needs it, one have to return information via pointers passed as function's arguments.

So, usually, if a function needs to return several values, it returns only one, and all the rest—via pointers.

Now it has become possible to return, let's say, an entire structure, but that is still not very popular. If a function has to return a large structure, the caller must allocate it and pass a pointer to it via the first argument, transparently for the programmer. That is almost the same as to pass a pointer in the first argument manually, but the compiler hides it.

Small example:

```
struct s
{
    int a;
    int b;
    int c;
};

struct s get_some_values (int a)
{
    struct s rt;

    rt.a=a+1;
    rt.b=a+2;
    rt.c=a+3;

    return rt;
};
```

...what we got (MSVC 2010 /Ox):

```
$T3853 = 8                      ; size = 4
_a$ = 12                        ; size = 4
?get_some_values@@YA?AUs@@H@Z PROC            ; get_some_values
    mov    ecx, DWORD PTR _a$[esp-4]
    mov    eax, DWORD PTR $T3853[esp-4]
    lea    edx, DWORD PTR [ecx+1]
    mov    DWORD PTR [eax], edx
    lea    edx, DWORD PTR [ecx+2]
    add    ecx, 3
    mov    DWORD PTR [eax+4], edx
    mov    DWORD PTR [eax+8], ecx
    ret    0
?get_some_values@@YA?AUs@@H@Z ENDP            ; get_some_values
```

The macro name for internal passing of pointer to a structure here is $T3853.

This example can be rewritten using the C99 language extensions:

```
struct s
{
    int a;
    int b;
    int c;
};

struct s get_some_values (int a)
{
    return (struct s){.a=a+1, .b=a+2, .c=a+3};
};
```

Listing 1.98: GCC 4.8.1

```
_get_some_values proc near
```

```
ptr_to_struct   = dword ptr  4
a               = dword ptr  8

                mov     edx, [esp+a]
                mov     eax, [esp+ptr_to_struct]
                lea     ecx, [edx+1]
                mov     [eax], ecx
                lea     ecx, [edx+2]
                add     edx, 3
                mov     [eax+4], ecx
                mov     [eax+8], edx
                retn
_get_some_values endp
```

As we see, the function is just filling the structure's fields allocated by the caller function, as if a pointer to the structure has been passed. So there are no performance drawbacks.

1.12 Pointers

1.12.1 Swap input values

This will do the job:

```
#include <memory.h>
#include <stdio.h>

void swap_bytes (unsigned char* first, unsigned char* second)
{
        unsigned char tmp1;
        unsigned char tmp2;

        tmp1=*first;
        tmp2=*second;

        *first=tmp2;
        *second=tmp1;
};

int main()
{
        // copy string into heap, so we will be able to modify it
        char *s=strdup("string");

        // swap 2nd and 3rd characters
        swap_bytes (s+1, s+2);

        printf ("%s\n", s);
};
```

As we can see, bytes are loaded into lower 8-bit parts of ECX and EBX using MOVZX (so higher parts of these registers will be cleared) and then bytes are written back swapped.

Listing 1.99: Optimizing GCC 5.4

```
swap_bytes:
        push    ebx
        mov     edx, DWORD PTR [esp+8]
        mov     eax, DWORD PTR [esp+12]
        movzx   ecx, BYTE PTR [edx]
        movzx   ebx, BYTE PTR [eax]
        mov     BYTE PTR [edx], bl
        mov     BYTE PTR [eax], cl
        pop     ebx
        ret
```

Addresses of both bytes are taken from arguments and through execution of the function are located in EDX and EAX.

So we use pointers: probably, there is no better way to solve this task without them.

1.12.2 Returning values

Pointers are often used to return values from functions (recall `scanf()` case (1.9 on page 66)).

For example, when a function needs to return two values.

Global variables example

```
#include <stdio.h>

void f1 (int x, int y, int *sum, int *product)
{
        *sum=x+y;
        *product=x*y;
};

int sum, product;

void main()
{
        f1(123, 456, &sum, &product);
        printf ("sum=%d, product=%d\n", sum, product);
};
```

This compiles to:

Listing 1.100: Optimizing MSVC 2010 (/Ob0)

```
COMM    _product:DWORD
COMM    _sum:DWORD
$SG2803 DB      'sum=%d, product=%d', 0aH, 00H

_x$ = 8                 ; size = 4
_y$ = 12                ; size = 4
_sum$ = 16              ; size = 4
_product$ = 20          ; size = 4
_f1     PROC
        mov     ecx, DWORD PTR _y$[esp-4]
        mov     eax, DWORD PTR _x$[esp-4]
        lea     edx, DWORD PTR [eax+ecx]
        imul    eax, ecx
        mov     ecx, DWORD PTR _product$[esp-4]
        push    esi
        mov     esi, DWORD PTR _sum$[esp]
        mov     DWORD PTR [esi], edx
        mov     DWORD PTR [ecx], eax
        pop     esi
        ret     0
_f1     ENDP

_main   PROC
        push    OFFSET _product
        push    OFFSET _sum
        push    456     ; 000001c8H
        push    123     ; 0000007bH
        call    _f1
        mov     eax, DWORD PTR _product
        mov     ecx, DWORD PTR _sum
        push    eax
        push    ecx
        push    OFFSET $SG2803
        call    DWORD PTR __imp__printf
        add     esp, 28
        xor     eax, eax
        ret     0
```

```
_main   ENDP
```

Let's see this in OllyDbg:

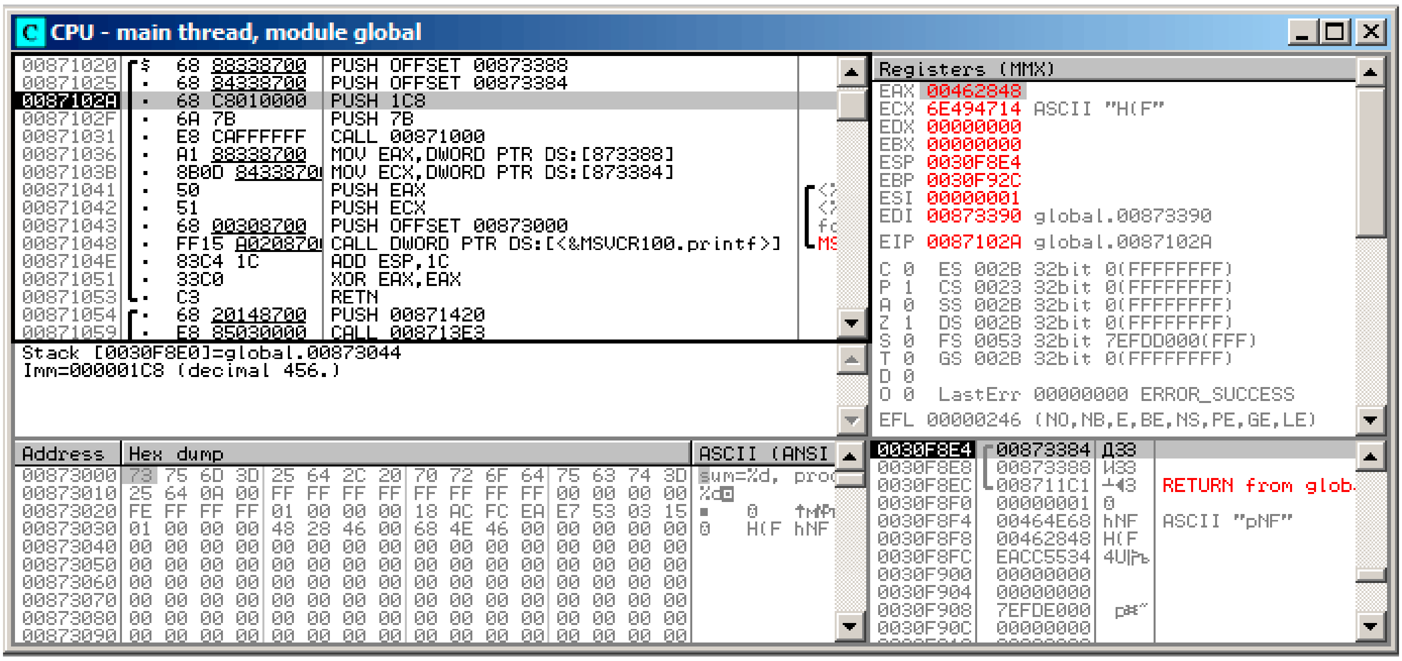


Figure 1.24: OllyDbg: global variables addresses are passed to `f1()`

First, global variables' addresses are passed to `f1()`. We can click "Follow in dump" on the stack element, and we can see the place in the data segment allocated for the two variables.

These variables are zeroed, because non-initialized data (from BSS) is cleared before the execution begins, [see *ISO/IEC 9899:TC3 (C C99 standard)*, (2007) 6.7.8p10].

They reside in the data segment, we can verify this by pressing Alt-M and reviewing the memory map:

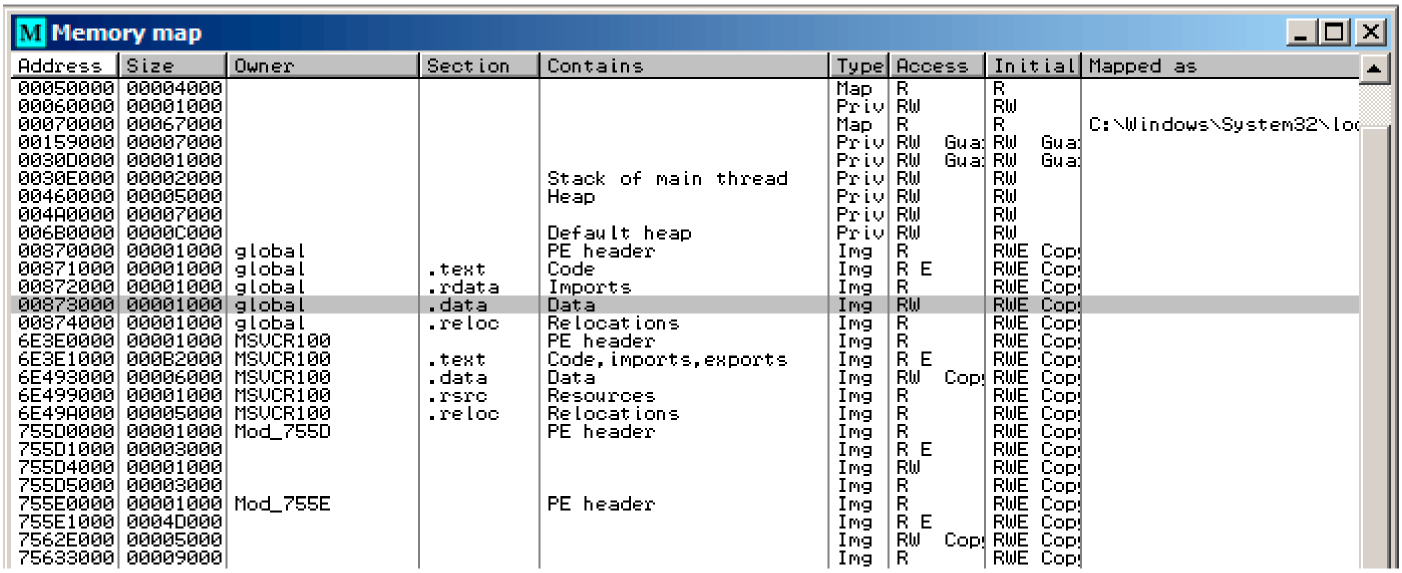


Figure 1.25: OllyDbg: memory map

Let's trace (F7) to the start of `f1()`:

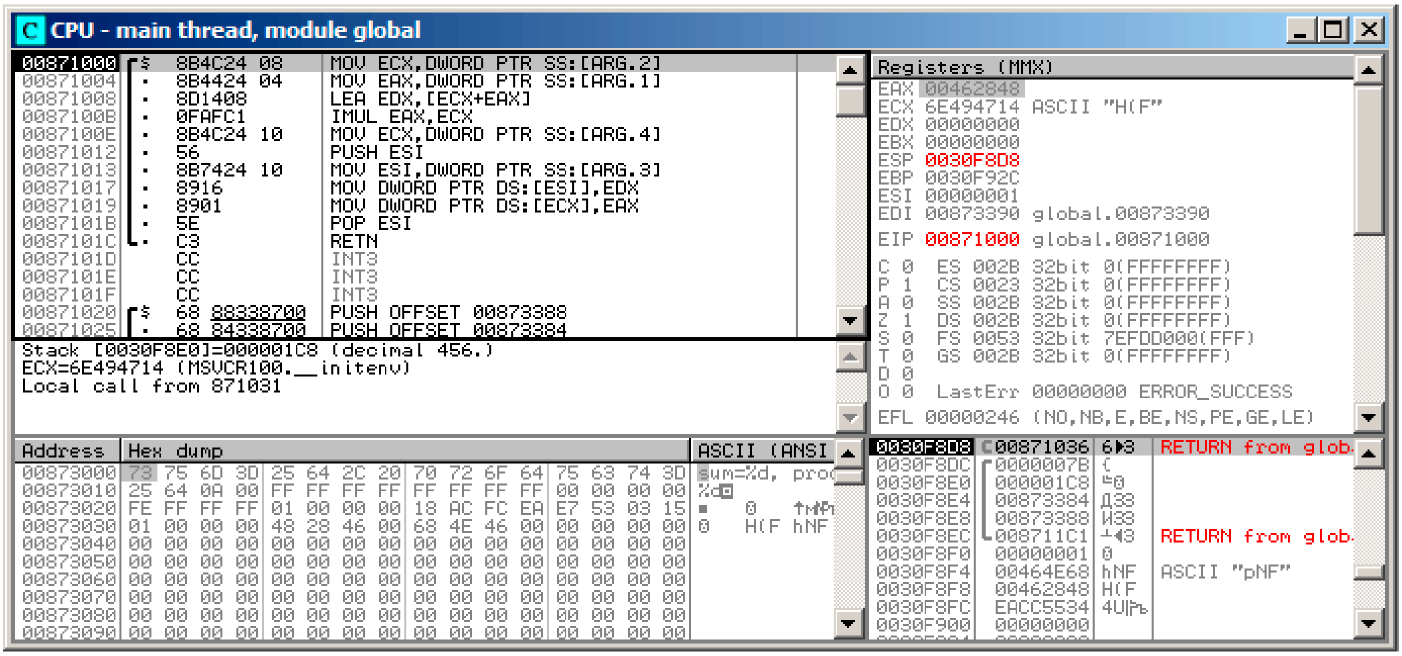


Figure 1.26: OllyDbg: `f1()` starts

Two values are visible in the stack: 456 (`0x1C8`) and 123 (`0x7B`), and also the addresses of the two global variables.

Let's trace until the end of f1(). In the left bottom window we see how the results of the calculation appear in the global variables:

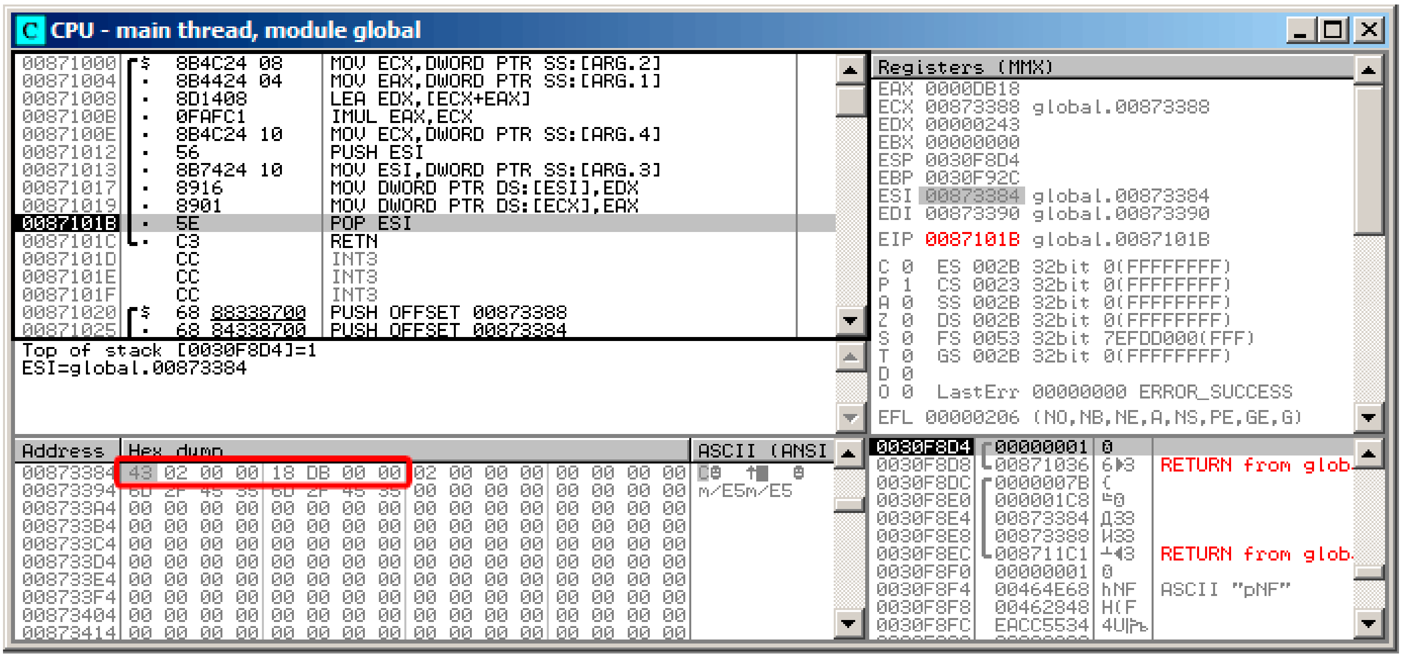


Figure 1.27: OllyDbg: f1() execution completed

Now the global variables' values are loaded into registers ready for passing to printf() (via the stack):

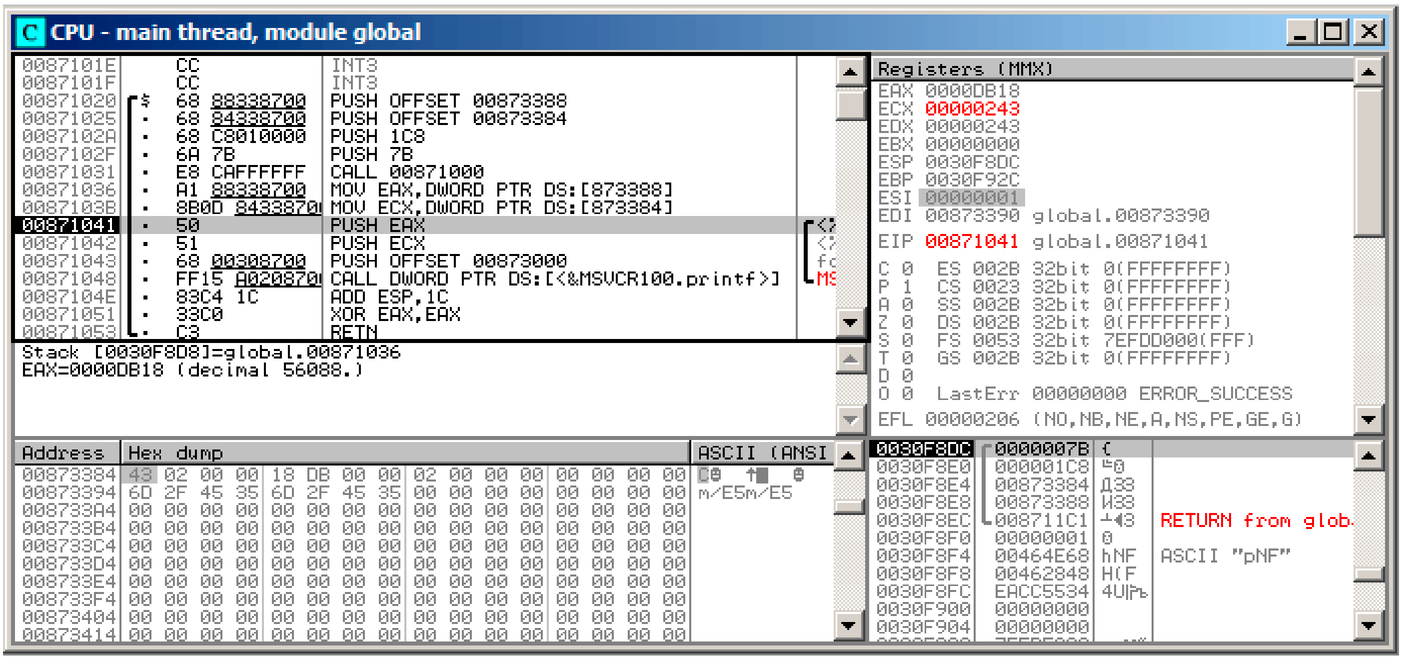


Figure 1.28: OllyDbg: global variables' values are passed into printf()

Local variables example

Let's rework our example slightly:

Listing 1.101: now the sum and product variables are local

```
void main()
{
        int sum, product; // now variables are local in this function

        f1(123, 456, &sum, &product);
        printf ("sum=%d, product=%d\n", sum, product);
};
```

f1() code will not change. Only the code of main() will do:

Listing 1.102: Optimizing MSVC 2010 (/Ob0)

```
_product$ = -8          ; size = 4
_sum$ = -4              ; size = 4
_main   PROC
; Line 10
        sub     esp, 8
; Line 13
        lea     eax, DWORD PTR _product$[esp+8]
        push    eax
        lea     ecx, DWORD PTR _sum$[esp+12]
        push    ecx
        push    456     ; 000001c8H
        push    123     ; 0000007bH
        call    _f1
; Line 14
        mov     edx, DWORD PTR _product$[esp+24]
        mov     eax, DWORD PTR _sum$[esp+24]
        push    edx
        push    eax
        push    OFFSET $SG2803
        call    DWORD PTR __imp__printf
; Line 15
        xor     eax, eax
        add     esp, 36
```

```
        ret     0
```

Let's look again with OllyDbg. The addresses of the local variables in the stack are 0x2EF854 and 0x2EF858. We see how these are pushed into the stack:

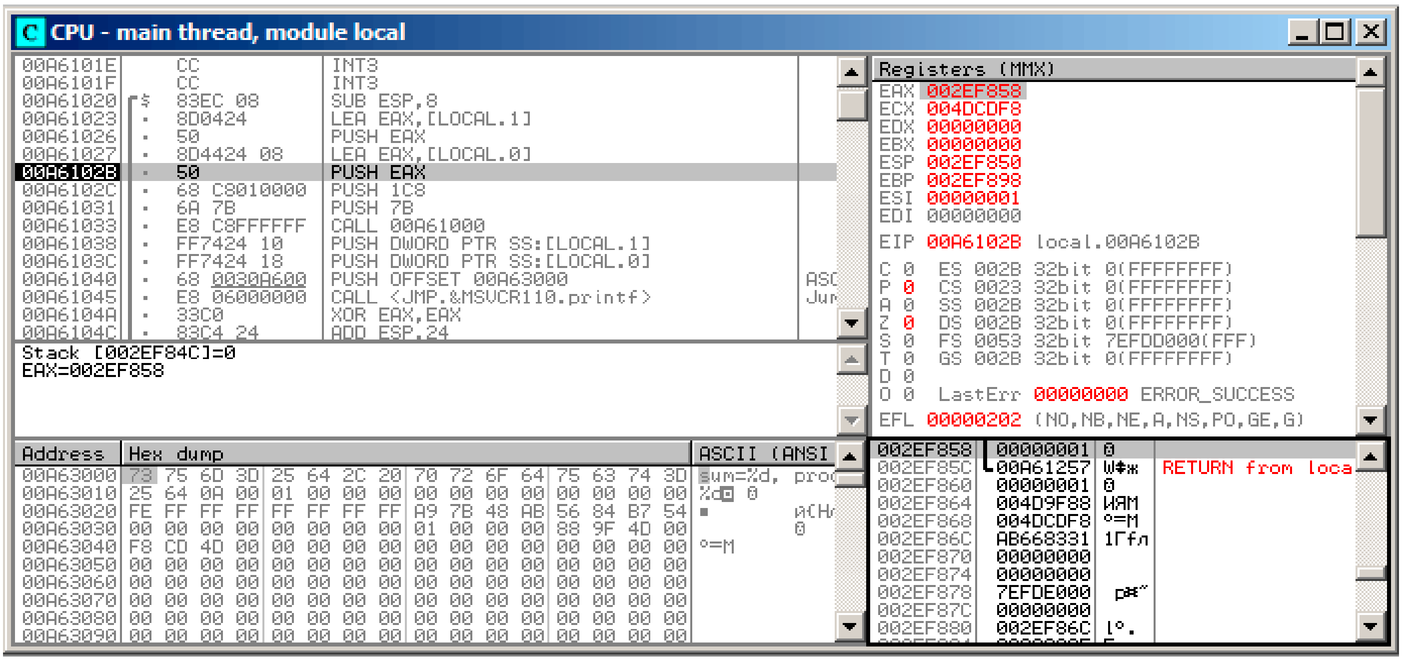


Figure 1.29: OllyDbg: local variables' addresses are pushed into the stack

f1() starts. So far there is only random garbage in the stack at 0x2EF854 and 0x2EF858:

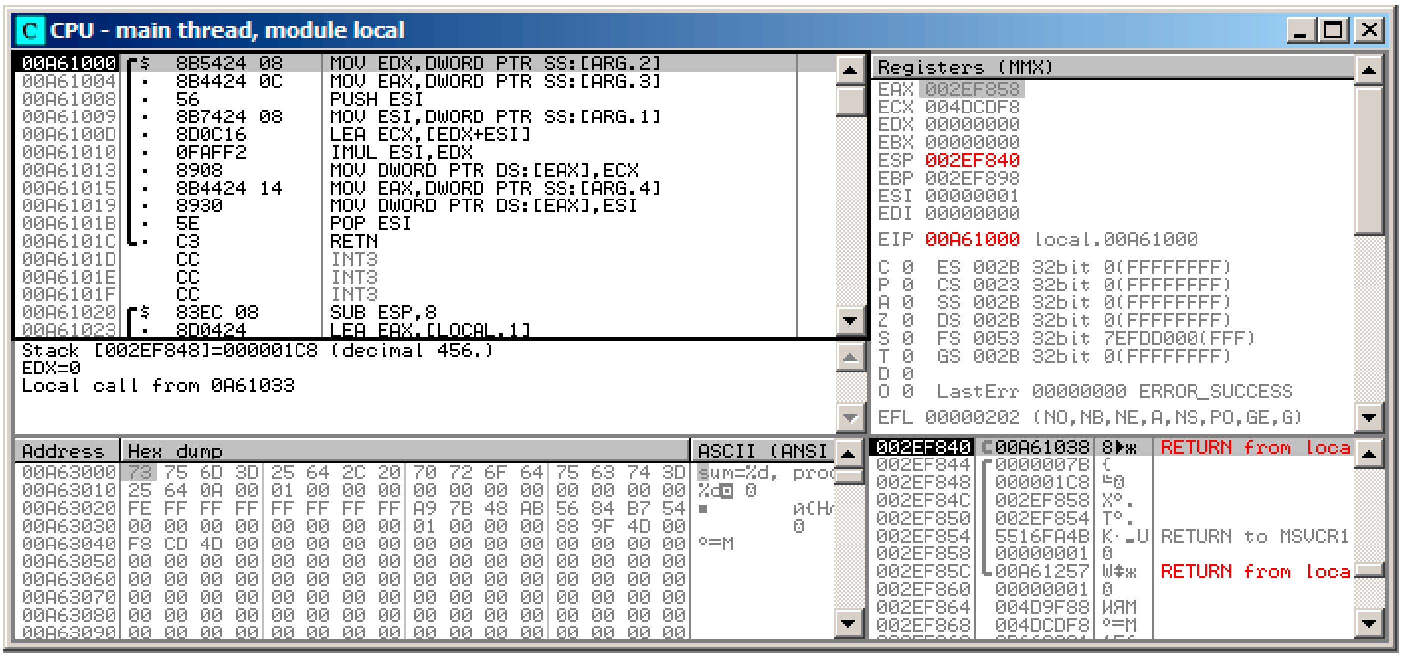


Figure 1.30: OllyDbg: f1() starting

f1() completes:

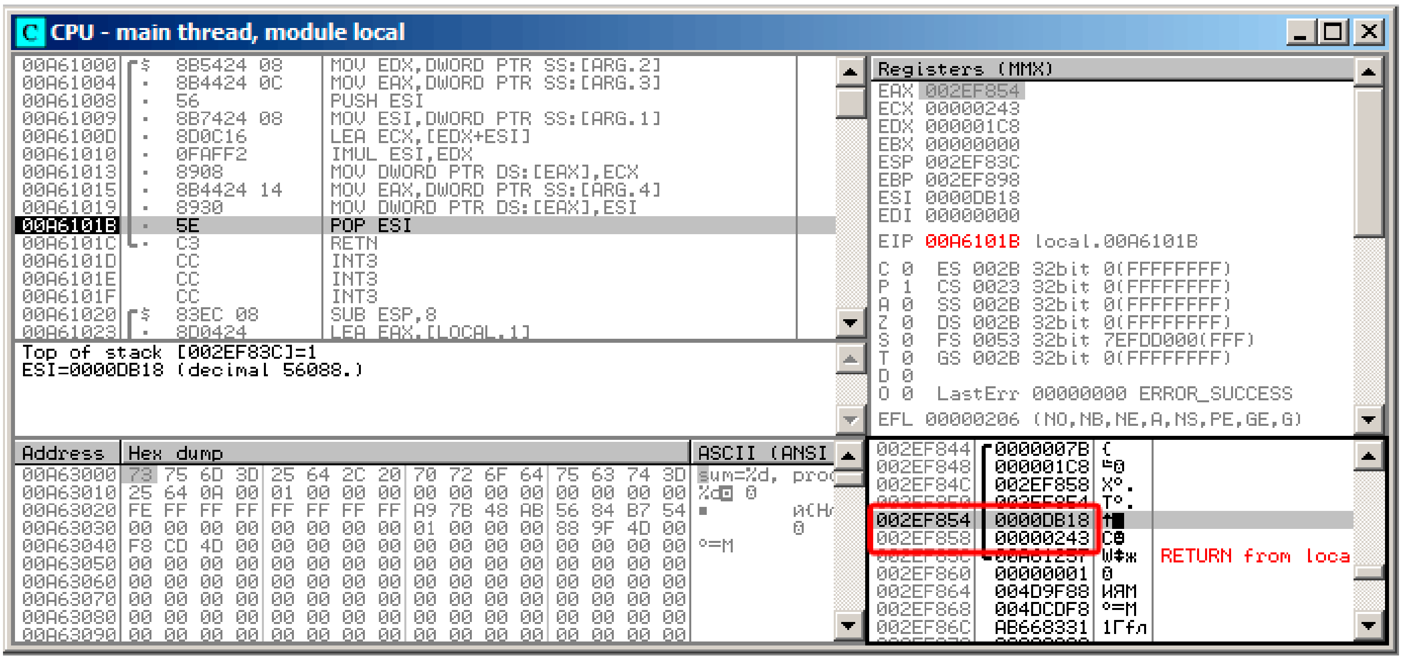


Figure 1.31: OllyDbg: f1() completes execution

We now find 0xDB18 and 0x243 at addresses 0x2EF854 and 0x2EF858. These values are the f1() results.

Conclusion

f1() could return pointers to any place in memory, located anywhere.

This is in essence the usefulness of the pointers.

By the way, C++ *references* work exactly the same way. Read more about them: (3.18.3 on page 558).

1.13 GOTO operator

The GOTO operator is generally considered as anti-pattern, see [Edgar Dijkstra, *Go To Statement Considered Harmful* (1968)[88]]. Nevertheless, it can be used reasonably, see [Donald E. Knuth, *Structured Programming with go to Statements* (1974)[89]] [90].

Here is a very simple example:

```
#include <stdio.h>

int main()
{
        printf ("begin\n");
        goto exit;
        printf ("skip me!\n");
exit:
        printf ("end\n");
};
```

Here is what we have got in MSVC 2012:

Listing 1.103: MSVC 2012

```
$SG2934 DB      'begin', 0aH, 00H
```

88 http://yurichev.com/mirrors/Dijkstra68.pdf

89 http://yurichev.com/mirrors/KnuthStructuredProgrammingGoTo.pdf

90 [Dennis Yurichev, *C/C++ programming language notes*] also has some examples.

```
$SG2936 DB      'skip me!', 0aH, 00H
$SG2937 DB      'end', 0aH, 00H

_main   PROC
        push    ebp
        mov     ebp, esp
        push    OFFSET $SG2934 ; 'begin'
        call    _printf
        add     esp, 4
        jmp     SHORT $exit$3
        push    OFFSET $SG2936 ; 'skip me!'
        call    _printf
        add     esp, 4
$exit$3:
        push    OFFSET $SG2937 ; 'end'
        call    _printf
        add     esp, 4
        xor     eax, eax
        pop     ebp
        ret     0
_main   ENDP
```

The *goto* statement has been simply replaced by a JMP instruction, which has the same effect: unconditional jump to another place. The second `printf()` could be executed only with human intervention, by using a debugger or by patching the code.

This could also be useful as a simple patching exercise. Let's open the resulting executable in Hiew:

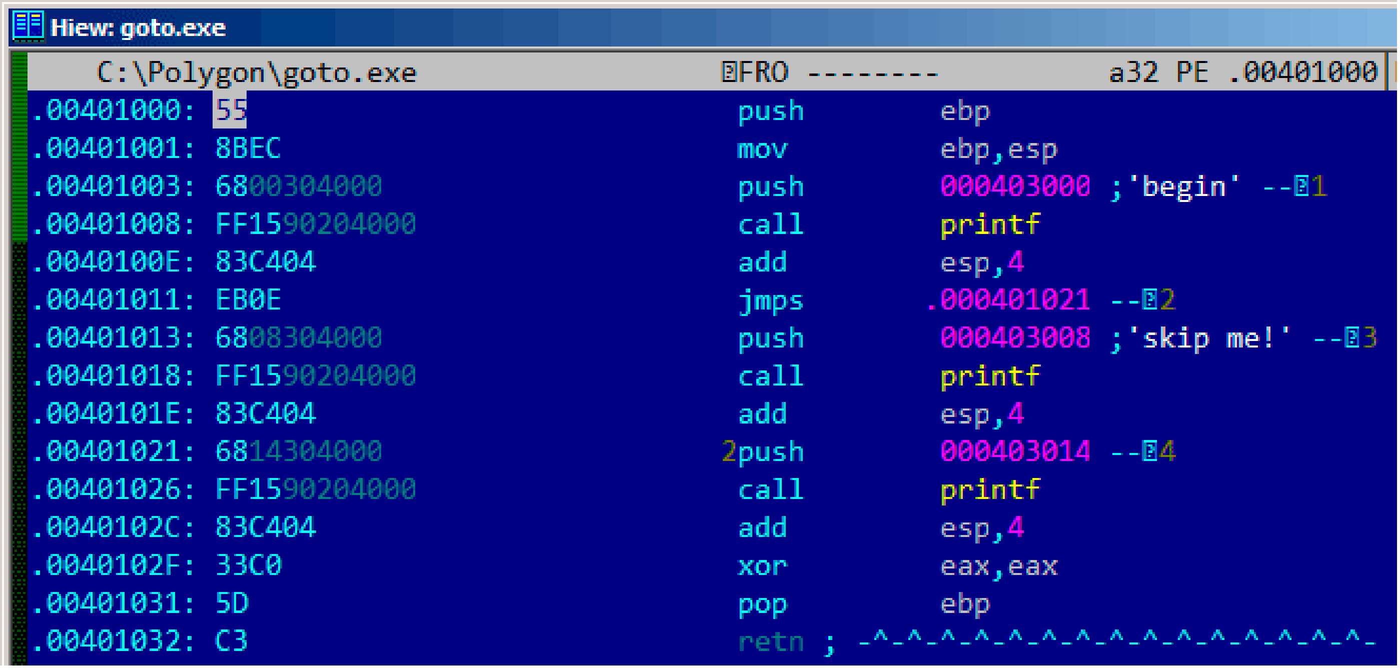


Figure 1.32: Hiew

Place the cursor to address JMP (0x410), press F3 (edit), press zero twice, so the opcode becomes EB 00:

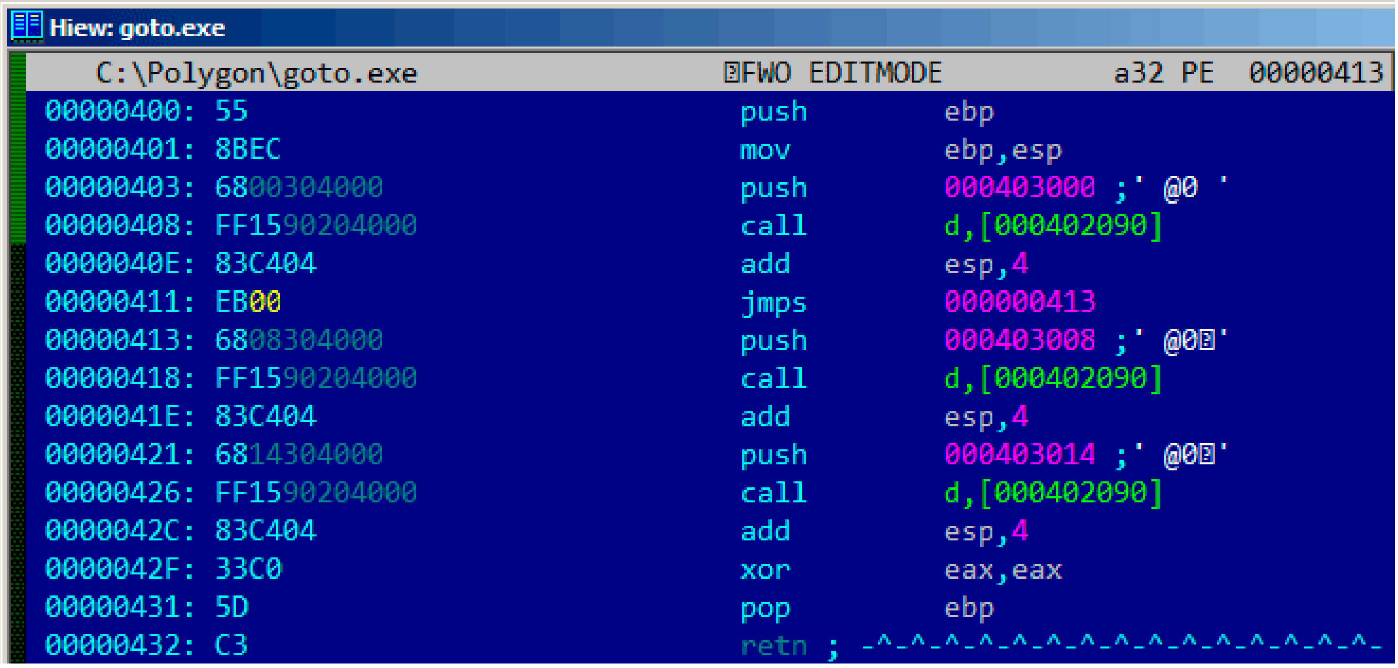


Figure 1.33: Hiew

The second byte of the JMP opcode denotes the relative offset for the jump, 0 means the point right after the current instruction.

So now JMP not skipping the second `printf()` call.

Press F9 (save) and exit. Now if we run the executable we will see this:

Listing 1.104: Patched executable output

```
C:\...>goto.exe

begin
skip me!
end
```

The same result could be achieved by replacing the JMP instruction with 2 NOP instructions.

NOP has an opcode of 0x90 and length of 1 byte, so we need 2 instructions as JMP replacement (which is 2 bytes in size).

1.13.1 Dead code

The second `printf()` call is also called “dead code” in compiler terms.

This means that the code will never be executed. So when you compile this example with optimizations, the compiler removes “dead code”, leaving no trace of it:

Listing 1.105: Optimizing MSVC 2012

```
$SG2981 DB      'begin', 0aH, 00H
$SG2983 DB      'skip me!', 0aH, 00H
$SG2984 DB      'end', 0aH, 00H

_main   PROC
        push    OFFSET $SG2981 ; 'begin'
        call    _printf
        push    OFFSET $SG2984 ; 'end'
$exit$4:
        call    _printf
        add     esp, 8
```

```
        xor     eax, eax
        ret     0
_main   ENDP
```

However, the compiler forgot to remove the “skip me!” string.

1.13.2 Exercise

Try to achieve the same result using your favorite compiler and debugger.

1.14 Conditional jumps

1.14.1 Simple example

```
#include <stdio.h>

void f_signed (int a, int b)
{
    if (a>b)
        printf ("a>b\n");
    if (a==b)
        printf ("a==b\n");
    if (a<b)
        printf ("a<b\n");
};

void f_unsigned (unsigned int a, unsigned int b)
{
    if (a>b)
        printf ("a>b\n");
    if (a==b)
        printf ("a==b\n");
    if (a<b)
        printf ("a<b\n");
};

int main()
{
    f_signed(1, 2);
    f_unsigned(1, 2);
    return 0;
};
```

x86

x86 + MSVC

Here is how the `f_signed()` function looks like:

Listing 1.106: Non-optimizing MSVC 2010

```
_a$ = 8
_b$ = 12
_f_signed PROC
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _a$[ebp]
    cmp    eax, DWORD PTR _b$[ebp]
    jle    SHORT $LN3@f_signed
    push   OFFSET $SG737        ; 'a>b'
    call   _printf
    add    esp, 4
```

```
$LN3@f_signed:
    mov    ecx, DWORD PTR _a$[ebp]
    cmp    ecx, DWORD PTR _b$[ebp]
    jne    SHORT $LN2@f_signed
    push   OFFSET $SG739        ; 'a==b'
    call   _printf
    add    esp, 4
$LN2@f_signed:
    mov    edx, DWORD PTR _a$[ebp]
    cmp    edx, DWORD PTR _b$[ebp]
    jge    SHORT $LN4@f_signed
    push   OFFSET $SG741        ; 'a<b'
    call   _printf
    add    esp, 4
$LN4@f_signed:
    pop    ebp
    ret    0
_f_signed ENDP
```

The first instruction, JLE, stands for *Jump if Less or Equal*. In other words, if the second operand is larger or equal to the first one, the control flow will be passed to the address or label specified in the instruction. If this condition does not trigger because the second operand is smaller than the first one, the control flow would not be altered and the first `printf()` would be executed. The second check is JNE: *Jump if Not Equal*. The control flow will not change if the operands are equal.

The third check is JGE: *Jump if Greater or Equal*—jump if the first operand is larger than the second or if they are equal. So, if all three conditional jumps are triggered, none of the `printf()` calls would be executed whatsoever. This is impossible without special intervention. Now let's take a look at the `f_unsigned()` function. The `f_unsigned()` function is the same as `f_signed()`, with the exception that the JBE and JAE instructions are used instead of JLE and JGE, as follows:

Listing 1.107: GCC

```
_a$ = 8   ; size = 4
_b$ = 12  ; size = 4
_f_unsigned PROC
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _a$[ebp]
    cmp    eax, DWORD PTR _b$[ebp]
    jbe    SHORT $LN3@f_unsigned
    push   OFFSET $SG2761    ; 'a>b'
    call   _printf
    add    esp, 4
$LN3@f_unsigned:
    mov    ecx, DWORD PTR _a$[ebp]
    cmp    ecx, DWORD PTR _b$[ebp]
    jne    SHORT $LN2@f_unsigned
    push   OFFSET $SG2763    ; 'a==b'
    call   _printf
    add    esp, 4
$LN2@f_unsigned:
    mov    edx, DWORD PTR _a$[ebp]
    cmp    edx, DWORD PTR _b$[ebp]
    jae    SHORT $LN4@f_unsigned
    push   OFFSET $SG2765    ; 'a<b'
    call   _printf
    add    esp, 4
$LN4@f_unsigned:
    pop    ebp
    ret    0
_f_unsigned ENDP
```

As already mentioned, the branch instructions are different: JBE—*Jump if Below or Equal* and JAE—*Jump if Above or Equal*. These instructions (JA/JAE/JB/JBE) differ from JG/JGE/JL/JLE in the fact that they work with unsigned numbers.

See also the section about signed number representations (2.2 on page 452). That is why if we see JG/JL in use instead of JA/JB or vice-versa, we can be almost sure that the variables are signed or unsigned, respectively. Here is also the `main()` function, where there is nothing much new to us:

Listing 1.108: main()

```
_main   PROC
        push    ebp
        mov     ebp, esp
        push    2
        push    1
        call    _f_signed
        add     esp, 8
        push    2
        push    1
        call    _f_unsigned
        add     esp, 8
        xor     eax, eax
        pop     ebp
        ret     0
_main   ENDP
```

x86 + MSVC + OllyDbg

We can see how flags are set by running this example in OllyDbg. Let's begin with `f_unsigned()`, which works with unsigned numbers.

CMP is executed thrice here, but for the same arguments, so the flags are the same each time.

Result of the first comparison:

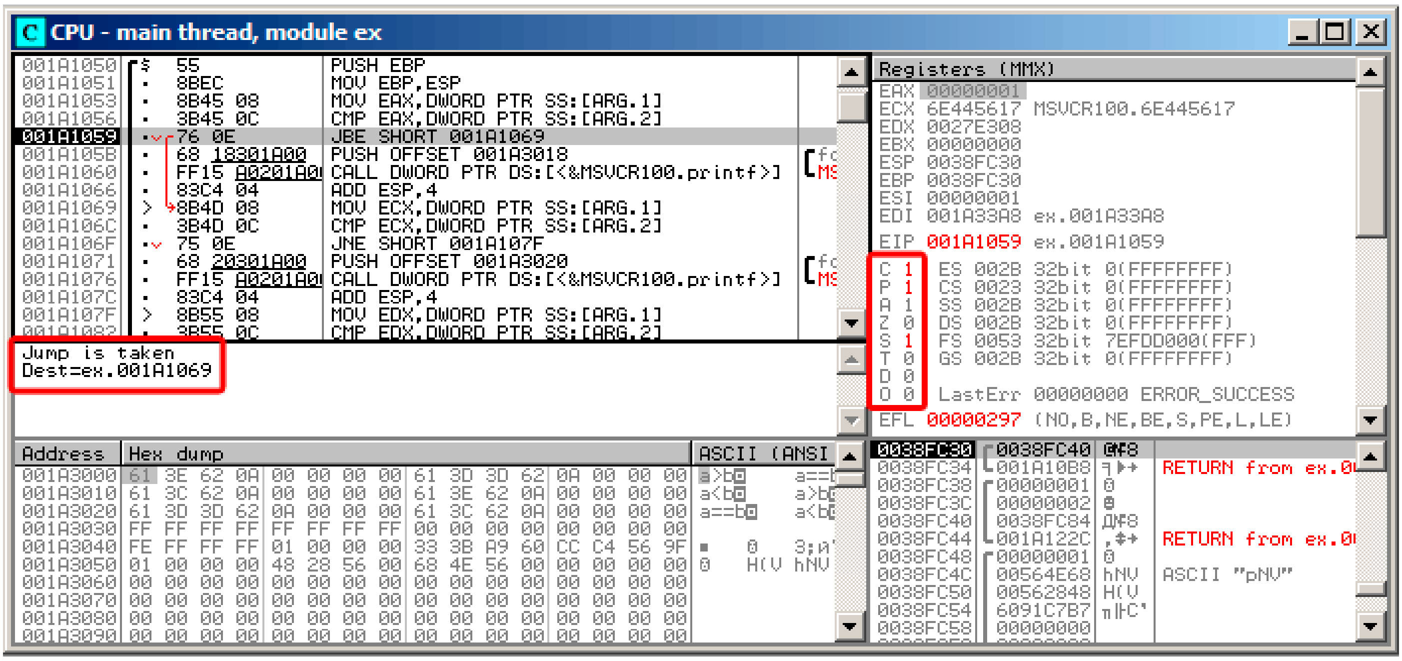


Figure 1.34: OllyDbg: `f_unsigned()`: first conditional jump

So, the flags are: C=1, P=1, A=1, Z=0, S=1, T=0, D=0, O=0.

They are named with one character for brevity in OllyDbg.

OllyDbg gives a hint that the (JBE) jump is to be triggered now. Indeed, if we take a look into Intel manuals (12.1.4 on page 1013), we can read there that JBE is triggering if CF=1 or ZF=1. The condition is true here, so the jump is triggered.

The next conditional jump:

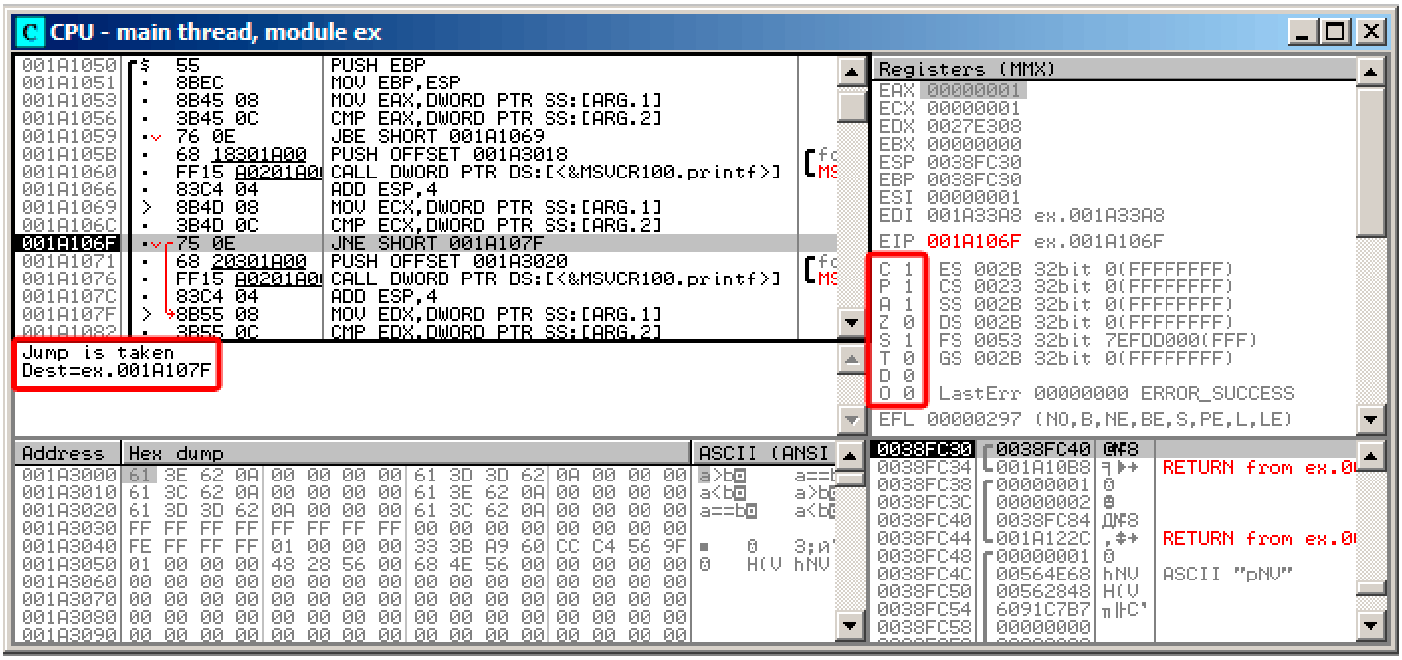


Figure 1.35: OllyDbg: f_unsigned(): second conditional jump

OllyDbg gives a hint that JNZ is to be triggered now. Indeed, JNZ triggering if ZF=0 (zero flag).

The third conditional jump, JNB:

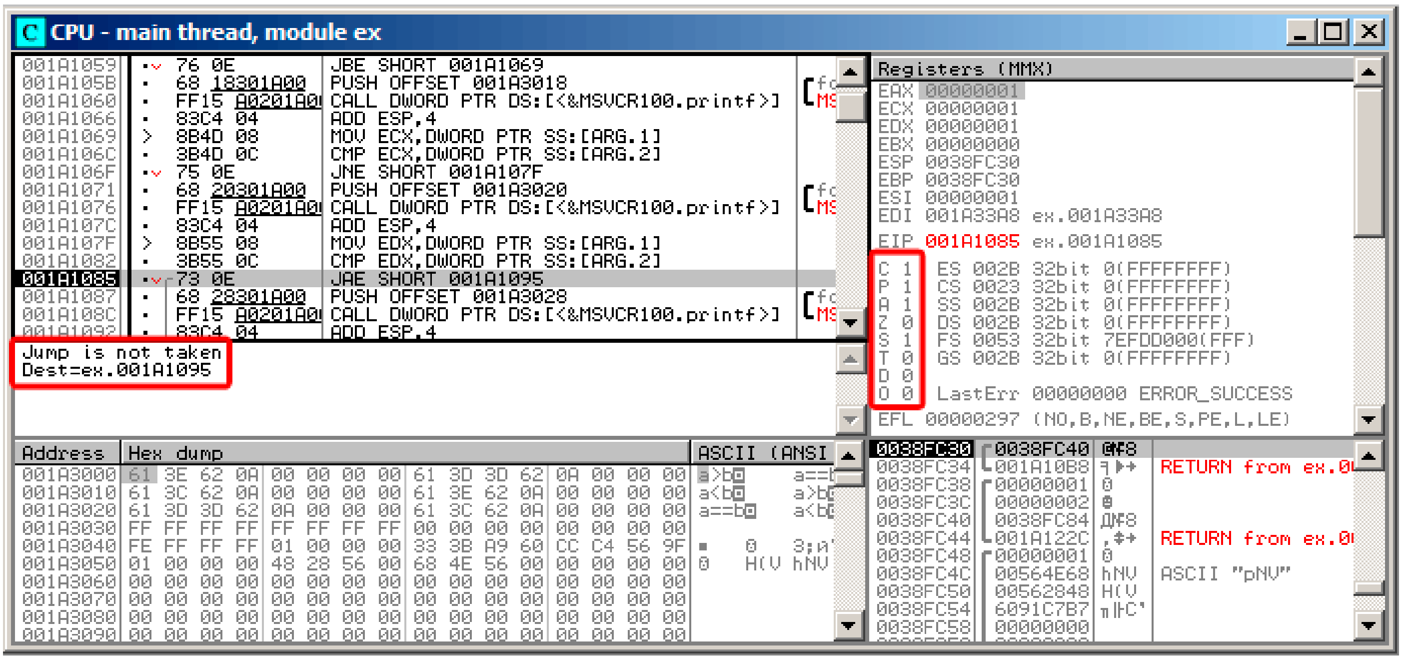


Figure 1.36: OllyDbg: `f_unsigned()`: third conditional jump

In Intel manuals (12.1.4 on page 1013) we can see that JNB triggers if CF=0 (carry flag). That is not true in our case, so the third `printf()` will execute.

Now let's review the `f_signed()` function, which works with signed values, in OllyDbg. Flags are set in the same way: C=1, P=1, A=1, Z=0, S=1, T=0, D=0, O=0. The first conditional jump JLE is to be triggered:

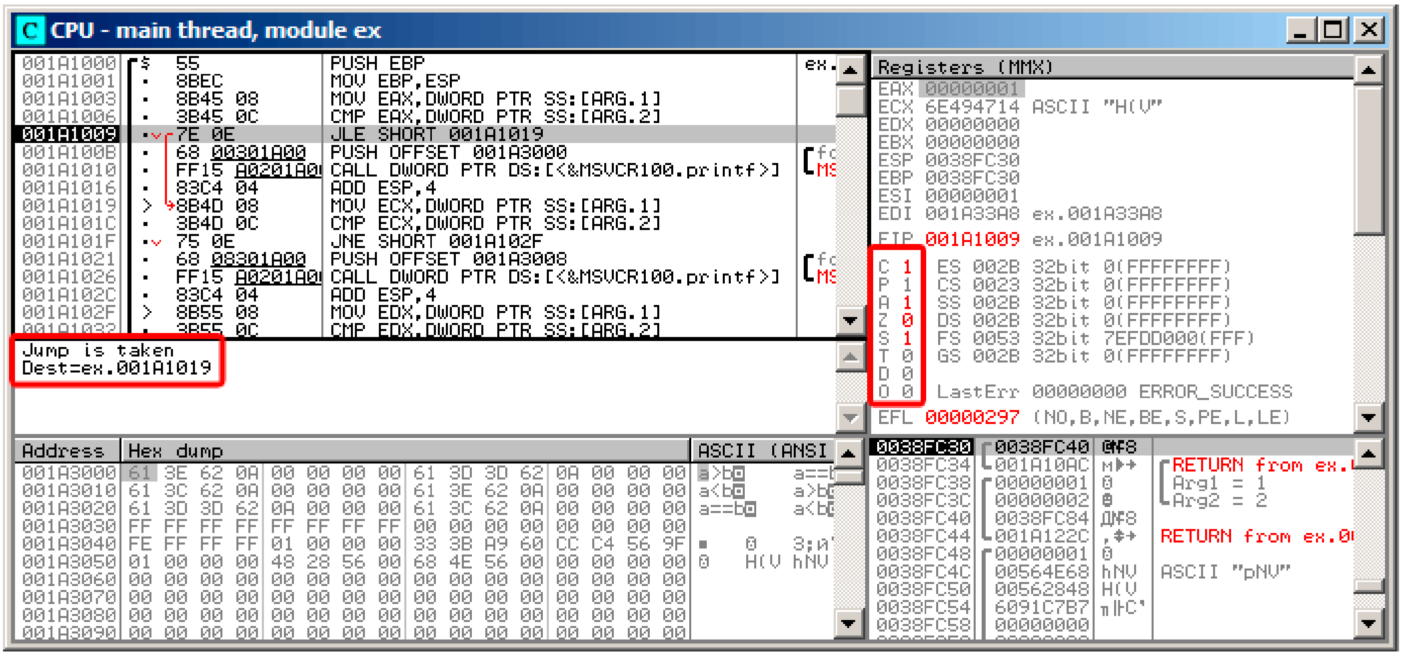


Figure 1.37: OllyDbg: `f_signed()`: first conditional jump

In Intel manuals (12.1.4 on page 1013) we find that this instruction is triggered if ZF=1 or SF≠OF. SF≠OF in our case, so the jump triggers.

The second JNZ conditional jump triggering: if ZF=0 (zero flag):

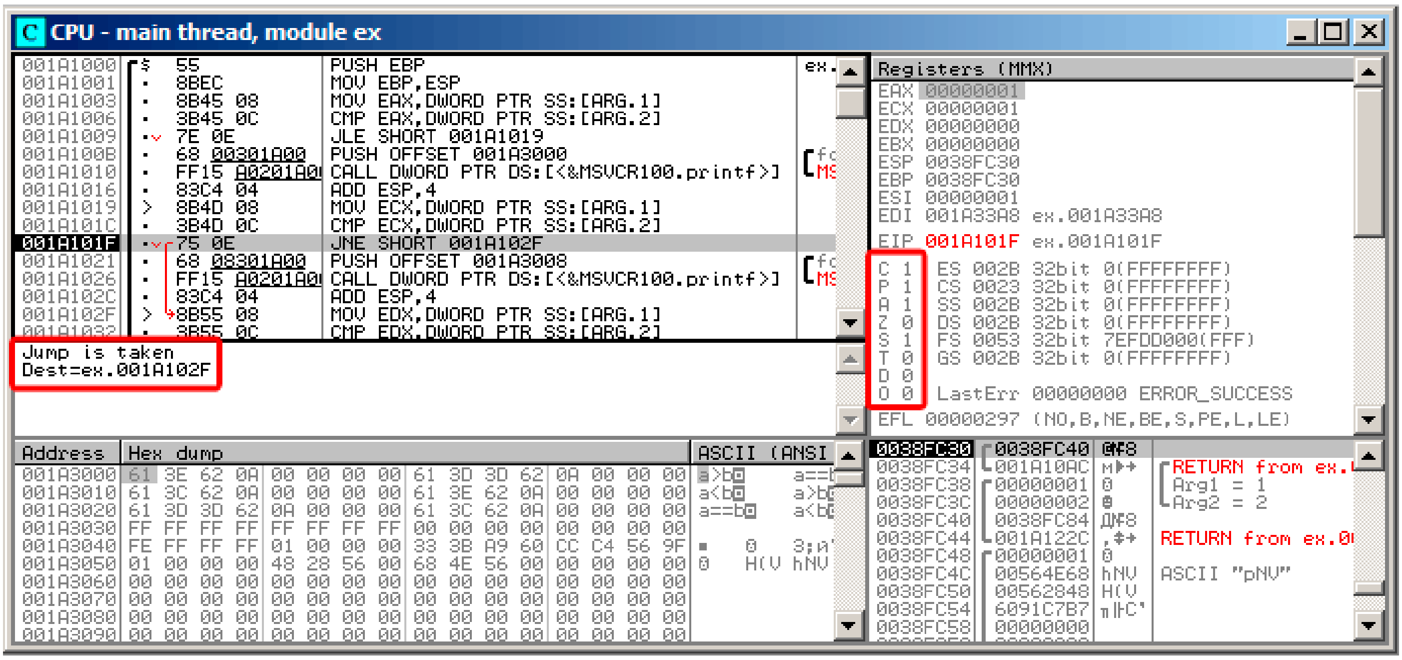


Figure 1.38: OllyDbg: `f_signed()`: second conditional jump

The third conditional jump JGE will not trigger because it would only do so if SF=OF, and that is not true in our case:

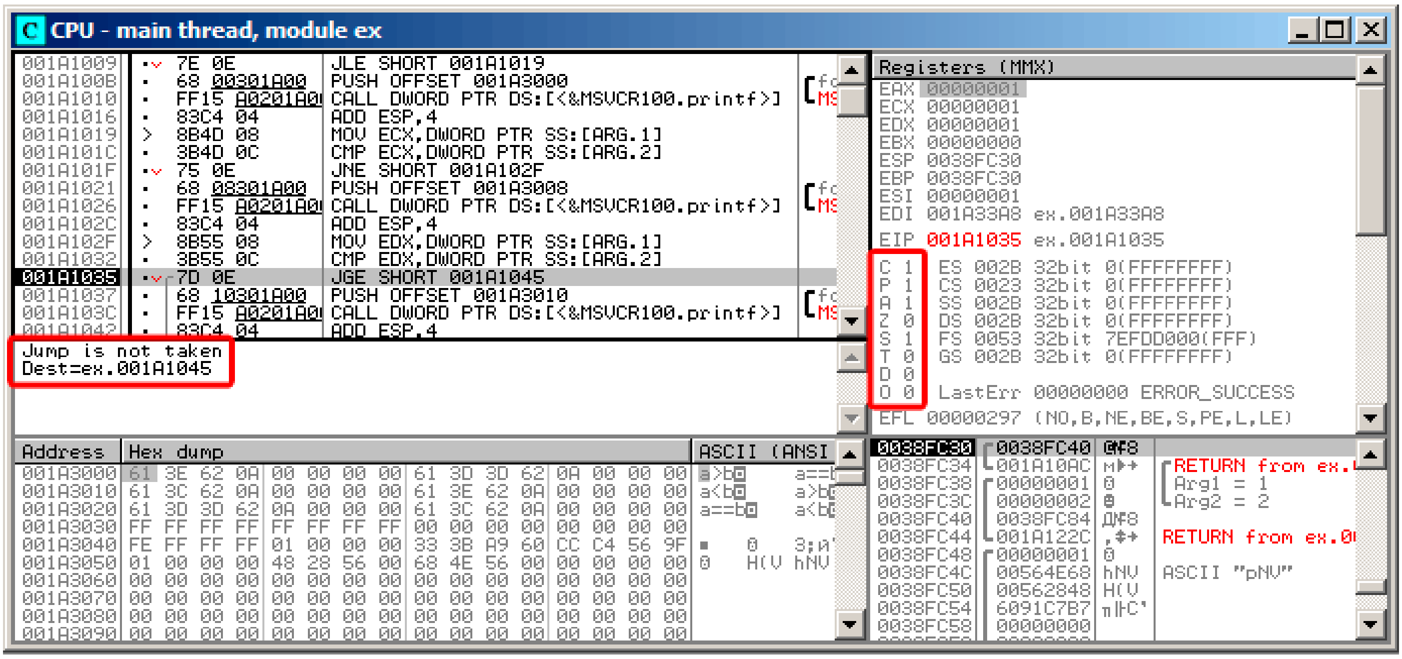


Figure 1.39: OllyDbg: f_signed(): third conditional jump

x86 + MSVC + Hiew

We can try to patch the executable file in a way that the `f_unsigned()` function would always print "a==b", no matter the input values. Here is how it looks in Hiew:

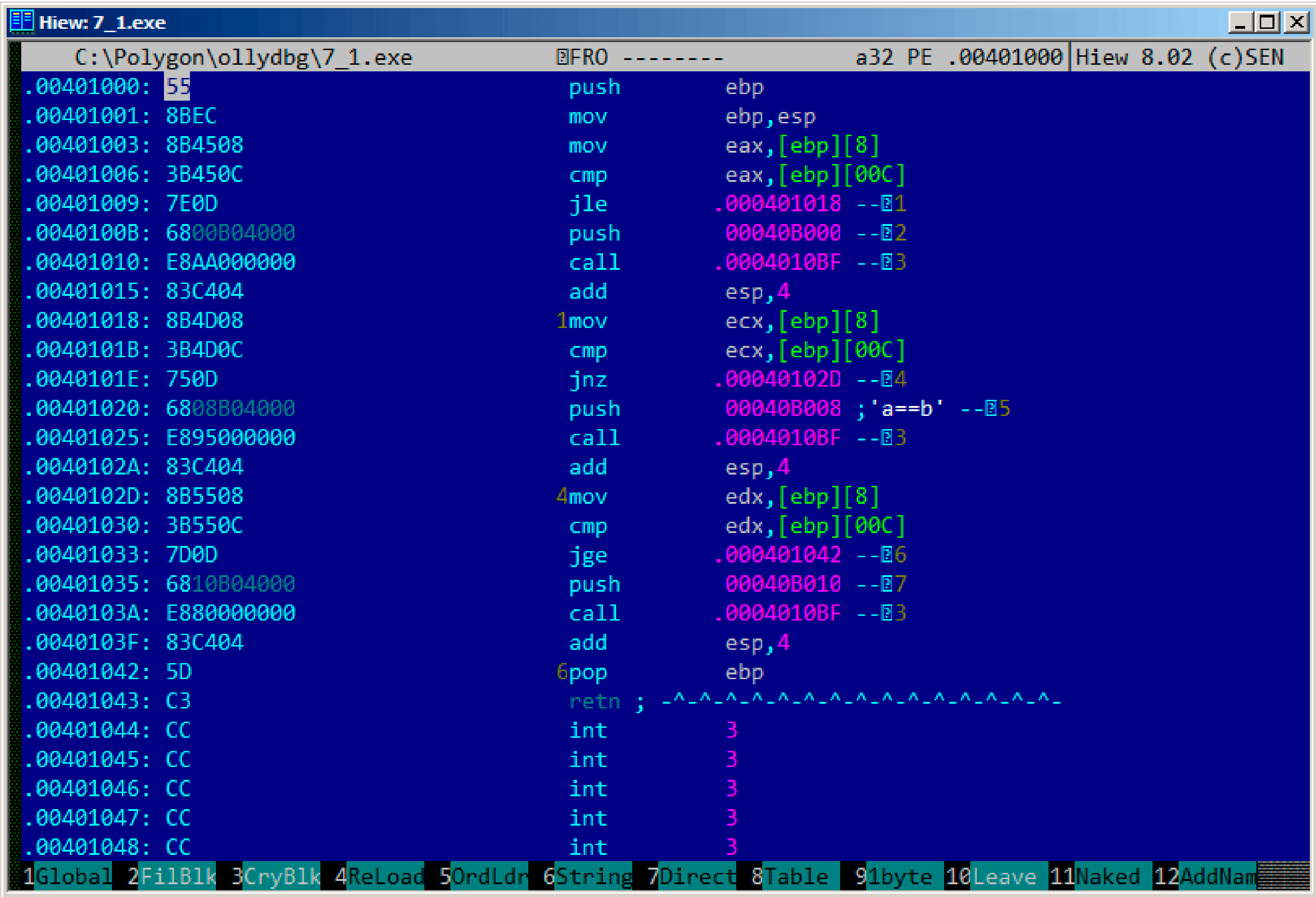


Figure 1.40: Hiew: `f_unsigned()` function

Essentially, we have to accomplish three tasks:

- force the first jump to always trigger;
- force the second jump to never trigger;
- force the third jump to always trigger.

Thus we can direct the code flow to always pass through the second `printf()`, and output "a==b".

Three instructions (or bytes) has to be patched:

- The first jump becomes JMP, but the jump offset would remain the same.
- The second jump might be triggered sometimes, but in any case it will jump to the next instruction, because, we set the jump offset to 0.

  In these instructions the jump offset is added to the address for the next instruction. So if the offset is 0, the jump will transfer the control to the next instruction.
- The third jump we replace with JMP just as we do with the first one, so it will always trigger.

Here is the modified code:

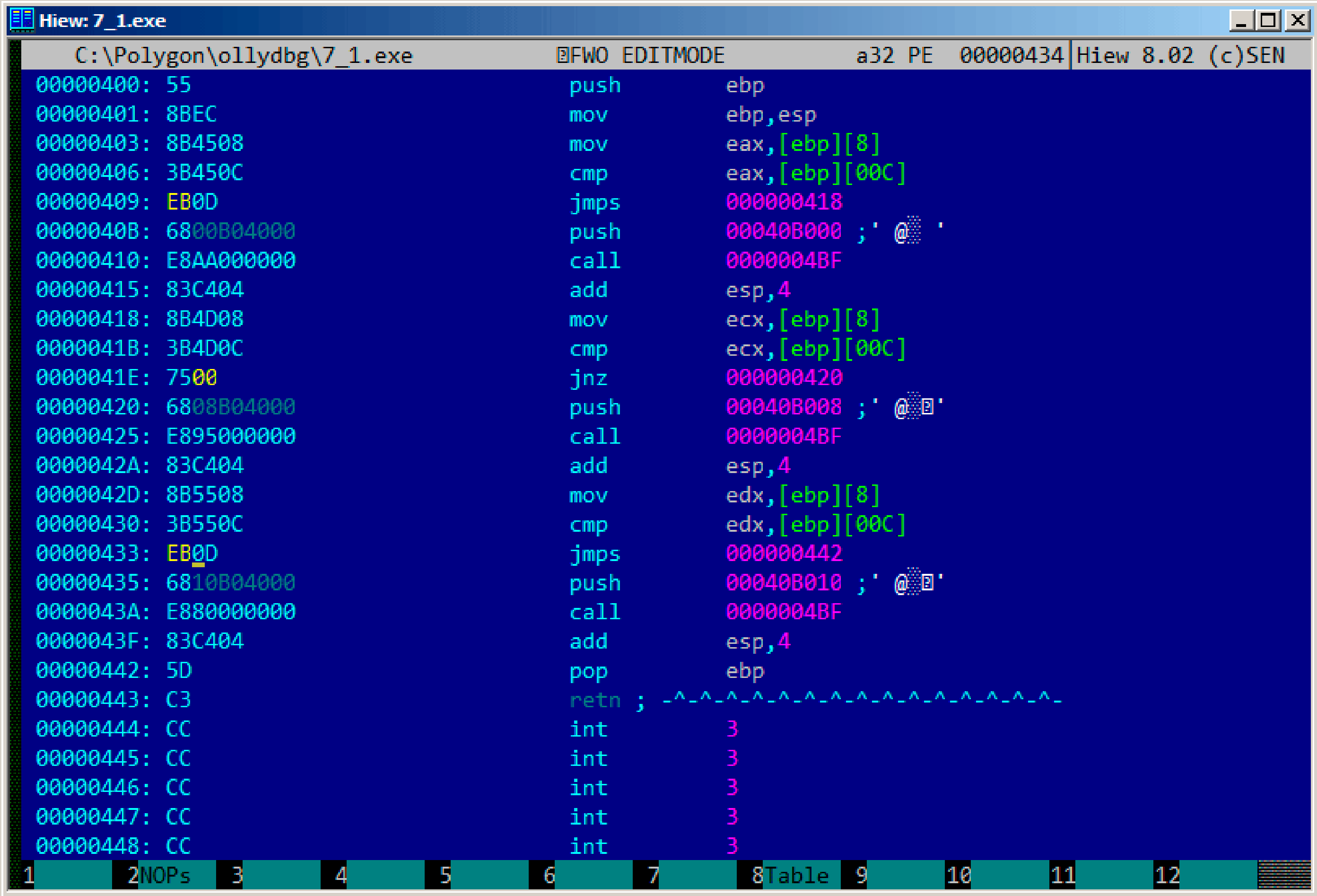


Figure 1.41: Hiew: let's modify the `f_unsigned()` function

If we miss to change any of these jumps, then several `printf()` calls may execute, while we want to execute only one.

Non-optimizing GCC

Non-optimizing GCC 4.4.1 produces almost the same code, but with `puts()` (1.5.4 on page 21) instead of `printf()`.

Optimizing GCC

An observant reader may ask, why execute CMP several times, if the flags has the same values after each execution?

Perhaps optimizing MSVC cannot do this, but optimizing GCC 4.8.1 can go deeper:

Listing 1.109: GCC 4.8.1 f_signed()

```
f_signed:
        mov     eax, DWORD PTR [esp+8]
        cmp     DWORD PTR [esp+4], eax
        jg      .L6
        je      .L7
        jge     .L1
        mov     DWORD PTR [esp+4], OFFSET FLAT:.LC2 ; "a<b"
        jmp     puts
.L6:
        mov     DWORD PTR [esp+4], OFFSET FLAT:.LC0 ; "a>b"
```

```
        jmp     puts
.L1:
        rep ret
.L7:
        mov     DWORD PTR [esp+4], OFFSET FLAT:.LC1 ; "a==b"
        jmp     puts
```

We also see JMP puts here instead of CALL puts / RETN.

This kind of trick will have explained later: 1.15.1 on page 154.

This type of x86 code is somewhat rare. MSVC 2012 as it seems, can't generate such code. On the other hand, assembly language programmers are fully aware of the fact that Jcc instructions can be stacked.

So if you see such stacking somewhere, it is highly probable that the code was hand-written.

The f_unsigned() function is not that æsthetically short:

Listing 1.110: GCC 4.8.1 f_unsigned()

```
f_unsigned:
        push    esi
        push    ebx
        sub     esp, 20
        mov     esi, DWORD PTR [esp+32]
        mov     ebx, DWORD PTR [esp+36]
        cmp     esi, ebx
        ja      .L13
        cmp     esi, ebx  ; this instruction could be removed
        je      .L14
.L10:
        jb      .L15
        add     esp, 20
        pop     ebx
        pop     esi
        ret
.L15:
        mov     DWORD PTR [esp+32], OFFSET FLAT:.LC2 ; "a<b"
        add     esp, 20
        pop     ebx
        pop     esi
        jmp     puts
.L13:
        mov     DWORD PTR [esp], OFFSET FLAT:.LC0 ; "a>b"
        call    puts
        cmp     esi, ebx
        jne     .L10
.L14:
        mov     DWORD PTR [esp+32], OFFSET FLAT:.LC1 ; "a==b"
        add     esp, 20
        pop     ebx
        pop     esi
        jmp     puts
```

Nevertheless, there are two CMP instructions instead of three.

So optimization algorithms of GCC 4.8.1 are probably not perfect yet.

ARM

32-bit ARM

Optimizing Keil 6/2013 (ARM mode)

Listing 1.111: Optimizing Keil 6/2013 (ARM mode)

```
.text:000000B8                          EXPORT f_signed
```

```
.text:000000B8             f_signed              ; CODE XREF: main+C
.text:000000B8 70 40 2D E9         STMFD   SP!, {R4-R6,LR}
.text:000000BC 01 40 A0 E1         MOV     R4, R1
.text:000000C0 04 00 50 E1         CMP     R0, R4
.text:000000C4 00 50 A0 E1         MOV     R5, R0
.text:000000C8 1A 0E 8F C2         ADRGT   R0, aAB         ; "a>b\n"
.text:000000CC A1 18 00 CB         BLGT    __2printf
.text:000000D0 04 00 55 E1         CMP     R5, R4
.text:000000D4 67 0F 8F 02         ADREQ   R0, aAB_0       ; "a==b\n"
.text:000000D8 9E 18 00 0B         BLEQ    __2printf
.text:000000DC 04 00 55 E1         CMP     R5, R4
.text:000000E0 70 80 BD A8         LDMGEFD SP!, {R4-R6,PC}
.text:000000E4 70 40 BD E8         LDMFD   SP!, {R4-R6,LR}
.text:000000E8 19 0E 8F E2         ADR     R0, aAB_1       ; "a<b\n"
.text:000000EC 99 18 00 EA         B       __2printf
.text:000000EC             ; End of function f_signed
```

Many instructions in ARM mode could be executed only when specific flags are set. E.g. this is often used when comparing numbers.

For instance, the ADD instruction is in fact named ADDAL internally, where AL stands for *Always*, i.e., execute always. The predicates are encoded in 4 high bits of the 32-bit ARM instructions (*condition field*). The B instruction for unconditional jumping is in fact conditional and encoded just like any other conditional jump, but has AL in the *condition field*, and it implies *execute ALways*, ignoring flags.

The ADRGT instruction works just like ADR but executes only in case the previous CMP instruction founds one of the numbers greater than the another, while comparing the two (*Greater Than*).

The next BLGT instruction behaves exactly as BL and is triggered only if the result of the comparison has been (*Greater Than*). ADRGT writes a pointer to the string a>b\n into R0 and BLGT calls printf(). Therefore, instructions suffixed with -GT are to execute only in case the value in R0 (which is a) is bigger than the value in R4 (which is b).

Moving forward we see the ADREQ and BLEQ instructions. They behave just like ADR and BL, but are to be executed only if operands were equal to each other during the last comparison. Another CMP is located before them (because the printf() execution may have tampered the flags).

Then we see LDMGEFD, this instruction works just like LDMFD[91], but is triggered only when one of the values is greater or equal than the other (*Greater or Equal*). The LDMGEFD SP!, {R4-R6,PC} instruction acts like a function epilogue, but it will be triggered only if $a >= b$, and only then the function execution will finish.

But if that condition is not satisfied, i.e., $a < b$, then the control flow will continue to the next "LDMFD SP!, {R4-R6,LR}" instruction, which is one more function epilogue. This instruction restores not only the R4-R6 registers state, but also LR instead of PC, thus, it does not return from the function. The last two instructions call printf() with the string «a<b\n» as a sole argument. We already examined an unconditional jump to the printf() function instead of function return in «printf() with several arguments» section (1.8.2 on page 54).

f_unsigned is similar, only the ADRHI, BLHI, and LDMCSFD instructions are used there, these predicates (*HI = Unsigned higher, CS = Carry Set (greater than or equal)*) are analogous to those examined before, but for unsigned values.

There is not much new in the main() function for us:

Listing 1.112: main()

```
.text:00000128                 EXPORT main
.text:00000128             main
.text:00000128 10 40 2D E9     STMFD   SP!, {R4,LR}
.text:0000012C 02 10 A0 E3     MOV     R1, #2
.text:00000130 01 00 A0 E3     MOV     R0, #1
.text:00000134 DF FF FF EB     BL      f_signed
.text:00000138 02 10 A0 E3     MOV     R1, #2
.text:0000013C 01 00 A0 E3     MOV     R0, #1
.text:00000140 EA FF FF EB     BL      f_unsigned
.text:00000144 00 00 A0 E3     MOV     R0, #0
.text:00000148 10 80 BD E8     LDMFD   SP!, {R4,PC}
.text:00000148             ; End of function main
```

[91] LDMFD

That is how you can get rid of conditional jumps in ARM mode.

Why is this so good? Read here: 2.10.1 on page 466.

There is no such feature in x86, except the CMOVcc instruction, it is the same as MOV, but triggered only when specific flags are set, usually set by CMP.

Optimizing Keil 6/2013 (Thumb mode)

Listing 1.113: Optimizing Keil 6/2013 (Thumb mode)

```
.text:00000072             f_signed ; CODE XREF: main+6
.text:00000072 70 B5         PUSH    {R4-R6,LR}
.text:00000074 0C 00         MOVS    R4, R1
.text:00000076 05 00         MOVS    R5, R0
.text:00000078 A0 42         CMP     R0, R4
.text:0000007A 02 DD         BLE     loc_82
.text:0000007C A4 A0         ADR     R0, aAB         ; "a>b\n"
.text:0000007E 06 F0 B7 F8   BL      __2printf
.text:00000082
.text:00000082             loc_82 ; CODE XREF: f_signed+8
.text:00000082 A5 42         CMP     R5, R4
.text:00000084 02 D1         BNE     loc_8C
.text:00000086 A4 A0         ADR     R0, aAB_0       ; "a==b\n"
.text:00000088 06 F0 B2 F8   BL      __2printf
.text:0000008C
.text:0000008C             loc_8C ; CODE XREF: f_signed+12
.text:0000008C A5 42         CMP     R5, R4
.text:0000008E 02 DA         BGE     locret_96
.text:00000090 A3 A0         ADR     R0, aAB_1       ; "a<b\n"
.text:00000092 06 F0 AD F8   BL      __2printf
.text:00000096
.text:00000096             locret_96 ; CODE XREF: f_signed+1C
.text:00000096 70 BD         POP     {R4-R6,PC}
.text:00000096             ; End of function f_signed
```

Only B instructions in Thumb mode may be supplemented by *condition codes*, so the Thumb code looks more ordinary.

BLE is a normal conditional jump *Less than or Equal*, BNE—*Not Equal*, BGE—*Greater than or Equal*.

f_unsigned is similar, only other instructions are used while dealing with unsigned values: BLS (*Unsigned lower or same*) and BCS (*Carry Set (Greater than or equal)*).

ARM64: Optimizing GCC (Linaro) 4.9

Listing 1.114: f_signed()

```
f_signed:
; W0=a, W1=b
        cmp     w0, w1
        bgt     .L19    ; Branch if Greater Than (a>b)
        beq     .L20    ; Branch if Equal (a==b)
        bge     .L15    ; Branch if Greater than or Equal (a>=b) (impossible here)
        ; a<b
        adrp    x0, .LC11       ; "a<b"
        add     x0, x0, :lo12:.LC11
        b       puts
.L19:
        adrp    x0, .LC9        ; "a>b"
        add     x0, x0, :lo12:.LC9
        b       puts
.L15:   ; impossible to get here
        ret
.L20:
        adrp    x0, .LC10       ; "a==b"
        add     x0, x0, :lo12:.LC10
        b       puts
```

Listing 1.115: f_unsigned()

```
f_unsigned:
        stp     x29, x30, [sp, -48]!
; W0=a, W1=b
        cmp     w0, w1
        add     x29, sp, 0
        str     x19, [sp,16]
        mov     w19, w0
        bhi     .L25    ; Branch if HIgher (a>b)
        cmp     w19, w1
        beq     .L26    ; Branch if Equal (a==b)
.L23:
        bcc     .L27    ; Branch if Carry Clear (if less than) (a<b)
; function epilogue, impossible to be here
        ldr     x19, [sp,16]
        ldp     x29, x30, [sp], 48
        ret
.L27:
        ldr     x19, [sp,16]
        adrp    x0, .LC11       ; "a<b"
        ldp     x29, x30, [sp], 48
        add     x0, x0, :lo12:.LC11
        b       puts
.L25:
        adrp    x0, .LC9        ; "a>b"
        str     x1, [x29,40]
        add     x0, x0, :lo12:.LC9
        bl      puts
        ldr     x1, [x29,40]
        cmp     w19, w1
        bne     .L23    ; Branch if Not Equal
.L26:
        ldr     x19, [sp,16]
        adrp    x0, .LC10       ; "a==b"
        ldp     x29, x30, [sp], 48
        add     x0, x0, :lo12:.LC10
        b       puts
```

The comments were added by the author of this book. What is striking is that the compiler is not aware that some conditions are not possible at all, so there is dead code at some places, which can never be executed.

Exercise

Try to optimize these functions manually for size, removing redundant instructions, without adding new ones.

MIPS

One distinctive MIPS feature is the absence of flags. Apparently, it was done to simplify the analysis of data dependencies.

There are instructions similar to SETcc in x86: SLT ("Set on Less Than": signed version) and SLTU (unsigned version). These instructions sets destination register value to 1 if the condition is true or to 0 if otherwise.

The destination register is then checked using BEQ ("Branch on Equal") or BNE ("Branch on Not Equal") and a jump may occur. So, this instruction pair has to be used in MIPS for comparison and branch. Let's first start with the signed version of our function:

Listing 1.116: Non-optimizing GCC 4.4.5 (IDA)

```
.text:00000000 f_signed:                                             # CODE XREF: main+18
.text:00000000
.text:00000000 var_10          = -0x10
.text:00000000 var_8           = -8
.text:00000000 var_4           = -4
```

```
.text:00000000 arg_0           =  0
.text:00000000 arg_4           =  4
.text:00000000
.text:00000000                 addiu   $sp, -0x20
.text:00000004                 sw      $ra, 0x20+var_4($sp)
.text:00000008                 sw      $fp, 0x20+var_8($sp)
.text:0000000C                 move    $fp, $sp
.text:00000010                 la      $gp, __gnu_local_gp
.text:00000018                 sw      $gp, 0x20+var_10($sp)
; store input values into local stack:
.text:0000001C                 sw      $a0, 0x20+arg_0($fp)
.text:00000020                 sw      $a1, 0x20+arg_4($fp)
; reload them.
.text:00000024                 lw      $v1, 0x20+arg_0($fp)
.text:00000028                 lw      $v0, 0x20+arg_4($fp)
; $v0=b
; $v1=a
.text:0000002C                 or      $at, $zero ; NOP
; this is pseudoinstruction. in fact, "slt $v0,$v0,$v1" is there.
; so $v0 will be set to 1 if $v0<$v1 (b<a) or to 0 if otherwise:
.text:00000030                 slt     $v0, $v1
; jump to loc_5c, if condition is not true.
; this is pseudoinstruction. in fact, "beq $v0,$zero,loc_5c" is there:
.text:00000034                 beqz    $v0, loc_5C
; print "a>b" and finish
.text:00000038                 or      $at, $zero ; branch delay slot, NOP
.text:0000003C                 lui     $v0, (unk_230 >> 16) # "a>b"
.text:00000040                 addiu   $a0, $v0, (unk_230 & 0xFFFF) # "a>b"
.text:00000044                 lw      $v0, (puts & 0xFFFF)($gp)
.text:00000048                 or      $at, $zero ; NOP
.text:0000004C                 move    $t9, $v0
.text:00000050                 jalr    $t9
.text:00000054                 or      $at, $zero ; branch delay slot, NOP
.text:00000058                 lw      $gp, 0x20+var_10($fp)
.text:0000005C
.text:0000005C loc_5C:                                   # CODE XREF: f_signed+34
.text:0000005C                 lw      $v1, 0x20+arg_0($fp)
.text:00000060                 lw      $v0, 0x20+arg_4($fp)
.text:00000064                 or      $at, $zero ; NOP
; check if a==b, jump to loc_90 if its not true':
.text:00000068                 bne     $v1, $v0, loc_90
.text:0000006C                 or      $at, $zero ; branch delay slot, NOP
; condition is true, so print "a==b" and finish:
.text:00000070                 lui     $v0, (aAB >> 16)  # "a==b"
.text:00000074                 addiu   $a0, $v0, (aAB & 0xFFFF)  # "a==b"
.text:00000078                 lw      $v0, (puts & 0xFFFF)($gp)
.text:0000007C                 or      $at, $zero ; NOP
.text:00000080                 move    $t9, $v0
.text:00000084                 jalr    $t9
.text:00000088                 or      $at, $zero ; branch delay slot, NOP
.text:0000008C                 lw      $gp, 0x20+var_10($fp)
.text:00000090
.text:00000090 loc_90:                                   # CODE XREF: f_signed+68
.text:00000090                 lw      $v1, 0x20+arg_0($fp)
.text:00000094                 lw      $v0, 0x20+arg_4($fp)
.text:00000098                 or      $at, $zero ; NOP
; check if $v1<$v0 (a<b), set $v0 to 1 if condition is true:
.text:0000009C                 slt     $v0, $v1, $v0
; if condition is not true (i.e., $v0==0), jump to loc_c8:
.text:000000A0                 beqz    $v0, loc_C8
.text:000000A4                 or      $at, $zero ; branch delay slot, NOP
; condition is true, print "a<b" and finish
.text:000000A8                 lui     $v0, (aAB_0 >> 16)  # "a<b"
.text:000000AC                 addiu   $a0, $v0, (aAB_0 & 0xFFFF)  # "a<b"
.text:000000B0                 lw      $v0, (puts & 0xFFFF)($gp)
.text:000000B4                 or      $at, $zero ; NOP
.text:000000B8                 move    $t9, $v0
.text:000000BC                 jalr    $t9
.text:000000C0                 or      $at, $zero ; branch delay slot, NOP
.text:000000C4                 lw      $gp, 0x20+var_10($fp)
```

```
.text:000000C8
; all 3 conditions were false, so just finish:
.text:000000C8 loc_C8:                                  # CODE XREF: f_signed+A0
.text:000000C8                 move    $sp, $fp
.text:000000CC                 lw      $ra, 0x20+var_4($sp)
.text:000000D0                 lw      $fp, 0x20+var_8($sp)
.text:000000D4                 addiu   $sp, 0x20
.text:000000D8                 jr      $ra
.text:000000DC                 or      $at, $zero ; branch delay slot, NOP
.text:000000DC  # End of function f_signed
```

SLT REG0, REG0, REG1 is reduced by IDA to its shorter form:
SLT REG0, REG1.

We also see there BEQZ pseudo instruction ("Branch if Equal to Zero"),
which are in fact BEQ REG, $ZERO, LABEL.

The unsigned version is just the same, but SLTU (unsigned version, hence "U" in name) is used instead of SLT:

Listing 1.117: Non-optimizing GCC 4.4.5 (IDA)

```
.text:000000E0 f_unsigned:                              # CODE XREF: main+28
.text:000000E0
.text:000000E0 var_10          = -0x10
.text:000000E0 var_8           = -8
.text:000000E0 var_4           = -4
.text:000000E0 arg_0           =  0
.text:000000E0 arg_4           =  4
.text:000000E0
.text:000000E0                 addiu   $sp, -0x20
.text:000000E4                 sw      $ra, 0x20+var_4($sp)
.text:000000E8                 sw      $fp, 0x20+var_8($sp)
.text:000000EC                 move    $fp, $sp
.text:000000F0                 la      $gp, __gnu_local_gp
.text:000000F8                 sw      $gp, 0x20+var_10($sp)
.text:000000FC                 sw      $a0, 0x20+arg_0($fp)
.text:00000100                 sw      $a1, 0x20+arg_4($fp)
.text:00000104                 lw      $v1, 0x20+arg_0($fp)
.text:00000108                 lw      $v0, 0x20+arg_4($fp)
.text:0000010C                 or      $at, $zero
.text:00000110                 sltu    $v0, $v1
.text:00000114                 beqz    $v0, loc_13C
.text:00000118                 or      $at, $zero
.text:0000011C                 lui     $v0, (unk_230 >> 16)
.text:00000120                 addiu   $a0, $v0, (unk_230 & 0xFFFF)
.text:00000124                 lw      $v0, (puts & 0xFFFF)($gp)
.text:00000128                 or      $at, $zero
.text:0000012C                 move    $t9, $v0
.text:00000130                 jalr    $t9
.text:00000134                 or      $at, $zero
.text:00000138                 lw      $gp, 0x20+var_10($fp)
.text:0000013C
.text:0000013C loc_13C:                                 # CODE XREF: f_unsigned+34
.text:0000013C                 lw      $v1, 0x20+arg_0($fp)
.text:00000140                 lw      $v0, 0x20+arg_4($fp)
.text:00000144                 or      $at, $zero
.text:00000148                 bne     $v1, $v0, loc_170
.text:0000014C                 or      $at, $zero
.text:00000150                 lui     $v0, (aAB >> 16)  # "a==b"
.text:00000154                 addiu   $a0, $v0, (aAB & 0xFFFF)  # "a==b"
.text:00000158                 lw      $v0, (puts & 0xFFFF)($gp)
.text:0000015C                 or      $at, $zero
.text:00000160                 move    $t9, $v0
.text:00000164                 jalr    $t9
.text:00000168                 or      $at, $zero
.text:0000016C                 lw      $gp, 0x20+var_10($fp)
.text:00000170
.text:00000170 loc_170:                                 # CODE XREF: f_unsigned+68
.text:00000170                 lw      $v1, 0x20+arg_0($fp)
.text:00000174                 lw      $v0, 0x20+arg_4($fp)
```

```
.text:00000178                 or      $at, $zero
.text:0000017C                 sltu    $v0, $v1, $v0
.text:00000180                 beqz    $v0, loc_1A8
.text:00000184                 or      $at, $zero
.text:00000188                 lui     $v0, (aAB_0 >> 16)  # "a<b"
.text:0000018C                 addiu   $a0, $v0, (aAB_0 & 0xFFFF)  # "a<b"
.text:00000190                 lw      $v0, (puts & 0xFFFF)($gp)
.text:00000194                 or      $at, $zero
.text:00000198                 move    $t9, $v0
.text:0000019C                 jalr    $t9
.text:000001A0                 or      $at, $zero
.text:000001A4                 lw      $gp, 0x20+var_10($fp)
.text:000001A8
.text:000001A8 loc_1A8:                                 # CODE XREF: f_unsigned+A0
.text:000001A8                 move    $sp, $fp
.text:000001AC                 lw      $ra, 0x20+var_4($sp)
.text:000001B0                 lw      $fp, 0x20+var_8($sp)
.text:000001B4                 addiu   $sp, 0x20
.text:000001B8                 jr      $ra
.text:000001BC                 or      $at, $zero
.text:000001BC  # End of function f_unsigned
```

1.14.2 Calculating absolute value

A simple function:

```
int my_abs (int i)
{
        if (i<0)
                return -i;
        else
                return i;
};
```

Optimizing MSVC

This is how the code is usually generated:

Listing 1.118: Optimizing MSVC 2012 x64

```
i$ = 8
my_abs  PROC
; ECX = input
        test    ecx, ecx
; check for sign of input value
; skip NEG instruction if sign is positive
        jns     SHORT $LN2@my_abs
; negate value
        neg     ecx
$LN2@my_abs:
; prepare result in EAX:
        mov     eax, ecx
        ret     0
my_abs  ENDP
```

GCC 4.9 does mostly the same.

Optimizing Keil 6/2013: Thumb mode

Listing 1.119: Optimizing Keil 6/2013: Thumb mode

```
my_abs PROC
        CMP      r0,#0
; is input value equal to zero or greater than zero?
```

```
; skip RSBS instruction then
        BGE      |L0.6|
; subtract input value from 0:
        RSBS     r0,r0,#0
|L0.6|
        BX       lr
        ENDP
```

ARM lacks a negate instruction, so the Keil compiler uses the “Reverse Subtract” instruction, which just subtracts with reversed operands.

Optimizing Keil 6/2013: ARM mode

It is possible to add condition codes to some instructions in ARM mode, so that is what the Keil compiler does:

Listing 1.120: Optimizing Keil 6/2013: ARM mode

```
my_abs PROC
        CMP      r0,#0
; execute "Reverse Subtract" instruction only if input value is less than 0:
        RSBLT    r0,r0,#0
        BX       lr
        ENDP
```

Now there are no conditional jumps and this is good: 2.10.1 on page 466.

Non-optimizing GCC 4.9 (ARM64)

ARM64 has instruction NEG for negating:

Listing 1.121: Optimizing GCC 4.9 (ARM64)

```
my_abs:
        sub     sp, sp, #16
        str     w0, [sp,12]
        ldr     w0, [sp,12]
; compare input value with contents of WZR register
; (which always holds zero)
        cmp     w0, wzr
        bge     .L2
        ldr     w0, [sp,12]
        neg     w0, w0
        b       .L3
.L2:
        ldr     w0, [sp,12]
.L3:
        add     sp, sp, 16
        ret
```

MIPS

Listing 1.122: Optimizing GCC 4.4.5 (IDA)

```
my_abs:
; jump if $a0<0:
                bltz    $a0, locret_10
; just return input value ($a0) in $v0:
                move    $v0, $a0
                jr      $ra
                or      $at, $zero ; branch delay slot, NOP
locret_10:
; negate input value and store it in $v0:
                jr      $ra
; this is pseudoinstruction. in fact, this is "subu $v0,$zero,$a0" ($v0=0-$a0)
                negu    $v0, $a0
```

Here we see a new instruction: BLTZ ("Branch if Less Than Zero").

There is also the NEGU pseudo instruction, which just does subtraction from zero. The "U" suffix in both SUBU and NEGU implies that no exception to be raised in case of integer overflow.

Branchless version?

You could have also a branchless version of this code. This we will review later: 3.13 on page 518.

1.14.3 Ternary conditional operator

The ternary conditional operator in C/C++ has the following syntax:

```
expression ? expression : expression
```

Here is an example:

```
const char* f (int a)
{
        return a==10 ? "it is ten" : "it is not ten";
};
```

x86

Old and non-optimizing compilers generate assembly code just as if an if/else statement was used:

Listing 1.123: Non-optimizing MSVC 2008

```
$SG746  DB      'it is ten', 00H
$SG747  DB      'it is not ten', 00H

tv65 = -4 ; this will be used as a temporary variable
_a$ = 8
_f      PROC
        push    ebp
        mov     ebp, esp
        push    ecx
; compare input value with 10
        cmp     DWORD PTR _a$[ebp], 10
; jump to $LN3@f if not equal
        jne     SHORT $LN3@f
; store pointer to the string into temporary variable:
        mov     DWORD PTR tv65[ebp], OFFSET $SG746 ; 'it is ten'
; jump to exit
        jmp     SHORT $LN4@f
$LN3@f:
; store pointer to the string into temporary variable:
        mov     DWORD PTR tv65[ebp], OFFSET $SG747 ; 'it is not ten'
$LN4@f:
; this is exit. copy pointer to the string from temporary variable to EAX.
        mov     eax, DWORD PTR tv65[ebp]
        mov     esp, ebp
        pop     ebp
        ret     0
_f      ENDP
```

Listing 1.124: Optimizing MSVC 2008

```
$SG792  DB      'it is ten', 00H
$SG793  DB      'it is not ten', 00H

_a$ = 8 ; size = 4
_f      PROC
; compare input value with 10
        cmp     DWORD PTR _a$[esp-4], 10
```

```
        mov     eax, OFFSET $SG792 ; 'it is ten'
; jump to $LN4@f if equal
        je      SHORT $LN4@f
        mov     eax, OFFSET $SG793 ; 'it is not ten'
$LN4@f:
        ret     0
_f      ENDP
```

Newer compilers are more concise:

Listing 1.125: Optimizing MSVC 2012 x64

```
$SG1355 DB      'it is ten', 00H
$SG1356 DB      'it is not ten', 00H

a$ = 8
f       PROC
; load pointers to the both strings
        lea     rdx, OFFSET FLAT:$SG1355 ; 'it is ten'
        lea     rax, OFFSET FLAT:$SG1356 ; 'it is not ten'
; compare input value with 10
        cmp     ecx, 10
; if equal, copy value from RDX ("it is ten")
; if not, do nothing. pointer to the string "it is not ten" is still in RAX as for now.
        cmove   rax, rdx
        ret     0
f       ENDP
```

Optimizing GCC 4.8 for x86 also uses the CMOVcc instruction, while the non-optimizing GCC 4.8 uses conditional jumps.

ARM

Optimizing Keil for ARM mode also uses the conditional instructions ADRcc:

Listing 1.126: Optimizing Keil 6/2013 (ARM mode)

```
f PROC
; compare input value with 10
        CMP      r0,#0xa
; if comparison result is EQual, copy pointer to the "it is ten" string into R0
        ADREQ    r0,|L0.16| ; "it is ten"
; if comparison result is Not Equal, copy pointer to the "it is not ten" string into R0
        ADRNE    r0,|L0.28| ; "it is not ten"
        BX       lr
        ENDP

|L0.16|
        DCB      "it is ten",0
|L0.28|
        DCB      "it is not ten",0
```

Without manual intervention, the two instructions ADREQ and ADRNE cannot be executed in the same run.

Optimizing Keil for Thumb mode needs to use conditional jump instructions, since there are no load instructions that support conditional flags:

Listing 1.127: Optimizing Keil 6/2013 (Thumb mode)

```
f PROC
; compare input value with 10
        CMP      r0,#0xa
; jump to |L0.8| if EQual
        BEQ      |L0.8|
        ADR      r0,|L0.12| ; "it is not ten"
        BX       lr
|L0.8|
        ADR      r0,|L0.28| ; "it is ten"
        BX       lr
        ENDP
```

```
|L0.12|
        DCB      "it is not ten",0
|L0.28|
        DCB      "it is ten",0
```

ARM64

Optimizing GCC (Linaro) 4.9 for ARM64 also uses conditional jumps:

Listing 1.128: Optimizing GCC (Linaro) 4.9

```
f:
        cmp     x0, 10
        beq     .L3             ; branch if equal
        adrp    x0, .LC1        ; "it is ten"
        add     x0, x0, :lo12:.LC1
        ret
.L3:
        adrp    x0, .LC0        ; "it is not ten"
        add     x0, x0, :lo12:.LC0
        ret
.LC0:
        .string "it is ten"
.LC1:
        .string "it is not ten"
```

That is because ARM64 does not have a simple load instruction with conditional flags, like `ADRcc` in 32-bit ARM mode or `CMOVcc` in x86.

It has, however, "Conditional SELect" instruction (`CSEL`)[*ARM Architecture Reference Manual, ARMv8, for ARMv8-A architecture profile*, (2013)p390, C5.5], but GCC 4.9 does not seem to be smart enough to use it in such piece of code.

MIPS

Unfortunately, GCC 4.4.5 for MIPS is not very smart, either:

Listing 1.129: Optimizing GCC 4.4.5 (assembly output)

```
$LC0:
        .ascii  "it is not ten\000"
$LC1:
        .ascii  "it is ten\000"
f:
        li      $2,10                   # 0xa
; compare $a0 and 10, jump if equal:
        beq     $4,$2,$L2
        nop ; branch delay slot

; leave address of "it is not ten" string in $v0 and return:
        lui     $2,%hi($LC0)
        j       $31
        addiu   $2,$2,%lo($LC0)

$L2:
; leave address of "it is ten" string in $v0 and return:
        lui     $2,%hi($LC1)
        j       $31
        addiu   $2,$2,%lo($LC1)
```

Let's rewrite it in an `if/else` way

```
const char* f (int a)
{
        if (a==10)
                return "it is ten";
        else
                return "it is not ten";
};
```

Interestingly, optimizing GCC 4.8 for x86 was also able to use CMOVcc in this case:

Listing 1.130: Optimizing GCC 4.8

```
.LC0:
        .string "it is ten"
.LC1:
        .string "it is not ten"
f:
.LFB0:
; compare input value with 10
        cmp     DWORD PTR [esp+4], 10
        mov     edx, OFFSET FLAT:.LC1 ; "it is not ten"
        mov     eax, OFFSET FLAT:.LC0 ; "it is ten"
; if comparison result is Not Equal, copy EDX value to EAX
; if not, do nothing
        cmovne  eax, edx
        ret
```

Optimizing Keil in ARM mode generates code identical to listing.1.126.

But the optimizing MSVC 2012 is not that good (yet).

Conclusion

Why optimizing compilers try to get rid of conditional jumps? Read here about it: 2.10.1 on page 466.

1.14.4 Getting minimal and maximal values

32-bit

```
int my_max(int a, int b)
{
        if (a>b)
                return a;
        else
                return b;
};

int my_min(int a, int b)
{
        if (a<b)
                return a;
        else
                return b;
};
```

Listing 1.131: Non-optimizing MSVC 2013

```
_a$ = 8
_b$ = 12
_my_min PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _a$[ebp]
; compare A and B:
        cmp     eax, DWORD PTR _b$[ebp]
; jump, if A is greater or equal to B:
```

```
        jge     SHORT $LN2@my_min
; reload A to EAX if otherwise and jump to exit
        mov     eax, DWORD PTR _a$[ebp]
        jmp     SHORT $LN3@my_min
        jmp     SHORT $LN3@my_min ; this is redundant JMP
$LN2@my_min:
; return B
        mov     eax, DWORD PTR _b$[ebp]
$LN3@my_min:
        pop     ebp
        ret     0
_my_min ENDP

_a$ = 8
_b$ = 12
_my_max PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _a$[ebp]
; compare A and B:
        cmp     eax, DWORD PTR _b$[ebp]
; jump if A is less or equal to B:
        jle     SHORT $LN2@my_max
; reload A to EAX if otherwise and jump to exit
        mov     eax, DWORD PTR _a$[ebp]
        jmp     SHORT $LN3@my_max
        jmp     SHORT $LN3@my_max ; this is redundant JMP
$LN2@my_max:
; return B
        mov     eax, DWORD PTR _b$[ebp]
$LN3@my_max:
        pop     ebp
        ret     0
_my_max ENDP
```

These two functions differ only in the conditional jump instruction: JGE ("Jump if Greater or Equal") is used in the first one and JLE ("Jump if Less or Equal") in the second.

There is one unneeded JMP instruction in each function, which MSVC presumably left by mistake.

Branchless

ARM for Thumb mode reminds us of x86 code:

Listing 1.132: Optimizing Keil 6/2013 (Thumb mode)

```
my_max PROC
; R0=A
; R1=B
; compare A and B:
        CMP      r0,r1
; branch if A is greater then B:
        BGT      |L0.6|
; otherwise (A<=B) return R1 (B):
        MOVS     r0,r1
|L0.6|
; return
        BX       lr
        ENDP

my_min PROC
; R0=A
; R1=B
; compare A and B:
        CMP      r0,r1
; branch if A is less then B:
        BLT      |L0.14|
; otherwise (A>=B) return R1 (B):
        MOVS     r0,r1
```

```
|L0.14|
; return
        BX       lr
        ENDP
```

The functions differ in the branching instruction: BGT and BLT. It's possible to use conditional suffixes in ARM mode, so the code is shorter.

MOVcc is to be executed only if the condition is met:

Listing 1.133: Optimizing Keil 6/2013 (ARM mode)

```
my_max PROC
; R0=A
; R1=B
; compare A and B:
        CMP      r0,r1
; return B instead of A by placing B in R0
; this instruction will trigger only if A<=B (hence, LE - Less or Equal)
; if instruction is not triggered (in case of A>B), A is still in R0 register
        MOVLE    r0,r1
        BX       lr
        ENDP

my_min PROC
; R0=A
; R1=B
; compare A and B:
        CMP      r0,r1
; return B instead of A by placing B in R0
; this instruction will trigger only if A>=B (hence, GE - Greater or Equal)
; if instruction is not triggered (in case of A<B), A value is still in R0 register
        MOVGE    r0,r1
        BX       lr
        ENDP
```

Optimizing GCC 4.8.1 and optimizing MSVC 2013 can use CMOVcc instruction, which is analogous to MOVcc in ARM:

Listing 1.134: Optimizing MSVC 2013

```
my_max:
        mov     edx, DWORD PTR [esp+4]
        mov     eax, DWORD PTR [esp+8]
; EDX=A
; EAX=B
; compare A and B:
        cmp     edx, eax
; if A>=B, load A value into EAX
; the instruction idle if otherwise (if A<B)
        cmovge  eax, edx
        ret

my_min:
        mov     edx, DWORD PTR [esp+4]
        mov     eax, DWORD PTR [esp+8]
; EDX=A
; EAX=B
; compare A and B:
        cmp     edx, eax
; if A<=B, load A value into EAX
; the instruction idle if otherwise (if A>B)
        cmovle  eax, edx
        ret
```

64-bit

```
#include <stdint.h>
```

```
int64_t my_max(int64_t a, int64_t b)
{
        if (a>b)
                return a;
        else
                return b;
};

int64_t my_min(int64_t a, int64_t b)
{
        if (a<b)
                return a;
        else
                return b;
};
```

There is some unneeded value shuffling, but the code is comprehensible:

Listing 1.135: Non-optimizing GCC 4.9.1 ARM64

```
my_max:
        sub     sp, sp, #16
        str     x0, [sp,8]
        str     x1, [sp]
        ldr     x1, [sp,8]
        ldr     x0, [sp]
        cmp     x1, x0
        ble     .L2
        ldr     x0, [sp,8]
        b       .L3
.L2:
        ldr     x0, [sp]
.L3:
        add     sp, sp, 16
        ret

my_min:
        sub     sp, sp, #16
        str     x0, [sp,8]
        str     x1, [sp]
        ldr     x1, [sp,8]
        ldr     x0, [sp]
        cmp     x1, x0
        bge     .L5
        ldr     x0, [sp,8]
        b       .L6
.L5:
        ldr     x0, [sp]
.L6:
        add     sp, sp, 16
        ret
```

Branchless

No need to load function arguments from the stack, as they are already in the registers:

Listing 1.136: Optimizing GCC 4.9.1 x64

```
my_max:
; RDI=A
; RSI=B
; compare A and B:
        cmp     rdi, rsi
; prepare B in RAX for return:
        mov     rax, rsi
; if A>=B, put A (RDI) in RAX for return.
; this instruction is idle if otherwise (if A<B)
```

```
        cmovge  rax, rdi
        ret

my_min:
; RDI=A
; RSI=B
; compare A and B:
        cmp     rdi, rsi
; prepare B in RAX for return:
        mov     rax, rsi
; if A<=B, put A (RDI) in RAX for return.
; this instruction is idle if otherwise (if A>B)
        cmovle  rax, rdi
        ret
```

MSVC 2013 does almost the same.

ARM64 has the CSEL instruction, which works just as MOVcc in ARM or CMOVcc in x86, just the name is different: "Conditional SELect".

Listing 1.137: Optimizing GCC 4.9.1 ARM64

```
my_max:
; X0=A
; X1=B
; compare A and B:
        cmp     x0, x1
; select X0 (A) to X0 if X0>=X1 or A>=B (Greater or Equal)
; select X1 (B) to X0 if A<B
        csel    x0, x0, x1, ge
        ret

my_min:
; X0=A
; X1=B
; compare A and B:
        cmp     x0, x1
; select X0 (A) to X0 if X0<=X1 or A<=B (Less or Equal)
; select X1 (B) to X0 if A>B
        csel    x0, x0, x1, le
        ret
```

MIPS

Unfortunately, GCC 4.4.5 for MIPS is not that good:

Listing 1.138: Optimizing GCC 4.4.5 (IDA)

```
my_max:
; set $v1 to 1 if $a1<$a0, or clear otherwise (if $a1>$a0):
                slt     $v1, $a1, $a0
; jump, if $v1 is 0 (or $a1>$a0):
                beqz    $v1, locret_10
; this is branch delay slot
; prepare $a1 in $v0 in case of branch triggered:
                move    $v0, $a1
; no branch triggered, prepare $a0 in $v0:
                move    $v0, $a0

locret_10:
                jr      $ra
                or      $at, $zero ; branch delay slot, NOP

; the min() function is same, but input operands in SLT instruction are swapped:
my_min:
                slt     $v1, $a0, $a1
                beqz    $v1, locret_28
                move    $v0, $a1
                move    $v0, $a0
```

```
locret_28:
                jr      $ra
                or      $at, $zero ; branch delay slot, NOP
```

Do not forget about the *branch delay slots*: the first MOVE is executed *before* BEQZ, the second MOVE is executed only if the branch hasn't been taken.

1.14.5 Conclusion

x86

Here's the rough skeleton of a conditional jump:

Listing 1.139: x86

```
CMP register, register/value
Jcc true ; cc=condition code
false:
... some code to be executed if comparison result is false ...
JMP exit
true:
... some code to be executed if comparison result is true ...
exit:
```

ARM

Listing 1.140: ARM

```
CMP register, register/value
Bcc true ; cc=condition code
false:
... some code to be executed if comparison result is false ...
JMP exit
true:
... some code to be executed if comparison result is true ...
exit:
```

MIPS

Listing 1.141: Check for zero

```
BEQZ REG, label
...
```

Listing 1.142: Check for less than zero using pseudoinstruction

```
BLTZ REG, label
...
```

Listing 1.143: Check for equal values

```
BEQ REG1, REG2, label
...
```

Listing 1.144: Check for non-equal values

```
BNE REG1, REG2, label
...
```

Listing 1.145: Check for less than (signed)

```
SLT REG1, REG2, REG3
BEQ REG1, label
...
```

Listing 1.146: Check for less than (unsigned)

```
SLTU REG1, REG2, REG3
BEQ REG1, label
...
```

Branchless

If the body of a condition statement is very short, the conditional move instruction can be used: MOVcc in ARM (in ARM mode), CSEL in ARM64, CMOVcc in x86.

ARM

It's possible to use conditional suffixes in ARM mode for some instructions:

Listing 1.147: ARM (ARM mode)

```
CMP register, register/value
instr1_cc ; some instruction will be executed if condition code is true
instr2_cc ; some other instruction will be executed if other condition code is true
... etc...
```

Of course, there is no limit for the number of instructions with conditional code suffixes, as long as the CPU flags are not modified by any of them.

Thumb mode has the IT instruction, allowing to add conditional suffixes to the next four instructions. Read more about it: 1.19.7 on page 263.

Listing 1.148: ARM (Thumb mode)

```
CMP register, register/value
ITEEE EQ ; set these suffixes: if-then-else-else-else
instr1   ; instruction will be executed if condition is true
instr2   ; instruction will be executed if condition is false
instr3   ; instruction will be executed if condition is false
instr4   ; instruction will be executed if condition is false
```

1.14.6 Exercise

(ARM64) Try rewriting the code in listing.1.128 by removing all conditional jump instructions and using the CSEL instruction.

1.15 switch()/case/default

1.15.1 Small number of cases

```
#include <stdio.h>

void f (int a)
{
    switch (a)
    {
    case 0: printf ("zero\n"); break;
    case 1: printf ("one\n"); break;
    case 2: printf ("two\n"); break;
    default: printf ("something unknown\n"); break;
    };
};

int main()
{
```

```
    f (2); // test
};
```

x86

Non-optimizing MSVC

Result (MSVC 2010):

Listing 1.149: MSVC 2010

```
tv64 = -4 ; size = 4
_a$ = 8   ; size = 4
_f    PROC
    push   ebp
    mov    ebp, esp
    push   ecx
    mov    eax, DWORD PTR _a$[ebp]
    mov    DWORD PTR tv64[ebp], eax
    cmp    DWORD PTR tv64[ebp], 0
    je     SHORT $LN4@f
    cmp    DWORD PTR tv64[ebp], 1
    je     SHORT $LN3@f
    cmp    DWORD PTR tv64[ebp], 2
    je     SHORT $LN2@f
    jmp    SHORT $LN1@f
$LN4@f:
    push   OFFSET $SG739 ; 'zero', 0aH, 00H
    call   _printf
    add    esp, 4
    jmp    SHORT $LN7@f
$LN3@f:
    push   OFFSET $SG741 ; 'one', 0aH, 00H
    call   _printf
    add    esp, 4
    jmp    SHORT $LN7@f
$LN2@f:
    push   OFFSET $SG743 ; 'two', 0aH, 00H
    call   _printf
    add    esp, 4
    jmp    SHORT $LN7@f
$LN1@f:
    push   OFFSET $SG745 ; 'something unknown', 0aH, 00H
    call   _printf
    add    esp, 4
$LN7@f:
    mov    esp, ebp
    pop    ebp
    ret    0
_f    ENDP
```

Our function with a few cases in switch() is in fact analogous to this construction:

```
void f (int a)
{
    if (a==0)
        printf ("zero\n");
    else if (a==1)
        printf ("one\n");
    else if (a==2)
        printf ("two\n");
    else
        printf ("something unknown\n");
};
```

If we work with switch() with a few cases it is impossible to be sure if it was a real switch() in the source code, or just a pack of if() statements.

This implies that switch() is like syntactic sugar for a large number of nested if()s.

There is nothing especially new to us in the generated code, with the exception of the compiler moving input variable a to a temporary local variable `tv64` [92].

If we compile this in GCC 4.4.1, we'll get almost the same result, even with maximal optimization turned on (`-O3` option).

Optimizing MSVC

Now let's turn on optimization in MSVC (`/Ox`): `cl 1.c /Fa1.asm /Ox`

Listing 1.150: MSVC

```
_a$ = 8 ; size = 4
_f    PROC
    mov    eax, DWORD PTR _a$[esp-4]
    sub    eax, 0
    je     SHORT $LN4@f
    sub    eax, 1
    je     SHORT $LN3@f
    sub    eax, 1
    je     SHORT $LN2@f
    mov    DWORD PTR _a$[esp-4], OFFSET $SG791 ; 'something unknown', 0aH, 00H
    jmp    _printf
$LN2@f:
    mov    DWORD PTR _a$[esp-4], OFFSET $SG789 ; 'two', 0aH, 00H
    jmp    _printf
$LN3@f:
    mov    DWORD PTR _a$[esp-4], OFFSET $SG787 ; 'one', 0aH, 00H
    jmp    _printf
$LN4@f:
    mov    DWORD PTR _a$[esp-4], OFFSET $SG785 ; 'zero', 0aH, 00H
    jmp    _printf
_f    ENDP
```

Here we can see some dirty hacks.

First: the value of a is placed in EAX and 0 is subtracted from it. Sounds absurd, but it is done to check if the value in EAX is 0. If yes, the ZF flag is to be set (e.g. subtracting from 0 is 0) and the first conditional jump JE (*Jump if Equal* or synonym JZ —*Jump if Zero*) is to be triggered and control flow is to be passed to the `$LN4@f` label, where the `'zero'` message is being printed. If the first jump doesn't get triggered, 1 is subtracted from the input value and if at some stage the result is 0, the corresponding jump is to be triggered.

And if no jump gets triggered at all, the control flow passes to `printf()` with string argument `'something unknown'`.

Second: we see something unusual for us: a string pointer is placed into the a variable, and then `printf()` is called not via CALL, but via JMP. There is a simple explanation for that: the caller pushes a value to the stack and calls our function via CALL. CALL itself pushes the return address (RA) to the stack and does an unconditional jump to our function address. Our function at any point of execution (since it do not contain any instruction that moves the stack pointer) has the following stack layout:

- ESP—points to RA
- ESP+4—points to the a variable

On the other side, when we have to call `printf()` here we need exactly the same stack layout, except for the first `printf()` argument, which needs to point to the string. And that is what our code does.

It replaces the function's first argument with the address of the string and jumps to `printf()`, as if we didn't call our function `f()`, but directly `printf()`. `printf()` prints a string to stdout and then executes the RET instruction, which POPs RA from the stack and control flow is returned not to `f()` but rather to `f()`'s caller, bypassing the end of the `f()` function.

All this is possible because `printf()` is called right at the end of the `f()` function in all cases. In some way, it is similar to the `longjmp()`[93] function. And of course, it is all done for the sake of speed.

[92] Local variables in stack are prefixed with `tv`—that's how MSVC names internal variables for its needs
[93] wikipedia

A similar case with the ARM compiler is described in “printf() with several arguments” section, here (1.8.2 on page 54).

OllyDbg

Since this example is tricky, let's trace it in OllyDbg.

OllyDbg can detect such switch() constructs, and it can add some useful comments. EAX is 2 at the beginning, that's the function's input value:

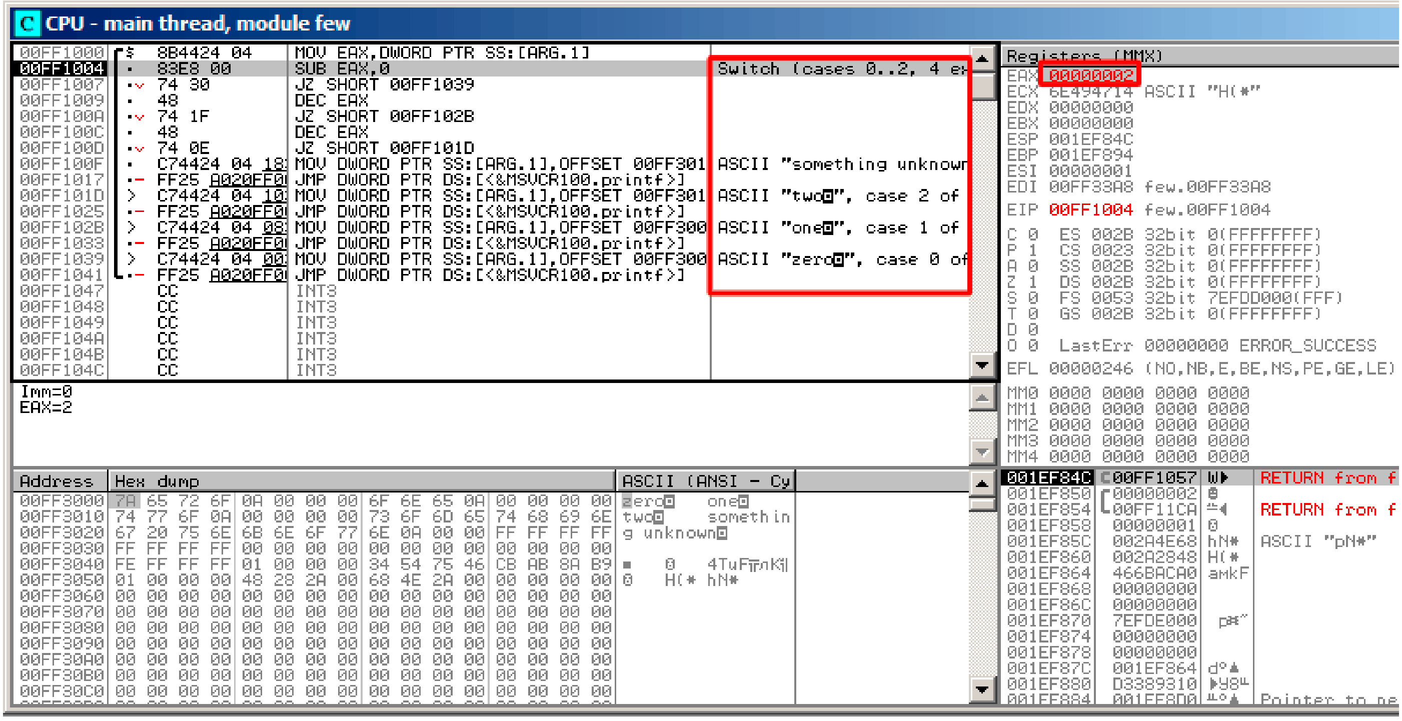


Figure 1.42: OllyDbg: EAX now contain the first (and only) function argument

0 is subtracted from 2 in EAX. Of course, EAX still contains 2. But the ZF flag is now 0, indicating that the resulting value is non-zero:

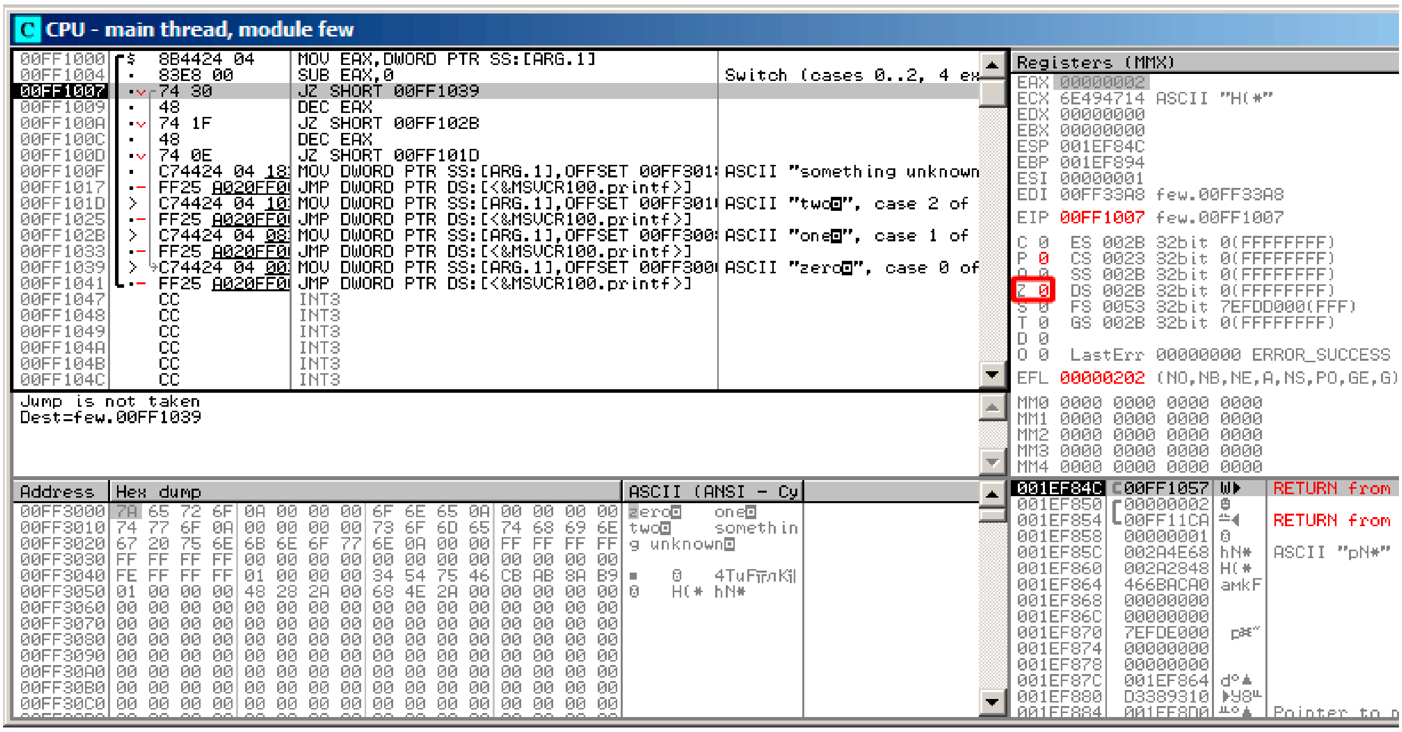


Figure 1.43: OllyDbg: SUB executed

DEC is executed and EAX now contains 1. But 1 is non-zero, so the ZF flag is still 0:

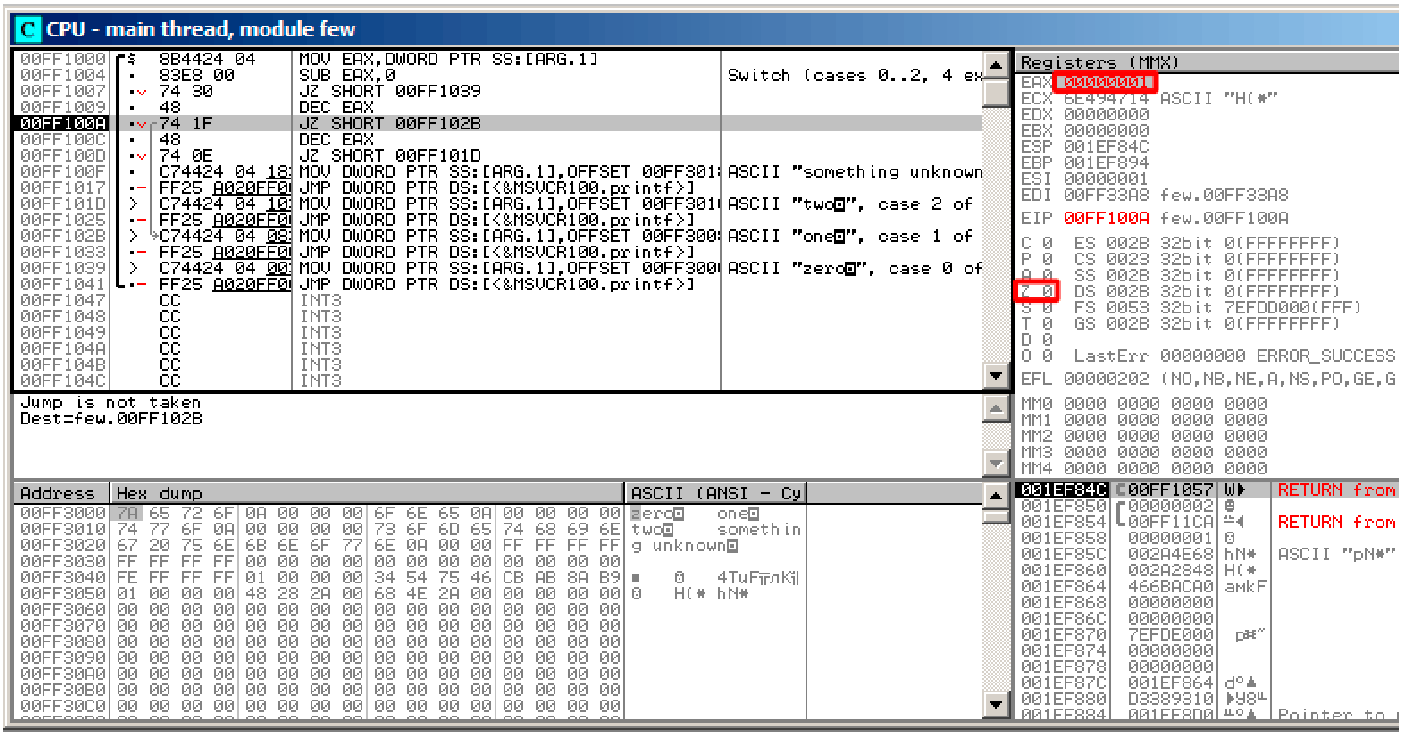


Figure 1.44: OllyDbg: first DEC executed

Next DEC is executed. EAX is finally 0 and the ZF flag gets set, because the result is zero:

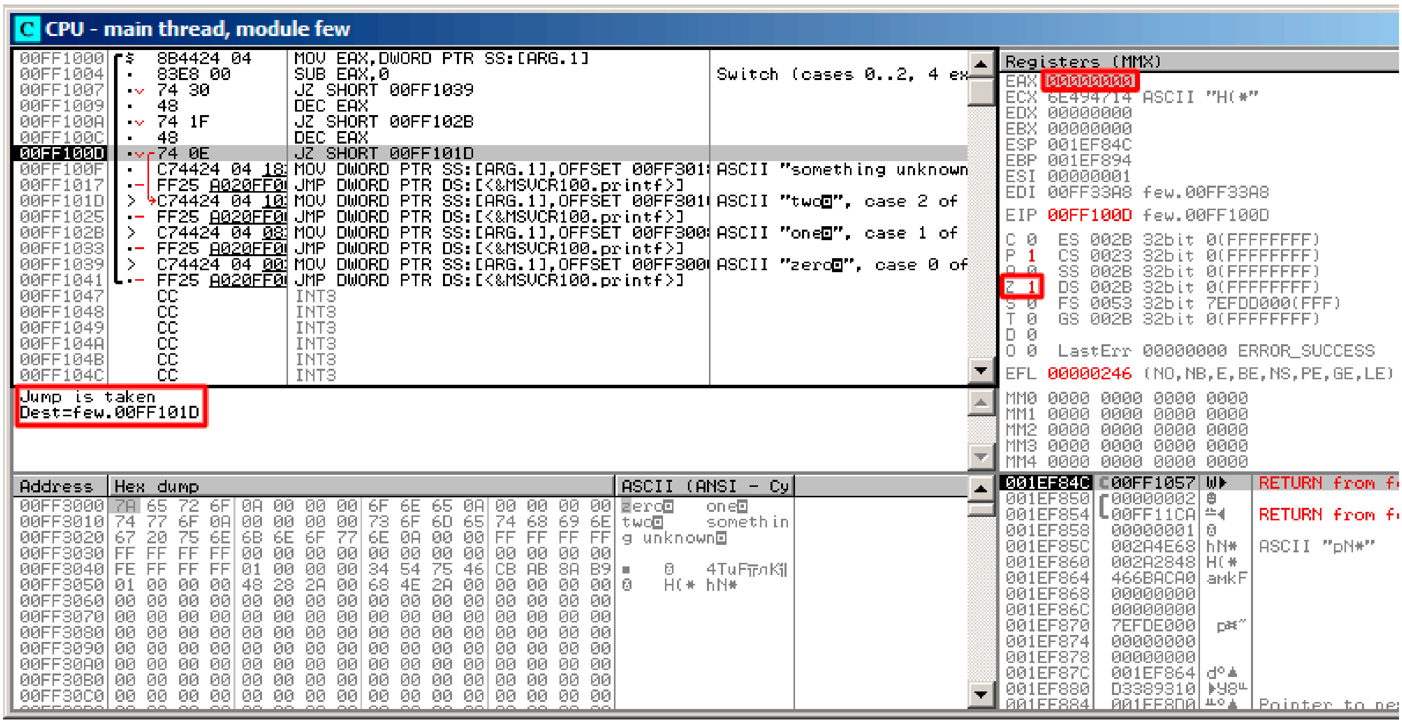


Figure 1.45: OllyDbg: second DEC executed

OllyDbg shows that this jump is to be taken now.

A pointer to the string "two" is to be written into the stack now:

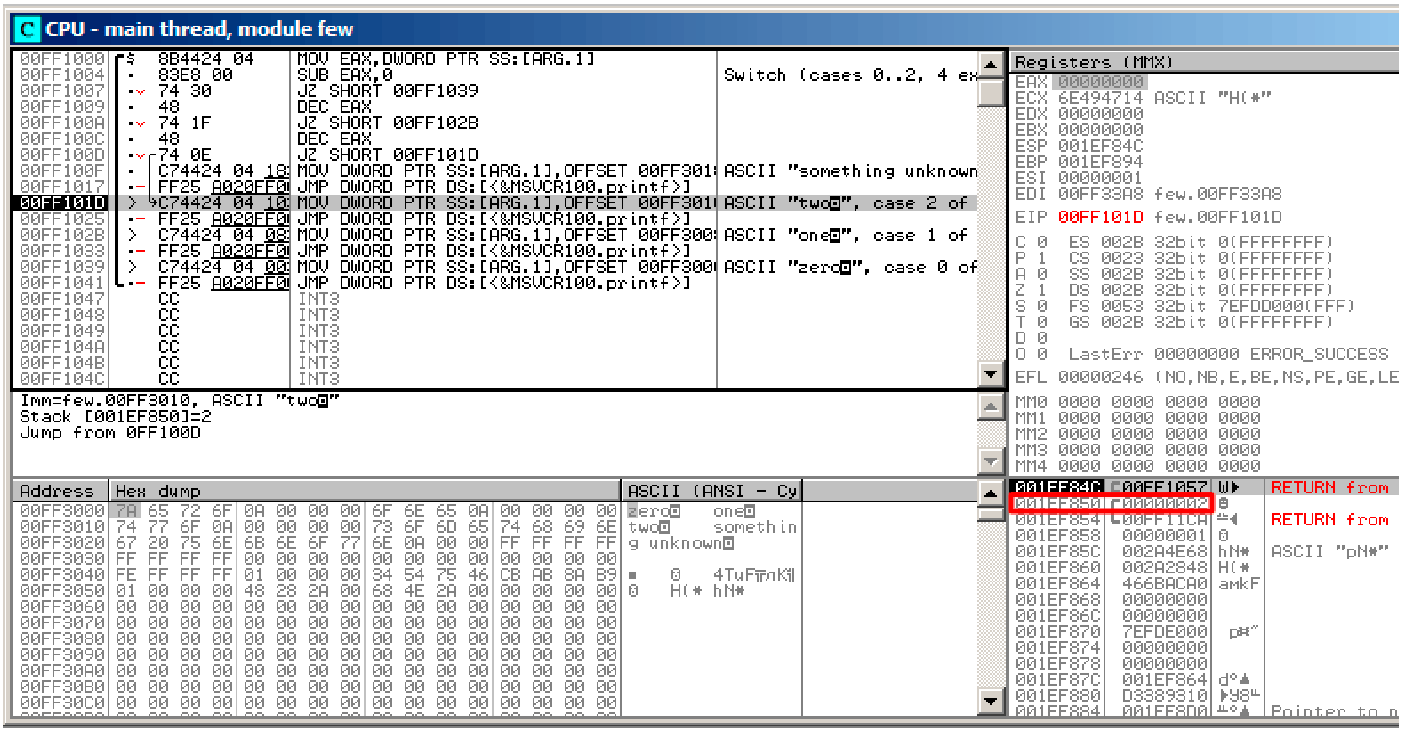


Figure 1.46: OllyDbg: pointer to the string is to be written at the place of the first argument

Please note: the current argument of the function is 2 and 2 is now in the stack at the address `0x001EF850`.

MOV writes the pointer to the string at address 0x001EF850 (see the stack window). Then, jump happens. This is the first instruction of the printf() function in MSVCR100.DLL (This example was compiled with /MD switch):

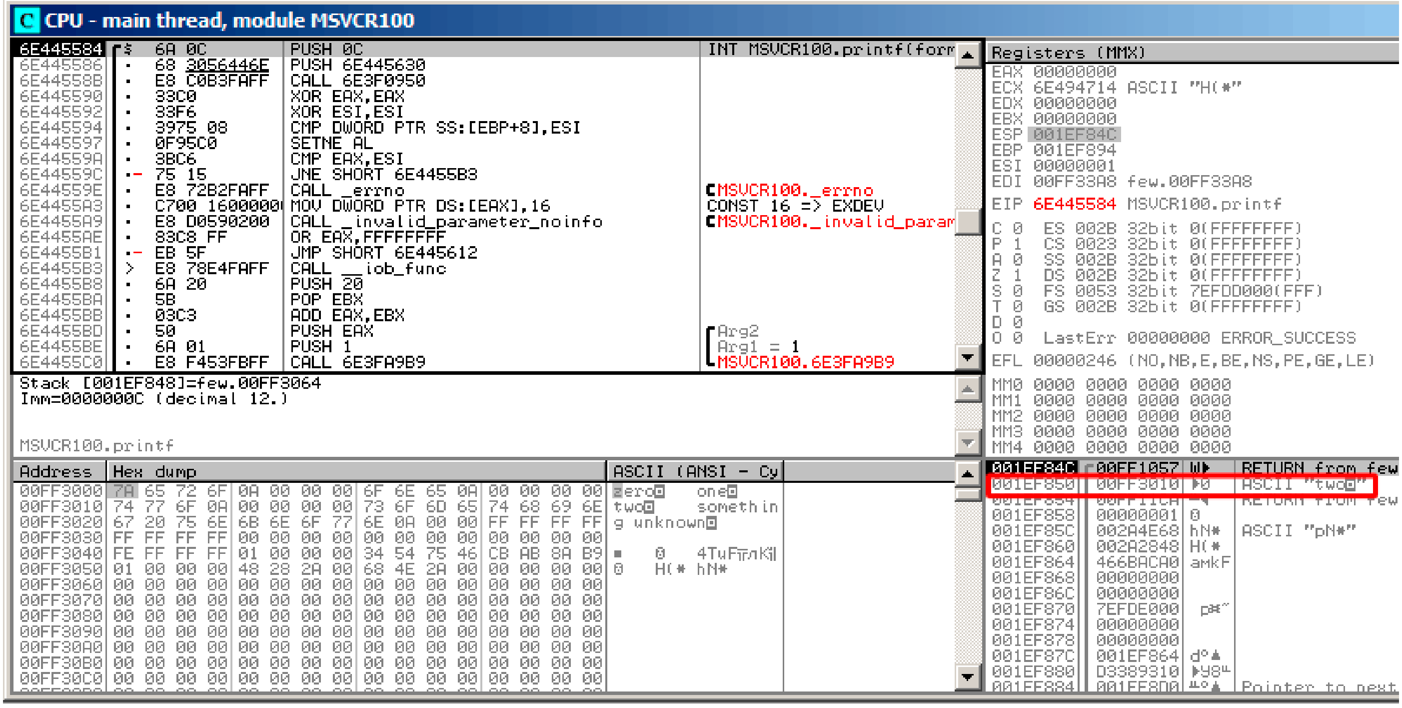


Figure 1.47: OllyDbg: first instruction of printf() in MSVCR100.DLL

Now printf() treats the string at 0x00FF3010 as its only argument and prints the string.

This is the last instruction of `printf()`:

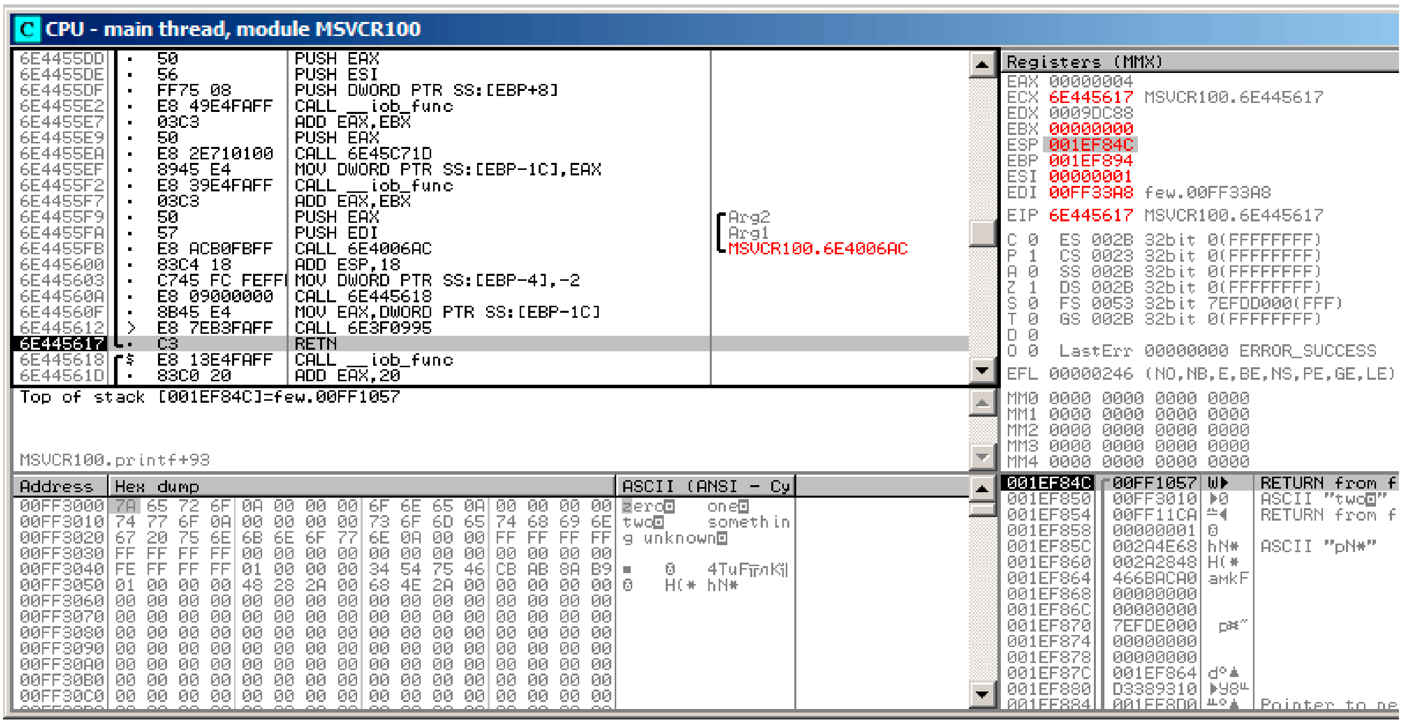


Figure 1.48: OllyDbg: last instruction of `printf()` in MSVCR100.DLL

The string "two" has just been printed to the console window.

Now let's press F7 or F8 (step over) and return…not to `f()`, but rather to `main()`:

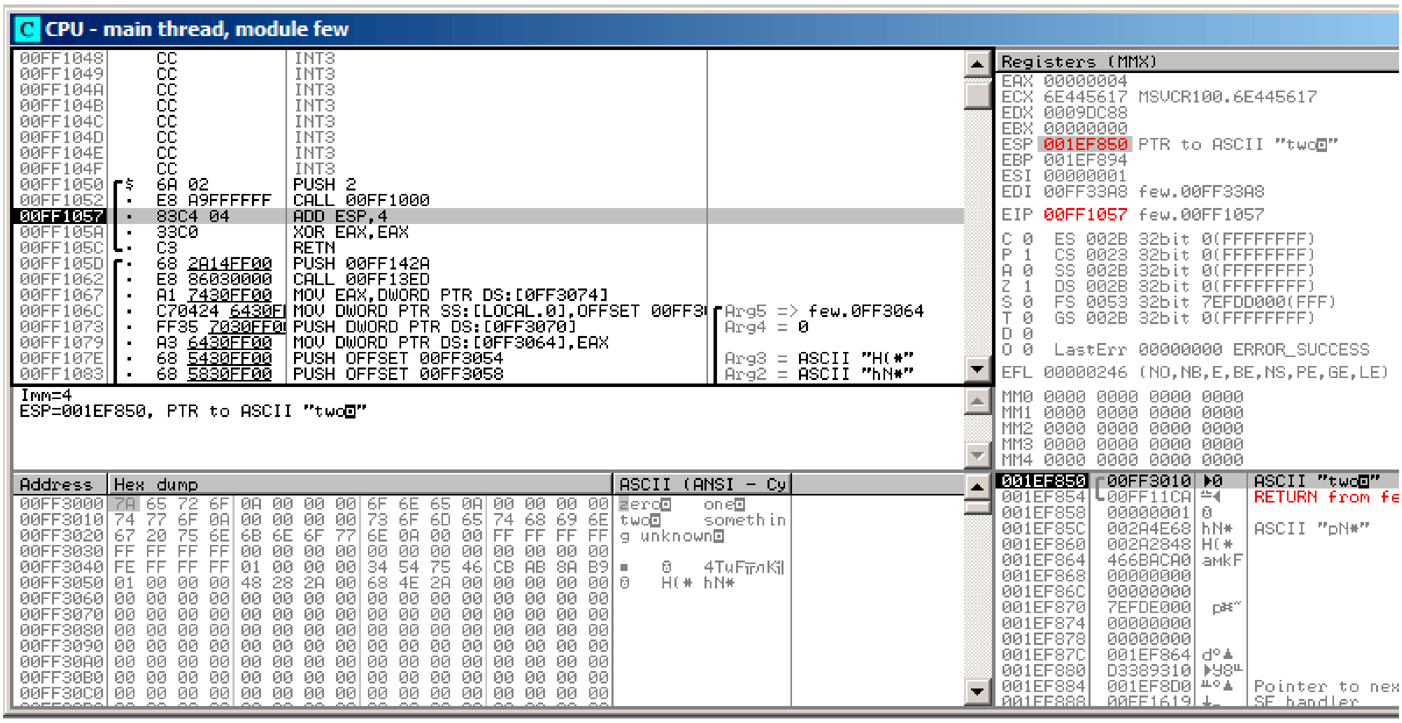


Figure 1.49: OllyDbg: return to `main()`

Yes, the jump has been direct, from the guts of `printf()` to `main()`. Because RA in the stack points not to some place in `f()`, but rather to `main()`. And `CALL 0x00FF1000` has been the actual instruction which called `f()`.

ARM: Optimizing Keil 6/2013 (ARM mode)

```
.text:0000014C                 f1:
.text:0000014C 00 00 50 E3     CMP     R0, #0
.text:00000150 13 0E 8F 02     ADREQ   R0, aZero ; "zero\n"
.text:00000154 05 00 00 0A     BEQ     loc_170
.text:00000158 01 00 50 E3     CMP     R0, #1
.text:0000015C 4B 0F 8F 02     ADREQ   R0, aOne  ; "one\n"
.text:00000160 02 00 00 0A     BEQ     loc_170
.text:00000164 02 00 50 E3     CMP     R0, #2
.text:00000168 4A 0F 8F 12     ADRNE   R0, aSomethingUnkno ; "something unknown\n"
.text:0000016C 4E 0F 8F 02     ADREQ   R0, aTwo  ; "two\n"
.text:00000170
.text:00000170                 loc_170: ; CODE XREF: f1+8
.text:00000170                          ; f1+14
.text:00000170 78 18 00 EA     B       __2printf
```

Again, by investigating this code we cannot say if it was a switch() in the original source code, or just a pack of if() statements.

Anyway, we see here predicated instructions again (like `ADREQ` (*Equal*)) which is triggered only in case $R0 = 0$, and then loads the address of the string *«zero\n»* into `R0`. The next instruction BEQ redirects control flow to `loc_170`, if $R0 = 0$.

An astute reader may ask, will BEQ trigger correctly since `ADREQ` it has already filled the `R0` register before with another value?

Yes, it will since BEQ checks the flags set by the `CMP` instruction, and `ADREQ` does not modify any flags at all.

The rest of the instructions are already familiar to us. There is only one call to `printf()`, at the end, and we have already examined this trick here (1.8.2 on page 54). At the end, there are three paths to `printf()`.

The last instruction, CMP R0, #2, is needed to check if $a = 2$.

If it is not true, then ADRNE loads a pointer to the string *«something unknown \n»* into R0, since a has already been checked to be equal to 0 or 1, and we can sure that the a variable is not equal to these numbers at this point. And if $R0 = 2$, a pointer to the string *«two\n»* will be loaded by ADREQ into R0.

ARM: Optimizing Keil 6/2013 (Thumb mode)

```
.text:000000D4             f1:
.text:000000D4 10 B5       PUSH    {R4,LR}
.text:000000D6 00 28       CMP     R0, #0
.text:000000D8 05 D0       BEQ     zero_case
.text:000000DA 01 28       CMP     R0, #1
.text:000000DC 05 D0       BEQ     one_case
.text:000000DE 02 28       CMP     R0, #2
.text:000000E0 05 D0       BEQ     two_case
.text:000000E2 91 A0       ADR     R0, aSomethingUnkno ; "something unknown\n"
.text:000000E4 04 E0       B       default_case

.text:000000E6             zero_case: ; CODE XREF: f1+4
.text:000000E6 95 A0       ADR     R0, aZero ; "zero\n"
.text:000000E8 02 E0       B       default_case

.text:000000EA             one_case: ; CODE XREF: f1+8
.text:000000EA 96 A0       ADR     R0, aOne ; "one\n"
.text:000000EC 00 E0       B       default_case

.text:000000EE             two_case: ; CODE XREF: f1+C
.text:000000EE 97 A0       ADR     R0, aTwo ; "two\n"
.text:000000F0             default_case ; CODE XREF: f1+10
.text:000000F0                                  ; f1+14
.text:000000F0 06 F0 7E F8 BL      __2printf
.text:000000F4 10 BD       POP     {R4,PC}
```

As was already mentioned, it is not possible to add conditional predicates to most instructions in Thumb mode, so the Thumb-code here is somewhat similar to the easily understandable x86 CISC-style code.

ARM64: Non-optimizing GCC (Linaro) 4.9

```
.LC12:
        .string "zero"
.LC13:
        .string "one"
.LC14:
        .string "two"
.LC15:
        .string "something unknown"
f12:
        stp     x29, x30, [sp, -32]!
        add     x29, sp, 0
        str     w0, [x29,28]
        ldr     w0, [x29,28]
        cmp     w0, 1
        beq     .L34
        cmp     w0, 2
        beq     .L35
        cmp     w0, wzr
        bne     .L38            ; jump to default label
        adrp    x0, .LC12       ; "zero"
        add     x0, x0, :lo12:.LC12
        bl      puts
        b       .L32
.L34:
        adrp    x0, .LC13       ; "one"
        add     x0, x0, :lo12:.LC13
        bl      puts
```

```
        b       .L32
.L35:
        adrp    x0, .LC14       ; "two"
        add     x0, x0, :lo12:.LC14
        bl      puts
        b       .L32
.L38:
        adrp    x0, .LC15       ; "something unknown"
        add     x0, x0, :lo12:.LC15
        bl      puts
        nop
.L32:
        ldp     x29, x30, [sp], 32
        ret
```

The type of the input value is *int*, hence register W0 is used to hold it instead of the whole X0 register.

The string pointers are passed to puts() using an ADRP/ADD instructions pair just like it was demonstrated in the "Hello, world!" example: 1.5.4 on page 24.

ARM64: Optimizing GCC (Linaro) 4.9

```
f12:
        cmp     w0, 1
        beq     .L31
        cmp     w0, 2
        beq     .L32
        cbz     w0, .L35
; default case
        adrp    x0, .LC15       ; "something unknown"
        add     x0, x0, :lo12:.LC15
        b       puts
.L35:
        adrp    x0, .LC12       ; "zero"
        add     x0, x0, :lo12:.LC12
        b       puts
.L32:
        adrp    x0, .LC14       ; "two"
        add     x0, x0, :lo12:.LC14
        b       puts
.L31:
        adrp    x0, .LC13       ; "one"
        add     x0, x0, :lo12:.LC13
        b       puts
```

Better optimized piece of code. CBZ (*Compare and Branch on Zero*) instruction does jump if W0 is zero. There is also a direct jump to puts() instead of calling it, like it was explained before: 1.15.1 on page 154.

MIPS

Listing 1.151: Optimizing GCC 4.4.5 (IDA)

```
f:
                lui     $gp, (__gnu_local_gp >> 16)
; is it 1?
                li      $v0, 1
                beq     $a0, $v0, loc_60
                la      $gp, (__gnu_local_gp & 0xFFFF) ; branch delay slot
; is it 2?
                li      $v0, 2
                beq     $a0, $v0, loc_4C
                or      $at, $zero ; branch delay slot, NOP
; jump, if not equal to 0:
                bnez    $a0, loc_38
                or      $at, $zero ; branch delay slot, NOP
; zero case:
```

```
                lui     $a0, ($LC0 >> 16)  # "zero"
                lw      $t9, (puts & 0xFFFF)($gp)
                or      $at, $zero ; load delay slot, NOP
                jr      $t9 ; branch delay slot, NOP
                la      $a0, ($LC0 & 0xFFFF)  # "zero" ; branch delay slot

loc_38:                                 # CODE XREF: f+1C
                lui     $a0, ($LC3 >> 16)  # "something unknown"
                lw      $t9, (puts & 0xFFFF)($gp)
                or      $at, $zero ; load delay slot, NOP
                jr      $t9
                la      $a0, ($LC3 & 0xFFFF)  # "something unknown" ; branch delay slot

loc_4C:                                 # CODE XREF: f+14
                lui     $a0, ($LC2 >> 16)  # "two"
                lw      $t9, (puts & 0xFFFF)($gp)
                or      $at, $zero ; load delay slot, NOP
                jr      $t9
                la      $a0, ($LC2 & 0xFFFF)  # "two" ; branch delay slot

loc_60:                                 # CODE XREF: f+8
                lui     $a0, ($LC1 >> 16)  # "one"
                lw      $t9, (puts & 0xFFFF)($gp)
                or      $at, $zero ; load delay slot, NOP
                jr      $t9
                la      $a0, ($LC1 & 0xFFFF)  # "one" ; branch delay slot
```

The function always ends with calling `puts()`, so here we see a jump to `puts()` (JR: "Jump Register") instead of "jump and link". We talked about this earlier: 1.15.1 on page 154.

We also often see NOP instructions after LW ones. This is "load delay slot": another *delay slot* in MIPS.

An instruction next to LW may execute at the moment while LW loads value from memory.

However, the next instruction must not use the result of LW.

Modern MIPS CPUs have a feature to wait if the next instruction uses result of LW, so this is somewhat outdated, but GCC still adds NOPs for older MIPS CPUs. In general, it can be ignored.

Conclusion

A *switch()* with few cases is indistinguishable from an *if/else* construction, for example: listing.1.15.1.

1.15.2 A lot of cases

If a `switch()` statement contains a lot of cases, it is not very convenient for the compiler to emit too large code with a lot JE/JNE instructions.

```
#include <stdio.h>

void f (int a)
{
    switch (a)
    {
    case 0: printf ("zero\n"); break;
    case 1: printf ("one\n"); break;
    case 2: printf ("two\n"); break;
    case 3: printf ("three\n"); break;
    case 4: printf ("four\n"); break;
    default: printf ("something unknown\n"); break;
    };
};

int main()
{
    f (2); // test
};
```

x86

Non-optimizing MSVC

We get (MSVC 2010):

Listing 1.152: MSVC 2010

```
tv64 = -4  ; size = 4
_a$ = 8    ; size = 4
_f    PROC
    push   ebp
    mov    ebp, esp
    push   ecx
    mov    eax, DWORD PTR _a$[ebp]
    mov    DWORD PTR tv64[ebp], eax
    cmp    DWORD PTR tv64[ebp], 4
    ja     SHORT $LN1@f
    mov    ecx, DWORD PTR tv64[ebp]
    jmp    DWORD PTR $LN11@f[ecx*4]
$LN6@f:
    push   OFFSET $SG739 ; 'zero', 0aH, 00H
    call   _printf
    add    esp, 4
    jmp    SHORT $LN9@f
$LN5@f:
    push   OFFSET $SG741 ; 'one', 0aH, 00H
    call   _printf
    add    esp, 4
    jmp    SHORT $LN9@f
$LN4@f:
    push   OFFSET $SG743 ; 'two', 0aH, 00H
    call   _printf
    add    esp, 4
    jmp    SHORT $LN9@f
$LN3@f:
    push   OFFSET $SG745 ; 'three', 0aH, 00H
    call   _printf
    add    esp, 4
    jmp    SHORT $LN9@f
$LN2@f:
    push   OFFSET $SG747 ; 'four', 0aH, 00H
    call   _printf
    add    esp, 4
    jmp    SHORT $LN9@f
$LN1@f:
    push   OFFSET $SG749 ; 'something unknown', 0aH, 00H
    call   _printf
    add    esp, 4
$LN9@f:
    mov    esp, ebp
    pop    ebp
    ret    0
    npad    2 ; align next label
$LN11@f:
    DD    $LN6@f ; 0
    DD    $LN5@f ; 1
    DD    $LN4@f ; 2
    DD    $LN3@f ; 3
    DD    $LN2@f ; 4
_f    ENDP
```

What we see here is a set of `printf()` calls with various arguments. All they have not only addresses in the memory of the process, but also internal symbolic labels assigned by the compiler. All these labels are also mentioned in the `$LN11@f` internal table.

At the function start, if a is greater than 4, control flow is passed to label `$LN1@f`, where `printf()` with argument `'something unknown'` is called.

But if the value of a is less or equals to 4, then it gets multiplied by 4 and added with the `$LN11@f` table address. That is how an address inside the table is constructed, pointing exactly to the element we need. For example, let's say a is equal to 2. $2 * 4 = 8$ (all table elements are addresses in a 32-bit process and that is why all elements are 4 bytes wide). The address of the `$LN11@f` table + 8 is the table element where the `$LN4@f` label is stored. `JMP` fetches the `$LN4@f` address from the table and jumps to it.

This table is sometimes called *jumptable* or *branch table*[94].

Then the corresponding `printf()` is called with argument `'two'`.
Literally, the `jmp DWORD PTR $LN11@f[ecx*4]` instruction implies *jump to the DWORD that is stored at address* `$LN11@f + ecx * 4`.

npad (.1.7 on page 1038) is an assembly language macro that align the next label so that it will be stored at an address aligned on a 4 bytes (or 16 bytes) boundary. This is very suitable for the processor since it is able to fetch 32-bit values from memory through the memory bus, cache memory, etc., in a more effective way if it is aligned.

[94] The whole method was once called *computed GOTO* in early versions of Fortran: wikipedia. Not quite relevant these days, but what a term!

OllyDbg

Let's try this example in OllyDbg. The input value of the function (2) is loaded into EAX:

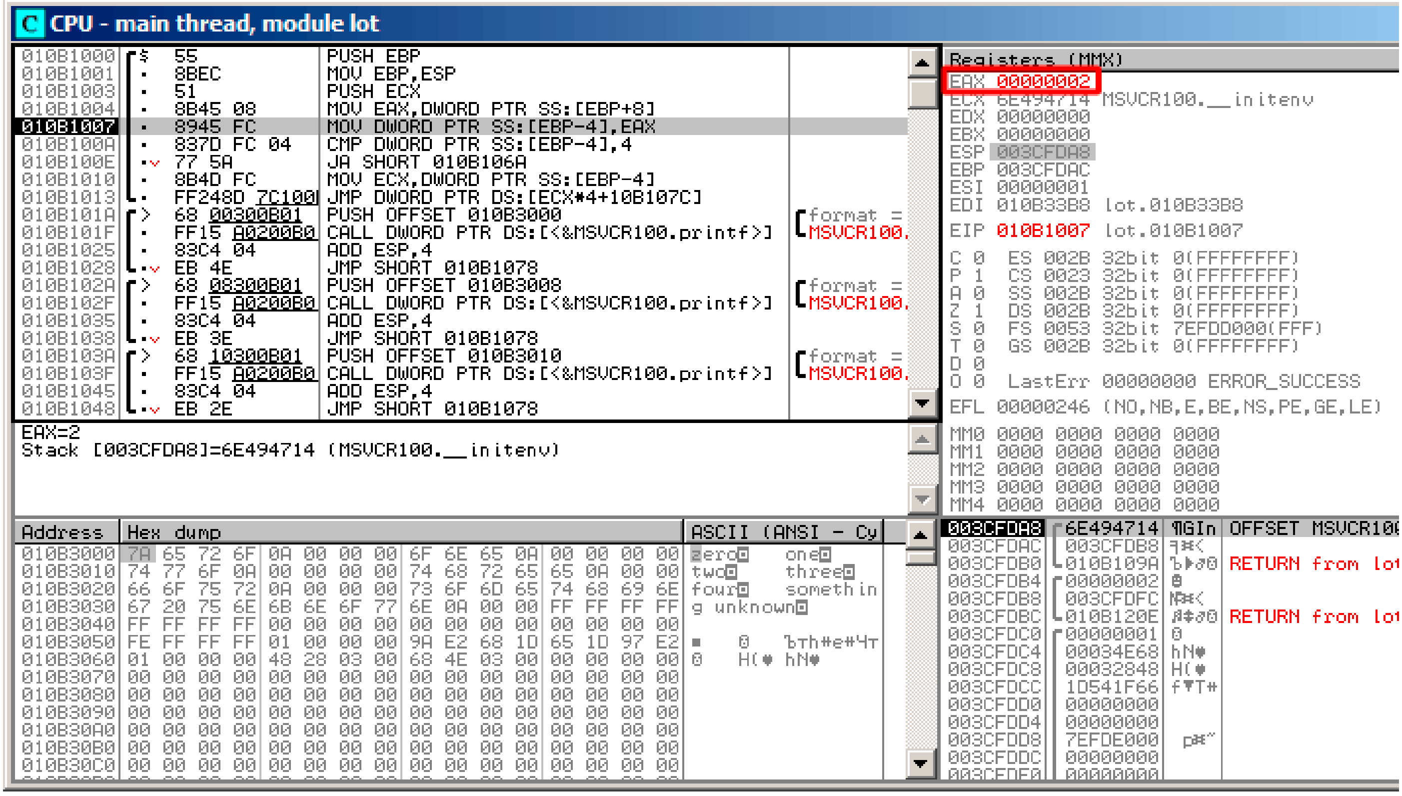


Figure 1.50: OllyDbg: function's input value is loaded in EAX

The input value is checked, is it bigger than 4? If not, the "default" jump is not taken:

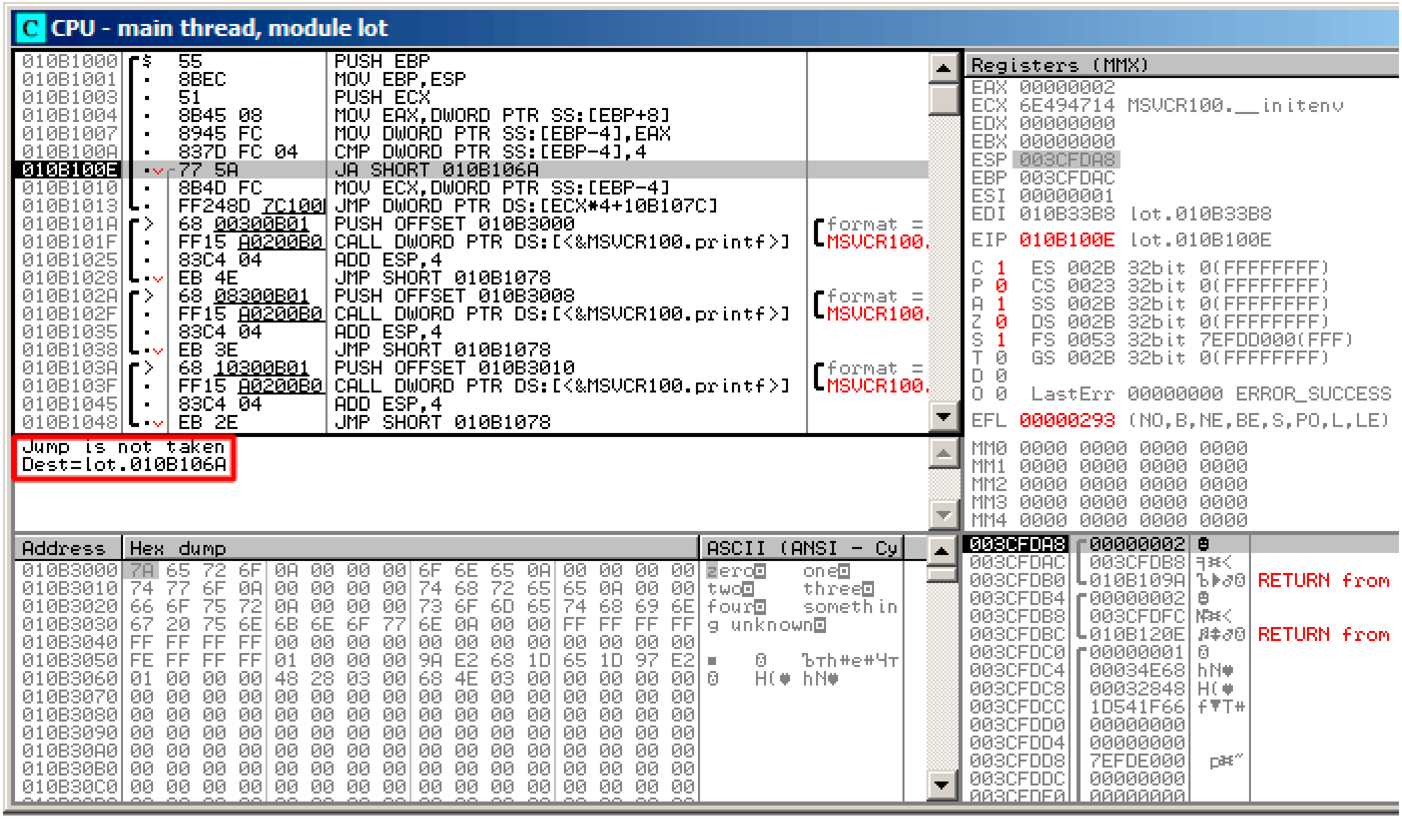


Figure 1.51: OllyDbg: 2 is no bigger than 4: no jump is taken

Here we see a jumptable:

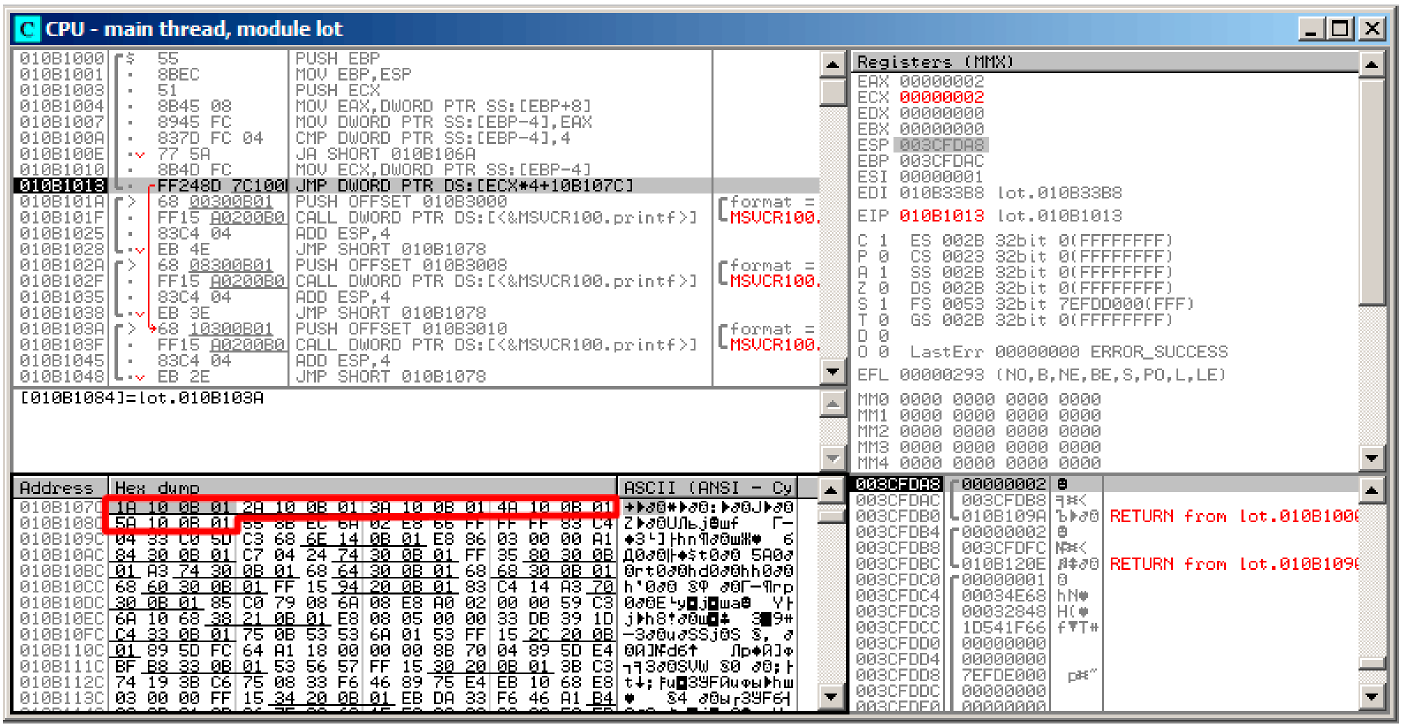


Figure 1.52: OllyDbg: calculating destination address using jumptable

Here we've clicked "Follow in Dump" → "Address constant", so now we see the *jumptable* in the data window. These are 5 32-bit values[95]. ECX is now 2, so the third element (can be indexed as 2[96]) of the table is to be used. It's also possible to click "Follow in Dump" → "Memory address" and OllyDbg will show the element addressed by the JMP instruction. That's `0x010B103A`.

[95]They are underlined by OllyDbg because these are also FIXUPs: 6.5.2 on page 759, we are going to come back to them later

[96]About indexing, see also: 3.19.3

After the jump we are at 0x010B103A: the code printing “two” will now be executed:

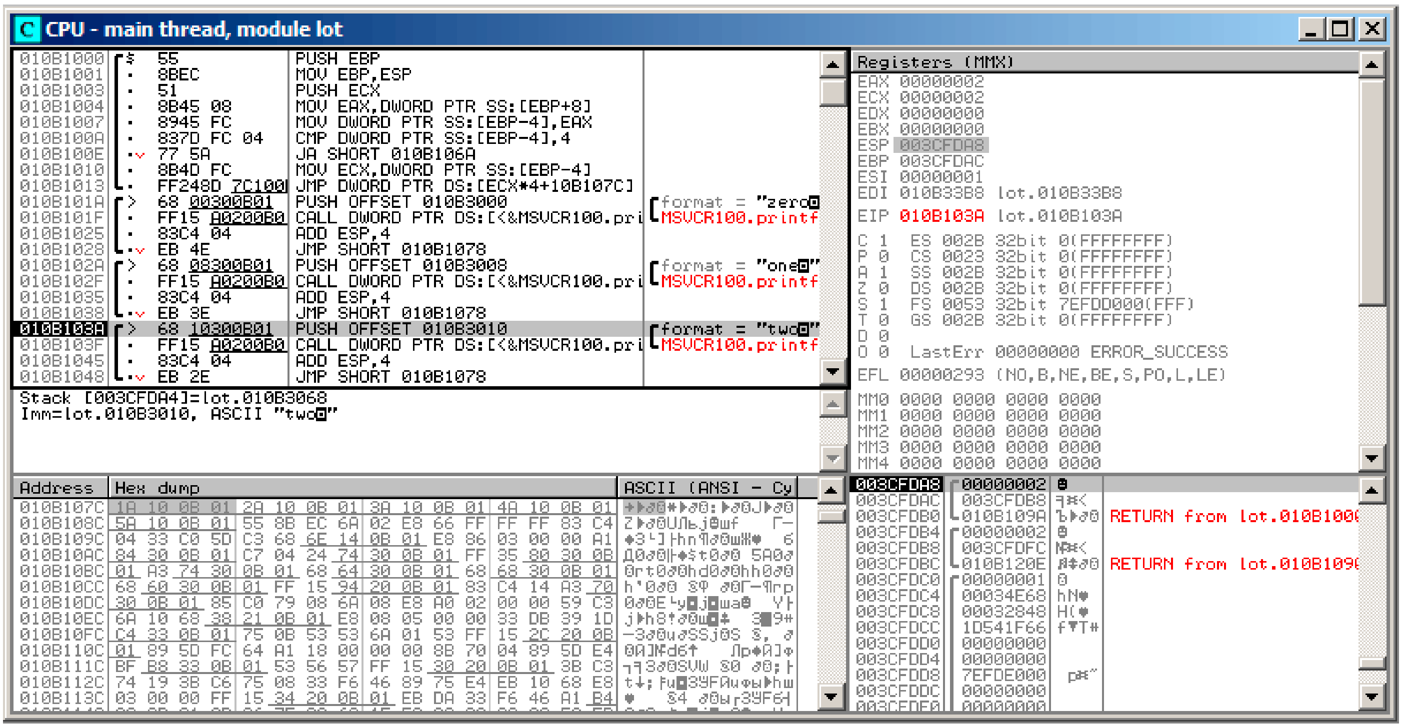


Figure 1.53: OllyDbg: now we at the *case:* label

Non-optimizing GCC

Let’s see what GCC 4.4.1 generates:

Listing 1.153: GCC 4.4.1

```
        public f
f       proc near ; CODE XREF: main+10

var_18 = dword ptr -18h
arg_0  = dword ptr  8

        push    ebp
        mov     ebp, esp
        sub     esp, 18h
        cmp     [ebp+arg_0], 4
        ja      short loc_8048444
        mov     eax, [ebp+arg_0]
        shl     eax, 2
        mov     eax, ds:off_804855C[eax]
        jmp     eax

loc_80483FE: ; DATA XREF: .rodata:off_804855C
        mov     [esp+18h+var_18], offset aZero ; "zero"
        call    _puts
        jmp     short locret_8048450

loc_804840C: ; DATA XREF: .rodata:08048560
        mov     [esp+18h+var_18], offset aOne ; "one"
        call    _puts
        jmp     short locret_8048450

loc_804841A: ; DATA XREF: .rodata:08048564
        mov     [esp+18h+var_18], offset aTwo ; "two"
        call    _puts
        jmp     short locret_8048450

loc_8048428: ; DATA XREF: .rodata:08048568
```

```
        mov     [esp+18h+var_18], offset aThree ; "three"
        call    _puts
        jmp     short locret_8048450

loc_8048436: ; DATA XREF: .rodata:0804856C
        mov     [esp+18h+var_18], offset aFour ; "four"
        call    _puts
        jmp     short locret_8048450

loc_8048444: ; CODE XREF: f+A
        mov     [esp+18h+var_18], offset aSomethingUnkno ; "something unknown"
        call    _puts

locret_8048450: ; CODE XREF: f+26
                ; f+34...
        leave
        retn
f       endp

off_804855C dd offset loc_80483FE   ; DATA XREF: f+12
            dd offset loc_804840C
            dd offset loc_804841A
            dd offset loc_8048428
            dd offset loc_8048436
```

It is almost the same, with a little nuance: argument `arg_0` is multiplied by 4 by shifting it to left by 2 bits (it is almost the same as multiplication by 4) (1.18.2 on page 217). Then the address of the label is taken from the `off_804855C` array, stored in EAX, and then `JMP EAX` does the actual jump.

ARM: Optimizing Keil 6/2013 (ARM mode)

Listing 1.154: Optimizing Keil 6/2013 (ARM mode)

```
00000174             f2
00000174 05 00 50 E3     CMP     R0, #5           ; switch 5 cases
00000178 00 F1 8F 30     ADDCC   PC, PC, R0,LSL#2 ; switch jump
0000017C 0E 00 00 EA     B       default_case     ; jumptable 00000178 default case

00000180
00000180             loc_180 ; CODE XREF: f2+4
00000180 03 00 00 EA     B       zero_case       ; jumptable 00000178 case 0

00000184
00000184             loc_184 ; CODE XREF: f2+4
00000184 04 00 00 EA     B       one_case        ; jumptable 00000178 case 1

00000188
00000188             loc_188 ; CODE XREF: f2+4
00000188 05 00 00 EA     B       two_case        ; jumptable 00000178 case 2

0000018C
0000018C             loc_18C ; CODE XREF: f2+4
0000018C 06 00 00 EA     B       three_case      ; jumptable 00000178 case 3

00000190
00000190             loc_190 ; CODE XREF: f2+4
00000190 07 00 00 EA     B       four_case       ; jumptable 00000178 case 4

00000194
00000194             zero_case ; CODE XREF: f2+4
00000194                       ; f2:loc_180
00000194 EC 00 8F E2     ADR     R0, aZero       ; jumptable 00000178 case 0
00000198 06 00 00 EA     B       loc_1B8

0000019C
0000019C             one_case ; CODE XREF: f2+4
0000019C                      ; f2:loc_184
0000019C EC 00 8F E2     ADR     R0, aOne        ; jumptable 00000178 case 1
```

```
000001A0 04 00 00 EA     B       loc_1B8

000001A4
000001A4             two_case ; CODE XREF: f2+4
000001A4                      ; f2:loc_188
000001A4 01 0C 8F E2     ADR     R0, aTwo        ; jumptable 00000178 case 2
000001A8 02 00 00 EA     B       loc_1B8

000001AC
000001AC             three_case ; CODE XREF: f2+4
000001AC                        ; f2:loc_18C
000001AC 01 0C 8F E2     ADR     R0, aThree      ; jumptable 00000178 case 3
000001B0 00 00 00 EA     B       loc_1B8

000001B4
000001B4             four_case ; CODE XREF: f2+4
000001B4                       ; f2:loc_190
000001B4 01 0C 8F E2     ADR     R0, aFour       ; jumptable 00000178 case 4
000001B8
000001B8             loc_1B8   ; CODE XREF: f2+24
000001B8                       ; f2+2C
000001B8 66 18 00 EA     B       __2printf

000001BC
000001BC             default_case ; CODE XREF: f2+4
000001BC                          ; f2+8
000001BC D4 00 8F E2     ADR     R0, aSomethingUnkno ; jumptable 00000178 default case
000001C0 FC FF FF EA     B       loc_1B8
```

This code makes use of the ARM mode feature in which all instructions have a fixed size of 4 bytes.

Let's keep in mind that the maximum value for a is 4 and any greater value will cause *«something unknown\n»* string to be printed.

The first `CMP R0, #5` instruction compares the input value of a with 5.

[97] The next `ADDCC PC, PC, R0,LSL#2` instruction is being executed only if $R0 < 5$ (*CC=Carry clear / Less than*). Consequently, if `ADDCC` does not trigger (it is a $R0 \geq 5$ case), a jump to *default_case* label will occur.

But if $R0 < 5$ and `ADDCC` triggers, the following is to be happen:

The value in `R0` is multiplied by 4. In fact, `LSL#2` at the instruction's suffix stands for "shift left by 2 bits". But as we will see later (1.18.2 on page 217) in section "Shifts", shift left by 2 bits is equivalent to multiplying by 4.

Then we add $R0 * 4$ to the current value in PC, thus jumping to one of the B (*Branch*) instructions located below.

At the moment of the execution of `ADDCC`, the value in PC is 8 bytes ahead (`0x180`) than the address at which the `ADDCC` instruction is located (`0x178`), or, in other words, 2 instructions ahead.

This is how the pipeline in ARM processors works: when `ADDCC` is executed, the processor at the moment is beginning to process the instruction after the next one, so that is why PC points there. This has to be memorized.

If $a = 0$, then is to be added to the value in PC, and the actual value of the PC will be written into PC (which is 8 bytes ahead) and a jump to the label *loc_180* will happen, which is 8 bytes ahead of the point where the `ADDCC` instruction is.

If $a = 1$, then $PC + 8 + a * 4 = PC + 8 + 1 * 4 = PC + 12 = 0x184$ will be written to PC, which is the address of the *loc_184* label.

With every 1 added to a, the resulting PC is increased by 4.

4 is the instruction length in ARM mode and also, the length of each B instruction, of which there are 5 in row.

Each of these five B instructions passes control further, to what was programmed in the *switch()*.

Pointer loading of the corresponding string occurs there, etc.

[97] ADD—addition

ARM: Optimizing Keil 6/2013 (Thumb mode)

Listing 1.155: Optimizing Keil 6/2013 (Thumb mode)

```
000000F6                        EXPORT f2
000000F6                    f2
000000F6 10 B5                  PUSH    {R4,LR}
000000F8 03 00                  MOVS    R3, R0
000000FA 06 F0 69 F8            BL      __ARM_common_switch8_thumb ; switch 6 cases

000000FE 05                     DCB 5
000000FF 04 06 08 0A 0C 10      DCB 4, 6, 8, 0xA, 0xC, 0x10 ; jump table for switch statement
00000105 00                     ALIGN 2
00000106
00000106                    zero_case ; CODE XREF: f2+4
00000106 8D A0                  ADR     R0, aZero ; jumptable 000000FA case 0
00000108 06 E0                  B       loc_118

0000010A
0000010A                    one_case ; CODE XREF: f2+4
0000010A 8E A0                  ADR     R0, aOne ; jumptable 000000FA case 1
0000010C 04 E0                  B       loc_118

0000010E
0000010E                    two_case ; CODE XREF: f2+4
0000010E 8F A0                  ADR     R0, aTwo ; jumptable 000000FA case 2
00000110 02 E0                  B       loc_118

00000112
00000112                    three_case ; CODE XREF: f2+4
00000112 90 A0                  ADR     R0, aThree ; jumptable 000000FA case 3
00000114 00 E0                  B       loc_118

00000116
00000116                    four_case ; CODE XREF: f2+4
00000116 91 A0                  ADR     R0, aFour ; jumptable 000000FA case 4
00000118
00000118                    loc_118 ; CODE XREF: f2+12
00000118                            ; f2+16
00000118 06 F0 6A F8            BL      __2printf
0000011C 10 BD                  POP     {R4,PC}

0000011E
0000011E                    default_case ; CODE XREF: f2+4
0000011E 82 A0                  ADR     R0, aSomethingUnkno ; jumptable 000000FA default case
00000120 FA E7                  B       loc_118


000061D0                        EXPORT __ARM_common_switch8_thumb
000061D0                    __ARM_common_switch8_thumb ; CODE XREF: example6_f2+4
000061D0 78 47                  BX      PC

000061D2 00 00                  ALIGN 4
000061D2                    ; End of function __ARM_common_switch8_thumb
000061D2
000061D4                    __32__ARM_common_switch8_thumb ; CODE XREF: ↙
    ↳ __ARM_common_switch8_thumb
000061D4 01 C0 5E E5            LDRB    R12, [LR,#-1]
000061D8 0C 00 53 E1            CMP     R3, R12
000061DC 0C 30 DE 27            LDRCSB  R3, [LR,R12]
000061E0 03 30 DE 37            LDRCCB  R3, [LR,R3]
000061E4 83 C0 8E E0            ADD     R12, LR, R3,LSL#1
000061E8 1C FF 2F E1            BX      R12
000061E8                    ; End of function __32__ARM_common_switch8_thumb
```

One cannot be sure that all instructions in Thumb and Thumb-2 modes has the same size. It can even be said that in these modes the instructions have variable lengths, just like in x86.

So there is a special table added that contains information about how much cases are there (not including default-case), and an offset for each with a label to which control must be passed in the corresponding case.

A special function is present here in order to deal with the table and pass control, named *__ARM_common_switch8_thumb*. It starts with `BX PC`, whose function is to switch the processor to ARM-mode. Then you see the function for table processing.

It is too advanced to describe it here now, so let's omit it.

It is interesting to note that the function uses the LR register as a pointer to the table.

Indeed, after calling of this function, LR contains the address after `BL __ARM_common_switch8_thumb` instruction, where the table starts.

It is also worth noting that the code is generated as a separate function in order to reuse it, so the compiler doesn't generate the same code for every switch() statement.

IDA successfully perceived it as a service function and a table, and added comments to the labels like `jumptable 000000FA case 0`.

MIPS

Listing 1.156: Optimizing GCC 4.4.5 (IDA)

```
f:
                lui     $gp, (__gnu_local_gp >> 16)
; jump to loc_24 if input value is lesser than 5:
                sltiu   $v0, $a0, 5
                bnez    $v0, loc_24
                la      $gp, (__gnu_local_gp & 0xFFFF) ; branch delay slot
; input value is greater or equal to 5.
; print "something unknown" and finish:
                lui     $a0, ($LC5 >> 16)  # "something unknown"
                lw      $t9, (puts & 0xFFFF)($gp)
                or      $at, $zero ; NOP
                jr      $t9
                la      $a0, ($LC5 & 0xFFFF)  # "something unknown" ; branch delay slot

loc_24:                                  # CODE XREF: f+8
; load address of jumptable
; LA is pseudoinstruction, LUI and ADDIU pair are there in fact:
                la      $v0, off_120
; multiply input value by 4:
                sll     $a0, 2
; sum up multiplied value and jumptable address:
                addu    $a0, $v0, $a0
; load element from jumptable:
                lw      $v0, 0($a0)
                or      $at, $zero ; NOP
; jump to the address we got in jumptable:
                jr      $v0
                or      $at, $zero ; branch delay slot, NOP

sub_44:                                  # DATA XREF: .rodata:0000012C
; print "three" and finish
                lui     $a0, ($LC3 >> 16)  # "three"
                lw      $t9, (puts & 0xFFFF)($gp)
                or      $at, $zero ; NOP
                jr      $t9
                la      $a0, ($LC3 & 0xFFFF)  # "three" ; branch delay slot

sub_58:                                  # DATA XREF: .rodata:00000130
; print "four" and finish
                lui     $a0, ($LC4 >> 16)  # "four"
                lw      $t9, (puts & 0xFFFF)($gp)
                or      $at, $zero ; NOP
                jr      $t9
                la      $a0, ($LC4 & 0xFFFF)  # "four" ; branch delay slot

sub_6C:                                  # DATA XREF: .rodata:off_120
; print "zero" and finish
```

```
                lui     $a0, ($LC0 >> 16)  # "zero"
                lw      $t9, (puts & 0xFFFF)($gp)
                or      $at, $zero ; NOP
                jr      $t9
                la      $a0, ($LC0 & 0xFFFF)  # "zero" ; branch delay slot

sub_80:                                  # DATA XREF: .rodata:00000124
; print "one" and finish
                lui     $a0, ($LC1 >> 16)  # "one"
                lw      $t9, (puts & 0xFFFF)($gp)
                or      $at, $zero ; NOP
                jr      $t9
                la      $a0, ($LC1 & 0xFFFF)  # "one" ; branch delay slot

sub_94:                                  # DATA XREF: .rodata:00000128
; print "two" and finish
                lui     $a0, ($LC2 >> 16)  # "two"
                lw      $t9, (puts & 0xFFFF)($gp)
                or      $at, $zero ; NOP
                jr      $t9
                la      $a0, ($LC2 & 0xFFFF)  # "two" ; branch delay slot

; may be placed in .rodata section:
off_120:        .word sub_6C
                .word sub_80
                .word sub_94
                .word sub_44
                .word sub_58
```

The new instruction for us is SLTIU (“Set on Less Than Immediate Unsigned”).

This is the same as SLTU (“Set on Less Than Unsigned”), but “I” stands for “immediate”, i.e., a number has to be specified in the instruction itself.

BNEZ is “Branch if Not Equal to Zero”.

Code is very close to the other ISAs. SLL (“Shift Word Left Logical”) does multiplication by 4.

MIPS is a 32-bit CPU after all, so all addresses in the *jumptable* are 32-bit ones.

Conclusion

Rough skeleton of *switch()*:

Listing 1.157: x86

```
MOV REG, input
CMP REG, 4 ; maximal number of cases
JA default
SHL REG, 2 ; find element in table. shift for 3 bits in x64.
MOV REG, jump_table[REG]
JMP REG

case1:
    ; do something
    JMP exit
case2:
    ; do something
    JMP exit
case3:
    ; do something
    JMP exit
case4:
    ; do something
    JMP exit
case5:
    ; do something
    JMP exit

default:
```

```
    ...

exit:

    ....

jump_table dd case1
           dd case2
           dd case3
           dd case4
           dd case5
```

The jump to the address in the jump table may also be implemented using this instruction:
`JMP jump_table[REG*4]`. Or `JMP jump_table[REG*8]` in x64.

A *jumptable* is just array of pointers, like the one described later: 1.20.5 on page 287.

1.15.3 When there are several *case* statements in one block

Here is a very widespread construction: several *case* statements for a single block:

```
#include <stdio.h>

void f(int a)
{
        switch (a)
        {
        case 1:
        case 2:
        case 7:
        case 10:
                printf ("1, 2, 7, 10\n");
                break;
        case 3:
        case 4:
        case 5:
        case 6:
                printf ("3, 4, 5\n");
                break;
        case 8:
        case 9:
        case 20:
        case 21:
                printf ("8, 9, 21\n");
                break;
        case 22:
                printf ("22\n");
                break;
        default:
                printf ("default\n");
                break;
        };
};

int main()
{
        f(4);
};
```

It's too wasteful to generate a block for each possible case, so what is usually done is to generate each block plus some kind of dispatcher.

MSVC

Listing 1.158: Optimizing MSVC 2010

```
1  $SG2798 DB      '1, 2, 7, 10', 0aH, 00H
2  $SG2800 DB      '3, 4, 5', 0aH, 00H
3  $SG2802 DB      '8, 9, 21', 0aH, 00H
4  $SG2804 DB      '22', 0aH, 00H
5  $SG2806 DB      'default', 0aH, 00H
6
7  _a$ = 8
8  _f      PROC
9          mov     eax, DWORD PTR _a$[esp-4]
10         dec     eax
11         cmp     eax, 21
12         ja      SHORT $LN1@f
13         movzx   eax, BYTE PTR $LN10@f[eax]
14         jmp     DWORD PTR $LN11@f[eax*4]
15 $LN5@f:
16         mov     DWORD PTR _a$[esp-4], OFFSET $SG2798 ; '1, 2, 7, 10'
17         jmp     DWORD PTR __imp__printf
18 $LN4@f:
19         mov     DWORD PTR _a$[esp-4], OFFSET $SG2800 ; '3, 4, 5'
20         jmp     DWORD PTR __imp__printf
21 $LN3@f:
22         mov     DWORD PTR _a$[esp-4], OFFSET $SG2802 ; '8, 9, 21'
23         jmp     DWORD PTR __imp__printf
24 $LN2@f:
25         mov     DWORD PTR _a$[esp-4], OFFSET $SG2804 ; '22'
26         jmp     DWORD PTR __imp__printf
27 $LN1@f:
28         mov     DWORD PTR _a$[esp-4], OFFSET $SG2806 ; 'default'
29         jmp     DWORD PTR __imp__printf
30         npad    2 ; align $LN11@f table on 16-byte boundary
31 $LN11@f:
32         DD      $LN5@f ; print '1, 2, 7, 10'
33         DD      $LN4@f ; print '3, 4, 5'
34         DD      $LN3@f ; print '8, 9, 21'
35         DD      $LN2@f ; print '22'
36         DD      $LN1@f ; print 'default'
37 $LN10@f:
38         DB      0 ; a=1
39         DB      0 ; a=2
40         DB      1 ; a=3
41         DB      1 ; a=4
42         DB      1 ; a=5
43         DB      1 ; a=6
44         DB      0 ; a=7
45         DB      2 ; a=8
46         DB      2 ; a=9
47         DB      0 ; a=10
48         DB      4 ; a=11
49         DB      4 ; a=12
50         DB      4 ; a=13
51         DB      4 ; a=14
52         DB      4 ; a=15
53         DB      4 ; a=16
54         DB      4 ; a=17
55         DB      4 ; a=18
56         DB      4 ; a=19
57         DB      2 ; a=20
58         DB      2 ; a=21
59         DB      3 ; a=22
60 _f      ENDP
```

We see two tables here: the first table ($LN10@f) is an index table, and the second one ($LN11@f) is an array of pointers to blocks.

First, the input value is used as an index in the index table (line 13).

Here is a short legend for the values in the table: 0 is the first *case* block (for values 1, 2, 7, 10), 1 is the second one (for values 3, 4, 5), 2 is the third one (for values 8, 9, 21), 3 is the fourth one (for value 22), 4 is for the default block.

There we get an index for the second table of code pointers and we jump to it (line 14).

What is also worth noting is that there is no case for input value 0.

That's why we see the DEC instruction at line 10, and the table starts at $a = 1$, because there is no need to allocate a table element for $a = 0$.

This is a very widespread pattern.

So why is this economical? Why isn't it possible to make it as before (1.15.2 on page 172), just with one table consisting of block pointers? The reason is that the elements in index table are 8-bit, hence it's all more compact.

GCC

GCC does the job in the way we already discussed (1.15.2 on page 172), using just one table of pointers.

ARM64: Optimizing GCC 4.9.1

There is no code to be triggered if the input value is 0, so GCC tries to make the jump table more compact and so it starts at 1 as an input value.

GCC 4.9.1 for ARM64 uses an even cleverer trick. It's able to encode all offsets as 8-bit bytes.

Let's recall that all ARM64 instructions have a size of 4 bytes.

GCC is uses the fact that all offsets in my tiny example are in close proximity to each other. So the jump table consisting of single bytes.

Listing 1.159: Optimizing GCC 4.9.1 ARM64

```
f14:
; input value in W0
        sub     w0, w0, #1
        cmp     w0, 21
; branch if less or equal (unsigned):
        bls     .L9
.L2:
; print "default":
        adrp    x0, .LC4
        add     x0, x0, :lo12:.LC4
        b       puts
.L9:
; load jumptable address to X1:
        adrp    x1, .L4
        add     x1, x1, :lo12:.L4
; W0=input_value-1
; load byte from the table:
        ldrb    w0, [x1,w0,uxtw]
; load address of the Lrtx label:
        adr     x1, .Lrtx4
; multiply table element by 4 (by shifting 2 bits left) and add (or subtract) to the address of
    Lrtx:
        add     x0, x1, w0, sxtb #2
; jump to the calculated address:
        br      x0
; this label is pointing in code (text) segment:
.Lrtx4:
        .section        .rodata
; everything after ".section" statement is allocated in the read-only data (rodata) segment:
.L4:
        .byte   (.L3 - .Lrtx4) / 4      ; case 1
        .byte   (.L3 - .Lrtx4) / 4      ; case 2
        .byte   (.L5 - .Lrtx4) / 4      ; case 3
        .byte   (.L5 - .Lrtx4) / 4      ; case 4
        .byte   (.L5 - .Lrtx4) / 4      ; case 5
        .byte   (.L5 - .Lrtx4) / 4      ; case 6
        .byte   (.L3 - .Lrtx4) / 4      ; case 7
        .byte   (.L6 - .Lrtx4) / 4      ; case 8
        .byte   (.L6 - .Lrtx4) / 4      ; case 9
```

```
        .byte   (.L3 - .Lrtx4) / 4     ; case 10
        .byte   (.L2 - .Lrtx4) / 4     ; case 11
        .byte   (.L2 - .Lrtx4) / 4     ; case 12
        .byte   (.L2 - .Lrtx4) / 4     ; case 13
        .byte   (.L2 - .Lrtx4) / 4     ; case 14
        .byte   (.L2 - .Lrtx4) / 4     ; case 15
        .byte   (.L2 - .Lrtx4) / 4     ; case 16
        .byte   (.L2 - .Lrtx4) / 4     ; case 17
        .byte   (.L2 - .Lrtx4) / 4     ; case 18
        .byte   (.L2 - .Lrtx4) / 4     ; case 19
        .byte   (.L6 - .Lrtx4) / 4     ; case 20
        .byte   (.L6 - .Lrtx4) / 4     ; case 21
        .byte   (.L7 - .Lrtx4) / 4     ; case 22
        .text
; everything after ".text" statement is allocated in the code (text) segment:
.L7:
; print "22"
        adrp    x0, .LC3
        add     x0, x0, :lo12:.LC3
        b       puts
.L6:
; print "8, 9, 21"
        adrp    x0, .LC2
        add     x0, x0, :lo12:.LC2
        b       puts
.L5:
; print "3, 4, 5"
        adrp    x0, .LC1
        add     x0, x0, :lo12:.LC1
        b       puts
.L3:
; print "1, 2, 7, 10"
        adrp    x0, .LC0
        add     x0, x0, :lo12:.LC0
        b       puts
.LC0:
        .string "1, 2, 7, 10"
.LC1:
        .string "3, 4, 5"
.LC2:
        .string "8, 9, 21"
.LC3:
        .string "22"
.LC4:
        .string "default"
```

Let's compile this example to object file and open it in IDA. Here is the jump table:

Listing 1.160: jumptable in IDA

```
.rodata:0000000000000064           AREA .rodata, DATA, READONLY
.rodata:0000000000000064           ; ORG 0x64
.rodata:0000000000000064 $d        DCB    9    ; case 1
.rodata:0000000000000065           DCB    9    ; case 2
.rodata:0000000000000066           DCB    6    ; case 3
.rodata:0000000000000067           DCB    6    ; case 4
.rodata:0000000000000068           DCB    6    ; case 5
.rodata:0000000000000069           DCB    6    ; case 6
.rodata:000000000000006A           DCB    9    ; case 7
.rodata:000000000000006B           DCB    3    ; case 8
.rodata:000000000000006C           DCB    3    ; case 9
.rodata:000000000000006D           DCB    9    ; case 10
.rodata:000000000000006E           DCB 0xF7    ; case 11
.rodata:000000000000006F           DCB 0xF7    ; case 12
.rodata:0000000000000070           DCB 0xF7    ; case 13
.rodata:0000000000000071           DCB 0xF7    ; case 14
.rodata:0000000000000072           DCB 0xF7    ; case 15
.rodata:0000000000000073           DCB 0xF7    ; case 16
.rodata:0000000000000074           DCB 0xF7    ; case 17
.rodata:0000000000000075           DCB 0xF7    ; case 18
.rodata:0000000000000076           DCB 0xF7    ; case 19
```

```
.rodata:0000000000000077           DCB    3    ; case 20
.rodata:0000000000000078           DCB    3    ; case 21
.rodata:0000000000000079           DCB    0    ; case 22
.rodata:000000000000007B ; .rodata ends
```

So in case of 1, 9 is to be multiplied by 4 and added to the address of `Lrtx4` label.

In case of 22, 0 is to be multiplied by 4, resulting in 0.

Right after the `Lrtx4` label is the L7 label, where you can find the code that prints “22”.

There is no jump table in the code segment, it’s allocated in a separate .rodata section (there is no special necessity to place it in the code section).

There are also negative bytes (0xF7), they are used for jumping back to the code that prints the “default” string (at `.L2`).

1.15.4 Fall-through

Another popular usage of `switch()` operator is so-called “fallthrough”. Here is simple example[98]:

```
bool is_whitespace(char c) {
        switch (c) {
                case ' ': // fallthrough
                case '\t': // fallthrough
                case '\r': // fallthrough
                case '\n':
                        return true;
                default: // not whitespace
                        return false;
        }
}
```

Slightly harder, from Linux kernel[99]:

```
char nco1, nco2;

void f(int if_freq_khz)
{

        switch (if_freq_khz) {
                default:
                        printf("IF=%d KHz is not supportted, 3250 assumed\n", if_freq_khz);
                        /* fallthrough */
                case 3250: /* 3.25Mhz */
                        nco1 = 0x34;
                        nco2 = 0x00;
                        break;
                case 3500: /* 3.50Mhz */
                        nco1 = 0x38;
                        nco2 = 0x00;
                        break;
                case 4000: /* 4.00Mhz */
                        nco1 = 0x40;
                        nco2 = 0x00;
                        break;
                case 5000: /* 5.00Mhz */
                        nco1 = 0x50;
                        nco2 = 0x00;
                        break;
                case 5380: /* 5.38Mhz */
                        nco1 = 0x56;
                        nco2 = 0x14;
                        break;
        }
};
```

[98]Copypasted from https://github.com/azonalon/prgraas/blob/master/prog1lib/lecture_examples/is_whitespace.c
[99]Copypasted from https://github.com/torvalds/linux/blob/master/drivers/media/dvb-frontends/lgdt3306a.c

Listing 1.161: Optimizing GCC 5.4.0 x86

```
.LC0:
        .string "IF=%d KHz is not supportted, 3250 assumed\n"
f:
        sub     esp, 12
        mov     eax, DWORD PTR [esp+16]
        cmp     eax, 4000
        je      .L3
        jg      .L4
        cmp     eax, 3250
        je      .L5
        cmp     eax, 3500
        jne     .L2
        mov     BYTE PTR nco1, 56
        mov     BYTE PTR nco2, 0
        add     esp, 12
        ret
.L4:
        cmp     eax, 5000
        je      .L7
        cmp     eax, 5380
        jne     .L2
        mov     BYTE PTR nco1, 86
        mov     BYTE PTR nco2, 20
        add     esp, 12
        ret
.L2:
        sub     esp, 8
        push    eax
        push    OFFSET FLAT:.LC0
        call    printf
        add     esp, 16
.L5:
        mov     BYTE PTR nco1, 52
        mov     BYTE PTR nco2, 0
        add     esp, 12
        ret
.L3:
        mov     BYTE PTR nco1, 64
        mov     BYTE PTR nco2, 0
        add     esp, 12
        ret
.L7:
        mov     BYTE PTR nco1, 80
        mov     BYTE PTR nco2, 0
        add     esp, 12
        ret
```

We can get to `.L5` label if there is number 3250 at function's input. But we can get to this label from the other side: we see that there are no jumps between `printf()` call and `.L5` label.

Now we can understand why *switch()* statement is sometimes a source of bugs: one forgotten *break* will transform your *switch()* statement into *fallthrough* one, and several blocks will be executed instead of single one.

1.15.5 Exercises

Exercise #1

It's possible to rework the C example in 1.15.2 on page 166 in such way that the compiler can produce even smaller code, but will work just the same. Try to achieve it.

1.16 Loops

1.16.1 Simple example

x86

There is a special LOOP instruction in x86 instruction set for checking the value in register ECX and if it is not 0, to decrement ECX and pass control flow to the label in the LOOP operand. Probably this instruction is not very convenient, and there are no any modern compilers which emit it automatically. So, if you see this instruction somewhere in code, it is most likely that this is a manually written piece of assembly code.

In C/C++ loops are usually constructed using `for()`, `while()` or `do/while()` statements.

Let's start with `for()`.

This statement defines loop initialization (set loop counter to initial value), loop condition (is the counter bigger than a limit?), what is performed at each iteration (increment/decrement) and of course loop body.

```
for (initialization; condition; at each iteration)
{
    loop_body;
}
```

The generated code is consisting of four parts as well.

Let's start with a simple example:

```
#include <stdio.h>

void printing_function(int i)
{
        printf ("f(%d)\n", i);
};

int main()
{
        int i;

        for (i=2; i<10; i++)
                printing_function(i);

        return 0;
};
```

Result (MSVC 2010):

Listing 1.162: MSVC 2010

```
_i$ = -4
_main    PROC
    push   ebp
    mov    ebp, esp
    push   ecx
    mov    DWORD PTR _i$[ebp], 2   ; loop initialization
    jmp    SHORT $LN3@main
$LN2@main:
    mov    eax, DWORD PTR _i$[ebp] ; here is what we do after each iteration:
    add    eax, 1                  ; add 1 to (i) value
    mov    DWORD PTR _i$[ebp], eax
$LN3@main:
    cmp    DWORD PTR _i$[ebp], 10  ; this condition is checked before each iteration
    jge    SHORT $LN1@main         ; if (i) is biggest or equals to 10, lets finish loop
    mov    ecx, DWORD PTR _i$[ebp] ; loop body: call printing_function(i)
    push   ecx
    call   _printing_function
    add    esp, 4
    jmp    SHORT $LN2@main         ; jump to loop begin
$LN1@main:                         ; loop end
    xor    eax, eax
    mov    esp, ebp
```

```
    pop    ebp
    ret    0
_main    ENDP
```

As we see, nothing special.

GCC 4.4.1 emits almost the same code, with one subtle difference:

Listing 1.163: GCC 4.4.1

```
main            proc near

var_20          = dword ptr -20h
var_4           = dword ptr -4

                push    ebp
                mov     ebp, esp
                and     esp, 0FFFFFFF0h
                sub     esp, 20h
                mov     [esp+20h+var_4], 2  ; (i) initializing
                jmp     short loc_8048476

loc_8048465:
                mov     eax, [esp+20h+var_4]
                mov     [esp+20h+var_20], eax
                call    printing_function
                add     [esp+20h+var_4], 1  ; (i) increment

loc_8048476:
                cmp     [esp+20h+var_4], 9
                jle     short loc_8048465   ; if i<=9, continue loop
                mov     eax, 0
                leave
                retn
main            endp
```

Now let's see what we get with optimization turned on (/Ox):

Listing 1.164: Optimizing MSVC

```
_main    PROC
    push   esi
    mov    esi, 2
$LL3@main:
    push   esi
    call   _printing_function
    inc    esi
    add    esp, 4
    cmp    esi, 10     ; 0000000aH
    jl     SHORT $LL3@main
    xor    eax, eax
    pop    esi
    ret    0
_main    ENDP
```

What happens here is that space for the i variable is not allocated in the local stack anymore, but uses an individual register for it, ESI. This is possible in such small functions where there aren't many local variables.

One very important thing is that the `f()` function must not change the value in ESI. Our compiler is sure here. And if the compiler decides to use the ESI register in `f()` too, its value would have to be saved at the function's prologue and restored at the function's epilogue, almost like in our listing: please note `PUSH ESI/POP ESI` at the function start and end.

Let's try GCC 4.4.1 with maximal optimization turned on (-O3 option):

Listing 1.165: Optimizing GCC 4.4.1

```
main            proc near

var_10          = dword ptr -10h
```

```
                push    ebp
                mov     ebp, esp
                and     esp, 0FFFFFFF0h
                sub     esp, 10h
                mov     [esp+10h+var_10], 2
                call    printing_function
                mov     [esp+10h+var_10], 3
                call    printing_function
                mov     [esp+10h+var_10], 4
                call    printing_function
                mov     [esp+10h+var_10], 5
                call    printing_function
                mov     [esp+10h+var_10], 6
                call    printing_function
                mov     [esp+10h+var_10], 7
                call    printing_function
                mov     [esp+10h+var_10], 8
                call    printing_function
                mov     [esp+10h+var_10], 9
                call    printing_function
                xor     eax, eax
                leave
                retn
main            endp
```

Huh, GCC just unwound our loop.

Loop unwinding has an advantage in the cases when there aren't much iterations and we could cut some execution time by removing all loop support instructions. On the other side, the resulting code is obviously larger.

Big unrolled loops are not recommended in modern times, because bigger functions may require bigger cache footprint[100].

OK, let's increase the maximum value of the i variable to 100 and try again. GCC does:

Listing 1.166: GCC

```
                public main
main            proc near

var_20          = dword ptr -20h

                push    ebp
                mov     ebp, esp
                and     esp, 0FFFFFFF0h
                push    ebx
                mov     ebx, 2    ; i=2
                sub     esp, 1Ch

; aligning label loc_80484D0 (loop body begin) by 16-byte border:
                nop

loc_80484D0:
; pass (i) as first argument to printing_function():
                mov     [esp+20h+var_20], ebx
                add     ebx, 1    ; i++
                call    printing_function
                cmp     ebx, 64h  ; i==100?
                jnz     short loc_80484D0 ; if not, continue
                add     esp, 1Ch
                xor     eax, eax  ; return 0
                pop     ebx
                mov     esp, ebp
                pop     ebp
                retn
main            endp
```

[100] A very good article about it: [Ulrich Drepper, *What Every Programmer Should Know About Memory*, (2007)][101]. Another recommendations about loop unrolling from Intel are here: [[*Intel® 64 and IA-32 Architectures Optimization Reference Manual*, (2014)]3.4.1.7].

It is quite similar to what MSVC 2010 with optimization (/Ox) produce, with the exception that the EBX register is allocated for the i variable.

GCC is sure this register will not be modified inside of the `f()` function, and if it will, it will be saved at the function prologue and restored at epilogue, just like here in the `main()` function.

x86: OllyDbg

Let's compile our example in MSVC 2010 with `/Ox` and `/Ob0` options and load it into OllyDbg.

It seems that OllyDbg is able to detect simple loops and show them in square brackets, for convenience:

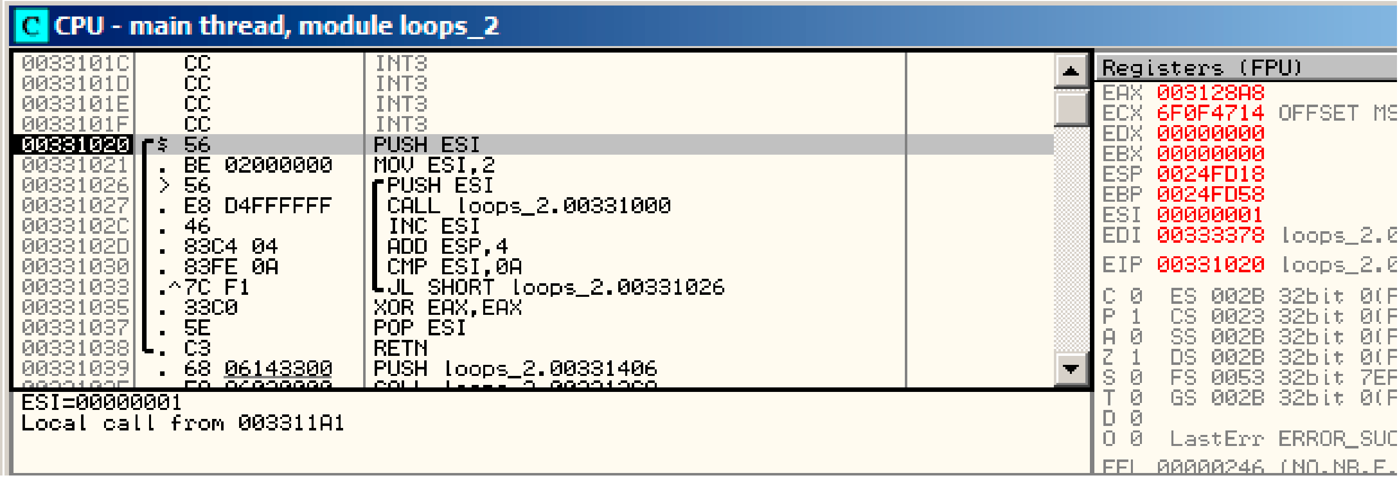


Figure 1.54: OllyDbg: `main()` begin

By tracing (F8 — step over) we see ESI incrementing. Here, for instance, $ESI = i = 6$:

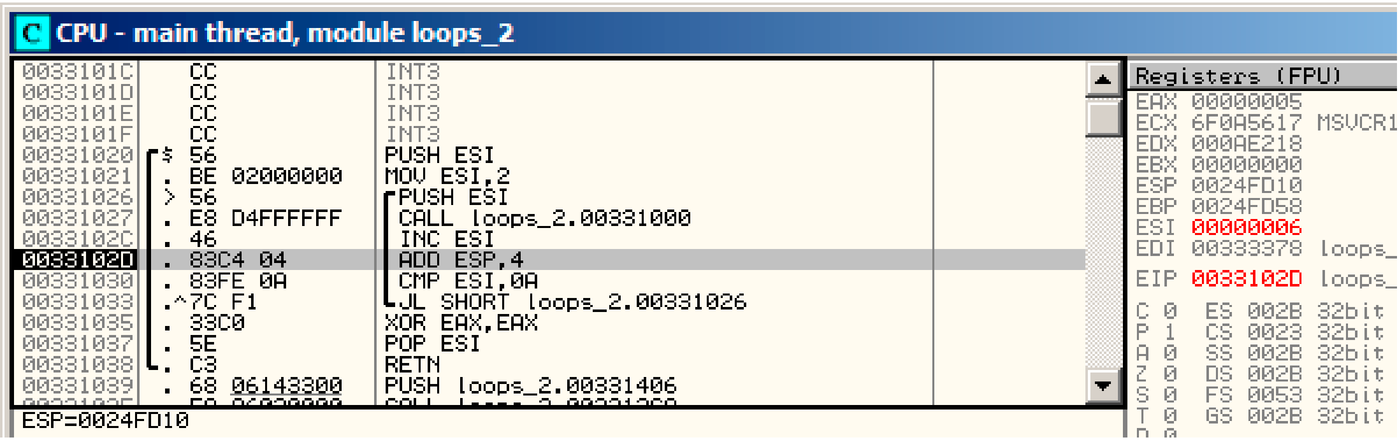


Figure 1.55: OllyDbg: loop body just executed with $i = 6$

9 is the last loop value. That's why JL is not triggering after the increment, and the function will finish:

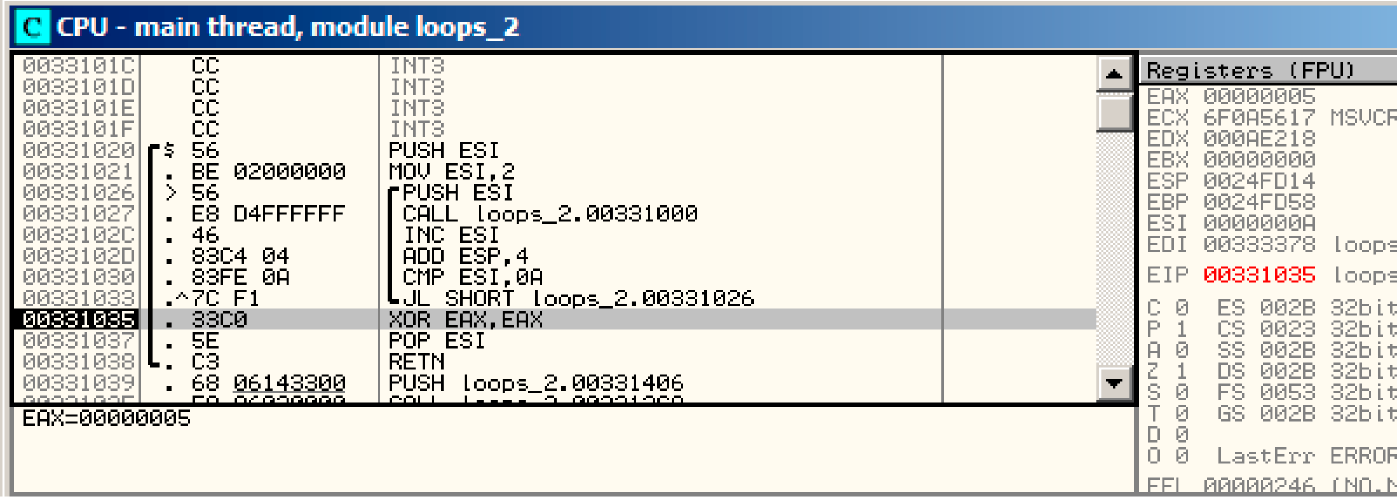


Figure 1.56: OllyDbg: $ESI = 10$, loop end

x86: tracer

As we might see, it is not very convenient to trace manually in the debugger. That's a reason we will try tracer.

We open compiled example in IDA, find the address of the instruction `PUSH ESI` (passing the sole argument to `f()`), which is `0x401026` for this case and we run the tracer:

```
tracer.exe -l:loops_2.exe bpx=loops_2.exe!0x00401026
```

BPX just sets a breakpoint at the address and tracer will then print the state of the registers.

In the `tracer.log`, this is what we see:

```
PID=12884|New process loops_2.exe
(0) loops_2.exe!0x401026
EAX=0x00a328c8 EBX=0x00000000 ECX=0x6f0f4714 EDX=0x00000000
ESI=0x00000002 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=PF ZF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000003 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF PF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000004 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF PF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000005 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000006 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF PF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000007 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000008 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
```

```
EIP=0x00331026
FLAGS=CF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000009 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF PF AF SF IF
PID=12884|Process loops_2.exe exited. ExitCode=0 (0x0)
```

We see how the value of ESI register changes from 2 to 9.

Even more than that, the tracer can collect register values for all addresses within the function. This is called *trace* there. Every instruction gets traced, all interesting register values are recorded.

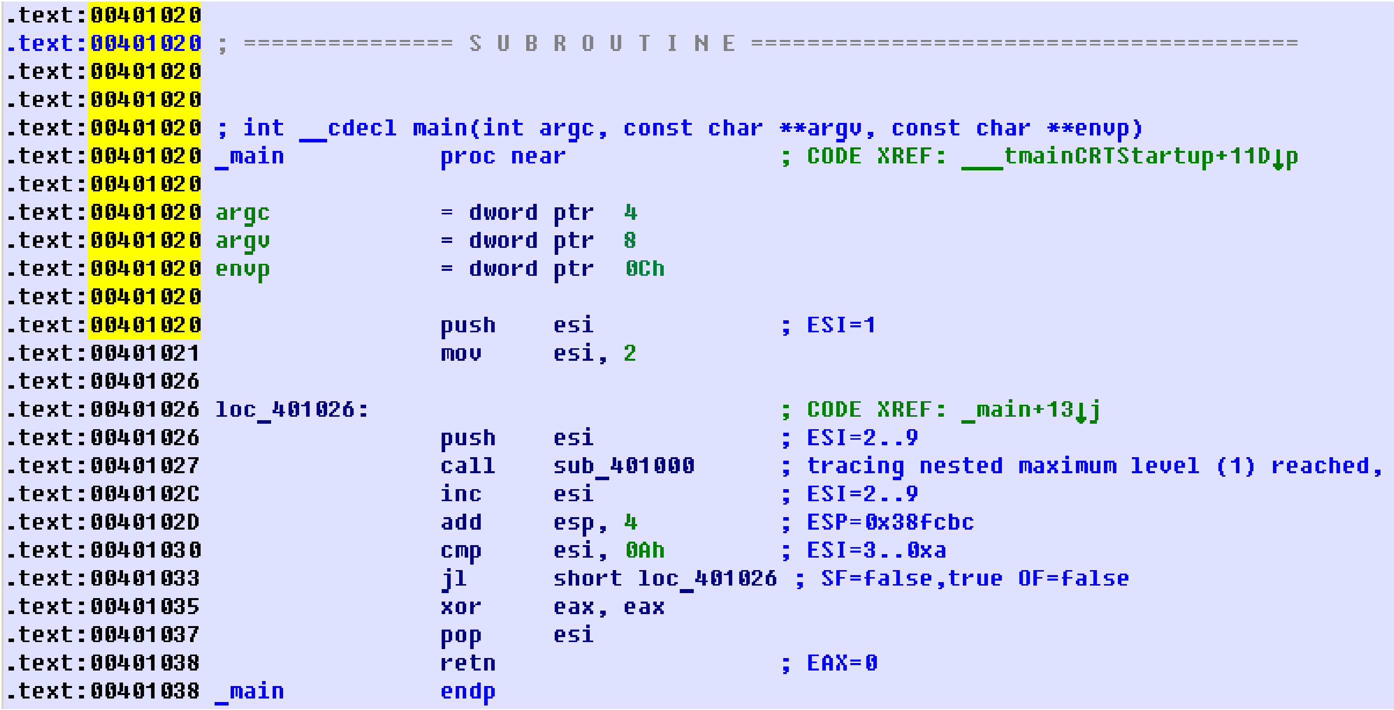
Then, an IDA.idc-script is generated, that adds comments. So, in the IDA we've learned that the `main()` function address is `0x00401020` and we run:

```
tracer.exe -l:loops_2.exe bpf=loops_2.exe!0x00401020,trace:cc
```

BPF stands for set breakpoint on function.

As a result, we get the `loops_2.exe.idc` and `loops_2.exe_clear.idc` scripts.

We load `loops_2.exe.idc` into IDA and see:



```
.text:00401020
.text:00401020 ; =============== S U B R O U T I N E =======================================
.text:00401020
.text:00401020
.text:00401020 ; int __cdecl main(int argc, const char **argv, const char **envp)
.text:00401020 _main           proc near               ; CODE XREF: ___tmainCRTStartup+11D↓p
.text:00401020
.text:00401020 argc            = dword ptr  4
.text:00401020 argv            = dword ptr  8
.text:00401020 envp            = dword ptr  0Ch
.text:00401020
.text:00401020                 push    esi             ; ESI=1
.text:00401021                 mov     esi, 2
.text:00401026
.text:00401026 loc_401026:                             ; CODE XREF: _main+13↓j
.text:00401026                 push    esi             ; ESI=2..9
.text:00401027                 call    sub_401000      ; tracing nested maximum level (1) reached,
.text:0040102C                 inc     esi             ; ESI=2..9
.text:0040102D                 add     esp, 4          ; ESP=0x38fcbc
.text:00401030                 cmp     esi, 0Ah        ; ESI=3..0xa
.text:00401033                 jl      short loc_401026 ; SF=false,true OF=false
.text:00401035                 xor     eax, eax
.text:00401037                 pop     esi
.text:00401038                 retn                    ; EAX=0
.text:00401038 _main           endp
```

Figure 1.57: IDA with .idc-script loaded

We see that ESI can be from 2 to 9 at the start of the loop body, but from 3 to 0xA (10) after the increment. We can also see that `main()` is finishing with 0 in EAX.

tracer also generates `loops_2.exe.txt`, that contains information about how many times each instruction has been executed and register values:

Listing 1.167: loops_2.exe.txt

```
0x401020 (.text+0x20), e=       1 [PUSH ESI] ESI=1
0x401021 (.text+0x21), e=       1 [MOV ESI, 2]
0x401026 (.text+0x26), e=       8 [PUSH ESI] ESI=2..9
0x401027 (.text+0x27), e=       8 [CALL 8D1000h] tracing nested maximum level (1) reached, ↙
    ↳ skipping this CALL 8D1000h=0x8d1000
0x40102c (.text+0x2c), e=       8 [INC ESI] ESI=2..9
0x40102d (.text+0x2d), e=       8 [ADD ESP, 4] ESP=0x38fcbc
0x401030 (.text+0x30), e=       8 [CMP ESI, 0Ah] ESI=3..0xa
0x401033 (.text+0x33), e=       8 [JL 8D1026h] SF=false,true OF=false
0x401035 (.text+0x35), e=       1 [XOR EAX, EAX]
0x401037 (.text+0x37), e=       1 [POP ESI]
0x401038 (.text+0x38), e=       1 [RETN] EAX=0
```

We can use grep here.

ARM

Non-optimizing Keil 6/2013 (ARM mode)

```
main
        STMFD   SP!, {R4,LR}
        MOV     R4, #2
        B       loc_368
loc_35C  ; CODE XREF: main+1C
        MOV     R0, R4
        BL      printing_function
        ADD     R4, R4, #1

loc_368  ; CODE XREF: main+8
```

```
        CMP     R4, #0xA
        BLT     loc_35C
        MOV     R0, #0
        LDMFD   SP!, {R4,PC}
```

Iteration counter i is to be stored in the R4 register. The MOV R4, #2 instruction just initializes i. The MOV R0, R4 and BL printing_function instructions compose the body of the loop, the first instruction preparing the argument for f() function and the second calling the function. The ADD R4, R4, #1 instruction just adds 1 to the i variable at each iteration. CMP R4, #0xA compares i with 0xA (10). The next instruction BLT (*Branch Less Than*) jumps if i is less than 10. Otherwise, 0 is to be written into R0 (since our function returns 0) and function execution finishes.

Optimizing Keil 6/2013 (Thumb mode)

```
_main
                PUSH    {R4,LR}
                MOVS    R4, #2

loc_132                                 ; CODE XREF: _main+E
                MOVS    R0, R4
                BL      printing_function
                ADDS    R4, R4, #1
                CMP     R4, #0xA
                BLT     loc_132
                MOVS    R0, #0
                POP     {R4,PC}
```

Practically the same.

Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```
_main
       PUSH            {R4,R7,LR}
       MOVW            R4, #0x1124 ; "%d\n"
       MOVS            R1, #2
       MOVT.W          R4, #0
       ADD             R7, SP, #4
       ADD             R4, PC
       MOV             R0, R4
       BLX             _printf
       MOV             R0, R4
       MOVS            R1, #3
       BLX             _printf
       MOV             R0, R4
       MOVS            R1, #4
       BLX             _printf
       MOV             R0, R4
       MOVS            R1, #5
       BLX             _printf
       MOV             R0, R4
       MOVS            R1, #6
       BLX             _printf
       MOV             R0, R4
       MOVS            R1, #7
       BLX             _printf
       MOV             R0, R4
       MOVS            R1, #8
       BLX             _printf
       MOV             R0, R4
       MOVS            R1, #9
       BLX             _printf
       MOVS            R0, #0
       POP             {R4,R7,PC}
```

In fact, this was in my f() function:

```
void printing_function(int i)
{
    printf ("%d\n", i);
};
```

So, LLVM not just *unrolled* the loop, but also *inlined* my very simple function f(), and inserted its body 8 times instead of calling it.

This is possible when the function is so simple (like mine) and when it is not called too much (like here).

ARM64: Optimizing GCC 4.9.1

Listing 1.168: Optimizing GCC 4.9.1

```
printing_function:
; prepare second argument of printf():
        mov     w1, w0
; load address of the "f(%d)\n" string
        adrp    x0, .LC0
        add     x0, x0, :lo12:.LC0
; just branch here instead of branch with link and return:
        b       printf
main:
; save FP and LR in the local stack:
        stp     x29, x30, [sp, -32]!
; set up stack frame:
        add     x29, sp, 0
; save contents of X19 register in the local stack:
        str     x19, [sp,16]
; we will use W19 register as counter.
; set initial value of 2 to it:
        mov     w19, 2
.L3:
; prepare first argument of printing_function():
        mov     w0, w19
; increment counter register.
        add     w19, w19, 1
; W0 here still holds value of counter value before increment.
        bl      printing_function
; is it end?
        cmp     w19, 10
; no, jump to the loop body begin:
        bne     .L3
; return 0
        mov     w0, 0
; restore contents of X19 register:
        ldr     x19, [sp,16]
; restore FP and LR values:
        ldp     x29, x30, [sp], 32
        ret
.LC0:
        .string "f(%d)\n"
```

ARM64: Non-optimizing GCC 4.9.1

Listing 1.169: Non-optimizing GCC 4.9.1 -fno-inline

```
printing_function:
; prepare second argument of printf():
        mov     w1, w0
; load address of the "f(%d)\n" string
        adrp    x0, .LC0
        add     x0, x0, :lo12:.LC0
; just branch here instead of branch with link and return:
        b       printf
```

```
main:
; save FP and LR in the local stack:
        stp     x29, x30, [sp, -32]!
; set up stack frame:
        add     x29, sp, 0
; save contents of X19 register in the local stack:
        str     x19, [sp,16]
; we will use W19 register as counter.
; set initial value of 2 to it:
        mov     w19, 2
.L3:
; prepare first argument of printing_function():
        mov     w0, w19
; increment counter register.
        add     w19, w19, 1
; W0 here still holds value of counter value before increment.
        bl      printing_function
; is it end?
        cmp     w19, 10
; no, jump to the loop body begin:
        bne     .L3
; return 0
        mov     w0, 0
; restore contents of X19 register:
        ldr     x19, [sp,16]
; restore FP and LR values:
        ldp     x29, x30, [sp], 32
        ret
.LC0:
        .string "f(%d)\n"
```

MIPS

Listing 1.170: Non-optimizing GCC 4.4.5 (IDA)

```
main:

; IDA is not aware of variable names in local stack
; We gave them names manually:
i               = -0x10
saved_FP        = -8
saved_RA        = -4

; function prologue:
                addiu   $sp, -0x28
                sw      $ra, 0x28+saved_RA($sp)
                sw      $fp, 0x28+saved_FP($sp)
                move    $fp, $sp
; initialize counter at 2 and store this value in local stack
                li      $v0, 2
                sw      $v0, 0x28+i($fp)
; pseudoinstruction. "BEQ $ZERO, $ZERO, loc_9C" there in fact:
                b       loc_9C
                or      $at, $zero ; branch delay slot, NOP

loc_80:                                  # CODE XREF: main+48
; load counter value from local stack and call printing_function():
                lw      $a0, 0x28+i($fp)
                jal     printing_function
                or      $at, $zero ; branch delay slot, NOP
; load counter, increment it, store it back:
                lw      $v0, 0x28+i($fp)
                or      $at, $zero ; NOP
                addiu   $v0, 1
                sw      $v0, 0x28+i($fp)

loc_9C:                                  # CODE XREF: main+18
; check counter, is it 10?
```

```
                lw      $v0, 0x28+i($fp)
                or      $at, $zero ; NOP
                slti    $v0, 0xA
; if it is less than 10, jump to loc_80 (loop body begin):
                bnez    $v0, loc_80
                or      $at, $zero ; branch delay slot, NOP
; finishing, return 0:
                move    $v0, $zero
; function epilogue:
                move    $sp, $fp
                lw      $ra, 0x28+saved_RA($sp)
                lw      $fp, 0x28+saved_FP($sp)
                addiu   $sp, 0x28
                jr      $ra
                or      $at, $zero ; branch delay slot, NOP
```

The instruction that's new to us is B. It is actually the pseudo instruction (BEQ).

One more thing

In the generated code we can see: after initializing i, the body of the loop is not to be executed, as the condition for i is checked first, and only after that loop body can be executed. And that is correct.

Because, if the loop condition is not met at the beginning, the body of the loop must not be executed. This is possible in the following case:

```
for (i=0; i<total_entries_to_process; i++)
    loop_body;
```

If *total_entries_to_process* is 0, the body of the loop must not be executed at all.

This is why the condition checked before the execution.

However, an optimizing compiler may swap the condition check and loop body, if it sure that the situation described here is not possible (like in the case of our very simple example and using compilers like Keil, Xcode (LLVM), MSVC in optimization mode).

1.16.2 Memory blocks copying routine

Real-world memory copy routines may copy 4 or 8 bytes at each iteration, use SIMD[102], vectorization, etc. But for the sake of simplicity, this example is the simplest possible.

```
#include <stdio.h>

void my_memcpy (unsigned char* dst, unsigned char* src, size_t cnt)
{
        size_t i;
        for (i=0; i<cnt; i++)
                dst[i]=src[i];
};
```

Straight-forward implementation

Listing 1.171: GCC 4.9 x64 optimized for size (-Os)

```
my_memcpy:
; RDI = destination address
; RSI = source address
; RDX = size of block

; initialize counter (i) at 0
        xor     eax, eax
.L2:
```

[102] Single Instruction, Multiple Data

```
; all bytes copied? exit then:
        cmp     rax, rdx
        je      .L5
; load byte at RSI+i:
        mov     cl, BYTE PTR [rsi+rax]
; store byte at RDI+i:
        mov     BYTE PTR [rdi+rax], cl
        inc     rax ; i++
        jmp     .L2
.L5:
        ret
```

Listing 1.172: GCC 4.9 ARM64 optimized for size (-Os)

```
my_memcpy:
; X0 = destination address
; X1 = source address
; X2 = size of block

; initialize counter (i) at 0
        mov     x3, 0
.L2:
; all bytes copied? exit then:
        cmp     x3, x2
        beq     .L5
; load byte at X1+i:
        ldrb    w4, [x1,x3]
; store byte at X0+i:
        strb    w4, [x0,x3]
        add     x3, x3, 1 ; i++
        b       .L2
.L5:
        ret
```

Listing 1.173: Optimizing Keil 6/2013 (Thumb mode)

```
my_memcpy PROC
; R0 = destination address
; R1 = source address
; R2 = size of block

        PUSH     {r4,lr}
; initialize counter (i) at 0
        MOVS     r3,#0
; condition checked at the end of function, so jump there:
        B        |L0.12|
|L0.6|
; load byte at R1+i:
        LDRB     r4,[r1,r3]
; store byte at R0+i:
        STRB     r4,[r0,r3]
; i++
        ADDS     r3,r3,#1
|L0.12|
; i<size?
        CMP      r3,r2
; jump to the loop begin if its so:
        BCC      |L0.6|
        POP      {r4,pc}
        ENDP
```

ARM in ARM mode

Keil in ARM mode takes full advantage of conditional suffixes:

Listing 1.174: Optimizing Keil 6/2013 (ARM mode)

```
my_memcpy PROC
```

```
; R0 = destination address
; R1 = source address
; R2 = size of block

; initialize counter (i) at 0
        MOV      r3,#0
|L0.4|
; all bytes copied?
        CMP      r3,r2
; the following block is executed only if less than condition,
; i.e., if R2<R3 or i<size.
; load byte at R1+i:
        LDRBCC   r12,[r1,r3]
; store byte at R0+i:
        STRBCC   r12,[r0,r3]
; i++
        ADDCC    r3,r3,#1
; the last instruction of the conditional block.
; jump to loop begin if i<size
; do nothing otherwise (i.e., if i>=size)
        BCC      |L0.4|
; return
        BX       lr
        ENDP
```

That's why there is only one branch instruction instead of 2.

MIPS

Listing 1.175: GCC 4.4.5 optimized for size (-Os) (IDA)

```
my_memcpy:
; jump to loop check part:
                b       loc_14
; initialize counter (i) at 0
; it will always reside in $v0:
                move    $v0, $zero ; branch delay slot

loc_8:                                   # CODE XREF: my_memcpy+1C
; load byte as unsigned at address in $t0 to $v1:
                lbu     $v1, 0($t0)
; increment counter (i):
                addiu   $v0, 1
; store byte at $a3
                sb      $v1, 0($a3)

loc_14:                                  # CODE XREF: my_memcpy
; check if counter (i) in $v0 is still less then 3rd function argument ("cnt" in $a2):
                sltu    $v1, $v0, $a2
; form address of byte in source block:
                addu    $t0, $a1, $v0
; $t0 = $a1+$v0 = src+i
; jump to loop body if counter sill less then "cnt":
                bnez    $v1, loc_8
; form address of byte in destination block ($a3 = $a0+$v0 = dst+i):
                addu    $a3, $a0, $v0 ; branch delay slot
; finish if BNEZ wasnt triggered:
                jr      $ra
                or      $at, $zero ; branch delay slot, NOP
```

Here we have two new instructions: LBU ("Load Byte Unsigned") and SB ("Store Byte").

Just like in ARM, all MIPS registers are 32-bit wide, there are no byte-wide parts like in x86.

So when dealing with single bytes, we have to allocate whole 32-bit registers for them.

LBU loads a byte and clears all other bits ("Unsigned").

On the other hand, LB ("Load Byte") instruction sign-extends the loaded byte to a 32-bit value.

SB just writes a byte from lowest 8 bits of register to memory.

Vectorization

Optimizing GCC can do much more on this example: 1.29.1 on page 412.

1.16.3 Condition check

It's important to keep in mind that in *for()* construct, condition is checked not at the end, but at the beginning, before execution of loop body. But often, it's more convenient for compiler to check it at the end, after body. Sometimes, additional check can be appended at the beginning.

For example:

```
#include <stdio.h>

void f(int start, int finish)
{
        for (; start<finish; start++)
                printf ("%d\n", start);
};
```

Optimizing GCC 5.4.0 x64:

```
f:
; check condition (1):
        cmp     edi, esi
        jge     .L9
        push    rbp
        push    rbx
        mov     ebp, esi
        mov     ebx, edi
        sub     rsp, 8
.L5:
        mov     edx, ebx
        xor     eax, eax
        mov     esi, OFFSET FLAT:.LC0 ; '%d\n"
        mov     edi, 1
        add     ebx, 1
        call    __printf_chk
; check condition (2):
        cmp     ebp, ebx
        jne     .L5
        add     rsp, 8
        pop     rbx
        pop     rbp
.L9:
        rep ret
```

We see two checks.

Hex-Rays (at least version 2.2.0) decompiles this as:

```
void __cdecl f(unsigned int start, unsigned int finish)
{
  unsigned int v2; // ebx@2
  __int64 v3; // rdx@3

  if ( (signed int)start < (signed int)finish )
  {
    v2 = start;
    do
    {
      v3 = v2++;
      _printf_chk(1LL, "%d\n", v3);
    }
    while ( finish != v2 );
```

```
  }
}
```

In this case, *do/while()* can be replaced by *for()* without any doubt, and the first check can be removed.

1.16.4 Conclusion

Rough skeleton of loop from 2 to 9 inclusive:

Listing 1.176: x86

```
    mov [counter], 2 ; initialization
    jmp check
body:
    ; loop body
    ; do something here
    ; use counter variable in local stack
    add [counter], 1 ; increment
check:
    cmp [counter], 9
    jle body
```

The increment operation may be represented as 3 instructions in non-optimized code:

Listing 1.177: x86

```
    MOV [counter], 2 ; initialization
    JMP check
body:
    ; loop body
    ; do something here
    ; use counter variable in local stack
    MOV REG, [counter] ; increment
    INC REG
    MOV [counter], REG
check:
    CMP [counter], 9
    JLE body
```

If the body of the loop is short, a whole register can be dedicated to the counter variable:

Listing 1.178: x86

```
    MOV EBX, 2 ; initialization
    JMP check
body:
    ; loop body
    ; do something here
    ; use counter in EBX, but do not modify it!
    INC EBX ; increment
check:
    CMP EBX, 9
    JLE body
```

Some parts of the loop may be generated by compiler in different order:

Listing 1.179: x86

```
    MOV [counter], 2 ; initialization
    JMP label_check
label_increment:
    ADD [counter], 1 ; increment
label_check:
    CMP [counter], 10
    JGE exit
    ; loop body
    ; do something here
    ; use counter variable in local stack
    JMP label_increment
exit:
```

Usually the condition is checked *before* loop body, but the compiler may rearrange it in a way that the condition is checked *after* loop body.

This is done when the compiler is sure that the condition is always *true* on the first iteration, so the body of the loop is to be executed at least once:

Listing 1.180: x86

```
    MOV REG, 2 ; initialization
body:
    ; loop body
    ; do something here
    ; use counter in REG, but do not modify it!
    INC REG ; increment
    CMP REG, 10
    JL body
```

Using the LOOP instruction. This is rare, compilers are not using it. When you see it, it's a sign that this piece of code is hand-written:

Listing 1.181: x86

```
    ; count from 10 to 1
    MOV ECX, 10
body:
    ; loop body
    ; do something here
    ; use counter in ECX, but do not modify it!
    LOOP body
```

ARM.

The R4 register is dedicated to counter variable in this example:

Listing 1.182: ARM

```
    MOV R4, 2 ; initialization
    B check
body:
    ; loop body
    ; do something here
    ; use counter in R4, but do not modify it!
    ADD R4,R4, #1 ; increment
check:
    CMP R4, #10
    BLT body
```

1.16.5 Exercises

- `http://challenges.re/54`
- `http://challenges.re/55`
- `http://challenges.re/56`
- `http://challenges.re/57`

1.17 More about strings

1.17.1 strlen()

Let's talk about loops one more time. Often, the `strlen()` function [103] is implemented using a `while()` statement. Here is how it is done in the MSVC standard libraries:

[103] counting the characters in a string in the C language

```
int my_strlen (const char * str)
{
        const char *eos = str;

        while( *eos++ ) ;

        return( eos - str - 1 );
}

int main()
{
        // test
        return my_strlen("hello!");
};
```

x86

Non-optimizing MSVC

Let's compile:

```
_eos$ = -4                          ; size = 4
_str$ = 8                           ; size = 4
_strlen PROC
    push    ebp
    mov     ebp, esp
    push    ecx
    mov     eax, DWORD PTR _str$[ebp]  ; place pointer to string from "str"
    mov     DWORD PTR _eos$[ebp], eax  ; place it to local variable "eos"
$LN2@strlen_:
    mov     ecx, DWORD PTR _eos$[ebp]  ; ECX=eos

    ; take 8-bit byte from address in ECX and place it as 32-bit value to EDX with sign ↙
    ↳ extension

    movsx   edx, BYTE PTR [ecx]
    mov     eax, DWORD PTR _eos$[ebp]  ; EAX=eos
    add     eax, 1                     ; increment EAX
    mov     DWORD PTR _eos$[ebp], eax  ; place EAX back to "eos"
    test    edx, edx                   ; EDX is zero?
    je      SHORT $LN1@strlen_         ; yes, then finish loop
    jmp     SHORT $LN2@strlen_         ; continue loop
$LN1@strlen_:

    ; here we calculate the difference between two pointers

    mov    eax, DWORD PTR _eos$[ebp]
    sub    eax, DWORD PTR _str$[ebp]
    sub    eax, 1                      ; subtract 1 and return result
    mov    esp, ebp
    pop    ebp
    ret    0
_strlen_ ENDP
```

We get two new instructions here: MOVSX and TEST.

The first one—MOVSX—takes a byte from an address in memory and stores the value in a 32-bit register. MOVSX stands for *MOV with Sign-Extend*. MOVSX sets the rest of the bits, from the 8th to the 31th, to 1 if the source byte is *negative* or to 0 if is *positive*.

And here is why.

By default, the *char* type is signed in MSVC and GCC. If we have two values of which one is *char* and the other is *int*, (*int* is signed too), and if the first value contain -2 (coded as 0xFE) and we just copy this byte into the *int* container, it makes 0x000000FE, and this from the point of signed *int* view is 254, but not -2. In signed int, -2 is coded as 0xFFFFFFFE. So if we have to transfer 0xFE from a variable of *char* type to *int*, we have to identify its sign and extend it. That is what MOVSX does.

You can also read about it in "*Signed number representations*" section (2.2 on page 452).

It's hard to say if the compiler needs to store a *char* variable in EDX, it could just take a 8-bit register part (for example DL). Apparently, the compiler's register allocator works like that.

Then we see TEST EDX, EDX. You can read more about the TEST instruction in the section about bit fields (1.22 on page 304). Here this instruction just checks if the value in EDX equals to 0.

Non-optimizing GCC

Let's try GCC 4.4.1:

```
                public strlen
strlen          proc near

eos             = dword ptr -4
arg_0           = dword ptr  8

                push    ebp
                mov     ebp, esp
                sub     esp, 10h
                mov     eax, [ebp+arg_0]
                mov     [ebp+eos], eax

loc_80483F0:
                mov     eax, [ebp+eos]
                movzx   eax, byte ptr [eax]
                test    al, al
                setnz   al
                add     [ebp+eos], 1
                test    al, al
                jnz     short loc_80483F0
                mov     edx, [ebp+eos]
                mov     eax, [ebp+arg_0]
                mov     ecx, edx
                sub     ecx, eax
                mov     eax, ecx
                sub     eax, 1
                leave
                retn
strlen          endp
```

The result is almost the same as in MSVC, but here we see MOVZX instead of MOVSX. MOVZX stands for *MOV with Zero-Extend*. This instruction copies a 8-bit or 16-bit value into a 32-bit register and sets the rest of the bits to 0. In fact, this instruction is convenient only because it enable us to replace this instruction pair:
`xor eax, eax / mov al, [...]`.

On the other hand, it is obvious that the compiler could produce this code:
`mov al, byte ptr [eax] / test al, al`—it is almost the same, however, the highest bits of the EAX register will contain random noise. But let's think it is compiler's drawback—it cannot produce more understandable code. Strictly speaking, the compiler is not obliged to emit understandable (to humans) code at all.

The next new instruction for us is SETNZ. Here, if AL doesn't contain zero, `test al, al` sets the ZF flag to 0, but SETNZ, if ZF==0 (*NZ* stands for *not zero*) sets AL to 1. Speaking in natural language, *if AL is not zero, let's jump to loc_80483F0*. The compiler emits some redundant code, but let's not forget that the optimizations are turned off.

Optimizing MSVC

Now let's compile all this in MSVC 2012, with optimizations turned on (/Ox):

Listing 1.183: Optimizing MSVC 2012 /Ob0

```
_str$ = 8                               ; size = 4
_strlen PROC
```

```
        mov     edx, DWORD PTR _str$[esp-4] ; EDX -> pointer to the string
        mov     eax, edx                    ; move to EAX
$LL2@strlen:
        mov     cl, BYTE PTR [eax]          ; CL = *EAX
        inc     eax                         ; EAX++
        test    cl, cl                      ; CL==0?
        jne     SHORT $LL2@strlen           ; no, continue loop
        sub     eax, edx                    ; calculate pointers difference
        dec     eax                         ; decrement EAX
        ret     0
_strlen ENDP
```

Now it is all simpler. Needless to say, the compiler could use registers with such efficiency only in small functions with a few local variables.

INC/DEC—are increment/decrement instructions, in other words: add or subtract 1 to/from a variable.

Optimizing MSVC + OllyDbg

We can try this (optimized) example in OllyDbg. Here is the first iteration:

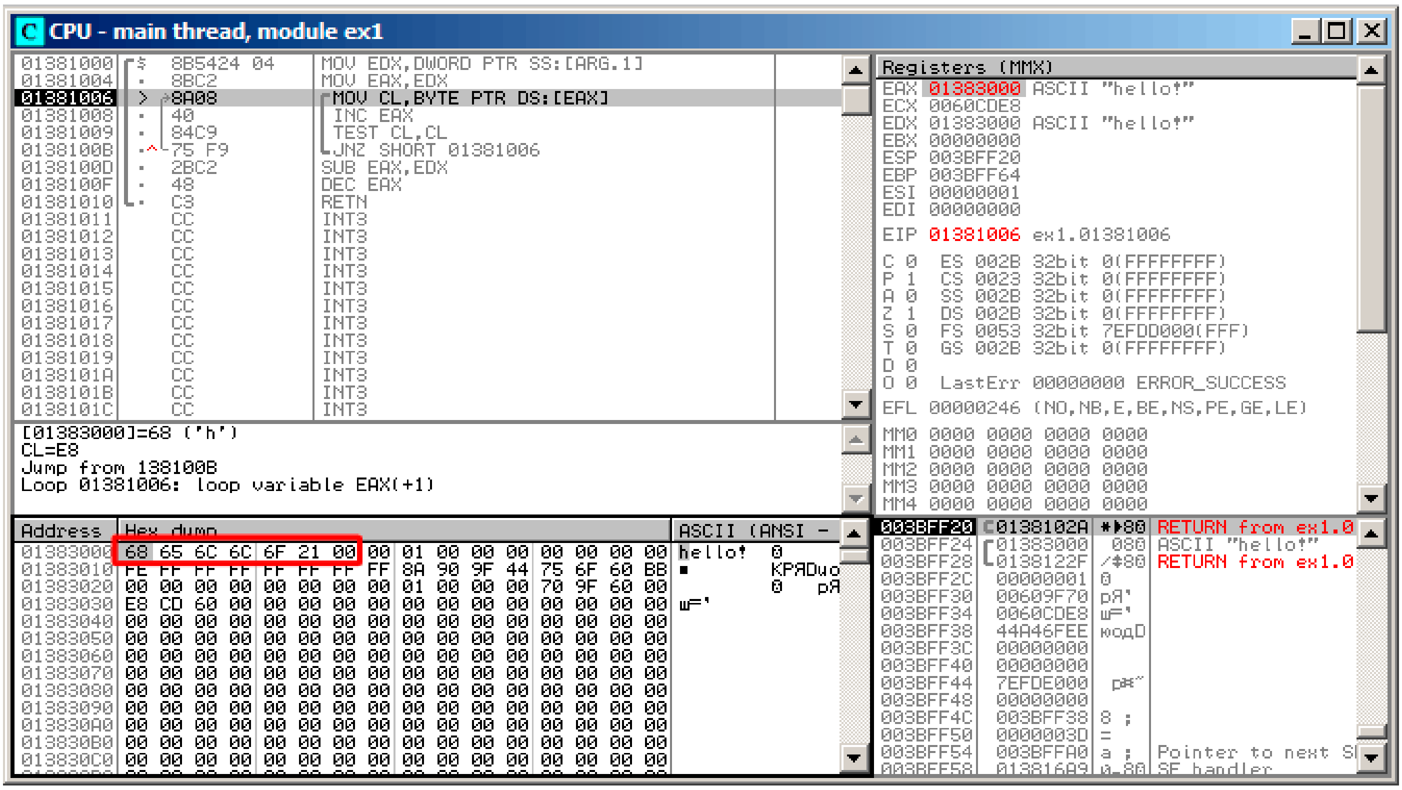


Figure 1.58: OllyDbg: first iteration start

We see that OllyDbg found a loop and, for convenience, *wrapped* its instructions in brackets. By clicking the right button on EAX, we can choose “Follow in Dump” and the memory window scrolls to the right place. Here we can see the string “hello!” in memory. There is at least one zero byte after it and then random garbage.

If OllyDbg sees a register with a valid address in it, that points to some string, it is shown as a string.

Let's press F8 (step over) a few times, to get to the start of the body of the loop:

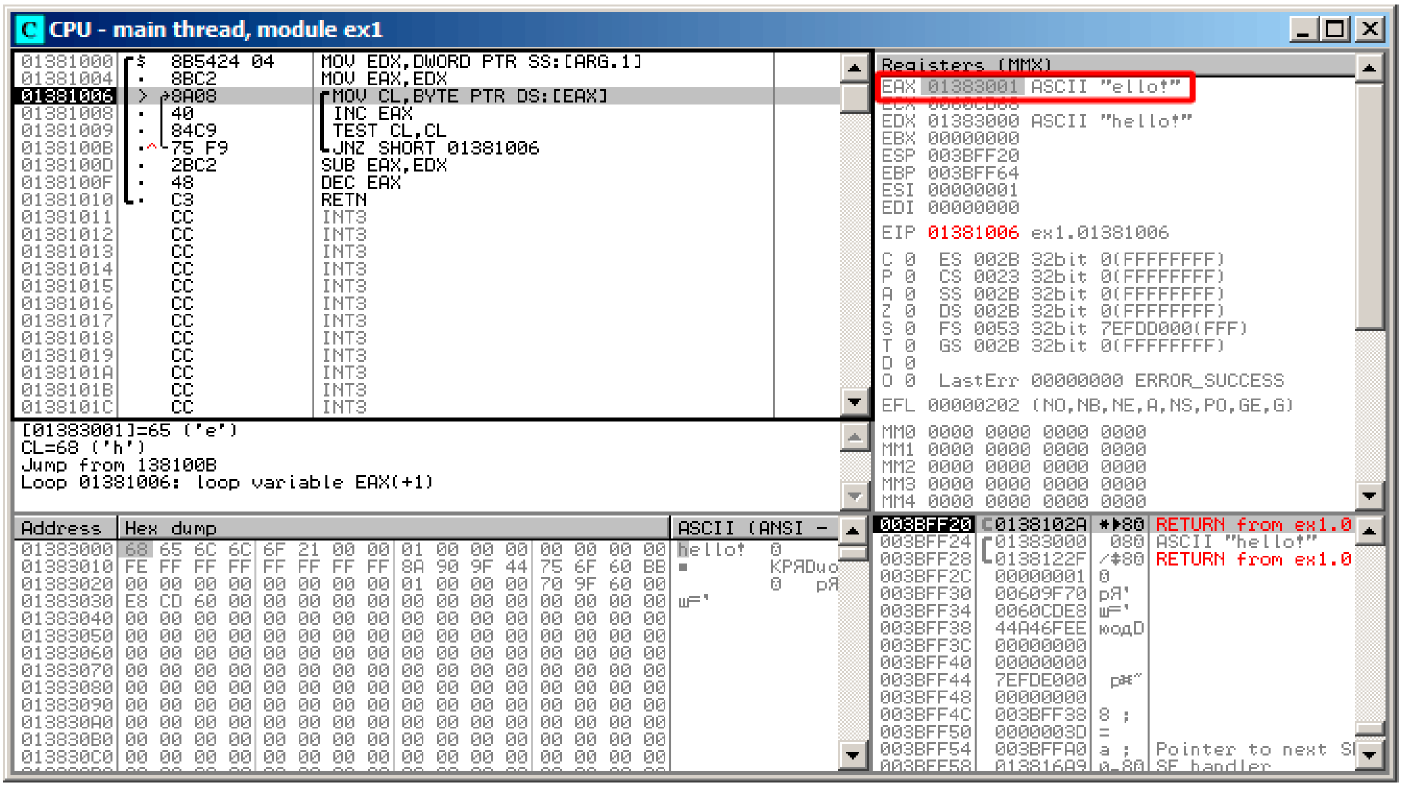


Figure 1.59: OllyDbg: second iteration start

We see that EAX contains the address of the second character in the string.

We have to press F8 enough number of times in order to escape from the loop:

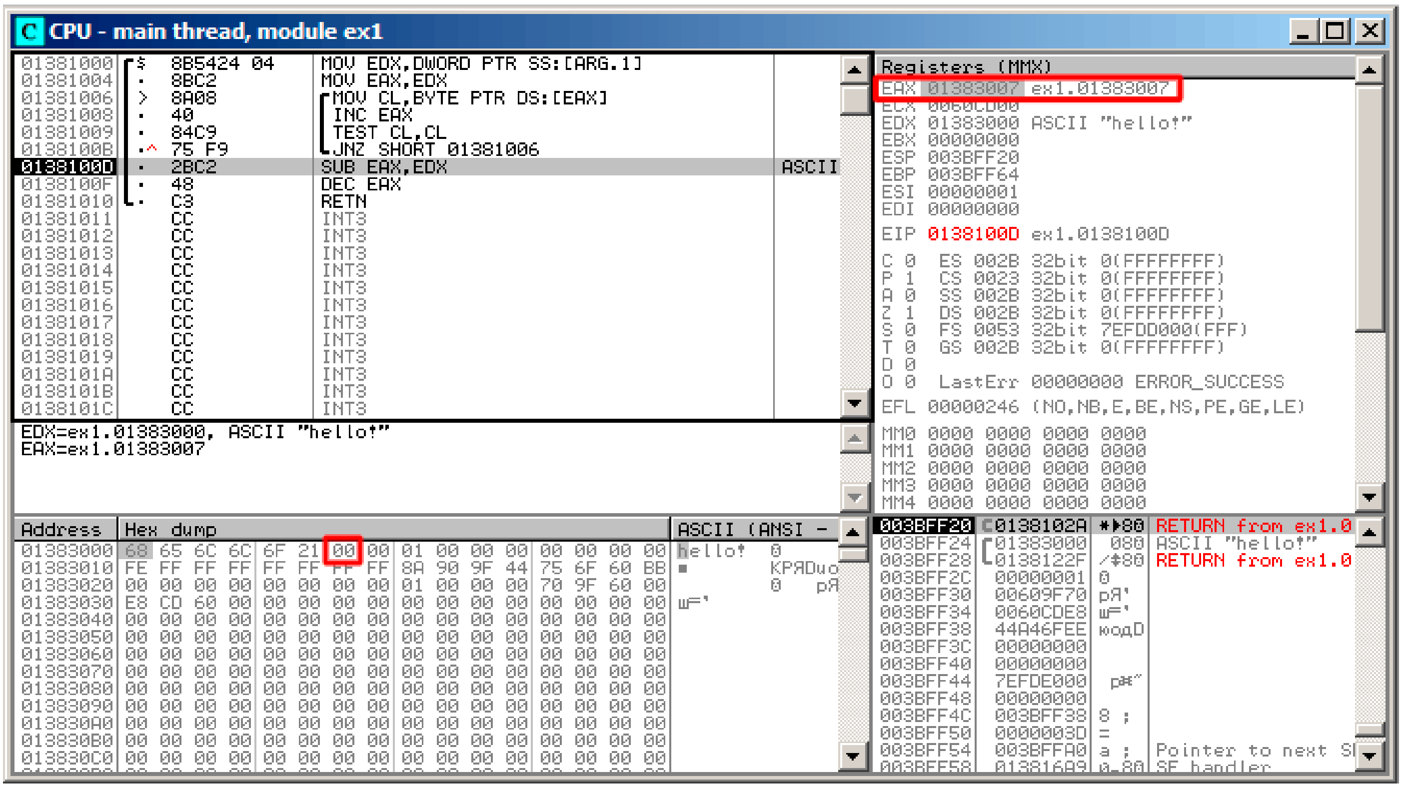


Figure 1.60: OllyDbg: pointers difference to be calculated now

We see that EAX now contains the address of zero byte that's right after the string. Meanwhile, EDX hasn't changed, so it still pointing to the start of the string.

The difference between these two addresses is being calculated now.

The SUB instruction just got executed:

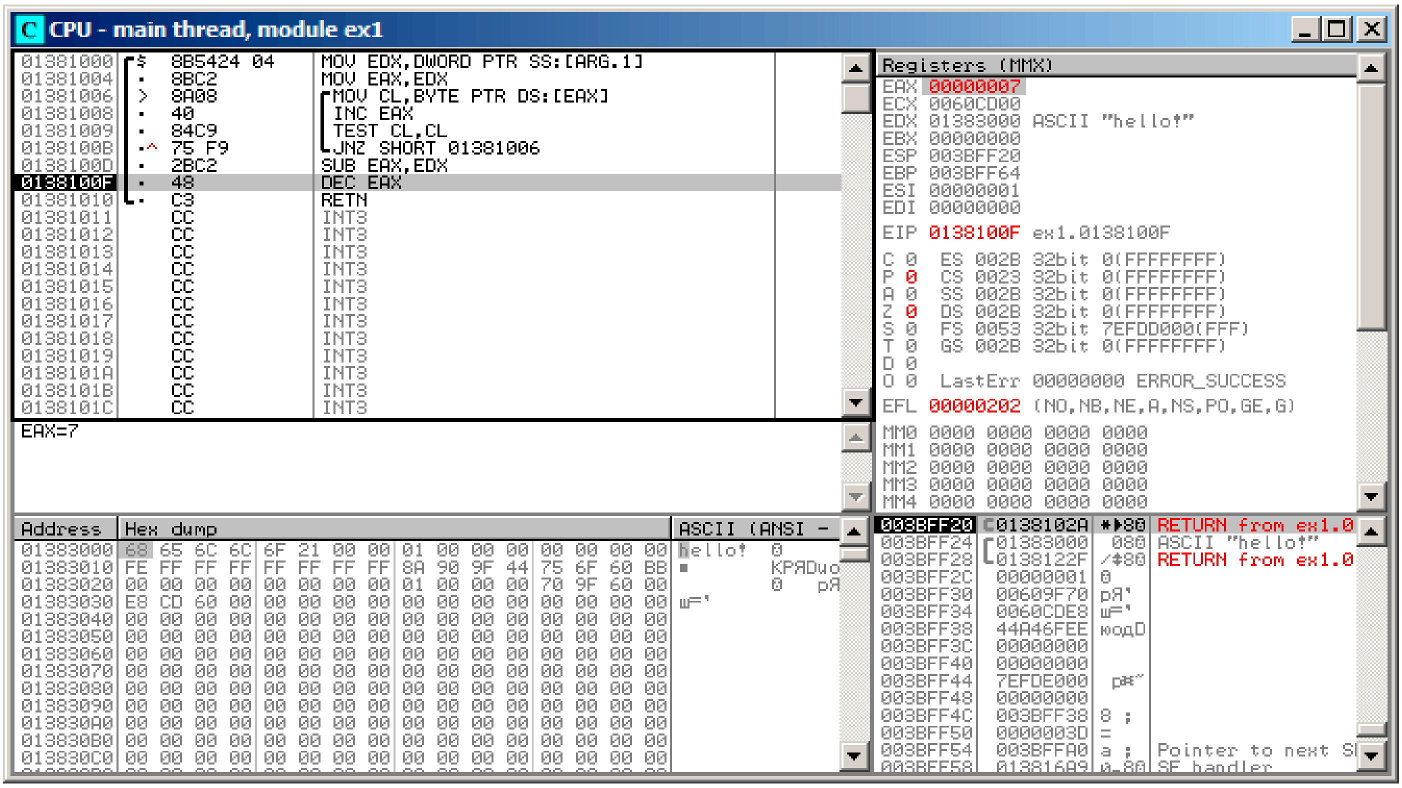


Figure 1.61: OllyDbg: EAX to be decremented now

The difference of pointers is in the EAX register now—7. Indeed, the length of the "hello!" string is 6, but with the zero byte included—7. But `strlen()` must return the number of non-zero characters in the string. So the decrement executes and then the function returns.

Optimizing GCC

Let's check GCC 4.4.1 with optimizations turned on (-O3 key):

```
                public strlen
strlen          proc near

arg_0           = dword ptr  8

                push    ebp
                mov     ebp, esp
                mov     ecx, [ebp+arg_0]
                mov     eax, ecx

loc_8048418:
                movzx   edx, byte ptr [eax]
                add     eax, 1
                test    dl, dl
                jnz     short loc_8048418
                not     ecx
                add     eax, ecx
                pop     ebp
                retn
strlen          endp
```

Here GCC is almost the same as MSVC, except for the presence of MOVZX. However, here MOVZX could be replaced with
`mov dl, byte ptr [eax]`.

Perhaps it is simpler for GCC's code generator to *remember* the whole 32-bit EDX register is allocated for a *char* variable and it then can be sure that the highest bits has no any noise at any point.

After that we also see a new instruction—NOT. This instruction inverts all bits in the operand.
You can say that it is a synonym to the XOR ECX, 0ffffffffh instruction. NOT and the following ADD calculate the pointer difference and subtract 1, just in a different way. At the start ECX, where the pointer to *str* is stored, gets inverted and 1 is subtracted from it.

See also: "Signed number representations" (2.2 on page 452).

In other words, at the end of the function just after loop body, these operations are executed:

```
ecx=str;
eax=eos;
ecx=(-ecx)-1;
eax=eax+ecx
return eax
```

... and this is effectively equivalent to:

```
ecx=str;
eax=eos;
eax=eax-ecx;
eax=eax-1;
return eax
```

Why did GCC decide it would be better? Hard to guess. But perhaps the both variants are equivalent in efficiency.

ARM

32-bit ARM

Non-optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 1.184: Non-optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
_strlen

eos  = -8
str  = -4

     SUB    SP, SP, #8 ; allocate 8 bytes for local variables
     STR    R0, [SP,#8+str]
     LDR    R0, [SP,#8+str]
     STR    R0, [SP,#8+eos]

loc_2CB8 ; CODE XREF: _strlen+28
     LDR    R0, [SP,#8+eos]
     ADD    R1, R0, #1
     STR    R1, [SP,#8+eos]
     LDRSB  R0, [R0]
     CMP    R0, #0
     BEQ    loc_2CD4
     B      loc_2CB8
loc_2CD4 ; CODE XREF: _strlen+24
     LDR    R0, [SP,#8+eos]
     LDR    R1, [SP,#8+str]
     SUB    R0, R0, R1 ; R0=eos-str
     SUB    R0, R0, #1 ; R0=R0-1
     ADD    SP, SP, #8 ; free allocated 8 bytes
     BX     LR
```

Non-optimizing LLVM generates too much code, however, here we can see how the function works with local variables in the stack. There are only two local variables in our function: *eos* and *str*. In this listing, generated by IDA, we have manually renamed *var_8* and *var_4* to *eos* and *str*.

The first instructions just saves the input values into both *str* and *eos*.

The body of the loop starts at label *loc_2CB8*.

The first three instruction in the loop body (LDR, ADD, STR) load the value of *eos* into R0. Then the value is incremented and saved back into *eos*, which is located in the stack.

The next instruction, LDRSB R0, [R0] ("Load Register Signed Byte"), loads a byte from memory at the address stored in R0 and sign-extends it to 32-bit [104]. This is similar to the MOVSX instruction in x86.

The compiler treats this byte as signed since the *char* type is signed according to the C standard. It was already written about it (1.17.1 on page 201) in this section, in relation to x86.

It has to be noted that it is impossible to use 8- or 16-bit part of a 32-bit register in ARM separately of the whole register, as it is in x86.

Apparently, it is because x86 has a huge history of backwards compatibility with its ancestors up to the 16-bit 8086 and even 8-bit 8080, but ARM was developed from scratch as a 32-bit RISC-processor.

Consequently, in order to process separate bytes in ARM, one has to use 32-bit registers anyway.

So, LDRSB loads bytes from the string into R0, one by one. The following CMP and BEQ instructions check if the loaded byte is 0. If it's not 0, control passes to the start of the body of the loop. And if it's 0, the loop ends.

At the end of the function, the difference between *eos* and *str* is calculated, 1 is subtracted from it, and resulting value is returned via R0.

N.B. Registers were not saved in this function.

That's because in the ARM calling convention registers R0-R3 are "scratch registers", intended for arguments passing, and we're not required to restore their value when the function exits, since the calling function will not use them anymore. Consequently, they may be used for anything we want.

No other registers are used here, so that is why we have nothing to save on the stack.

Thus, control may be returned back to calling function by a simple jump (BX), to the address in the LR register.

Optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

Listing 1.185: Optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

```
_strlen
           MOV       R1, R0

loc_2DF6
           LDRB.W    R2, [R1],#1
           CMP       R2, #0
           BNE       loc_2DF6
           MVNS      R0, R0
           ADD       R0, R1
           BX        LR
```

As optimizing LLVM concludes, *eos* and *str* do not need space on the stack, and can always be stored in registers.

Before the start of the loop body, *str* is always in R0, and *eos*—in R1.

The LDRB.W R2, [R1],#1 instruction loads a byte from the memory at the address stored in R1, to R2, sign-extending it to a 32-bit value, but not just that. #1 at the instruction's end is implies "Post-indexed addressing", which means that 1 is to be added to R1 after the byte is loaded. Read more about it: 1.32.2 on page 439.

Then you can see CMP and BNE[105] in the body of the loop, these instructions continue looping until 0 is found in the string.

[104] The Keil compiler treats the *char* type as signed, just like MSVC and GCC.
[105] (PowerPC, ARM) Branch if Not Equal

MVNS[106] (inverts all bits, like NOT in x86) and ADD instructions compute $eos - str - 1$. In fact, these two instructions compute $R0 = str + eos$, which is effectively equivalent to what was in the source code, and why it is so, was already explained here (1.17.1 on page 208).

Apparently, LLVM, just like GCC, concludes that this code can be shorter (or faster).

Optimizing Keil 6/2013 (ARM mode)

Listing 1.186: Optimizing Keil 6/2013 (ARM mode)

```
_strlen
                MOV     R1, R0

loc_2C8
                LDRB    R2, [R1],#1
                CMP     R2, #0
                SUBEQ   R0, R1, R0
                SUBEQ   R0, R0, #1
                BNE     loc_2C8
                BX      LR
```

Almost the same as what we saw before, with the exception that the $str-eos-1$ expression can be computed not at the function's end, but right in the body of the loop. The -EQ suffix, as we may recall, implies that the instruction executes only if the operands in the CMP that has been executed before were equal to each other. Thus, if R0 contains 0, both SUBEQ instructions executes and result is left in the R0 register.

ARM64

Optimizing GCC (Linaro) 4.9

```
my_strlen:
        mov     x1, x0
        ; X1 is now temporary pointer (eos), acting like cursor
.L58:
        ; load byte from X1 to W2, increment X1 (post-index)
        ldrb    w2, [x1],1
        ; Compare and Branch if NonZero: compare W2 with 0, jump to .L58 if it is not
        cbnz    w2, .L58
        ; calculate difference between initial pointer in X0 and current address in X1
        sub     x0, x1, x0
        ; decrement lowest 32-bit of result
        sub     w0, w0, #1
        ret
```

The algorithm is the same as in 1.17.1 on page 202: find a zero byte, calculate the difference between the pointers and decrement the result by 1. Some comments were added by the author of this book.

The only thing worth noting is that our example is somewhat wrong:
my_strlen() returns 32-bit *int*, while it has to return size_t or another 64-bit type.

The reason is that, theoretically, strlen() can be called for a huge blocks in memory that exceeds 4GB, so it must able to return a 64-bit value on 64-bit platforms.

Because of my mistake, the last SUB instruction operates on a 32-bit part of register, while the penultimate SUB instruction works on full the 64-bit register (it calculates the difference between the pointers).

It's my mistake, it is better to leave it as is, as an example of how the code could look like in such case.

[106] MoVe Not

Non-optimizing GCC (Linaro) 4.9

```
my_strlen:
; function prologue
        sub     sp, sp, #32
; first argument (str) will be stored in [sp,8]
        str     x0, [sp,8]
        ldr     x0, [sp,8]
; copy "str" to "eos" variable
        str     x0, [sp,24]
        nop
.L62:
; eos++
        ldr     x0, [sp,24]  ; load "eos" to X0
        add     x1, x0, 1    ; increment X0
        str     x1, [sp,24]  ; save X0 to "eos"
; load byte from memory at address in X0 to W0
        ldrb    w0, [x0]
; is it zero? (WZR is the 32-bit register always contain zero)
        cmp     w0, wzr
; jump if not zero (Branch Not Equal)
        bne     .L62
; zero byte found. now calculate difference.
; load "eos" to X1
        ldr     x1, [sp,24]
; load "str" to X0
        ldr     x0, [sp,8]
; calculate difference
        sub     x0, x1, x0
; decrement result
        sub     w0, w0, #1
; function epilogue
        add     sp, sp, 32
        ret
```

It's more verbose. The variables are often tossed here to and from memory (local stack). The same mistake here: the decrement operation happens on a 32-bit register part.

MIPS

Listing 1.187: Optimizing GCC 4.4.5 (IDA)

```
my_strlen:
; "eos" variable will always reside in $v1:
                move    $v1, $a0

loc_4:
; load byte at address in "eos" into $a1:
                lb      $a1, 0($v1)
                or      $at, $zero ; load delay slot, NOP
; if loaded byte is not zero, jump to loc_4:
                bnez    $a1, loc_4
; increment "eos" anyway:
                addiu   $v1, 1 ; branch delay slot
; loop finished. invert "str" variable:
                nor     $v0, $zero, $a0
; $v0=-str-1
                jr      $ra
; return value = $v1 + $v0 = eos + ( -str-1 ) = eos - str - 1
                addu    $v0, $v1, $v0 ; branch delay slot
```

MIPS lacks a NOT instruction, but has NOR which is OR + NOT operation.

This operation is widely used in digital electronics[107]. For example, the Apollo Guidance Computer used in the Apollo program, was built by only using 5600 NOR gates: [Jens Eickhoff, *Onboard Computers,*

[107] NOR is called "universal gate"

Onboard Software and Satellite Operations: An Introduction, (2011)]. But NOR element isn't very popular in computer programming.

So, the NOT operation is implemented here as `NOR DST, $ZERO, SRC`.

From fundamentals 2.2 on page 452 we know that bitwise inverting a signed number is the same as changing its sign and subtracting 1 from the result.

So what NOT does here is to take the value of str and transform it into $-str-1$. The addition operation that follows prepares result.

1.17.2 Boundaries of strings

It's interesting to note, how parameters are passed into win32 *GetOpenFileName()* function. In order to call it, one must set list of allowed file extensions:

```
        OPENFILENAME *LPOPENFILENAME;
        ...
        char * filter = "Text files (*.txt)\0*.txt\0MS Word files (*.doc)\0*.doc\0\0";
        ...
        LPOPENFILENAME = (OPENFILENAME *)malloc(sizeof(OPENFILENAME));
        ...
        LPOPENFILENAME->lpstrFilter = filter;
        ...

        if(GetOpenFileName(LPOPENFILENAME))
        {
                ...
```

What happens here is that list of strings are passed into *GetOpenFileName()*. It is not a problem to parse it: whenever you encounter single zero byte, this is an item. Whenever you encounter two zero bytes, this is end of the list. If you will pass this string into `printf()`, it will treat first item as a single string.

So this is string, or...? It's better say this is buffer containing several zero-terminated C-strings, which can be stored and processed as a whole.

Another exmaple is *strtok()* function. It takes a string and write zero bytes in the middle of it. It thus transforms input string into some kind of buffer, which has several zero-terminated C-strings.

1.18 Replacing arithmetic instructions to other ones

In the pursuit of optimization, one instruction may be replaced by another, or even with a group of instructions. For example, ADD and SUB can replace each other: line 18 in listing.3.119.

For example, the LEA instruction is often used for simple arithmetic calculations: .1.6 on page 1028.

1.18.1 Multiplication

Multiplication using addition

Here is a simple example:

```
unsigned int f(unsigned int a)
{
        return a*8;
};
```

Multiplication by 8 is replaced by 3 addition instructions, which do the same. Apparently, MSVC's optimizer decided that this code can be faster.

Listing 1.188: Optimizing MSVC 2010

```
_TEXT   SEGMENT
_a$ = 8         ; size = 4
_f      PROC
```

```
; File c:\polygon\c\2.c
        mov     eax, DWORD PTR _a$[esp-4]
        add     eax, eax
        add     eax, eax
        add     eax, eax
        ret     0
_f      ENDP
_TEXT   ENDS
END
```

Multiplication using shifting

Multiplication and division instructions by a numbers that's a power of 2 are often replaced by shift instructions.

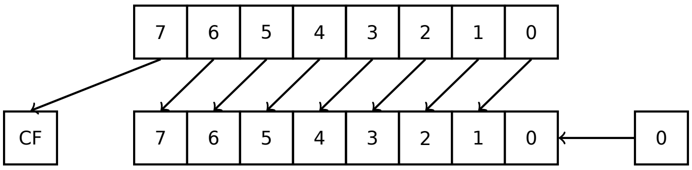
```
unsigned int f(unsigned int a)
{
        return a*4;
};
```

Listing 1.189: Non-optimizing MSVC 2010

```
_a$ = 8         ; size = 4
_f      PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _a$[ebp]
        shl     eax, 2
        pop     ebp
        ret     0
_f      ENDP
```

Multiplication by 4 is just shifting the number to the left by 2 bits and inserting 2 zero bits at the right (as the last two bits). It is just like multiplying 3 by 100 —we just have to add two zeros at the right.

That's how the shift left instruction works:



The added bits at right are always zeros.

Multiplication by 4 in ARM:

Listing 1.190: Non-optimizing Keil 6/2013 (ARM mode)

```
f PROC
        LSL      r0,r0,#2
        BX       lr
        ENDP
```

Multiplication by 4 in MIPS:

Listing 1.191: Optimizing GCC 4.4.5 (IDA)

```
      jr      $ra
      sll     $v0, $a0, 2 ; branch delay slot
```

SLL is "Shift Left Logical".

Multiplication using shifting, subtracting, and adding

It's still possible to get rid of the multiplication operation when you multiply by numbers like 7 or 17 again by using shifting. The mathematics used here is relatively easy.

32-bit

```
#include <stdint.h>

int f1(int a)
{
        return a*7;
};

int f2(int a)
{
        return a*28;
};

int f3(int a)
{
        return a*17;
};
```

x86

Listing 1.192: Optimizing MSVC 2012

```
; a*7
_a$ = 8
_f1     PROC
        mov     ecx, DWORD PTR _a$[esp-4]
; ECX=a
        lea     eax, DWORD PTR [ecx*8]
; EAX=ECX*8
        sub     eax, ecx
; EAX=EAX-ECX=ECX*8-ECX=ECX*7=a*7
        ret     0
_f1     ENDP

; a*28
_a$ = 8
_f2     PROC
        mov     ecx, DWORD PTR _a$[esp-4]
; ECX=a
        lea     eax, DWORD PTR [ecx*8]
; EAX=ECX*8
        sub     eax, ecx
; EAX=EAX-ECX=ECX*8-ECX=ECX*7=a*7
        shl     eax, 2
; EAX=EAX<<2=(a*7)*4=a*28
        ret     0
_f2     ENDP

; a*17
_a$ = 8
_f3     PROC
        mov     eax, DWORD PTR _a$[esp-4]
; EAX=a
        shl     eax, 4
; EAX=EAX<<4=EAX*16=a*16
        add     eax, DWORD PTR _a$[esp-4]
; EAX=EAX+a=a*16+a=a*17
        ret     0
_f3     ENDP
```

ARM

Keil for ARM mode takes advantage of the second operand’s shift modifiers:

Listing 1.193: Optimizing Keil 6/2013 (ARM mode)

```
; a*7
||f1|| PROC
        RSB      r0,r0,r0,LSL #3
; R0=R0<<3-R0=R0*8-R0=a*8-a=a*7
        BX       lr
        ENDP

; a*28
||f2|| PROC
        RSB      r0,r0,r0,LSL #3
; R0=R0<<3-R0=R0*8-R0=a*8-a=a*7
        LSL      r0,r0,#2
; R0=R0<<2=R0*4=a*7*4=a*28
        BX       lr
        ENDP

; a*17
||f3|| PROC
        ADD      r0,r0,r0,LSL #4
; R0=R0+R0<<4=R0+R0*16=R0*17=a*17
        BX       lr
        ENDP
```

But there are no such modifiers in Thumb mode. It also can't optimize `f2()`:

Listing 1.194: Optimizing Keil 6/2013 (Thumb mode)

```
; a*7
||f1|| PROC
        LSLS     r1,r0,#3
; R1=R0<<3=a<<3=a*8
        SUBS     r0,r1,r0
; R0=R1-R0=a*8-a=a*7
        BX       lr
        ENDP

; a*28
||f2|| PROC
        MOVS     r1,#0x1c ; 28
; R1=28
        MULS     r0,r1,r0
; R0=R1*R0=28*a
        BX       lr
        ENDP

; a*17
||f3|| PROC
        LSLS     r1,r0,#4
; R1=R0<<4=R0*16=a*16
        ADDS     r0,r0,r1
; R0=R0+R1=a+a*16=a*17
        BX       lr
        ENDP
```

MIPS

Listing 1.195: Optimizing GCC 4.4.5 (IDA)

```
_f1:
                sll     $v0, $a0, 3
; $v0 = $a0<<3 = $a0*8
                jr      $ra
                subu    $v0, $a0 ; branch delay slot
; $v0 = $v0-$a0 = $a0*8-$a0 = $a0*7

_f2:
                sll     $v0, $a0, 5
```

```
; $v0 = $a0<<5 = $a0*32
                sll     $a0, 2
; $a0 = $a0<<2 = $a0*4
                jr      $ra
                subu    $v0, $a0 ; branch delay slot
; $v0 = $a0*32-$a0*4 = $a0*28

_f3:
                sll     $v0, $a0, 4
; $v0 = $a0<<4 = $a0*16
                jr      $ra
                addu    $v0, $a0 ; branch delay slot
; $v0 = $a0*16+$a0 = $a0*17
```

64-bit

```
#include <stdint.h>

int64_t f1(int64_t a)
{
        return a*7;
};

int64_t f2(int64_t a)
{
        return a*28;
};

int64_t f3(int64_t a)
{
        return a*17;
};
```

x64

Listing 1.196: Optimizing MSVC 2012

```
; a*7
f1:
        lea     rax, [0+rdi*8]
; RAX=RDI*8=a*8
        sub     rax, rdi
; RAX=RAX-RDI=a*8-a=a*7
        ret

; a*28
f2:
        lea     rax, [0+rdi*4]
; RAX=RDI*4=a*4
        sal     rdi, 5
; RDI=RDI<<5=RDI*32=a*32
        sub     rdi, rax
; RDI=RDI-RAX=a*32-a*4=a*28
        mov     rax, rdi
        ret

; a*17
f3:
        mov     rax, rdi
        sal     rax, 4
; RAX=RAX<<4=a*16
        add     rax, rdi
; RAX=a*16+a=a*17
        ret
```

ARM64

GCC 4.9 for ARM64 is also terse, thanks to the shift modifiers:

Listing 1.197: Optimizing GCC (Linaro) 4.9 ARM64

```
; a*7
f1:
        lsl     x1, x0, 3
; X1=X0<<3=X0*8=a*8
        sub     x0, x1, x0
; X0=X1-X0=a*8-a=a*7
        ret

; a*28
f2:
        lsl     x1, x0, 5
; X1=X0<<5=a*32
        sub     x0, x1, x0, lsl 2
; X0=X1-X0<<2=a*32-a<<2=a*32-a*4=a*28
        ret

; a*17
f3:
        add     x0, x0, x0, lsl 4
; X0=X0+X0<<4=a+a*16=a*17
        ret
```

Booth's multiplication algorithm

There was a time when computers were big and that expensive, that some of them lacked hardware support of multiplication operation in CPU, like Data General Nova. And when one need multiplication operation, it can be provided at software level, for example, using Booth's multiplication algorithm. This is a multiplication algorithm which uses only addition operation and shifts.

What modern optimizing compilers do, isn't the same, but the goal (multiplication) and resources (faster operations) are the same.

1.18.2 Division

Division using shifts

Example of division by 4:

```
unsigned int f(unsigned int a)
{
        return a/4;
};
```

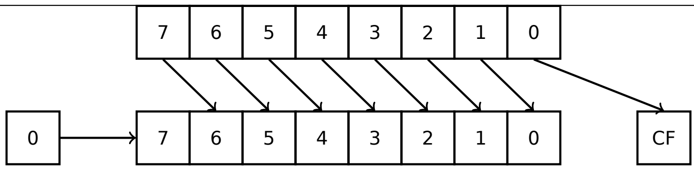
We get (MSVC 2010):

Listing 1.198: MSVC 2010

```
_a$ = 8         ; size = 4
_f      PROC
        mov     eax, DWORD PTR _a$[esp-4]
        shr     eax, 2
        ret     0
_f      ENDP
```

The SHR (*SHift Right*) instruction in this example is shifting a number by 2 bits to the right. The two freed bits at left (e.g., two most significant bits) are set to zero. The two least significant bits are dropped. In fact, these two dropped bits are the division operation remainder.

The SHR instruction works just like SHL, but in the other direction.



It is easy to understand if you imagine the number 23 in the decimal numeral system. 23 can be easily divided by 10 just by dropping last digit (3—division remainder). 2 is left after the operation as a quotient.

So the remainder is dropped, but that's OK, we work on integer values anyway, these are not a real numbers!

Division by 4 in ARM:

Listing 1.199: Non-optimizing Keil 6/2013 (ARM mode)

```
f PROC
        LSR      r0,r0,#2
        BX       lr
        ENDP
```

Division by 4 in MIPS:

Listing 1.200: Optimizing GCC 4.4.5 (IDA)

```
        jr      $ra
        srl     $v0, $a0, 2 ; branch delay slot
```

The SRL instruction is "Shift Right Logical".

1.18.3 Exercise

- http://challenges.re/59

1.19 Floating-point unit

The FPU is a device within the main CPU, specially designed to deal with floating point numbers.

It was called "coprocessor" in the past and it stays somewhat aside of the main CPU.

1.19.1 IEEE 754

A number in the IEEE 754 format consists of a *sign*, a *significand* (also called *fraction*) and an *exponent*.

1.19.2 x86

It is worth looking into stack machines[108] or learning the basics of the Forth language[109], before studying the FPU in x86.

It is interesting to know that in the past (before the 80486 CPU) the coprocessor was a separate chip and it was not always pre-installed on the motherboard. It was possible to buy it separately and install it [110].

Starting with the 80486 DX CPU, the FPU is integrated in the CPU.

The FWAIT instruction reminds us of that fact—it switches the CPU to a waiting state, so it can wait until the FPU has finished with its work.

Another rudiment is the fact that the FPU instruction opcodes start with the so called "escape"-opcodes (D8..DF), i.e., opcodes passed to a separate coprocessor.

[108] wikipedia.org/wiki/Stack_machine
[109] wikipedia.org/wiki/Forth_(programming_language)
[110] For example, John Carmack used fixed-point arithmetic (wikipedia.org/wiki/Fixed-point_arithmetic) values in his Doom video game, stored in 32-bit GPR registers (16 bit for integral part and another 16 bit for fractional part), so Doom could work on 32-bit computers without FPU, i.e., 80386 and 80486 SX.

The FPU has a stack capable to holding 8 80-bit registers, and each register can hold a number in the IEEE 754[111]format.

They are ST(0)..ST(7). For brevity, IDA and OllyDbg show ST(0) as ST, which is represented in some textbooks and manuals as "Stack Top".

1.19.3 ARM, MIPS, x86/x64 SIMD

In ARM and MIPS the FPU is not a stack, but a set of registers, which can be accessed randomly, like GPR.

The same ideology is used in the SIMD extensions of x86/x64 CPUs.

1.19.4 C/C++

The standard C/C++ languages offer at least two floating number types, *float* (*single-precision*[112], 32 bits) [113] and *double* (*double-precision*[114], 64 bits).

In [Donald E. Knuth, *The Art of Computer Programming*, Volume 2, 3rd ed., (1997)246] we can find the *single-precision* means that the floating point value can be placed into a single [32-bit] machine word, *double-precision* means it can be stored in two words (64 bits).

GCC also supports the *long double* type (*extended precision*[115], 80 bit), which MSVC doesn't.

The *float* type requires the same number of bits as the *int* type in 32-bit environments, but the number representation is completely different.

1.19.5 Simple example

Let's consider this simple example:

```
#include <stdio.h>

double f (double a, double b)
{
        return a/3.14 + b*4.1;
};

int main()
{
        printf ("%f\n", f(1.2, 3.4));
};
```

x86

MSVC

Compile it in MSVC 2010:

Listing 1.201: MSVC 2010: f()

```
CONST    SEGMENT
__real@4010666666666666 DQ 04010666666666666r    ; 4.1
CONST    ENDS
CONST    SEGMENT
__real@40091eb851eb851f DQ 040091eb851eb851fr    ; 3.14
CONST    ENDS
_TEXT    SEGMENT
```

[111]wikipedia.org/wiki/IEEE_floating_point
[112]wikipedia.org/wiki/Single-precision_floating-point_format
[113]the single precision floating point number format is also addressed in the *Handling float data type as a structure* (1.24.6 on page 373) section
[114]wikipedia.org/wiki/Double-precision_floating-point_format
[115]wikipedia.org/wiki/Extended_precision

```
_a$ = 8             ; size = 8
_b$ = 16            ; size = 8
_f   PROC
    push   ebp
    mov    ebp, esp
    fld    QWORD PTR _a$[ebp]

; current stack state: ST(0) = _a

    fdiv   QWORD PTR __real@40091eb851eb851f

; current stack state: ST(0) = result of _a divided by 3.14

    fld    QWORD PTR _b$[ebp]

; current stack state: ST(0) = _b;
; ST(1) = result of _a divided by 3.14

    fmul   QWORD PTR __real@4010666666666666

; current stack state:
; ST(0) = result of _b * 4.1;
; ST(1) = result of _a divided by 3.14

    faddp  ST(1), ST(0)

; current stack state: ST(0) = result of addition

    pop    ebp
    ret    0
_f   ENDP
```

FLD takes 8 bytes from stack and loads the number into the ST(0) register, automatically converting it into the internal 80-bit format (*extended precision*).

FDIV divides the value in ST(0) by the number stored at address __real@40091eb851eb851f —the value 3.14 is encoded there. The assembly syntax doesn't support floating point numbers, so what we see here is the hexadecimal representation of 3.14 in 64-bit IEEE 754 format.

After the execution of FDIV ST(0) holds the quotient.

By the way, there is also the FDIVP instruction, which divides ST(1) by ST(0), popping both these values from stack and then pushing the result. If you know the Forth language[116], you can quickly understand that this is a stack machine[117].

The subsequent FLD instruction pushes the value of b into the stack.

After that, the quotient is placed in ST(1), and ST(0) has the value of b.

The next FMUL instruction does multiplication: b from ST(0) is multiplied by value at __real@4010666666666666 (the number 4.1 is there) and leaves the result in the ST(0) register.

The last FADDP instruction adds the two values at top of stack, storing the result in ST(1) and then popping the value of ST(0), thereby leaving the result at the top of the stack, in ST(0).

The function must return its result in the ST(0) register, so there are no any other instructions except the function epilogue after FADDP.

[116] wikipedia.org/wiki/Forth_(programming_language)
[117] wikipedia.org/wiki/Stack_machine

MSVC + OllyDbg

2 pairs of 32-bit words are marked by red in the stack. Each pair is a double-number in IEEE 754 format and is passed from `main()`.

We see how the first FLD loads a value (1.2) from the stack and puts it into `ST(0)`:

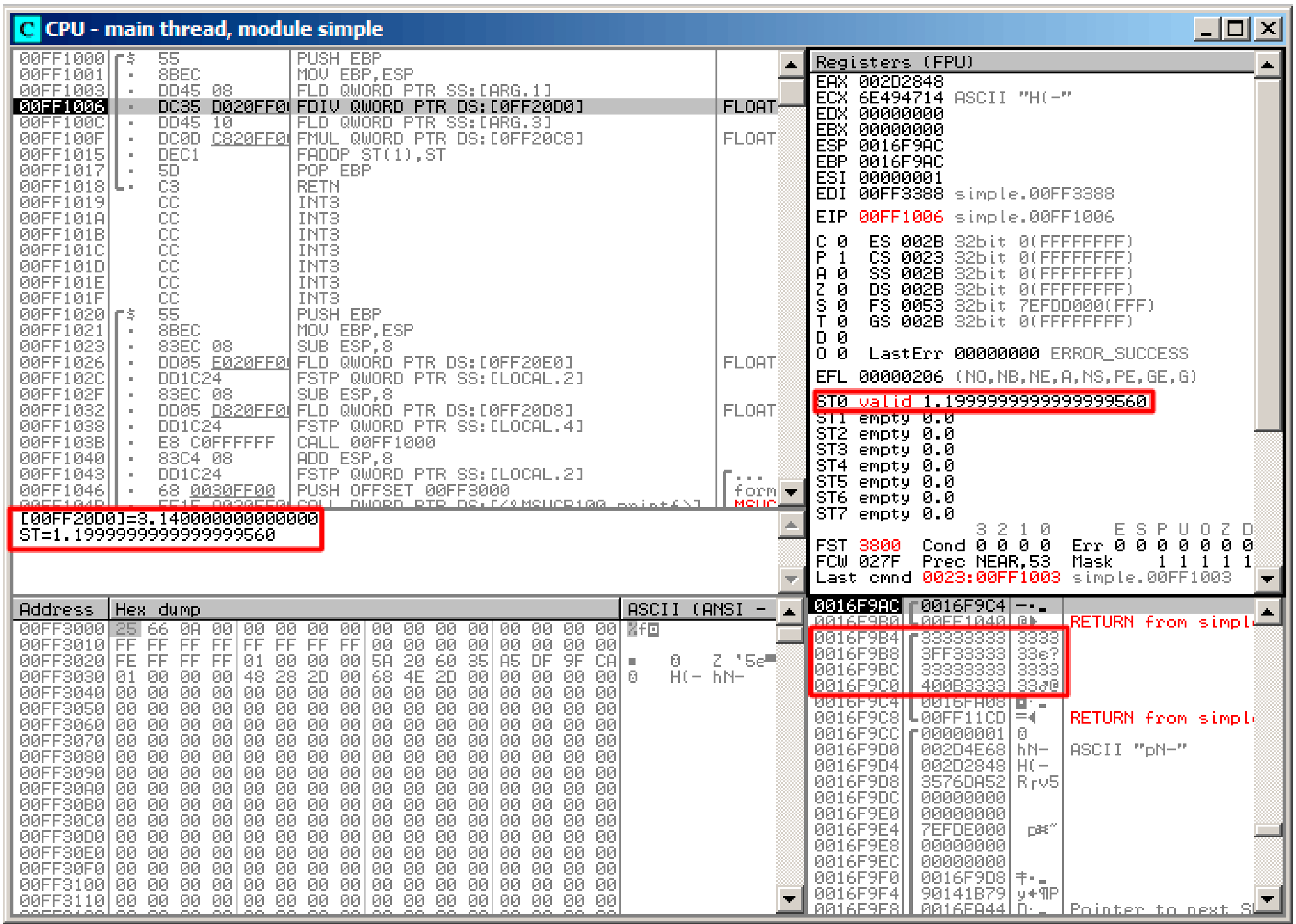


Figure 1.62: OllyDbg: the first FLD has been executed

Because of unavoidable conversion errors from 64-bit IEEE 754 floating point to 80-bit (used internally in the FPU), here we see 1.1999…, which is close to 1.2.

EIP now points to the next instruction (FDIV), which loads a double-number (a constant) from memory. For convenience, OllyDbg shows its value: 3.14

Let's trace further. FDIV has been executed, now ST(0) contains 0.382...(quotient):

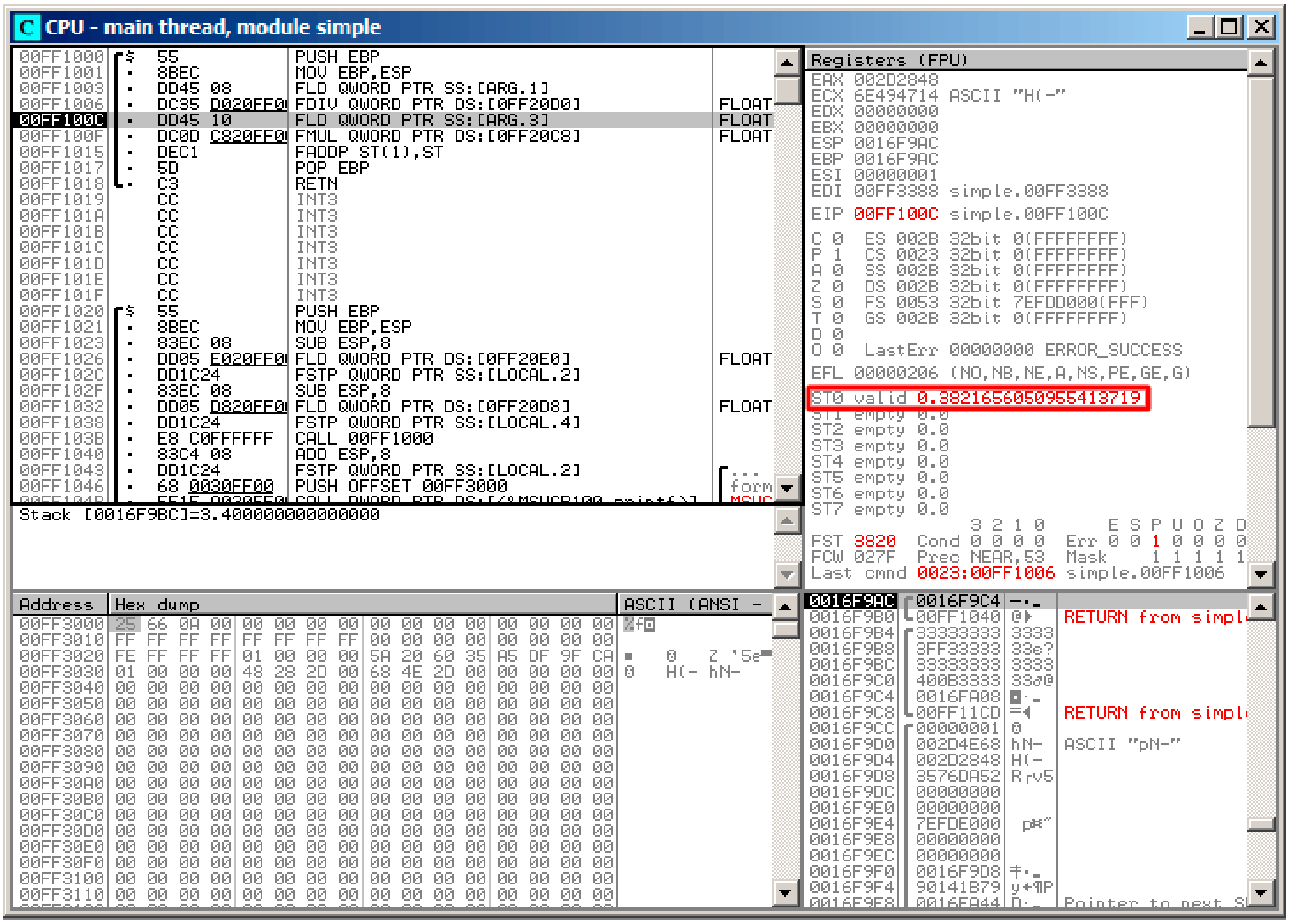


Figure 1.63: OllyDbg: FDIV has been executed

Third step: the next FLD has been executed, loading 3.4 into ST(0) (here we see the approximate value 3.39999...):

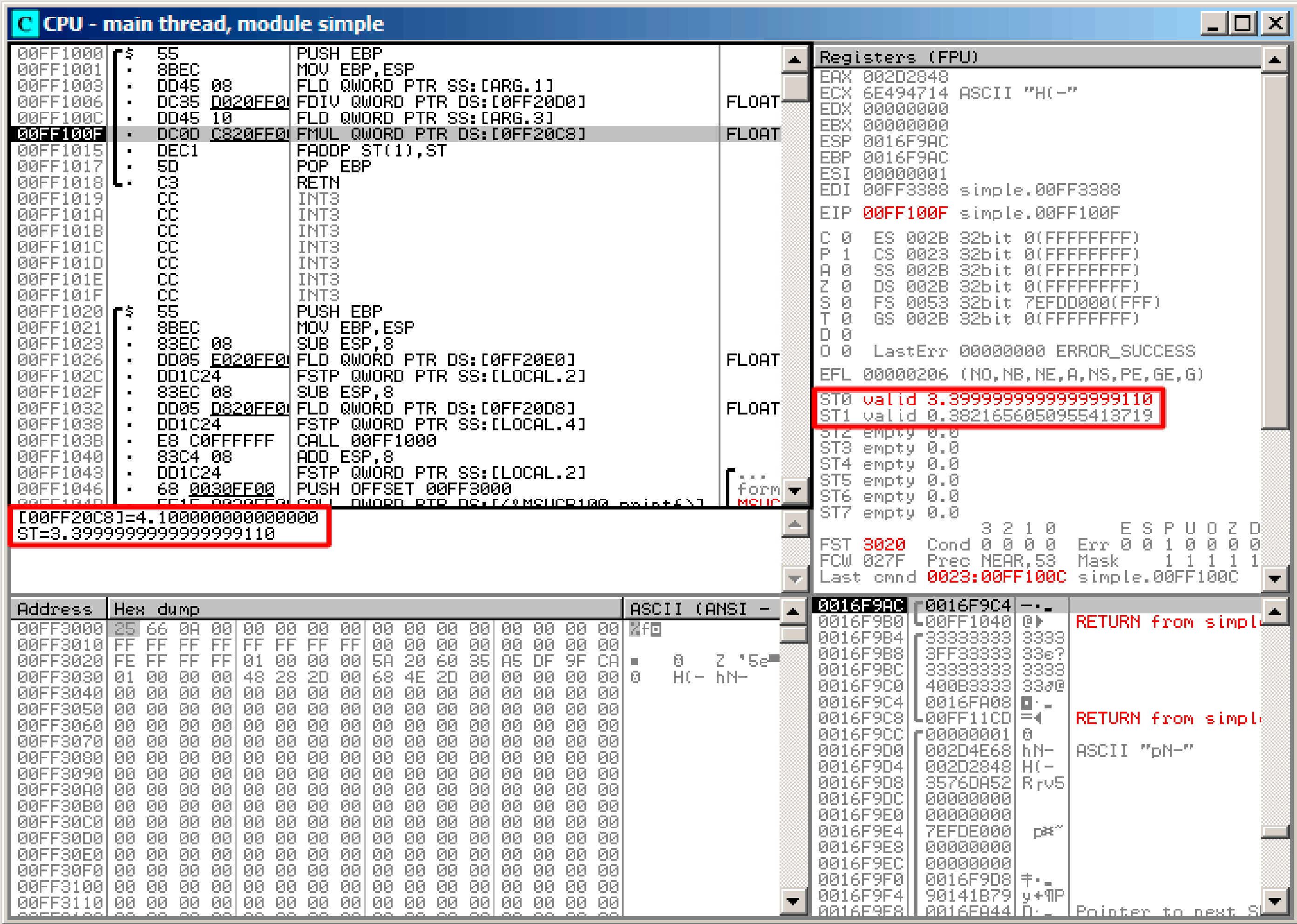


Figure 1.64: OllyDbg: the second FLD has been executed

At the same time, quotient *is pushed* into ST(1). Right now, EIP points to the next instruction: FMUL. It loads the constant 4.1 from memory, which OllyDbg shows.

Next: FMUL has been executed, so now the product is in ST(0):

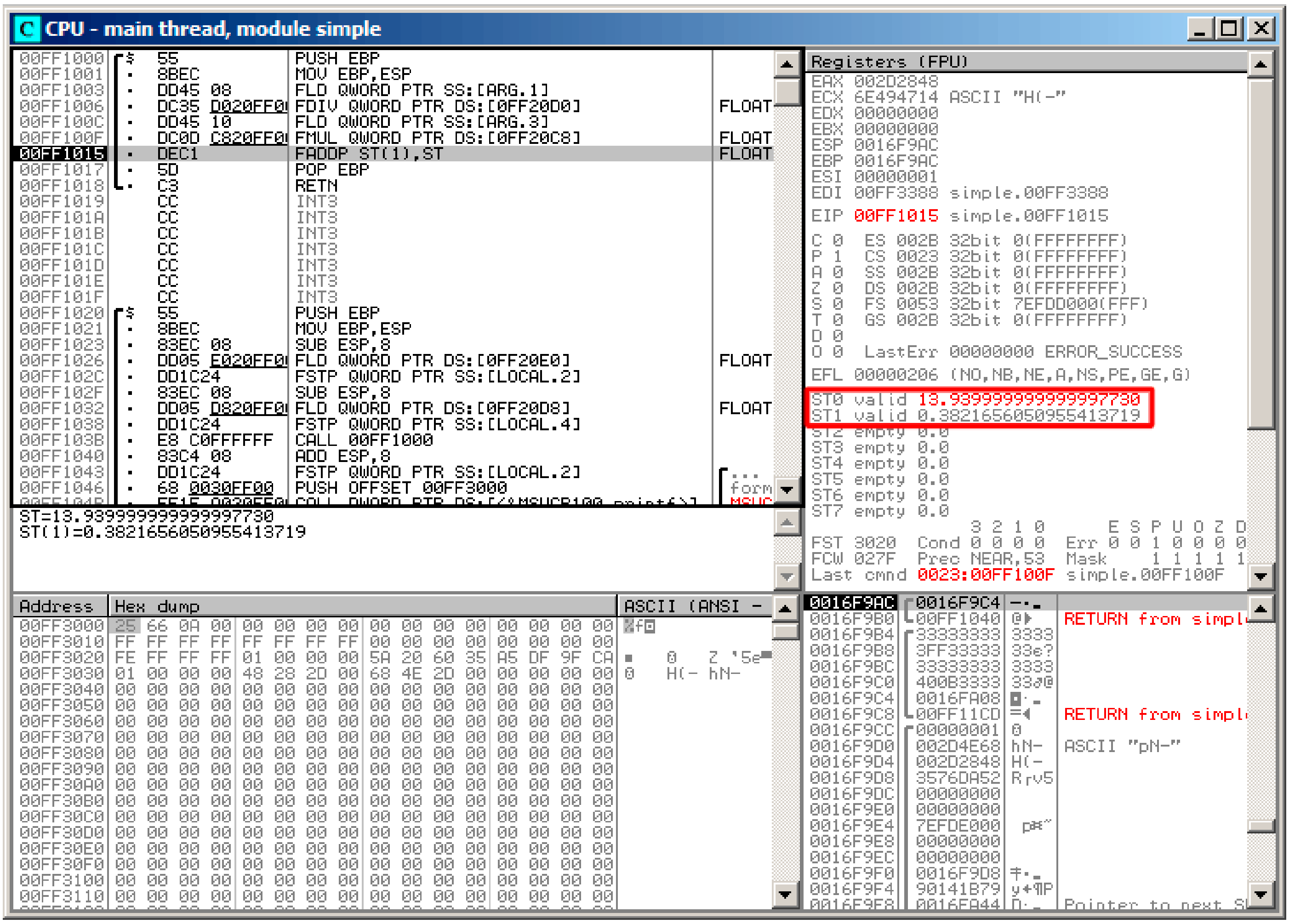


Figure 1.65: OllyDbg: the FMUL has been executed

Next: the FADDP has been executed, now the result of the addition is in ST(0), and ST(1) is cleared:

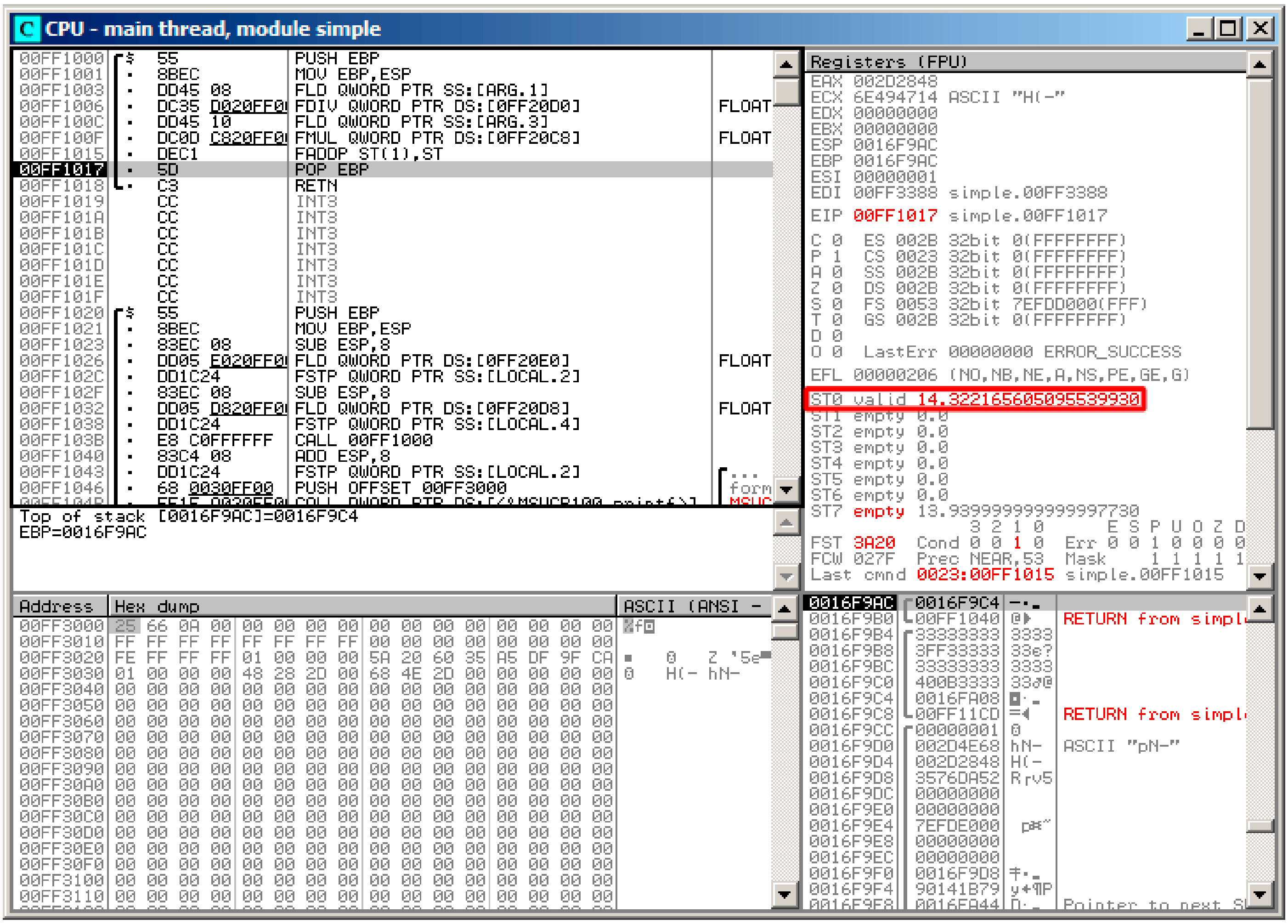


Figure 1.66: OllyDbg: FADDP has been executed

The result is left in ST(0), because the function returns its value in ST(0).

main() takes this value from the register later.

We also see something unusual: the 13.93...value is now located in ST(7). Why?

As we have read some time before in this book, the FPU registers are a stack: 1.19.2 on page 218. But this is a simplification.

Imagine if it was implemented *in hardware* as it's described, then all 7 register's contents must be moved (or copied) to adjacent registers during pushing and popping, and that's a lot of work.

In reality, the FPU has just 8 registers and a pointer (called TOP) which contains a register number, which is the current "top of stack".

When a value is pushed to the stack, TOP is pointed to the next available register, and then a value is written to that register.

The procedure is reversed if a value is popped, however, the register which has been freed is not cleared (it could possibly be cleared, but this is more work which can degrade performance). So that's what we see here.

It can be said that FADDP saved the sum in the stack, and then popped one element.

But in fact, this instruction saved the sum and then shifted TOP.

More precisely, the registers of the FPU are a circular buffer.

GCC

GCC 4.4.1 (with -O3 option) emits the same code, just slightly different:

Listing 1.202: Optimizing GCC 4.4.1

```
                public f
f               proc near

arg_0           = qword ptr  8
arg_8           = qword ptr  10h

                push    ebp
                fld     ds:dbl_8048608 ; 3.14

; stack state now: ST(0) = 3.14

                mov     ebp, esp
                fdivr   [ebp+arg_0]

; stack state now: ST(0) = result of division

                fld     ds:dbl_8048610 ; 4.1

; stack state now: ST(0) = 4.1, ST(1) = result of division

                fmul    [ebp+arg_8]

; stack state now: ST(0) = result of multiplication, ST(1) = result of division

                pop     ebp
                faddp   st(1), st

; stack state now: ST(0) = result of addition

                retn
f               endp
```

The difference is that, first of all, 3.14 is pushed to the stack (into ST(0)), and then the value in arg_0 is divided by the value in ST(0).

FDIVR stands for *Reverse Divide* —to divide with divisor and dividend swapped with each other. There is no likewise instruction for multiplication since it is a commutative operation, so we just have FMUL without its -R counterpart.

FADDP adds the two values but also pops one value from the stack. After that operation, ST(0) holds the sum.

ARM: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Until ARM got standardized floating point support, several processor manufacturers added their own instructions extensions. Then, VFP (*Vector Floating Point*) was standardized.

One important difference from x86 is that in ARM, there is no stack, you work just with registers.

Listing 1.203: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
f
                VLDR            D16, =3.14
                VMOV            D17, R0, R1 ; load "a"
                VMOV            D18, R2, R3 ; load "b"
                VDIV.F64        D16, D17, D16 ; a/3.14
                VLDR            D17, =4.1
                VMUL.F64        D17, D18, D17 ; b*4.1
                VADD.F64        D16, D17, D16 ; +
                VMOV            R0, R1, D16
                BX              LR

dbl_2C98        DCFD 3.14               ; DATA XREF: f
dbl_2CA0        DCFD 4.1                ; DATA XREF: f+10
```

So, we see here new some registers used, with D prefix.

These are 64-bit registers, there are 32 of them, and they can be used both for floating-point numbers (double) but also for SIMD (it is called NEON here in ARM).

There are also 32 32-bit S-registers, intended to be used for single precision floating pointer numbers (float).

It is easy to memorize: D-registers are for double precision numbers, while S-registers—for single precision numbers. More about it: .2.3 on page 1040.

Both constants (3.14 and 4.1) are stored in memory in IEEE 754 format.

VLDR and VMOV, as it can be easily deduced, are analogous to the LDR and MOV instructions, but they work with D-registers.

It has to be noted that these instructions, just like the D-registers, are intended not only for floating point numbers, but can be also used for SIMD (NEON) operations and this will also be shown soon.

The arguments are passed to the function in a common way, via the R-registers, however each number that has double precision has a size of 64 bits, so two R-registers are needed to pass each one.

VMOV D17, R0, R1 at the start, composes two 32-bit values from R0 and R1 into one 64-bit value and saves it to D17.

VMOV R0, R1, D16 is the inverse operation: what has been in D16 is split in two registers, R0 and R1, because a double-precision number that needs 64 bits for storage, is returned in R0 and R1.

VDIV, VMUL and VADD, are instruction for processing floating point numbers that compute quotient, product and sum, respectively.

The code for Thumb-2 is same.

ARM: Optimizing Keil 6/2013 (Thumb mode)

```
f
                PUSH    {R3-R7,LR}
                MOVS    R7, R2
                MOVS    R4, R3
                MOVS    R5, R0
                MOVS    R6, R1
                LDR     R2, =0x66666666 ; 4.1
                LDR     R3, =0x40106666
                MOVS    R0, R7
                MOVS    R1, R4
                BL      __aeabi_dmul
                MOVS    R7, R0
                MOVS    R4, R1
                LDR     R2, =0x51EB851F ; 3.14
                LDR     R3, =0x40091EB8
                MOVS    R0, R5
                MOVS    R1, R6
                BL      __aeabi_ddiv
                MOVS    R2, R7
                MOVS    R3, R4
                BL      __aeabi_dadd
                POP     {R3-R7,PC}

; 4.1 in IEEE 754 form:
dword_364       DCD 0x66666666          ; DATA XREF: f+A
dword_368       DCD 0x40106666          ; DATA XREF: f+C
; 3.14 in IEEE 754 form:
dword_36C       DCD 0x51EB851F          ; DATA XREF: f+1A
dword_370       DCD 0x40091EB8          ; DATA XREF: f+1C
```

Keil generated code for a processor without FPU or NEON support.

The double-precision floating-point numbers are passed via generic R-registers, and instead of FPU-instructions, service library functions are called
(like __aeabi_dmul, __aeabi_ddiv, __aeabi_dadd) which emulate multiplication, division and addition for floating-point numbers.

Of course, that is slower than FPU-coprocessor, but it's still better than nothing.

By the way, similar FPU-emulating libraries were very popular in the x86 world when coprocessors were rare and expensive, and were installed only on expensive computers.

The FPU-coprocessor emulation is called *soft float* or *armel* (*emulation*) in the ARM world, while using the coprocessor's FPU-instructions is called *hard float* or *armhf*.

ARM64: Optimizing GCC (Linaro) 4.9

Very compact code:

Listing 1.204: Optimizing GCC (Linaro) 4.9

```
f:
; D0 = a, D1 = b
        ldr     d2, .LC25       ; 3.14
; D2 = 3.14
        fdiv    d0, d0, d2
; D0 = D0/D2 = a/3.14
        ldr     d2, .LC26       ; 4.1
; D2 = 4.1
        fmadd   d0, d1, d2, d0
; D0 = D1*D2+D0 = b*4.1+a/3.14
        ret

; constants in IEEE 754 format:
.LC25:
        .word   1374389535      ; 3.14
        .word   1074339512
.LC26:
        .word   1717986918      ; 4.1
        .word   1074816614
```

ARM64: Non-optimizing GCC (Linaro) 4.9

Listing 1.205: Non-optimizing GCC (Linaro) 4.9

```
f:
        sub     sp, sp, #16
        str     d0, [sp,8]      ; save "a" in Register Save Area
        str     d1, [sp]        ; save "b" in Register Save Area
        ldr     x1, [sp,8]
; X1 = a
        ldr     x0, .LC25
; X0 = 3.14
        fmov    d0, x1
        fmov    d1, x0
; D0 = a, D1 = 3.14
        fdiv    d0, d0, d1
; D0 = D0/D1 = a/3.14

        fmov    x1, d0
; X1 = a/3.14
        ldr     x2, [sp]
; X2 = b
        ldr     x0, .LC26
; X0 = 4.1
        fmov    d0, x2
; D0 = b
        fmov    d1, x0
; D1 = 4.1
        fmul    d0, d0, d1
; D0 = D0*D1 = b*4.1

        fmov    x0, d0
; X0 = D0 = b*4.1
        fmov    d0, x1
```

```
; D0 = a/3.14
        fmov    d1, x0
; D1 = X0 = b*4.1
        fadd    d0, d0, d1
; D0 = D0+D1 = a/3.14 + b*4.1

        fmov    x0, d0 ; \ redundant code
        fmov    d0, x0 ; /
        add     sp, sp, 16
        ret
.LC25:
        .word   1374389535      ; 3.14
        .word   1074339512
.LC26:
        .word   1717986918      ; 4.1
        .word   1074816614
```

Non-optimizing GCC is more verbose.

There is a lot of unnecessary value shuffling, including some clearly redundant code (the last two FMOV instructions). Probably, GCC 4.9 is not yet good in generating ARM64 code.

What is worth noting is that ARM64 has 64-bit registers, and the D-registers are 64-bit ones as well.

So the compiler is free to save values of type *double* in GPRs instead of the local stack. This isn't possible on 32-bit CPUs.

And again, as an exercise, you can try to optimize this function manually, without introducing new instructions like FMADD.

MIPS

MIPS can support several coprocessors (up to 4), the zeroth of which[118] is a special control coprocessor, and first coprocessor is the FPU.

As in ARM, the MIPS coprocessor is not a stack machine, it has 32 32-bit registers ($F0-$F31): .3.1 on page 1042.

When one needs to work with 64-bit *double* values, a pair of 32-bit F-registers is used.

Listing 1.206: Optimizing GCC 4.4.5 (IDA)

```
f:
; $f12-$f13=A
; $f14-$f15=B
                lui     $v0, (dword_C4 >> 16) ; ?
; load low 32-bit part of 3.14 constant to $f0:
                lwc1    $f0, dword_BC
                or      $at, $zero            ; load delay slot, NOP
; load high 32-bit part of 3.14 constant to $f1:
                lwc1    $f1, $LC0
                lui     $v0, ($LC1 >> 16)     ; ?
; A in $f12-$f13, 3.14 constant in $f0-$f1, do division:
                div.d   $f0, $f12, $f0
; $f0-$f1=A/3.14
; load low 32-bit part of 4.1 to $f2:
                lwc1    $f2, dword_C4
                or      $at, $zero            ; load delay slot, NOP
; load high 32-bit part of 4.1 to $f3:
                lwc1    $f3, $LC1
                or      $at, $zero            ; load delay slot, NOP
; B in $f14-$f15, 4.1 constant in $f2-$f3, do multiplication:
                mul.d   $f2, $f14, $f2
; $f2-$f3=B*4.1
                jr      $ra
; sum 64-bit parts and leave result in $f0-$f1:
                add.d   $f0, $f2              ; branch delay slot, NOP
```

[118] Starting at 0.

```
.rodata.cst8:000000B8 $LC0:           .word 0x40091EB8         # DATA XREF: f+C
.rodata.cst8:000000BC dword_BC:       .word 0x51EB851F         # DATA XREF: f+4
.rodata.cst8:000000C0 $LC1:           .word 0x40106666         # DATA XREF: f+10
.rodata.cst8:000000C4 dword_C4:       .word 0x66666666         # DATA XREF: f
```

The new instructions here are:

- LWC1 loads a 32-bit word into a register of the first coprocessor (hence “1” in instruction name).

  A pair of LWC1 instructions may be combined into a L.D pseudo instruction.
- DIV.D, MUL.D, ADD.D do division, multiplication, and addition respectively (“.D” in the suffix stands for double precision, “.S” stands for single precision)

There is also a weird compiler anomaly: the LUI instructions that we’ve marked with a question mark. It’s hard for me to understand why load a part of a 64-bit constant of *double* type into the $V0 register. These instructions has no effect. If someone knows more about it, please drop an email to author[119].

1.19.6 Passing floating point numbers via arguments

```
#include <math.h>
#include <stdio.h>

int main ()
{
        printf ("32.01 ^ 1.54 = %lf\n", pow (32.01,1.54));

        return 0;
}
```

x86

Let’s see what we get in (MSVC 2010):

Listing 1.207: MSVC 2010

```
CONST    SEGMENT
__real@40400147ae147ae1 DQ 040400147ae147ae1r    ; 32.01
__real@3ff8a3d70a3d70a4 DQ 03ff8a3d70a3d70a4r    ; 1.54
CONST    ENDS

_main    PROC
    push   ebp
    mov    ebp, esp
    sub    esp, 8  ; allocate space for the first variable
    fld    QWORD PTR __real@3ff8a3d70a3d70a4
    fstp   QWORD PTR [esp]
    sub    esp, 8  ; allocate space for the second variable
    fld    QWORD PTR __real@40400147ae147ae1
    fstp   QWORD PTR [esp]
    call   _pow
    add    esp, 8  ; return back place of one variable.

; in local stack here 8 bytes still reserved for us.
; result now in ST(0)

    fstp   QWORD PTR [esp] ; move result from ST(0) to local stack for printf()
    push   OFFSET $SG2651
    call   _printf
    add    esp, 12
    xor    eax, eax
    pop    ebp
    ret    0
_main    ENDP
```

[119] dennis@yurichev.com

FLD and FSTP move variables between the data segment and the FPU stack. pow()[120] takes both values from the stack and returns its result in the ST(0) register. printf() takes 8 bytes from the local stack and interprets them as *double* type variable.

By the way, a pair of MOV instructions could be used here for moving values from the memory into the stack, because the values in memory are stored in IEEE 754 format, and pow() also takes them in this format, so no conversion is necessary. That's how it's done in the next example, for ARM: 1.19.6.

ARM + Non-optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```
_main

var_C     = -0xC

          PUSH     {R7,LR}
          MOV      R7, SP
          SUB      SP, SP, #4
          VLDR     D16, =32.01
          VMOV     R0, R1, D16
          VLDR     D16, =1.54
          VMOV     R2, R3, D16
          BLX      _pow
          VMOV     D16, R0, R1
          MOV      R0, 0xFC1 ; "32.01 ^ 1.54 = %lf\n"
          ADD      R0, PC
          VMOV     R1, R2, D16
          BLX      _printf
          MOVS     R1, 0
          STR      R0, [SP,#0xC+var_C]
          MOV      R0, R1
          ADD      SP, SP, #4
          POP      {R7,PC}

dbl_2F90  DCFD 32.01      ; DATA XREF: _main+6
dbl_2F98  DCFD 1.54       ; DATA XREF: _main+E
```

As it was mentioned before, 64-bit floating pointer numbers are passed in R-registers pairs.

This code is a bit redundant (certainly because optimization is turned off), since it is possible to load values into the R-registers directly without touching the D-registers.

So, as we see, the _pow function receives its first argument in R0 and R1, and its second one in R2 and R3. The function leaves its result in R0 and R1. The result of _pow is moved into D16, then in the R1 and R2 pair, from where printf() takes the resulting number.

ARM + Non-optimizing Keil 6/2013 (ARM mode)

```
_main
      STMFD   SP!, {R4-R6,LR}
      LDR     R2, =0xA3D70A4  ; y
      LDR     R3, =0x3FF8A3D7
      LDR     R0, =0xAE147AE1 ; x
      LDR     R1, =0x40400147
      BL      pow
      MOV     R4, R0
      MOV     R2, R4
      MOV     R3, R1
      ADR     R0, a32_011_54Lf ; "32.01 ^ 1.54 = %lf\n"
      BL      __2printf
      MOV     R0, #0
      LDMFD   SP!, {R4-R6,PC}

y               DCD 0xA3D70A4           ; DATA XREF: _main+4
dword_520       DCD 0x3FF8A3D7          ; DATA XREF: _main+8
x               DCD 0xAE147AE1          ; DATA XREF: _main+C
```

[120] a standard C function, raises a number to the given power (exponentiation)

```
dword_528       DCD 0x40400147          ; DATA XREF: _main+10
a32_011_54Lf    DCB "32.01 ^ 1.54 = %lf",0xA,0
                                        ; DATA XREF: _main+24
```

D-registers are not used here, just R-register pairs.

ARM64 + Optimizing GCC (Linaro) 4.9

Listing 1.208: Optimizing GCC (Linaro) 4.9

```
f:
        stp     x29, x30, [sp, -16]!
        add     x29, sp, 0
        ldr     d1, .LC1 ; load 1.54 into D1
        ldr     d0, .LC0 ; load 32.01 into D0
        bl      pow
; result of pow() in D0
        adrp    x0, .LC2
        add     x0, x0, :lo12:.LC2
        bl      printf
        mov     w0, 0
        ldp     x29, x30, [sp], 16
        ret
.LC0:
; 32.01 in IEEE 754 format
        .word   -1374389535
        .word   1077936455
.LC1:
; 1.54 in IEEE 754 format
        .word   171798692
        .word   1073259479
.LC2:
        .string "32.01 ^ 1.54 = %lf\n"
```

The constants are loaded into D0 and D1: pow() takes them from there. The result will be in D0 after the execution of pow(). It is to be passed to printf() without any modification and moving, because printf() takes arguments of integral types and pointers from X-registers, and floating point arguments from D-registers.

MIPS

Listing 1.209: Optimizing GCC 4.4.5 (IDA)

```
main:

var_10          = -0x10
var_4           = -4

; function prologue:
                lui     $gp, (dword_9C >> 16)
                addiu   $sp, -0x20
                la      $gp, (__gnu_local_gp & 0xFFFF)
                sw      $ra, 0x20+var_4($sp)
                sw      $gp, 0x20+var_10($sp)
                lui     $v0, (dword_A4 >> 16) ; ?
; load low 32-bit part of 32.01:
                lwc1    $f12, dword_9C
; load address of pow() function:
                lw      $t9, (pow & 0xFFFF)($gp)
; load high 32-bit part of 32.01:
                lwc1    $f13, $LC0
                lui     $v0, ($LC1 >> 16) ; ?
; load low 32-bit part of 1.54:
                lwc1    $f14, dword_A4
                or      $at, $zero ; load delay slot, NOP
; load high 32-bit part of 1.54:
```

```
                lwc1    $f15, $LC1
; call pow():
                jalr    $t9
                or      $at, $zero ; branch delay slot, NOP
                lw      $gp, 0x20+var_10($sp)
; copy result from $f0 and $f1 to $a3 and $a2:
                mfc1    $a3, $f0
                lw      $t9, (printf & 0xFFFF)($gp)
                mfc1    $a2, $f1
; call printf():
                lui     $a0, ($LC2 >> 16)  # "32.01 ^ 1.54 = %lf\n"
                jalr    $t9
                la      $a0, ($LC2 & 0xFFFF)  # "32.01 ^ 1.54 = %lf\n"
; function epilogue:
                lw      $ra, 0x20+var_4($sp)
; return 0:
                move    $v0, $zero
                jr      $ra
                addiu   $sp, 0x20

.rodata.str1.4:00000084 $LC2:           .ascii "32.01 ^ 1.54 = %lf\n"<0>

; 32.01:
.rodata.cst8:00000098 $LC0:           .word 0x40400147         # DATA XREF: main+20
.rodata.cst8:0000009C dword_9C:       .word 0xAE147AE1         # DATA XREF: main
.rodata.cst8:0000009C                                          # main+18
; 1.54:
.rodata.cst8:000000A0 $LC1:           .word 0x3FF8A3D7         # DATA XREF: main+24
.rodata.cst8:000000A0                                          # main+30
.rodata.cst8:000000A4 dword_A4:       .word 0xA3D70A4          # DATA XREF: main+14
```

And again, we see here LUI loading a 32-bit part of a *double* number into $V0. And again, it's hard to comprehend why.

The new instruction for us here is MFC1 ("Move From Coprocessor 1"). The FPU is coprocessor number 1, hence "1" in the instruction name. This instruction transfers values from the coprocessor's registers to the registers of the CPU (GPR). So at the end the result of `pow()` is moved to registers $A3 and $A2, and `printf()` takes a 64-bit double value from this register pair.

1.19.7 Comparison example

Let's try this:

```
#include <stdio.h>

double d_max (double a, double b)
{
        if (a>b)
                return a;

        return b;
};

int main()
{
        printf ("%f\n", d_max (1.2, 3.4));
        printf ("%f\n", d_max (5.6, -4));
};
```

Despite the simplicity of the function, it will be harder to understand how it works.

x86

Non-optimizing MSVC

MSVC 2010 generates the following:

Listing 1.210: Non-optimizing MSVC 2010

```
PUBLIC    _d_max
_TEXT    SEGMENT
_a$ = 8                ; size = 8
_b$ = 16               ; size = 8
_d_max     PROC
    push   ebp
    mov    ebp, esp
    fld    QWORD PTR _b$[ebp]

; current stack state: ST(0) = _b
; compare _b (ST(0)) and _a, and pop register

    fcomp  QWORD PTR _a$[ebp]

; stack is empty here

    fnstsw ax
    test   ah, 5
    jp     SHORT $LN1@d_max

; we are here only if a>b

    fld    QWORD PTR _a$[ebp]
    jmp    SHORT $LN2@d_max
$LN1@d_max:
    fld    QWORD PTR _b$[ebp]
$LN2@d_max:
    pop    ebp
    ret    0
_d_max     ENDP
```

So, FLD loads _b into ST(0).

FCOMP compares the value in ST(0) with what is in _a and sets C3/C2/C0 bits in FPU status word register, accordingly. This is a 16-bit register that reflects the current state of the FPU.

After the bits are set, the FCOMP instruction also pops one variable from the stack. This is what distinguishes it from FCOM, which is just compares values, leaving the stack in the same state.

Unfortunately, CPUs before Intel P6 [121] don't have any conditional jumps instructions which check the C3/C2/C0 bits. Perhaps, it is a matter of history (recall: FPU was a separate chip in past).
Modern CPU starting at Intel P6 have FCOMI/FCOMIP/FUCOMI/FUCOMIP instructions —which do the same, but modify the ZF/PF/CF CPU flags.

The FNSTSW instruction copies FPU the status word register to AX. C3/C2/C0 bits are placed at positions 14/10/8, they are at the same positions in the AX register and all they are placed in the high part of AX —AH.

- If $b > a$ in our example, then C3/C2/C0 bits are to be set as following: 0, 0, 0.
- If $a > b$, then the bits are: 0, 0, 1.
- If $a = b$, then the bits are: 1, 0, 0.
- If the result is unordered (in case of error), then the set bits are: 1, 1, 1.

This is how C3/C2/C0 bits are located in the AX register:

	14		10	9	8	
	C3		C2	C1	C0	

This is how C3/C2/C0 bits are located in the AH register:

	6		2	1	0
	C3		C2	C1	C0

After the execution of `test ah, 5`[122], only C0 and C2 bits (on 0 and 2 position) are considered, all other bits are just ignored.

[121] Intel P6 is Pentium Pro, Pentium II, etc.
[122] 5=101b

Now let's talk about the *parity flag*, another notable historical rudiment.

This flag is set to 1 if the number of ones in the result of the last calculation is even, and to 0 if it is odd.

Let's look into Wikipedia[123]:

> One common reason to test the parity flag actually has nothing to do with parity. The FPU has four condition flags (C0 to C3), but they cannot be tested directly, and must instead be first copied to the flags register. When this happens, C0 is placed in the carry flag, C2 in the parity flag and C3 in the zero flag. The C2 flag is set when e.g. incomparable floating point values (NaN or unsupported format) are compared with the FUCOM instructions.

As noted in Wikipedia, the parity flag used sometimes in FPU code, let's see how.

The PF flag is to be set to 1 if both `C0` and `C2` are set to 0 or both are 1, in which case the subsequent `JP` (*jump if PF==1*) is triggering. If we recall the values of `C3`/`C2`/`C0` for various cases, we can see that the conditional jump `JP` is triggering in two cases: if $b > a$ or $a = b$ (`C3` bit is not considered here, since it has been cleared by the `test ah, 5` instruction).

It is all simple after that. If the conditional jump has been triggered, `FLD` loads the value of _b in `ST(0)`, and if it hasn't been triggered, the value of _a is loaded there.

And what about checking C2?

The C2 flag is set in case of error (NaN, etc.), but our code doesn't check it.

If the programmer cares about FPU errors, he/she must add additional checks.

[123] wikipedia.org/wiki/Parity_flag

First OllyDbg example: a=1.2 and b=3.4

Let's load the example into OllyDbg:

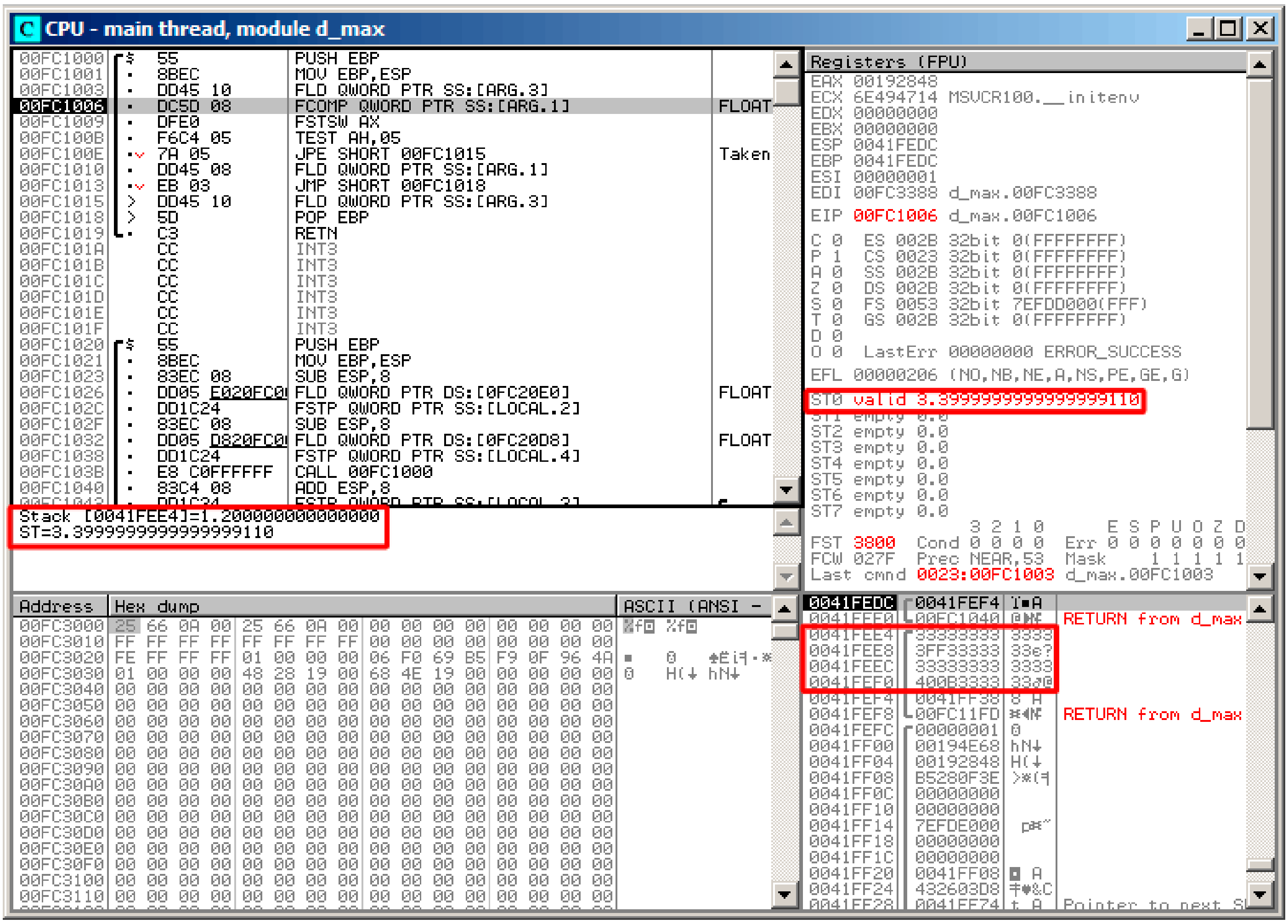


Figure 1.67: OllyDbg: first FLD has been executed

Current arguments of the function: $a = 1.2$ and $b = 3.4$ (We can see them in the stack: two pairs of 32-bit values). b (3.4) is already loaded in ST(0). Now FCOMP is being executed. OllyDbg shows the second FCOMP argument, which is in stack right now.

FCOMP has been executed:

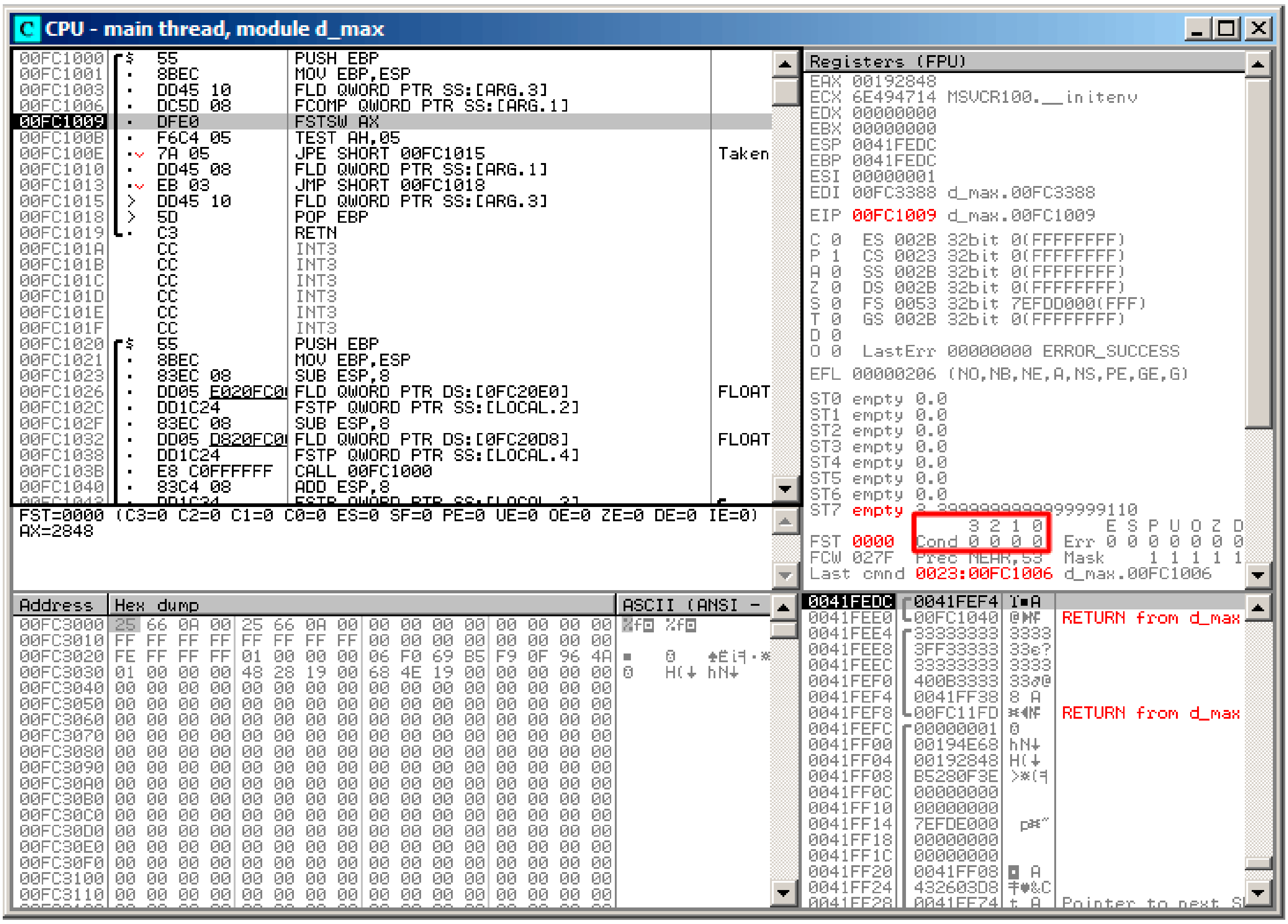


Figure 1.68: OllyDbg: FCOMP has been executed

We see the state of the FPU's condition flags: all zeros. The popped value is reflected as ST(7), it was written earlier about reason for this: 1.19.5 on page 225.

FNSTSW has been executed:

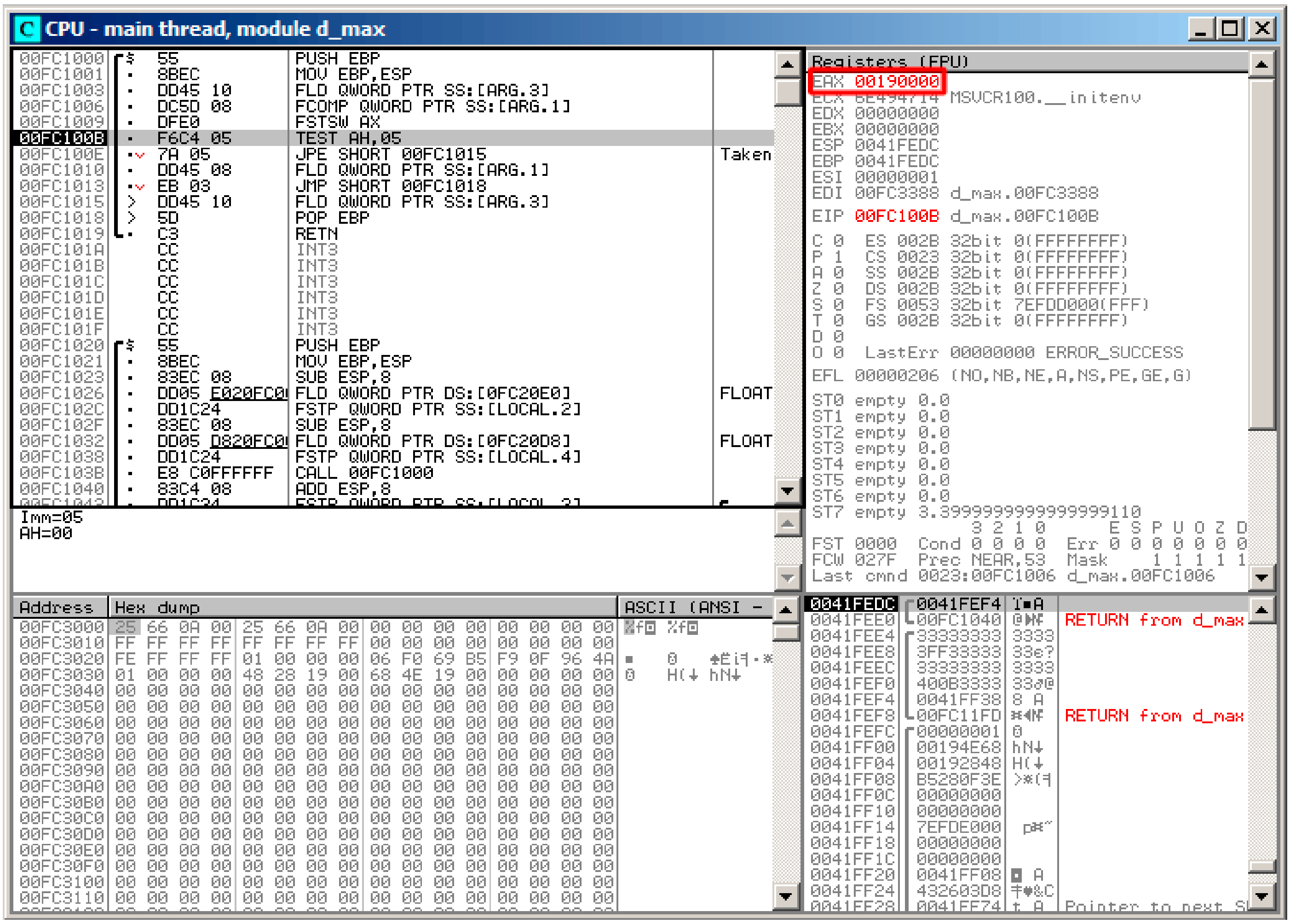


Figure 1.69: OllyDbg: FNSTSW has been executed

We see that the AX register contain zeros: indeed, all condition flags are zero. (OllyDbg disassembles the FNSTSW instruction as FSTSW—they are synonyms).

TEST has been executed:

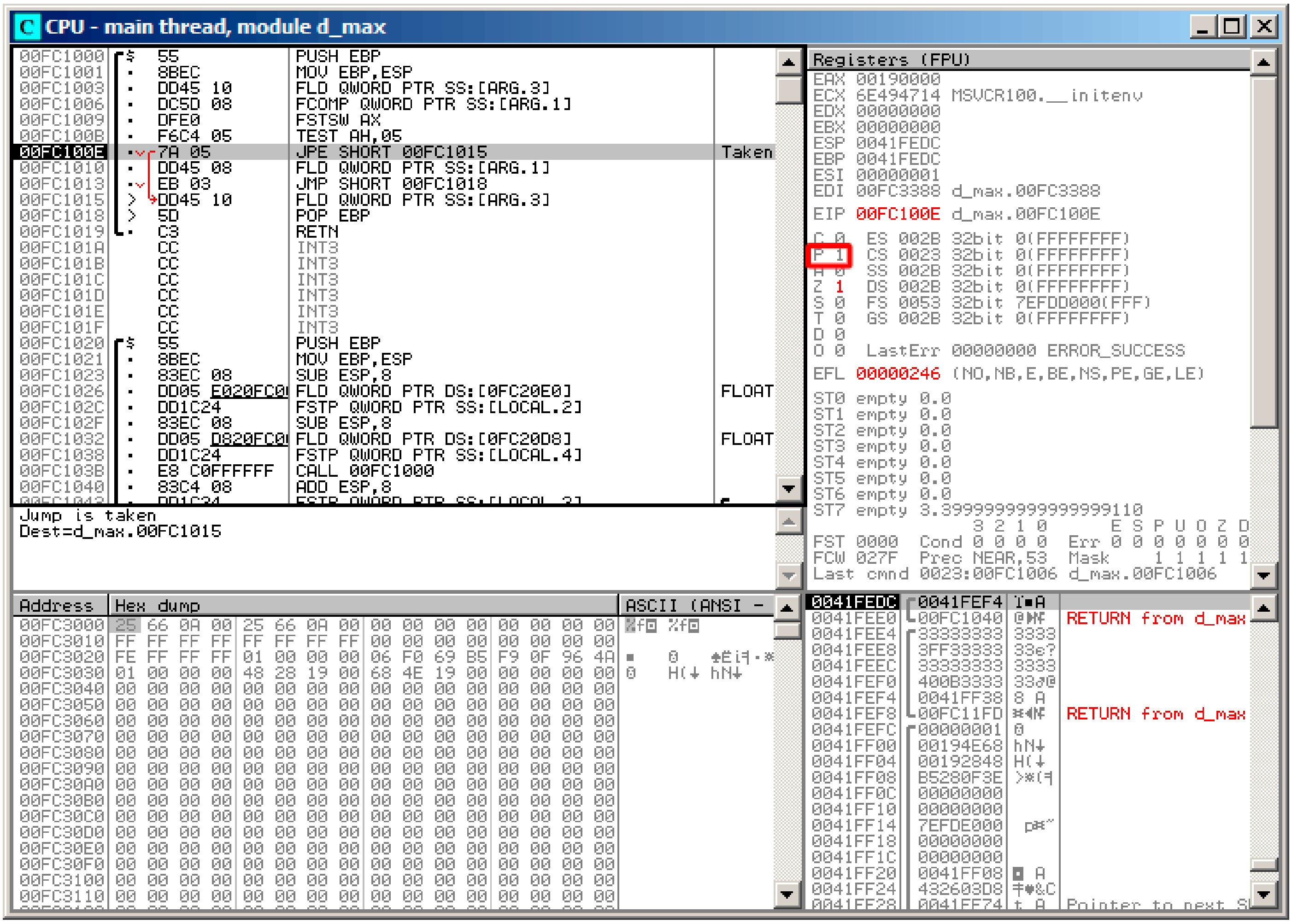


Figure 1.70: OllyDbg: TEST has been executed

The PF flag is set to 1.

Indeed: the number of bits set in 0 is 0 and 0 is an even number. OllyDbg disassembles JP as JPE[124]—they are synonyms. And it is about to trigger now.

[124] Jump Parity Even (x86 instruction)

JPE triggered, FLD loads the value of b (3.4) in ST(0):

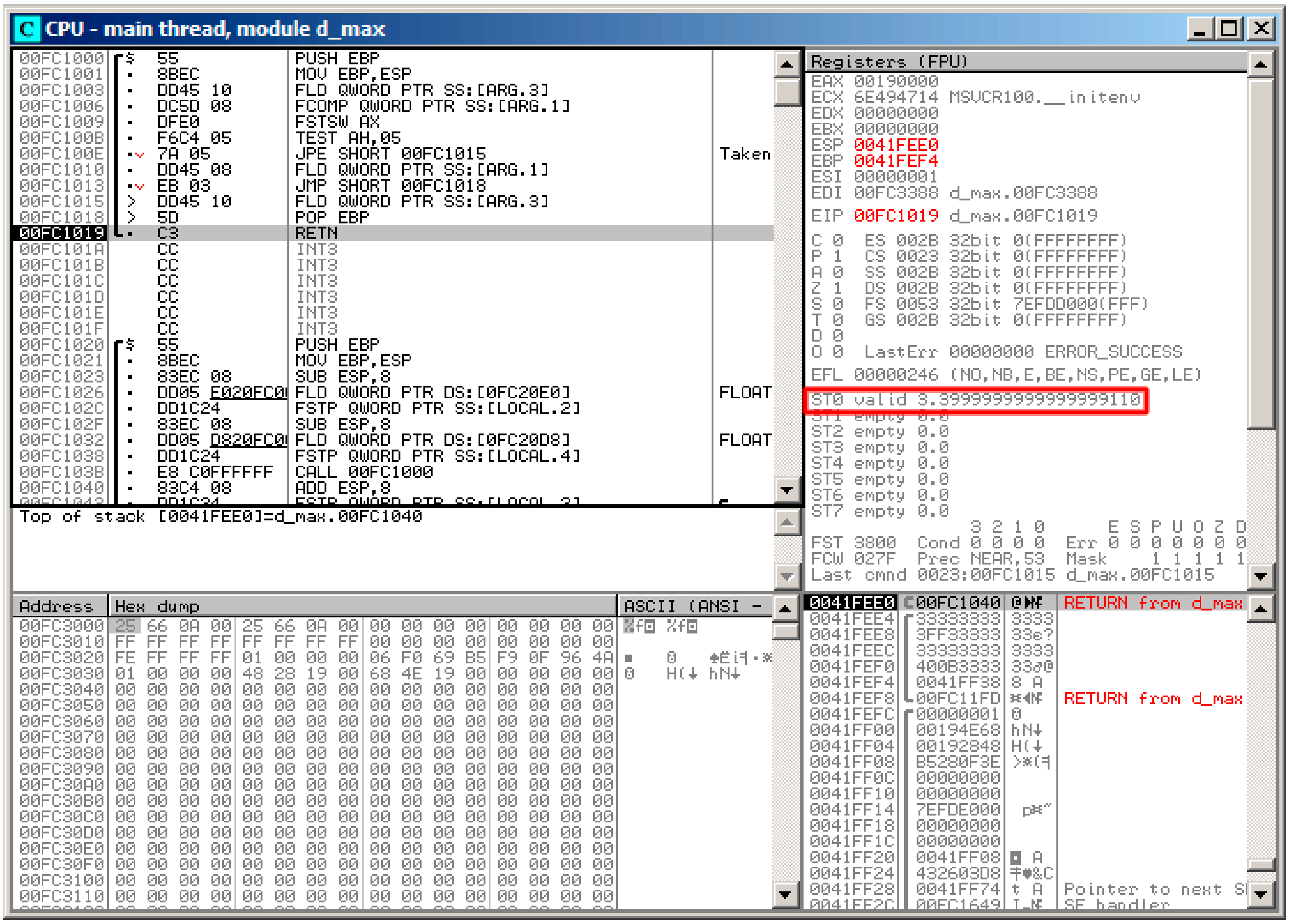


Figure 1.71: OllyDbg: the second FLD has been executed

The function finishes its work.

Second OllyDbg example: a=5.6 and b=-4

Let's load example into OllyDbg:

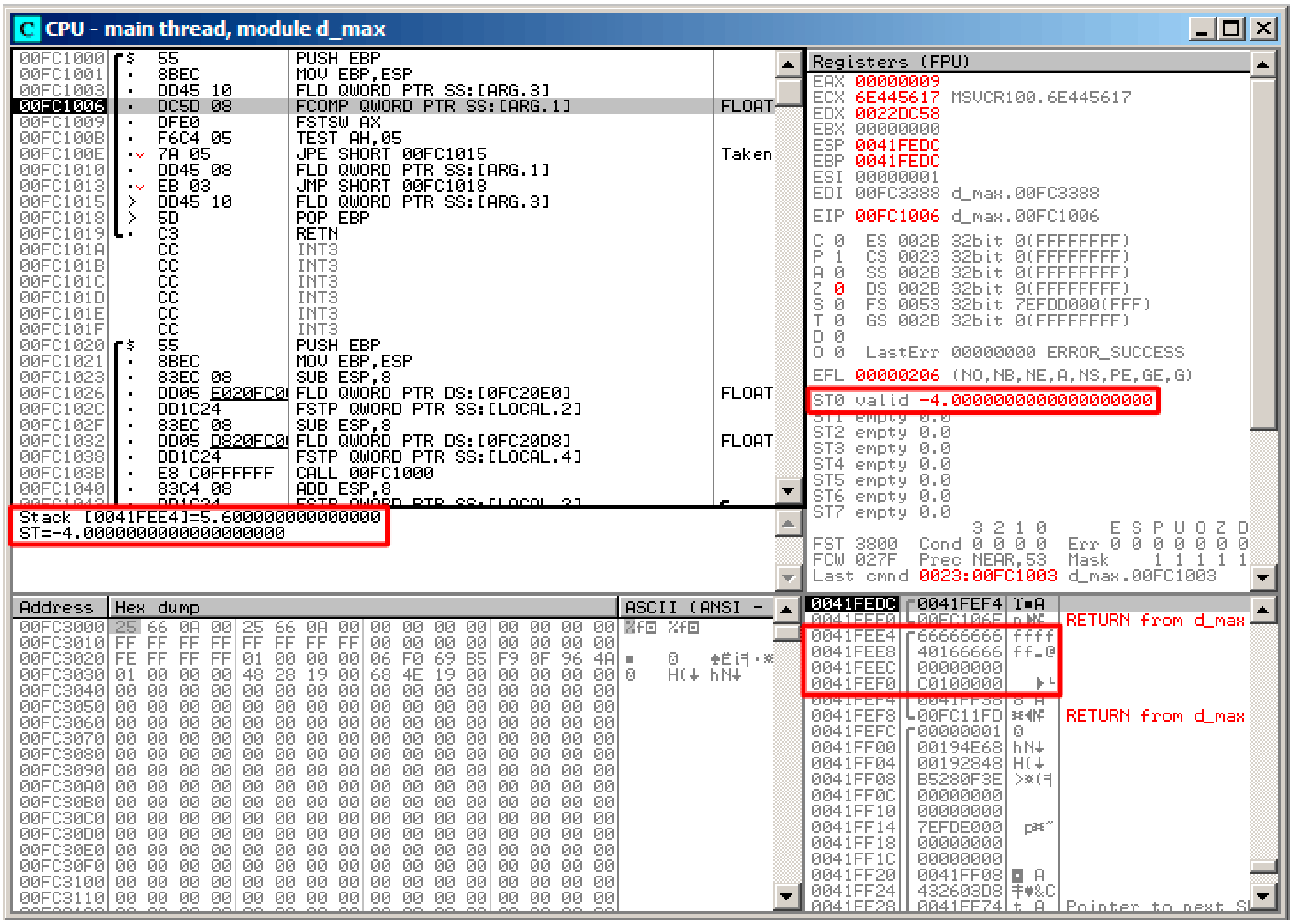


Figure 1.72: OllyDbg: first FLD executed

Current function arguments: $a = 5.6$ and $b = -4$. b (-4) is already loaded in ST(0). FCOMP about to execute now. OllyDbg shows the second FCOMP argument, which is in stack right now.

FCOMP executed:

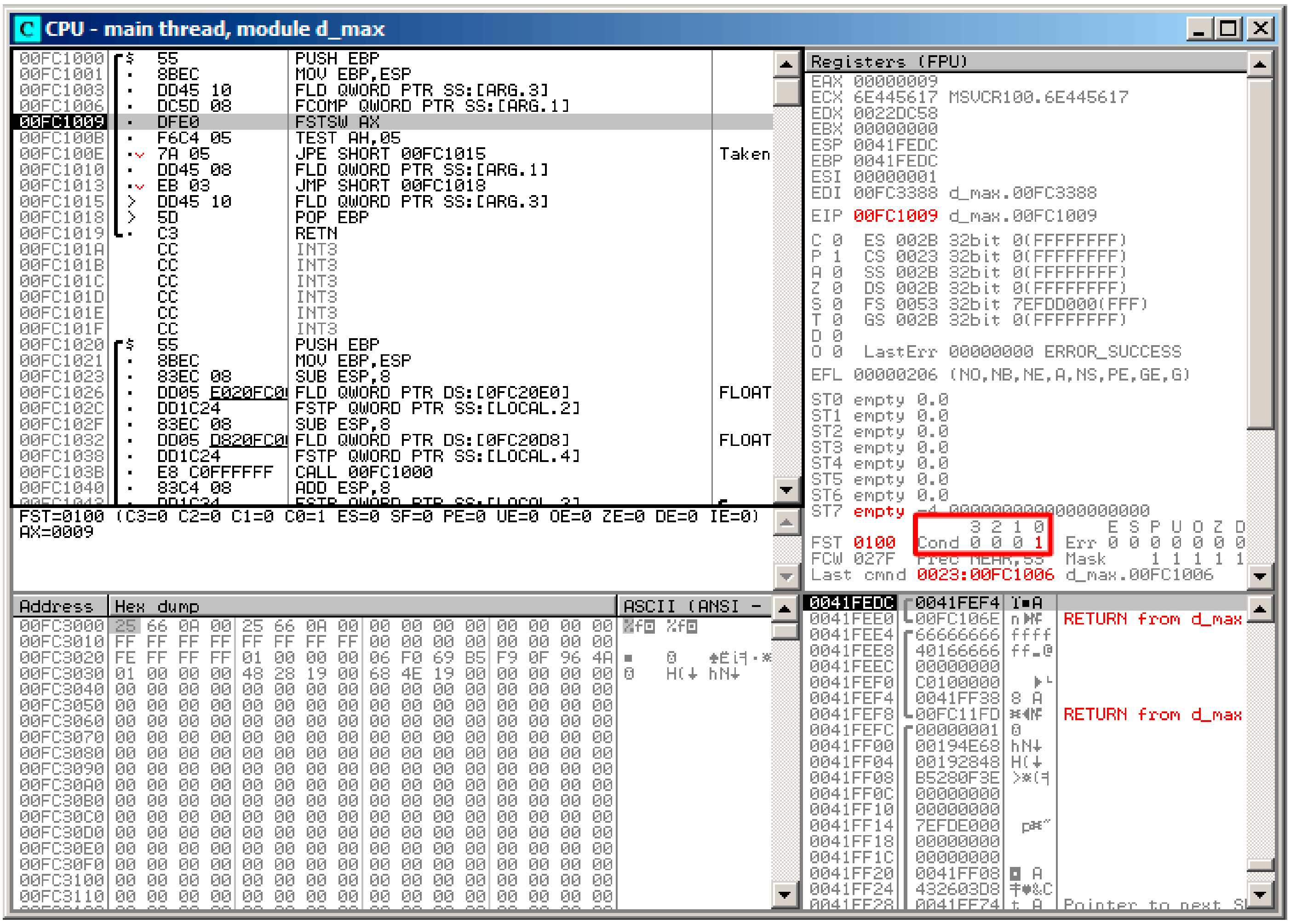


Figure 1.73: OllyDbg: FCOMP executed

We see the state of the FPU's condition flags: all zeros except C0.

FNSTSW executed:

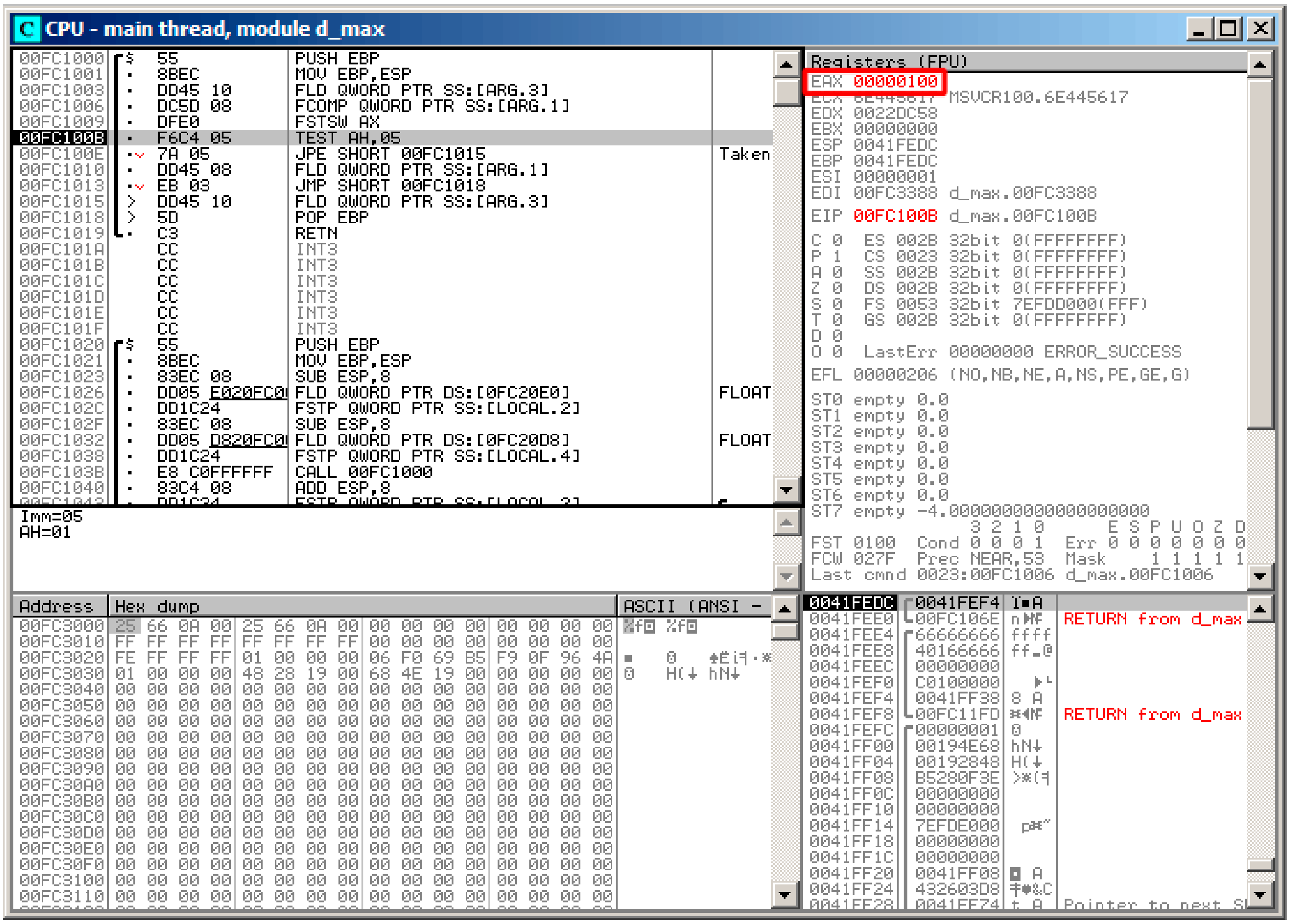


Figure 1.74: OllyDbg: FNSTSW executed

We see that the AX register contains `0x100`: the `C0` flag is at the 8th bit.

TEST executed:

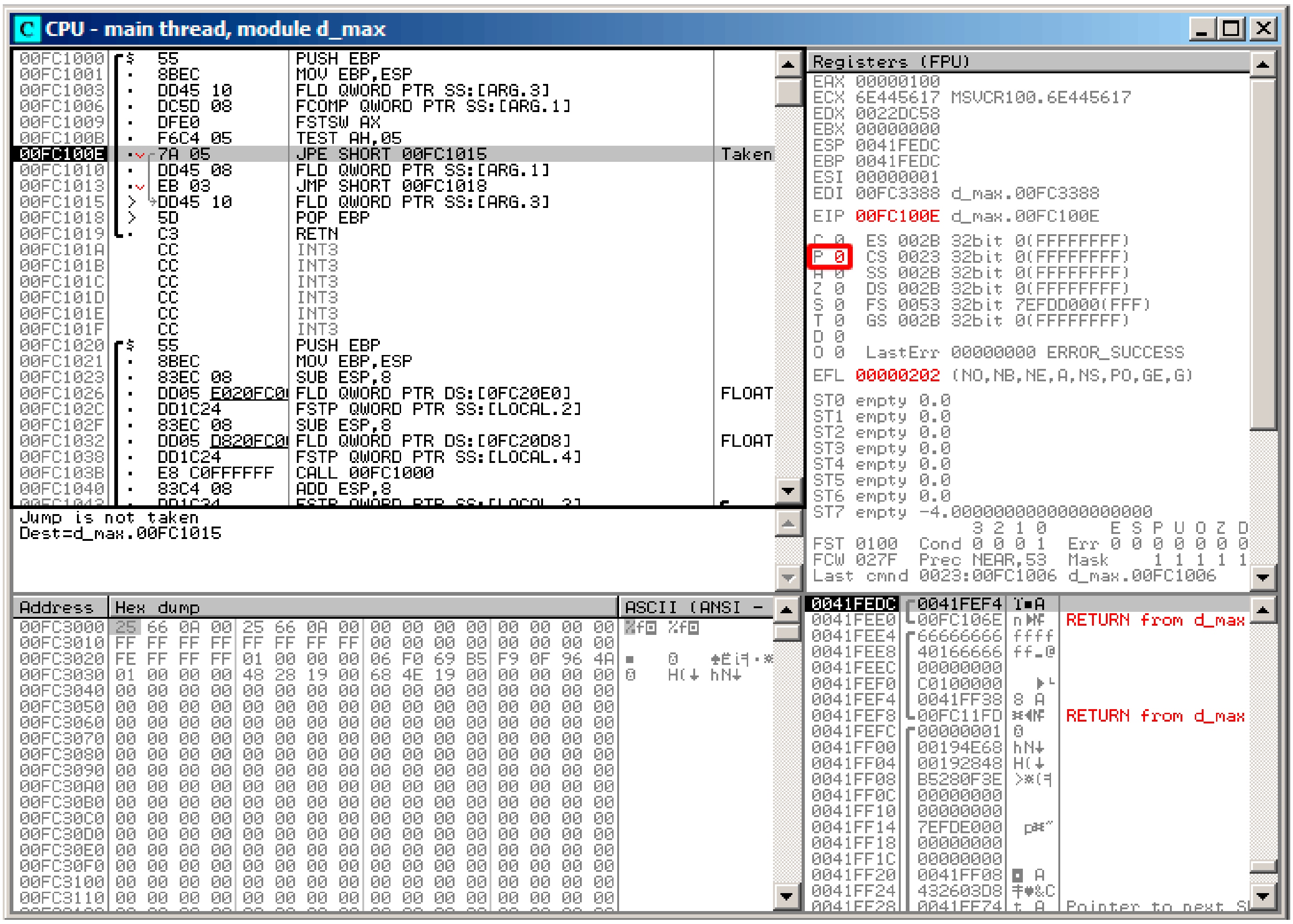


Figure 1.75: OllyDbg: TEST executed

The PF flag is cleared. Indeed:

the count of bits set in `0x100` is 1 and 1 is an odd number. JPE is being skipped now.

JPE hasn't been triggered, so FLD loads the value of a (5.6) in ST(0):

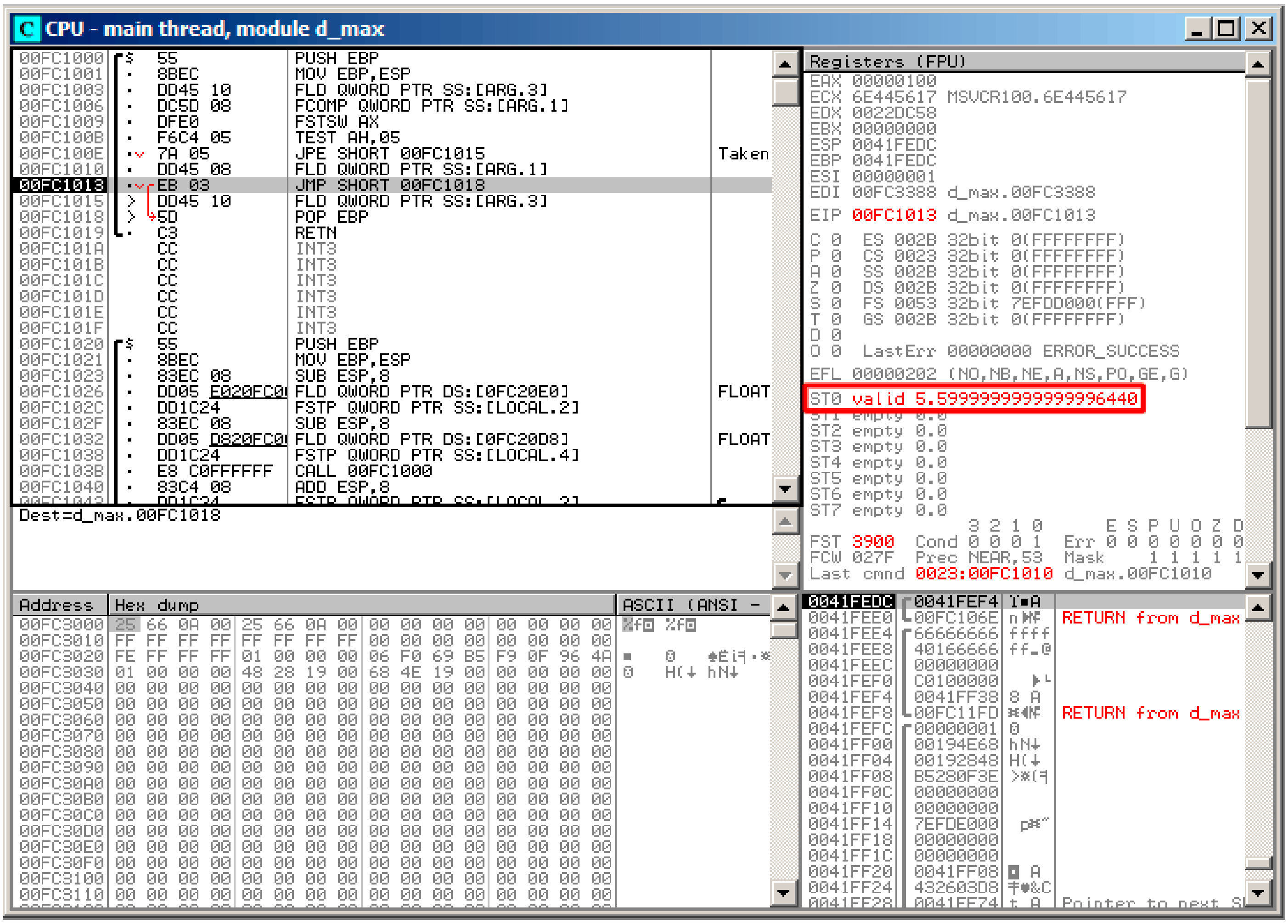


Figure 1.76: OllyDbg: second FLD executed

The function finishes its work.

Optimizing MSVC 2010

Listing 1.211: Optimizing MSVC 2010

```
_a$ = 8                    ; size = 8
_b$ = 16                   ; size = 8
_d_max    PROC
    fld    QWORD PTR _b$[esp-4]
    fld    QWORD PTR _a$[esp-4]

; current stack state: ST(0) = _a, ST(1) = _b

    fcom    ST(1) ; compare _a and ST(1) = (_b)
    fnstsw  ax
    test    ah, 65 ; 00000041H
    jne     SHORT $LN5@d_max
; copy ST(0) to ST(1) and pop register,
; leave (_a) on top
    fstp    ST(1)

; current stack state: ST(0) = _a

    ret    0
$LN5@d_max:
; copy ST(0) to ST(0) and pop register,
```

```
; leave (_b) on top
    fstp    ST(0)

; current stack state: ST(0) = _b

    ret     0
_d_max    ENDP
```

FCOM differs from FCOMP in the sense that it just compares the values and doesn't change the FPU stack. Unlike the previous example, here the operands are in reverse order, which is why the result of the comparison in C3/C2/C0 is different:

- If $a > b$ in our example, then C3/C2/C0 bits are to be set as: 0, 0, 0.
- If $b > a$, then the bits are: 0, 0, 1.
- If $a = b$, then the bits are: 1, 0, 0.

The `test ah, 65` instruction leaves just two bits —C3 and C0. Both will be zero if $a > b$: in that case the JNE jump will not be triggered. Then FSTP ST(1) follows —this instruction copies the value from ST(0) to the operand and pops one value from the FPU stack. In other words, the instruction copies ST(0) (where the value of _a is now) into ST(1). After that, two copies of _a are at the top of the stack. Then, one value is popped. After that, ST(0) contains _a and the function is finishes.

The conditional jump JNE is triggering in two cases: if $b > a$ or $a = b$. ST(0) is copied into ST(0), it is just like an idle (NOP) operation, then one value is popped from the stack and the top of the stack (ST(0)) is contain what has been in ST(1) before (that is _b). Then the function finishes. The reason this instruction is used here probably is because the FPU has no other instruction to pop a value from the stack and discard it.

First OllyDbg example: a=1.2 and b=3.4

Both FLD are executed:

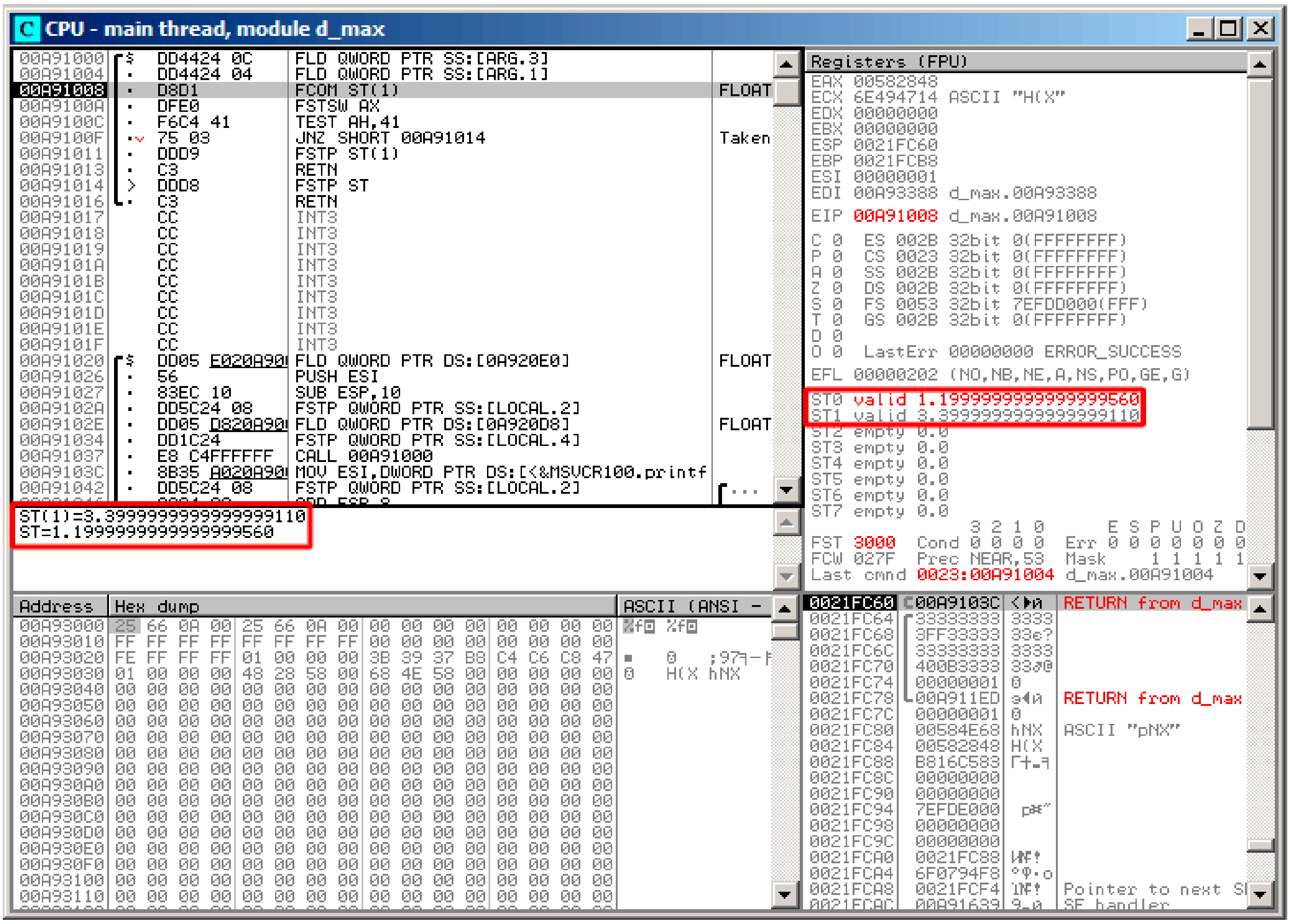


Figure 1.77: OllyDbg: both FLD are executed

FCOM being executed: OllyDbg shows the contents of ST(0) and ST(1) for convenience.

FCOM has been executed:

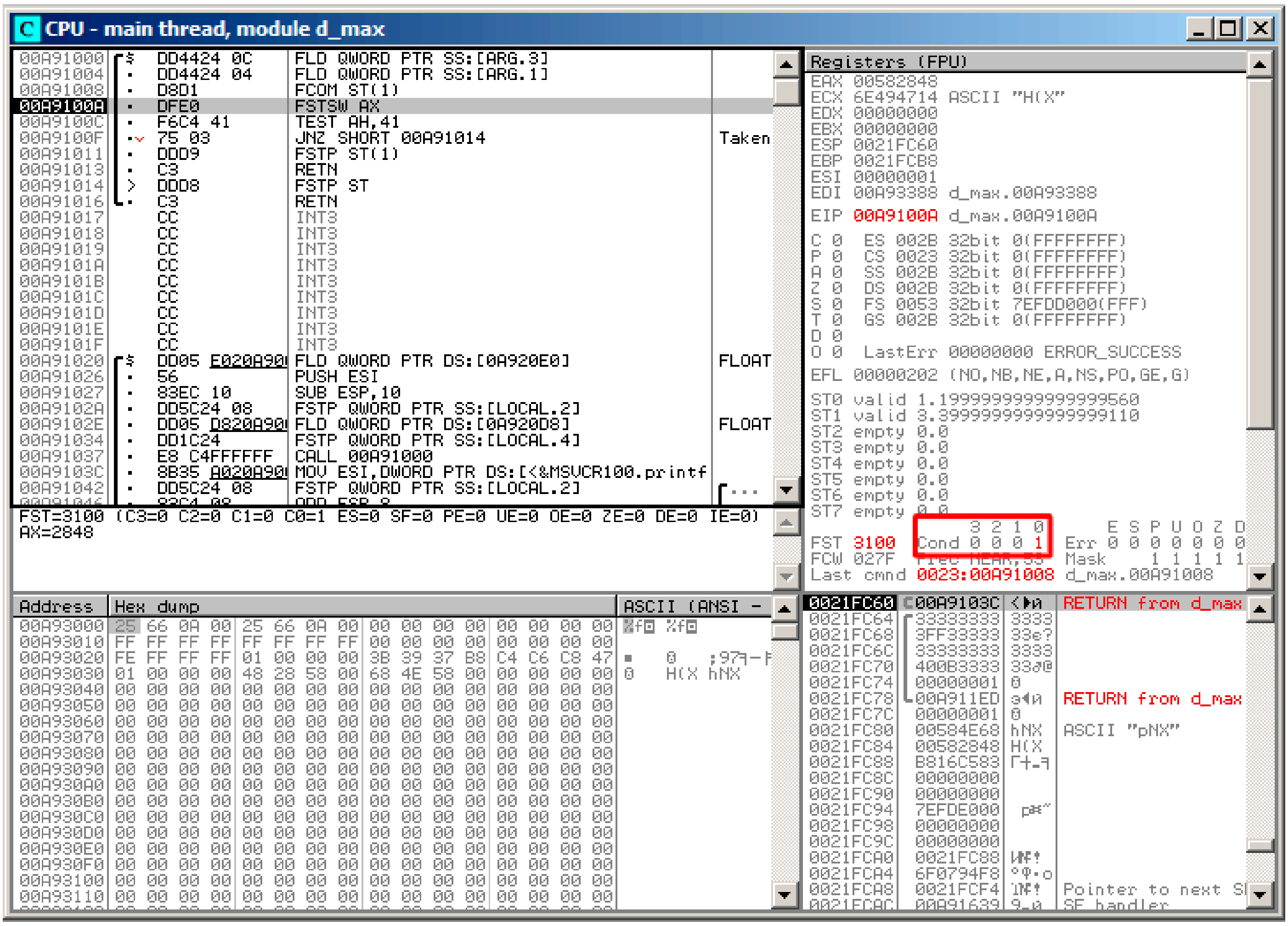


Figure 1.78: OllyDbg: FCOM has been executed

C0 is set, all other condition flags are cleared.

FNSTSW has been executed, AX=0x3100:

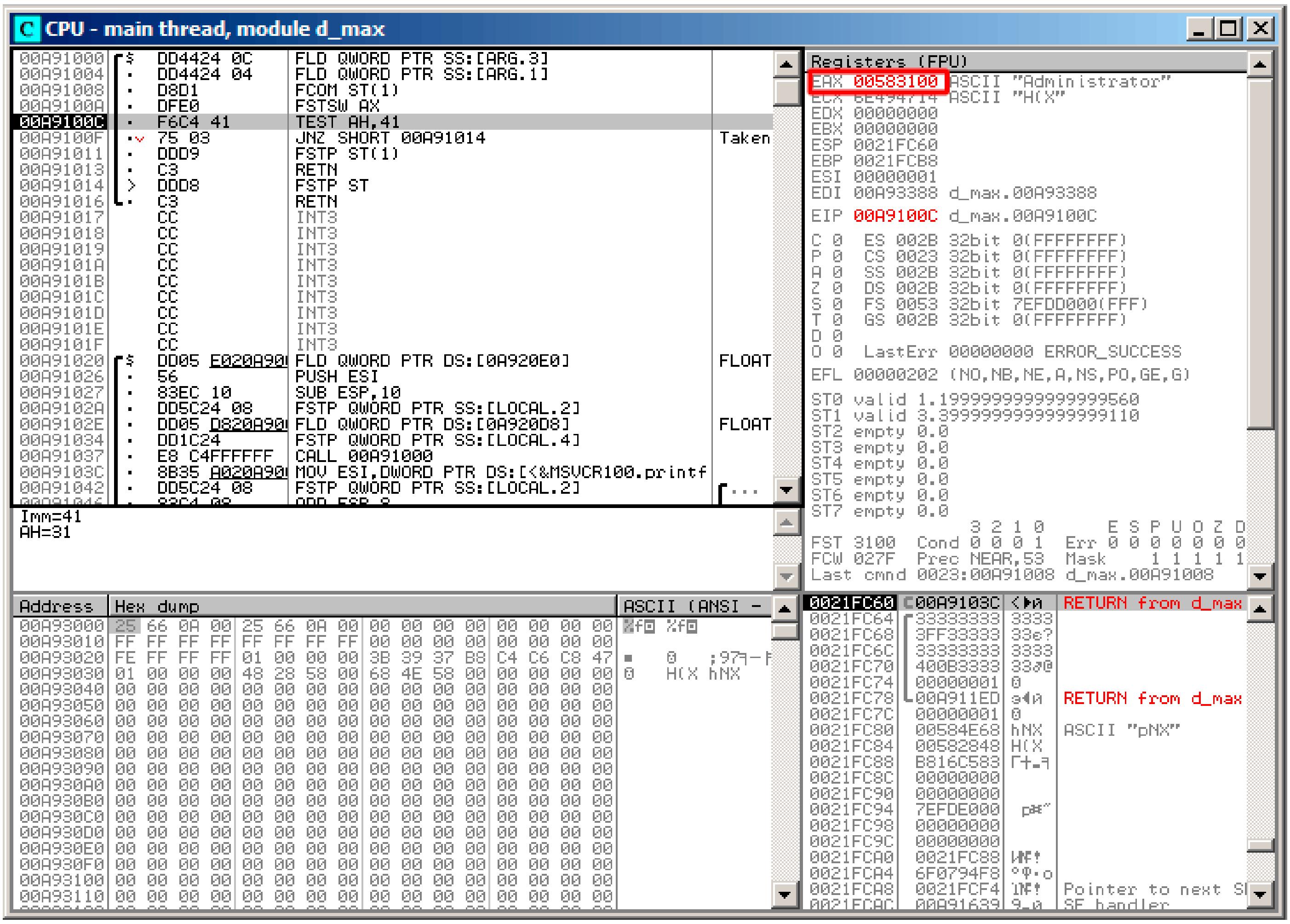


Figure 1.79: OllyDbg: FNSTSW is executed

TEST is executed:

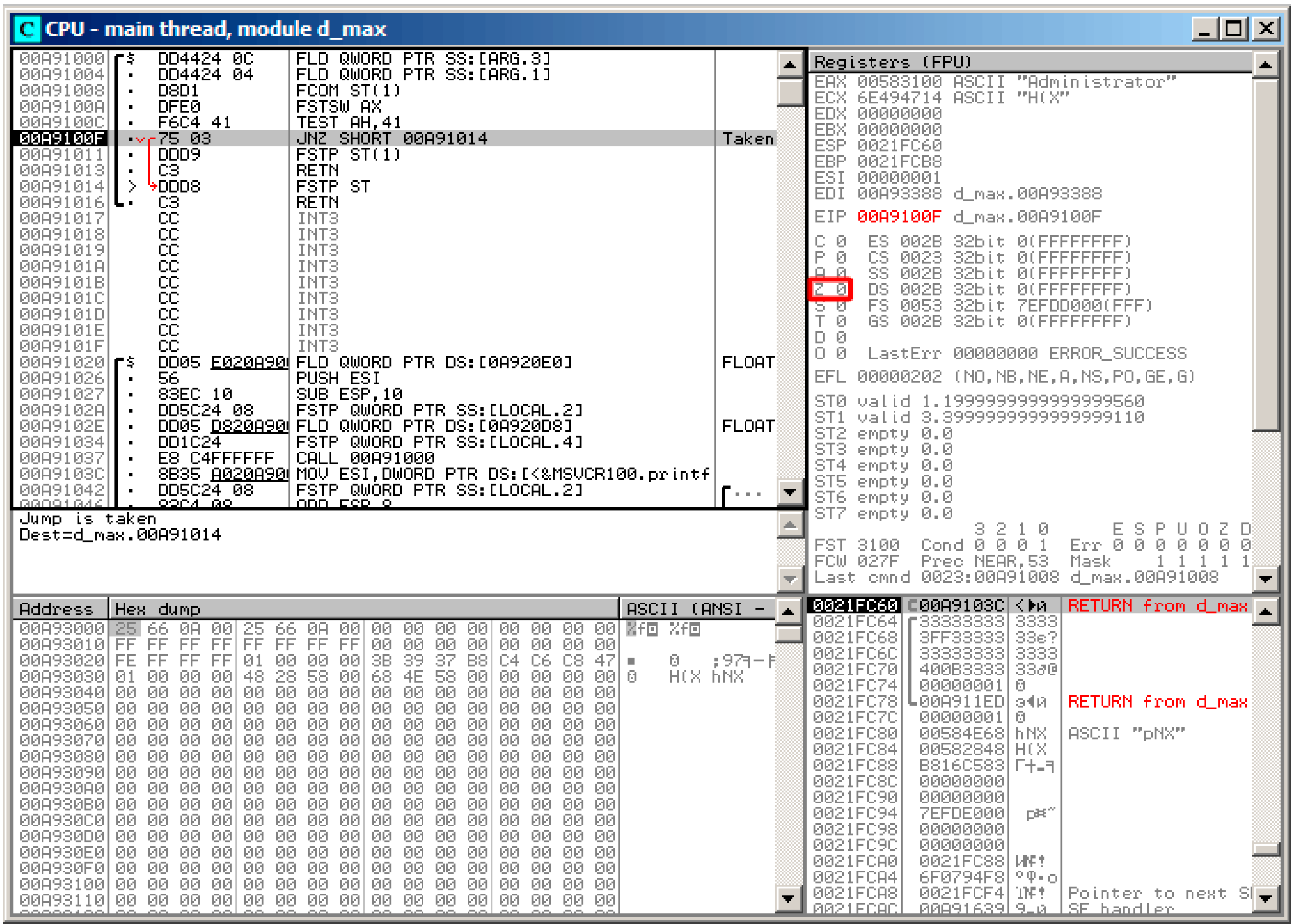


Figure 1.80: OllyDbg: TEST is executed

ZF=0, conditional jump is about to trigger now.

FSTP ST (or FSTP ST(0)) has been executed —1.2 has been popped from the stack, and 3.4 was left on top:

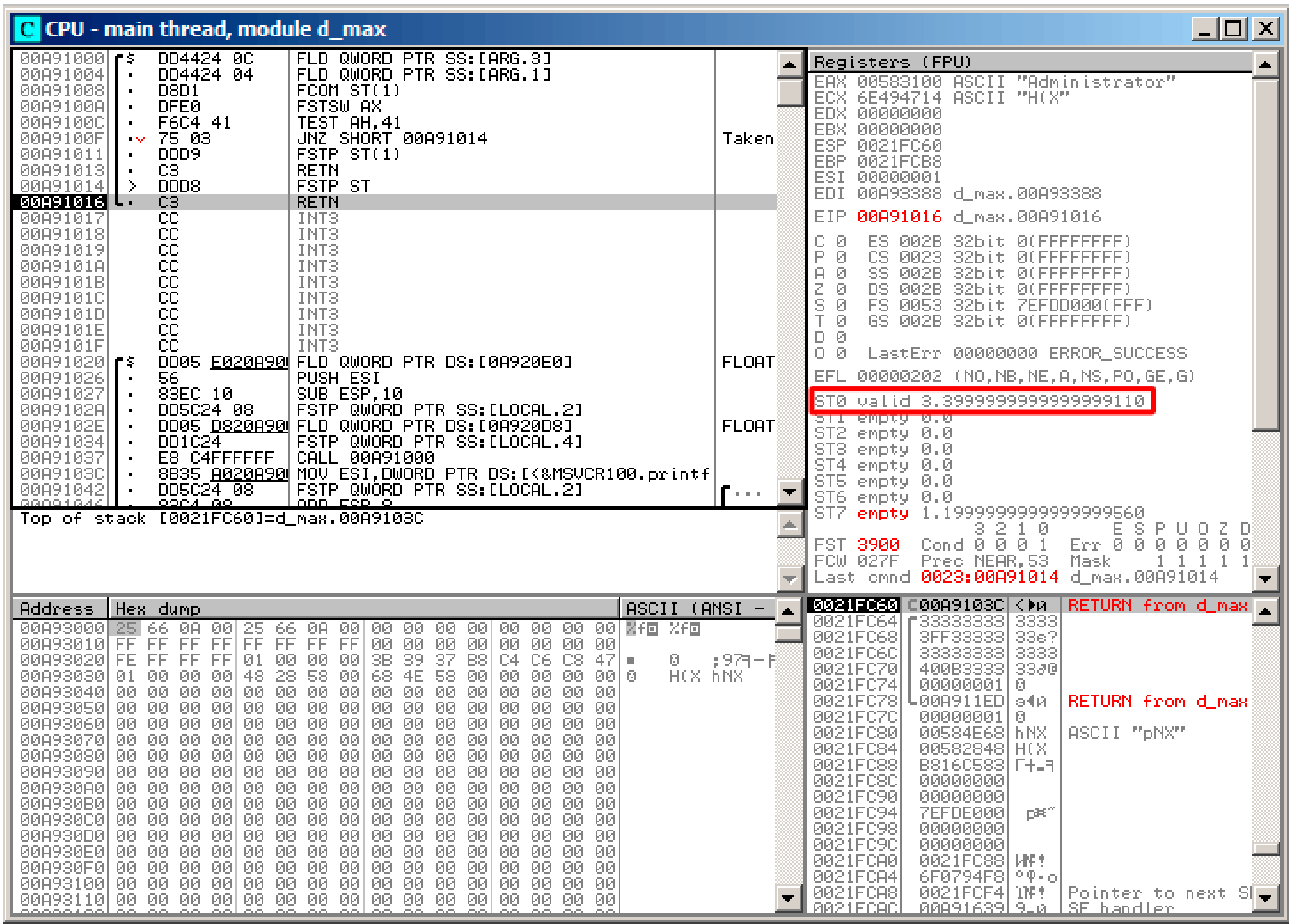


Figure 1.81: OllyDbg: FSTP is executed

We see that the FSTP ST

instruction works just like popping one value from the FPU stack.

Second OllyDbg example: a=5.6 and b=-4

Both FLD are executed:

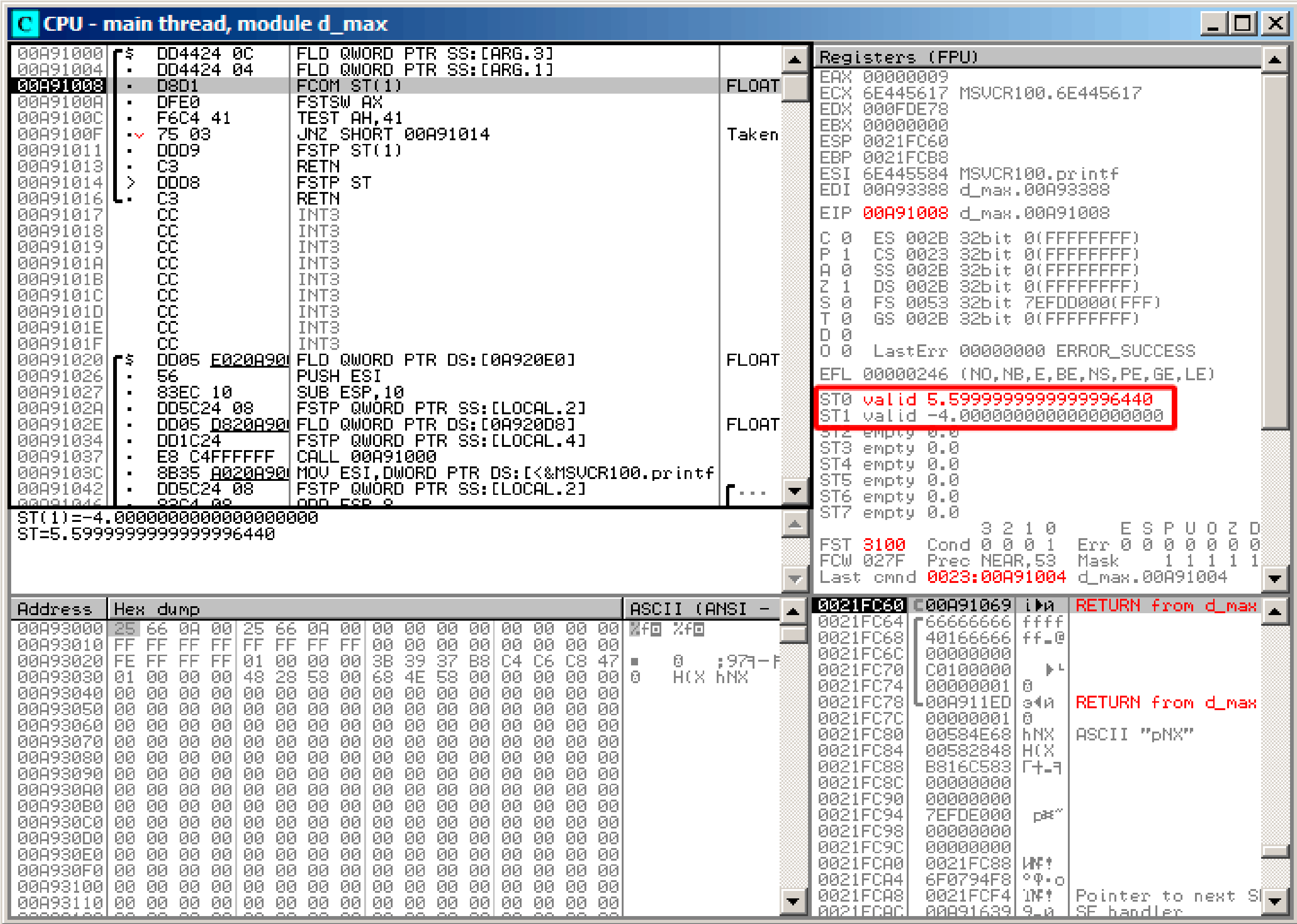


Figure 1.82: OllyDbg: both FLD are executed

FCOM is about to execute.

FCOM has been executed:

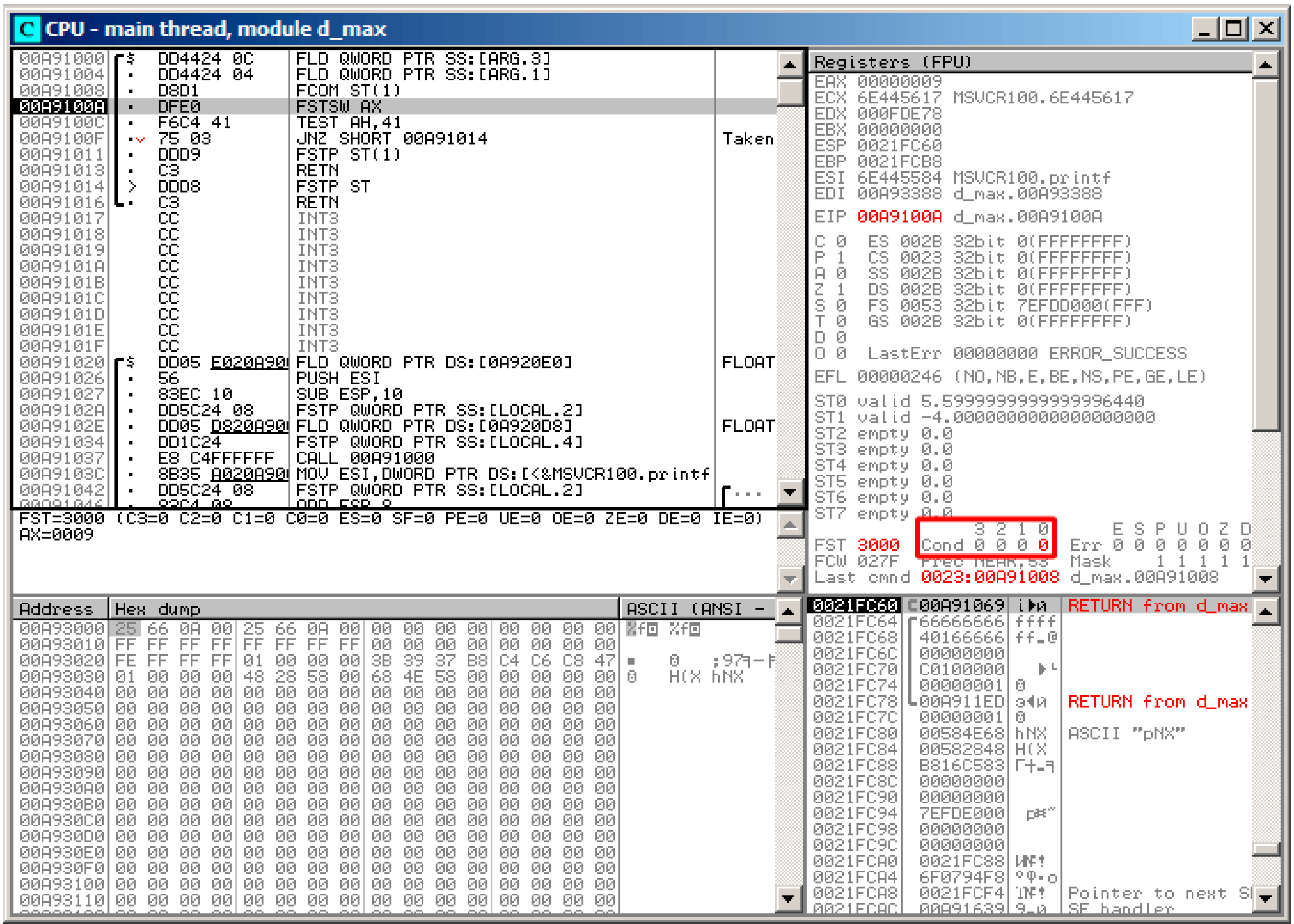


Figure 1.83: OllyDbg: FCOM is finished

All conditional flags are cleared.

FNSTSW done, AX=0x3000:

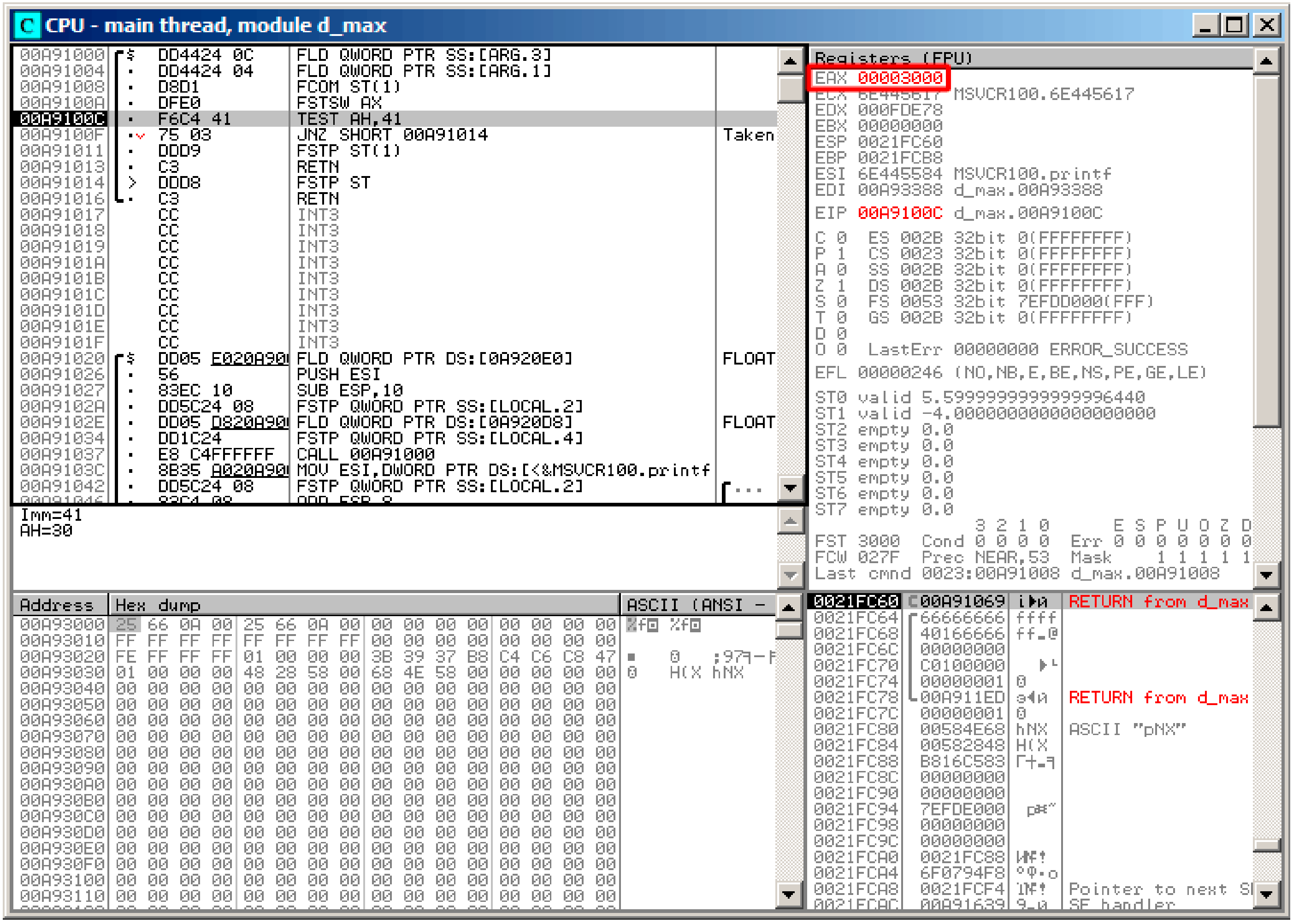


Figure 1.84: OllyDbg: FNSTSW has been executed

TEST has been executed:

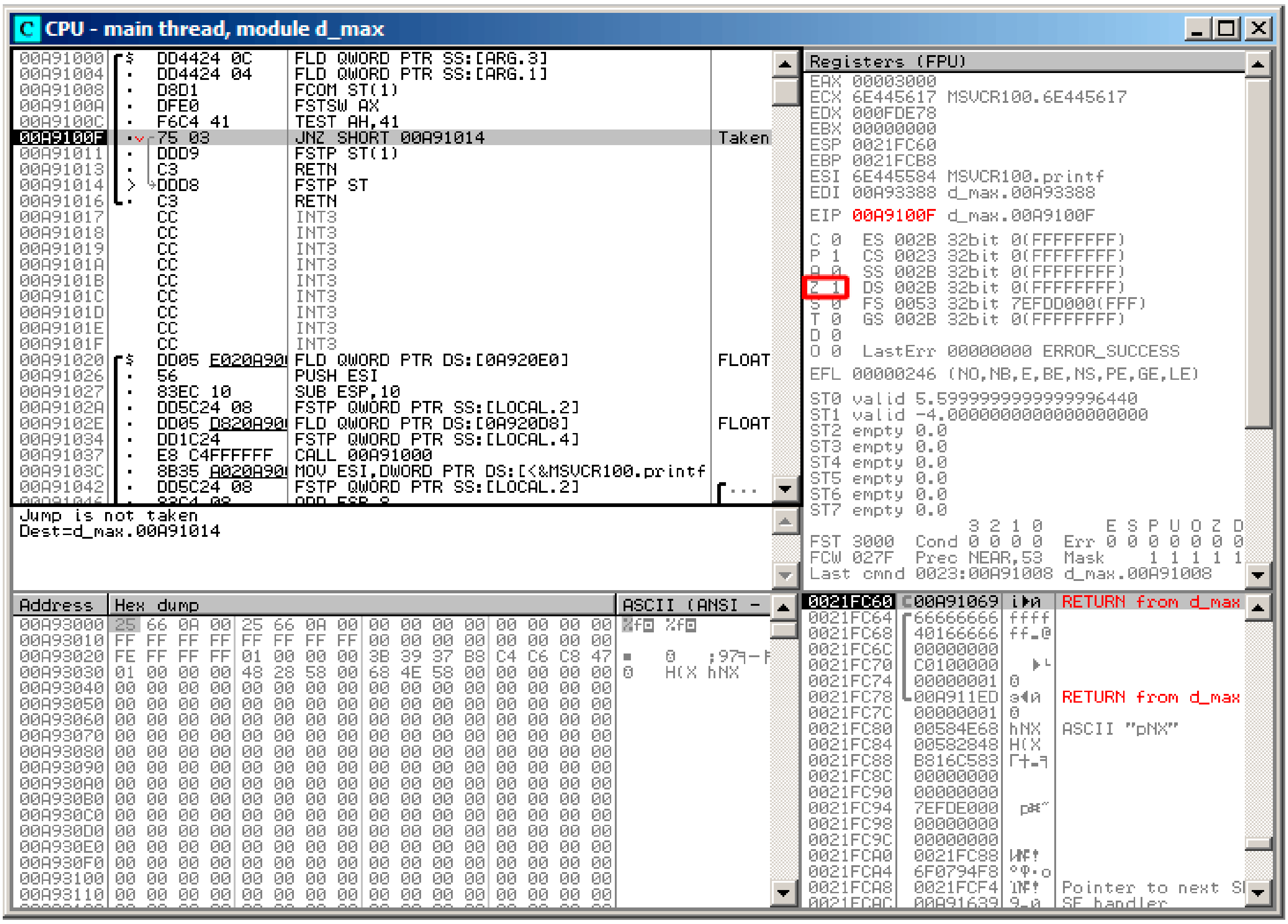


Figure 1.85: OllyDbg: TEST has been executed

ZF=1, jump will not happen now.

FSTP ST(1) has been executed: a value of 5.6 is now at the top of the FPU stack.

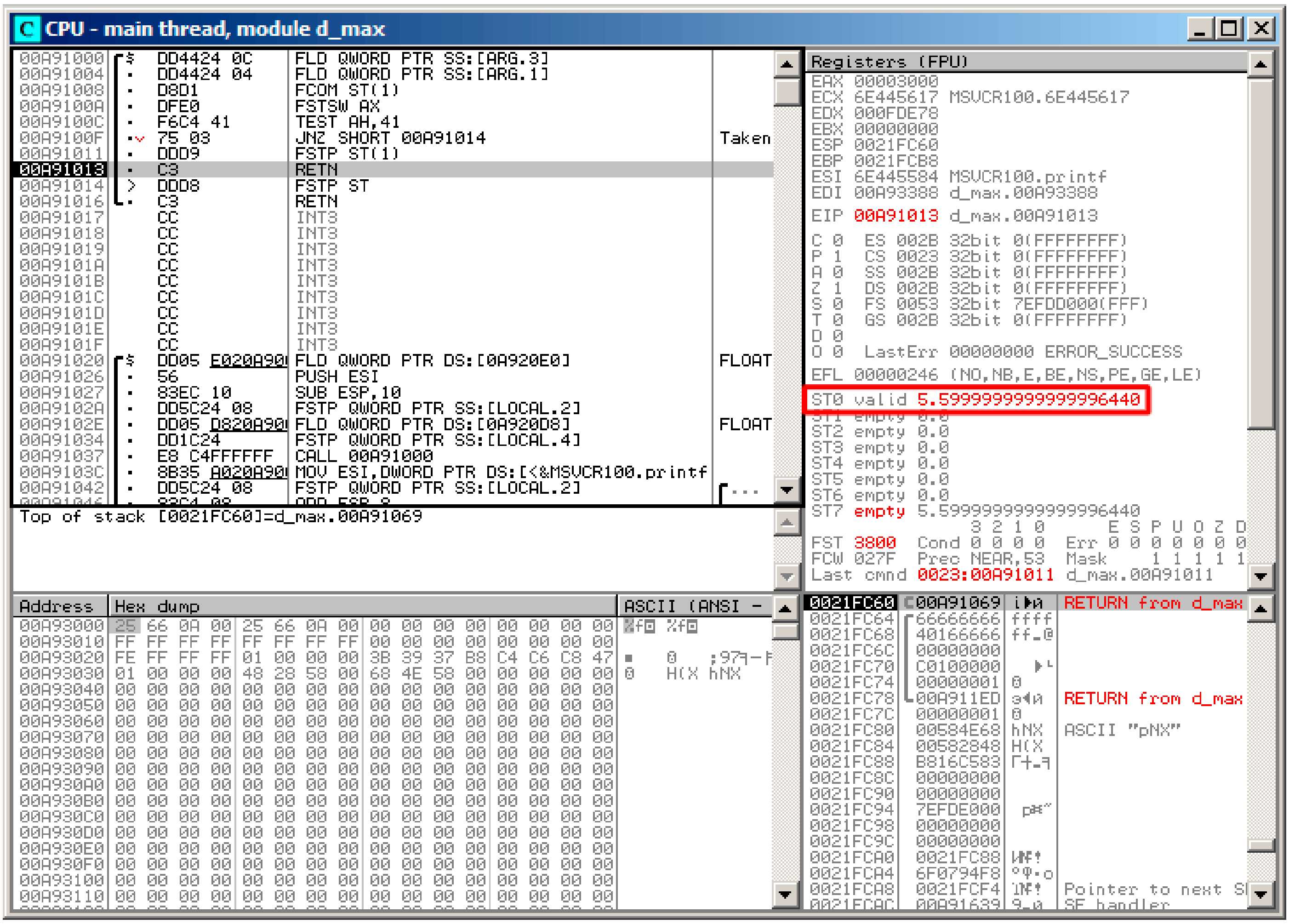


Figure 1.86: OllyDbg: FSTP has been executed

We now see that the FSTP ST(1) instruction works as follows: it leaves what has been at the top of the stack, but clears ST(1).

GCC 4.4.1

Listing 1.212: GCC 4.4.1

```
d_max proc near

b               = qword ptr -10h
a               = qword ptr -8
a_first_half    = dword ptr  8
a_second_half   = dword ptr  0Ch
b_first_half    = dword ptr  10h
b_second_half   = dword ptr  14h

    push    ebp
    mov     ebp, esp
    sub     esp, 10h

; put a and b to local stack:

    mov     eax, [ebp+a_first_half]
    mov     dword ptr [ebp+a], eax
    mov     eax, [ebp+a_second_half]
    mov     dword ptr [ebp+a+4], eax
    mov     eax, [ebp+b_first_half]
```

```
    mov     dword ptr [ebp+b], eax
    mov     eax, [ebp+b_second_half]
    mov     dword ptr [ebp+b+4], eax

; load a and b to FPU stack:

    fld     [ebp+a]
    fld     [ebp+b]

; current stack state: ST(0) - b; ST(1) - a

    fxch    st(1) ; this instruction swapping ST(1) and ST(0)

; current stack state: ST(0) - a; ST(1) - b

    fucompp    ; compare a and b and pop two values from stack, i.e., a and b
    fnstsw  ax ; store FPU status to AX
    sahf       ; load SF, ZF, AF, PF, and CF flags state from AH
    setnbe  al ; store 1 to AL, if CF=0 and ZF=0
    test    al, al            ; AL==0 ?
    jz      short loc_8048453 ; yes
    fld     [ebp+a]
    jmp     short locret_8048456

loc_8048453:
    fld     [ebp+b]

locret_8048456:
    leave
    retn
d_max endp
```

FUCOMPP is almost like FCOM, but pops both values from the stack and handles "not-a-numbers" differently.

A bit about *not-a-numbers*.

The FPU is able to deal with special values which are *not-a-numbers* or NaNs[125]. These are infinity, result of division by 0, etc. Not-a-numbers can be "quiet" and "signaling". It is possible to continue to work with "quiet" NaNs, but if one tries to do any operation with "signaling" NaNs, an exception is to be raised.

FCOM raising an exception if any operand is NaN. FUCOM raising an exception only if any operand is a signaling NaN (SNaN).

The next instruction is SAHF (*Store AH into Flags*) —this is a rare instruction in code not related to the FPU. 8 bits from AH are moved into the lower 8 bits of the CPU flags in the following order:

7	6		4		2		0
SF	ZF		AF		PF		CF

Let's recall that FNSTSW moves the bits that interest us (C3/C2/C0) into AH and they are in positions 6, 2, 0 of the AH register:

	6				2	1	0
	C3				C2	C1	C0

In other words, the `fnstsw ax / sahf` instruction pair moves C3/C2/C0 into ZF, PF and CF.

Now let's also recall the values of C3/C2/C0 in different conditions:

- If a is greater than b in our example, then C3/C2/C0 are to be set to: 0, 0, 0.
- if a is less than b, then the bits are to be set to: 0, 0, 1.
- If $a = b$, then: 1, 0, 0.

In other words, these states of the CPU flags are possible after three FUCOMPP/FNSTSW/SAHF instructions:

- If $a > b$, the CPU flags are to be set as: ZF=0, PF=0, CF=0.
- If $a < b$, then the flags are to be set as: ZF=0, PF=0, CF=1.

[125] wikipedia.org/wiki/NaN

- And if $a = b$, then: ZF=1, PF=0, CF=0.

Depending on the CPU flags and conditions, SETNBE stores 1 or 0 to AL. It is almost the counterpart of JNBE, with the exception that SETcc[126] stores 1 or 0 in AL, but Jcc does actually jump or not. SETNBE stores 1 only if CF=0 and ZF=0. If it is not true, 0 is to be stored into AL.

Only in one case both CF and ZF are 0: if $a > b$.

Then 1 is to be stored to AL, the subsequent JZ is not to be triggered and the function will return _a. In all other cases, _b is to be returned.

Optimizing GCC 4.4.1

Listing 1.213: Optimizing GCC 4.4.1

```
                public d_max
d_max           proc near

arg_0           = qword ptr  8
arg_8           = qword ptr  10h

                push    ebp
                mov     ebp, esp
                fld     [ebp+arg_0] ; _a
                fld     [ebp+arg_8] ; _b

; stack state now: ST(0) = _b, ST(1) = _a
                fxch    st(1)

; stack state now: ST(0) = _a, ST(1) = _b
                fucom   st(1) ; compare _a and _b
                fnstsw  ax
                sahf
                ja      short loc_8048448

; store ST(0) to ST(0) (idle operation),
; pop value at top of stack,
; leave _b at top
                fstp    st
                jmp     short loc_804844A

loc_8048448:
; store _a to ST(1), pop value at top of stack, leave _a at top
                fstp    st(1)

loc_804844A:
                pop     ebp
                retn
d_max           endp
```

It is almost the same except that JA is used after SAHF. Actually, conditional jump instructions that check "larger", "lesser" or "equal" for unsigned number comparison (these are JA, JAE, JB, JBE, JE/JZ, JNA, JNAE, JNB, JNBE, JNE/JNZ) check only flags CF and ZF.

Let's recall where bits C3/C2/C0 are located in the AH register after the execution of FSTSW/FNSTSW:

	6		2	1	0
	C3		C2	C1	C0

Let's also recall, how the bits from AH are stored into the CPU flags after the execution of SAHF:

7	6		4		2		0
SF	ZF		AF		PF		CF

After the comparison, the C3 and C0 bits are moved into ZF and CF, so the conditional jumps are able work after. JA is triggering if both CF are ZF zero.

[126] *cc* is *condition code*

Thereby, the conditional jumps instructions listed here can be used after a FNSTSW/SAHF instruction pair.

Apparently, the FPU C3/C2/C0 status bits were placed there intentionally, to easily map them to base CPU flags without additional permutations?

GCC 4.8.1 with -O3 optimization turned on

Some new FPU instructions were added in the P6 Intel family[127]. These are FUCOMI (compare operands and set flags of the main CPU) and FCMOVcc (works like CMOVcc, but on FPU registers).

Apparently, the maintainers of GCC decided to drop support of pre-P6 Intel CPUs (early Pentiums, 80486, etc.).

And also, the FPU is no longer separate unit in P6 Intel family, so now it is possible to modify/check flags of the main CPU from the FPU.

So what we get is:

Listing 1.214: Optimizing GCC 4.8.1

```
        fld     QWORD PTR [esp+4]       ; load "a"
        fld     QWORD PTR [esp+12]      ; load "b"
        ; ST0=b, ST1=a
        fxch    st(1)
        ; ST0=a, ST1=b
        ; compare "a" and "b"
        fucomi  st, st(1)
        ; copy ST1 ("b" here) to ST0 if a<=b
        ; leave "a" in ST0 otherwise
        fcmovbe st, st(1)
        ; discard value in ST1
        fstp    st(1)
        ret
```

Hard to guess why FXCH (swap operands) is here.

It's possible to get rid of it easily by swapping the first two FLD instructions or by replacing FCMOVBE (*below or equal*) by FCMOVA (*above*). Probably it's a compiler inaccuracy.

So FUCOMI compares ST(0) (a) and ST(1) (b) and then sets some flags in the main CPU. FCMOVBE checks the flags and copies ST(1) (b here at the moment) to ST(0) (a here) if $ST0(a) <= ST1(b)$. Otherwise ($a > b$), it leaves a in ST(0).

The last FSTP leaves ST(0) on top of the stack, discarding the contents of ST(1).

Let's trace this function in GDB:

Listing 1.215: Optimizing GCC 4.8.1 and GDB

```
dennis@ubuntuvm:~/polygon$ gcc -O3 d_max.c -o d_max -fno-inline
dennis@ubuntuvm:~/polygon$ gdb d_max
GNU gdb (GDB) 7.6.1-ubuntu
...
Reading symbols from /home/dennis/polygon/d_max...(no debugging symbols found)...done.
(gdb) b d_max
Breakpoint 1 at 0x80484a0
(gdb) run
Starting program: /home/dennis/polygon/d_max

Breakpoint 1, 0x080484a0 in d_max ()
(gdb) ni
0x080484a4 in d_max ()
(gdb) disas $eip
Dump of assembler code for function d_max:
   0x080484a0 <+0>:     fldl   0x4(%esp)
=> 0x080484a4 <+4>:     fldl   0xc(%esp)
   0x080484a8 <+8>:     fxch   %st(1)
   0x080484aa <+10>:    fucomi %st(1),%st
   0x080484ac <+12>:    fcmovbe %st(1),%st
   0x080484ae <+14>:    fstp   %st(1)
```

[127] Starting at Pentium Pro, Pentium-II, etc.

```
   0x080484b0 <+16>:    ret
End of assembler dump.
(gdb) ni
0x080484a8 in d_max ()
(gdb) info float
  R7: Valid   0x3fff9999999999999800 +1.199999999999999956
=>R6: Valid   0x4000d999999999999800 +3.399999999999999911
  R5: Empty   0x00000000000000000000
  R4: Empty   0x00000000000000000000
  R3: Empty   0x00000000000000000000
  R2: Empty   0x00000000000000000000
  R1: Empty   0x00000000000000000000
  R0: Empty   0x00000000000000000000

Status Word:         0x3000
                       TOP: 6
Control Word:        0x037f   IM DM ZM OM UM PM
                       PC: Extended Precision (64-bits)
                       RC: Round to nearest
Tag Word:            0x0fff
Instruction Pointer: 0x73:0x080484a4
Operand Pointer:     0x7b:0xbffff118
Opcode:              0x0000
(gdb) ni
0x080484aa in d_max ()
(gdb) info float
  R7: Valid   0x4000d999999999999800 +3.399999999999999911
=>R6: Valid   0x3fff9999999999999800 +1.199999999999999956
  R5: Empty   0x00000000000000000000
  R4: Empty   0x00000000000000000000
  R3: Empty   0x00000000000000000000
  R2: Empty   0x00000000000000000000
  R1: Empty   0x00000000000000000000
  R0: Empty   0x00000000000000000000

Status Word:         0x3000
                       TOP: 6
Control Word:        0x037f   IM DM ZM OM UM PM
                       PC: Extended Precision (64-bits)
                       RC: Round to nearest
Tag Word:            0x0fff
Instruction Pointer: 0x73:0x080484a8
Operand Pointer:     0x7b:0xbffff118
Opcode:              0x0000
(gdb) disas $eip
Dump of assembler code for function d_max:
   0x080484a0 <+0>:     fldl   0x4(%esp)
   0x080484a4 <+4>:     fldl   0xc(%esp)
   0x080484a8 <+8>:     fxch   %st(1)
=> 0x080484aa <+10>:    fucomi %st(1),%st
   0x080484ac <+12>:    fcmovbe %st(1),%st
   0x080484ae <+14>:    fstp   %st(1)
   0x080484b0 <+16>:    ret
End of assembler dump.
(gdb) ni
0x080484ac in d_max ()
(gdb) info registers
eax            0x1      1
ecx            0xbffff1c4       -1073745468
edx            0x8048340        134513472
ebx            0xb7fbf000       -1208225792
esp            0xbffff10c       0xbffff10c
ebp            0xbffff128       0xbffff128
esi            0x0      0
edi            0x0      0
eip            0x80484ac        0x80484ac <d_max+12>
eflags         0x203    [ CF IF ]
cs             0x73     115
ss             0x7b     123
ds             0x7b     123
```

```
92  es             0x7b     123
93  fs             0x0      0
94  gs             0x33     51
95  (gdb) ni
96  0x080484ae in d_max ()
97  (gdb) info float
98    R7: Valid   0x4000d999999999999800 +3.399999999999999911
99  =>R6: Valid   0x4000d999999999999800 +3.399999999999999911
100   R5: Empty   0x00000000000000000000
101   R4: Empty   0x00000000000000000000
102   R3: Empty   0x00000000000000000000
103   R2: Empty   0x00000000000000000000
104   R1: Empty   0x00000000000000000000
105   R0: Empty   0x00000000000000000000
106
107 Status Word:         0x3000
108                        TOP: 6
109 Control Word:        0x037f   IM DM ZM OM UM PM
110                        PC: Extended Precision (64-bits)
111                        RC: Round to nearest
112 Tag Word:            0x0fff
113 Instruction Pointer: 0x73:0x080484ac
114 Operand Pointer:     0x7b:0xbffff118
115 Opcode:              0x0000
116 (gdb) disas $eip
117 Dump of assembler code for function d_max:
118    0x080484a0 <+0>:     fldl   0x4(%esp)
119    0x080484a4 <+4>:     fldl   0xc(%esp)
120    0x080484a8 <+8>:     fxch   %st(1)
121    0x080484aa <+10>:    fucomi %st(1),%st
122    0x080484ac <+12>:    fcmovbe %st(1),%st
123 => 0x080484ae <+14>:    fstp   %st(1)
124    0x080484b0 <+16>:    ret
125 End of assembler dump.
126 (gdb) ni
127 0x080484b0 in d_max ()
128 (gdb) info float
129 =>R7: Valid   0x4000d999999999999800 +3.399999999999999911
130   R6: Empty   0x4000d999999999999800
131   R5: Empty   0x00000000000000000000
132   R4: Empty   0x00000000000000000000
133   R3: Empty   0x00000000000000000000
134   R2: Empty   0x00000000000000000000
135   R1: Empty   0x00000000000000000000
136   R0: Empty   0x00000000000000000000
137
138 Status Word:         0x3800
139                        TOP: 7
140 Control Word:        0x037f   IM DM ZM OM UM PM
141                        PC: Extended Precision (64-bits)
142                        RC: Round to nearest
143 Tag Word:            0x3fff
144 Instruction Pointer: 0x73:0x080484ae
145 Operand Pointer:     0x7b:0xbffff118
146 Opcode:              0x0000
147 (gdb) quit
148 A debugging session is active.
149
150         Inferior 1 [process 30194] will be killed.
151
152 Quit anyway? (y or n) y
153 dennis@ubuntuvm:~/polygon$
```

Using "ni", let's execute the first two FLD instructions.

Let's examine the FPU registers (line 33).

As it was mentioned before, the FPU registers set is a circular buffer rather than a stack (1.19.5 on page 225). And GDB doesn't show STx registers, but internal the FPU registers (Rx). The arrow (at line 35) points to the current top of the stack.

You can also see the TOP register contents in *Status Word* (line 44)—it is 6 now, so the stack top is now pointing to internal register 6.

The values of a and b are swapped after FXCH is executed (line 54).

FUCOMI is executed (line 83). Let's see the flags: CF is set (line 95).

FCMOVBE has copied the value of b (see line 104).

FSTP leaves one value at the top of stack (line 136). The value of TOP is now 7, so the FPU stack top is pointing to internal register 7.

ARM

Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 1.216: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
VMOV            D16, R2, R3 ; b
VMOV            D17, R0, R1 ; a
VCMPE.F64       D17, D16
VMRS            APSR_nzcv, FPSCR
VMOVGT.F64      D16, D17 ; copy "a" to D16
VMOV            R0, R1, D16
BX              LR
```

A very simple case. The input values are placed into the D17 and D16 registers and then compared using the VCMPE instruction.

Just like in the x86 coprocessor, the ARM coprocessor has its own status and flags register (FPSCR[128]), since there is a necessity to store coprocessor-specific flags. And just like in x86, there are no conditional jump instruction in ARM, that can check bits in the status register of the coprocessor. So there is VMRS, which copies 4 bits (N, Z, C, V) from the coprocessor status word into bits of the *general* status register (APSR[129]).

VMOVGT is the analog of the MOVGT, instruction for D-registers, it executes if one operand is greater than the other while comparing (*GT—Greater Than*).

If it gets executed, the value of a is to be written into D16 (that is currently stored in D17). Otherwise the value of b stays in the D16 register.

The penultimate instruction VMOV prepares the value in the D16 register for returning it via the R0 and R1 register pair.

Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

Listing 1.217: Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```
VMOV            D16, R2, R3 ; b
VMOV            D17, R0, R1 ; a
VCMPE.F64       D17, D16
VMRS            APSR_nzcv, FPSCR
IT GT
VMOVGT.F64      D16, D17
VMOV            R0, R1, D16
BX              LR
```

Almost the same as in the previous example, however slightly different. As we already know, many instructions in ARM mode can be supplemented by condition predicate. But there is no such thing in Thumb mode. There is no space in the 16-bit instructions for 4 more bits in which conditions can be encoded.

However, Thumb-2 was extended to make it possible to specify predicates to old Thumb instructions. Here, in the IDA-generated listing, we see the VMOVGT instruction, as in previous example.

[128](ARM) Floating-Point Status and Control Register
[129](ARM) Application Program Status Register

In fact, the usual VMOV is encoded there, but IDA adds the -GT suffix to it, since there is a IT GT instruction placed right before it.

The IT instruction defines a so-called *if-then block*.

After the instruction it is possible to place up to 4 instructions, each of them has a predicate suffix. In our example, IT GT implies that the next instruction is to be executed, if the *GT* (*Greater Than*) condition is true.

Here is a more complex code fragment, by the way, from Angry Birds (for iOS):

Listing 1.218: Angry Birds Classic

```
...
ITE NE
VMOVNE          R2, R3, D16
VMOVEQ          R2, R3, D17
BLX             _objc_msgSend ; not suffixed
...
```

ITE stands for *if-then-else*

and it encodes suffixes for the next two instructions.

The first instruction executes if the condition encoded in ITE (*NE, not equal*) is true at, and the second—if the condition is not true. (The inverse condition of NE is EQ (*equal*)).

The instruction followed after the second VMOV (or VMOVEQ) is a normal one, not suffixed (BLX).

One more that's slightly harder, which is also from Angry Birds:

Listing 1.219: Angry Birds Classic

```
...
ITTTT EQ
MOVEQ           R0, R4
ADDEQ           SP, SP, #0x20
POPEQ.W         {R8,R10}
POPEQ           {R4-R7,PC}
BLX             ___stack_chk_fail ; not suffixed
...
```

Four "T" symbols in the instruction mnemonic mean that the four subsequent instructions are to be executed if the condition is true.

That's why IDA adds the -EQ suffix to each one of them.

And if there was, for example, ITEEE EQ (*if-then-else-else-else*), then the suffixes would have been set as follows:

```
-EQ
-NE
-NE
-NE
```

Another fragment from Angry Birds:

Listing 1.220: Angry Birds Classic

```
...
CMP.W           R0, #0xFFFFFFFF
ITTE LE
SUBLE.W         R10, R0, #1
NEGLE           R0, R0
MOVGT           R10, R0
MOVS            R6, #0         ; not suffixed
CBZ             R0, loc_1E7E32 ; not suffixed
...
```

ITTE (*if-then-then-else*)

implies that the 1st and 2nd instructions are to be executed if the LE (*Less or Equal*) condition is true, and the 3rd—if the inverse condition (GT—*Greater Than*) is true.

Compilers usually don't generate all possible combinations.

For example, in the mentioned Angry Birds game (*classic* version for iOS) only these variants of the IT instruction are used: IT, ITE, ITT, ITTE, ITTT, ITTTT. How to learn this? In IDA, it is possible to produce listing files, so it was created with an option to show 4 bytes for each opcode. Then, knowing the high part of the 16-bit opcode (IT is 0xBF), we do the following using grep:

```
cat AngryBirdsClassic.lst | grep " BF" | grep "IT" > results.lst
```

By the way, if you program in ARM assembly language manually for Thumb-2 mode, and you add conditional suffixes, the assembler will add the IT instructions automatically with the required flags where it is necessary.

Non-optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 1.221: Non-optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
b               = -0x20
a               = -0x18
val_to_return   = -0x10
saved_R7        = -4

                STR             R7, [SP,#saved_R7]!
                MOV             R7, SP
                SUB             SP, SP, #0x1C
                BIC             SP, SP, #7
                VMOV            D16, R2, R3
                VMOV            D17, R0, R1
                VSTR            D17, [SP,#0x20+a]
                VSTR            D16, [SP,#0x20+b]
                VLDR            D16, [SP,#0x20+a]
                VLDR            D17, [SP,#0x20+b]
                VCMPE.F64       D16, D17
                VMRS            APSR_nzcv, FPSCR
                BLE             loc_2E08
                VLDR            D16, [SP,#0x20+a]
                VSTR            D16, [SP,#0x20+val_to_return]
                B               loc_2E10

loc_2E08
                VLDR            D16, [SP,#0x20+b]
                VSTR            D16, [SP,#0x20+val_to_return]

loc_2E10
                VLDR            D16, [SP,#0x20+val_to_return]
                VMOV            R0, R1, D16
                MOV             SP, R7
                LDR             R7, [SP+0x20+b],#4
                BX              LR
```

Almost the same as we already saw, but there is too much redundant code because the a and b variables are stored in the local stack, as well as the return value.

Optimizing Keil 6/2013 (Thumb mode)

Listing 1.222: Optimizing Keil 6/2013 (Thumb mode)

```
                PUSH    {R3-R7,LR}
                MOVS    R4, R2
                MOVS    R5, R3
                MOVS    R6, R0
                MOVS    R7, R1
                BL      __aeabi_cdrcmple
                BCS     loc_1C0
                MOVS    R0, R6
                MOVS    R1, R7
```

```
                POP     {R3-R7,PC}

loc_1C0
                MOVS    R0, R4
                MOVS    R1, R5
                POP     {R3-R7,PC}
```

Keil doesn't generate FPU-instructions since it cannot rely on them being supported on the target CPU, and it cannot be done by straightforward bitwise comparing. So it calls an external library function to do the comparison: `__aeabi_cdrcmple`.

N.B. The result of the comparison is to be left in the flags by this function, so the following BCS (*Carry set—Greater than or equal*) instruction can work without any additional code.

ARM64

Optimizing GCC (Linaro) 4.9

```
d_max:
; D0 - a, D1 - b
        fcmpe   d0, d1
        fcsel   d0, d0, d1, gt
; now result in D0
        ret
```

The ARM64 ISA has FPU-instructions which set APSR the CPU flags instead of FPSCR for convenience. TheFPU is not a separate device here anymore (at least, logically). Here we see FCMPE. It compares the two values passed in D0 and D1 (which are the first and second arguments of the function) and sets APSR flags (N, Z, C, V).

FCSEL (*Floating Conditional Select*) copies the value of D0 or D1 into D0 depending on the condition (GT—Greater Than), and again, it uses flags in APSR register instead of FPSCR.

This is much more convenient, compared to the instruction set in older CPUs.

If the condition is true (GT), then the value of D0 is copied into D0 (i.e., nothing happens). If the condition is not true, the value of D1 is copied into D0.

Non-optimizing GCC (Linaro) 4.9

```
d_max:
; save input arguments in "Register Save Area"
        sub     sp, sp, #16
        str     d0, [sp,8]
        str     d1, [sp]
; reload values
        ldr     x1, [sp,8]
        ldr     x0, [sp]
        fmov    d0, x1
        fmov    d1, x0
; D0 - a, D1 - b
        fcmpe   d0, d1
        ble     .L76
; a>b; load D0 (a) into X0
        ldr     x0, [sp,8]
        b       .L74
.L76:
; a<=b; load D1 (b) into X0
        ldr     x0, [sp]
.L74:
; result in X0
        fmov    d0, x0
; result in D0
        add     sp, sp, 16
        ret
```

Non-optimizing GCC is more verbose.

First, the function saves its input argument values in the local stack (*Register Save Area*). Then the code reloads these values into registers X0/X1 and finally copies them to D0/D1 to be compared using FCMPE. A lot of redundant code, but that is how non-optimizing compilers work. FCMPE compares the values and sets the APSR flags. At this moment, the compiler is not thinking yet about the more convenient FCSEL instruction, so it proceed using old methods: using the BLE instruction (*Branch if Less than or Equal*). In the first case ($a > b$), the value of a gets loaded into X0. In the other case ($a <= b$), the value of b gets loaded into X0. Finally, the value from X0 gets copied into D0, because the return value needs to be in this register.

Exercise

As an exercise, you can try optimizing this piece of code manually by removing redundant instructions and not introducing new ones (including FCSEL).

Optimizing GCC (Linaro) 4.9—float

Let's also rewrite this example to use *float* instead of *double*.

```
float f_max (float a, float b)
{
        if (a>b)
                return a;

        return b;
};
```

```
f_max:
; S0 - a, S1 - b
        fcmpe   s0, s1
        fcsel   s0, s0, s1, gt
; now result in S0
        ret
```

It is the same code, but the S-registers are used instead of D- ones. It's because numbers of type *float* are passed in 32-bit S-registers (which are in fact the lower parts of the 64-bit D-registers).

MIPS

The co-processor of the MIPS processor has a condition bit which can be set in the FPU and checked in the CPU.

Earlier MIPS-es have only one condition bit (called FCC0), later ones have 8 (called FCC7-FCC0).

This bit (or bits) are located in the register called FCCR.

Listing 1.223: Optimizing GCC 4.4.5 (IDA)

```
d_max:
; set FPU condition bit if $f14<$f12 (b<a):
                c.lt.d  $f14, $f12
                or      $at, $zero ; NOP
; jump to locret_14 if condition bit is set
                bc1t    locret_14
; this instruction is always executed (set return value to "a"):
                mov.d   $f0, $f12  ; branch delay slot
; this instruction is executed only if branch was not taken (i.e., if b>=a)
; set return value to "b":
                mov.d   $f0, $f14

locret_14:
                jr      $ra
                or      $at, $zero ; branch delay slot, NOP
```

`C.LT.D` compares two values. LT is the condition "Less Than". `D` implies values of type *double*. Depending on the result of the comparison, the FCC0 condition bit is either set or cleared.

`BC1T` checks the FCC0 bit and jumps if the bit is set. T means that the jump is to be taken if the bit is set ("True"). There is also the instruction `BC1F` which jumps if the bit is cleared ("False").

Depending on the jump, one of function arguments is placed into `$F0`.

1.19.8 Some constants

It's easy to find representations of some constants in Wikipedia for IEEE 754 encoded numbers. It's interesting to know that 0.0 in IEEE 754 is represented as 32 zero bits (for single precision) or 64 zero bits (for double). So in order to set a floating point variable to 0.0 in register or memory, one can use `MOV` or `XOR reg, reg` instruction. This is suitable for structures where many variables present of various data types. With usual memset() function one can set all integer variables to 0, all boolean variables to *false*, all pointers to NULL, and all floating point variables (of any precision) to 0.0.

1.19.9 Copying

One may think inertially that `FLD`/`FST` instructions must be used to load and store (and hence, copy) IEEE 754 values. Nevertheless, same can be achieved easier by usual `MOV` instruction, which, of course, copies values bitwisely.

1.19.10 Stack, calculators and reverse Polish notation

Now we understand why some old calculators use reverse Polish notation [130].

For example, for addition of 12 and 34 one has to enter 12, then 34, then press "plus" sign.

It's because old calculators were just stack machine implementations, and this was much simpler than to handle complex parenthesized expressions.

1.19.11 80 bits?

Internal numbers representation in FPU — 80-bit. Strange number, because the number not in 2^n form. There is a hypothesis that this is probably due to historical reasons—the standard IBM puched card can encode 12 rows of 80 bits. $80 \cdot 25$ text mode resolution was also popular in past.

Wikipedia has another explanation: `https://en.wikipedia.org/wiki/Extended_precision`.

If you know better, please a drop email to the author: dennis@yurichev.com.

1.19.12 x64

On how floating point numbers are processed in x86-64, read more here: 1.31 on page 427.

1.19.13 Exercises

- `http://challenges.re/60`
- `http://challenges.re/61`

1.20 Arrays

An array is just a set of variables in memory that lie next to each other and that have the same type[131].

[130] wikipedia.org/wiki/Reverse_Polish_notation
[131] AKA "homogeneous container"

1.20.1 Simple example

```
#include <stdio.h>

int main()
{
    int a[20];
    int i;

    for (i=0; i<20; i++)
        a[i]=i*2;

    for (i=0; i<20; i++)
        printf ("a[%d]=%d\n", i, a[i]);

    return 0;
};
```

x86

MSVC

Let's compile:

Listing 1.224: MSVC 2008

```
_TEXT    SEGMENT
_i$ = -84                        ; size = 4
_a$ = -80                        ; size = 80
_main      PROC
    push   ebp
    mov    ebp, esp
    sub    esp, 84        ; 00000054H
    mov    DWORD PTR _i$[ebp], 0
    jmp    SHORT $LN6@main
$LN5@main:
    mov    eax, DWORD PTR _i$[ebp]
    add    eax, 1
    mov    DWORD PTR _i$[ebp], eax
$LN6@main:
    cmp    DWORD PTR _i$[ebp], 20   ; 00000014H
    jge    SHORT $LN4@main
    mov    ecx, DWORD PTR _i$[ebp]
    shl    ecx, 1
    mov    edx, DWORD PTR _i$[ebp]
    mov    DWORD PTR _a$[ebp+edx*4], ecx
    jmp    SHORT $LN5@main
$LN4@main:
    mov    DWORD PTR _i$[ebp], 0
    jmp    SHORT $LN3@main
$LN2@main:
    mov    eax, DWORD PTR _i$[ebp]
    add    eax, 1
    mov    DWORD PTR _i$[ebp], eax
$LN3@main:
    cmp    DWORD PTR _i$[ebp], 20    ; 00000014H
    jge    SHORT $LN1@main
    mov    ecx, DWORD PTR _i$[ebp]
    mov    edx, DWORD PTR _a$[ebp+ecx*4]
    push   edx
    mov    eax, DWORD PTR _i$[ebp]
    push   eax
    push   OFFSET $SG2463
    call   _printf
    add    esp, 12        ; 0000000cH
    jmp    SHORT $LN2@main
$LN1@main:
```

```
    xor    eax, eax
    mov    esp, ebp
    pop    ebp
    ret    0
_main      ENDP
```

Nothing very special, just two loops: the first is a filling loop and second is a printing loop. The `shl ecx, 1` instruction is used for value multiplication by 2 in ECX, more about below 1.18.2 on page 217.

80 bytes are allocated on the stack for the array, 20 elements of 4 bytes.

Let's try this example in OllyDbg.

We see how the array gets filled:

each element is 32-bit word of *int* type and its value is the index multiplied by 2:

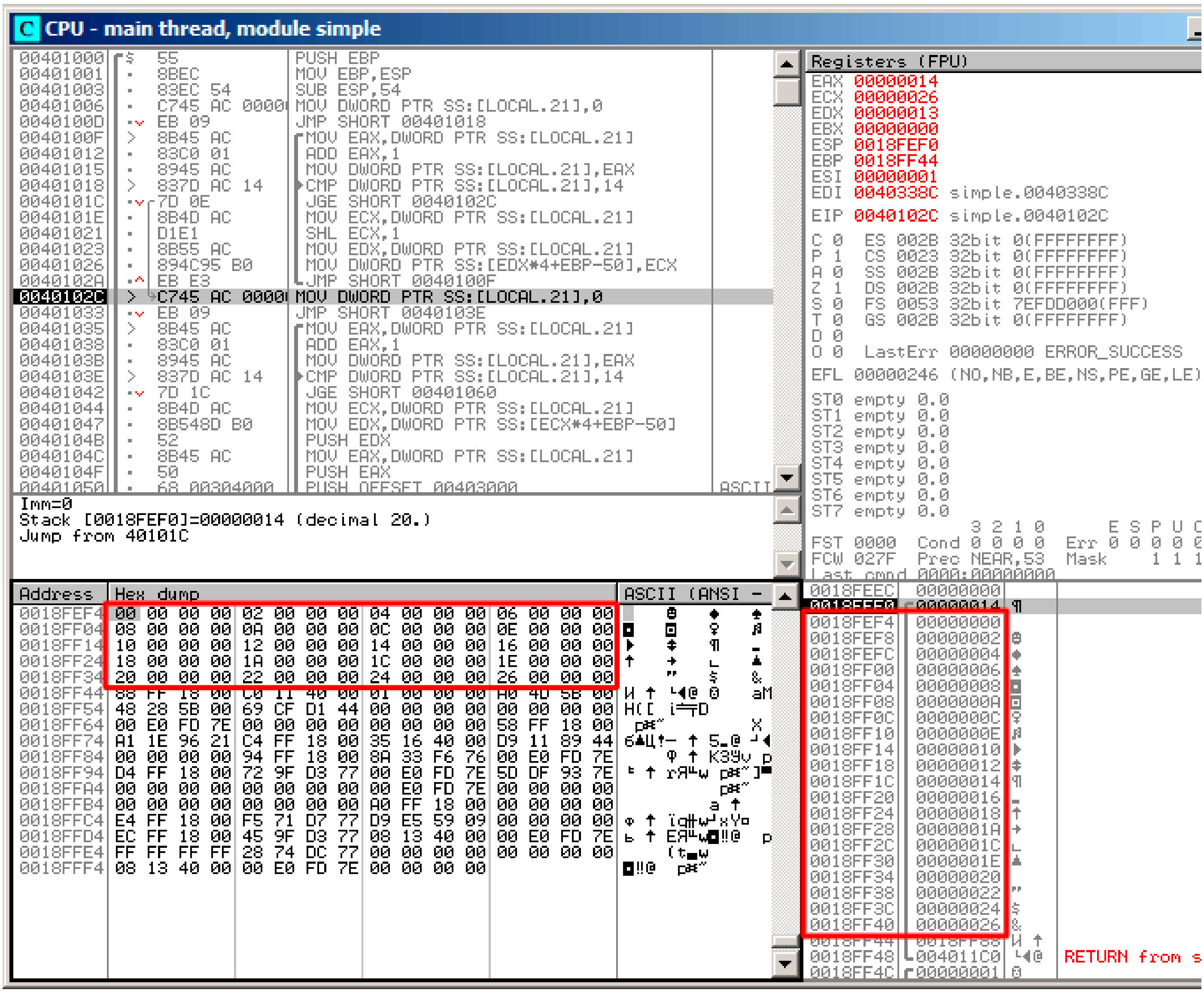


Figure 1.87: OllyDbg: after array filling

Since this array is located in the stack, we can see all its 20 elements there.

GCC

Here is what GCC 4.4.1 does:

Listing 1.225: GCC 4.4.1

```
                public main
main            proc near               ; DATA XREF: _start+17

var_70          = dword ptr -70h
var_6C          = dword ptr -6Ch
var_68          = dword ptr -68h
i_2             = dword ptr -54h
i               = dword ptr -4

                push    ebp
                mov     ebp, esp
```

```
                and     esp, 0FFFFFFF0h
                sub     esp, 70h
                mov     [esp+70h+i], 0          ; i=0
                jmp     short loc_804840A

loc_80483F7:
                mov     eax, [esp+70h+i]
                mov     edx, [esp+70h+i]
                add     edx, edx                ; edx=i*2
                mov     [esp+eax*4+70h+i_2], edx
                add     [esp+70h+i], 1          ; i++

loc_804840A:
                cmp     [esp+70h+i], 13h
                jle     short loc_80483F7
                mov     [esp+70h+i], 0
                jmp     short loc_8048441

loc_804841B:
                mov     eax, [esp+70h+i]
                mov     edx, [esp+eax*4+70h+i_2]
                mov     eax, offset aADD ; "a[%d]=%d\n"
                mov     [esp+70h+var_68], edx
                mov     edx, [esp+70h+i]
                mov     [esp+70h+var_6C], edx
                mov     [esp+70h+var_70], eax
                call    _printf
                add     [esp+70h+i], 1

loc_8048441:
                cmp     [esp+70h+i], 13h
                jle     short loc_804841B
                mov     eax, 0
                leave
                retn
main            endp
```

By the way, variable a is of type *int** (the pointer to *int*)—you can pass a pointer to an array to another function, but it's more correct to say that a pointer to the first element of the array is passed (the addresses of rest of the elements are calculated in an obvious way).

If you index this pointer as *a[idx]*, *idx* is just to be added to the pointer and the element placed there (to which calculated pointer is pointing) is to be returned.

An interesting example: a string of characters like *"string"* is an array of characters and it has a type of *const char[]*.

An index can also be applied to this pointer.

And that is why it is possible to write things like "`string`"`[i]`—this is a correct C/C++ expression!

ARM

Non-optimizing Keil 6/2013 (ARM mode)

```
            EXPORT _main
_main
            STMFD   SP!, {R4,LR}
            SUB     SP, SP, #0x50      ; allocate place for 20 int variables

; first loop

            MOV     R4, #0             ; i
            B       loc_4A0
loc_494
            MOV     R0, R4,LSL#1       ; R0=R4*2
            STR     R0, [SP,R4,LSL#2]  ; store R0 to SP+R4<<2 (same as SP+R4*4)
            ADD     R4, R4, #1         ; i=i+1
```

```
loc_4A0
            CMP     R4, #20             ; i<20?
            BLT     loc_494             ; yes, run loop body again

; second loop

            MOV     R4, #0              ; i
            B       loc_4C4
loc_4B0
            LDR     R2, [SP,R4,LSL#2]  ; (second printf argument) R2=*(SP+R4<<4) (same as *(SP+↙
    ↘ R4*4))
            MOV     R1, R4              ; (first printf argument) R1=i
            ADR     R0, aADD            ; "a[%d]=%d\n"
            BL      __2printf
            ADD     R4, R4, #1          ; i=i+1

loc_4C4
            CMP     R4, #20             ; i<20?
            BLT     loc_4B0             ; yes, run loop body again
            MOV     R0, #0              ; value to return
            ADD     SP, SP, #0x50       ; deallocate chunk, allocated for 20 int variables
            LDMFD   SP!, {R4,PC}
```

int type requires 32 bits for storage (or 4 bytes),

so to store 20 *int* variables 80 (0x50) bytes are needed. So that is why the SUB SP, SP, #0x50

instruction in the function's prologue allocates exactly this amount of space in the stack.

In both the first and second loops, the loop iterator *i* is placed in the R4 register.

The number that is to be written into the array is calculated as $i * 2$, which is effectively equivalent to shifting it left by one bit,
so MOV R0, R4,LSL#1 instruction does this.

STR R0, [SP,R4,LSL#2] writes the contents of R0 into the array.

Here is how a pointer to array element is calculated: SP points to the start of the array, R4 is i.

So shifting i left by 2 bits is effectively equivalent to multiplication by 4 (since each array element has a size of 4 bytes) and then it's added to the address of the start of the array.

The second loop has an inverse LDR R2, [SP,R4,LSL#2] instruction. It loads the value we need from the array, and the pointer to it is calculated likewise.

Optimizing Keil 6/2013 (Thumb mode)

```
_main
          PUSH    {R4,R5,LR}
; allocate place for 20 int variables + one more variable
          SUB     SP, SP, #0x54

; first loop

          MOVS    R0, #0          ; i
          MOV     R5, SP          ; pointer to first array element

loc_1CE
          LSLS    R1, R0, #1      ; R1=i<<1 (same as i*2)
          LSLS    R2, R0, #2      ; R2=i<<2 (same as i*4)
          ADDS    R0, R0, #1      ; i=i+1
          CMP     R0, #20         ; i<20?
          STR     R1, [R5,R2]     ; store R1 to *(R5+R2) (same R5+i*4)
          BLT     loc_1CE         ; yes, i<20, run loop body again

; second loop

          MOVS    R4, #0          ; i=0
loc_1DC
```

```
        LSLS    R0, R4, #2      ; R0=i<<2 (same as i*4)
        LDR     R2, [R5,R0]     ; load from *(R5+R0) (same as R5+i*4)
        MOVS    R1, R4
        ADR     R0, aADD        ; "a[%d]=%d\n"
        BL      __2printf
        ADDS    R4, R4, #1      ; i=i+1
        CMP     R4, #20         ; i<20?
        BLT     loc_1DC         ; yes, i<20, run loop body again
        MOVS    R0, #0          ; value to return
; deallocate chunk, allocated for 20 int variables + one more variable
        ADD     SP, SP, #0x54
        POP     {R4,R5,PC}
```

Thumb code is very similar.

Thumb mode has special instructions for bit shifting (like LSLS), which calculates the value to be written into the array and the address of each element in the array as well.

The compiler allocates slightly more space in the local stack, however, the last 4 bytes are not used.

Non-optimizing GCC 4.9.1 (ARM64)

Listing 1.226: Non-optimizing GCC 4.9.1 (ARM64)

```
.LC0:
        .string "a[%d]=%d\n"
main:
; save FP and LR in stack frame:
        stp     x29, x30, [sp, -112]!
; set stack frame (FP=SP)
        add     x29, sp, 0
; setting initial counter variable at 0 (WZR is the register always holding zero):
        str     wzr, [x29,108]
; jump to loop condition checking code:
        b       .L2
.L3:
; load value of "i" variable:
        ldr     w0, [x29,108]
; multiplicate it by 2:
        lsl     w2, w0, 1
; find a place of an array in local stack:
        add     x0, x29, 24
; load 32-bit integer from local stack and sign extend it to 64-bit one:
        ldrsw   x1, [x29,108]
; calculate address of element (X0+X1<<2=array address+i*4) and store W2 (i*2) there:
        str     w2, [x0,x1,lsl 2]
; increment counter (i):
        ldr     w0, [x29,108]
        add     w0, w0, 1
        str     w0, [x29,108]
.L2:
; check if we finished:
        ldr     w0, [x29,108]
        cmp     w0, 19
; jump to L3 (loop body begin) if not:
        ble     .L3
; second part of the function begins here.
; setting initial counter variable at 0.
; by the way, the same place in the local stack was used for counter,
; because the same local variable (i) is being used as counter.
        str     wzr, [x29,108]
        b       .L4
.L5:
; calculate array address:
        add     x0, x29, 24
; load "i" value:
        ldrsw   x1, [x29,108]
; load value from the array at the address (X0+X1<<2 = address of array + i*4)
        ldr     w2, [x0,x1,lsl 2]
```

```
; load address of the "a[%d]=%d\n" string:
        adrp    x0, .LC0
        add     x0, x0, :lo12:.LC0
; load "i" variable to W1 and pass it to printf() as second argument:
        ldr     w1, [x29,108]
; W2 still contains the value of array element which was just loaded.
; call printf():
        bl      printf
; increment "i" variable:
        ldr     w0, [x29,108]
        add     w0, w0, 1
        str     w0, [x29,108]
.L4:
; are we finished?
        ldr     w0, [x29,108]
        cmp     w0, 19
; jump to the loop body begin if not:
        ble     .L5
; return 0
        mov     w0, 0
; restore FP and LR:
        ldp     x29, x30, [sp], 112
        ret
```

MIPS

The function uses a lot of S- registers which must be preserved, so that's why its values are saved in the function prologue and restored in the epilogue.

Listing 1.227: Optimizing GCC 4.4.5 (IDA)

```
main:

var_70          = -0x70
var_68          = -0x68
var_14          = -0x14
var_10          = -0x10
var_C           = -0xC
var_8           = -8
var_4           = -4
; function prologue:
                lui     $gp, (__gnu_local_gp >> 16)
                addiu   $sp, -0x80
                la      $gp, (__gnu_local_gp & 0xFFFF)
                sw      $ra, 0x80+var_4($sp)
                sw      $s3, 0x80+var_8($sp)
                sw      $s2, 0x80+var_C($sp)
                sw      $s1, 0x80+var_10($sp)
                sw      $s0, 0x80+var_14($sp)
                sw      $gp, 0x80+var_70($sp)
                addiu   $s1, $sp, 0x80+var_68
                move    $v1, $s1
                move    $v0, $zero
; that value will be used as a loop terminator.
; it was precalculated by GCC compiler at compile stage:
                li      $a0, 0x28  # '('

loc_34:                                  # CODE XREF: main+3C
; store value into memory:
                sw      $v0, 0($v1)
; increase value to be stored by 2 at each iteration:
                addiu   $v0, 2
; loop terminator reached?
                bne     $v0, $a0, loc_34
; add 4 to address anyway:
                addiu   $v1, 4
; array filling loop is ended
; second loop begin
```

```
                la      $s3, $LC0        # "a[%d]=%d\n"
; "i" variable will reside in $s0:
                move    $s0, $zero
                li      $s2, 0x14

loc_54:                                  # CODE XREF: main+70
; call printf():
                lw      $t9, (printf & 0xFFFF)($gp)
                lw      $a2, 0($s1)
                move    $a1, $s0
                move    $a0, $s3
                jalr    $t9
; increment "i":
                addiu   $s0, 1
                lw      $gp, 0x80+var_70($sp)
; jump to loop body if end is not reached:
                bne     $s0, $s2, loc_54
; move memory pointer to the next 32-bit word:
                addiu   $s1, 4
; function epilogue
                lw      $ra, 0x80+var_4($sp)
                move    $v0, $zero
                lw      $s3, 0x80+var_8($sp)
                lw      $s2, 0x80+var_C($sp)
                lw      $s1, 0x80+var_10($sp)
                lw      $s0, 0x80+var_14($sp)
                jr      $ra
                addiu   $sp, 0x80

$LC0:           .ascii "a[%d]=%d\n"<0>   # DATA XREF: main+44
```

Something interesting: there are two loops and the first one doesn't need i, it needs only $i*2$ (increased by 2 at each iteration) and also the address in memory (increased by 4 at each iteration).

So here we see two variables, one (in $V0) increasing by 2 each time, and another (in $V1) — by 4.

The second loop is where `printf()` is called and it reports the value of i to the user, so there is a variable which is increased by 1 each time (in $S0) and also a memory address (in $S1) increased by 4 each time.

That reminds us of loop optimizations we considered earlier: 3.7 on page 490.

Their goal is to get rid of multiplications.

1.20.2 Buffer overflow

Reading outside array bounds

So, array indexing is just *array[index]*. If you study the generated code closely, you'll probably note the missing index bounds checking, which could check *if it is less than 20*. What if the index is 20 or greater? That's the one C/C++ feature it is often blamed for.

Here is a code that successfully compiles and works:

```
#include <stdio.h>

int main()
{
        int a[20];
        int i;

        for (i=0; i<20; i++)
                a[i]=i*2;

        printf ("a[20]=%d\n", a[20]);

        return 0;
};
```

Compilation results (MSVC 2008):

Listing 1.228: Non-optimizing MSVC 2008

```
$SG2474 DB    'a[20]=%d', 0aH, 00H

_i$ = -84 ; size = 4
_a$ = -80 ; size = 80
_main    PROC
    push   ebp
    mov    ebp, esp
    sub    esp, 84
    mov    DWORD PTR _i$[ebp], 0
    jmp    SHORT $LN3@main
$LN2@main:
    mov    eax, DWORD PTR _i$[ebp]
    add    eax, 1
    mov    DWORD PTR _i$[ebp], eax
$LN3@main:
    cmp    DWORD PTR _i$[ebp], 20
    jge    SHORT $LN1@main
    mov    ecx, DWORD PTR _i$[ebp]
    shl    ecx, 1
    mov    edx, DWORD PTR _i$[ebp]
    mov    DWORD PTR _a$[ebp+edx*4], ecx
    jmp    SHORT $LN2@main
$LN1@main:
    mov    eax, DWORD PTR _a$[ebp+80]
    push   eax
    push   OFFSET $SG2474 ; 'a[20]=%d'
    call   DWORD PTR __imp__printf
    add    esp, 8
    xor    eax, eax
    mov    esp, ebp
    pop    ebp
    ret    0
_main    ENDP
_TEXT    ENDS
END
```

The code produced this result:

Listing 1.229: OllyDbg: console output

```
a[20]=1638280
```

It is just *something* that has been lying in the stack near to the array, 80 bytes away from its first element.

Let's try to find out where did this value come from, using OllyDbg.

Let's load and find the value located right after the last array element:

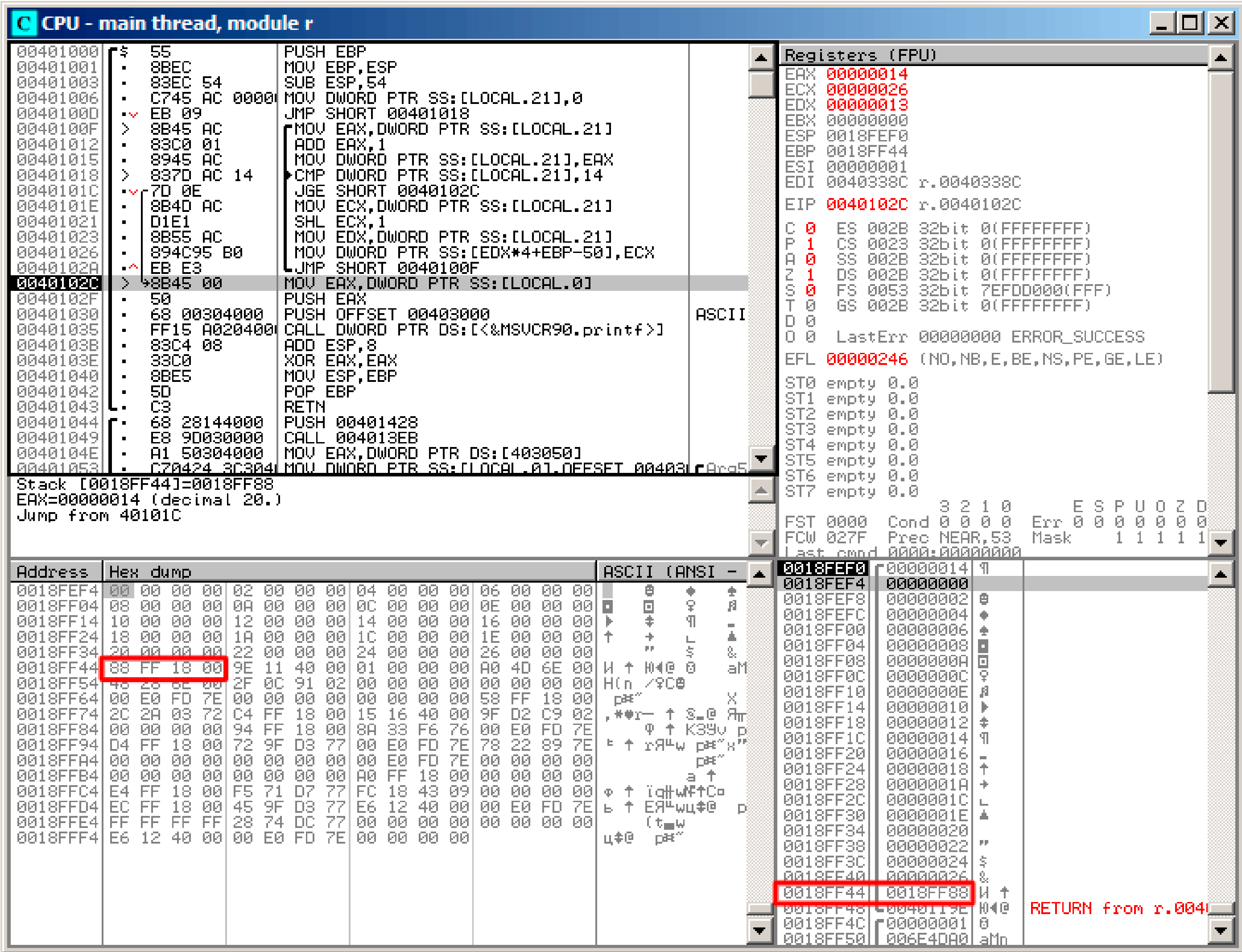


Figure 1.88: OllyDbg: reading of the 20th element and execution of `printf()`

What is this? Judging by the stack layout, this is the saved value of the EBP register.

Let's trace further and see how it gets restored:

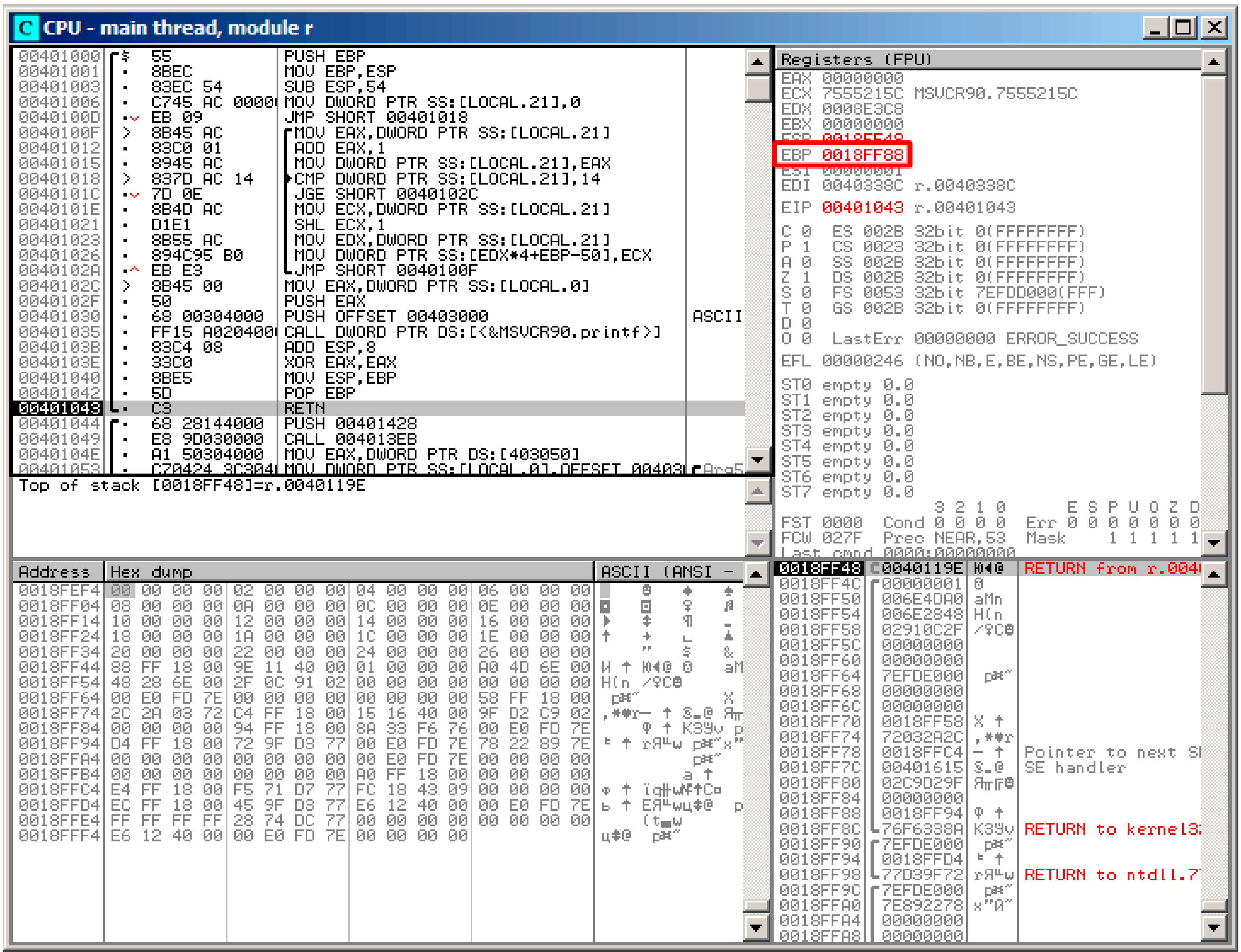


Figure 1.89: OllyDbg: restoring value of EBP

Indeed, how it could be different? The compiler may generate some additional code to check the index value to be always in the array's bounds (like in higher-level programming languages[132]) but this makes the code slower.

Writing beyond array bounds

OK, we read some values from the stack *illegally*, but what if we could write something to it?

Here is what we have got:

```
#include <stdio.h>

int main()
{
        int a[20];
        int i;

        for (i=0; i<30; i++)
                a[i]=i;

        return 0;
};
```

[132] Java, Python, etc.

MSVC

And what we get:

Listing 1.230: Non-optimizing MSVC 2008

```
_TEXT    SEGMENT
_i$ = -84 ; size = 4
_a$ = -80 ; size = 80
_main   PROC
 push   ebp
 mov    ebp, esp
 sub    esp, 84
 mov    DWORD PTR _i$[ebp], 0
 jmp    SHORT $LN3@main
$LN2@main:
 mov    eax, DWORD PTR _i$[ebp]
 add    eax, 1
 mov    DWORD PTR _i$[ebp], eax
$LN3@main:
 cmp    DWORD PTR _i$[ebp], 30 ; 0000001eH
 jge    SHORT $LN1@main
 mov    ecx, DWORD PTR _i$[ebp]
 mov    edx, DWORD PTR _i$[ebp]      ; that instruction is obviously redundant
 mov    DWORD PTR _a$[ebp+ecx*4], edx ; ECX could be used as second operand here instead
 jmp    SHORT $LN2@main
$LN1@main:
 xor    eax, eax
 mov    esp, ebp
 pop    ebp
 ret    0
_main   ENDP
```

The compiled program crashes after running. No wonder. Let’s see where exactly does it is crash.

Let's load it into OllyDbg, and trace until all 30 elements are written:

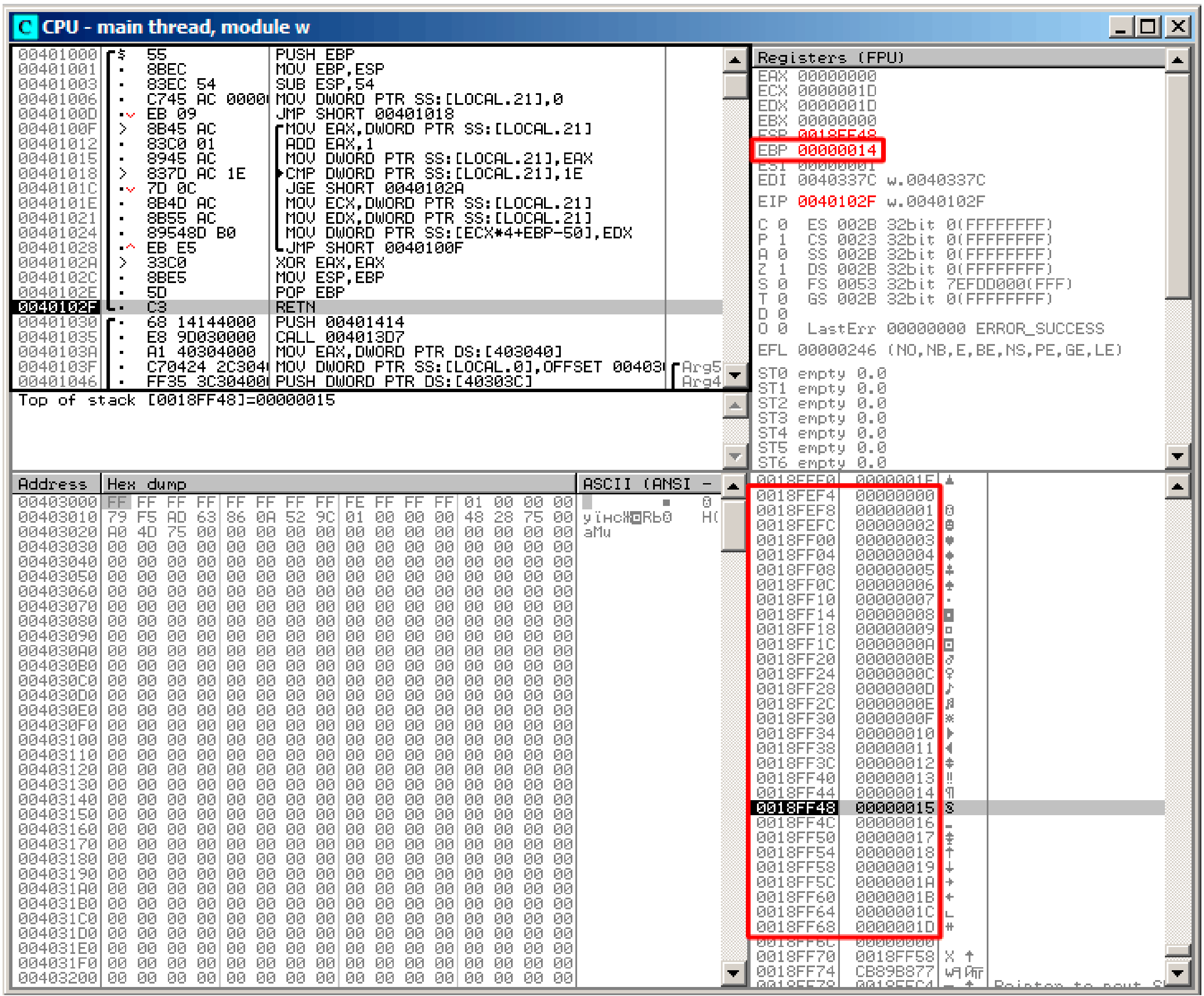


Figure 1.90: OllyDbg: after restoring the value of EBP

Trace until the function end:

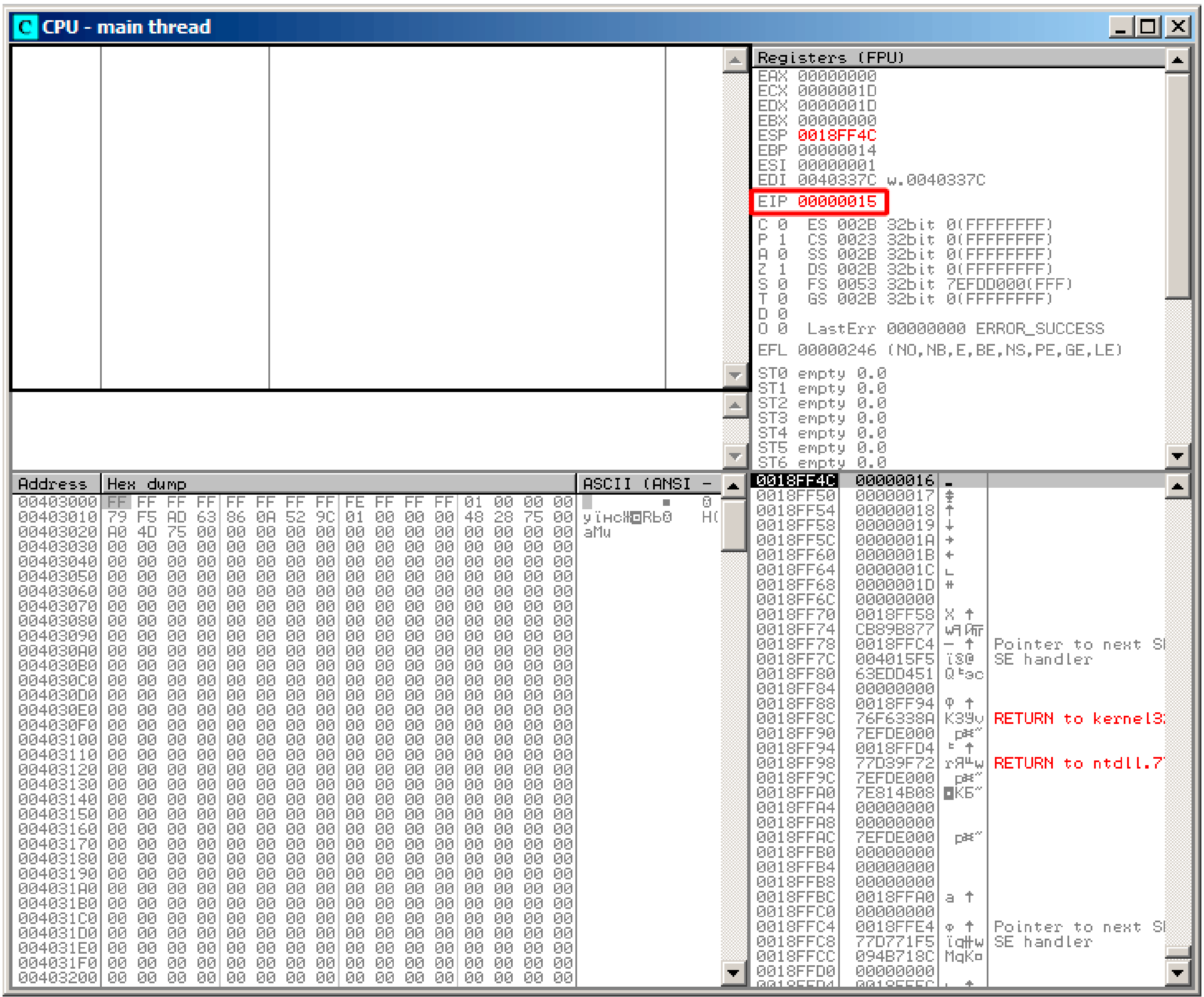


Figure 1.91: OllyDbg: EIP has been restored, but OllyDbg can't disassemble at 0x15

Now please keep your eyes on the registers.

EIP is 0x15 now. It is not a legal address for code—at least for win32 code! We got there somehow against our will. It is also interesting that the EBP register contain 0x14, ECX and EDX contain 0x1D.

Let's study stack layout a bit more.

After the control flow has been passed to `main()`, the value in the EBP register was saved on the stack. Then, 84 bytes were allocated for the array and the i variable. That's `(20+1)*sizeof(int)`. ESP now points to the `_i` variable in the local stack and after the execution of the next `PUSH something`, *something* is appearing next to `_i`.

That's the stack layout while the control is in `main()`:

ESP	4 bytes allocated for i variable
ESP+4	80 bytes allocated for `a[20]` array
ESP+84	saved EBP value
ESP+88	return address

`a[19]=something` statement writes the last *int* in the bounds of the array (in bounds so far!).

`a[20]=something` statement writes *something* to the place where the value of EBP is saved.

Please take a look at the register state at the moment of the crash. In our case, 20 has been written in the 20th element. At the function end, the function epilogue restores the original EBP value. (20 in decimal is 0x14 in hexadecimal). Then RET gets executed, which is effectively equivalent to POP EIP instruction.

The RET instruction takes the return address from the stack (that is the address in CRT, which has called main()), and 21 is stored there (0x15 in hexadecimal). The CPU traps at address 0x15, but there is no executable code there, so exception gets raised.

Welcome! It is called a *buffer overflow*[133].

Replace the *int* array with a string (*char* array), create a long string deliberately and pass it to the program, to the function, which doesn't check the length of the string and copies it in a short buffer, and you'll able to point the program to an address to which it must jump. It's not that simple in reality, but that is how it emerged. Classic article about it: [Aleph One, *Smashing The Stack For Fun And Profit*, (1996)][134].

GCC

Let's try the same code in GCC 4.4.1. We get:

```
                public main
main            proc near

a               = dword ptr -54h
i               = dword ptr -4

                push    ebp
                mov     ebp, esp
                sub     esp, 60h ; 96
                mov     [ebp+i], 0
                jmp     short loc_80483D1
loc_80483C3:
                mov     eax, [ebp+i]
                mov     edx, [ebp+i]
                mov     [ebp+eax*4+a], edx
                add     [ebp+i], 1
loc_80483D1:
                cmp     [ebp+i], 1Dh
                jle     short loc_80483C3
                mov     eax, 0
                leave
                retn
main            endp
```

Running this in Linux will produce: Segmentation fault.

If we run this in the GDB debugger, we get this:

```
(gdb) r
Starting program: /home/dennis/RE/1

Program received signal SIGSEGV, Segmentation fault.
0x00000016 in ?? ()
(gdb) info registers
eax            0x0      0
ecx            0xd2f96388       -755407992
edx            0x1d     29
ebx            0x26eff4 2551796
esp            0xbffff4b0       0xbffff4b0
ebp            0x15     0x15
esi            0x0      0
edi            0x0      0
eip            0x16     0x16
eflags         0x10202  [ IF RF ]
cs             0x73     115
ss             0x7b     123
ds             0x7b     123
es             0x7b     123
fs             0x0      0
gs             0x33     51
```

[133] wikipedia

[134] Also available as http://go.yurichev.com/17266

```
(gdb)
```

The register values are slightly different than in win32 example, since the stack layout is slightly different too.

1.20.3 Buffer overflow protection methods

There are several methods to protect against this scourge, regardless of the C/C++ programmers' negligence. MSVC has options like[135]:

```
/RTCs Stack Frame runtime checking
/GZ Enable stack checks (/RTCs)
```

One of the methods is to write a random value between the local variables in stack at function prologue and to check it in function epilogue before the function exits. If value is not the same, do not execute the last instruction RET, but stop (or hang). The process will halt, but that is much better than a remote attack to your host.

This random value is called a "canary" sometimes, it is related to the miners' canary[136], they were used by miners in the past days in order to detect poisonous gases quickly.

Canaries are very sensitive to mine gases, they become very agitated in case of danger, or even die.

If we compile our very simple array example (1.20.1 on page 268) in MSVC with RTC1 and RTCs option, you can see a call to `@_RTC_CheckStackVars@8` a function at the end of the function that checks if the "canary" is correct.

Let's see how GCC handles this. Let's take an `alloca()` (1.7.2 on page 35) example:

```
#ifdef __GNUC__
#include <alloca.h> // GCC
#else
#include <malloc.h> // MSVC
#endif
#include <stdio.h>

void f()
{
    char *buf=(char*)alloca (600);
#ifdef __GNUC__
    snprintf (buf, 600, "hi! %d, %d, %d\n", 1, 2, 3); // GCC
#else
    _snprintf (buf, 600, "hi! %d, %d, %d\n", 1, 2, 3); // MSVC
#endif

    puts (buf);
};
```

By default, without any additional options, GCC 4.7.3 inserts a "canary" check into the code:

Listing 1.231: GCC 4.7.3

```
.LC0:
        .string "hi! %d, %d, %d\n"
f:
        push    ebp
        mov     ebp, esp
        push    ebx
        sub     esp, 676
        lea     ebx, [esp+39]
        and     ebx, -16
        mov     DWORD PTR [esp+20], 3
        mov     DWORD PTR [esp+16], 2
        mov     DWORD PTR [esp+12], 1
        mov     DWORD PTR [esp+8], OFFSET FLAT:.LC0  ; "hi! %d, %d, %d\n"
        mov     DWORD PTR [esp+4], 600
```

[135] compiler-side buffer overflow protection methods: wikipedia.org/wiki/Buffer_overflow_protection
[136] wikipedia.org/wiki/Domestic_canary#Miner.27s_canary

```
        mov     DWORD PTR [esp], ebx
        mov     eax, DWORD PTR gs:20     ; canary
        mov     DWORD PTR [ebp-12], eax
        xor     eax, eax
        call    _snprintf
        mov     DWORD PTR [esp], ebx
        call    puts
        mov     eax, DWORD PTR [ebp-12]
        xor     eax, DWORD PTR gs:20     ; check canary
        jne     .L5
        mov     ebx, DWORD PTR [ebp-4]
        leave
        ret
.L5:
        call    __stack_chk_fail
```

The random value is located in gs:20. It gets written on the stack and then at the end of the function the value in the stack is compared with the correct "canary" in gs:20. If the values are not equal, the __stack_chk_fail function is called and we can see in the console something like that (Ubuntu 13.04 x86):

```
*** buffer overflow detected ***: ./2_1 terminated
======= Backtrace: =========
/lib/i386-linux-gnu/libc.so.6(__fortify_fail+0x63)[0xb7699bc3]
/lib/i386-linux-gnu/libc.so.6(+0x10593a)[0xb769893a]
/lib/i386-linux-gnu/libc.so.6(+0x105008)[0xb7698008]
/lib/i386-linux-gnu/libc.so.6(_IO_default_xsputn+0x8c)[0xb7606e5c]
/lib/i386-linux-gnu/libc.so.6(_IO_vfprintf+0x165)[0xb75d7a45]
/lib/i386-linux-gnu/libc.so.6(__vsprintf_chk+0xc9)[0xb76980d9]
/lib/i386-linux-gnu/libc.so.6(__sprintf_chk+0x2f)[0xb7697fef]
./2_1[0x8048404]
/lib/i386-linux-gnu/libc.so.6(__libc_start_main+0xf5)[0xb75ac935]
======= Memory map: ========
08048000-08049000 r-xp 00000000 08:01 2097586    /home/dennis/2_1
08049000-0804a000 r--p 00000000 08:01 2097586    /home/dennis/2_1
0804a000-0804b000 rw-p 00001000 08:01 2097586    /home/dennis/2_1
094d1000-094f2000 rw-p 00000000 00:00 0          [heap]
b7560000-b757b000 r-xp 00000000 08:01 1048602    /lib/i386-linux-gnu/libgcc_s.so.1
b757b000-b757c000 r--p 0001a000 08:01 1048602    /lib/i386-linux-gnu/libgcc_s.so.1
b757c000-b757d000 rw-p 0001b000 08:01 1048602    /lib/i386-linux-gnu/libgcc_s.so.1
b7592000-b7593000 rw-p 00000000 00:00 0
b7593000-b7740000 r-xp 00000000 08:01 1050781    /lib/i386-linux-gnu/libc-2.17.so
b7740000-b7742000 r--p 001ad000 08:01 1050781    /lib/i386-linux-gnu/libc-2.17.so
b7742000-b7743000 rw-p 001af000 08:01 1050781    /lib/i386-linux-gnu/libc-2.17.so
b7743000-b7746000 rw-p 00000000 00:00 0
b775a000-b775d000 rw-p 00000000 00:00 0
b775d000-b775e000 r-xp 00000000 00:00 0          [vdso]
b775e000-b777e000 r-xp 00000000 08:01 1050794    /lib/i386-linux-gnu/ld-2.17.so
b777e000-b777f000 r--p 0001f000 08:01 1050794    /lib/i386-linux-gnu/ld-2.17.so
b777f000-b7780000 rw-p 00020000 08:01 1050794    /lib/i386-linux-gnu/ld-2.17.so
bff35000-bff56000 rw-p 00000000 00:00 0          [stack]
Aborted (core dumped)
```

gs is the so-called segment register. These registers were used widely in MS-DOS and DOS-extenders times. Today, its function is different.

To say it briefly, the gs register in Linux always points to the TLS[137] (6.2 on page 742)—some information specific to thread is stored there. By the way, in win32 the fs register plays the same role, pointing to TIB[138] [139].

More information can be found in the Linux kernel source code (at least in 3.11 version), in *arch/x86/include/asm/stackprotector.h* this variable is described in the comments.

[137]Thread Local Storage
[138]Thread Information Block
[139]wikipedia.org/wiki/Win32_Thread_Information_Block

Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

Let's get back to our simple array example (1.20.1 on page 268),

again, now we can see how LLVM checks the correctness of the "canary":

```
_main

var_64          = -0x64
var_60          = -0x60
var_5C          = -0x5C
var_58          = -0x58
var_54          = -0x54
var_50          = -0x50
var_4C          = -0x4C
var_48          = -0x48
var_44          = -0x44
var_40          = -0x40
var_3C          = -0x3C
var_38          = -0x38
var_34          = -0x34
var_30          = -0x30
var_2C          = -0x2C
var_28          = -0x28
var_24          = -0x24
var_20          = -0x20
var_1C          = -0x1C
var_18          = -0x18
canary          = -0x14
var_10          = -0x10

    PUSH     {R4-R7,LR}
    ADD      R7, SP, #0xC
    STR.W    R8, [SP,#0xC+var_10]!
    SUB      SP, SP, #0x54
    MOVW     R0, #aObjc_methtype ; "objc_methtype"
    MOVS     R2, #0
    MOVT.W   R0, #0
    MOVS     R5, #0
    ADD      R0, PC
    LDR.W    R8, [R0]
    LDR.W    R0, [R8]
    STR      R0, [SP,#0x64+canary]
    MOVS     R0, #2
    STR      R2, [SP,#0x64+var_64]
    STR      R0, [SP,#0x64+var_60]
    MOVS     R0, #4
    STR      R0, [SP,#0x64+var_5C]
    MOVS     R0, #6
    STR      R0, [SP,#0x64+var_58]
    MOVS     R0, #8
    STR      R0, [SP,#0x64+var_54]
    MOVS     R0, #0xA
    STR      R0, [SP,#0x64+var_50]
    MOVS     R0, #0xC
    STR      R0, [SP,#0x64+var_4C]
    MOVS     R0, #0xE
    STR      R0, [SP,#0x64+var_48]
    MOVS     R0, #0x10
    STR      R0, [SP,#0x64+var_44]
    MOVS     R0, #0x12
    STR      R0, [SP,#0x64+var_40]
    MOVS     R0, #0x14
    STR      R0, [SP,#0x64+var_3C]
    MOVS     R0, #0x16
    STR      R0, [SP,#0x64+var_38]
    MOVS     R0, #0x18
    STR      R0, [SP,#0x64+var_34]
    MOVS     R0, #0x1A
    STR      R0, [SP,#0x64+var_30]
```

```
    MOVS     R0, #0x1C
    STR      R0, [SP,#0x64+var_2C]
    MOVS     R0, #0x1E
    STR      R0, [SP,#0x64+var_28]
    MOVS     R0, #0x20
    STR      R0, [SP,#0x64+var_24]
    MOVS     R0, #0x22
    STR      R0, [SP,#0x64+var_20]
    MOVS     R0, #0x24
    STR      R0, [SP,#0x64+var_1C]
    MOVS     R0, #0x26
    STR      R0, [SP,#0x64+var_18]
    MOV      R4, 0xFDA ; "a[%d]=%d\n"
    MOV      R0, SP
    ADDS     R6, R0, #4
    ADD      R4, PC
    B        loc_2F1C

; second loop begin

loc_2F14
    ADDS     R0, R5, #1
    LDR.W    R2, [R6,R5,LSL#2]
    MOV      R5, R0

loc_2F1C
    MOV      R0, R4
    MOV      R1, R5
    BLX      _printf
    CMP      R5, #0x13
    BNE      loc_2F14
    LDR.W    R0, [R8]
    LDR      R1, [SP,#0x64+canary]
    CMP      R0, R1
    ITTTT EQ            ; is canary still correct?
    MOVEQ    R0, #0
    ADDEQ    SP, SP, #0x54
    LDREQ.W  R8, [SP+0x64+var_64],#4
    POPEQ    {R4-R7,PC}
    BLX      ___stack_chk_fail
```

First of all, as we see, LLVM “unrolled” the loop and all values were written into an array one-by-one, pre-calculated, as LLVM concluded it can work faster. By the way, instructions in ARM mode may help to do this even faster, and finding this could be your homework.

At the function end we see the comparison of the “canaries”—the one in the local stack and the correct one, to which R8 points.

If they are equal to each other, a 4-instruction block is triggered by `ITTTT EQ`, which contains writing 0 in `R0`, the function epilogue and exit. If the “canaries” are not equal, the block being skipped, and the jump to `___stack_chk_fail` function will occur, which, perhaps will halt execution.

1.20.4 One more word about arrays

Now we understand why it is impossible to write something like this in C/C++ code:

```
void f(int size)
{
    int a[size];
...
};
```

That’s just because the compiler must know the exact array size to allocate space for it in the local stack layout on at the compiling stage.

If you need an array of arbitrary size, allocate it by using `malloc()`, then access the allocated memory block as an array of variables of the type you need.

Or use the C99 standard feature [*ISO/IEC 9899:TC3 (C C99 standard)*, (2007)6.7.5/2], and it works like *alloca()* (1.7.2 on page 35) internally.

It's also possible to use garbage collecting libraries for C.

And there are also libraries supporting smart pointers for C++.

1.20.5 Array of pointers to strings

Here is an example for an array of pointers.

Listing 1.232: Get month name

```
#include <stdio.h>

const char* month1[]=
{
        "January", "February", "March", "April",
        "May", "June", "July", "August",
        "September", "October", "November", "December"
};

// in 0..11 range
const char* get_month1 (int month)
{
        return month1[month];
};
```

x64

Listing 1.233: Optimizing MSVC 2013 x64

```
_DATA   SEGMENT
month1  DQ      FLAT:$SG3122
        DQ      FLAT:$SG3123
        DQ      FLAT:$SG3124
        DQ      FLAT:$SG3125
        DQ      FLAT:$SG3126
        DQ      FLAT:$SG3127
        DQ      FLAT:$SG3128
        DQ      FLAT:$SG3129
        DQ      FLAT:$SG3130
        DQ      FLAT:$SG3131
        DQ      FLAT:$SG3132
        DQ      FLAT:$SG3133
$SG3122 DB      'January', 00H
$SG3123 DB      'February', 00H
$SG3124 DB      'March', 00H
$SG3125 DB      'April', 00H
$SG3126 DB      'May', 00H
$SG3127 DB      'June', 00H
$SG3128 DB      'July', 00H
$SG3129 DB      'August', 00H
$SG3130 DB      'September', 00H
$SG3156 DB      '%s', 0aH, 00H
$SG3131 DB      'October', 00H
$SG3132 DB      'November', 00H
$SG3133 DB      'December', 00H
_DATA   ENDS

month$ = 8
get_month1 PROC
        movsxd  rax, ecx
        lea     rcx, OFFSET FLAT:month1
        mov     rax, QWORD PTR [rcx+rax*8]
        ret     0
get_month1 ENDP
```

The code is very simple:

- The first MOVSXD instruction copies a 32-bit value from ECX (where $month$ argument is passed) to RAX with sign-extension (because the $month$ argument is of type *int*).

  The reason for the sign extension is that this 32-bit value is to be used in calculations with other 64-bit values.

  Hence, it has to be promoted to 64-bit[140].

- Then the address of the pointer table is loaded into RCX.

- Finally, the input value ($month$) is multiplied by 8 and added to the address. Indeed: we are in a 64-bit environment and all address (or pointers) require exactly 64 bits (or 8 bytes) for storage. Hence, each table element is 8 bytes wide. And that's why to pick a specific element, $month * 8$ bytes has to be skipped from the start. That's what MOV does. In addition, this instruction also loads the element at this address. For 1, an element would be a pointer to a string that contains "February", etc.

Optimizing GCC 4.9 can do the job even better [141]:

Listing 1.234: Optimizing GCC 4.9 x64

```
        movsx   rdi, edi
        mov     rax, QWORD PTR month1[0+rdi*8]
        ret
```

32-bit MSVC

Let's also compile it in the 32-bit MSVC compiler:

Listing 1.235: Optimizing MSVC 2013 x86

```
_month$ = 8
_get_month1 PROC
        mov     eax, DWORD PTR _month$[esp-4]
        mov     eax, DWORD PTR _month1[eax*4]
        ret     0
_get_month1 ENDP
```

The input value does not need to be extended to 64-bit value, so it is used as is.

And it's multiplied by 4, because the table elements are 32-bit (or 4 bytes) wide.

32-bit ARM

ARM in ARM mode

Listing 1.236: Optimizing Keil 6/2013 (ARM mode)

```
get_month1 PROC
        LDR      r1,|L0.100|
        LDR      r0,[r1,r0,LSL #2]
        BX       lr
        ENDP

|L0.100|
        DCD      ||.data||

        DCB      "January",0
        DCB      "February",0
        DCB      "March",0
        DCB      "April",0
        DCB      "May",0
```

[140] It is somewhat weird, but negative array index could be passed here as $month$ (negative array indices will have been explained later: 3.19 on page 593). And if this happens, the negative input value of *int* type is sign-extended correctly and the corresponding element before table is picked. It is not going to work correctly without sign-extension.

[141] "0+" was left in the listing because GCC assembler output is not tidy enough to eliminate it. It's *displacement*, and it's zero here.

```
        DCB      "June",0
        DCB      "July",0
        DCB      "August",0
        DCB      "September",0
        DCB      "October",0
        DCB      "November",0
        DCB      "December",0

        AREA ||.data||, DATA, ALIGN=2
month1
        DCD      ||.conststring||
        DCD      ||.conststring||+0x8
        DCD      ||.conststring||+0x11
        DCD      ||.conststring||+0x17
        DCD      ||.conststring||+0x1d
        DCD      ||.conststring||+0x21
        DCD      ||.conststring||+0x26
        DCD      ||.conststring||+0x2b
        DCD      ||.conststring||+0x32
        DCD      ||.conststring||+0x3c
        DCD      ||.conststring||+0x44
        DCD      ||.conststring||+0x4d
```

The address of the table is loaded in R1.

All the rest is done using just one LDR instruction.

Then input value $month$ is shifted left by 2 (which is the same as multiplying by 4), then added to R1 (where the address of the table is) and then a table element is loaded from this address.

The 32-bit table element is loaded into R0 from the table.

ARM in Thumb mode

The code is mostly the same, but less dense, because the LSL suffix cannot be specified in the LDR instruction here:

```
get_month1 PROC
        LSLS     r0,r0,#2
        LDR      r1,|L0.64|
        LDR      r0,[r1,r0]
        BX       lr
        ENDP
```

ARM64

Listing 1.237: Optimizing GCC 4.9 ARM64

```
get_month1:
        adrp    x1, .LANCHOR0
        add     x1, x1, :lo12:.LANCHOR0
        ldr     x0, [x1,w0,sxtw 3]
        ret

.LANCHOR0 = . + 0
        .type   month1, %object
        .size   month1, 96
month1:
        .xword  .LC2
        .xword  .LC3
        .xword  .LC4
        .xword  .LC5
        .xword  .LC6
        .xword  .LC7
        .xword  .LC8
        .xword  .LC9
        .xword  .LC10
```

```
        .xword  .LC11
        .xword  .LC12
        .xword  .LC13
.LC2:
        .string "January"
.LC3:
        .string "February"
.LC4:
        .string "March"
.LC5:
        .string "April"
.LC6:
        .string "May"
.LC7:
        .string "June"
.LC8:
        .string "July"
.LC9:
        .string "August"
.LC10:
        .string "September"
.LC11:
        .string "October"
.LC12:
        .string "November"
.LC13:
        .string "December"
```

The address of the table is loaded in X1 using ADRP/ADD pair.

Then corresponding element is picked using just one LDR, which takes W0 (the register where input argument $month$ is), shifts it 3 bits to the left (which is the same as multiplying by 8), sign-extends it (this is what "sxtw" suffix implies) and adds to X0. Then the 64-bit value is loaded from the table into X0.

MIPS

Listing 1.238: Optimizing GCC 4.4.5 (IDA)

```
get_month1:
; load address of table into $v0:
                la      $v0, month1
; take input value and multiply it by 4:
                sll     $a0, 2
; sum up address of table and multiplied value:
                addu    $a0, $v0
; load table element at this address into $v0:
                lw      $v0, 0($a0)
; return
                jr      $ra
                or      $at, $zero ; branch delay slot, NOP

                .data # .data.rel.local
                .globl month1
month1:         .word aJanuary          # "January"
                .word aFebruary         # "February"
                .word aMarch            # "March"
                .word aApril            # "April"
                .word aMay              # "May"
                .word aJune             # "June"
                .word aJuly             # "July"
                .word aAugust           # "August"
                .word aSeptember        # "September"
                .word aOctober          # "October"
                .word aNovember         # "November"
                .word aDecember         # "December"

                .data # .rodata.str1.4
aJanuary:       .ascii "January"<0>
aFebruary:      .ascii "February"<0>
```

```
aMarch:         .ascii "March"<0>
aApril:         .ascii "April"<0>
aMay:           .ascii "May"<0>
aJune:          .ascii "June"<0>
aJuly:          .ascii "July"<0>
aAugust:        .ascii "August"<0>
aSeptember:     .ascii "September"<0>
aOctober:       .ascii "October"<0>
aNovember:      .ascii "November"<0>
aDecember:      .ascii "December"<0>
```

Array overflow

Our function accepts values in the range of 0..11, but what if 12 is passed? There is no element in table at this place.

So the function will load some value which happens to be there, and return it.

Soon after, some other function can try to get a text string from this address and may crash.

Let's compile the example in MSVC for win64 and open it in IDA to see what the linker has placed after the table:

Listing 1.239: Executable file in IDA

```
off_140011000   dq offset aJanuary_1    ; DATA XREF: .text:0000000140001003
                                        ; "January"
                dq offset aFebruary_1   ; "February"
                dq offset aMarch_1      ; "March"
                dq offset aApril_1      ; "April"
                dq offset aMay_1        ; "May"
                dq offset aJune_1       ; "June"
                dq offset aJuly_1       ; "July"
                dq offset aAugust_1     ; "August"
                dq offset aSeptember_1  ; "September"
                dq offset aOctober_1    ; "October"
                dq offset aNovember_1   ; "November"
                dq offset aDecember_1   ; "December"
aJanuary_1      db 'January',0          ; DATA XREF: sub_140001020+4
                                        ; .data:off_140011000
aFebruary_1     db 'February',0         ; DATA XREF: .data:0000000140011008
                align 4
aMarch_1        db 'March',0            ; DATA XREF: .data:0000000140011010
                align 4
aApril_1        db 'April',0            ; DATA XREF: .data:0000000140011018
```

Month names are came right after.

Our program is tiny, so there isn't much data to pack in the data segment, so it just the month names. But it has to be noted that there might be really *anything* that linker has decided to put by chance.

So what if 12 is passed to the function? The 13th element will be returned.

Let's see how the CPU treats the bytes there as a 64-bit value:

Listing 1.240: Executable file in IDA

```
off_140011000   dq offset qword_140011060
                                        ; DATA XREF: .text:0000000140001003
                dq offset aFebruary_1   ; "February"
                dq offset aMarch_1      ; "March"
                dq offset aApril_1      ; "April"
                dq offset aMay_1        ; "May"
                dq offset aJune_1       ; "June"
                dq offset aJuly_1       ; "July"
                dq offset aAugust_1     ; "August"
                dq offset aSeptember_1  ; "September"
                dq offset aOctober_1    ; "October"
                dq offset aNovember_1   ; "November"
                dq offset aDecember_1   ; "December"
qword_140011060 dq 797261756E614Ah      ; DATA XREF: sub_140001020+4
```

```
                                        ; .data:off_140011000
aFebruary_1     db 'February',0         ; DATA XREF: .data:0000000140011008
                align 4
aMarch_1        db 'March',0            ; DATA XREF: .data:0000000140011010
```

And this is 0x797261756E614A.

Soon after, some other function (presumably, one that processes strings) may try to read bytes at this address, expecting a C-string there.

Most likely it is about to crash, because this value doesn't look like a valid address.

Array overflow protection

> If something can go wrong, it will
>
> Murphy's Law

It's a bit naïve to expect that every programmer who use your function or library will never pass an argument larger than 11.

There exists the philosophy that says "fail early and fail loudly" or "fail-fast", which teaches to report problems as early as possible and halt.

One such method in C/C++ is assertions.

We can modify our program to fail if an incorrect value is passed:

Listing 1.241: assert() added

```
const char* get_month1_checked (int month)
{
        assert (month<12);
        return month1[month];
};
```

The assertion macro checks for valid values at every function start and fails if the expression is false.

Listing 1.242: Optimizing MSVC 2013 x64

```
$SG3143 DB      'm', 00H, 'o', 00H, 'n', 00H, 't', 00H, 'h', 00H, '.', 00H
        DB      'c', 00H, 00H, 00H
$SG3144 DB      'm', 00H, 'o', 00H, 'n', 00H, 't', 00H, 'h', 00H, '<', 00H
        DB      '1', 00H, '2', 00H, 00H, 00H

month$ = 48
get_month1_checked PROC
$LN5:
        push    rbx
        sub     rsp, 32
        movsxd  rbx, ecx
        cmp     ebx, 12
        jl      SHORT $LN3@get_month1
        lea     rdx, OFFSET FLAT:$SG3143
        lea     rcx, OFFSET FLAT:$SG3144
        mov     r8d, 29
        call    _wassert
$LN3@get_month1:
        lea     rcx, OFFSET FLAT:month1
        mov     rax, QWORD PTR [rcx+rbx*8]
        add     rsp, 32
        pop     rbx
        ret     0
get_month1_checked ENDP
```

In fact, assert() is not a function, but macro. It checks for a condition, then passes also the line number and file name to another function which reports this information to the user.

Here we see that both file name and condition are encoded in UTF-16. The line number is also passed (it's 29).

This mechanism is probably the same in all compilers. Here is what GCC does:

Listing 1.243: Optimizing GCC 4.9 x64

```
.LC1:
        .string "month.c"
.LC2:
        .string "month<12"

get_month1_checked:
        cmp     edi, 11
        jg      .L6
        movsx   rdi, edi
        mov     rax, QWORD PTR month1[0+rdi*8]
        ret
.L6:
        push    rax
        mov     ecx, OFFSET FLAT:__PRETTY_FUNCTION__.2423
        mov     edx, 29
        mov     esi, OFFSET FLAT:.LC1
        mov     edi, OFFSET FLAT:.LC2
        call    __assert_fail

__PRETTY_FUNCTION__.2423:
        .string "get_month1_checked"
```

So the macro in GCC also passes the function name for convenience.

Nothing is really free, and this is true for the sanitizing checks as well.

They make your program slower, especially if the assert() macros used in small time-critical functions.

So MSVC, for example, leaves the checks in debug builds, but in release builds they all disappear.

Microsoft Windows NT kernels come in "checked" and "free" builds [142].

The first has validation checks (hence, "checked"), the second one doesn't (hence, "free" of checks).

Of course, "checked" kernel works slower because of all these checks, so it is usually used only in debug sessions.

Accessing specific character

An array of pointers to strings can be accessed like this:

```
#include <stdio.h>

const char* month[]=
{
        "January", "February", "March", "April",
        "May", "June", "July", "August",
        "September", "October", "November", "December"
};

int main()
{
        // 4th month, 5th character:
        printf ("%c\n", month[3][4]);
};
```

…since *month[3]* expression has a *const char** type. And then, 5th character is taken from that expression by adding 4 bytes to its address.

By the way, arguments list passed to *main()* function has the same data type:

```
#include <stdio.h>

int main(int argc, char *argv[])
{
        printf ("3rd argument, 2nd character: %c\n", argv[3][1]);
```

142 msdn.microsoft.com/en-us/library/windows/hardware/ff543450(v=vs.85).aspx

```
};
```

It's very important to understand, that, despite similar syntax, this is different from two-dimensional arrays, which we will consider later.

Another important thing to notice: strings to be addressed must be encoded in a system, where each character occupies single byte, like ASCII[143] and extended ASCII. UTF-8 wouldn't work here.

1.20.6 Multidimensional arrays

Internally, a multidimensional array is essentially the same thing as a linear array.

Since the computer memory is linear, it is an one-dimensional array. For convenience, this multi-dimensional array can be easily represented as one-dimensional.

For example, this is how the elements of the 3x4 array are placed in one-dimensional array of 12 cells:

Offset in memory	array element
0	[0][0]
1	[0][1]
2	[0][2]
3	[0][3]
4	[1][0]
5	[1][1]
6	[1][2]
7	[1][3]
8	[2][0]
9	[2][1]
10	[2][2]
11	[2][3]

Table 1.3: Two-dimensional array represented in memory as one-dimensional

Here is how each cell of 3*4 array are placed in memory:

0	1	2	3
4	5	6	7
8	9	10	11

Table 1.4: Memory addresses of each cell of two-dimensional array

So, in order to calculate the address of the element we need, we first multiply the first index by 4 (array width) and then add the second index. That's called *row-major order*, and this method of array and matrix representation is used in at least C/C++ and Python. The term *row-major order* in plain English language means: "first, write the elements of the first row, then the second row …and finally the elements of the last row".

Another method for representation is called *column-major order* (the array indices are used in reverse order) and it is used at least in Fortran, MATLAB and R. *column-major order* term in plain English language means: "first, write the elements of the first column, then the second column …and finally the elements of the last column".

Which method is better?

In general, in terms of performance and cache memory, the best scheme for data organization is the one, in which the elements are accessed sequentially.

So if your function accesses data per row, *row-major order* is better, and vice versa.

Two-dimensional array example

We are going to work with an array of type *char*, which implies that each element requires only one byte in memory.

[143] American Standard Code for Information Interchange

Row filling example

Let's fill the second row with these values 0..3:

Listing 1.244: Row filling example

```
#include <stdio.h>

char a[3][4];

int main()
{
        int x, y;

        // clear array
        for (x=0; x<3; x++)
                for (y=0; y<4; y++)
                        a[x][y]=0;

        // fill second row by 0..3:
        for (y=0; y<4; y++)
                a[1][y]=y;
};
```

All three rows are marked with red. We see that second row now has values 0, 1, 2 and 3:

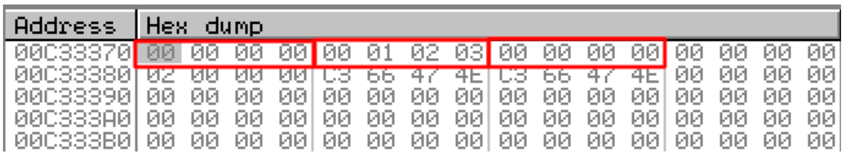


Figure 1.92: OllyDbg: array is filled

Column filling example

Let's fill the third column with values: 0..2:

Listing 1.245: Column filling example

```
#include <stdio.h>

char a[3][4];

int main()
{
        int x, y;

        // clear array
        for (x=0; x<3; x++)
                for (y=0; y<4; y++)
                        a[x][y]=0;

        // fill third column by 0..2:
        for (x=0; x<3; x++)
                a[x][2]=x;
};
```

The three rows are also marked in red here.

We see that in each row, at third position these values are written: 0, 1 and 2.

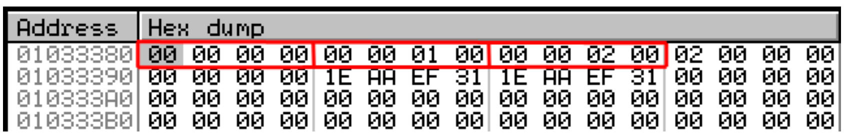


Figure 1.93: OllyDbg: array is filled

Access two-dimensional array as one-dimensional

We can be easily assured that it's possible to access a two-dimensional array as one-dimensional array in at least two ways:

```
#include <stdio.h>

char a[3][4];

char get_by_coordinates1 (char array[3][4], int a, int b)
{
        return array[a][b];
};

char get_by_coordinates2 (char *array, int a, int b)
{
        // treat input array as one-dimensional
        // 4 is array width here
        return array[a*4+b];
};

char get_by_coordinates3 (char *array, int a, int b)
{
        // treat input array as pointer,
        // calculate address, get value at it
        // 4 is array width here
        return *(array+a*4+b);
};

int main()
{
        a[2][3]=123;
        printf ("%d\n", get_by_coordinates1(a, 2, 3));
        printf ("%d\n", get_by_coordinates2(a, 2, 3));
        printf ("%d\n", get_by_coordinates3(a, 2, 3));
};
```

Compile[144] and run it: it shows correct values.

What MSVC 2013 did is fascinating, all three routines are just the same!

Listing 1.246: Optimizing MSVC 2013 x64

```
array$ = 8
a$ = 16
b$ = 24
get_by_coordinates3 PROC
; RCX=address of array
; RDX=a
; R8=b
        movsxd  rax, r8d
; EAX=b
        movsxd  r9, edx
; R9=a
        add     rax, rcx
; RAX=b+address of array
        movzx   eax, BYTE PTR [rax+r9*4]
; AL=load byte at address RAX+R9*4=b+address of array+a*4=address of array+a*4+b
        ret     0
get_by_coordinates3 ENDP

array$ = 8
a$ = 16
b$ = 24
get_by_coordinates2 PROC
        movsxd  rax, r8d
        movsxd  r9, edx
        add     rax, rcx
        movzx   eax, BYTE PTR [rax+r9*4]
```

144This program is to be compiled as C program, not C++, save it to a file with .c extension to compile it using MSVC

```
        ret     0
get_by_coordinates2 ENDP

array$ = 8
a$ = 16
b$ = 24
get_by_coordinates1 PROC
        movsxd  rax, r8d
        movsxd  r9, edx
        add     rax, rcx
        movzx   eax, BYTE PTR [rax+r9*4]
        ret     0
get_by_coordinates1 ENDP
```

GCC also generates equivalent routines, but slightly different:

Listing 1.247: Optimizing GCC 4.9 x64

```
; RDI=address of array
; RSI=a
; RDX=b

get_by_coordinates1:
; sign-extend input 32-bit int values "a" and "b" to 64-bit ones
        movsx   rsi, esi
        movsx   rdx, edx
        lea     rax, [rdi+rsi*4]
; RAX=RDI+RSI*4=address of array+a*4
        movzx   eax, BYTE PTR [rax+rdx]
; AL=load byte at address RAX+RDX=address of array+a*4+b
        ret

get_by_coordinates2:
        lea     eax, [rdx+rsi*4]
; RAX=RDX+RSI*4=b+a*4
        cdqe
        movzx   eax, BYTE PTR [rdi+rax]
; AL=load byte at address RDI+RAX=address of array+b+a*4
        ret

get_by_coordinates3:
        sal     esi, 2
; ESI=a<<2=a*4
; sign-extend input 32-bit int values "a*4" and "b" to 64-bit ones
        movsx   rdx, edx
        movsx   rsi, esi
        add     rdi, rsi
; RDI=RDI+RSI=address of array+a*4
        movzx   eax, BYTE PTR [rdi+rdx]
; AL=load byte at address RDI+RDX=address of array+a*4+b
        ret
```

Three-dimensional array example

It’s the same for multidimensional arrays.

Now we are going to work with an array of type *int*: each element requires 4 bytes in memory.

Let’s see:

Listing 1.248: simple example

```
#include <stdio.h>

int a[10][20][30];

void insert(int x, int y, int z, int value)
{
        a[x][y][z]=value;
};
```

x86

We get (MSVC 2010):

Listing 1.249: MSVC 2010

```
_DATA    SEGMENT
COMM     _a:DWORD:01770H
_DATA    ENDS
PUBLIC   _insert
_TEXT    SEGMENT
_x$ = 8               ; size = 4
_y$ = 12              ; size = 4
_z$ = 16              ; size = 4
_value$ = 20          ; size = 4
_insert    PROC
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _x$[ebp]
    imul   eax, 2400                    ; eax=600*4*x
    mov    ecx, DWORD PTR _y$[ebp]
    imul   ecx, 120                     ; ecx=30*4*y
    lea    edx, DWORD PTR _a[eax+ecx]   ; edx=a + 600*4*x + 30*4*y
    mov    eax, DWORD PTR _z$[ebp]
    mov    ecx, DWORD PTR _value$[ebp]
    mov    DWORD PTR [edx+eax*4], ecx   ; *(edx+z*4)=value
    pop    ebp
    ret    0
_insert    ENDP
_TEXT      ENDS
```

Nothing special. For index calculation, three input arguments are used in the formula $address = 600 \cdot 4 \cdot x + 30 \cdot 4 \cdot y + 4z$, to represent the array as multidimensional. Do not forget that the *int* type is 32-bit (4 bytes), so all coefficients must be multiplied by 4.

Listing 1.250: GCC 4.4.1

```
         public insert
insert   proc near

x        = dword ptr  8
y        = dword ptr  0Ch
z        = dword ptr  10h
value    = dword ptr  14h

         push    ebp
         mov     ebp, esp
         push    ebx
         mov     ebx, [ebp+x]
         mov     eax, [ebp+y]
         mov     ecx, [ebp+z]
         lea     edx, [eax+eax]    ; edx=y*2
         mov     eax, edx          ; eax=y*2
         shl     eax, 4            ; eax=(y*2)<<4 = y*2*16 = y*32
         sub     eax, edx          ; eax=y*32 - y*2=y*30
         imul    edx, ebx, 600     ; edx=x*600
         add     eax, edx          ; eax=eax+edx=y*30 + x*600
         lea     edx, [eax+ecx]    ; edx=y*30 + x*600 + z
         mov     eax, [ebp+value]
         mov     dword ptr ds:a[edx*4], eax  ; *(a+edx*4)=value
         pop     ebx
         pop     ebp
         retn
insert   endp
```

The GCC compiler does it differently.

For one of the operations in the calculation ($30y$), GCC produces code without multiplication instructions. This is how it done: $(y + y) \ll 4 - (y + y) = (2y) \ll 4 - 2y = 2 \cdot 16 \cdot y - 2y = 32y - 2y = 30y$. Thus, for the $30y$ calculation, only one addition operation, one bitwise shift operation and one subtraction operation are used. This works faster.

ARM + Non-optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

Listing 1.251: Non-optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

```
_insert

value   = -0x10
z       = -0xC
y       = -8
x       = -4

; allocate place in local stack for 4 values of int type
SUB     SP, SP, #0x10
MOV     R9, 0xFC2 ; a
ADD     R9, PC
LDR.W   R9, [R9] ; get pointer to array
STR     R0, [SP,#0x10+x]
STR     R1, [SP,#0x10+y]
STR     R2, [SP,#0x10+z]
STR     R3, [SP,#0x10+value]
LDR     R0, [SP,#0x10+value]
LDR     R1, [SP,#0x10+z]
LDR     R2, [SP,#0x10+y]
LDR     R3, [SP,#0x10+x]
MOV     R12, 2400
MUL.W   R3, R3, R12
ADD     R3, R9
MOV     R9, 120
MUL.W   R2, R2, R9
ADD     R2, R3
LSLS    R1, R1, #2 ; R1=R1<<2
ADD     R1, R2
STR     R0, [R1]   ; R1 - address of array element
; deallocate chunk in local stack, allocated for 4 values of int type
ADD     SP, SP, #0x10
BX      LR
```

Non-optimizing LLVM saves all variables in local stack, which is redundant.

The address of the array element is calculated by the formula we already saw.

ARM + Optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

Listing 1.252: Optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

```
_insert
MOVW    R9, #0x10FC
MOV.W   R12, #2400
MOVT.W  R9, #0
RSB.W   R1, R1, R1,LSL#4  ; R1 - y. R1=y<<4 - y = y*16 - y = y*15
ADD     R9, PC
LDR.W   R9, [R9]          ; R9 = pointer to a array
MLA.W   R0, R0, R12, R9   ; R0 - x, R12 - 2400, R9 - pointer to a. R0=x*2400 + ptr to a
ADD.W   R0, R0, R1,LSL#3  ; R0 = R0+R1<<3 = R0+R1*8 = x*2400 + ptr to a + y*15*8 =
                          ; ptr to a + y*30*4 + x*600*4
STR.W   R3, [R0,R2,LSL#2] ; R2 - z, R3 - value. address=R0+z*4 =
                          ; ptr to a + y*30*4 + x*600*4 + z*4
BX      LR
```

The tricks for replacing multiplication by shift, addition and subtraction which we already saw are also present here.

Here we also see a new instruction for us: RSB (*Reverse Subtract*).

It works just as SUB, but it swaps its operands with each other before execution. Why? SUB and RSB are instructions, to the second operand of which shift coefficient may be applied: (LSL#4).

But this coefficient can be applied only to second operand.

That's fine for commutative operations like addition or multiplication (operands may be swapped there without changing the result).

But subtraction is a non-commutative operation, so RSB exist for these cases.

MIPS

My example is tiny, so the GCC compiler decided to put the a array into the 64KiB area addressable by the Global Pointer.

Listing 1.253: Optimizing GCC 4.4.5 (IDA)

```
insert:
; $a0=x
; $a1=y
; $a2=z
; $a3=value
                sll     $v0, $a0, 5
; $v0 = $a0<<5 = x*32
                sll     $a0, 3
; $a0 = $a0<<3 = x*8
                addu    $a0, $v0
; $a0 = $a0+$v0 = x*8+x*32 = x*40
                sll     $v1, $a1, 5
; $v1 = $a1<<5 = y*32
                sll     $v0, $a0, 4
; $v0 = $a0<<4 = x*40*16 = x*640
                sll     $a1, 1
; $a1 = $a1<<1 = y*2
                subu    $a1, $v1, $a1
; $a1 = $v1-$a1 = y*32-y*2 = y*30
                subu    $a0, $v0, $a0
; $a0 = $v0-$a0 = x*640-x*40 = x*600
                la      $gp, __gnu_local_gp
                addu    $a0, $a1, $a0
; $a0 = $a1+$a0 = y*30+x*600
                addu    $a0, $a2
; $a0 = $a0+$a2 = y*30+x*600+z
; load address of table:
                lw      $v0, (a & 0xFFFF)($gp)
; multiply index by 4 to seek array element:
                sll     $a0, 2
; sum up multiplied index and table address:
                addu    $a0, $v0, $a0
; store value into table and return:
                jr      $ra
                sw      $a3, 0($a0)

                .comm a:0x1770
```

More examples

The computer screen is represented as a 2D array, but the video-buffer is a linear 1D array. We talk about it here: 8.13.2 on page 916.

Another example in this book is Minesweeper game: it's field is also two-dimensional array: 8.3.

1.20.7 Pack of strings as a two-dimensional array

Let's revisit the function that returns the name of a month: listing.1.232.

As you see, at least one memory load operation is needed to prepare a pointer to the string that's the month's name.

Is it possible to get rid of this memory load operation?

In fact yes, if you represent the list of strings as a two-dimensional array:

```
#include <stdio.h>
#include <assert.h>

const char month2[12][10]=
{
	{ 'J','a','n','u','a','r','y',  0,  0,  0 },
	{ 'F','e','b','r','u','a','r','y',  0,  0 },
	{ 'M','a','r','c','h',  0,  0,  0,  0,  0 },
	{ 'A','p','r','i','l',  0,  0,  0,  0,  0 },
	{ 'M','a','y',  0,  0,  0,  0,  0,  0,  0 },
	{ 'J','u','n','e',  0,  0,  0,  0,  0,  0 },
	{ 'J','u','l','y',  0,  0,  0,  0,  0,  0 },
	{ 'A','u','g','u','s','t',  0,  0,  0,  0 },
	{ 'S','e','p','t','e','m','b','e','r',  0 },
	{ 'O','c','t','o','b','e','r',  0,  0,  0 },
	{ 'N','o','v','e','m','b','e','r',  0,  0 },
	{ 'D','e','c','e','m','b','e','r',  0,  0 }
};

// in 0..11 range
const char* get_month2 (int month)
{
	return &month2[month][0];
};
```

Here is what we've get:

Listing 1.254: Optimizing MSVC 2013 x64

```
month2  DB      04aH
        DB      061H
        DB      06eH
        DB      075H
        DB      061H
        DB      072H
        DB      079H
        DB      00H
        DB      00H
        DB      00H
...

get_month2 PROC
; sign-extend input argument and promote to 64-bit value
        movsxd  rax, ecx
        lea     rcx, QWORD PTR [rax+rax*4]
; RCX=month+month*4=month*5
        lea     rax, OFFSET FLAT:month2
; RAX=pointer to table
        lea     rax, QWORD PTR [rax+rcx*2]
; RAX=pointer to table + RCX*2=pointer to table + month*5*2=pointer to table + month*10
        ret     0
get_month2 ENDP
```

There are no memory accesses at all.

All this function does is to calculate a point at which the first character of the name of the month is: $pointer\_to\_the\_table + month * 10$.

There are also two LEA instructions, which effectively work as several MUL and MOV instructions.

The width of the array is 10 bytes.

Indeed, the longest string here—"September"—is 9 bytes, and plus the terminating zero is 10 bytes.

The rest of the month names are padded by zero bytes, so they all occupy the same space (10 bytes).

Thus, our function works even faster, because all string start at an address which can be calculated easily.

Optimizing GCC 4.9 can do it even shorter:

Listing 1.255: Optimizing GCC 4.9 x64

```
        movsx   rdi, edi
        lea     rax, [rdi+rdi*4]
        lea     rax, month2[rax+rax]
        ret
```

LEA is also used here for multiplication by 10.

Non-optimizing compilers do multiplication differently.

Listing 1.256: Non-optimizing GCC 4.9 x64

```
get_month2:
        push    rbp
        mov     rbp, rsp
        mov     DWORD PTR [rbp-4], edi
        mov     eax, DWORD PTR [rbp-4]
        movsx   rdx, eax
; RDX = sign-extended input value
        mov     rax, rdx
; RAX = month
        sal     rax, 2
; RAX = month<<2 = month*4
        add     rax, rdx
; RAX = RAX+RDX = month*4+month = month*5
        add     rax, rax
; RAX = RAX*2 = month*5*2 = month*10
        add     rax, OFFSET FLAT:month2
; RAX = month*10 + pointer to the table
        pop     rbp
        ret
```

Non-optimizing MSVC just uses IMUL instruction:

Listing 1.257: Non-optimizing MSVC 2013 x64

```
month$ = 8
get_month2 PROC
        mov     DWORD PTR [rsp+8], ecx
        movsxd  rax, DWORD PTR month$[rsp]
; RAX = sign-extended input value into 64-bit one
        imul    rax, rax, 10
; RAX = RAX*10
        lea     rcx, OFFSET FLAT:month2
; RCX = pointer to the table
        add     rcx, rax
; RCX = RCX+RAX = pointer to the table+month*10
        mov     rax, rcx
; RAX = pointer to the table+month*10
        mov     ecx, 1
; RCX = 1
        imul    rcx, rcx, 0
; RCX = 1*0 = 0
        add     rax, rcx
; RAX = pointer to the table+month*10 + 0 = pointer to the table+month*10
        ret     0
get_month2 ENDP
```

But one thing is weird here: why add multiplication by zero and adding zero to the final result?

This looks like a compiler code generator quirk, which wasn't caught by the compiler's tests (the resulting code works correctly, after all). We intentionally consider such pieces of code so the reader would understand, that sometimes one shouldn't puzzle over such compiler artifacts.

32-bit ARM

Optimizing Keil for Thumb mode uses the multiplication instruction MULS:

Listing 1.258: Optimizing Keil 6/2013 (Thumb mode)

```
; R0 = month
        MOVS     r1,#0xa
; R1 = 10
        MULS     r0,r1,r0
; R0 = R1*R0 = 10*month
        LDR      r1,|L0.68|
; R1 = pointer to the table
        ADDS     r0,r0,r1
; R0 = R0+R1 = 10*month + pointer to the table
        BX       lr
```

Optimizing Keil for ARM mode uses add and shift operations:

Listing 1.259: Optimizing Keil 6/2013 (ARM mode)

```
; R0 = month
        LDR      r1,|L0.104|
; R1 = pointer to the table
        ADD      r0,r0,r0,LSL #2
; R0 = R0+R0<<2 = R0+R0*4 = month*5
        ADD      r0,r1,r0,LSL #1
; R0 = R1+R0<<2 = pointer to the table + month*5*2 = pointer to the table + month*10
        BX       lr
```

ARM64

Listing 1.260: Optimizing GCC 4.9 ARM64

```
; W0 = month
        sxtw    x0, w0
; X0 = sign-extended input value
        adrp    x1, .LANCHOR1
        add     x1, x1, :lo12:.LANCHOR1
; X1 = pointer to the table
        add     x0, x0, x0, lsl 2
; X0 = X0+X0<<2 = X0+X0*4 = X0*5
        add     x0, x1, x0, lsl 1
; X0 = X1+X0<<1 = X1+X0*2 = pointer to the table + X0*10
        ret
```

SXTW is used for sign-extension and promoting input 32-bit value into a 64-bit one and storing it in X0.

ADRP/ADD pair is used for loading the address of the table.

The ADD instructions also has a LSL suffix, which helps with multiplications.

MIPS

Listing 1.261: Optimizing GCC 4.4.5 (IDA)

```
                .globl get_month2
get_month2:
; $a0=month
                sll     $v0, $a0, 3
; $v0 = $a0<<3 = month*8
                sll     $a0, 1
; $a0 = $a0<<1 = month*2
                addu    $a0, $v0
; $a0 = month*2+month*8 = month*10
; load address of the table:
                la      $v0, month2
; sum up table address and index we calculated and return:
                jr      $ra
                addu    $v0, $a0

month2:         .ascii "January"<0>
```

```
                .byte 0, 0
aFebruary:      .ascii "February"<0>
                .byte    0
aMarch:         .ascii "March"<0>
                .byte 0, 0, 0, 0
aApril:         .ascii "April"<0>
                .byte 0, 0, 0, 0
aMay:           .ascii "May"<0>
                .byte 0, 0, 0, 0, 0, 0
aJune:          .ascii "June"<0>
                .byte 0, 0, 0, 0, 0
aJuly:          .ascii "July"<0>
                .byte 0, 0, 0, 0, 0
aAugust:        .ascii "August"<0>
                .byte 0, 0, 0
aSeptember:     .ascii "September"<0>
aOctober:       .ascii "October"<0>
                .byte 0, 0
aNovember:      .ascii "November"<0>
                .byte    0
aDecember:      .ascii "December"<0>
                .byte 0, 0, 0, 0, 0, 0, 0, 0, 0
```

Conclusion

This is a bit old-school technique to store text strings. You may find a lot of it in Oracle RDBMS, for example. It's hard to say if it's worth doing on modern computers. Nevertheless, it is a good example of arrays, so it was added to this book.

1.20.8 Conclusion

An array is a pack of values in memory located adjacently.

It's true for any element type, including structures.

Access to a specific array element is just a calculation of its address.

1.21 By the way

So, pointer to an array and address of a first element—is the same thing. This is why `ptr[0]` and `*ptr` expressions are equivalent in C/C++. It's interesting to note that Hex-Rays often replaces the first by the second. It does so when it have no idea that it works with pointer to the whole array, and thinks that this is a pointer to single variable.

1.21.1 Exercises

- http://challenges.re/62
- http://challenges.re/63
- http://challenges.re/64
- http://challenges.re/65
- http://challenges.re/66

1.22 Manipulating specific bit(s)

A lot of functions define their input arguments as flags in bit fields.

Of course, they could be substituted by a set of *bool*-typed variables, but it is not frugally.

1.22.1 Specific bit checking

x86

Win32 API example:

```
        HANDLE fh;

        fh=CreateFile ("file", GENERIC_WRITE | GENERIC_READ, FILE_SHARE_READ, NULL, OPEN_ALWAYS↙
    ↳ , FILE_ATTRIBUTE_NORMAL, NULL);
```

We get (MSVC 2010):

Listing 1.262: MSVC 2010

```
        push    0
        push    128             ; 00000080H
        push    4
        push    0
        push    1
        push    -1073741824     ; c0000000H
        push    OFFSET $SG78813
        call    DWORD PTR __imp__CreateFileA@28
        mov     DWORD PTR _fh$[ebp], eax
```

Let's take a look in WinNT.h:

Listing 1.263: WinNT.h

```
#define GENERIC_READ                     (0x80000000L)
#define GENERIC_WRITE                    (0x40000000L)
#define GENERIC_EXECUTE                  (0x20000000L)
#define GENERIC_ALL                      (0x10000000L)
```

Everything is clear, GENERIC_READ | GENERIC_WRITE = 0x80000000 | 0x40000000 = 0xC0000000, and that value is used as the second argument for the `CreateFile()`[145]function.

How would `CreateFile()` check these flags?

If we look in KERNEL32.DLL in Windows XP SP3 x86, we'll find this fragment of code in `CreateFileW`:

Listing 1.264: KERNEL32.DLL (Windows XP SP3 x86)

```
.text:7C83D429     test    byte ptr [ebp+dwDesiredAccess+3], 40h
.text:7C83D42D     mov     [ebp+var_8], 1
.text:7C83D434     jz      short loc_7C83D417
.text:7C83D436     jmp     loc_7C810817
```

Here we see the TEST instruction, however it doesn't take the whole second argument,
but only the most significant byte (ebp+dwDesiredAccess+3) and checks it for flag `0x40` (which implies the `GENERIC_WRITE` flag here).

TEST is basically the same instruction as AND, but without saving the result (recall the fact CMP is merely the same as SUB, but without saving the result (1.9.4 on page 86)).

The logic of this code fragment is as follows:

```
if ((dwDesiredAccess&0x40000000) == 0) goto loc_7C83D417
```

If AND instruction leaves this bit, the ZF flag is to be cleared and the JZ conditional jump is not to be triggered. The conditional jump is triggered only if the `0x40000000` bit is absent in `dwDesiredAccess` variable —then the result of AND is 0, ZF is to be set and the conditional jump is to be triggered.

Let's try GCC 4.4.1 and Linux:

```
#include <stdio.h>
#include <fcntl.h>

void main()
{
```

[145] msdn.microsoft.com/en-us/library/aa363858(VS.85).aspx

```
        int handle;

        handle=open ("file", O_RDWR | O_CREAT);
};
```

We get:

Listing 1.265: GCC 4.4.1

```
                public main
main            proc near

var_20          = dword ptr -20h
var_1C          = dword ptr -1Ch
var_4           = dword ptr -4

                push    ebp
                mov     ebp, esp
                and     esp, 0FFFFFFF0h
                sub     esp, 20h
                mov     [esp+20h+var_1C], 42h
                mov     [esp+20h+var_20], offset aFile ; "file"
                call    _open
                mov     [esp+20h+var_4], eax
                leave
                retn
main            endp
```

If we take a look in the `open()` function in the `libc.so.6` library, it is only a syscall:

Listing 1.266: open() (libc.so.6)

```
.text:000BE69B     mov     edx, [esp+4+mode] ; mode
.text:000BE69F     mov     ecx, [esp+4+flags] ; flags
.text:000BE6A3     mov     ebx, [esp+4+filename] ; filename
.text:000BE6A7     mov     eax, 5
.text:000BE6AC     int     80h              ; LINUX - sys_open
```

So, the bit fields for `open()` are apparently checked somewhere in the Linux kernel.

Of course, it is easy to download both Glibc and the Linux kernel source code, but we are interested in understanding the matter without it.

So, as of Linux 2.6, when the `sys_open` syscall is called, control eventually passes to `do_sys_open`, and from there—to the `do_filp_open()` function (it's located in the kernel source tree in `fs/namei.c`).

N.B. Aside from passing arguments via the stack, there is also a method of passing some of them via registers. This is also called fastcall (6.1.3 on page 735). This works faster since CPU does not need to access the stack in memory to read argument values. GCC has the option *regparm*[146], through which it's possible to set the number of arguments that can be passed via registers.

The Linux 2.6 kernel is compiled with `-mregparm=3` option [147] [148].

What this means to us is that the first 3 arguments are to be passed via registers EAX, EDX and ECX, and the rest via the stack. Of course, if the number of arguments is less than 3, only part of registers set is to be used.

So, let's download Linux Kernel 2.6.31, compile it in Ubuntu: `make vmlinux`, open it in IDA, and find the `do_filp_open()` function. At the beginning, we see (the comments are mine):

Listing 1.267: do_filp_open() (linux kernel 2.6.31)

```
do_filp_open    proc near
...
                push    ebp
                mov     ebp, esp
                push    edi
                push    esi
                push    ebx
```

[146] ohse.de/uwe/articles/gcc-attributes.html#func-regparm
[147] kernelnewbies.org/Linux_2_6_20#head-042c62f290834eb1fe0a1942bbf5bb9a4accbc8f
[148] See also `arch/x86/include/asm/calling.h` file in kernel tree

```
                mov     ebx, ecx
                add     ebx, 1
                sub     esp, 98h
                mov     esi, [ebp+arg_4] ; acc_mode (5th argument)
                test    bl, 3
                mov     [ebp+var_80], eax ; dfd (1th argument)
                mov     [ebp+var_7C], edx ; pathname (2th argument)
                mov     [ebp+var_78], ecx ; open_flag (3th argument)
                jnz     short loc_C01EF684
                mov     ebx, ecx        ; ebx <- open_flag
```

GCC saves the values of the first 3 arguments in the local stack. If that wasn't done, the compiler would not touch these registers, and that would be too tight environment for the compiler's register allocator.

Let's find this fragment of code:

Listing 1.268: do_filp_open() (linux kernel 2.6.31)

```
loc_C01EF6B4:       ; CODE XREF: do_filp_open+4F
                test    bl, 40h         ; O_CREAT
                jnz     loc_C01EF810
                mov     edi, ebx
                shr     edi, 11h
                xor     edi, 1
                and     edi, 1
                test    ebx, 10000h
                jz      short loc_C01EF6D3
                or      edi, 2
```

0x40—is what the O_CREAT macro equals to. open_flag gets checked for the presence of the 0x40 bit, and if this bit is 1, the next JNZ instruction is triggered.

ARM

The O_CREAT bit is checked differently in Linux kernel 3.8.0.

Listing 1.269: linux kernel 3.8.0

```
struct file *do_filp_open(int dfd, struct filename *pathname,
                const struct open_flags *op)
{
...
        filp = path_openat(dfd, pathname, &nd, op, flags | LOOKUP_RCU);
...
}

static struct file *path_openat(int dfd, struct filename *pathname,
                struct nameidata *nd, const struct open_flags *op, int flags)
{
...
        error = do_last(nd, &path, file, op, &opened, pathname);
...
}


static int do_last(struct nameidata *nd, struct path *path,
                   struct file *file, const struct open_flags *op,
                   int *opened, struct filename *name)
{
...
        if (!(open_flag & O_CREAT)) {
    ...
                error = lookup_fast(nd, path, &inode);
    ...
        } else {
    ...
                error = complete_walk(nd);
        }
...
}
```

Here is how the kernel compiled for ARM mode looks in IDA:

Listing 1.270: do_last() from vmlinux (IDA)

```
...
.text:C0169EA8      MOV       R9, R3  ; R3 - (4th argument) open_flag
...
.text:C0169ED4      LDR       R6, [R9] ; R6 - open_flag
...
.text:C0169F68      TST       R6, #0x40 ; jumptable C0169F00 default case
.text:C0169F6C      BNE       loc_C016A128
.text:C0169F70      LDR       R2, [R4,#0x10]
.text:C0169F74      ADD       R12, R4, #8
.text:C0169F78      LDR       R3, [R4,#0xC]
.text:C0169F7C      MOV       R0, R4
.text:C0169F80      STR       R12, [R11,#var_50]
.text:C0169F84      LDRB      R3, [R2,R3]
.text:C0169F88      MOV       R2, R8
.text:C0169F8C      CMP       R3, #0
.text:C0169F90      ORRNE     R1, R1, #3
.text:C0169F94      STRNE     R1, [R4,#0x24]
.text:C0169F98      ANDS      R3, R6, #0x200000
.text:C0169F9C      MOV       R1, R12
.text:C0169FA0      LDRNE     R3, [R4,#0x24]
.text:C0169FA4      ANDNE     R3, R3, #1
.text:C0169FA8      EORNE     R3, R3, #1
.text:C0169FAC      STR       R3, [R11,#var_54]
.text:C0169FB0      SUB       R3, R11, #-var_38
.text:C0169FB4      BL        lookup_fast
...
.text:C016A128 loc_C016A128   ; CODE XREF: do_last.isra.14+DC
.text:C016A128      MOV       R0, R4
.text:C016A12C      BL        complete_walk
...
```

TST is analogous to the TEST instruction in x86. We can "spot" visually this code fragment by the fact the `lookup_fast()` is to be executed in one case and `complete_walk()` in the other. This corresponds to the source code of the `do_last()` function. The O_CREAT macro equals to `0x40` here too.

1.22.2 Setting and clearing specific bits

For example:

```
#include <stdio.h>

#define IS_SET(flag, bit)       ((flag) & (bit))
#define SET_BIT(var, bit)       ((var) |= (bit))
#define REMOVE_BIT(var, bit)    ((var) &= ~(bit))

int f(int a)
{
    int rt=a;

    SET_BIT (rt, 0x4000);
    REMOVE_BIT (rt, 0x200);

    return rt;
};

int main()
{
    f(0x12340678);
};
```

x86

Non-optimizing MSVC

We get (MSVC 2010):

Listing 1.271: MSVC 2010

```
_rt$ = -4         ; size = 4
_a$ = 8           ; size = 4
_f  PROC
    push   ebp
    mov    ebp, esp
    push   ecx
    mov    eax, DWORD PTR _a$[ebp]
    mov    DWORD PTR _rt$[ebp], eax
    mov    ecx, DWORD PTR _rt$[ebp]
    or     ecx, 16384                ; 00004000H
    mov    DWORD PTR _rt$[ebp], ecx
    mov    edx, DWORD PTR _rt$[ebp]
    and    edx, -513                ; fffffdffH
    mov    DWORD PTR _rt$[ebp], edx
    mov    eax, DWORD PTR _rt$[ebp]
    mov    esp, ebp
    pop    ebp
    ret    0
_f  ENDP
```

The OR instruction sets one bit into a register while ignoring other 1 bits.

AND resets one bit. It can be said that AND just copies all bits except one. Indeed, in the second AND operand only the bits that need to be saved are set, just the one do not want to copy is not (which is 0 in the bitmask). It is the easier way to memorize the logic.

OllyDbg

Let's try this example in OllyDbg.

First, let's see the binary form of the constants we are going to use:

`0x200` (0b00000000000000000000001000000000) (i.e., the 10th bit (counting from 1st)).

Inverted `0x200` is `0xFFFFFDFF` (0b11111111111111111111110111111111).

`0x4000` (0b00000000000000000100000000000000) (i.e., the 15th bit).

The input value is: `0x12340678` (0b10010001101000000011001111000). We see how it's loaded:

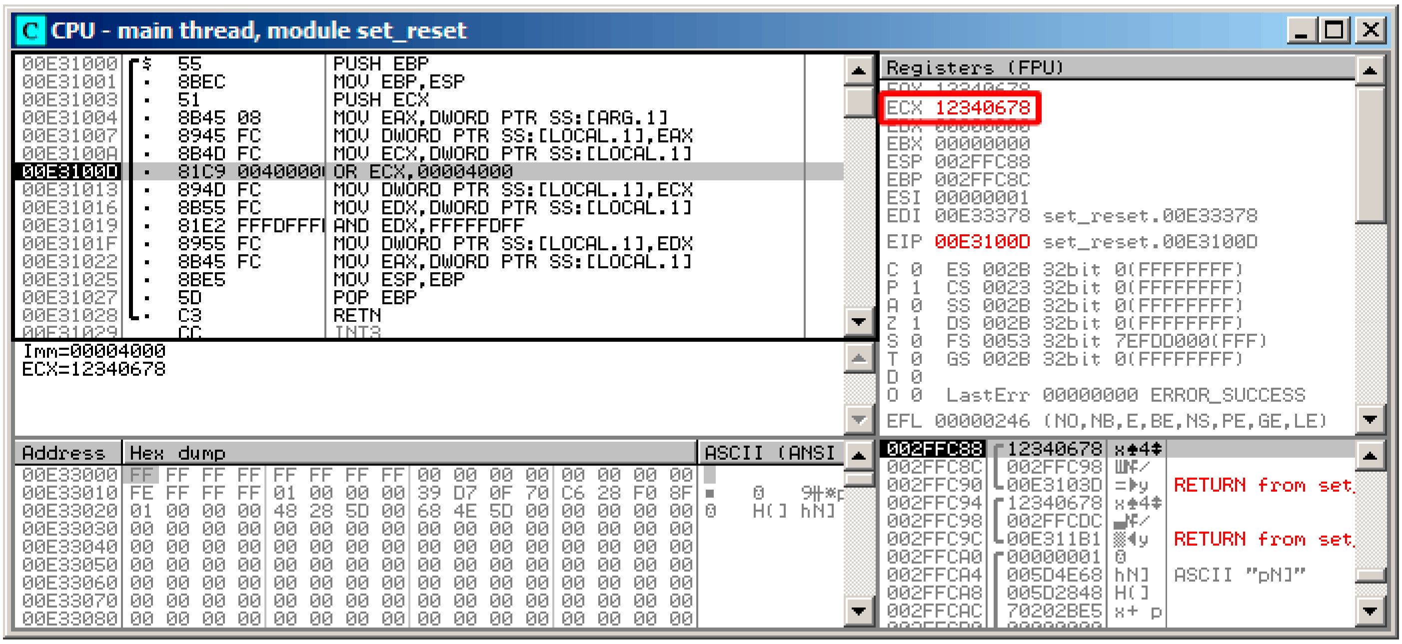


Figure 1.94: OllyDbg: value is loaded into ECX

OR got executed:

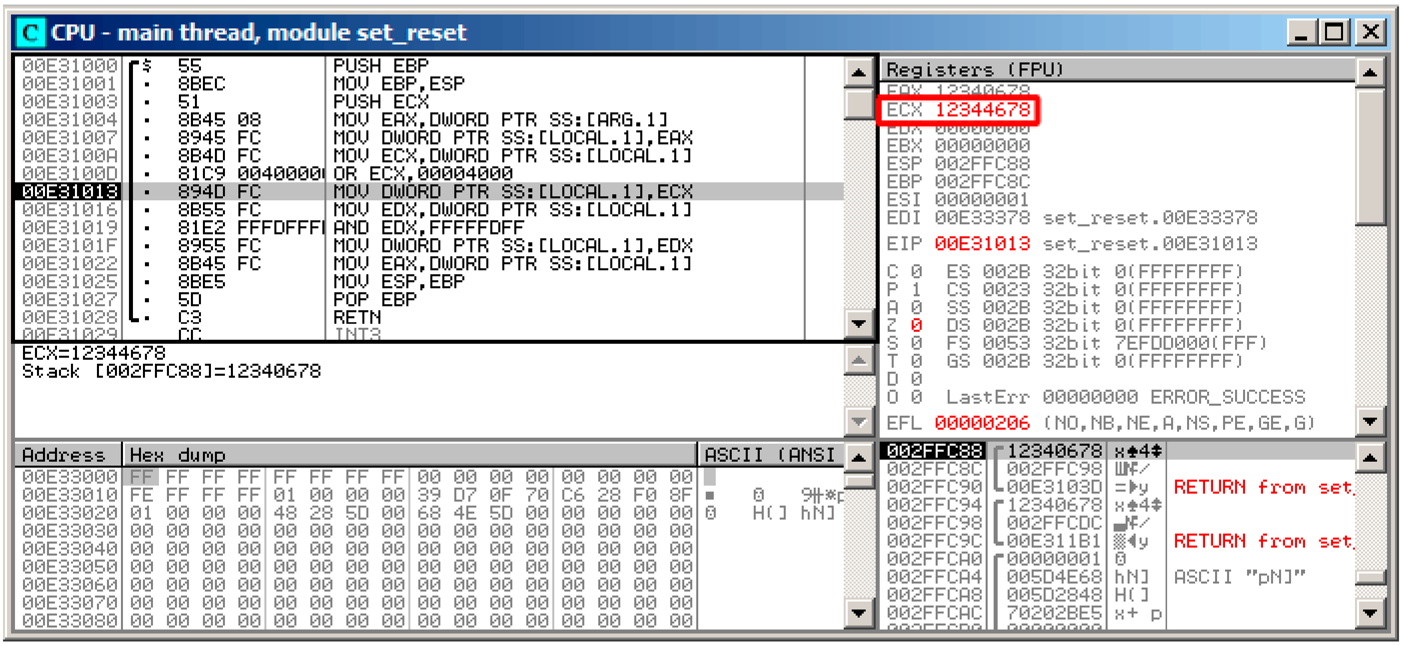


Figure 1.95: OllyDbg: OR executed

15th bit is set: 0x12344678 (0b10010001101000100011001111000).

The value is reloaded again (because the compiler is not in optimizing mode):

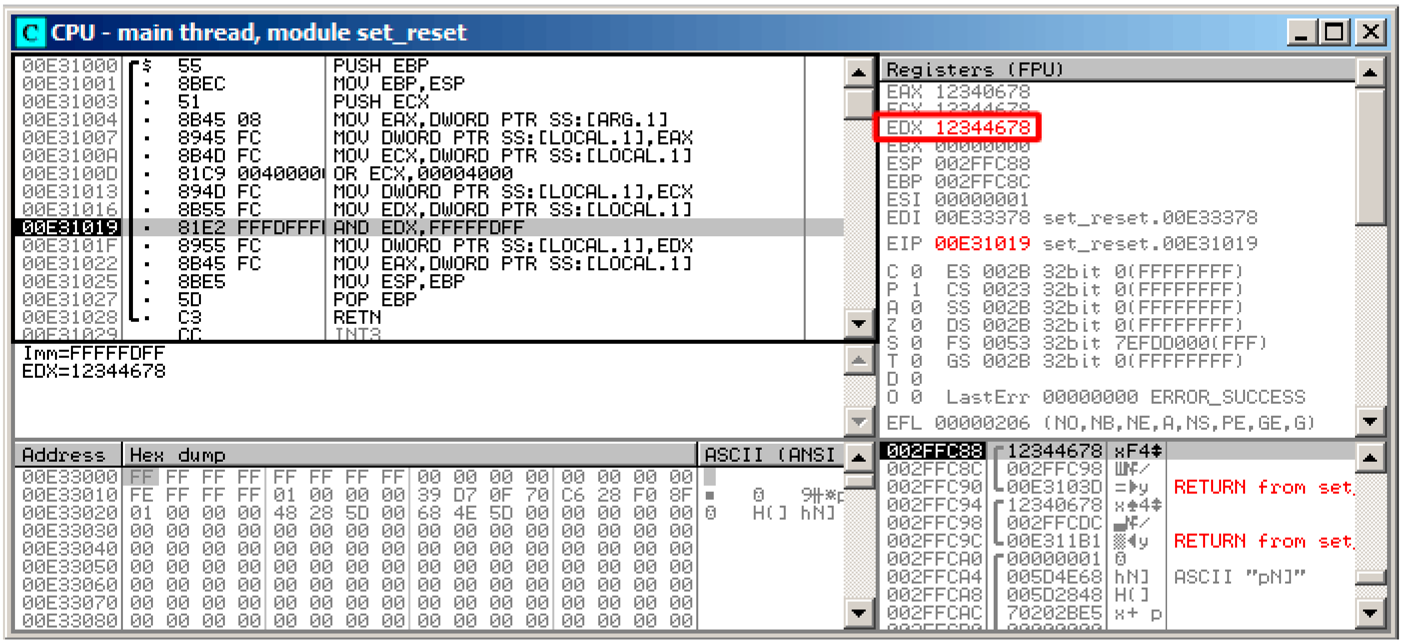


Figure 1.96: OllyDbg: value has been reloaded into EDX

AND got executed:

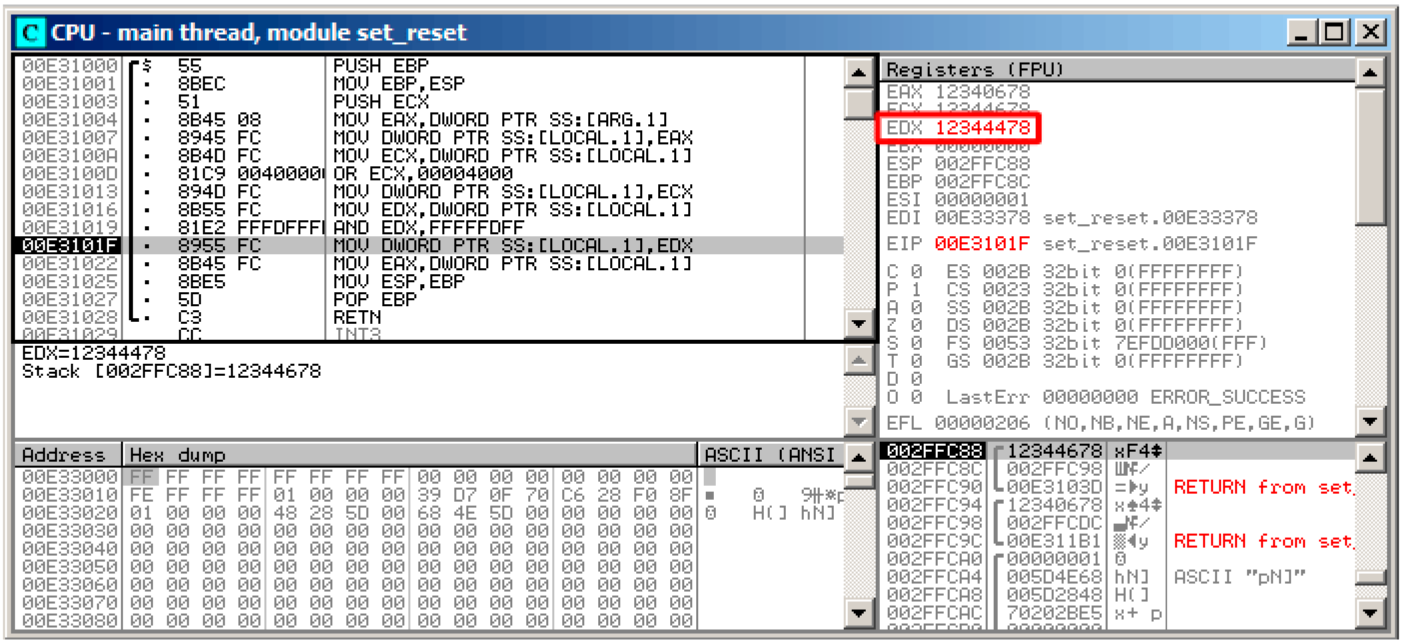


Figure 1.97: OllyDbg: AND executed

The 10th bit has been cleared (or, in other words, all bits were left except the 10th) and the final value now is
0x12344478 (0b10010001101000100010001111000).

Optimizing MSVC

If we compile it in MSVC with optimization turned on (/Ox), the code is even shorter:

Listing 1.272: Optimizing MSVC

```
_a$ = 8                         ; size = 4
_f    PROC
    mov     eax, DWORD PTR _a$[esp-4]
    and     eax, -513           ; fffffdffH
    or      eax, 16384          ; 00004000H
    ret     0
_f    ENDP
```

Non-optimizing GCC

Let's try GCC 4.4.1 without optimization:

Listing 1.273: Non-optimizing GCC

```
                public f
f               proc near

var_4           = dword ptr -4
arg_0           = dword ptr  8

                push    ebp
                mov     ebp, esp
                sub     esp, 10h
                mov     eax, [ebp+arg_0]
                mov     [ebp+var_4], eax
                or      [ebp+var_4], 4000h
                and     [ebp+var_4], 0FFFFFDFFh
                mov     eax, [ebp+var_4]
```

```
                leave
                retn
f               endp
```

There is a redundant code present, however, it is shorter than the MSVC version without optimization.

Now let's try GCC with optimization turned on `-O3`:

Optimizing GCC

Listing 1.274: Optimizing GCC

```
                public f
f               proc near

arg_0           = dword ptr  8

                push    ebp
                mov     ebp, esp
                mov     eax, [ebp+arg_0]
                pop     ebp
                or      ah, 40h
                and     ah, 0FDh
                retn
f               endp
```

That's shorter. It is worth noting the compiler works with the EAX register part via the AH register—that is the EAX register part from the 8th to the 15th bits included.

<table>
<tr><td colspan="8">Byte number:</td></tr>
<tr><td>7th</td><td>6th</td><td>5th</td><td>4th</td><td>3rd</td><td>2nd</td><td>1st</td><td>0th</td></tr>
<tr><td colspan="8">RAX[x64]</td></tr>
<tr><td colspan="4"></td><td colspan="4">EAX</td></tr>
<tr><td colspan="6"></td><td colspan="2">AX</td></tr>
<tr><td colspan="6"></td><td>AH</td><td>AL</td></tr>
</table>

N.B. The 16-bit CPU 8086 accumulator was named AX and consisted of two 8-bit halves—AL (lower byte) and AH (higher byte). In 80386 almost all registers were extended to 32-bit, the accumulator was named EAX, but for the sake of compatibility, its *older parts* may be still accessed as AX/AH/AL.

Since all x86 CPUs are successors of the 16-bit 8086 CPU, these *older* 16-bit opcodes are shorter than the newer 32-bit ones. That's why the `or ah, 40h` instruction occupies only 3 bytes. It would be more logical way to emit here `or eax, 04000h` but that is 5 bytes, or even 6 (in case the register in the first operand is not EAX).

Optimizing GCC and regparm

It would be even shorter if to turn on the `-O3` optimization flag and also set `regparm=3`.

Listing 1.275: Optimizing GCC

```
                public f
f               proc near
                push    ebp
                or      ah, 40h
                mov     ebp, esp
                and     ah, 0FDh
                pop     ebp
                retn
f               endp
```

Indeed, the first argument is already loaded in EAX, so it is possible to work with it in-place. It is worth noting that both the function prologue (`push ebp / mov ebp,esp`) and epilogue (`pop ebp`) can easily be omitted here, but GCC probably is not good enough to do such code size optimizations. However, such short functions are better to be *inlined functions* (3.11 on page 507).

ARM + Optimizing Keil 6/2013 (ARM mode)

Listing 1.276: Optimizing Keil 6/2013 (ARM mode)

```
02 0C C0 E3          BIC     R0, R0, #0x200
01 09 80 E3          ORR     R0, R0, #0x4000
1E FF 2F E1          BX      LR
```

BIC (*BItwise bit Clear*) is an instruction for clearing specific bits. This is just like the AND instruction, but with inverted operand. I.e., it's analogous to a NOT +AND instruction pair.

ORR is "logical or", analogous to OR in x86.

So far it's easy.

ARM + Optimizing Keil 6/2013 (Thumb mode)

Listing 1.277: Optimizing Keil 6/2013 (Thumb mode)

```
01 21 89 03          MOVS    R1, 0x4000
08 43                ORRS    R0, R1
49 11                ASRS    R1, R1, #5   ; generate 0x200 and place to R1
88 43                BICS    R0, R1
70 47                BX      LR
```

Seems like Keil decided that the code in Thumb mode, making 0x200 from 0x4000, is more compact than the code for writing 0x200 to an arbitrary register.

So that is why, with the help of ASRS (arithmetic shift right), this value is calculated as 0x4000 $\gg 5$.

ARM + Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 1.278: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
42 0C C0 E3          BIC             R0, R0, #0x4200
01 09 80 E3          ORR             R0, R0, #0x4000
1E FF 2F E1          BX              LR
```

The code that was generated by LLVM, in source code form could be something like this:

```
    REMOVE_BIT (rt, 0x4200);
    SET_BIT (rt, 0x4000);
```

And it does exactly what we need. But why 0x4200? Perhaps that an artifact from LLVM's optimizer [149].

Probably a compiler's optimizer error, but the generated code works correctly anyway.

You can read more about compiler anomalies here (11.4 on page 1000).

Optimizing Xcode 4.6.3 (LLVM) for Thumb mode generates the same code.

ARM: more about the BIC instruction

Let's rework the example slightly:

```
int f(int a)
{
    int rt=a;

    REMOVE_BIT (rt, 0x1234);

    return rt;
};
```

Then the optimizing Keil 5.03 in ARM mode does:

[149] It was LLVM build 2410.2.00 bundled with Apple Xcode 4.6.3

```
f PROC
        BIC      r0,r0,#0x1000
        BIC      r0,r0,#0x234
        BX       lr
        ENDP
```

There are two BIC instructions, i.e., bits 0x1234 are cleared in two passes.

This is because it's not possible to encode 0x1234 in a BIC instruction, but it's possible to encode 0x1000 and 0x234.

ARM64: Optimizing GCC (Linaro) 4.9

Optimizing GCCcompiling for ARM64 can use the AND instruction instead of BIC:

Listing 1.279: Optimizing GCC (Linaro) 4.9

```
f:
        and     w0, w0, -513    ; 0xFFFFFFFFFFFFFDFF
        orr     w0, w0, 16384   ; 0x4000
        ret
```

ARM64: Non-optimizing GCC (Linaro) 4.9

Non-optimizing GCC generates more redundant code, but works just like optimized:

Listing 1.280: Non-optimizing GCC (Linaro) 4.9

```
f:
        sub     sp, sp, #32
        str     w0, [sp,12]
        ldr     w0, [sp,12]
        str     w0, [sp,28]
        ldr     w0, [sp,28]
        orr     w0, w0, 16384   ; 0x4000
        str     w0, [sp,28]
        ldr     w0, [sp,28]
        and     w0, w0, -513    ; 0xFFFFFFFFFFFFFDFF
        str     w0, [sp,28]
        ldr     w0, [sp,28]
        add     sp, sp, 32
        ret
```

MIPS

Listing 1.281: Optimizing GCC 4.4.5 (IDA)

```
f:
; $a0=a
                ori     $a0, 0x4000
; $a0=a|0x4000
                li      $v0, 0xFFFFFDFF
                jr      $ra
                and     $v0, $a0, $v0
; at finish: $v0 = $a0&$v0 = a|0x4000 & 0xFFFFFDFF
```

ORI is, of course, the OR operation. "I" in the instruction name means that the value is embedded in the machine code.

But after that we have AND. There is no way to use ANDI because it's not possible to embed the 0xFFFFFDFF number in a single instruction, so the compiler has to load 0xFFFFFDFF into register $V0 first and then generates AND which takes all its values from registers.

1.22.3 Shifts

Bit shifts in C/C++ are implemented using $\ll$ and $\gg$ operators. The x86 ISA has the SHL (SHift Left) and SHR (SHift Right) instructions for this. Shift instructions are often used in division and multiplications by powers of two: 2^n (e.g., 1, 2, 4, 8, etc.): 1.18.1 on page 213, 1.18.2 on page 217.

Shifting operations are also so important because they are often used for specific bit isolation or for constructing a value of several scattered bits.

1.22.4 Setting and clearing specific bits: FPU example

Here is how bits are located in the *float* type in IEEE 754 form:

(S—sign)

The sign of number is in the MSB[150]. Will it be possible to change the sign of a floating point number without any FPU instructions?

```
#include <stdio.h>

float my_abs (float i)
{
        unsigned int tmp=(*(unsigned int*)&i) & 0x7FFFFFFF;
        return *(float*)&tmp;
};

float set_sign (float i)
{
        unsigned int tmp=(*(unsigned int*)&i) | 0x80000000;
        return *(float*)&tmp;
};

float negate (float i)
{
        unsigned int tmp=(*(unsigned int*)&i) ^ 0x80000000;
        return *(float*)&tmp;
};

int main()
{
        printf ("my_abs():\n");
        printf ("%f\n", my_abs (123.456));
        printf ("%f\n", my_abs (-456.123));
        printf ("set_sign():\n");
        printf ("%f\n", set_sign (123.456));
        printf ("%f\n", set_sign (-456.123));
        printf ("negate():\n");
        printf ("%f\n", negate (123.456));
        printf ("%f\n", negate (-456.123));
};
```

We need this trickery in C/C++ to copy to/from *float* value without actual conversion. So there are three functions: my_abs() resets MSB; `set_sign()` sets MSB and negate() flips it.

XOR can be used to flip a bit: 2.6 on page 461.

x86

The code is pretty straightforward:

[150] Most Significant Bit

Listing 1.282: Optimizing MSVC 2012

```
_tmp$ = 8
_i$ = 8
_my_abs PROC
        and     DWORD PTR _i$[esp-4], 2147483647 ; 7fffffffH
        fld     DWORD PTR _tmp$[esp-4]
        ret     0
_my_abs ENDP

_tmp$ = 8
_i$ = 8
_set_sign PROC
        or      DWORD PTR _i$[esp-4], -2147483648 ; 80000000H
        fld     DWORD PTR _tmp$[esp-4]
        ret     0
_set_sign ENDP

_tmp$ = 8
_i$ = 8
_negate PROC
        xor     DWORD PTR _i$[esp-4], -2147483648 ; 80000000H
        fld     DWORD PTR _tmp$[esp-4]
        ret     0
_negate ENDP
```

An input value of type *float* is taken from the stack, but treated as an integer value.

AND and OR reset and set the desired bit. XOR flips it.

Finally, the modified value is loaded into ST0, because floating-point numbers are returned in this register.

Now let's try optimizing MSVC 2012 for x64:

Listing 1.283: Optimizing MSVC 2012 x64

```
tmp$ = 8
i$ = 8
my_abs  PROC
        movss   DWORD PTR [rsp+8], xmm0
        mov     eax, DWORD PTR i$[rsp]
        btr     eax, 31
        mov     DWORD PTR tmp$[rsp], eax
        movss   xmm0, DWORD PTR tmp$[rsp]
        ret     0
my_abs  ENDP
_TEXT   ENDS

tmp$ = 8
i$ = 8
set_sign PROC
        movss   DWORD PTR [rsp+8], xmm0
        mov     eax, DWORD PTR i$[rsp]
        bts     eax, 31
        mov     DWORD PTR tmp$[rsp], eax
        movss   xmm0, DWORD PTR tmp$[rsp]
        ret     0
set_sign ENDP

tmp$ = 8
i$ = 8
negate  PROC
        movss   DWORD PTR [rsp+8], xmm0
        mov     eax, DWORD PTR i$[rsp]
        btc     eax, 31
        mov     DWORD PTR tmp$[rsp], eax
        movss   xmm0, DWORD PTR tmp$[rsp]
        ret     0
negate  ENDP
```

The input value is passed in XMM0, then it is copied into the local stack and then we see some instructions that are new to us: BTR, BTS, BTC.

These instructions are used for resetting (BTR), setting (BTS) and inverting (or complementing: BTC) specific bits. The 31st bit is MSB, counting from 0.

Finally, the result is copied into XMM0, because floating point values are returned through XMM0 in Win64 environment.

MIPS

GCC 4.4.5 for MIPS does mostly the same:

Listing 1.284: Optimizing GCC 4.4.5 (IDA)

```
my_abs:
; move from coprocessor 1:
                mfc1    $v1, $f12
                li      $v0, 0x7FFFFFFF
; $v0=0x7FFFFFFF
; do AND:
                and     $v0, $v1
; move to coprocessor 1:
                mtc1    $v0, $f0
; return
                jr      $ra
                or      $at, $zero ; branch delay slot

set_sign:
; move from coprocessor 1:
                mfc1    $v0, $f12
                lui     $v1, 0x8000
; $v1=0x80000000
; do OR:
                or      $v0, $v1, $v0
; move to coprocessor 1:
                mtc1    $v0, $f0
; return
                jr      $ra
                or      $at, $zero ; branch delay slot

negate:
; move from coprocessor 1:
                mfc1    $v0, $f12
                lui     $v1, 0x8000
; $v1=0x80000000
; do XOR:
                xor     $v0, $v1, $v0
; move to coprocessor 1:
                mtc1    $v0, $f0
; return
                jr      $ra
                or      $at, $zero ; branch delay slot
```

One single LUI instruction is used to load 0x80000000 into a register, because LUI is clearing the low 16 bits and these are zeros in the constant, so one LUI without subsequent ORI is enough.

ARM

Optimizing Keil 6/2013 (ARM mode)

Listing 1.285: Optimizing Keil 6/2013 (ARM mode)

```
my_abs PROC
; clear bit:
        BIC      r0,r0,#0x80000000
        BX       lr
        ENDP

set_sign PROC
```

```
; do OR:
        ORR      r0,r0,#0x80000000
        BX       lr
        ENDP

negate PROC
; do XOR:
        EOR      r0,r0,#0x80000000
        BX       lr
        ENDP
```

So far so good.

ARM has the BIC instruction, which explicitly clears specific bit(s). EOR is the ARM instruction name for XOR ("Exclusive OR").

Optimizing Keil 6/2013 (Thumb mode)

Listing 1.286: Optimizing Keil 6/2013 (Thumb mode)

```
my_abs PROC
        LSLS     r0,r0,#1
; r0=i<<1
        LSRS     r0,r0,#1
; r0=(i<<1)>>1
        BX       lr
        ENDP

set_sign PROC
        MOVS     r1,#1
; r1=1
        LSLS     r1,r1,#31
; r1=1<<31=0x80000000
        ORRS     r0,r0,r1
; r0=r0 | 0x80000000
        BX       lr
        ENDP

negate PROC
        MOVS     r1,#1
; r1=1
        LSLS     r1,r1,#31
; r1=1<<31=0x80000000
        EORS     r0,r0,r1
; r0=r0 ^ 0x80000000
        BX       lr
        ENDP
```

Thumb mode in ARM offers 16-bit instructions and not much data can be encoded in them, so here a MOVS/LSLS instruction pair is used for forming the 0x80000000 constant. It works like this: $1 << 31 = 0x80000000$.

The code of my_abs is weird and it effectively works like this expression: $(i << 1) >> 1$. This statement looks meaningless. But nevertheless, when $input << 1$ is executed, the MSB (sign bit) is just dropped. When the subsequent $result >> 1$ statement is executed, all bits are now in their own places, but MSB is zero, because all "new" bits appearing from the shift operations are always zeros. That is how the LSLS/LSRS instruction pair clears MSB.

Optimizing GCC 4.6.3 (Raspberry Pi, ARM mode)

Listing 1.287: Optimizing GCC 4.6.3 for Raspberry Pi (ARM mode)

```
my_abs
; copy from S0 to R2:
                FMRS    R2, S0
; clear bit:
```

```
                BIC     R3, R2, #0x80000000
; copy from R3 to S0:
                FMSR    S0, R3
                BX      LR

set_sign
; copy from S0 to R2:
                FMRS    R2, S0
; do OR:
                ORR     R3, R2, #0x80000000
; copy from R3 to S0:
                FMSR    S0, R3
                BX      LR

negate
; copy from S0 to R2:
                FMRS    R2, S0
; do ADD:
                ADD     R3, R2, #0x80000000
; copy from R3 to S0:
                FMSR    S0, R3
                BX      LR
```

Let's run Raspberry Pi Linux in QEMU and it emulates an ARM FPU, so S-registers are used here for floating point numbers instead of R-registers.

The FMRS instruction copies data from GPR to the FPU and back.

`my_abs()` and `set_sign()` looks as expected, but negate()? Why is there ADD instead of XOR?

It's hard to believe, but the instruction `ADD register, 0x80000000` works just like `XOR register, 0x80000000`. First of all, what's our goal? The goal is to flip the MSB, so let's forget about the XOR operation. From school-level mathematics we may recall that adding values like 1000 to other values never affects the last 3 digits. For example: $1234567 + 10000 = 1244567$ (last 4 digits are never affected).

But here we operate in binary base and 0x80000000 is 0b100000000000000000000000000000000, i.e., only the highest bit is set.

Adding 0x80000000 to any value never affects the lowest 31 bits, but affects only the MSB. Adding 1 to 0 is resulting in 1.

Adding 1 to 1 is resulting in 0b10 in binary form, but the 32th bit (counting from zero) gets dropped, because our registers are 32 bit wide, so the result is 0. That's why XOR can be replaced by ADD here.

It's hard to say why GCC decided to do this, but it works correctly.

1.22.5 Counting bits set to 1

Here is a simple example of a function that calculates the number of bits set in the input value.

This operation is also called "population count"[151].

```
#include <stdio.h>

#define IS_SET(flag, bit)       ((flag) & (bit))

int f(unsigned int a)
{
    int i;
    int rt=0;

    for (i=0; i<32; i++)
        if (IS_SET (a, 1<<i))
            rt++;

    return rt;
};
```

[151]modern x86 CPUs (supporting SSE4) even have a POPCNT instruction for it

```
int main()
{
    f(0x12345678); // test
};
```

In this loop, the iteration count value i is counting from 0 to 31, so the $1 \ll i$ statement is counting from 1 to `0x80000000`. Describing this operation in natural language, we would say *shift 1 by n bits left*. In other words, $1 \ll i$ statement consequently produces all possible bit positions in a 32-bit number. The freed bit at right is always cleared.

Here is a table of all possible $1 \ll i$ for $i = 0 \dots 31$:

C/C++ expression	Power of two	Decimal form	Hexadecimal form
$1 \ll 0$	1	1	1
$1 \ll 1$	2^1	2	2
$1 \ll 2$	2^2	4	4
$1 \ll 3$	2^3	8	8
$1 \ll 4$	2^4	16	0x10
$1 \ll 5$	2^5	32	0x20
$1 \ll 6$	2^6	64	0x40
$1 \ll 7$	2^7	128	0x80
$1 \ll 8$	2^8	256	0x100
$1 \ll 9$	2^9	512	0x200
$1 \ll 10$	2^{10}	1024	0x400
$1 \ll 11$	2^{11}	2048	0x800
$1 \ll 12$	2^{12}	4096	0x1000
$1 \ll 13$	2^{13}	8192	0x2000
$1 \ll 14$	2^{14}	16384	0x4000
$1 \ll 15$	2^{15}	32768	0x8000
$1 \ll 16$	2^{16}	65536	0x10000
$1 \ll 17$	2^{17}	131072	0x20000
$1 \ll 18$	2^{18}	262144	0x40000
$1 \ll 19$	2^{19}	524288	0x80000
$1 \ll 20$	2^{20}	1048576	0x100000
$1 \ll 21$	2^{21}	2097152	0x200000
$1 \ll 22$	2^{22}	4194304	0x400000
$1 \ll 23$	2^{23}	8388608	0x800000
$1 \ll 24$	2^{24}	16777216	0x1000000
$1 \ll 25$	2^{25}	33554432	0x2000000
$1 \ll 26$	2^{26}	67108864	0x4000000
$1 \ll 27$	2^{27}	134217728	0x8000000
$1 \ll 28$	2^{28}	268435456	0x10000000
$1 \ll 29$	2^{29}	536870912	0x20000000
$1 \ll 30$	2^{30}	1073741824	0x40000000
$1 \ll 31$	2^{31}	2147483648	0x80000000

These constant numbers (bit masks) very often appear in code and a practicing reverse engineer must be able to spot them quickly.

Decimal numbers below 63356 and hexadecimal ones are very easy to memorize. While decimal numbers above 65536 are, probably, not worth memorizing.

These constants are very often used for mapping flags to specific bits. For example, here is excerpt from `ssl_private.h` from Apache 2.4.6 source code:

```
/**
 * Define the SSL options
 */
#define SSL_OPT_NONE           (0)
#define SSL_OPT_RELSET         (1<<0)
#define SSL_OPT_STDENVVARS     (1<<1)
#define SSL_OPT_EXPORTCERTDATA (1<<3)
#define SSL_OPT_FAKEBASICAUTH  (1<<4)
#define SSL_OPT_STRICTREQUIRE  (1<<5)
#define SSL_OPT_OPTRENEGOTIATE (1<<6)
#define SSL_OPT_LEGACYDNFORMAT (1<<7)
```

Let’s get back to our example.

The `IS_SET` macro checks bit presence in a.

The IS_SET macro is in fact the logical AND operation (*AND*) and it returns 0 if the specific bit is absent there, or the bit mask, if the bit is present. *The if()* operator in C/C++ triggers if the expression in it is not zero, it might be even 123456, that is why it always works correctly.

x86

MSVC

Let's compile (MSVC 2010):

Listing 1.288: MSVC 2010

```
_rt$ = -8            ; size = 4
_i$ = -4             ; size = 4
_a$ = 8              ; size = 4
_f  PROC
    push   ebp
    mov    ebp, esp
    sub    esp, 8
    mov    DWORD PTR _rt$[ebp], 0
    mov    DWORD PTR _i$[ebp], 0
    jmp    SHORT $LN4@f
$LN3@f:
    mov    eax, DWORD PTR _i$[ebp]   ; increment of i
    add    eax, 1
    mov    DWORD PTR _i$[ebp], eax
$LN4@f:
    cmp    DWORD PTR _i$[ebp], 32    ; 00000020H
    jge    SHORT $LN2@f              ; loop finished?
    mov    edx, 1
    mov    ecx, DWORD PTR _i$[ebp]
    shl    edx, cl                   ; EDX=EDX<<CL
    and    edx, DWORD PTR _a$[ebp]
    je     SHORT $LN1@f              ; result of AND instruction was 0?
                                     ; then skip next instructions
    mov    eax, DWORD PTR _rt$[ebp]  ; no, not zero
    add    eax, 1                    ; increment rt
    mov    DWORD PTR _rt$[ebp], eax
$LN1@f:
    jmp    SHORT $LN3@f
$LN2@f:
    mov    eax, DWORD PTR _rt$[ebp]
    mov    esp, ebp
    pop    ebp
    ret    0
_f    ENDP
```

OllyDbg

Let's load this example into OllyDbg. Let the input value be 0x12345678.

For $i = 1$, we see how i is loaded into ECX:

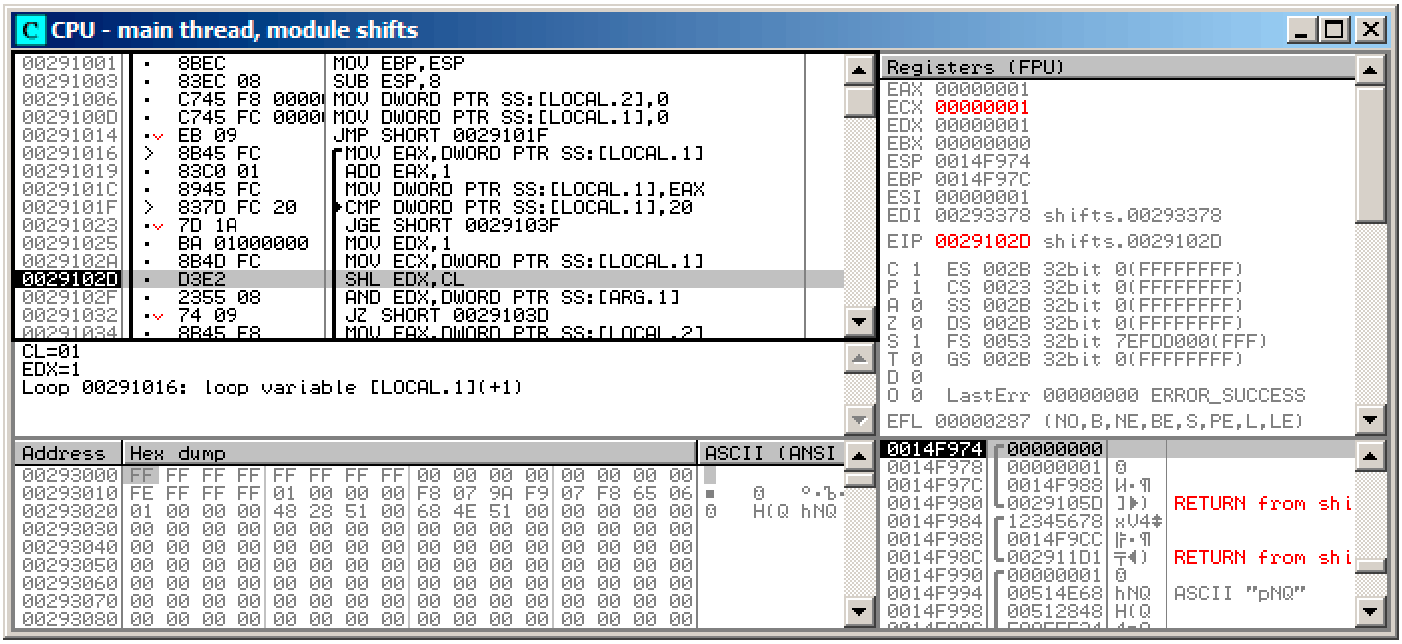


Figure 1.98: OllyDbg: $i = 1$, i is loaded into ECX

EDX is 1. SHL is to be executed now.

SHL has been executed:

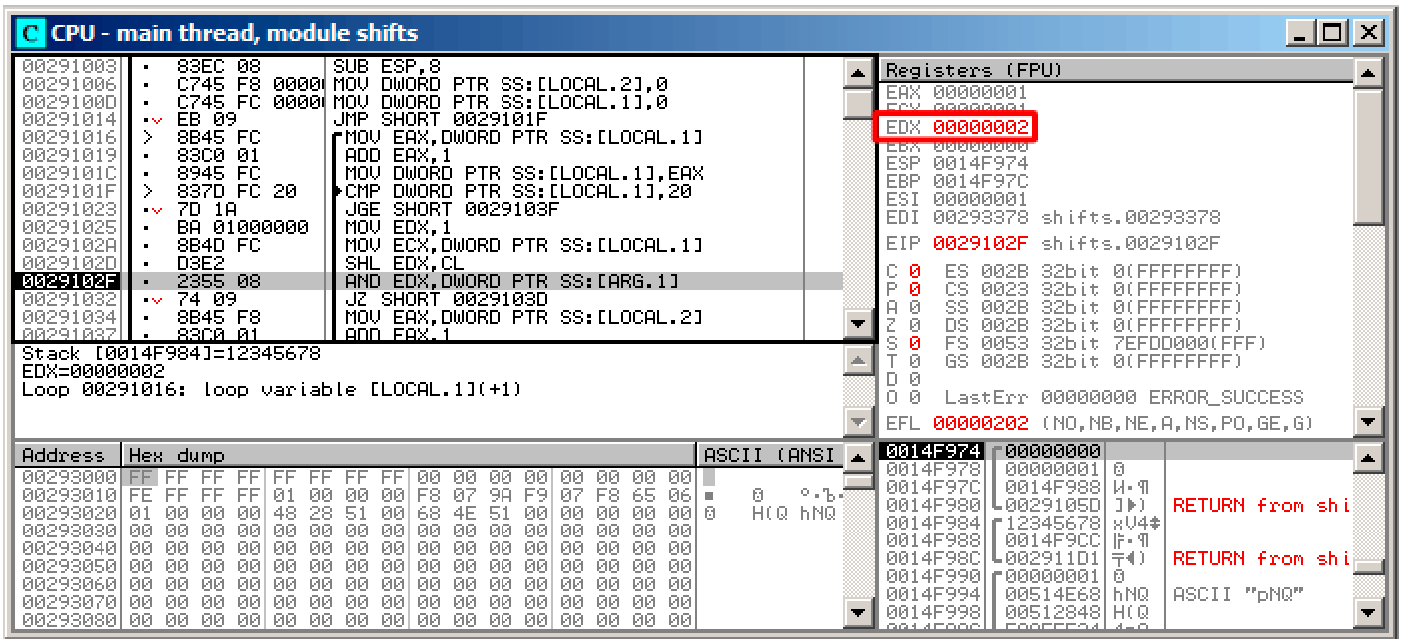


Figure 1.99: OllyDbg: $i = 1$, EDX $= 1 \ll 1 = 2$

EDX contain $1 \ll 1$ (or 2). This is a bit mask.

AND sets ZF to 1, which implies that the input value (0x12345678) ANDed with 2 results in 0:

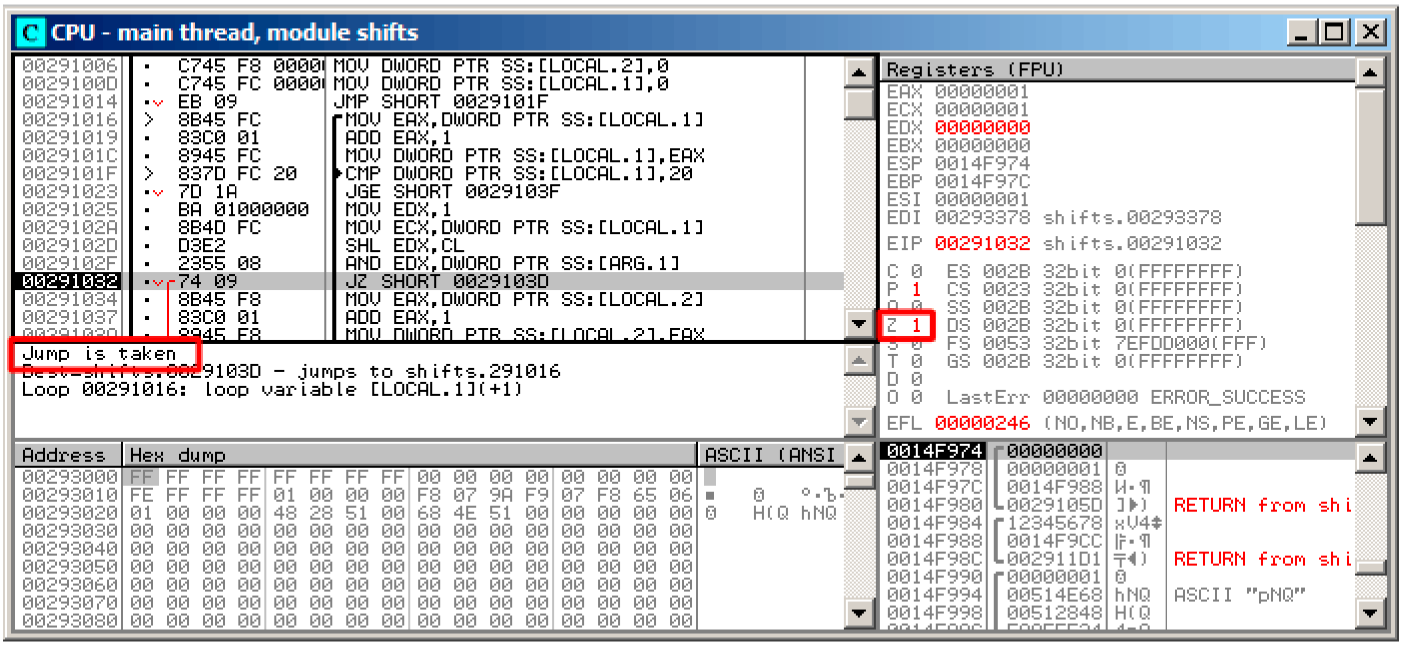


Figure 1.100: OllyDbg: $i = 1$, is there that bit in the input value? No. (ZF =1)

So, there is no corresponding bit in the input value.

The piece of code, which increments the counter is not to be executed: the JZ instruction *bypassing* it.

Let's trace a bit further and i is now 4. SHL is to be executed now:

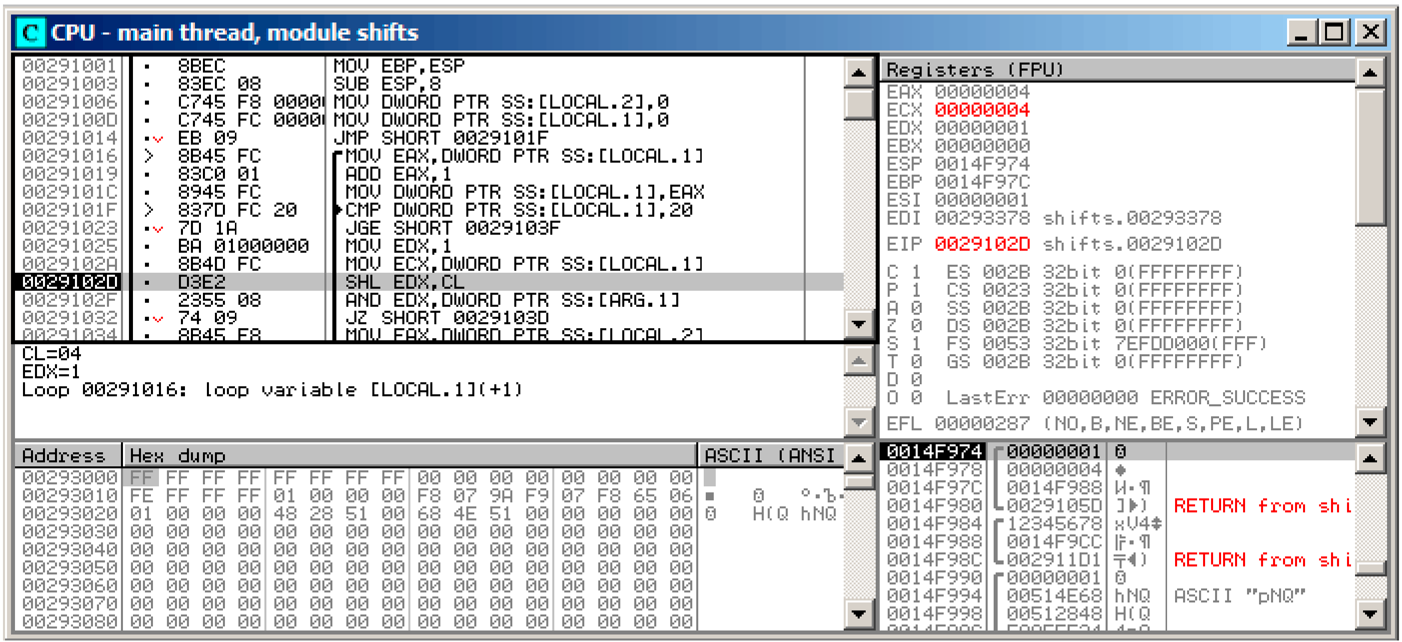


Figure 1.101: OllyDbg: $i = 4$, i is loaded into ECX

EDX $=1 \ll 4$ (or 0x10 or 16):

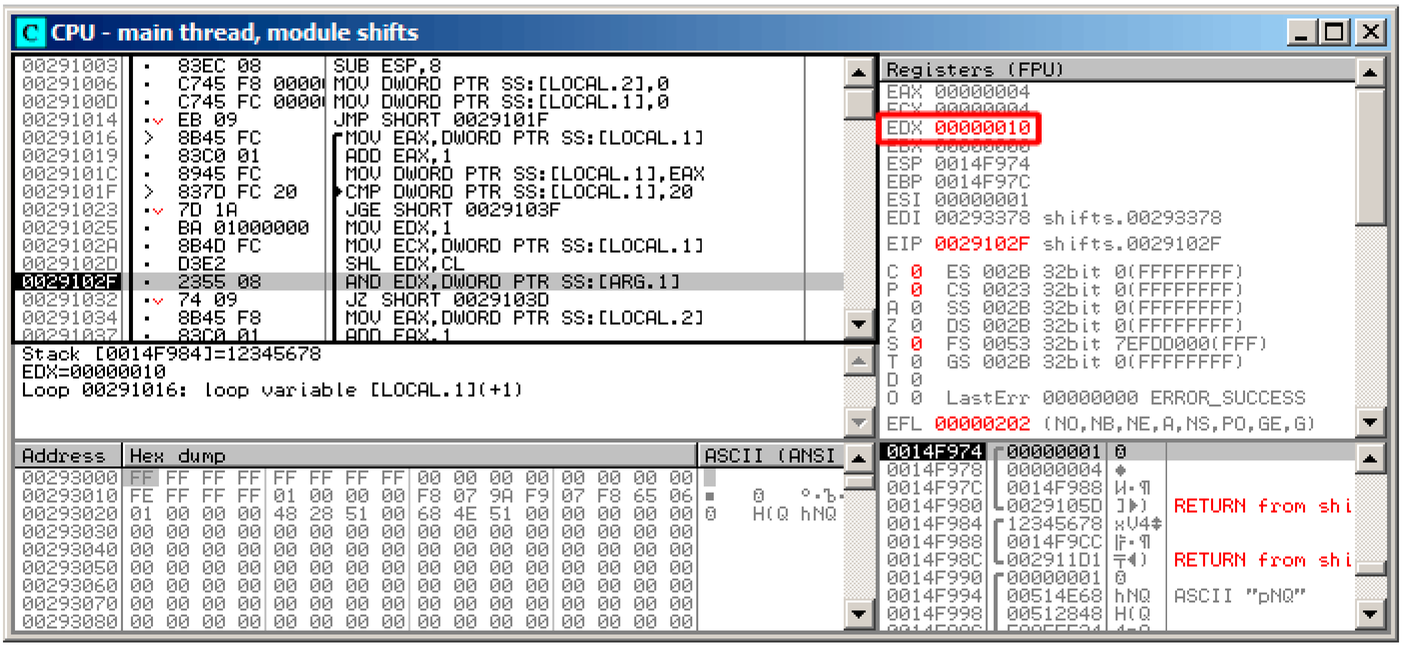


Figure 1.102: OllyDbg: $i = 4$, EDX $=1 \ll 4 = 0x10$

This is another bit mask.

AND is executed:

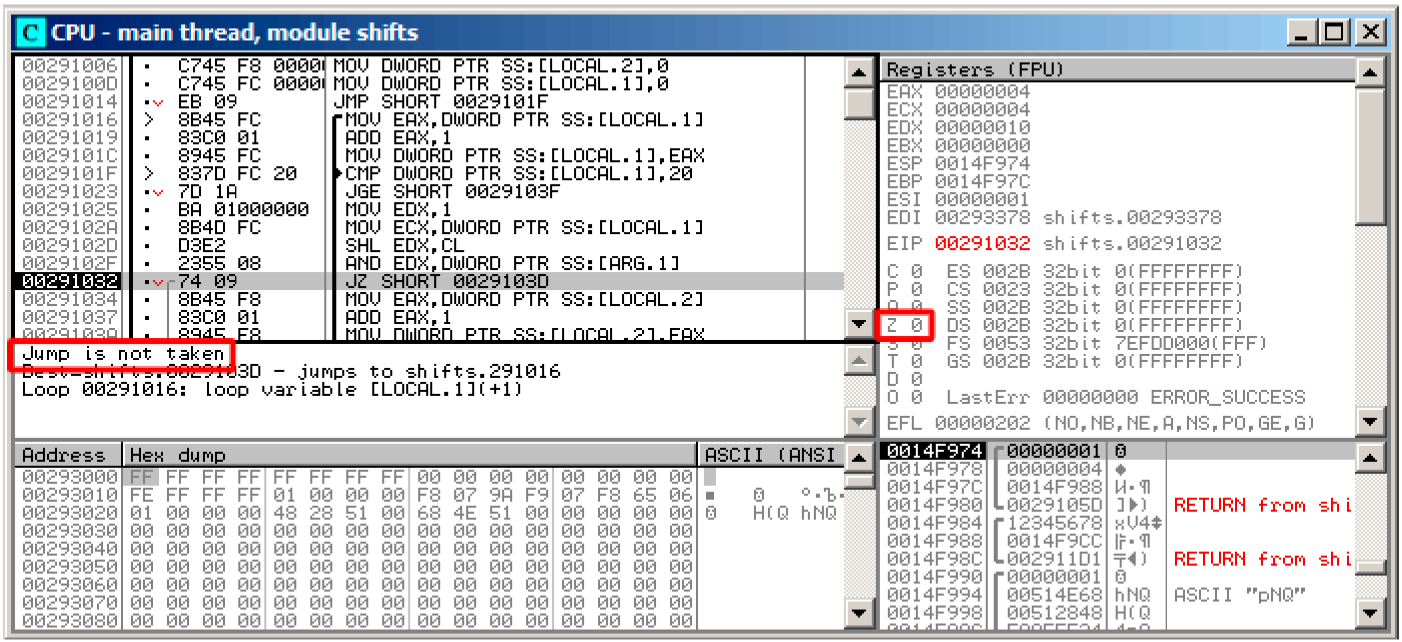


Figure 1.103: OllyDbg: $i = 4$, is there that bit in the input value? Yes. (ZF =0)

ZF is 0 because this bit is present in the input value.
Indeed, 0x12345678 & 0x10 = 0x10.

This bit counts: the jump is not triggering and the bit counter incrementing.

The function returns 13. This is total number of bits set in 0x12345678.

GCC

Let's compile it in GCC 4.4.1:

Listing 1.289: GCC 4.4.1

```
                public f
f               proc near

rt              = dword ptr -0Ch
i               = dword ptr -8
arg_0           = dword ptr  8

                push    ebp
                mov     ebp, esp
                push    ebx
                sub     esp, 10h
                mov     [ebp+rt], 0
                mov     [ebp+i], 0
                jmp     short loc_80483EF
loc_80483D0:
                mov     eax, [ebp+i]
                mov     edx, 1
                mov     ebx, edx
                mov     ecx, eax
                shl     ebx, cl
                mov     eax, ebx
                and     eax, [ebp+arg_0]
                test    eax, eax
                jz      short loc_80483EB
                add     [ebp+rt], 1
loc_80483EB:
                add     [ebp+i], 1
loc_80483EF:
```

```
                cmp     [ebp+i], 1Fh
                jle     short loc_80483D0
                mov     eax, [ebp+rt]
                add     esp, 10h
                pop     ebx
                pop     ebp
                retn
f               endp
```

x64

Let's modify the example slightly to extend it to 64-bit:

```
#include <stdio.h>
#include <stdint.h>

#define IS_SET(flag, bit)       ((flag) & (bit))

int f(uint64_t a)
{
    uint64_t i;
    int rt=0;

    for (i=0; i<64; i++)
        if (IS_SET (a, 1ULL<<i))
            rt++;

    return rt;
};
```

Non-optimizing GCC 4.8.2

So far so easy.

Listing 1.290: Non-optimizing GCC 4.8.2

```
f:
        push    rbp
        mov     rbp, rsp
        mov     QWORD PTR [rbp-24], rdi ; a
        mov     DWORD PTR [rbp-12], 0   ; rt=0
        mov     QWORD PTR [rbp-8], 0    ; i=0
        jmp     .L2
.L4:
        mov     rax, QWORD PTR [rbp-8]
        mov     rdx, QWORD PTR [rbp-24]
; RAX = i, RDX = a
        mov     ecx, eax
; ECX = i
        shr     rdx, cl
; RDX = RDX>>CL = a>>i
        mov     rax, rdx
; RAX = RDX = a>>i
        and     eax, 1
; EAX = EAX&1 = (a>>i)&1
        test    rax, rax
; the last bit is zero?
; skip the next ADD instruction, if it was so.
        je      .L3
        add     DWORD PTR [rbp-12], 1   ; rt++
.L3:
        add     QWORD PTR [rbp-8], 1    ; i++
.L2:
        cmp     QWORD PTR [rbp-8], 63   ; i<63?
        jbe     .L4                     ; jump to the loop body begin, if so
        mov     eax, DWORD PTR [rbp-12] ; return rt
```

```
        pop     rbp
        ret
```

Optimizing GCC 4.8.2

Listing 1.291: Optimizing GCC 4.8.2

```
1  f:
2          xor     eax, eax        ; rt variable will be in EAX register
3          xor     ecx, ecx        ; i variable will be in ECX register
4  .L3:
5          mov     rsi, rdi        ; load input value
6          lea     edx, [rax+1]    ; EDX=EAX+1
7  ; EDX here is a new version of rt,
8  ; which will be written into rt variable, if the last bit is 1
9          shr     rsi, cl         ; RSI=RSI>>CL
10         and     esi, 1          ; ESI=ESI&1
11 ; the last bit is 1? If so, write new version of rt into EAX
12         cmovne  eax, edx
13         add     rcx, 1          ; RCX++
14         cmp     rcx, 64
15         jne     .L3
16         rep ret                 ; AKA fatret
```

This code is terser, but has a quirk.

In all examples that we see so far, we were incrementing the "rt" value after comparing a specific bit, but the code here increments "rt" before (line 6), writing the new value into register EDX. Thus, if the last bit is 1, the CMOVNE[152] instruction (which is a synonym for CMOVNZ[153]) *commits* the new value of "rt" by moving EDX ("proposed rt value") into EAX ("current rt" to be returned at the end).

Hence, the incrementing is performed at each step of loop, i.e., 64 times, without any relation to the input value.

The advantage of this code is that it contain only one conditional jump (at the end of the loop) instead of two jumps (skipping the "rt" value increment and at the end of loop). And that might work faster on the modern CPUs with branch predictors: 2.10.1 on page 466.

The last instruction is REP RET (opcode F3 C3) which is also called FATRET by MSVC. This is somewhat optimized version of RET, which is recommended by AMD to be placed at the end of function, if RET goes right after conditional jump: [[*Software Optimization Guide for AMD Family 16h Processors*, (2013)]p.15] [154].

Optimizing MSVC 2010

Listing 1.292: Optimizing MSVC 2010

```
a$ = 8
f       PROC
; RCX = input value
        xor     eax, eax
        mov     edx, 1
        lea     r8d, QWORD PTR [rax+64]
; R8D=64
        npad    5
$LL4@f:
        test    rdx, rcx
; there are no such bit in input value?
; skip the next INC instruction then.
        je      SHORT $LN3@f
        inc     eax     ; rt++
$LN3@f:
        rol     rdx, 1  ; RDX=RDX<<1
```

[152] Conditional MOVe if Not Equal
[153] Conditional MOVe if Not Zero
[154] More information on it: http://go.yurichev.com/17328

```
        dec     r8      ; R8--
        jne     SHORT $LL4@f
        fatret  0
f       ENDP
```

Here the ROL instruction is used instead of SHL, which is in fact "rotate left" instead of "shift left", but in this example it works just as SHL.

You can read more about the rotate instruction here: .1.6 on page 1034.

R8 here is counting from 64 to 0. It's just like an inverted i.

Here is a table of some registers during the execution:

RDX	R8
0x0000000000000001	64
0x0000000000000002	63
0x0000000000000004	62
0x0000000000000008	61
...	...
0x4000000000000000	2
0x8000000000000000	1

At the end we see the FATRET instruction, which was explained here: 1.22.5 on the previous page.

Optimizing MSVC 2012

Listing 1.293: Optimizing MSVC 2012

```
a$ = 8
f       PROC
; RCX = input value
        xor     eax, eax
        mov     edx, 1
        lea     r8d, QWORD PTR [rax+32]
; EDX = 1, R8D = 32
        npad    5
$LL4@f:
; pass 1 ------------------------------
        test    rdx, rcx
        je      SHORT $LN3@f
        inc     eax     ; rt++
$LN3@f:
        rol     rdx, 1  ; RDX=RDX<<1
; -------------------------------------
; pass 2 ------------------------------
        test    rdx, rcx
        je      SHORT $LN11@f
        inc     eax     ; rt++
$LN11@f:
        rol     rdx, 1  ; RDX=RDX<<1
; -------------------------------------
        dec     r8      ; R8--
        jne     SHORT $LL4@f
        fatret  0
f       ENDP
```

Optimizing MSVC 2012 does almost the same job as optimizing MSVC 2010, but somehow, it generates two identical loop bodies and the loop count is now 32 instead of 64.

To be honest, it's not possible to say why. Some optimization trick? Maybe it's better for the loop body to be slightly longer?

Anyway, such code is relevant here to show that sometimes the compiler output may be really weird and illogical, but perfectly working.

ARM + Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 1.294: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
                MOV             R1, R0
                MOV             R0, #0
                MOV             R2, #1
                MOV             R3, R0
loc_2E54
                TST             R1, R2,LSL R3 ; set flags according to R1 & (R2<<R3)
                ADD             R3, R3, #1    ; R3++
                ADDNE           R0, R0, #1    ; if ZF flag is cleared by TST, then R0++
                CMP             R3, #32
                BNE             loc_2E54
                BX              LR
```

TST is the same things as TEST in x86.

As was noted before (3.9.3 on page 499), there are no separate shifting instructions in ARM mode. However, there are modifiers LSL (*Logical Shift Left*), LSR (*Logical Shift Right*), ASR (*Arithmetic Shift Right*), ROR (*Rotate Right*) and RRX (*Rotate Right with Extend*), which may be added to such instructions as MOV, TST, CMP, ADD, SUB, RSB[155].

These modificators define how to shift the second operand and by how many bits.

Thus the "TST R1, R2,LSL R3" instruction works here as $R1 \wedge (R2 \ll R3)$.

ARM + Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

Almost the same, but here are two LSL.W/TST instructions are used instead of a single TST, because in Thumb mode it is not possible to define LSL modifier directly in TST.

```
                MOV             R1, R0
                MOVS            R0, #0
                MOV.W           R9, #1
                MOVS            R3, #0
loc_2F7A
                LSL.W           R2, R9, R3
                TST             R2, R1
                ADD.W           R3, R3, #1
                IT NE
                ADDNE           R0, #1
                CMP             R3, #32
                BNE             loc_2F7A
                BX              LR
```

ARM64 + Optimizing GCC 4.9

Let's take the 64-bit example which has been already used: 1.22.5 on page 330.

Listing 1.295: Optimizing GCC (Linaro) 4.8

```
f:
        mov     w2, 0           ; rt=0
        mov     x5, 1
        mov     w1, w2
.L2:
        lsl     x4, x5, x1      ; w4 = w5<<w1 = 1<<i
        add     w3, w2, 1       ; new_rt=rt+1
        tst     x4, x0          ; (1<<i) & a
        add     w1, w1, 1       ; i++
; result of TST was non-zero?
; then w2=w3 or rt=new_rt.
; otherwise: w2=w2 or rt=rt (idle operation)
        csel    w2, w3, w2, ne
        cmp     w1, 64          ; i<64?
```

[155]These instructions are also called "data processing instructions"

```
        bne     .L2             ; yes
        mov     w0, w2          ; return rt
        ret
```

The result is very similar to what GCC generates for x64: 1.291 on page 331.

The CSEL instruction is “Conditional SELect”. It just chooses one variable of two depending on the flags set by TST and copies the value into W2, which holds the “rt” variable.

ARM64 + Non-optimizing GCC 4.9

And again, we’ll work on the 64-bit example which was already used: 1.22.5 on page 330. The code is more verbose, as usual.

Listing 1.296: Non-optimizing GCC (Linaro) 4.8

```
f:
        sub     sp, sp, #32
        str     x0, [sp,8]      ; store "a" value to Register Save Area
        str     wzr, [sp,24]    ; rt=0
        str     wzr, [sp,28]    ; i=0
        b       .L2
.L4:
        ldr     w0, [sp,28]
        mov     x1, 1
        lsl     x0, x1, x0      ; X0 = X1<<X0 = 1<<i
        mov     x1, x0
; X1 = 1<<i
        ldr     x0, [sp,8]
; X0 = a
        and     x0, x1, x0
; X0 = X1&X0 = (1<<i) & a
; X0 contain zero? then jump to .L3, skipping "rt" increment
        cmp     x0, xzr
        beq     .L3
; rt++
        ldr     w0, [sp,24]
        add     w0, w0, 1
        str     w0, [sp,24]
.L3:
; i++
        ldr     w0, [sp,28]
        add     w0, w0, 1
        str     w0, [sp,28]
.L2:
; i<=63? then jump to .L4
        ldr     w0, [sp,28]
        cmp     w0, 63
        ble     .L4
; return rt
        ldr     w0, [sp,24]
        add     sp, sp, 32
        ret
```

MIPS

Non-optimizing GCC

Listing 1.297: Non-optimizing GCC 4.4.5 (IDA)

```
f:
; IDA is not aware of variable names, we gave them manually:
rt              = -0x10
i               = -0xC
var_4           = -4
a               =  0
```

```
                addiu   $sp, -0x18
                sw      $fp, 0x18+var_4($sp)
                move    $fp, $sp
                sw      $a0, 0x18+a($fp)
; initialize rt and i variables to zero:
                sw      $zero, 0x18+rt($fp)
                sw      $zero, 0x18+i($fp)
; jump to loop check instructions:
                b       loc_68
                or      $at, $zero ; branch delay slot, NOP

loc_20:
                li      $v1, 1
                lw      $v0, 0x18+i($fp)
                or      $at, $zero ; load delay slot, NOP
                sllv    $v0, $v1, $v0
; $v0 = 1<<i
                move    $v1, $v0
                lw      $v0, 0x18+a($fp)
                or      $at, $zero ; load delay slot, NOP
                and     $v0, $v1, $v0
; $v0 = a&(1<<i)
; is a&(1<<i) equals to zero? jump to loc_58 then:
                beqz    $v0, loc_58
                or      $at, $zero
; no jump occurred, that means a&(1<<i)!=0, so increment "rt" then:
                lw      $v0, 0x18+rt($fp)
                or      $at, $zero ; load delay slot, NOP
                addiu   $v0, 1
                sw      $v0, 0x18+rt($fp)

loc_58:
; increment i:
                lw      $v0, 0x18+i($fp)
                or      $at, $zero ; load delay slot, NOP
                addiu   $v0, 1
                sw      $v0, 0x18+i($fp)

loc_68:
; load i and compare it with 0x20 (32).
; jump to loc_20 if it is less then 0x20 (32):
                lw      $v0, 0x18+i($fp)
                or      $at, $zero ; load delay slot, NOP
                slti    $v0, 0x20  # ' '
                bnez    $v0, loc_20
                or      $at, $zero ; branch delay slot, NOP
; function epilogue. return rt:
                lw      $v0, 0x18+rt($fp)
                move    $sp, $fp   ; load delay slot
                lw      $fp, 0x18+var_4($sp)
                addiu   $sp, 0x18  ; load delay slot
                jr      $ra
                or      $at, $zero ; branch delay slot, NOP
```

That is verbose: all local variables are located in the local stack and reloaded each time they're needed.

The SLLV instruction is "Shift Word Left Logical Variable", it differs from SLL only in that the shift amount is encoded in the SLL instruction (and is fixed, as a consequence), but SLLV takes shift amount from a register.

Optimizing GCC

That is terser. There are two shift instructions instead of one. Why?

It's possible to replace the first SLLV instruction with an unconditional branch instruction that jumps right to the second SLLV. But this is another branching instruction in the function, and it's always favorable to get rid of them: 2.10.1 on page 466.

Listing 1.298: Optimizing GCC 4.4.5 (IDA)

```
f:
; $a0=a
; rt variable will reside in $v0:
                move    $v0, $zero
; i variable will reside in $v1:
                move    $v1, $zero
                li      $t0, 1
                li      $a3, 32
                sllv    $a1, $t0, $v1
; $a1 = $t0<<$v1 = 1<<i

loc_14:
                and     $a1, $a0
; $a1 = a&(1<<i)
; increment i:
                addiu   $v1, 1
; jump to loc_28 if a&(1<<i)==0 and increment rt:
                beqz    $a1, loc_28
                addiu   $a2, $v0, 1
; if BEQZ was not triggered, save updated rt into $v0:
                move    $v0, $a2

loc_28:
; if i!=32, jump to loc_14 and also prepare next shifted value:
                bne     $v1, $a3, loc_14
                sllv    $a1, $t0, $v1
; return
                jr      $ra
                or      $at, $zero ; branch delay slot, NOP
```

1.22.6 Conclusion

Analogous to the C/C++ shifting operators ≪ and ≫, the shift instructions in x86 are SHR/SHL (for unsigned values) and SAR/SHL (for signed values).

The shift instructions in ARM are LSR/LSL (for unsigned values) and ASR/LSL (for signed values).

It's also possible to add shift suffix to some instructions (which are called "data processing instructions").

Check for specific bit (known at compile stage)

Test if the 0b1000000 bit (0x40) is present in the register's value:

Listing 1.299: C/C++

```
if (input&0x40)
    ...
```

Listing 1.300: x86

```
TEST REG, 40h
JNZ is_set
; bit is not set
```

Listing 1.301: x86

```
TEST REG, 40h
JZ is_cleared
; bit is set
```

Listing 1.302: ARM (ARM mode)

```
TST REG, #0x40
BNE is_set
; bit is not set
```

Sometimes, AND is used instead of TEST, but the flags that are set are the same.

Check for specific bit (specified at runtime)

This is usually done by this C/C++ code snippet (shift value by n bits right, then cut off lowest bit):

Listing 1.303: C/C++

```
if ((value>>n)&1)
    ....
```

This is usually implemented in x86 code as:

Listing 1.304: x86

```
; REG=input_value
; CL=n
SHR REG, CL
AND REG, 1
```

Or (shift 1 bit n times left, isolate this bit in input value and check if it's not zero):

Listing 1.305: C/C++

```
if (value & (1<<n))
    ....
```

This is usually implemented in x86 code as:

Listing 1.306: x86

```
; CL=n
MOV REG, 1
SHL REG, CL
AND input_value, REG
```

Set specific bit (known at compile stage)

Listing 1.307: C/C++

```
value=value|0x40;
```

Listing 1.308: x86

```
OR REG, 40h
```

Listing 1.309: ARM (ARM mode) and ARM64

```
ORR R0, R0, #0x40
```

Set specific bit (specified at runtime)

Listing 1.310: C/C++

```
value=value|(1<<n);
```

This is usually implemented in x86 code as:

Listing 1.311: x86

```
; CL=n
MOV REG, 1
SHL REG, CL
OR input_value, REG
```

Clear specific bit (known at compile stage)

Just apply AND operation with the inverted value:

Listing 1.312: C/C++
```
value=value&(~0x40);
```

Listing 1.313: x86
```
AND REG, 0FFFFFFBFh
```

Listing 1.314: x64
```
AND REG, 0FFFFFFFFFFFFFFBFh
```

This is actually leaving all bits set except one.

ARM in ARM mode has BIC instruction, which works like the NOT +AND instruction pair:

Listing 1.315: ARM (ARM mode)
```
BIC R0, R0, #0x40
```

Clear specific bit (specified at runtime)

Listing 1.316: C/C++
```
value=value&(~(1<<n));
```

Listing 1.317: x86
```
; CL=n
MOV REG, 1
SHL REG, CL
NOT REG
AND input_value, REG
```

1.22.7 Exercises

- http://challenges.re/67
- http://challenges.re/68
- http://challenges.re/69
- http://challenges.re/70

1.23 Linear congruential generator as pseudorandom number generator

Perhaps, the linear congruential generator is the simplest possible way to generate random numbers.

It's not in favour nowadays[156], but it's so simple (just one multiplication, one addition and AND operation), that we can use it as an example.

```
#include <stdint.h>

// constants from the Numerical Recipes book
#define RNG_a 1664525
#define RNG_c 1013904223

static uint32_t rand_state;
```

156 Mersenne twister is better

```
void my_srand (uint32_t init)
{
        rand_state=init;
}

int my_rand ()
{
        rand_state=rand_state*RNG_a;
        rand_state=rand_state+RNG_c;
        return rand_state & 0x7fff;
}
```

There are two functions: the first one is used to initialize the internal state, and the second one is called to generate pseudorandom numbers.

We see that two constants are used in the algorithm. They are taken from [William H. Press and Saul A. Teukolsky and William T. Vetterling and Brian P. Flannery, *Numerical Recipes*, (2007)].

Let's define them using a `#define` C/C++ statement. It's a macro.

The difference between a C/C++ macro and a constant is that all macros are replaced with their value by C/C++ preprocessor, and they don't take any memory, unlike variables.

In contrast, a constant is a read-only variable.

It's possible to take a pointer (or address) of a constant variable, but impossible to do so with a macro.

The last AND operation is needed because by C-standard `my_rand()` has to return a value in the 0..32767 range.

If you want to get 32-bit pseudorandom values, just omit the last AND operation.

1.23.1 x86

Listing 1.318: Optimizing MSVC 2013

```
_BSS    SEGMENT
_rand_state DD  01H DUP (?)
_BSS    ENDS

_init$ = 8
_srand  PROC
        mov     eax, DWORD PTR _init$[esp-4]
        mov     DWORD PTR _rand_state, eax
        ret     0
_srand  ENDP

_TEXT   SEGMENT
_rand   PROC
        imul    eax, DWORD PTR _rand_state, 1664525
        add     eax, 1013904223 ; 3c6ef35fH
        mov     DWORD PTR _rand_state, eax
        and     eax, 32767      ; 00007fffH
        ret     0
_rand   ENDP

_TEXT   ENDS
```

Here we see it: both constants are embedded into the code. There is no memory allocated for them.

The `my_srand()` function just copies its input value into the internal `rand_state` variable.

`my_rand()` takes it, calculates the next `rand_state`, cuts it and leaves it in the EAX register.

The non-optimized version is more verbose:

Listing 1.319: Non-optimizing MSVC 2013

```
_BSS    SEGMENT
_rand_state DD  01H DUP (?)
```

```
_BSS    ENDS

_init$ = 8
_srand  PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _init$[ebp]
        mov     DWORD PTR _rand_state, eax
        pop     ebp
        ret     0
_srand  ENDP

_TEXT   SEGMENT
_rand   PROC
        push    ebp
        mov     ebp, esp
        imul    eax, DWORD PTR _rand_state, 1664525
        mov     DWORD PTR _rand_state, eax
        mov     ecx, DWORD PTR _rand_state
        add     ecx, 1013904223 ; 3c6ef35fH
        mov     DWORD PTR _rand_state, ecx
        mov     eax, DWORD PTR _rand_state
        and     eax, 32767      ; 00007fffH
        pop     ebp
        ret     0
_rand   ENDP

_TEXT   ENDS
```

1.23.2 x64

The x64 version is mostly the same and uses 32-bit registers instead of 64-bit ones (because we are working with *int* values here).

But `my_srand()` takes its input argument from the ECX register rather than from stack:

Listing 1.320: Optimizing MSVC 2013 x64

```
_BSS    SEGMENT
rand_state DD   01H DUP (?)
_BSS    ENDS

init$ = 8
my_srand PROC
; ECX = input argument
        mov     DWORD PTR rand_state, ecx
        ret     0
my_srand ENDP

_TEXT   SEGMENT
my_rand PROC
        imul    eax, DWORD PTR rand_state, 1664525 ; 0019660dH
        add     eax, 1013904223 ; 3c6ef35fH
        mov     DWORD PTR rand_state, eax
        and     eax, 32767      ; 00007fffH
        ret     0
my_rand ENDP

_TEXT   ENDS
```

GCC compiler generates mostly the same code.

1.23.3 32-bit ARM

Listing 1.321: Optimizing Keil 6/2013 (ARM mode)

```
my_srand PROC
        LDR      r1,|L0.52|  ; load pointer to rand_state
        STR      r0,[r1,#0]  ; save rand_state
        BX       lr
        ENDP

my_rand PROC
        LDR      r0,|L0.52|  ; load pointer to rand_state
        LDR      r2,|L0.56|  ; load RNG_a
        LDR      r1,[r0,#0]  ; load rand_state
        MUL      r1,r2,r1
        LDR      r2,|L0.60|  ; load RNG_c
        ADD      r1,r1,r2
        STR      r1,[r0,#0]  ; save rand_state
; AND with 0x7FFF:
        LSL      r0,r1,#17
        LSR      r0,r0,#17
        BX       lr
        ENDP

|L0.52|
        DCD      ||.data||
|L0.56|
        DCD      0x0019660d
|L0.60|
        DCD      0x3c6ef35f

        AREA ||.data||, DATA, ALIGN=2

rand_state
        DCD      0x00000000
```

It's not possible to embed 32-bit constants into ARM instructions, so Keil has to place them externally and load them additionally. One interesting thing is that it's not possible to embed the 0x7FFF constant as well. So what Keil does is shifting rand_state left by 17 bits and then shifting it right by 17 bits. This is analogous to the $(rand\_state \ll 17) \gg 17$ statement in C/C++. It seems to be useless operation, but what it does is clearing the high 17 bits, leaving the low 15 bits intact, and that's our goal after all.

Optimizing Keil for Thumb mode generates mostly the same code.

1.23.4 MIPS

Listing 1.322: Optimizing GCC 4.4.5 (IDA)

```
my_srand:
; store $a0 to rand_state:
                lui     $v0, (rand_state >> 16)
                jr      $ra
                sw      $a0, rand_state
my_rand:
; load rand_state to $v0:
                lui     $v1, (rand_state >> 16)
                lw      $v0, rand_state
                or      $at, $zero  ; load delay slot
; multiplicate rand_state in $v0 by 1664525 (RNG_a):
                sll     $a1, $v0, 2
                sll     $a0, $v0, 4
                addu    $a0, $a1, $a0
                sll     $a1, $a0, 6
                subu    $a0, $a1, $a0
                addu    $a0, $v0
                sll     $a1, $a0, 5
                addu    $a0, $a1
                sll     $a0, 3
                addu    $v0, $a0, $v0
                sll     $a0, $v0, 2
                addu    $v0, $a0
; add 1013904223 (RNG_c)
```

```
; the LI instruction is coalesced by IDA from LUI and ORI
                li      $a0, 0x3C6EF35F
                addu    $v0, $a0
; store to rand_state:
                sw      $v0, (rand_state & 0xFFFF)($v1)
                jr      $ra
                andi    $v0, 0x7FFF ; branch delay slot
```

Wow, here we see only one constant (0x3C6EF35F or 1013904223). Where is the other one (1664525)?

It seems that multiplication by 1664525 is performed by just using shifts and additions! Let's check this assumption:

```
#define RNG_a 1664525

int f (int a)
{
        return a*RNG_a;
}
```

Listing 1.323: Optimizing GCC 4.4.5 (IDA)

```
f:
                sll     $v1, $a0, 2
                sll     $v0, $a0, 4
                addu    $v0, $v1, $v0
                sll     $v1, $v0, 6
                subu    $v0, $v1, $v0
                addu    $v0, $a0
                sll     $v1, $v0, 5
                addu    $v0, $v1
                sll     $v0, 3
                addu    $a0, $v0, $a0
                sll     $v0, $a0, 2
                jr      $ra
                addu    $v0, $a0, $v0 ; branch delay slot
```

Indeed!

MIPS relocations

We will also focus on how such operations as load from memory and store to memory actually work.

The listings here are produced by IDA, which hides some details.

We'll run objdump twice: to get a disassembled listing and also relocations list:

Listing 1.324: Optimizing GCC 4.4.5 (objdump)

```
# objdump -D rand_O3.o

...

00000000 <my_srand>:
   0:   3c020000        lui     v0,0x0
   4:   03e00008        jr      ra
   8:   ac440000        sw      a0,0(v0)

0000000c <my_rand>:
   c:   3c030000        lui     v1,0x0
  10:   8c620000        lw      v0,0(v1)
  14:   00200825        move    at,at
  18:   00022880        sll     a1,v0,0x2
  1c:   00022100        sll     a0,v0,0x4
  20:   00a42021        addu    a0,a1,a0
  24:   00042980        sll     a1,a0,0x6
  28:   00a42023        subu    a0,a1,a0
  2c:   00822021        addu    a0,a0,v0
  30:   00042940        sll     a1,a0,0x5
  34:   00852021        addu    a0,a0,a1
```

```
  38:   000420c0        sll     a0,a0,0x3
  3c:   00821021        addu    v0,a0,v0
  40:   00022080        sll     a0,v0,0x2
  44:   00441021        addu    v0,v0,a0
  48:   3c043c6e        lui     a0,0x3c6e
  4c:   3484f35f        ori     a0,a0,0xf35f
  50:   00441021        addu    v0,v0,a0
  54:   ac620000        sw      v0,0(v1)
  58:   03e00008        jr      ra
  5c:   30427fff        andi    v0,v0,0x7fff

...

# objdump -r rand_O3.o

...

RELOCATION RECORDS FOR [.text]:
OFFSET   TYPE              VALUE
00000000 R_MIPS_HI16       .bss
00000008 R_MIPS_LO16       .bss
0000000c R_MIPS_HI16       .bss
00000010 R_MIPS_LO16       .bss
00000054 R_MIPS_LO16       .bss

...
```

Let's consider the two relocations for the my_srand() function.

The first one, for address 0 has a type of R_MIPS_HI16 and the second one for address 8 has a type of R_MIPS_LO16.

That implies that address of the beginning of the .bss segment is to be written into the instructions at address of 0 (high part of address) and 8 (low part of address).

The rand_state variable is at the very start of the .bss segment.

So we see zeros in the operands of instructions LUI and SW, because nothing is there yet— the compiler don't know what to write there.

The linker will fix this, and the high part of the address will be written into the operand of LUI and the low part of the address—to the operand of SW.

SW will sum up the low part of the address and what is in register $V0 (the high part is there).

It's the same story with the my_rand() function: R_MIPS_HI16 relocation instructs the linker to write the high part of the .bss segment address into instruction LUI.

So the high part of the rand_state variable address is residing in register $V1.

The LW instruction at address 0x10 sums up the high and low parts and loads the value of the rand_state variable into $V0.

The SW instruction at address 0x54 do the summing again and then stores the new value to the rand_state global variable.

IDA processes relocations while loading, thus hiding these details, but we should keep them in mind.

1.23.5 Thread-safe version of the example

The thread-safe version of the example is to be demonstrated later: 6.2.1 on page 742.

1.24 Structures

A C/C++ structure, with some assumptions, is just a set of variables, always stored in memory together, not necessary of the same type [157].

[157] AKA "heterogeneous container"

1.24.1 MSVC: SYSTEMTIME example

Let's take the SYSTEMTIME[158] win32 structure that describes time.

This is how it's defined:

Listing 1.325: WinBase.h

```
typedef struct _SYSTEMTIME {
  WORD wYear;
  WORD wMonth;
  WORD wDayOfWeek;
  WORD wDay;
  WORD wHour;
  WORD wMinute;
  WORD wSecond;
  WORD wMilliseconds;
} SYSTEMTIME, *PSYSTEMTIME;
```

Let's write a C function to get the current time:

```
#include <windows.h>
#include <stdio.h>

void main()
{
    SYSTEMTIME t;
    GetSystemTime (&t);

    printf ("%04d-%02d-%02d %02d:%02d:%02d\n",
        t.wYear, t.wMonth, t.wDay,
        t.wHour, t.wMinute, t.wSecond);

    return;
};
```

We get (MSVC 2010):

Listing 1.326: MSVC 2010 /GS-

```
_t$ = -16 ; size = 16
_main      PROC
    push   ebp
    mov    ebp, esp
    sub    esp, 16
    lea    eax, DWORD PTR _t$[ebp]
    push   eax
    call   DWORD PTR __imp__GetSystemTime@4
    movzx  ecx, WORD PTR _t$[ebp+12] ; wSecond
    push   ecx
    movzx  edx, WORD PTR _t$[ebp+10] ; wMinute
    push   edx
    movzx  eax, WORD PTR _t$[ebp+8] ; wHour
    push   eax
    movzx  ecx, WORD PTR _t$[ebp+6] ; wDay
    push   ecx
    movzx  edx, WORD PTR _t$[ebp+2] ; wMonth
    push   edx
    movzx  eax, WORD PTR _t$[ebp] ; wYear
    push   eax
    push   OFFSET $SG78811 ; '%04d-%02d-%02d %02d:%02d:%02d', 0aH, 00H
    call   _printf
    add    esp, 28
    xor    eax, eax
    mov    esp, ebp
    pop    ebp
    ret    0
_main      ENDP
```

[158] MSDN: SYSTEMTIME structure

16 bytes are allocated for this structure in the local stack —that is exactly `sizeof(WORD)*8` (there are 8 WORD variables in the structure).

Pay attention to the fact that the structure begins with the `wYear` field. It can be said that a pointer to the SYSTEMTIME structure is passed to the `GetSystemTime()`[159], but it is also can be said that a pointer to the `wYear` field is passed, and that is the same! `GetSystemTime()` writes the current year to the WORD pointer pointing to, then shifts 2 bytes ahead, writes current month, etc., etc.

[159] MSDN: SYSTEMTIME structure

OllyDbg

Let's compile this example in MSVC 2010 with `/GS- /MD` keys and run it in OllyDbg.

Let's open windows for data and stack at the address which is passed as the first argument of the `GetSystemTime()` function, and let's wait until it's executed. We see this:

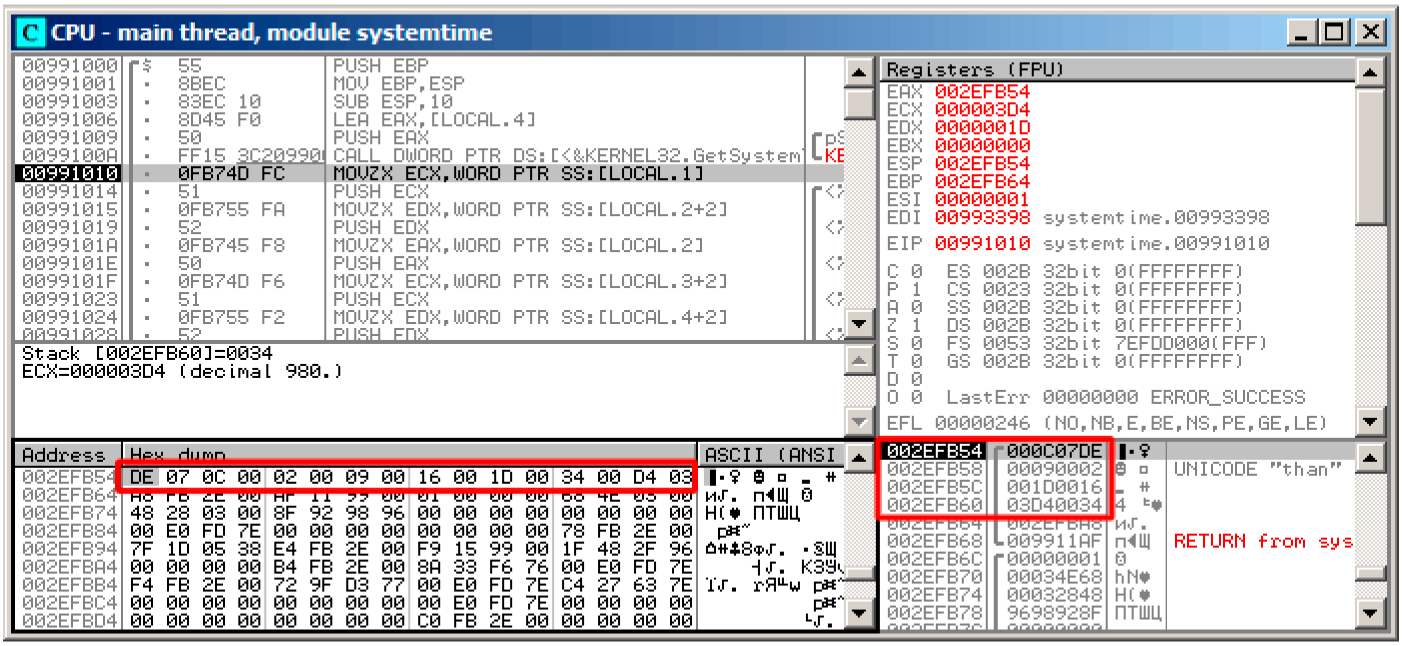


Figure 1.104: OllyDbg: `GetSystemTime()` just executed

The system time of the function execution on my computer is 9 December 2014, 22:29:52:

Listing 1.327: `printf()` output

```
2014-12-09 22:29:52
```

So we see these 16 bytes in the data window:

```
DE 07 0C 00 02 00 09 00 16 00 1D 00 34 00 D4 03
```

Each two bytes represent one field of the structure. Since the endianness is *little endian*, we see the low byte first and then the high one.

Hence, these are the values currently stored in memory:

Hexadecimal number	decimal number	field name
0x07DE	2014	wYear
0x000C	12	wMonth
0x0002	2	wDayOfWeek
0x0009	9	wDay
0x0016	22	wHour
0x001D	29	wMinute
0x0034	52	wSecond
0x03D4	980	wMilliseconds

The same values are seen in the stack window, but they are grouped as 32-bit values.

And then `printf()` just takes the values it needs and outputs them to the console.

Some values aren't output by `printf()` (`wDayOfWeek` and `wMilliseconds`), but they are in memory right now, available for use.

Replacing the structure with array

The fact that the structure fields are just variables located side-by-side, can be easily demonstrated by doing the following. Keeping in mind the `SYSTEMTIME` structure description, it's possible to rewrite this simple example like this:

```
#include <windows.h>
#include <stdio.h>

void main()
{
    WORD array[8];
    GetSystemTime (array);

    printf ("%04d-%02d-%02d %02d:%02d:%02d\n",
        array[0] /* wYear */, array[1] /* wMonth */, array[3] /* wDay */,
        array[4] /* wHour */, array[5] /* wMinute */, array[6] /* wSecond */);

    return;
};
```

The compiler grumbles a bit:

```
systemtime2.c(7) : warning C4133: 'function' : incompatible types - from 'WORD [8]' to '↙
    ↘ LPSYSTEMTIME'
```

But nevertheless, it produces this code:

Listing 1.328: Non-optimizing MSVC 2010

```
$SG78573 DB     '%04d-%02d-%02d %02d:%02d:%02d', 0aH, 00H

_array$ = -16   ; size = 16
_main   PROC
        push    ebp
        mov     ebp, esp
        sub     esp, 16
        lea     eax, DWORD PTR _array$[ebp]
        push    eax
        call    DWORD PTR __imp__GetSystemTime@4
        movzx   ecx, WORD PTR _array$[ebp+12] ; wSecond
        push    ecx
        movzx   edx, WORD PTR _array$[ebp+10] ; wMinute
        push    edx
        movzx   eax, WORD PTR _array$[ebp+8] ; wHoure
        push    eax
        movzx   ecx, WORD PTR _array$[ebp+6] ; wDay
        push    ecx
        movzx   edx, WORD PTR _array$[ebp+2] ; wMonth
        push    edx
        movzx   eax, WORD PTR _array$[ebp] ; wYear
        push    eax
        push    OFFSET $SG78573
        call    _printf
        add     esp, 28
        xor     eax, eax
        mov     esp, ebp
        pop     ebp
        ret     0
_main   ENDP
```

And it works just as the same!

It is very interesting that the result in assembly form cannot be distinguished from the result of the previous compilation.

So by looking at this code, one cannot say for sure if there was a structure declared, or an array.

Nevertheless, no sane person would do it, as it is not convenient.

Also the structure fields may be changed by developers, swapped, etc.

We will not study this example in OllyDbg, because it will be just the same as in the case with the structure.

1.24.2 Let's allocate space for a structure using malloc()

Sometimes it is simpler to place structures not the in local stack, but in the heap:

```
#include <windows.h>
#include <stdio.h>

void main()
{
    SYSTEMTIME *t;

    t=(SYSTEMTIME *)malloc (sizeof (SYSTEMTIME));

    GetSystemTime (t);

    printf ("%04d-%02d-%02d %02d:%02d:%02d\n",
        t->wYear, t->wMonth, t->wDay,
        t->wHour, t->wMinute, t->wSecond);

    free (t);

    return;
};
```

Let's compile it now with optimization (/Ox) so it would be easy to see what we need.

Listing 1.329: Optimizing MSVC

```
_main      PROC
    push   esi
    push   16
    call   _malloc
    add    esp, 4
    mov    esi, eax
    push   esi
    call   DWORD PTR __imp__GetSystemTime@4
    movzx  eax, WORD PTR [esi+12] ; wSecond
    movzx  ecx, WORD PTR [esi+10] ; wMinute
    movzx  edx, WORD PTR [esi+8] ; wHour
    push   eax
    movzx  eax, WORD PTR [esi+6] ; wDay
    push   ecx
    movzx  ecx, WORD PTR [esi+2] ; wMonth
    push   edx
    movzx  edx, WORD PTR [esi] ; wYear
    push   eax
    push   ecx
    push   edx
    push   OFFSET $SG78833
    call   _printf
    push   esi
    call   _free
    add    esp, 32
    xor    eax, eax
    pop    esi
    ret    0
_main      ENDP
```

So, `sizeof(SYSTEMTIME) = 16` and that is exact number of bytes to be allocated by `malloc()`. It returns a pointer to a freshly allocated memory block in the EAX register, which is then moved into the ESI register. `GetSystemTime()` win32 function takes care of saving value in ESI, and that is why it is not saved here and continues to be used after the `GetSystemTime()` call.

New instruction —MOVZX (*Move with Zero eXtend*). It may be used in most cases as MOVSX, but it sets the remaining bits to 0. That's because `printf()` requires a 32-bit *int*, but we got a WORD in the structure — that is 16-bit unsigned type. That's why by copying the value from a WORD into *int*, bits from 16 to 31 must be cleared, because a random noise may be there, which is left from the previous operations on the register(s).

In this example, it's possible to represent the structure as an array of 8 WORDs:

```
#include <windows.h>
#include <stdio.h>

void main()
{
    WORD *t;

    t=(WORD *)malloc (16);

    GetSystemTime (t);

    printf ("%04d-%02d-%02d %02d:%02d:%02d\n",
        t[0] /* wYear */, t[1] /* wMonth */, t[3] /* wDay */,
        t[4] /* wHour */, t[5] /* wMinute */, t[6] /* wSecond */);

    free (t);

    return;
};
```

We get:

Listing 1.330: Optimizing MSVC

```
$SG78594 DB     '%04d-%02d-%02d %02d:%02d:%02d', 0aH, 00H

_main   PROC
        push    esi
        push    16
        call    _malloc
        add     esp, 4
        mov     esi, eax
        push    esi
        call    DWORD PTR __imp__GetSystemTime@4
        movzx   eax, WORD PTR [esi+12]
        movzx   ecx, WORD PTR [esi+10]
        movzx   edx, WORD PTR [esi+8]
        push    eax
        movzx   eax, WORD PTR [esi+6]
        push    ecx
        movzx   ecx, WORD PTR [esi+2]
        push    edx
        movzx   edx, WORD PTR [esi]
        push    eax
        push    ecx
        push    edx
        push    OFFSET $SG78594
        call    _printf
        push    esi
        call    _free
        add     esp, 32
        xor     eax, eax
        pop     esi
        ret     0
_main   ENDP
```

Again, we got the code that cannot be distinguished from the previous one.

And again it has to be noted, you haven't to do this in practice, unless you really know what you are doing.

1.24.3 UNIX: struct tm

Linux

Let's take the `tm` structure from `time.h` in Linux for example:

```
#include <stdio.h>
#include <time.h>
```

```
void main()
{
    struct tm t;
    time_t unix_time;

    unix_time=time(NULL);

    localtime_r (&unix_time, &t);

    printf ("Year: %d\n", t.tm_year+1900);
    printf ("Month: %d\n", t.tm_mon);
    printf ("Day: %d\n", t.tm_mday);
    printf ("Hour: %d\n", t.tm_hour);
    printf ("Minutes: %d\n", t.tm_min);
    printf ("Seconds: %d\n", t.tm_sec);
};
```

Let's compile it in GCC 4.4.1:

Listing 1.331: GCC 4.4.1

```
main proc near
     push    ebp
     mov     ebp, esp
     and     esp, 0FFFFFFF0h
     sub     esp, 40h
     mov     dword ptr [esp], 0 ; first argument for time()
     call    time
     mov     [esp+3Ch], eax
     lea     eax, [esp+3Ch]  ; take pointer to what time() returned
     lea     edx, [esp+10h]  ; at ESP+10h struct tm will begin
     mov     [esp+4], edx    ; pass pointer to the structure begin
     mov     [esp], eax      ; pass pointer to result of time()
     call    localtime_r
     mov     eax, [esp+24h]  ; tm_year
     lea     edx, [eax+76Ch] ; edx=eax+1900
     mov     eax, offset format ; "Year: %d\n"
     mov     [esp+4], edx
     mov     [esp], eax
     call    printf
     mov     edx, [esp+20h]      ; tm_mon
     mov     eax, offset aMonthD ; "Month: %d\n"
     mov     [esp+4], edx
     mov     [esp], eax
     call    printf
     mov     edx, [esp+1Ch]     ; tm_mday
     mov     eax, offset aDayD  ; "Day: %d\n"
     mov     [esp+4], edx
     mov     [esp], eax
     call    printf
     mov     edx, [esp+18h]     ; tm_hour
     mov     eax, offset aHourD ; "Hour: %d\n"
     mov     [esp+4], edx
     mov     [esp], eax
     call    printf
     mov     edx, [esp+14h]        ; tm_min
     mov     eax, offset aMinutesD ; "Minutes: %d\n"
     mov     [esp+4], edx
     mov     [esp], eax
     call    printf
     mov     edx, [esp+10h]
     mov     eax, offset aSecondsD ; "Seconds: %d\n"
     mov     [esp+4], edx          ; tm_sec
     mov     [esp], eax
     call    printf
     leave
     retn
main endp
```

Somehow, IDA did not write the local variables' names in the local stack. But since we already are experienced reverse engineers :-) we may do it without this information in this simple example.

Please also pay attention to the `lea edx, [eax+76Ch]` —this instruction just adds `0x76C` (1900) to value in EAX, but doesn't modify any flags. See also the relevant section about LEA (.1.6 on page 1028).

GDB

Let's try to load the example into GDB [160]:

Listing 1.332: GDB

```
dennis@ubuntuvm:~/polygon$ date
Mon Jun  2 18:10:37 EEST 2014
dennis@ubuntuvm:~/polygon$ gcc GCC_tm.c -o GCC_tm
dennis@ubuntuvm:~/polygon$ gdb GCC_tm
GNU gdb (GDB) 7.6.1-ubuntu
...
Reading symbols from /home/dennis/polygon/GCC_tm...(no debugging symbols found)...done.
(gdb) b printf
Breakpoint 1 at 0x8048330
(gdb) run
Starting program: /home/dennis/polygon/GCC_tm

Breakpoint 1, __printf (format=0x80485c0 "Year: %d\n") at printf.c:29
29      printf.c: No such file or directory.
(gdb) x/20x $esp
0xbffff0dc:     0x080484c3      0x080485c0      0x000007de      0x00000000
0xbffff0ec:     0x08048301      0x538c93ed      0x00000025      0x0000000a
0xbffff0fc:     0x00000012      0x00000002      0x00000005      0x00000072
0xbffff10c:     0x00000001      0x00000098      0x00000001      0x00002a30
0xbffff11c:     0x0804b090      0x08048530      0x00000000      0x00000000
(gdb)
```

We can easily find our structure in the stack. First, let's see how it's defined in *time.h*:

Listing 1.333: time.h

```
struct tm
{
  int   tm_sec;
  int   tm_min;
  int   tm_hour;
  int   tm_mday;
  int   tm_mon;
  int   tm_year;
  int   tm_wday;
  int   tm_yday;
  int   tm_isdst;
};
```

Pay attention that 32-bit *int* is used here instead of WORD in SYSTEMTIME. So, each field occupies 32-bit.

Here are the fields of our structure in the stack:

```
0xbffff0dc:     0x080484c3      0x080485c0      0x000007de      0x00000000
0xbffff0ec:     0x08048301      0x538c93ed      0x00000025 sec  0x0000000a min
0xbffff0fc:     0x00000012 hour 0x00000002 mday 0x00000005 mon  0x00000072 year
0xbffff10c:     0x00000001 wday 0x00000098 yday 0x00000001 isdst0x00002a30
0xbffff11c:     0x0804b090      0x08048530      0x00000000      0x00000000
```

Or as a table:

[160] The *date* result is slightly corrected for demonstration purposes. Of course, it's not possible to run GDB that quickly, in the same second.

Hexadecimal number	decimal number	field name
0x00000025	37	tm_sec
0x0000000a	10	tm_min
0x00000012	18	tm_hour
0x00000002	2	tm_mday
0x00000005	5	tm_mon
0x00000072	114	tm_year
0x00000001	1	tm_wday
0x00000098	152	tm_yday
0x00000001	1	tm_isdst

Just like SYSTEMTIME (1.24.1 on page 344),

there are also other fields available that are not used, like tm_wday, tm_yday, tm_isdst.

ARM

Optimizing Keil 6/2013 (Thumb mode)

Same example:

Listing 1.334: Optimizing Keil 6/2013 (Thumb mode)

```
var_38 = -0x38
var_34 = -0x34
var_30 = -0x30
var_2C = -0x2C
var_28 = -0x28
var_24 = -0x24
timer  = -0xC

       PUSH    {LR}
       MOVS    R0, #0          ; timer
       SUB     SP, SP, #0x34
       BL      time
       STR     R0, [SP,#0x38+timer]
       MOV     R1, SP          ; tp
       ADD     R0, SP, #0x38+timer ; timer
       BL      localtime_r
       LDR     R1, =0x76C
       LDR     R0, [SP,#0x38+var_24]
       ADDS    R1, R0, R1
       ADR     R0, aYearD      ; "Year: %d\n"
       BL      __2printf
       LDR     R1, [SP,#0x38+var_28]
       ADR     R0, aMonthD     ; "Month: %d\n"
       BL      __2printf
       LDR     R1, [SP,#0x38+var_2C]
       ADR     R0, aDayD       ; "Day: %d\n"
       BL      __2printf
       LDR     R1, [SP,#0x38+var_30]
       ADR     R0, aHourD      ; "Hour: %d\n"
       BL      __2printf
       LDR     R1, [SP,#0x38+var_34]
       ADR     R0, aMinutesD   ; "Minutes: %d\n"
       BL      __2printf
       LDR     R1, [SP,#0x38+var_38]
       ADR     R0, aSecondsD   ; "Seconds: %d\n"
       BL      __2printf
       ADD     SP, SP, #0x34
       POP     {PC}
```

Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

IDA "knows" the `tm` structure (because IDA "knows" the types of the arguments of library functions like `localtime_r()`), so it shows here structure elements accesses and their names.

Listing 1.335: Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```
var_38 = -0x38
var_34 = -0x34

       PUSH {R7,LR}
       MOV  R7, SP
       SUB  SP, SP, #0x30
       MOVS R0, #0  ; time_t *
       BLX  _time
       ADD  R1, SP, #0x38+var_34 ; struct tm *
       STR  R0, [SP,#0x38+var_38]
       MOV  R0, SP  ; time_t *
       BLX  _localtime_r
       LDR  R1, [SP,#0x38+var_34.tm_year]
       MOV  R0, 0xF44 ; "Year: %d\n"
       ADD  R0, PC  ; char *
       ADDW R1, R1, #0x76C
       BLX  _printf
       LDR  R1, [SP,#0x38+var_34.tm_mon]
       MOV  R0, 0xF3A ; "Month: %d\n"
       ADD  R0, PC  ; char *
       BLX  _printf
       LDR  R1, [SP,#0x38+var_34.tm_mday]
       MOV  R0, 0xF35 ; "Day: %d\n"
       ADD  R0, PC  ; char *
       BLX  _printf
       LDR  R1, [SP,#0x38+var_34.tm_hour]
       MOV  R0, 0xF2E ; "Hour: %d\n"
       ADD  R0, PC  ; char *
       BLX  _printf
       LDR  R1, [SP,#0x38+var_34.tm_min]
       MOV  R0, 0xF28 ; "Minutes: %d\n"
       ADD  R0, PC  ; char *
       BLX  _printf
       LDR  R1, [SP,#0x38+var_34]
       MOV  R0, 0xF25 ; "Seconds: %d\n"
       ADD  R0, PC  ; char *
       BLX  _printf
       ADD  SP, SP, #0x30
       POP  {R7,PC}

...

00000000 tm        struc ; (sizeof=0x2C, standard type)
00000000 tm_sec    DCD ?
00000004 tm_min    DCD ?
00000008 tm_hour   DCD ?
0000000C tm_mday   DCD ?
00000010 tm_mon    DCD ?
00000014 tm_year   DCD ?
00000018 tm_wday   DCD ?
0000001C tm_yday   DCD ?
00000020 tm_isdst  DCD ?
00000024 tm_gmtoff DCD ?
00000028 tm_zone   DCD ? ; offset
0000002C tm        ends
```

MIPS

Listing 1.336: Optimizing GCC 4.4.5 (IDA)

```
main:

; IDA is not aware of structure field names, we named them manually:

var_40          = -0x40
```

```
var_38          = -0x38
seconds         = -0x34
minutes         = -0x30
hour            = -0x2C
day             = -0x28
month           = -0x24
year            = -0x20
var_4           = -4

                lui     $gp, (__gnu_local_gp >> 16)
                addiu   $sp, -0x50
                la      $gp, (__gnu_local_gp & 0xFFFF)
                sw      $ra, 0x50+var_4($sp)
                sw      $gp, 0x50+var_40($sp)
                lw      $t9, (time & 0xFFFF)($gp)
                or      $at, $zero ; load delay slot, NOP
                jalr    $t9
                move    $a0, $zero ; branch delay slot, NOP
                lw      $gp, 0x50+var_40($sp)
                addiu   $a0, $sp, 0x50+var_38
                lw      $t9, (localtime_r & 0xFFFF)($gp)
                addiu   $a1, $sp, 0x50+seconds
                jalr    $t9
                sw      $v0, 0x50+var_38($sp) ; branch delay slot
                lw      $gp, 0x50+var_40($sp)
                lw      $a1, 0x50+year($sp)
                lw      $t9, (printf & 0xFFFF)($gp)
                la      $a0, $LC0        # "Year: %d\n"
                jalr    $t9
                addiu   $a1, 1900 ; branch delay slot
                lw      $gp, 0x50+var_40($sp)
                lw      $a1, 0x50+month($sp)
                lw      $t9, (printf & 0xFFFF)($gp)
                lui     $a0, ($LC1 >> 16)  # "Month: %d\n"
                jalr    $t9
                la      $a0, ($LC1 & 0xFFFF)  # "Month: %d\n" ; branch delay slot
                lw      $gp, 0x50+var_40($sp)
                lw      $a1, 0x50+day($sp)
                lw      $t9, (printf & 0xFFFF)($gp)
                lui     $a0, ($LC2 >> 16)  # "Day: %d\n"
                jalr    $t9
                la      $a0, ($LC2 & 0xFFFF)  # "Day: %d\n" ; branch delay slot
                lw      $gp, 0x50+var_40($sp)
                lw      $a1, 0x50+hour($sp)
                lw      $t9, (printf & 0xFFFF)($gp)
                lui     $a0, ($LC3 >> 16)  # "Hour: %d\n"
                jalr    $t9
                la      $a0, ($LC3 & 0xFFFF)  # "Hour: %d\n" ; branch delay slot
                lw      $gp, 0x50+var_40($sp)
                lw      $a1, 0x50+minutes($sp)
                lw      $t9, (printf & 0xFFFF)($gp)
                lui     $a0, ($LC4 >> 16)  # "Minutes: %d\n"
                jalr    $t9
                la      $a0, ($LC4 & 0xFFFF)  # "Minutes: %d\n" ; branch delay slot
                lw      $gp, 0x50+var_40($sp)
                lw      $a1, 0x50+seconds($sp)
                lw      $t9, (printf & 0xFFFF)($gp)
                lui     $a0, ($LC5 >> 16)  # "Seconds: %d\n"
                jalr    $t9
                la      $a0, ($LC5 & 0xFFFF)  # "Seconds: %d\n" ; branch delay slot
                lw      $ra, 0x50+var_4($sp)
                or      $at, $zero ; load delay slot, NOP
                jr      $ra
                addiu   $sp, 0x50

$LC0:           .ascii "Year: %d\n"<0>
$LC1:           .ascii "Month: %d\n"<0>
$LC2:           .ascii "Day: %d\n"<0>
$LC3:           .ascii "Hour: %d\n"<0>
$LC4:           .ascii "Minutes: %d\n"<0>
```

```
76 $LC5:           .ascii "Seconds: %d\n"<0>
```

This is an example where the branch delay slots can confuse us.

For example, there is the instruction `addiu $a1, 1900` at line 35 which adds 1900 to the year number.

It's executed before the corresponding JALR at line 34, do not forget about it.

Structure as a set of values

In order to illustrate that the structure is just variables laying side-by-side in one place, let's rework our example while looking at the *tm* structure definition again: listing.1.333.

```
#include <stdio.h>
#include <time.h>

void main()
{
    int tm_sec, tm_min, tm_hour, tm_mday, tm_mon, tm_year, tm_wday, tm_yday, tm_isdst;
    time_t unix_time;

    unix_time=time(NULL);

    localtime_r (&unix_time, &tm_sec);

    printf ("Year: %d\n", tm_year+1900);
    printf ("Month: %d\n", tm_mon);
    printf ("Day: %d\n", tm_mday);
    printf ("Hour: %d\n", tm_hour);
    printf ("Minutes: %d\n", tm_min);
    printf ("Seconds: %d\n", tm_sec);
};
```

N.B. The pointer to the `tm_sec` field is passed into `localtime_r`, i.e., to the first element of the "structure".

The compiler warns us:

Listing 1.337: GCC 4.7.3

```
GCC_tm2.c: In function 'main':
GCC_tm2.c:11:5: warning: passing argument 2 of 'localtime_r' from incompatible pointer type [↙
    ↪ enabled by default]
In file included from GCC_tm2.c:2:0:
/usr/include/time.h:59:12: note: expected 'struct tm *' but argument is of type 'int *'
```

But nevertheless, it generates this:

Listing 1.338: GCC 4.7.3

```
main      proc near

var_30    = dword ptr -30h
var_2C    = dword ptr -2Ch
unix_time = dword ptr -1Ch
tm_sec    = dword ptr -18h
tm_min    = dword ptr -14h
tm_hour   = dword ptr -10h
tm_mday   = dword ptr -0Ch
tm_mon    = dword ptr -8
tm_year   = dword ptr -4

          push    ebp
          mov     ebp, esp
          and     esp, 0FFFFFFF0h
          sub     esp, 30h
          call    __main
          mov     [esp+30h+var_30], 0 ; arg 0
          call    time
          mov     [esp+30h+unix_time], eax
          lea     eax, [esp+30h+tm_sec]
```

```
            mov     [esp+30h+var_2C], eax
            lea     eax, [esp+30h+unix_time]
            mov     [esp+30h+var_30], eax
            call    localtime_r
            mov     eax, [esp+30h+tm_year]
            add     eax, 1900
            mov     [esp+30h+var_2C], eax
            mov     [esp+30h+var_30], offset aYearD ; "Year: %d\n"
            call    printf
            mov     eax, [esp+30h+tm_mon]
            mov     [esp+30h+var_2C], eax
            mov     [esp+30h+var_30], offset aMonthD ; "Month: %d\n"
            call    printf
            mov     eax, [esp+30h+tm_mday]
            mov     [esp+30h+var_2C], eax
            mov     [esp+30h+var_30], offset aDayD ; "Day: %d\n"
            call    printf
            mov     eax, [esp+30h+tm_hour]
            mov     [esp+30h+var_2C], eax
            mov     [esp+30h+var_30], offset aHourD ; "Hour: %d\n"
            call    printf
            mov     eax, [esp+30h+tm_min]
            mov     [esp+30h+var_2C], eax
            mov     [esp+30h+var_30], offset aMinutesD ; "Minutes: %d\n"
            call    printf
            mov     eax, [esp+30h+tm_sec]
            mov     [esp+30h+var_2C], eax
            mov     [esp+30h+var_30], offset aSecondsD ; "Seconds: %d\n"
            call    printf
            leave
            retn
main        endp
```

This code is identical to what we saw previously and it is not possible to say, was it a structure in original source code or just a pack of variables.

And this works. However, it is not recommended to do this in practice.

Usually, non-optimizing compilers allocates variables in the local stack in the same order as they were declared in the function.

Nevertheless, there is no guarantee.

By the way, some other compiler may warn about the `tm_year`, `tm_mon`, `tm_mday`, `tm_hour`, `tm_min` variables, but not `tm_sec` are used without being initialized.

Indeed, the compiler is not aware that these are to be filled by `localtime_r()` function.

We chose this example, since all structure fields are of type *int*.

This would not work if structure fields are 16-bit (WORD), like in the case of the SYSTEMTIME structure—`GetSystemTime()` will fill them incorrectly (because the local variables are aligned on a 32-bit boundary). Read more about it in next section: "Fields packing in structure" (1.24.4 on page 359).

So, a structure is just a pack of variables laying in one place, side-by-side. We could say that the structure is the instruction to the compiler, directing it to hold variables in one place. By the way, in some very early C versions (before 1972), there were no structures at all [Dennis M. Ritchie, *The development of the C language*, (1993)][161].

There is no debugger example here: it is just the same as you already saw.

Structure as an array of 32-bit words

```
#include <stdio.h>
#include <time.h>

void main()
{
```

[161] Also available as http://go.yurichev.com/17264

```
    struct tm t;
    time_t unix_time;
    int i;

    unix_time=time(NULL);

    localtime_r (&unix_time, &t);

    for (i=0; i<9; i++)
    {
        int tmp=((int*)&t)[i];
        printf ("0x%08X (%d)\n", tmp, tmp);
    };
};
```

We just *cast* a pointer to structure to an array of *int*'s. And that works! We run the example at 23:51:45 26-July-2014.

```
0x0000002D (45)
0x00000033 (51)
0x00000017 (23)
0x0000001A (26)
0x00000006 (6)
0x00000072 (114)
0x00000006 (6)
0x000000CE (206)
0x00000001 (1)
```

The variables here are in the same order as they are enumerated in the definition of the structure: 1.333 on page 351.

Here is how it gets compiled:

Listing 1.339: Optimizing GCC 4.8.1

```
main            proc near
                push    ebp
                mov     ebp, esp
                push    esi
                push    ebx
                and     esp, 0FFFFFFF0h
                sub     esp, 40h
                mov     dword ptr [esp], 0 ; timer
                lea     ebx, [esp+14h]
                call    _time
                lea     esi, [esp+38h]
                mov     [esp+4], ebx    ; tp
                mov     [esp+10h], eax
                lea     eax, [esp+10h]
                mov     [esp], eax      ; timer
                call    _localtime_r
                nop
                lea     esi, [esi+0]    ; NOP
loc_80483D8:
; EBX here is pointer to structure, ESI is the pointer to the end of it.
                mov     eax, [ebx]      ; get 32-bit word from array
                add     ebx, 4          ; next field in structure
                mov     dword ptr [esp+4], offset a0x08xD ; "0x%08X (%d)\n"
                mov     dword ptr [esp], 1
                mov     [esp+0Ch], eax  ; pass value to printf()
                mov     [esp+8], eax    ; pass value to printf()
                call    ___printf_chk
                cmp     ebx, esi        ; meet structure end?
                jnz     short loc_80483D8       ; no - load next value then
                lea     esp, [ebp-8]
                pop     ebx
                pop     esi
                pop     ebp
                retn
main            endp
```

Indeed: the space in the local stack is first treated as a structure, and then it's treated as an array.

It's even possible to modify the fields of the structure through this pointer.

And again, it's dubiously hackish way to do things, not recommended for use in production code.

Exercise

As an exercise, try to modify (increase by 1) the current month number, treating the structure as an array.

Structure as an array of bytes

We can go even further. Let's *cast* the pointer to an array of bytes and dump it:

```
#include <stdio.h>
#include <time.h>

void main()
{
    struct tm t;
    time_t unix_time;
    int i, j;

    unix_time=time(NULL);

    localtime_r (&unix_time, &t);

    for (i=0; i<9; i++)
    {
        for (j=0; j<4; j++)
            printf ("0x%02X ", ((unsigned char*)&t)[i*4+j]);
        printf ("\n");
    };
};
```

```
0x2D 0x00 0x00 0x00
0x33 0x00 0x00 0x00
0x17 0x00 0x00 0x00
0x1A 0x00 0x00 0x00
0x06 0x00 0x00 0x00
0x72 0x00 0x00 0x00
0x06 0x00 0x00 0x00
0xCE 0x00 0x00 0x00
0x01 0x00 0x00 0x00
```

We also run this example at 23:51:45 26-July-2014 [162]. The values are just the same as in the previous dump (1.24.3 on the preceding page), and of course, the lowest byte goes first, because this is a little-endian architecture (2.8 on page 464).

Listing 1.340: Optimizing GCC 4.8.1

```
main            proc near
                push    ebp
                mov     ebp, esp
                push    edi
                push    esi
                push    ebx
                and     esp, 0FFFFFFF0h
                sub     esp, 40h
                mov     dword ptr [esp], 0 ; timer
                lea     esi, [esp+14h]
                call    _time
                lea     edi, [esp+38h]  ; struct end
                mov     [esp+4], esi    ; tp
                mov     [esp+10h], eax
```

[162] The time and date are the same for demonstration purposes. Byte values are fixed up.

```
                lea     eax, [esp+10h]
                mov     [esp], eax      ; timer
                call    _localtime_r
                lea     esi, [esi+0]    ; NOP
; ESI here is the pointer to structure in local stack. EDI is the pointer to structure end.
loc_8048408:
                xor     ebx, ebx        ; j=0

loc_804840A:
                movzx   eax, byte ptr [esi+ebx] ; load byte
                add     ebx, 1          ; j=j+1
                mov     dword ptr [esp+4], offset a0x02x ; "0x%02X "
                mov     dword ptr [esp], 1
                mov     [esp+8], eax    ; pass loaded byte to printf()
                call    ___printf_chk
                cmp     ebx, 4
                jnz     short loc_804840A
; print carriage return character (CR)
                mov     dword ptr [esp], 0Ah ; c
                add     esi, 4
                call    _putchar
                cmp     esi, edi        ; meet struct end?
                jnz     short loc_8048408 ; j=0
                lea     esp, [ebp-0Ch]
                pop     ebx
                pop     esi
                pop     edi
                pop     ebp
                retn
main            endp
```

1.24.4 Fields packing in structure

One important thing is fields packing in structures[163].

Let's take a simple example:

```
#include <stdio.h>

struct s
{
    char a;
    int b;
    char c;
    int d;
};

void f(struct s s)
{
    printf ("a=%d; b=%d; c=%d; d=%d\n", s.a, s.b, s.c, s.d);
};

int main()
{
    struct s tmp;
    tmp.a=1;
    tmp.b=2;
    tmp.c=3;
    tmp.d=4;
    f(tmp);
};
```

As we see, we have two *char* fields (each is exactly one byte) and two more —*int* (each — 4 bytes).

[163] See also: Wikipedia: Data structure alignment

x86

This compiles to:

Listing 1.341: MSVC 2012 /GS- /Ob0

```
1  _tmp$ = -16
2  _main    PROC
3      push   ebp
4      mov    ebp, esp
5      sub    esp, 16
6      mov    BYTE PTR _tmp$[ebp], 1     ; set field a
7      mov    DWORD PTR _tmp$[ebp+4], 2  ; set field b
8      mov    BYTE PTR _tmp$[ebp+8], 3   ; set field c
9      mov    DWORD PTR _tmp$[ebp+12], 4 ; set field d
10     sub    esp, 16                    ; allocate place for temporary structure
11     mov    eax, esp
12     mov    ecx, DWORD PTR _tmp$[ebp]  ; copy our structure to the temporary one
13     mov    DWORD PTR [eax], ecx
14     mov    edx, DWORD PTR _tmp$[ebp+4]
15     mov    DWORD PTR [eax+4], edx
16     mov    ecx, DWORD PTR _tmp$[ebp+8]
17     mov    DWORD PTR [eax+8], ecx
18     mov    edx, DWORD PTR _tmp$[ebp+12]
19     mov    DWORD PTR [eax+12], edx
20     call    _f
21     add    esp, 16
22     xor    eax, eax
23     mov    esp, ebp
24     pop    ebp
25     ret    0
26 _main    ENDP
27
28 _s$ = 8 ; size = 16
29 ?f@@YAXUs@@@Z PROC ; f
30     push   ebp
31     mov    ebp, esp
32     mov    eax, DWORD PTR _s$[ebp+12]
33     push   eax
34     movsx  ecx, BYTE PTR _s$[ebp+8]
35     push   ecx
36     mov    edx, DWORD PTR _s$[ebp+4]
37     push   edx
38     movsx  eax, BYTE PTR _s$[ebp]
39     push   eax
40     push   OFFSET $SG3842
41     call   _printf
42     add    esp, 20
43     pop    ebp
44     ret    0
45 ?f@@YAXUs@@@Z ENDP ; f
46 _TEXT    ENDS
```

We pass the structure as a whole, but in fact, as we can see, the structure is being copied to a temporary one (a place in stack is allocated in line 10 for it, and then all 4 fields, one by one, are copied in lines 12 … 19), and then its pointer (address) is to be passed.

The structure is copied because it's not known whether the `f()` function going to modify the structure or not. If it gets changed, then the structure in `main()` has to remain as it has been.

We could use C/C++ pointers, and the resulting code will be almost the same, but without the copying.

As we can see, each field's address is aligned on a 4-byte boundary. That's why each *char* occupies 4 bytes here (like *int*). Why? Because it is easier for the CPU to access memory at aligned addresses and to cache data from it.

However, it is not very economical.

Let's try to compile it with option (`/Zp1`) (*/Zp[n] pack structures on n-byte boundary*).

Listing 1.342: MSVC 2012 /GS- /Zp1

```
_main    PROC
    push   ebp
    mov    ebp, esp
    sub    esp, 12
    mov    BYTE PTR _tmp$[ebp], 1     ; set field a
    mov    DWORD PTR _tmp$[ebp+1], 2  ; set field b
    mov    BYTE PTR _tmp$[ebp+5], 3   ; set field c
    mov    DWORD PTR _tmp$[ebp+6], 4  ; set field d
    sub    esp, 12                    ; allocate place for temporary structure
    mov    eax, esp
    mov    ecx, DWORD PTR _tmp$[ebp]  ; copy 10 bytes
    mov    DWORD PTR [eax], ecx
    mov    edx, DWORD PTR _tmp$[ebp+4]
    mov    DWORD PTR [eax+4], edx
    mov    cx, WORD PTR _tmp$[ebp+8]
    mov    WORD PTR [eax+8], cx
    call    _f
    add    esp, 12
    xor    eax, eax
    mov    esp, ebp
    pop    ebp
    ret    0
_main    ENDP

_TEXT    SEGMENT
_s$ = 8 ; size = 10
?f@@YAXUs@@@Z PROC    ; f
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _s$[ebp+6]
    push   eax
    movsx  ecx, BYTE PTR _s$[ebp+5]
    push   ecx
    mov    edx, DWORD PTR _s$[ebp+1]
    push   edx
    movsx  eax, BYTE PTR _s$[ebp]
    push   eax
    push   OFFSET $SG3842
    call   _printf
    add    esp, 20
    pop    ebp
    ret    0
?f@@YAXUs@@@Z ENDP    ; f
```

Now the structure takes only 10 bytes and each *char* value takes 1 byte. What does it give to us? Size economy. And as drawback —the CPU accessing these fields slower than it could.

The structure is also copied in `main()`. Not field-by-field, but directly 10 bytes, using three pairs of `MOV`. Why not 4?

The compiler decided that it's better to copy 10 bytes using 3 `MOV` pairs than to copy two 32-bit words and two bytes using 4 `MOV` pairs.

By the way, such copy implementation using `MOV` instead of calling the `memcpy()` function is widely used, because it's faster than a call to `memcpy()`—for short blocks, of course: 3.11.1 on page 511.

As it can be easily guessed, if the structure is used in many source and object files, all these must be compiled with the same convention about structures packing.

Aside from MSVC `/Zp` option which sets how to align each structure field, there is also the `#pragma pack` compiler option, which can be defined right in the source code. It is available in both MSVC[164] and GCC[165].

Let's get back to the `SYSTEMTIME` structure that consists of 16-bit fields. How does our compiler know to pack them on 1-byte alignment boundary?

`WinNT.h` file has this:

Listing 1.343: WinNT.h

```
#include "pshpack1.h"
```

[164] MSDN: Working with Packing Structures
[165] Structure-Packing Pragmas

And this:

Listing 1.344: WinNT.h

```
#include "pshpack4.h"                   // 4 byte packing is the default
```

The file PshPack1.h looks like:

Listing 1.345: PshPack1.h

```
#if ! (defined(lint) || defined(RC_INVOKED))
#if ( _MSC_VER >= 800 && !defined(_M_I86)) || defined(_PUSHPOP_SUPPORTED)
#pragma warning(disable:4103)
#if !(defined( MIDL_PASS )) || defined( __midl )
#pragma pack(push,1)
#else
#pragma pack(1)
#endif
#else
#pragma pack(1)
#endif
#endif /* ! (defined(lint) || defined(RC_INVOKED)) */
```

This tell the compiler how to pack the structures defined after `#pragma pack`.

OllyDbg + fields are packed by default

Let's try our example (where the fields are aligned by default (4 bytes)) in OllyDbg:

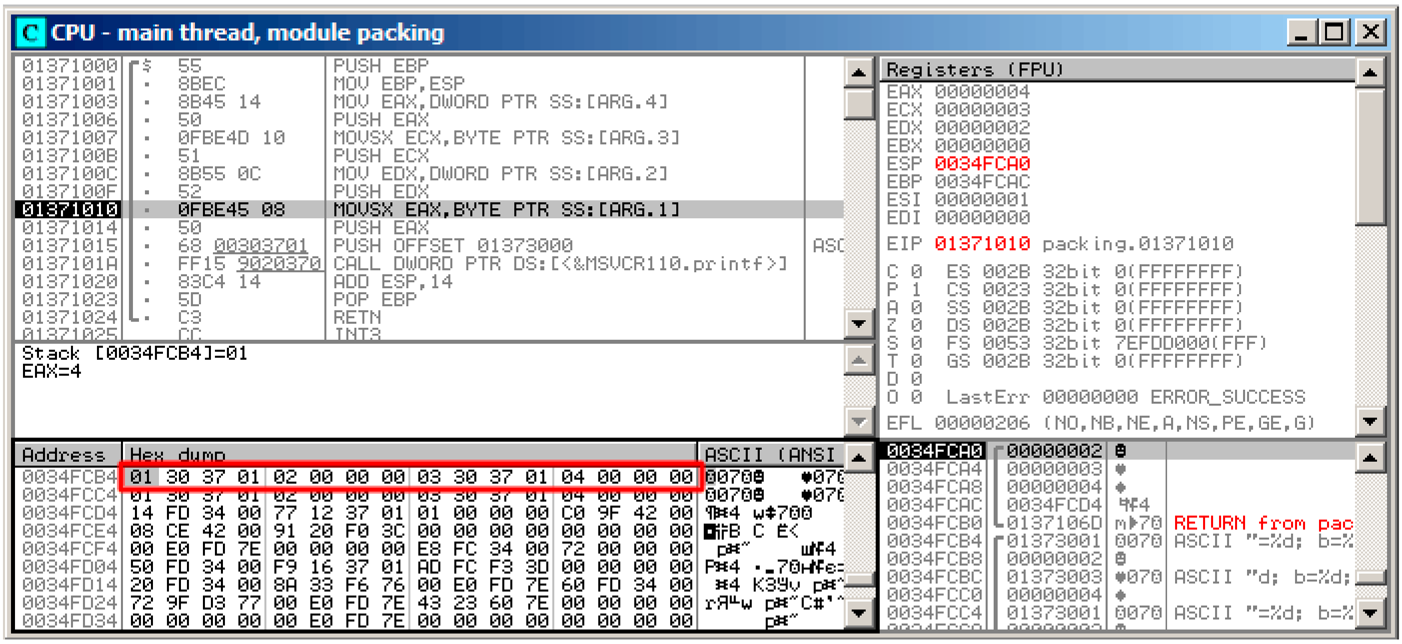


Figure 1.105: OllyDbg: Before `printf()` execution

We see our 4 fields in the data window.

But where do the random bytes (0x30, 0x37, 0x01) come from, that are next to the first (a) and third (c) fields?

By looking at our listing 1.341 on page 360, we can see that the first and third fields are *char*, therefore only one byte is written, 1 and 3 respectively (lines 6 and 8).

The remaining 3 bytes of the 32-bit words are not being modified in memory! Hence, random garbage is left there.

This garbage doesn't influence the `printf()` output in any way, because the values for it are prepared using the `MOVSX` instruction, which takes bytes, not words: listing.1.341 (lines 34 and 38).

By the way, the `MOVSX` (sign-extending) instruction is used here, because *char* is signed by default in MSVC and GCC. If the `unsigned char` data type or `uint8_t` was used here, `MOVZX` instruction would have been used instead.

OllyDbg + fields aligning on 1 byte boundary

Things are much clearer here: 4 fields occupy 10 bytes and the values are stored side-by-side

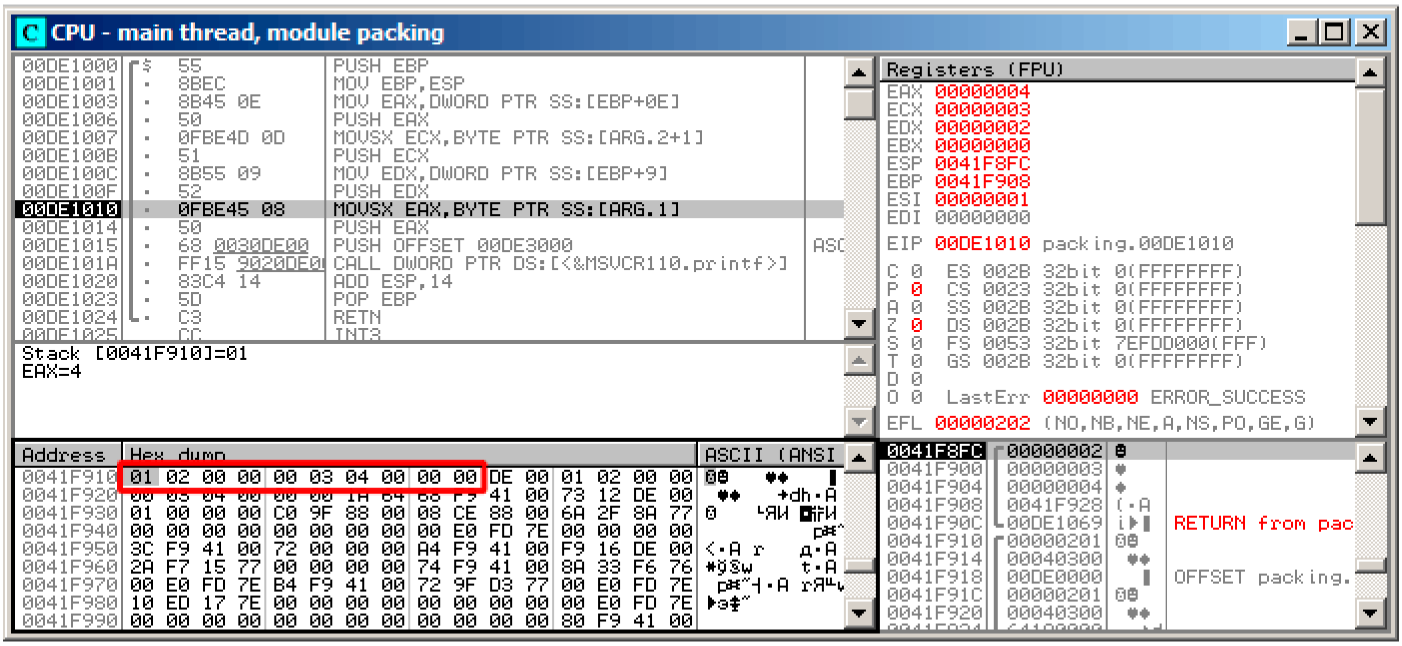


Figure 1.106: OllyDbg: Before `printf()` execution

ARM

Optimizing Keil 6/2013 (Thumb mode)

Listing 1.346: Optimizing Keil 6/2013 (Thumb mode)

```
.text:0000003E             exit ; CODE XREF: f+16
.text:0000003E 05 B0             ADD     SP, SP, #0x14
.text:00000040 00 BD             POP     {PC}


.text:00000280             f
.text:00000280
.text:00000280             var_18 = -0x18
.text:00000280             a      = -0x14
.text:00000280             b      = -0x10
.text:00000280             c      = -0xC
.text:00000280             d      = -8
.text:00000280
.text:00000280 0F B5             PUSH    {R0-R3,LR}
.text:00000282 81 B0             SUB     SP, SP, #4
.text:00000284 04 98             LDR     R0, [SP,#16]    ; d
.text:00000286 02 9A             LDR     R2, [SP,#8]     ; b
.text:00000288 00 90             STR     R0, [SP]
.text:0000028A 68 46             MOV     R0, SP
.text:0000028C 03 7B             LDRB    R3, [R0,#12]    ; c
.text:0000028E 01 79             LDRB    R1, [R0,#4]     ; a
.text:00000290 59 A0             ADR     R0, aADBDCDDD   ; "a=%d; b=%d; c=%d; d=%d\n"
.text:00000292 05 F0 AD FF       BL      __2printf
.text:00000296 D2 E6             B       exit
```

As we may recall, here a structure is passed instead of pointer to one, and since the first 4 function arguments in ARM are passed via registers, the structure's fields are passed via R0-R3.

LDRB loads one byte from memory and extends it to 32-bit, taking its sign into account. This is similar to MOVSX in x86. Here it is used to load fields a and c from the structure.

One more thing we spot easily is that instead of function epilogue, there is jump to another function's epilogue! Indeed, that was quite different function, not related in any way to ours, however, it has exactly the same epilogue (probably because, it hold 5 local variables too ($5 * 4 = 0x14$)).

Also it is located nearby (take a look at the addresses).

Indeed, it doesn't matter which epilogue gets executed, if it works just as we need.

Apparently, Keil decides to reuse a part of another function to economize.

The epilogue takes 4 bytes while jump—only 2.

ARM + Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

Listing 1.347: Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```
var_C = -0xC

      PUSH   {R7,LR}
      MOV    R7, SP
      SUB    SP, SP, #4
      MOV    R9, R1 ; b
      MOV    R1, R0 ; a
      MOVW   R0, #0xF10 ; "a=%d; b=%d; c=%d; d=%d\n"
      SXTB   R1, R1  ; prepare a
      MOVT.W R0, #0
      STR    R3, [SP,#0xC+var_C] ; place d to stack for printf()
      ADD    R0, PC  ; format-string
      SXTB   R3, R2  ; prepare c
      MOV    R2, R9  ; b
      BLX    _printf
      ADD    SP, SP, #4
      POP    {R7,PC}
```

SXTB (*Signed Extend Byte*) is analogous to MOVSX in x86. All the rest—just the same.

MIPS

Listing 1.348: Optimizing GCC 4.4.5 (IDA)

```
f:

var_18          = -0x18
var_10          = -0x10
var_4           = -4
arg_0           =  0
arg_4           =  4
arg_8           =  8
arg_C           =  0xC

; $a0=s.a
; $a1=s.b
; $a2=s.c
; $a3=s.d
                lui     $gp, (__gnu_local_gp >> 16)
                addiu   $sp, -0x28
                la      $gp, (__gnu_local_gp & 0xFFFF)
                sw      $ra, 0x28+var_4($sp)
                sw      $gp, 0x28+var_10($sp)
; prepare byte from 32-bit big-endian integer:
                sra     $t0, $a0, 24
                move    $v1, $a1
; prepare byte from 32-bit big-endian integer:
                sra     $v0, $a2, 24
                lw      $t9, (printf & 0xFFFF)($gp)
                sw      $a0, 0x28+arg_0($sp)
                lui     $a0, ($LC0 >> 16)  # "a=%d; b=%d; c=%d; d=%d\n"
                sw      $a3, 0x28+var_18($sp)
```

```
                sw      $a1, 0x28+arg_4($sp)
                sw      $a2, 0x28+arg_8($sp)
                sw      $a3, 0x28+arg_C($sp)
                la      $a0, ($LC0 & 0xFFFF)  # "a=%d; b=%d; c=%d; d=%d\n"
                move    $a1, $t0
                move    $a2, $v1
                jalr    $t9
                move    $a3, $v0 ; branch delay slot
                lw      $ra, 0x28+var_4($sp)
                or      $at, $zero ; load delay slot, NOP
                jr      $ra
                addiu   $sp, 0x28 ; branch delay slot

$LC0:           .ascii "a=%d; b=%d; c=%d; d=%d\n"<0>
```

Structure fields come in registers $A0..$A3 and then get reshuffled into $A1..$A3 for `printf()`, while 4th field (from $A3) is passed via local stack using SW.

But there are two SRA ("Shift Word Right Arithmetic") instructions, which prepare *char* fields. Why?

MIPS is a big-endian architecture by default 2.8 on page 464, and the Debian Linux we work in is big-endian as well.

So when byte variables are stored in 32-bit structure slots, they occupy the high 31..24 bits.

And when a *char* variable needs to be extended into a 32-bit value, it must be shifted right by 24 bits.

char is a signed type, so an arithmetical shift is used here instead of logical.

One more word

Passing a structure as a function argument (instead of a passing pointer to structure) is the same as passing all structure fields one by one.

If the structure fields are packed by default, the f() function can be rewritten as:

```
void f(char a, int b, char c, int d)
{
    printf ("a=%d; b=%d; c=%d; d=%d\n", a, b, c, d);
};
```

And that leads to the same code.

1.24.5 Nested structures

Now what about situations when one structure is defined inside of another?

```
#include <stdio.h>

struct inner_struct
{
    int a;
    int b;
};

struct outer_struct
{
    char a;
    int b;
    struct inner_struct c;
    char d;
    int e;
};

void f(struct outer_struct s)
{
    printf ("a=%d; b=%d; c.a=%d; c.b=%d; d=%d; e=%d\n",
        s.a, s.b, s.c.a, s.c.b, s.d, s.e);
```

```
};

int main()
{
    struct outer_struct s;
    s.a=1;
    s.b=2;
    s.c.a=100;
    s.c.b=101;
    s.d=3;
    s.e=4;
    f(s);
};
```

…in this case, both `inner_struct` fields are to be placed between the a,b and d,e fields of the `outer_struct`.

Let's compile (MSVC 2010):

Listing 1.349: Optimizing MSVC 2010 /Ob0

```
$SG2802 DB    'a=%d; b=%d; c.a=%d; c.b=%d; d=%d; e=%d', 0aH, 00H

_TEXT    SEGMENT
_s$ = 8
_f    PROC
    mov    eax, DWORD PTR _s$[esp+16]
    movsx  ecx, BYTE PTR _s$[esp+12]
    mov    edx, DWORD PTR _s$[esp+8]
    push   eax
    mov    eax, DWORD PTR _s$[esp+8]
    push   ecx
    mov    ecx, DWORD PTR _s$[esp+8]
    push   edx
    movsx  edx, BYTE PTR _s$[esp+8]
    push   eax
    push   ecx
    push   edx
    push   OFFSET $SG2802 ; 'a=%d; b=%d; c.a=%d; c.b=%d; d=%d; e=%d'
    call   _printf
    add    esp, 28
    ret    0
_f    ENDP

_s$ = -24
_main    PROC
    sub    esp, 24
    push   ebx
    push   esi
    push   edi
    mov    ecx, 2
    sub    esp, 24
    mov    eax, esp
; from this moment, EAX is synonymous to ESP:
    mov    BYTE PTR _s$[esp+60], 1
    mov    ebx, DWORD PTR _s$[esp+60]
    mov    DWORD PTR [eax], ebx
    mov    DWORD PTR [eax+4], ecx
    lea    edx, DWORD PTR [ecx+98]
    lea    esi, DWORD PTR [ecx+99]
    lea    edi, DWORD PTR [ecx+2]
    mov    DWORD PTR [eax+8], edx
    mov    BYTE PTR _s$[esp+76], 3
    mov    ecx, DWORD PTR _s$[esp+76]
    mov    DWORD PTR [eax+12], esi
    mov    DWORD PTR [eax+16], ecx
    mov    DWORD PTR [eax+20], edi
    call   _f
    add    esp, 24
    pop    edi
    pop    esi
    xor    eax, eax
```

```
    pop    ebx
    add    esp, 24
    ret    0
_main    ENDP
```

One curious thing here is that by looking onto this assembly code, we do not even see that another structure was used inside of it! Thus, we would say, nested structures are unfolded into *linear* or *one-dimensional* structure.

Of course, if we replace the `struct inner_struct c;` declaration with `struct inner_struct *c;` (thus making a pointer here) the situation will be quite different.

OllyDbg

Let's load the example into OllyDbg and take a look at `outer_struct` in memory:

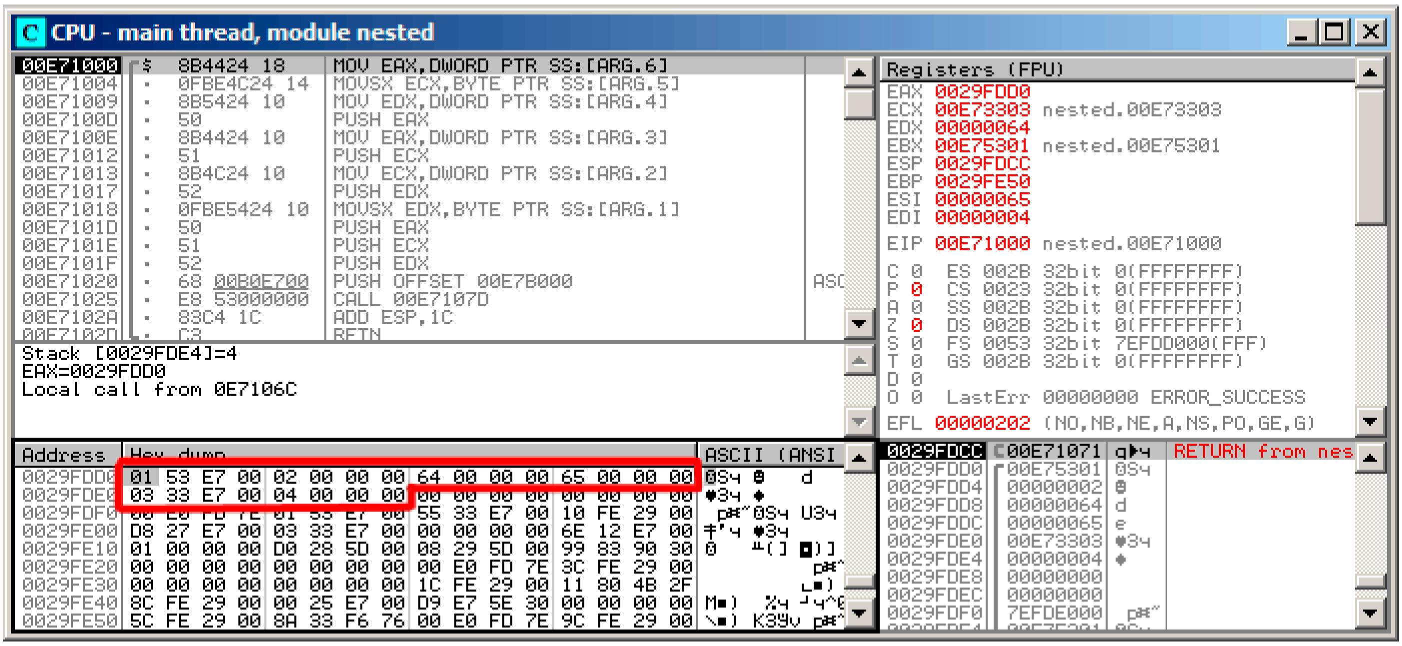


Figure 1.107: OllyDbg: Before `printf()` execution

That's how the values are located in memory:

- *(outer_struct.a)* (byte) 1 + 3 bytes of random garbage;
- *(outer_struct.b)* (32-bit word) 2;
- *(inner_struct.a)* (32-bit word) 0x64 (100);
- *(inner_struct.b)* (32-bit word) 0x65 (101);
- *(outer_struct.d)* (byte) 3 + 3 bytes of random garbage;
- *(outer_struct.e)* (32-bit word) 4.

1.24.6 Bit fields in a structure

CPUID example

The C/C++ language allows to define the exact number of bits for each structure field. It is very useful if one needs to save memory space. For example, one bit is enough for a *bool* variable. But of course, it is not rational if speed is important.

Let's consider the `CPUID`[166]instruction example. This instruction returns information about the current CPU and its features.

If the EAX is set to 1 before the instruction's execution, `CPUID` returning this information packed into the EAX register:

3:0 (4 bits)	Stepping
7:4 (4 bits)	Model
11:8 (4 bits)	Family
13:12 (2 bits)	Processor Type
19:16 (4 bits)	Extended Model
27:20 (8 bits)	Extended Family

MSVC 2010 has `CPUID` macro, but GCC 4.4.1 does not. So let's make this function by ourselves for GCC with the help of its built-in assembler[167].

[166] wikipedia
[167] More about internal GCC assembler

```
#include <stdio.h>

#ifdef __GNUC__
static inline void cpuid(int code, int *a, int *b, int *c, int *d) {
  asm volatile("cpuid":"=a"(*a),"=b"(*b),"=c"(*c),"=d"(*d):"a"(code));
}
#endif

#ifdef _MSC_VER
#include <intrin.h>
#endif

struct CPUID_1_EAX
{
    unsigned int stepping:4;
    unsigned int model:4;
    unsigned int family_id:4;
    unsigned int processor_type:2;
    unsigned int reserved1:2;
    unsigned int extended_model_id:4;
    unsigned int extended_family_id:8;
    unsigned int reserved2:4;
};

int main()
{
    struct CPUID_1_EAX *tmp;
    int b[4];

#ifdef _MSC_VER
    __cpuid(b,1);
#endif

#ifdef __GNUC__
    cpuid (1, &b[0], &b[1], &b[2], &b[3]);
#endif

    tmp=(struct CPUID_1_EAX *)&b[0];

    printf ("stepping=%d\n", tmp->stepping);
    printf ("model=%d\n", tmp->model);
    printf ("family_id=%d\n", tmp->family_id);
    printf ("processor_type=%d\n", tmp->processor_type);
    printf ("extended_model_id=%d\n", tmp->extended_model_id);
    printf ("extended_family_id=%d\n", tmp->extended_family_id);

    return 0;
};
```

After CPUID fills EAX/EBX/ECX/EDX, these registers are to be written in the b[] array. Then, we have a pointer to the CPUID_1_EAX structure and we point it to the value in EAX from the b[] array.

In other words, we treat a 32-bit *int* value as a structure. Then we read specific bits from the structure.

MSVC

Let's compile it in MSVC 2008 with /Ox option:

Listing 1.350: Optimizing MSVC 2008

```
_b$ = -16  ; size = 16
_main    PROC
    sub    esp, 16
    push   ebx

    xor    ecx, ecx
    mov    eax, 1
    cpuid
```

```
    push   esi
    lea    esi, DWORD PTR _b$[esp+24]
    mov    DWORD PTR [esi], eax
    mov    DWORD PTR [esi+4], ebx
    mov    DWORD PTR [esi+8], ecx
    mov    DWORD PTR [esi+12], edx

    mov    esi, DWORD PTR _b$[esp+24]
    mov    eax, esi
    and    eax, 15
    push   eax
    push   OFFSET $SG15435 ; 'stepping=%d', 0aH, 00H
    call   _printf

    mov    ecx, esi
    shr    ecx, 4
    and    ecx, 15
    push   ecx
    push   OFFSET $SG15436 ; 'model=%d', 0aH, 00H
    call   _printf

    mov    edx, esi
    shr    edx, 8
    and    edx, 15
    push   edx
    push   OFFSET $SG15437 ; 'family_id=%d', 0aH, 00H
    call   _printf

    mov    eax, esi
    shr    eax, 12
    and    eax, 3
    push   eax
    push   OFFSET $SG15438 ; 'processor_type=%d', 0aH, 00H
    call   _printf

    mov    ecx, esi
    shr    ecx, 16
    and    ecx, 15
    push   ecx
    push   OFFSET $SG15439 ; 'extended_model_id=%d', 0aH, 00H
    call   _printf

    shr    esi, 20
    and    esi, 255
    push   esi
    push   OFFSET $SG15440 ; 'extended_family_id=%d', 0aH, 00H
    call   _printf
    add    esp, 48
    pop    esi

    xor    eax, eax
    pop    ebx

    add    esp, 16
    ret    0
_main    ENDP
```

The SHR instruction shifting the value in EAX by the number of bits that must be *skipped*, e.g., we ignore some bits *at the right side*.

The AND instruction clears the unneeded bits *on the left*, or, in other words, leaves only those bits in the EAX register we need.

MSVC + OllyDbg

Let's load our example into OllyDbg and see, what values are set in EAX/EBX/ECX/EDX after the execution of CPUID:

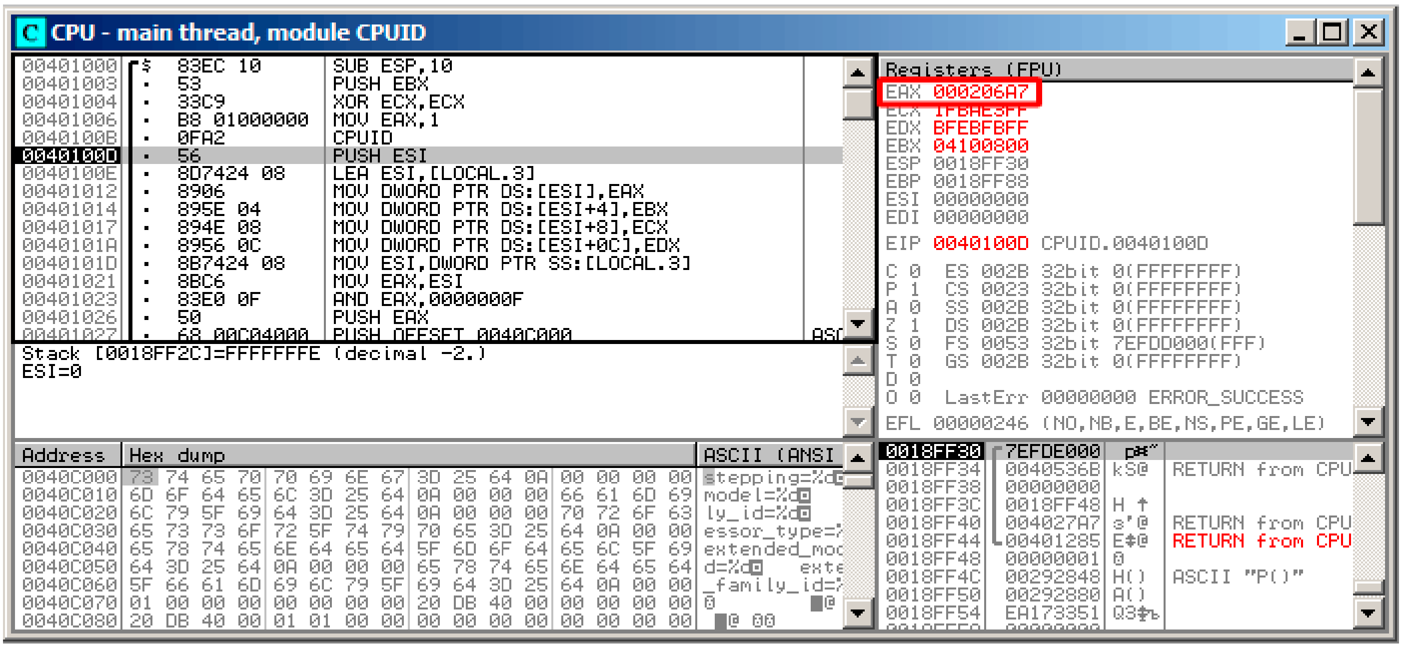


Figure 1.108: OllyDbg: After CPUID execution

EAX has `0x000206A7` (my CPU is Intel Xeon E3-1220).
This is $0b00000000000000100000011010100111$ in binary form.

Here is how the bits are distributed by fields:

field	in binary form	in decimal form
reserved2	0000	0
extended_family_id	00000000	0
extended_model_id	0010	2
reserved1	00	0
processor_id	00	0
family_id	0110	6
model	1010	10
stepping	0111	7

Listing 1.351: Console output

```
stepping=7
model=10
family_id=6
processor_type=0
extended_model_id=2
extended_family_id=0
```

GCC

Let's try GCC 4.4.1 with `-O3` option.

Listing 1.352: Optimizing GCC 4.4.1

```
main            proc near ; DATA XREF: _start+17
    push    ebp
    mov     ebp, esp
    and     esp, 0FFFFFFF0h
    push    esi
```

```
    mov     esi, 1
    push    ebx
    mov     eax, esi
    sub     esp, 18h
    cpuid
    mov     esi, eax
    and     eax, 0Fh
    mov     [esp+8], eax
    mov     dword ptr [esp+4], offset aSteppingD ; "stepping=%d\n"
    mov     dword ptr [esp], 1
    call    ___printf_chk
    mov     eax, esi
    shr     eax, 4
    and     eax, 0Fh
    mov     [esp+8], eax
    mov     dword ptr [esp+4], offset aModelD ; "model=%d\n"
    mov     dword ptr [esp], 1
    call    ___printf_chk
    mov     eax, esi
    shr     eax, 8
    and     eax, 0Fh
    mov     [esp+8], eax
    mov     dword ptr [esp+4], offset aFamily_idD ; "family_id=%d\n"
    mov     dword ptr [esp], 1
    call    ___printf_chk
    mov     eax, esi
    shr     eax, 0Ch
    and     eax, 3
    mov     [esp+8], eax
    mov     dword ptr [esp+4], offset aProcessor_type ; "processor_type=%d\n"
    mov     dword ptr [esp], 1
    call    ___printf_chk
    mov     eax, esi
    shr     eax, 10h
    shr     esi, 14h
    and     eax, 0Fh
    and     esi, 0FFh
    mov     [esp+8], eax
    mov     dword ptr [esp+4], offset aExtended_model ; "extended_model_id=%d\n"
    mov     dword ptr [esp], 1
    call    ___printf_chk
    mov     [esp+8], esi
    mov     dword ptr [esp+4], offset unk_80486D0
    mov     dword ptr [esp], 1
    call    ___printf_chk
    add     esp, 18h
    xor     eax, eax
    pop     ebx
    pop     esi
    mov     esp, ebp
    pop     ebp
    retn
main            endp
```

Almost the same. The only thing worth noting is that GCC somehow combines the calculation of `extended_model_id` and `extended_family_id` into one block, instead of calculating them separately before each `printf()` call.

Handling float data type as a structure

As we already noted in the section about FPU (1.19 on page 218), both *float* and *double* types consist of a *sign*, a *significand* (or *fraction*) and an *exponent*. But will we be able to work with these fields directly? Let's try this with *float*.

(S—sign)

```
#include <stdio.h>
#include <assert.h>
#include <stdlib.h>
#include <memory.h>

struct float_as_struct
{
    unsigned int fraction : 23; // fractional part
    unsigned int exponent : 8;  // exponent + 0x3FF
    unsigned int sign : 1;      // sign bit
};

float f(float _in)
{
    float f=_in;
    struct float_as_struct t;

    assert (sizeof (struct float_as_struct) == sizeof (float));

    memcpy (&t, &f, sizeof (float));

    t.sign=1; // set negative sign
    t.exponent=t.exponent+2; // multiply d by 2^n(n here is 2)

    memcpy (&f, &t, sizeof (float));

    return f;
};

int main()
{
    printf ("%f\n", f(1.234));
};
```

The `float_as_struct` structure occupies the same amount of memory as *float*, i.e., 4 bytes or 32 bits.

Now we are setting the negative sign in the input value and also, by adding 2 to the exponent, we thereby multiply the whole number by 2^2, i.e., by 4.

Let's compile in MSVC 2008 without optimization turned on:

Listing 1.353: Non-optimizing MSVC 2008

```
_t$ = -8   ; size = 4
_f$ = -4   ; size = 4
__in$ = 8  ; size = 4
?f@@YAMM@Z PROC ; f
    push   ebp
    mov    ebp, esp
    sub    esp, 8

    fld    DWORD PTR __in$[ebp]
    fstp   DWORD PTR _f$[ebp]

    push   4
    lea    eax, DWORD PTR _f$[ebp]
    push   eax
    lea    ecx, DWORD PTR _t$[ebp]
    push   ecx
    call   _memcpy
    add    esp, 12

    mov    edx, DWORD PTR _t$[ebp]
    or     edx, -2147483648 ; 80000000H - set minus sign
    mov    DWORD PTR _t$[ebp], edx

    mov    eax, DWORD PTR _t$[ebp]
    shr    eax, 23          ; 00000017H - drop significand
    and    eax, 255         ; 000000ffH - leave here only exponent
```

```
    add     eax, 2          ; add 2 to it
    and     eax, 255        ; 000000ffH
    shl     eax, 23         ; 00000017H - shift result to place of bits 30:23
    mov     ecx, DWORD PTR _t$[ebp]
    and     ecx, -2139095041 ; 807fffffH - drop exponent

; add original value without exponent with new calculated exponent:
    or      ecx, eax
    mov     DWORD PTR _t$[ebp], ecx

    push    4
    lea     edx, DWORD PTR _t$[ebp]
    push    edx
    lea     eax, DWORD PTR _f$[ebp]
    push    eax
    call    _memcpy
    add     esp, 12

    fld     DWORD PTR _f$[ebp]

    mov     esp, ebp
    pop     ebp
    ret     0
?f@@YAMM@Z ENDP   ; f
```

A bit redundant. If it was compiled with /Ox flag there would be no memcpy() call, the f variable is used directly. But it is easier to understand by looking at the unoptimized version.

What would GCC 4.4.1 with -O3 do?

Listing 1.354: Optimizing GCC 4.4.1

```
; f(float)
       public _Z1ff
_Z1ff  proc near

var_4  = dword ptr -4
arg_0  = dword ptr  8

       push    ebp
       mov     ebp, esp
       sub     esp, 4
       mov     eax, [ebp+arg_0]
       or      eax, 80000000h  ; set minus sign
       mov     edx, eax
       and     eax, 807FFFFFh  ; leave only sign and significand in EAX
       shr     edx, 23         ; prepare exponent
       add     edx, 2          ; add 2
       movzx   edx, dl         ; clear all bits except 7:0 in EAX
       shl     edx, 23         ; shift new calculated exponent to its place
       or      eax, edx        ; join new exponent and original value without exponent
       mov     [ebp+var_4], eax
       fld     [ebp+var_4]
       leave
       retn
_Z1ff  endp

       public main
main   proc near
       push    ebp
       mov     ebp, esp
       and     esp, 0FFFFFFF0h
       sub     esp, 10h
       fld     ds:dword_8048614 ; -4.936
       fstp    qword ptr [esp+8]
       mov     dword ptr [esp+4], offset asc_8048610 ; "%f\n"
       mov     dword ptr [esp], 1
       call    ___printf_chk
       xor     eax, eax
       leave
       retn
```

```
main   endp
```

The `f()` function is almost understandable. However, what is interesting is that GCC was able to calculate the result of `f(1.234)` during compilation despite all this hodge-podge with the structure fields and prepared this argument to `printf()` as precalculated at compile time!

1.24.7 Exercises

- http://challenges.re/71
- http://challenges.re/72

1.25 Unions

C/C++ *union* is mostly used for interpreting a variable (or memory block) of one data type as a variable of another data type.

1.25.1 Pseudo-random number generator example

If we need float random numbers between 0 and 1, the simplest thing is to use a PRNG like the Mersenne twister. It produces random unsigned 32-bit values (in other words, it produces random 32 bits). Then we can transform this value to *float* and then divide it by `RAND_MAX` (`0xFFFFFFFF` in our case)—we getting a value in the 0..1 interval.

But as we know, division is slow. Also, we would like to issue as few FPU operations as possible. Can we get rid of the division?

Let's recall what a floating point number consists of: sign bit, significand bits and exponent bits. We just have to store random bits in all significand bits to get a random float number!

The exponent cannot be zero (the floating number is denormalized in this case), so we are storing `0b01111111` to exponent—this means that the exponent is 1. Then we filling the significand with random bits, set the sign bit to 0 (which means a positive number) and voilà. The generated numbers is to be between 1 and 2, so we must also subtract 1.

A very simple linear congruential random numbers generator is used in my example[168], it produces 32-bit numbers. The PRNG is initialized with the current time in UNIX timestamp format.

Here we represent the *float* type as an *union*—it is the C/C++ construction that enables us to interpret a piece of memory as different types. In our case, we are able to create a variable of type *union* and then access to it as it is *float* or as it is *uint32_t*. It can be said, it is just a hack. A dirty one.

The integer PRNG code is the same as we already considered: 1.23 on page 338. So this code in compiled form is omitted.

```
#include <stdio.h>
#include <stdint.h>
#include <time.h>

// integer PRNG definitions, data and routines:

// constants from the Numerical Recipes book
const uint32_t RNG_a=1664525;
const uint32_t RNG_c=1013904223;
uint32_t RNG_state; // global variable

void my_srand(uint32_t i)
{
        RNG_state=i;
};

uint32_t my_rand()
{
```

[168] the idea was taken from: http://go.yurichev.com/17308

```
        RNG_state=RNG_state*RNG_a+RNG_c;
        return RNG_state;
};

// FPU PRNG definitions and routines:

union uint32_t_float
{
        uint32_t i;
        float f;
};

float float_rand()
{
        union uint32_t_float tmp;
        tmp.i=my_rand() & 0x007fffff | 0x3F800000;
        return tmp.f-1;
};

// test

int main()
{
        my_srand(time(NULL)); // PRNG initialization

        for (int i=0; i<100; i++)
                printf ("%f\n", float_rand());

        return 0;
};
```

x86

Listing 1.355: Optimizing MSVC 2010

```
$SG4238 DB      '%f', 0aH, 00H

__real@3ff0000000000000 DQ 03ff0000000000000r   ; 1

tv130 = -4
_tmp$ = -4
?float_rand@@YAMXZ PROC
        push    ecx
        call    ?my_rand@@YAIXZ
; EAX=pseudorandom value
        and     eax, 8388607            ; 007fffffH
        or      eax, 1065353216         ; 3f800000H
; EAX=pseudorandom value & 0x007fffff | 0x3f800000
; store it into local stack:
        mov     DWORD PTR _tmp$[esp+4], eax
; reload it as float point number:
        fld     DWORD PTR _tmp$[esp+4]
; subtract 1.0:
        fsub    QWORD PTR __real@3ff0000000000000
; store value we got into local stack and reload it:
        fstp    DWORD PTR tv130[esp+4] ; \  these instructions are redundant
        fld     DWORD PTR tv130[esp+4] ; /
        pop     ecx
        ret     0
?float_rand@@YAMXZ ENDP

_main   PROC
        push    esi
        xor     eax, eax
        call    _time
        push    eax
        call    ?my_srand@@YAXI@Z
        add     esp, 4
```

```
        mov     esi, 100
$LL3@main:
        call    ?float_rand@@YAMXZ
        sub     esp, 8
        fstp    QWORD PTR [esp]
        push    OFFSET $SG4238
        call    _printf
        add     esp, 12
        dec     esi
        jne     SHORT $LL3@main
        xor     eax, eax
        pop     esi
        ret     0
_main   ENDP
```

Function names are so strange here because this example was compiled as C++ and this is name mangling in C++, we will talk about it later: 3.18.1 on page 542. If we compile this in MSVC 2012, it uses the SIMD instructions for the FPU, read more about it here: 1.31.5 on page 438.

MIPS

Listing 1.356: Optimizing GCC 4.4.5

```
float_rand:

var_10          = -0x10
var_4           = -4

                lui     $gp, (__gnu_local_gp >> 16)
                addiu   $sp, -0x20
                la      $gp, (__gnu_local_gp & 0xFFFF)
                sw      $ra, 0x20+var_4($sp)
                sw      $gp, 0x20+var_10($sp)
; call my_rand():
                jal     my_rand
                or      $at, $zero ; branch delay slot, NOP
; $v0=32-bit pseudorandom value
                li      $v1, 0x7FFFFF
; $v1=0x7FFFFF
                and     $v1, $v0, $v1
; $v1=pseudorandom value & 0x7FFFFF
                lui     $a0, 0x3F80
; $a0=0x3F800000
                or      $v1, $a0
; $v1=pseudorandom value & 0x7FFFFF | 0x3F800000
; matter of the following instruction is still hard to get:
                lui     $v0, ($LC0 >> 16)
; load 1.0 into $f0:
                lwc1    $f0, $LC0
; move value from $v1 to coprocessor 1 (into register $f2)
; it behaves like bitwise copy, no conversion done:
                mtc1    $v1, $f2
                lw      $ra, 0x20+var_4($sp)
; subtract 1.0. leave result in $f0:
                sub.s   $f0, $f2, $f0
                jr      $ra
                addiu   $sp, 0x20  ; branch delay slot

main:

var_18          = -0x18
var_10          = -0x10
var_C           = -0xC
var_8           = -8
var_4           = -4

                lui     $gp, (__gnu_local_gp >> 16)
                addiu   $sp, -0x28
```

```
                la      $gp, (__gnu_local_gp & 0xFFFF)
                sw      $ra, 0x28+var_4($sp)
                sw      $s2, 0x28+var_8($sp)
                sw      $s1, 0x28+var_C($sp)
                sw      $s0, 0x28+var_10($sp)
                sw      $gp, 0x28+var_18($sp)
                lw      $t9, (time & 0xFFFF)($gp)
                or      $at, $zero ; load delay slot, NOP
                jalr    $t9
                move    $a0, $zero ; branch delay slot
                lui     $s2, ($LC1 >> 16)  # "%f\n"
                move    $a0, $v0
                la      $s2, ($LC1 & 0xFFFF)  # "%f\n"
                move    $s0, $zero
                jal     my_srand
                li      $s1, 0x64  # 'd' ; branch delay slot

loc_104:
                jal     float_rand
                addiu   $s0, 1
                lw      $gp, 0x28+var_18($sp)
; convert value we got from float_rand() to double type (printf() need it):
                cvt.d.s $f2, $f0
                lw      $t9, (printf & 0xFFFF)($gp)
                mfc1    $a3, $f2
                mfc1    $a2, $f3
                jalr    $t9
                move    $a0, $s2
                bne     $s0, $s1, loc_104
                move    $v0, $zero
                lw      $ra, 0x28+var_4($sp)
                lw      $s2, 0x28+var_8($sp)
                lw      $s1, 0x28+var_C($sp)
                lw      $s0, 0x28+var_10($sp)
                jr      $ra
                addiu   $sp, 0x28 ; branch delay slot

$LC1:           .ascii "%f\n"<0>
$LC0:           .float 1.0
```

There is also an useless LUI instruction added for some weird reason. We considered this artifact earlier: 1.19.5 on page 230.

ARM (ARM mode)

Listing 1.357: Optimizing GCC 4.6.3 (IDA)

```
float_rand
                STMFD   SP!, {R3,LR}
                BL      my_rand
; R0=pseudorandom value
                FLDS    S0, =1.0
; S0=1.0
                BIC     R3, R0, #0xFF000000
                BIC     R3, R3, #0x800000
                ORR     R3, R3, #0x3F800000
; R3=pseudorandom value & 0x007fffff | 0x3f800000
; copy from R3 to FPU (register S15).
; it behaves like bitwise copy, no conversion done:
                FMSR    S15, R3
; subtract 1.0 and leave result in S0:
                FSUBS   S0, S15, S0
                LDMFD   SP!, {R3,PC}

flt_5C          DCFS 1.0

main
                STMFD   SP!, {R4,LR}
```

```
                MOV     R0, #0
                BL      time
                BL      my_srand
                MOV     R4, #0x64 ; 'd'

loc_78
                BL      float_rand
; S0=pseudorandom value
                LDR     R0, =aF         ; "%f"
; convert float type value into double type value (printf() will need it):
                FCVTDS  D7, S0
; bitwise copy from D7 into R2/R3 pair of registers (for printf()):
                FMRRD   R2, R3, D7
                BL      printf
                SUBS    R4, R4, #1
                BNE     loc_78
                MOV     R0, R4
                LDMFD   SP!, {R4,PC}

aF              DCB "%f",0xA,0
```

We'll also make a dump in objdump and we'll see that the FPU instructions have different names than in IDA. Apparently, IDA and binutils developers used different manuals? Perhaps it would be good to know both instruction name variants.

Listing 1.358: Optimizing GCC 4.6.3 (objdump)

```
00000038 <float_rand>:
  38:   e92d4008        push    {r3, lr}
  3c:   ebfffffe        bl      10 <my_rand>
  40:   ed9f0a05        vldr    s0, [pc, #20]   ; 5c <float_rand+0x24>
  44:   e3c034ff        bic     r3, r0, #-16777216      ; 0xff000000
  48:   e3c33502        bic     r3, r3, #8388608        ; 0x800000
  4c:   e38335fe        orr     r3, r3, #1065353216     ; 0x3f800000
  50:   ee073a90        vmov    s15, r3
  54:   ee370ac0        vsub.f32        s0, s15, s0
  58:   e8bd8008        pop     {r3, pc}
  5c:   3f800000        svccc   0x00800000

00000000 <main>:
   0:   e92d4010        push    {r4, lr}
   4:   e3a00000        mov     r0, #0
   8:   ebfffffe        bl      0 <time>
   c:   ebfffffe        bl      0 <main>
  10:   e3a04064        mov     r4, #100        ; 0x64
  14:   ebfffffe        bl      38 <main+0x38>
  18:   e59f0018        ldr     r0, [pc, #24]   ; 38 <main+0x38>
  1c:   eeb77ac0        vcvt.f64.f32    d7, s0
  20:   ec532b17        vmov    r2, r3, d7
  24:   ebfffffe        bl      0 <printf>
  28:   e2544001        subs    r4, r4, #1
  2c:   1afffff8        bne     14 <main+0x14>
  30:   e1a00004        mov     r0, r4
  34:   e8bd8010        pop     {r4, pc}
  38:   00000000        andeq   r0, r0, r0
```

The instructions at 0x5c in `float_rand()` and at 0x38 in `main()` are (pseudo-)random noise.

1.25.2 Calculating machine epsilon

The machine epsilon is the smallest possible value the FPU can work with. The more bits allocated for floating point number, the smaller the machine epsilon. It is $2^{-23} = 1.19e-07$ for *float* and $2^{-52} = 2.22e-16$ for *double*. See also: Wikipedia article.

It's interesting, how easy it's to calculate the machine epsilon:

```
#include <stdio.h>
#include <stdint.h>
```

```
union uint_float
{
        uint32_t i;
        float f;
};

float calculate_machine_epsilon(float start)
{
        union uint_float v;
        v.f=start;
        v.i++;
        return v.f-start;
}

void main()
{
        printf ("%g\n", calculate_machine_epsilon(1.0));
};
```

What we do here is just treat the fraction part of the IEEE 754 number as integer and add 1 to it. The resulting floating number is equal to $starting\_value+machine\_epsilon$, so we just have to subtract the starting value (using floating point arithmetic) to measure, what difference one bit reflects in the single precision (*float*). The *union* serves here as a way to access IEEE 754 number as a regular integer. Adding 1 to it in fact adds 1 to the *fraction* part of the number, however, needless to say, overflow is possible, which will add another 1 to the exponent part.

x86

Listing 1.359: Optimizing MSVC 2010

```
tv130 = 8
_v$ = 8
_start$ = 8
_calculate_machine_epsilon PROC
        fld     DWORD PTR _start$[esp-4]
        fst     DWORD PTR _v$[esp-4]     ; this instruction is redundant
        inc     DWORD PTR _v$[esp-4]
        fsubr   DWORD PTR _v$[esp-4]
        fstp    DWORD PTR tv130[esp-4]   ; \ this instruction pair is also redundant
        fld     DWORD PTR tv130[esp-4]   ; /
        ret     0
_calculate_machine_epsilon ENDP
```

The second FST instruction is redundant: there is no necessity to store the input value in the same place (the compiler decided to allocate the v variable at the same point in the local stack as the input argument). Then it is incremented with INC, as it is a normal integer variable. Then it is loaded into the FPU as a 32-bit IEEE 754 number, FSUBR does the rest of job and the resulting value is stored in ST0. The last FSTP/FLD instruction pair is redundant, but the compiler didn't optimize it out.

ARM64

Let's extend our example to 64-bit:

```
#include <stdio.h>
#include <stdint.h>

typedef union
{
        uint64_t i;
        double d;
} uint_double;

double calculate_machine_epsilon(double start)
{
        uint_double v;
```

```
        v.d=start;
        v.i++;
        return v.d-start;
}

void main()
{
        printf ("%g\n", calculate_machine_epsilon(1.0));
};
```

ARM64 has no instruction that can add a number to a FPU D-register, so the input value (that came in D0) is first copied into GPR, incremented, copied to FPU register D1, and then subtraction occurs.

Listing 1.360: Optimizing GCC 4.9 ARM64

```
calculate_machine_epsilon:
        fmov    x0, d0       ; load input value of double type into X0
        add     x0, x0, 1    ; X0++
        fmov    d1, x0       ; move it to FPU register
        fsub    d0, d1, d0   ; subtract
        ret
```

See also this example compiled for x64 with SIMD instructions: 1.31.4 on page 437.

MIPS

The new instruction here is MTC1 ("Move To Coprocessor 1"), it just transfers data from GPR to the FPU's registers.

Listing 1.361: Optimizing GCC 4.4.5 (IDA)

```
calculate_machine_epsilon:
                mfc1    $v0, $f12
                or      $at, $zero ; NOP
                addiu   $v1, $v0, 1
                mtc1    $v1, $f2
                jr      $ra
                sub.s   $f0, $f2, $f12 ; branch delay slot
```

Conclusion

It's hard to say whether someone may need this trickery in real-world code, but as was mentioned many times in this book, this example serves well for explaining the IEEE 754 format and *union*s in C/C++.

1.26 FSCALE replacement

Agner Fog in his *Optimizing subroutines in assembly language / An optimization guide for x86 platforms* work [169] states that FSCALE FPU instruction (calculating 2^n) may be slow on many CPUs, and he offers faster replacement.

Here is my translation of his assembly code to C/C++:

```
#include <stdint.h>
#include <stdio.h>

union uint_float
{
        uint32_t i;
        float f;
};

float flt_2n(int N)
```

[169] http://www.agner.org/optimize/optimizing_assembly.pdf

```
{
        union uint_float tmp;

        tmp.i=(N<<23)+0x3f800000;
        return tmp.f;
};

struct float_as_struct
{
        unsigned int fraction : 23;
        unsigned int exponent : 8;
        unsigned int sign : 1;
};

float flt_2n_v2(int N)
{
        struct float_as_struct tmp;

        tmp.fraction=0;
        tmp.sign=0;
        tmp.exponent=N+0x7f;
        return *(float*)(&tmp);
};

union uint64_double
{
        uint64_t i;
        double d;
};

double dbl_2n(int N)
{
        union uint64_double tmp;

        tmp.i=((uint64_t)N<<52)+0x3ff0000000000000UL;
        return tmp.d;
};

struct double_as_struct
{
        uint64_t fraction : 52;
        int exponent : 11;
        int sign : 1;
};

double dbl_2n_v2(int N)
{
        struct double_as_struct tmp;

        tmp.fraction=0;
        tmp.sign=0;
        tmp.exponent=N+0x3ff;
        return *(double*)(&tmp);
};

int main()
{
        // 2^11=2048
        printf ("%f\n", flt_2n(11));
        printf ("%f\n", flt_2n_v2(11));
        printf ("%lf\n", dbl_2n(11));
        printf ("%lf\n", dbl_2n_v2(11));
};
```

FSCALE instruction may be faster in your environment, but still, it's a good example of *union*'s and the fact that exponent is stored in 2^n form, so an input n value is shifted to the exponent in IEEE 754 encoded number. Then exponent is then corrected with addition of 0x3f800000 or 0x3ff0000000000000.

The same can be done without shift using *struct*, but internally, shift operations still occurred.

1.26.1 Fast square root calculation

Another well-known algorithm where *float* is interpreted as integer is fast calculation of square root.

Listing 1.362: The source code is taken from Wikipedia: http://go.yurichev.com/17364

```
 * and that int is 32 bits. */
float sqrt_approx(float z)
{
    int val_int = *(int*)&z; /* Same bits, but as an int */
    /*
     * To justify the following code, prove that
     *
     * ((((val_int / 2^m) - b) / 2) + b) * 2^m = ((val_int - 2^m) / 2) + ((b + 1) / 2) * 2^m)
     *
     * where
     *
     * b = exponent bias
     * m = number of mantissa bits
     *
     * .
     */

    val_int -= 1 << 23; /* Subtract 2^m. */
    val_int >>= 1; /* Divide by 2. */
    val_int += 1 << 29; /* Add ((b + 1) / 2) * 2^m. */

    return *(float*)&val_int; /* Interpret again as float */
}
```

As an exercise, you can try to compile this function and to understand, how it works.

There is also well-known algorithm of fast calculation of $\frac{1}{\sqrt{x}}$. Algorithm became popular, supposedly, because it was used in Quake III Arena.

Algorithm description can be found in Wikipedia: http://go.yurichev.com/17360.

1.27 Pointers to functions

A pointer to a function, as any other pointer, is just the address of the function's start in its code segment.

They are often used for calling callback functions[170].

Well-known examples are:

- `qsort()`[171], `atexit()`[172] from the standard C library;
- *NIX OS signals[173];
- thread starting: `CreateThread()` (win32), `pthread_create()` (POSIX);
- lots of win32 functions, like `EnumChildWindows()`[174].
- lots of places in the Linux kernel, for example the filesystem driver functions are called via callbacks: http://go.yurichev.com/17076
- The GCC plugin functions are also called via callbacks: http://go.yurichev.com/17077
- Another example of function pointers is a table in the "dwm" Linux window manager that defines shortcuts. Each shortcut has a corresponding function to call if a specific key is pressed: GitHub. As we can see, such table is easier to handle than a large switch() statement.

So, the `qsort()` function is an implementation of quicksort in the C/C++ standard library. The functions is able to sort anything, any type of data, as long as you have a function to compare these two elements and `qsort()` is able to call it.

[170] wikipedia
[171] wikipedia
[172] http://go.yurichev.com/17073
[173] wikipedia
[174] MSDN

The comparison function can be defined as:

```
int (*compare)(const void *, const void *)
```

Let's use the following example:

```
/* ex3 Sorting ints with qsort */

#include <stdio.h>
#include <stdlib.h>

int comp(const void * _a, const void * _b)
{
  const int *a=(const int *)_a;
  const int *b=(const int *)_b;

  if (*a==*b)
    return 0;
  else
    if (*a < *b)
        return -1;
     else
      return 1;
}

int main(int argc, char* argv[])
{
   int numbers[10]={1892,45,200,-98,4087,5,-12345,1087,88,-100000};
   int i;

  /* Sort the array */
  qsort(numbers,10,sizeof(int),comp) ;
  for (i=0;i<9;i++)
    printf("Number = %d\n",numbers[ i ]) ;
  return 0;
}
```

1.27.1 MSVC

Let's compile it in MSVC 2010 (some parts were omitted for the sake of brevity) with `/Ox` option:

Listing 1.363: Optimizing MSVC 2010: /GS- /MD

```
__a$ = 8                                                ; size = 4
__b$ = 12                                               ; size = 4
_comp   PROC
        mov     eax, DWORD PTR __a$[esp-4]
        mov     ecx, DWORD PTR __b$[esp-4]
        mov     eax, DWORD PTR [eax]
        mov     ecx, DWORD PTR [ecx]
        cmp     eax, ecx
        jne     SHORT $LN4@comp
        xor     eax, eax
        ret     0
$LN4@comp:
        xor     edx, edx
        cmp     eax, ecx
        setge   dl
        lea     eax, DWORD PTR [edx+edx-1]
        ret     0
_comp   ENDP


_numbers$ = -40                                         ; size = 40
_argc$ = 8                                              ; size = 4
_argv$ = 12                                             ; size = 4
_main   PROC
        sub     esp, 40                                 ; 00000028H
```

```
        push    esi
        push    OFFSET _comp
        push    4
        lea     eax, DWORD PTR _numbers$[esp+52]
        push    10                                      ; 0000000aH
        push    eax
        mov     DWORD PTR _numbers$[esp+60], 1892       ; 00000764H
        mov     DWORD PTR _numbers$[esp+64], 45         ; 0000002dH
        mov     DWORD PTR _numbers$[esp+68], 200        ; 000000c8H
        mov     DWORD PTR _numbers$[esp+72], -98        ; ffffff9eH
        mov     DWORD PTR _numbers$[esp+76], 4087       ; 00000ff7H
        mov     DWORD PTR _numbers$[esp+80], 5
        mov     DWORD PTR _numbers$[esp+84], -12345     ; ffffcfc7H
        mov     DWORD PTR _numbers$[esp+88], 1087       ; 0000043fH
        mov     DWORD PTR _numbers$[esp+92], 88         ; 00000058H
        mov     DWORD PTR _numbers$[esp+96], -100000    ; fffe7960H
        call    _qsort
        add     esp, 16                                 ; 00000010H

...
```

Nothing surprising so far. As a fourth argument, the address of label `_comp` is passed, which is just a place where `comp()` is located, or, in other words, the address of the very first instruction of that function.

How does `qsort()` call it?

Let's take a look at this function, located in MSVCR80.DLL (a MSVC DLL module with C standard library functions):

Listing 1.364: MSVCR80.DLL

```
.text:7816CBF0 ; void __cdecl qsort(void *, unsigned int, unsigned int, int (__cdecl *)(const ↙
    ↘ void *, const void *))
.text:7816CBF0                 public _qsort
.text:7816CBF0 _qsort          proc near
.text:7816CBF0
.text:7816CBF0 lo              = dword ptr -104h
.text:7816CBF0 hi              = dword ptr -100h
.text:7816CBF0 var_FC          = dword ptr -0FCh
.text:7816CBF0 stkptr          = dword ptr -0F8h
.text:7816CBF0 lostk           = dword ptr -0F4h
.text:7816CBF0 histk           = dword ptr -7Ch
.text:7816CBF0 base            = dword ptr  4
.text:7816CBF0 num             = dword ptr  8
.text:7816CBF0 width           = dword ptr  0Ch
.text:7816CBF0 comp            = dword ptr  10h
.text:7816CBF0
.text:7816CBF0                 sub     esp, 100h

....

.text:7816CCE0 loc_7816CCE0:                           ; CODE XREF: _qsort+B1
.text:7816CCE0                 shr     eax, 1
.text:7816CCE2                 imul    eax, ebp
.text:7816CCE5                 add     eax, ebx
.text:7816CCE7                 mov     edi, eax
.text:7816CCE9                 push    edi
.text:7816CCEA                 push    ebx
.text:7816CCEB                 call    [esp+118h+comp]
.text:7816CCF2                 add     esp, 8
.text:7816CCF5                 test    eax, eax
.text:7816CCF7                 jle     short loc_7816CD04
```

`comp`—is the fourth function argument. Here the control gets passed to the address in the `comp` argument. Before it, two arguments are prepared for `comp()`. Its result is checked after its execution.

That's why it is dangerous to use pointers to functions. First of all, if you call `qsort()` with an incorrect function pointer, `qsort()` may pass control flow to an incorrect point, the process may crash and this bug will be hard to find.

The second reason is that the callback function types must comply strictly, calling the wrong function with wrong arguments of wrong types may lead to serious problems, however, the crashing of the process is not a problem here —the problem is how to determine the reason for the crash —because the compiler may be silent about the potential problems while compiling.

MSVC + OllyDbg

Let's load our example into OllyDbg and set a breakpoint on comp(). We can see how the values are compared at the first comp() call:

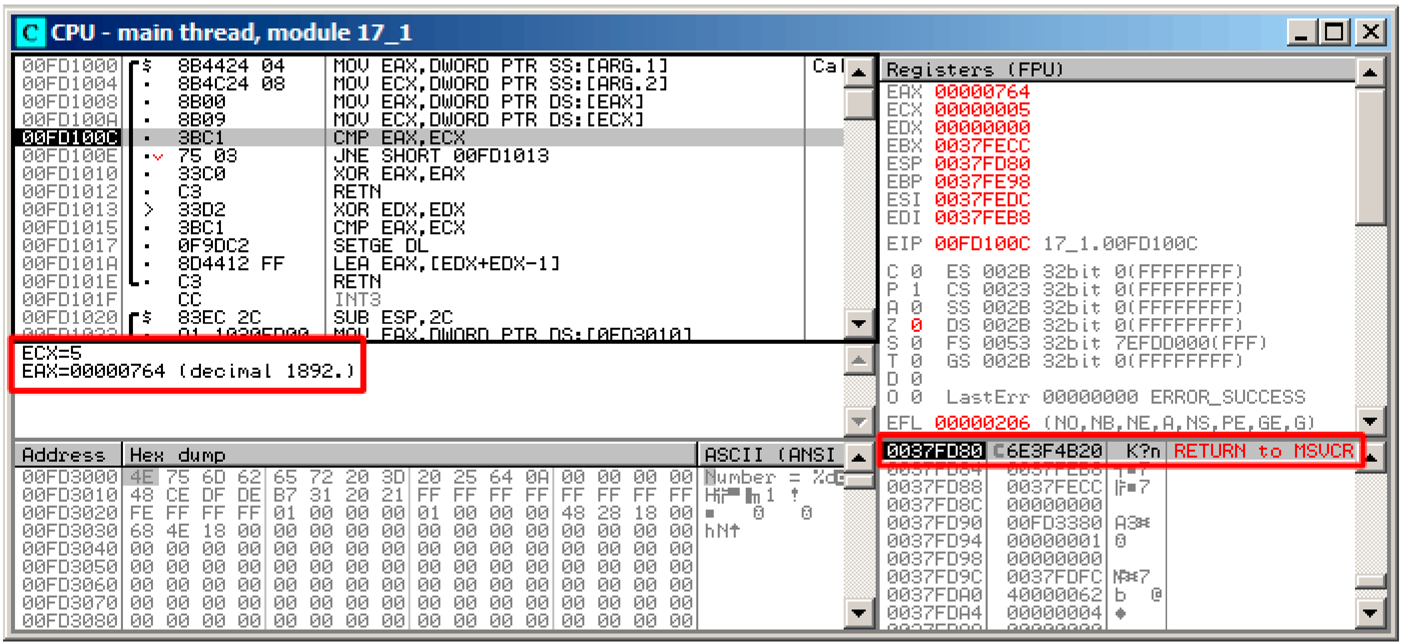


Figure 1.109: OllyDbg: first call of comp()

OllyDbg shows the compared values in the window under the code window, for convenience. We can also see that the SP points to RA, where the qsort() function is (located in MSVCR100.DLL).

By tracing (F8) until the RETN instruction and pressing F8 one more time, we return to the qsort() function:

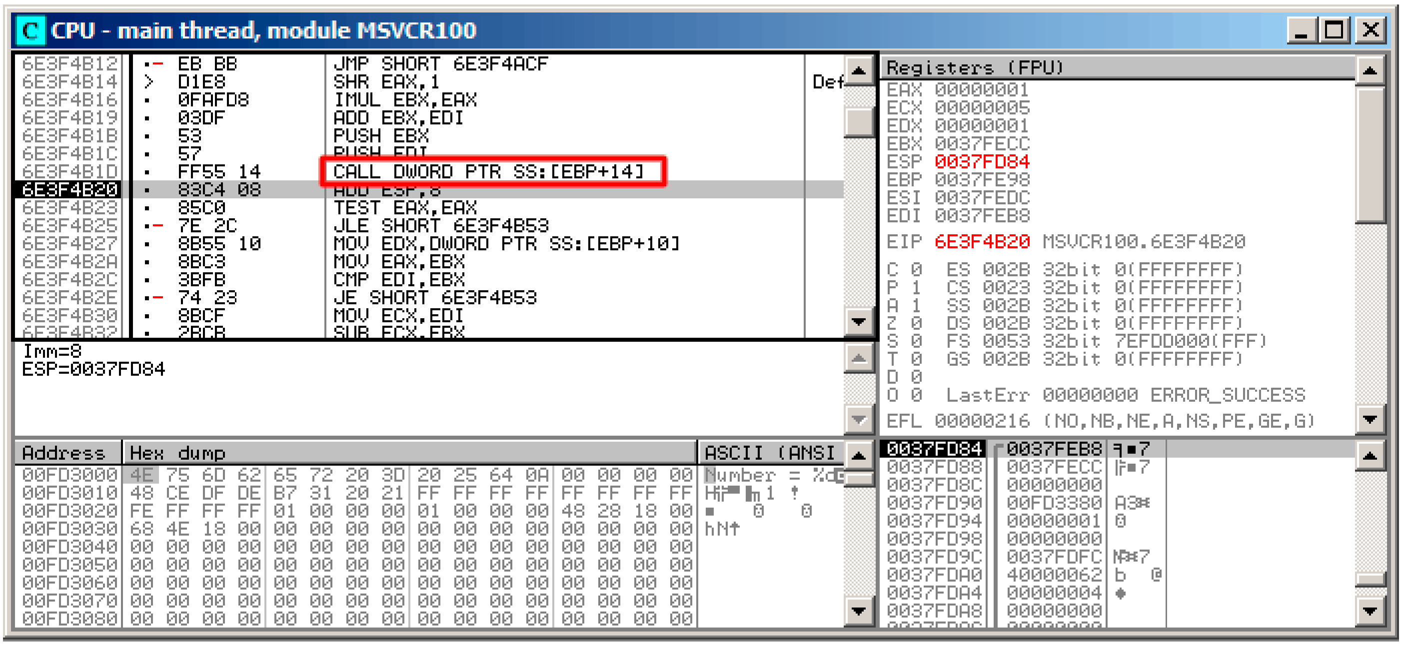


Figure 1.110: OllyDbg: the code in qsort() right after comp() call

That has been a call to the comparison function.

Here is also a screenshot of the moment of the second call of comp()—now values that have to be compared are different:

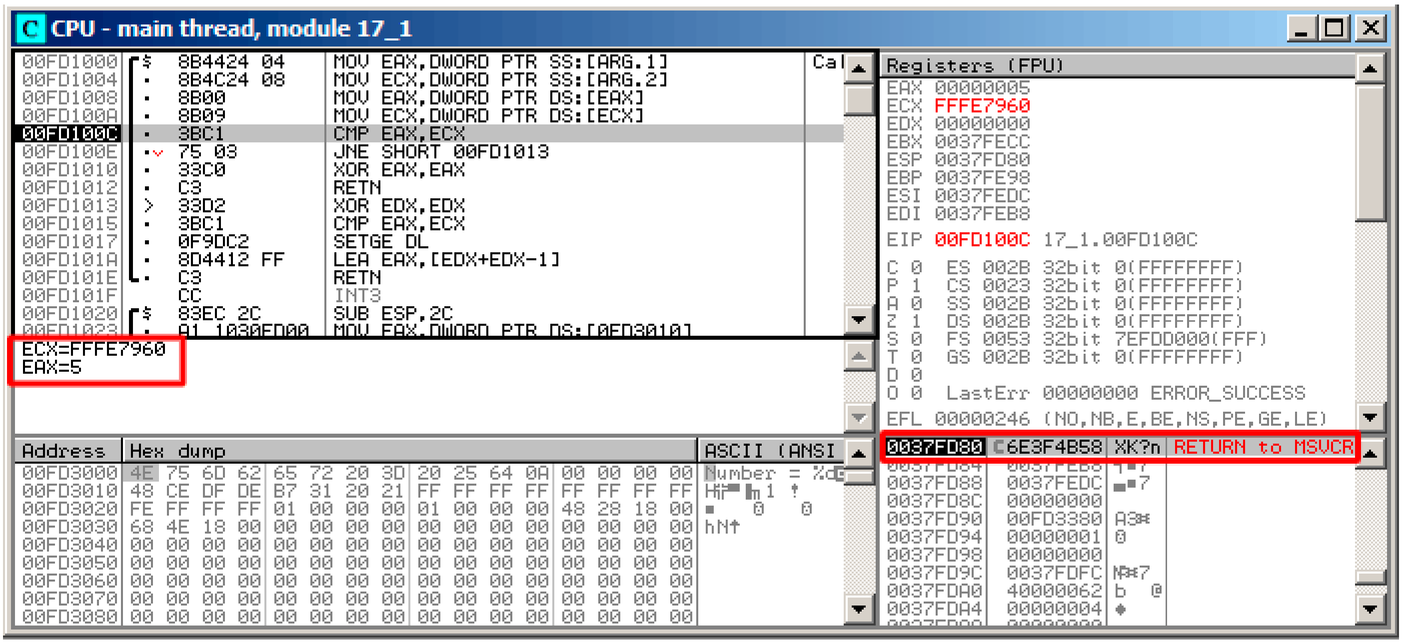


Figure 1.111: OllyDbg: second call of comp()

MSVC + tracer

Let's also see which pairs are compared. These 10 numbers are being sorted: 1892, 45, 200, -98, 4087, 5, -12345, 1087, 88, -100000.

We got the address of the first CMP instruction in comp(), it is 0x0040100C and we've set a breakpoint on it:

```
tracer.exe -l:17_1.exe bpx=17_1.exe!0x0040100C
```

Now we get some information about the registers at the breakpoint:

```
PID=4336|New process 17_1.exe
(0) 17_1.exe!0x40100c
EAX=0x00000764 EBX=0x0051f7c8 ECX=0x00000005 EDX=0x00000000
ESI=0x0051f7d8 EDI=0x0051f7b4 EBP=0x0051f794 ESP=0x0051f67c
EIP=0x0028100c
FLAGS=IF
(0) 17_1.exe!0x40100c
EAX=0x00000005 EBX=0x0051f7c8 ECX=0xfffe7960 EDX=0x00000000
ESI=0x0051f7d8 EDI=0x0051f7b4 EBP=0x0051f794 ESP=0x0051f67c
EIP=0x0028100c
FLAGS=PF ZF IF
(0) 17_1.exe!0x40100c
EAX=0x00000764 EBX=0x0051f7c8 ECX=0x00000005 EDX=0x00000000
ESI=0x0051f7d8 EDI=0x0051f7b4 EBP=0x0051f794 ESP=0x0051f67c
EIP=0x0028100c
FLAGS=CF PF ZF IF
...
```

Let's filter out EAX and ECX and we got:

```
EAX=0x00000764 ECX=0x00000005
EAX=0x00000005 ECX=0xfffe7960
EAX=0x00000764 ECX=0x00000005
EAX=0x0000002d ECX=0x00000005
EAX=0x00000058 ECX=0x00000005
EAX=0x0000043f ECX=0x00000005
EAX=0xffffcfc7 ECX=0x00000005
```

```
EAX=0x000000c8 ECX=0x00000005
EAX=0xffffff9e ECX=0x00000005
EAX=0x00000ff7 ECX=0x00000005
EAX=0x00000ff7 ECX=0x00000005
EAX=0xffffff9e ECX=0x00000005
EAX=0xffffff9e ECX=0x00000005
EAX=0xffffcfc7 ECX=0xfffe7960
EAX=0x00000005 ECX=0xffffcfc7
EAX=0xffffff9e ECX=0x00000005
EAX=0xffffcfc7 ECX=0xfffe7960
EAX=0xffffff9e ECX=0xffffcfc7
EAX=0xffffcfc7 ECX=0xfffe7960
EAX=0x000000c8 ECX=0x00000ff7
EAX=0x0000002d ECX=0x00000ff7
EAX=0x0000043f ECX=0x00000ff7
EAX=0x00000058 ECX=0x00000ff7
EAX=0x00000764 ECX=0x00000ff7
EAX=0x000000c8 ECX=0x00000764
EAX=0x0000002d ECX=0x00000764
EAX=0x0000043f ECX=0x00000764
EAX=0x00000058 ECX=0x00000764
EAX=0x000000c8 ECX=0x00000058
EAX=0x0000002d ECX=0x000000c8
EAX=0x0000043f ECX=0x000000c8
EAX=0x000000c8 ECX=0x00000058
EAX=0x0000002d ECX=0x000000c8
EAX=0x0000002d ECX=0x00000058
```

That's 34 pairs. Therefore, the quick sort algorithm needs 34 comparison operations to sort these 10 numbers.

MSVC + tracer (code coverage)

We can also use the tracer's feature to collect all possible register values and show them in IDA.

Let's trace all instructions in comp():

```
tracer.exe -l:17_1.exe bpf=17_1.exe!0x00401000,trace:cc
```

We get an .idc-script for loading into IDA and load it:

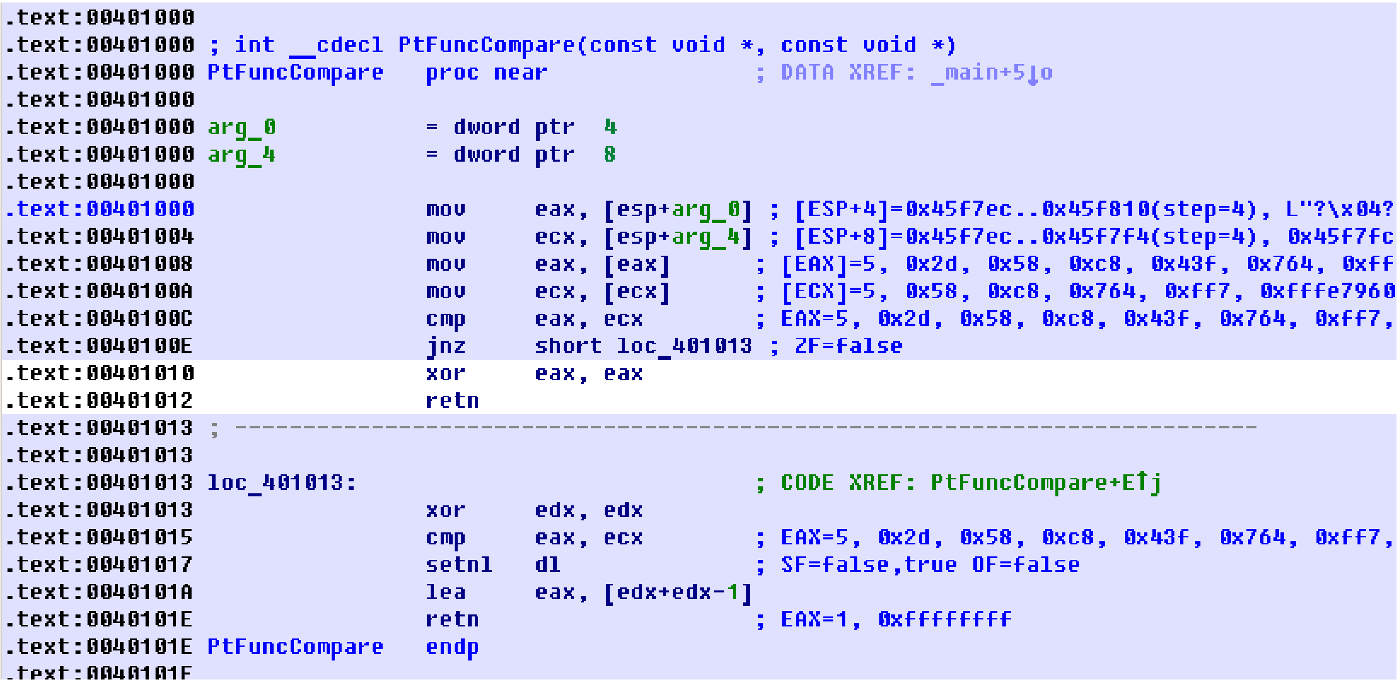


Figure 1.112: tracer and IDA. N.B.: some values are cut at right

IDA gave the function a name (PtFuncCompare)—because IDA sees that the pointer to this function is passed to qsort().

We see that the a and b pointers are pointing to various places in the array, but the step between them is 4, as 32-bit values are stored in the array.

We see that the instructions at 0x401010 and 0x401012 were never executed (so they left as white): indeed, comp() has never returned 0, because there no equal elements in the array.

1.27.2 GCC

Not a big difference:

Listing 1.365: GCC

```
                lea     eax, [esp+40h+var_28]
                mov     [esp+40h+var_40], eax
                mov     [esp+40h+var_28], 764h
                mov     [esp+40h+var_24], 2Dh
                mov     [esp+40h+var_20], 0C8h
                mov     [esp+40h+var_1C], 0FFFFFF9Eh
                mov     [esp+40h+var_18], 0FF7h
                mov     [esp+40h+var_14], 5
                mov     [esp+40h+var_10], 0FFFFCFC7h
                mov     [esp+40h+var_C], 43Fh
                mov     [esp+40h+var_8], 58h
                mov     [esp+40h+var_4], 0FFFE7960h
                mov     [esp+40h+var_34], offset comp
                mov     [esp+40h+var_38], 4
                mov     [esp+40h+var_3C], 0Ah
                call    _qsort
```

comp() function:

```
                public comp
comp            proc near

arg_0           = dword ptr  8
arg_4           = dword ptr  0Ch

                push    ebp
                mov     ebp, esp
                mov     eax, [ebp+arg_4]
                mov     ecx, [ebp+arg_0]
                mov     edx, [eax]
                xor     eax, eax
                cmp     [ecx], edx
                jnz     short loc_8048458
                pop     ebp
                retn
loc_8048458:
                setnl   al
                movzx   eax, al
                lea     eax, [eax+eax-1]
                pop     ebp
                retn
comp            endp
```

The implementation of qsort() is located in libc.so.6 and it is in fact just a wrapper [175] for qsort_r().

In turn, it is calling quicksort(), where our defined function is called via a passed pointer:

Listing 1.366: (file libc.so.6, glibc version—2.10.1)

```
...
.text:0002DDF6                 mov     edx, [ebp+arg_10]
.text:0002DDF9                 mov     [esp+4], esi
.text:0002DDFD                 mov     [esp], edi
.text:0002DE00                 mov     [esp+8], edx
.text:0002DE04                 call    [ebp+arg_C]
...
```

GCC + GDB (with source code)

Obviously, we have the C-source code of our example (1.27 on page 385), so we can set a breakpoint (b) on line number (11—the line where the first comparison occurs). We also have to compile the example with debugging information included (-g), so the table with addresses and corresponding line numbers is present.

We can also print values using variable names (p): the debugging information also has tells us which register and/or local stack element contains which variable.

We can also see the stack (bt) and find out that there is some intermediate function msort_with_tmp() used in Glibc.

Listing 1.367: GDB session

```
dennis@ubuntuvm:~/polygon$ gcc 17_1.c -g
dennis@ubuntuvm:~/polygon$ gdb ./a.out
GNU gdb (GDB) 7.6.1-ubuntu
Copyright (C) 2013 Free Software Foundation, Inc.
...
Reading symbols from /home/dennis/polygon/a.out...done.
(gdb) b 17_1.c:11
Breakpoint 1 at 0x804845f: file 17_1.c, line 11.
(gdb) run
Starting program: /home/dennis/polygon/./a.out

Breakpoint 1, comp (_a=0xbffff0f8, _b=_b@entry=0xbffff0fc) at 17_1.c:11
11          if (*a==*b)
```

[175] a concept like thunk function

```
(gdb) p *a
$1 = 1892
(gdb) p *b
$2 = 45
(gdb) c
Continuing.

Breakpoint 1, comp (_a=0xbffff104, _b=_b@entry=0xbffff108) at 17_1.c:11
11        if (*a==*b)
(gdb) p *a
$3 = -98
(gdb) p *b
$4 = 4087
(gdb) bt
#0  comp (_a=0xbffff0f8, _b=_b@entry=0xbffff0fc) at 17_1.c:11
#1  0xb7e42872 in msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=2)
    at msort.c:65
#2  0xb7e4273e in msort_with_tmp (n=2, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#3  msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=5) at msort.c:53
#4  0xb7e4273e in msort_with_tmp (n=5, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#5  msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=10) at msort.c:53
#6  0xb7e42cef in msort_with_tmp (n=10, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#7  __GI_qsort_r (b=b@entry=0xbffff0f8, n=n@entry=10, s=s@entry=4, cmp=cmp@entry=0x804844d <↙
    ↘ comp>,
    arg=arg@entry=0x0) at msort.c:297
#8  0xb7e42dcf in __GI_qsort (b=0xbffff0f8, n=10, s=4, cmp=0x804844d <comp>) at msort.c:307
#9  0x0804850d in main (argc=1, argv=0xbffff1c4) at 17_1.c:26
(gdb)
```

GCC + GDB (no source code)

But often there is no source code at all, so we can disassemble the `comp()` function (`disas`), find the very first CMP instruction and set a breakpoint (b) at that address.

At each breakpoint, we are going to dump all register contents (`info registers`). The stack information is also available (`bt`),

but partially: there is no line number information for `comp()`.

Listing 1.368: GDB session

```
dennis@ubuntuvm:~/polygon$ gcc 17_1.c
dennis@ubuntuvm:~/polygon$ gdb ./a.out
GNU gdb (GDB) 7.6.1-ubuntu
Copyright (C) 2013 Free Software Foundation, Inc.
...
Reading symbols from /home/dennis/polygon/a.out...(no debugging symbols found)...done.
(gdb) set disassembly-flavor intel
(gdb) disas comp
Dump of assembler code for function comp:
   0x0804844d <+0>:     push   ebp
   0x0804844e <+1>:     mov    ebp,esp
   0x08048450 <+3>:     sub    esp,0x10
   0x08048453 <+6>:     mov    eax,DWORD PTR [ebp+0x8]
   0x08048456 <+9>:     mov    DWORD PTR [ebp-0x8],eax
   0x08048459 <+12>:    mov    eax,DWORD PTR [ebp+0xc]
   0x0804845c <+15>:    mov    DWORD PTR [ebp-0x4],eax
   0x0804845f <+18>:    mov    eax,DWORD PTR [ebp-0x8]
   0x08048462 <+21>:    mov    edx,DWORD PTR [eax]
   0x08048464 <+23>:    mov    eax,DWORD PTR [ebp-0x4]
   0x08048467 <+26>:    mov    eax,DWORD PTR [eax]
   0x08048469 <+28>:    cmp    edx,eax
   0x0804846b <+30>:    jne    0x8048474 <comp+39>
   0x0804846d <+32>:    mov    eax,0x0
   0x08048472 <+37>:    jmp    0x804848e <comp+65>
   0x08048474 <+39>:    mov    eax,DWORD PTR [ebp-0x8]
   0x08048477 <+42>:    mov    edx,DWORD PTR [eax]
   0x08048479 <+44>:    mov    eax,DWORD PTR [ebp-0x4]
   0x0804847c <+47>:    mov    eax,DWORD PTR [eax]
```

```
   0x0804847e <+49>:    cmp    edx,eax
   0x08048480 <+51>:    jge    0x8048489 <comp+60>
   0x08048482 <+53>:    mov    eax,0xffffffff
   0x08048487 <+58>:    jmp    0x804848e <comp+65>
   0x08048489 <+60>:    mov    eax,0x1
   0x0804848e <+65>:    leave
   0x0804848f <+66>:    ret
End of assembler dump.
(gdb) b *0x08048469
Breakpoint 1 at 0x8048469
(gdb) run
Starting program: /home/dennis/polygon/./a.out

Breakpoint 1, 0x08048469 in comp ()
(gdb) info registers
eax            0x2d     45
ecx            0xbffff0f8       -1073745672
edx            0x764    1892
ebx            0xb7fc0000       -1208221696
esp            0xbfffeeb8       0xbfffeeb8
ebp            0xbfffeec8       0xbfffeec8
esi            0xbffff0fc       -1073745668
edi            0xbffff010       -1073745904
eip            0x8048469        0x8048469 <comp+28>
eflags         0x286    [ PF SF IF ]
cs             0x73     115
ss             0x7b     123
ds             0x7b     123
es             0x7b     123
fs             0x0      0
gs             0x33     51
(gdb) c
Continuing.

Breakpoint 1, 0x08048469 in comp ()
(gdb) info registers
eax            0xff7    4087
ecx            0xbffff104       -1073745660
edx            0xffffff9e       -98
ebx            0xb7fc0000       -1208221696
esp            0xbfffee58       0xbfffee58
ebp            0xbfffee68       0xbfffee68
esi            0xbffff108       -1073745656
edi            0xbffff010       -1073745904
eip            0x8048469        0x8048469 <comp+28>
eflags         0x282    [ SF IF ]
cs             0x73     115
ss             0x7b     123
ds             0x7b     123
es             0x7b     123
fs             0x0      0
gs             0x33     51
(gdb) c
Continuing.

Breakpoint 1, 0x08048469 in comp ()
(gdb) info registers
eax            0xffffff9e       -98
ecx            0xbffff100       -1073745664
edx            0xc8     200
ebx            0xb7fc0000       -1208221696
esp            0xbfffeeb8       0xbfffeeb8
ebp            0xbfffeec8       0xbfffeec8
esi            0xbffff104       -1073745660
edi            0xbffff010       -1073745904
eip            0x8048469        0x8048469 <comp+28>
eflags         0x286    [ PF SF IF ]
cs             0x73     115
ss             0x7b     123
ds             0x7b     123
```

```
es             0x7b     123
fs             0x0      0
gs             0x33     51
(gdb) bt
#0  0x08048469 in comp ()
#1  0xb7e42872 in msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=2)
    at msort.c:65
#2  0xb7e4273e in msort_with_tmp (n=2, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#3  msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=5) at msort.c:53
#4  0xb7e4273e in msort_with_tmp (n=5, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#5  msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=10) at msort.c:53
#6  0xb7e42cef in msort_with_tmp (n=10, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#7  __GI_qsort_r (b=b@entry=0xbffff0f8, n=n@entry=10, s=s@entry=4, cmp=cmp@entry=0x804844d <↙
    ↳ comp>,
    arg=arg@entry=0x0) at msort.c:297
#8  0xb7e42dcf in __GI_qsort (b=0xbffff0f8, n=10, s=4, cmp=0x804844d <comp>) at msort.c:307
#9  0x0804850d in main ()
```

1.27.3 Danger of pointers to functions

As we can see, `qsort()` function expects a pointer to function which takes two *void** arguments and returning integer. If you have several comparison functions in your code (one compares string, another—integers, etc), it's very easy to mix them up with each other. You could try to sort array of string using function which compares integers, and compiler will not warn you about bug.

1.28 64-bit values in 32-bit environment

In a 32-bit environment, GPR's are 32-bit, so 64-bit values are stored and passed as 32-bit value pairs [176].

1.28.1 Returning of 64-bit value

```
#include <stdint.h>

uint64_t f ()
{
        return 0x1234567890ABCDEF;
};
```

x86

In a 32-bit environment, 64-bit values are returned from functions in the EDX:EAX register pair.

Listing 1.369: Optimizing MSVC 2010

```
_f      PROC
        mov     eax, -1867788817 ; 90abcdefH
        mov     edx, 305419896   ; 12345678H
        ret     0
_f      ENDP
```

ARM

A 64-bit value is returned in the R0-R1 register pair (R1 is for the high part and R0 for the low part):

[176] By the way, 32-bit values are passed as pairs in 16-bit environment in the same way: 3.29.4 on page 652

Listing 1.370: Optimizing Keil 6/2013 (ARM mode)

```
||f|| PROC
        LDR      r0,|L0.12|
        LDR      r1,|L0.16|
        BX       lr
        ENDP

|L0.12|
        DCD      0x90abcdef
|L0.16|
        DCD      0x12345678
```

MIPS

A 64-bit value is returned in the V0-V1 ($2-$3) register pair (V0 ($2) is for the high part and V1 ($3) for the low part):

Listing 1.371: Optimizing GCC 4.4.5 (assembly listing)

```
        li      $3,-1867841536   # 0xffffffff90ab0000
        li      $2,305397760     # 0x12340000
        ori     $3,$3,0xcdef
        j       $31
        ori     $2,$2,0x5678
```

Listing 1.372: Optimizing GCC 4.4.5 (IDA)

```
       lui     $v1, 0x90AB
       lui     $v0, 0x1234
       li      $v1, 0x90ABCDEF
       jr      $ra
       li      $v0, 0x12345678
```

1.28.2 Arguments passing, addition, subtraction

```
#include <stdint.h>

uint64_t f_add (uint64_t a, uint64_t b)
{
        return a+b;
};

void f_add_test ()
{
#ifdef __GNUC__
        printf ("%lld\n", f_add(12345678901234, 23456789012345));
#else
        printf ("%I64d\n", f_add(12345678901234, 23456789012345));
#endif
};

uint64_t f_sub (uint64_t a, uint64_t b)
{
        return a-b;
};
```

x86

Listing 1.373: Optimizing MSVC 2012 /Ob1

```
_a$ = 8         ; size = 8
_b$ = 16        ; size = 8
_f_add  PROC
```

```
        mov     eax, DWORD PTR _a$[esp-4]
        add     eax, DWORD PTR _b$[esp-4]
        mov     edx, DWORD PTR _a$[esp]
        adc     edx, DWORD PTR _b$[esp]
        ret     0
_f_add  ENDP

_f_add_test PROC
        push    5461            ; 00001555H
        push    1972608889      ; 75939f79H
        push    2874            ; 00000b3aH
        push    1942892530      ; 73ce2ff_subH
        call    _f_add
        push    edx
        push    eax
        push    OFFSET $SG1436 ; '%I64d', 0aH, 00H
        call    _printf
        add     esp, 28
        ret     0
_f_add_test ENDP

_f_sub  PROC
        mov     eax, DWORD PTR _a$[esp-4]
        sub     eax, DWORD PTR _b$[esp-4]
        mov     edx, DWORD PTR _a$[esp]
        sbb     edx, DWORD PTR _b$[esp]
        ret     0
_f_sub  ENDP
```

We can see in the `f_add_test()` function that each 64-bit value is passed using two 32-bit values, high part first, then low part.

Addition and subtraction occur in pairs as well.

In addition, the low 32-bit part are added first. If carry has been occurred while adding, the CF flag is set.

The following ADC instruction adds the high parts of the values, and also adds 1 if $CF = 1$.

Subtraction also occurs in pairs. The first SUB may also turn on the CF flag, which is to be checked in the subsequent SBB instruction: if the carry flag is on, then 1 is also to be subtracted from the result.

It is easy to see how the `f_add()` function result is then passed to `printf()`.

Listing 1.374: GCC 4.8.1 -O1 -fno-inline

```
_f_add:
        mov     eax, DWORD PTR [esp+12]
        mov     edx, DWORD PTR [esp+16]
        add     eax, DWORD PTR [esp+4]
        adc     edx, DWORD PTR [esp+8]
        ret

_f_add_test:
        sub     esp, 28
        mov     DWORD PTR [esp+8], 1972608889   ; 75939f79H
        mov     DWORD PTR [esp+12], 5461        ; 00001555H
        mov     DWORD PTR [esp], 1942892530     ; 73ce2ff_subH
        mov     DWORD PTR [esp+4], 2874         ; 00000b3aH
        call    _f_add
        mov     DWORD PTR [esp+4], eax
        mov     DWORD PTR [esp+8], edx
        mov     DWORD PTR [esp], OFFSET FLAT:LC0 ; "%lld\12\0"
        call    _printf
        add     esp, 28
        ret

_f_sub:
        mov     eax, DWORD PTR [esp+4]
        mov     edx, DWORD PTR [esp+8]
        sub     eax, DWORD PTR [esp+12]
        sbb     edx, DWORD PTR [esp+16]
        ret
```

GCC code is the same.

ARM

Listing 1.375: Optimizing Keil 6/2013 (ARM mode)

```
f_add PROC
        ADDS     r0,r0,r2
        ADC      r1,r1,r3
        BX       lr
        ENDP

f_sub PROC
        SUBS     r0,r0,r2
        SBC      r1,r1,r3
        BX       lr
        ENDP

f_add_test PROC
        PUSH     {r4,lr}
        LDR      r2,|L0.68| ; 0x75939f79
        LDR      r3,|L0.72| ; 0x00001555
        LDR      r0,|L0.76| ; 0x73ce2ff2
        LDR      r1,|L0.80| ; 0x00000b3a
        BL       f_add
        POP      {r4,lr}
        MOV      r2,r0
        MOV      r3,r1
        ADR      r0,|L0.84| ; "%I64d\n"
        B        __2printf
        ENDP

|L0.68|
        DCD      0x75939f79
|L0.72|
        DCD      0x00001555
|L0.76|
        DCD      0x73ce2ff2
|L0.80|
        DCD      0x00000b3a
|L0.84|
        DCB      "%I64d\n",0
```

The first 64-bit value is passed in R0 and R1 register pair, the second in R2 and R3 register pair. ARM has the ADC instruction as well (which counts carry flag) and SBC ("subtract with carry"). Important thing: when the low parts are added/subtracted, ADDS and SUBS instructions with -S suffix are used. The -S suffix stands for "set flags", and flags (esp. carry flag) is what consequent ADC/SBC instructions definitely need. Otherwise, instructions without the -S suffix would do the job (ADD and SUB).

MIPS

Listing 1.376: Optimizing GCC 4.4.5 (IDA)

```
f_add:
; $a0 - high part of a
; $a1 - low part of a
; $a2 - high part of b
; $a3 - low part of b
                addu    $v1, $a3, $a1 ; sum up low parts
                addu    $a0, $a2, $a0 ; sum up high parts
; will carry generated while summing up low parts?
; if yes, set $v0 to 1
                sltu    $v0, $v1, $a3
                jr      $ra
; add 1 to high part of result if carry should be generated:
                addu    $v0, $a0 ; branch delay slot
; $v0 - high part of result
```

```
; $v1 - low part of result

f_sub:
; $a0 - high part of a
; $a1 - low part of a
; $a2 - high part of b
; $a3 - low part of b
                subu    $v1, $a1, $a3 ; subtract low parts
                subu    $v0, $a0, $a2 ; subtract high parts
; will carry generated while subtracting low parts?
; if yes, set $a0 to 1
                sltu    $a1, $v1
                jr      $ra
; subtract 1 from high part of result if carry should be generated:
                subu    $v0, $a1 ; branch delay slot
; $v0 - high part of result
; $v1 - low part of result

f_add_test:

var_10          = -0x10
var_4           = -4

                lui     $gp, (__gnu_local_gp >> 16)
                addiu   $sp, -0x20
                la      $gp, (__gnu_local_gp & 0xFFFF)
                sw      $ra, 0x20+var_4($sp)
                sw      $gp, 0x20+var_10($sp)
                lui     $a1, 0x73CE
                lui     $a3, 0x7593
                li      $a0, 0xB3A
                li      $a3, 0x75939F79
                li      $a2, 0x1555
                jal     f_add
                li      $a1, 0x73CE2FF2
                lw      $gp, 0x20+var_10($sp)
                lui     $a0, ($LC0 >> 16)  # "%lld\n"
                lw      $t9, (printf & 0xFFFF)($gp)
                lw      $ra, 0x20+var_4($sp)
                la      $a0, ($LC0 & 0xFFFF)  # "%lld\n"
                move    $a3, $v1
                move    $a2, $v0
                jr      $t9
                addiu   $sp, 0x20

$LC0:           .ascii "%lld\n"<0>
```

MIPS has no flags register, so there is no such information present after the execution of arithmetic operations. So there are no instructions like x86's ADC and SBB. To know if the carry flag would be set, a comparison (using SLTU instruction) also occurs, which sets the destination register to 1 or 0. This 1 or 0 is then added or subtracted to/from the final result.

1.28.3 Multiplication, division

```
#include <stdint.h>

uint64_t f_mul (uint64_t a, uint64_t b)
{
        return a*b;
};

uint64_t f_div (uint64_t a, uint64_t b)
{
        return a/b;
};

uint64_t f_rem (uint64_t a, uint64_t b)
{
```

```
        return a % b;
};
```

x86

Listing 1.377: Optimizing MSVC 2013 /Ob1

```
_a$ = 8 ; size = 8
_b$ = 16 ; size = 8
_f_mul  PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _b$[ebp+4]
        push    eax
        mov     ecx, DWORD PTR _b$[ebp]
        push    ecx
        mov     edx, DWORD PTR _a$[ebp+4]
        push    edx
        mov     eax, DWORD PTR _a$[ebp]
        push    eax
        call    __allmul ; long long multiplication
        pop     ebp
        ret     0
_f_mul  ENDP

_a$ = 8 ; size = 8
_b$ = 16 ; size = 8
_f_div  PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _b$[ebp+4]
        push    eax
        mov     ecx, DWORD PTR _b$[ebp]
        push    ecx
        mov     edx, DWORD PTR _a$[ebp+4]
        push    edx
        mov     eax, DWORD PTR _a$[ebp]
        push    eax
        call    __aulldiv ; unsigned long long division
        pop     ebp
        ret     0
_f_div  ENDP

_a$ = 8 ; size = 8
_b$ = 16 ; size = 8
_f_rem  PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _b$[ebp+4]
        push    eax
        mov     ecx, DWORD PTR _b$[ebp]
        push    ecx
        mov     edx, DWORD PTR _a$[ebp+4]
        push    edx
        mov     eax, DWORD PTR _a$[ebp]
        push    eax
        call    __aullrem ; unsigned long long remainder
        pop     ebp
        ret     0
_f_rem  ENDP
```

Multiplication and division are more complex operations, so usually the compiler embeds calls to a library functions doing that.

These functions are described here: .5 on page 1043.

Listing 1.378: Optimizing GCC 4.8.1 -fno-inline

```
_f_mul:
```

```
        push    ebx
        mov     edx, DWORD PTR [esp+8]
        mov     eax, DWORD PTR [esp+16]
        mov     ebx, DWORD PTR [esp+12]
        mov     ecx, DWORD PTR [esp+20]
        imul    ebx, eax
        imul    ecx, edx
        mul     edx
        add     ecx, ebx
        add     edx, ecx
        pop     ebx
        ret

_f_div:
        sub     esp, 28
        mov     eax, DWORD PTR [esp+40]
        mov     edx, DWORD PTR [esp+44]
        mov     DWORD PTR [esp+8], eax
        mov     eax, DWORD PTR [esp+32]
        mov     DWORD PTR [esp+12], edx
        mov     edx, DWORD PTR [esp+36]
        mov     DWORD PTR [esp], eax
        mov     DWORD PTR [esp+4], edx
        call    ___udivdi3 ; unsigned division
        add     esp, 28
        ret

_f_rem:
        sub     esp, 28
        mov     eax, DWORD PTR [esp+40]
        mov     edx, DWORD PTR [esp+44]
        mov     DWORD PTR [esp+8], eax
        mov     eax, DWORD PTR [esp+32]
        mov     DWORD PTR [esp+12], edx
        mov     edx, DWORD PTR [esp+36]
        mov     DWORD PTR [esp], eax
        mov     DWORD PTR [esp+4], edx
        call    ___umoddi3 ; unsigned modulo
        add     esp, 28
        ret
```

GCC does the expected, but the multiplication code is inlined right in the function, thinking it could be more efficient. GCC has different library function names: .4 on page 1043.

ARM

Keil for Thumb mode inserts library subroutine calls:

Listing 1.379: Optimizing Keil 6/2013 (Thumb mode)

```
||f_mul|| PROC
        PUSH     {r4,lr}
        BL       __aeabi_lmul
        POP      {r4,pc}
        ENDP

||f_div|| PROC
        PUSH     {r4,lr}
        BL       __aeabi_uldivmod
        POP      {r4,pc}
        ENDP

||f_rem|| PROC
        PUSH     {r4,lr}
        BL       __aeabi_uldivmod
        MOVS     r0,r2
        MOVS     r1,r3
        POP      {r4,pc}
        ENDP
```

Keil for ARM mode, on the other hand, is able to produce 64-bit multiplication code:

Listing 1.380: Optimizing Keil 6/2013 (ARM mode)

```
||f_mul|| PROC
        PUSH     {r4,lr}
        UMULL    r12,r4,r0,r2
        MLA      r1,r2,r1,r4
        MLA      r1,r0,r3,r1
        MOV      r0,r12
        POP      {r4,pc}
        ENDP

||f_div|| PROC
        PUSH     {r4,lr}
        BL       __aeabi_uldivmod
        POP      {r4,pc}
        ENDP

||f_rem|| PROC
        PUSH     {r4,lr}
        BL       __aeabi_uldivmod
        MOV      r0,r2
        MOV      r1,r3
        POP      {r4,pc}
        ENDP
```

MIPS

Optimizing GCC for MIPS can generate 64-bit multiplication code, but has to call a library routine for 64-bit division:

Listing 1.381: Optimizing GCC 4.4.5 (IDA)

```
f_mul:
       mult    $a2, $a1
       mflo    $v0
       or      $at, $zero  ; NOP
       or      $at, $zero  ; NOP
       mult    $a0, $a3
       mflo    $a0
       addu    $v0, $a0
       or      $at, $zero  ; NOP
       multu   $a3, $a1
       mfhi    $a2
       mflo    $v1
       jr      $ra
       addu    $v0, $a2

f_div:

var_10 = -0x10
var_4  = -4

       lui     $gp, (__gnu_local_gp >> 16)
       addiu   $sp, -0x20
       la      $gp, (__gnu_local_gp & 0xFFFF)
       sw      $ra, 0x20+var_4($sp)
       sw      $gp, 0x20+var_10($sp)
       lw      $t9, (__udivdi3 & 0xFFFF)($gp)
       or      $at, $zero
       jalr    $t9
       or      $at, $zero
       lw      $ra, 0x20+var_4($sp)
       or      $at, $zero
       jr      $ra
       addiu   $sp, 0x20

f_rem:
```

```
var_10 = -0x10
var_4  = -4

       lui     $gp, (__gnu_local_gp >> 16)
       addiu   $sp, -0x20
       la      $gp, (__gnu_local_gp & 0xFFFF)
       sw      $ra, 0x20+var_4($sp)
       sw      $gp, 0x20+var_10($sp)
       lw      $t9, (__umoddi3 & 0xFFFF)($gp)
       or      $at, $zero
       jalr    $t9
       or      $at, $zero
       lw      $ra, 0x20+var_4($sp)
       or      $at, $zero
       jr      $ra
       addiu   $sp, 0x20
```

There are a lot of NOPs, probably delay slots filled after the multiplication instruction (it's slower than other instructions, after all).

1.28.4 Shifting right

```
#include <stdint.h>

uint64_t f (uint64_t a)
{
        return a>>7;
};
```

x86

Listing 1.382: Optimizing MSVC 2012 /Ob1

```
_a$ = 8         ; size = 8
_f      PROC
        mov     eax, DWORD PTR _a$[esp-4]
        mov     edx, DWORD PTR _a$[esp]
        shrd    eax, edx, 7
        shr     edx, 7
        ret     0
_f      ENDP
```

Listing 1.383: Optimizing GCC 4.8.1 -fno-inline

```
_f:
        mov     edx, DWORD PTR [esp+8]
        mov     eax, DWORD PTR [esp+4]
        shrd    eax, edx, 7
        shr     edx, 7
        ret
```

Shifting also occurs in two passes: first the lower part is shifted, then the higher part. But the lower part is shifted with the help of the SHRD instruction, it shifts the value of EAX by 7 bits, but pulls new bits from EDX, i.e., from the higher part. In other words, 64-bit value from EDX:EAX register's pair, as a whole, is shifted by 7 bits and lowest 32 bits of result are placed into EAX. The higher part is shifted using the much more popular SHR instruction: indeed, the freed bits in the higher part must be filled with zeros.

ARM

ARM doesn't have such instruction as SHRD in x86, so the Keil compiler ought to do this using simple shifts and OR operations:

Listing 1.384: Optimizing Keil 6/2013 (ARM mode)

```
||f|| PROC
        LSR      r0,r0,#7
        ORR      r0,r0,r1,LSL #25
        LSR      r1,r1,#7
        BX       lr
        ENDP
```

Listing 1.385: Optimizing Keil 6/2013 (Thumb mode)

```
||f|| PROC
        LSLS     r2,r1,#25
        LSRS     r0,r0,#7
        ORRS     r0,r0,r2
        LSRS     r1,r1,#7
        BX       lr
        ENDP
```

MIPS

GCC for MIPS follows the same algorithm as Keil does for Thumb mode:

Listing 1.386: Optimizing GCC 4.4.5 (IDA)

```
f:
       sll     $v0, $a0, 25
       srl     $v1, $a1, 7
       or      $v1, $v0, $v1
       jr      $ra
       srl     $v0, $a0, 7
```

1.28.5 Converting 32-bit value into 64-bit one

```
#include <stdint.h>

int64_t f (int32_t a)
{
        return a;
};
```

x86

Listing 1.387: Optimizing MSVC 2012

```
_a$ = 8
_f      PROC
        mov     eax, DWORD PTR _a$[esp-4]
        cdq
        ret     0
_f      ENDP
```

Here we also run into necessity to extend a 32-bit signed value into a 64-bit signed one. Unsigned values are converted straightforwardly: all bits in the higher part must be set to 0. But this is not appropriate for signed data types: the sign has to be copied into the higher part of the resulting number.

The CDQ instruction does that here, it takes its input value in EAX, extends it to 64-bit and leaves it in the EDX:EAX register pair. In other words, CDQ gets the number sign from EAX (by getting the most significant bit in EAX), and depending of it, sets all 32 bits in EDX to 0 or 1. Its operation is somewhat similar to the MOVSX instruction.

ARM

Listing 1.388: Optimizing Keil 6/2013 (ARM mode)

```
||f|| PROC
        ASR      r1,r0,#31
        BX       lr
        ENDP
```

Keil for ARM is different: it just arithmetically shifts right the input value by 31 bits. As we know, the sign bit is MSB, and the arithmetical shift copies the sign bit into the "emerged" bits. So after "ASR r1,r0,#31", R1 containing 0xFFFFFFFF if the input value has been negative and 0 otherwise. R1 contains the high part of the resulting 64-bit value. In other words, this code just copies the MSB (sign bit) from the input value in R0 to all bits of the high 32-bit part of the resulting 64-bit value.

MIPS

GCC for MIPS does the same as Keil did for ARM mode:

Listing 1.389: Optimizing GCC 4.4.5 (IDA)

```
f:
    sra     $v0, $a0, 31
    jr      $ra
    move    $v1, $a0
```

1.29 SIMD

SIMD is an acronym: *Single Instruction, Multiple Data*.

As its name implies, it processes multiple data using only one instruction.

Like the FPU, that CPU subsystem looks like a separate processor inside x86.

SIMD began as MMX in x86. 8 new 64-bit registers appeared: MM0-MM7.

Each MMX register can hold 2 32-bit values, 4 16-bit values or 8 bytes. For example, it is possible to add 8 8-bit values (bytes) simultaneously by adding two values in MMX registers.

One simple example is a graphics editor that represents an image as a two dimensional array. When the user changes the brightness of the image, the editor must add or subtract a coefficient to/from each pixel value. For the sake of brevity if we say that the image is grayscale and each pixel is defined by one 8-bit byte, then it is possible to change the brightness of 8 pixels simultaneously.

By the way, this is the reason why the *saturation* instructions are present in SIMD.

When the user changes the brightness in the graphics editor, overflow and underflow are not desirable, so there are addition instructions in SIMD which are not adding anything if the maximum value is reached, etc.

When MMX appeared, these registers were actually located in the FPU's registers. It was possible to use either FPU or MMX at the same time. One might think that Intel saved on transistors, but in fact the reason of such symbiosis was simpler —older OSes that are not aware of the additional CPU registers would not save them at the context switch, but saving the FPU registers. Thus, MMX-enabled CPU + old OS + process utilizing MMX features will still work.

SSE—is extension of the SIMD registers to 128 bits, now separate from the FPU.

AVX—another extension, to 256 bits.

Now about practical usage.

Of course, this is memory copy routines (`memcpy`), memory comparing (`memcmp`) and so on.

One more example: the DES encryption algorithm takes a 64-bit block and a 56-bit key, encrypt the block and produces a 64-bit result. The DES algorithm may be considered as a very large electronic circuit, with wires and AND/OR/NOT gates.

Bitslice DES[177] —is the idea of processing groups of blocks and keys simultaneously. Let's say, variable of type *unsigned int* on x86 can hold up to 32 bits, so it is possible to store there intermediate results for 32 block-key pairs simultaneously, using 64+56 variables of type *unsigned int*.

There is an utility to brute-force Oracle RDBMS passwords/hashes (ones based on DES), using slightly modified bitslice DES algorithm for SSE2 and AVX—now it is possible to encrypt 128 or 256 block-keys pairs simultaneously.

http://go.yurichev.com/17313

1.29.1 Vectorization

Vectorization[178] is when, for example, you have a loop taking couple of arrays for input and producing one array. The loop body takes values from the input arrays, does something and puts the result into the output array. Vectorization is to process several elements simultaneously.

Vectorization is not very fresh technology: the author of this textbook saw it at least on the Cray Y-MP supercomputer line from 1988 when he played with its "lite" version Cray Y-MP EL [179].

For example:

```
for (i = 0; i < 1024; i++)
{
    C[i] = A[i]*B[i];
}
```

This fragment of code takes elements from A and B, multiplies them and saves the result into C.

If each array element we have is 32-bit *int*, then it is possible to load 4 elements from A into a 128-bit XMM-register, from B to another XMM-registers, and by executing *PMULLD* (*Multiply Packed Signed Dword Integers and Store Low Result*) and PMULHW (*Multiply Packed Signed Integers and Store High Result*), it is possible to get 4 64-bit products at once.

Thus, loop body execution count is $1024/4$ instead of 1024, that is 4 times less and, of course, faster.

Addition example

Some compilers can do vectorization automatically in simple cases, e.g., Intel C++[180].

Here is tiny function:

```
int f (int sz, int *ar1, int *ar2, int *ar3)
{
        for (int i=0; i<sz; i++)
                ar3[i]=ar1[i]+ar2[i];

        return 0;
};
```

Intel C++

Let's compile it with Intel C++ 11.1.051 win32:

`icl intel.cpp /QaxSSE2 /Faintel.asm /Ox`

We got (in IDA):

```
; int __cdecl f(int, int *, int *, int *)
                public ?f@@YAHHPAH00@Z
?f@@YAHHPAH00@Z proc near

var_10 = dword ptr -10h
```

[177] http://go.yurichev.com/17329
[178] Wikipedia: vectorization
[179] Remotely. It is installed in the museum of supercomputers: http://go.yurichev.com/17081
[180] More about Intel C++ automatic vectorization: Excerpt: Effective Automatic Vectorization

```
sz      = dword ptr  4
ar1     = dword ptr  8
ar2     = dword ptr  0Ch
ar3     = dword ptr  10h

        push    edi
        push    esi
        push    ebx
        push    esi
        mov     edx, [esp+10h+sz]
        test    edx, edx
        jle     loc_15B
        mov     eax, [esp+10h+ar3]
        cmp     edx, 6
        jle     loc_143
        cmp     eax, [esp+10h+ar2]
        jbe     short loc_36
        mov     esi, [esp+10h+ar2]
        sub     esi, eax
        lea     ecx, ds:0[edx*4]
        neg     esi
        cmp     ecx, esi
        jbe     short loc_55

loc_36: ; CODE XREF: f(int,int *,int *,int *)+21
        cmp     eax, [esp+10h+ar2]
        jnb     loc_143
        mov     esi, [esp+10h+ar2]
        sub     esi, eax
        lea     ecx, ds:0[edx*4]
        cmp     esi, ecx
        jb      loc_143

loc_55: ; CODE XREF: f(int,int *,int *,int *)+34
        cmp     eax, [esp+10h+ar1]
        jbe     short loc_67
        mov     esi, [esp+10h+ar1]
        sub     esi, eax
        neg     esi
        cmp     ecx, esi
        jbe     short loc_7F

loc_67: ; CODE XREF: f(int,int *,int *,int *)+59
        cmp     eax, [esp+10h+ar1]
        jnb     loc_143
        mov     esi, [esp+10h+ar1]
        sub     esi, eax
        cmp     esi, ecx
        jb      loc_143

loc_7F: ; CODE XREF: f(int,int *,int *,int *)+65
        mov     edi, eax        ; edi = ar3
        and     edi, 0Fh        ; is ar3 16-byte aligned?
        jz      short loc_9A    ; yes
        test    edi, 3
        jnz     loc_162
        neg     edi
        add     edi, 10h
        shr     edi, 2

loc_9A: ; CODE XREF: f(int,int *,int *,int *)+84
        lea     ecx, [edi+4]
        cmp     edx, ecx
        jl      loc_162
        mov     ecx, edx
        sub     ecx, edi
        and     ecx, 3
        neg     ecx
        add     ecx, edx
        test    edi, edi
```

```
        jbe     short loc_D6
        mov     ebx, [esp+10h+ar2]
        mov     [esp+10h+var_10], ecx
        mov     ecx, [esp+10h+ar1]
        xor     esi, esi

loc_C1: ; CODE XREF: f(int,int *,int *,int *)+CD
        mov     edx, [ecx+esi*4]
        add     edx, [ebx+esi*4]
        mov     [eax+esi*4], edx
        inc     esi
        cmp     esi, edi
        jb      short loc_C1
        mov     ecx, [esp+10h+var_10]
        mov     edx, [esp+10h+sz]

loc_D6: ; CODE XREF: f(int,int *,int *,int *)+B2
        mov     esi, [esp+10h+ar2]
        lea     esi, [esi+edi*4] ; is ar2+i*4 16-byte aligned?
        test    esi, 0Fh
        jz      short loc_109   ; yes!
        mov     ebx, [esp+10h+ar1]
        mov     esi, [esp+10h+ar2]

loc_ED: ; CODE XREF: f(int,int *,int *,int *)+105
        movdqu  xmm1, xmmword ptr [ebx+edi*4] ; ar1+i*4
        movdqu  xmm0, xmmword ptr [esi+edi*4] ; ar2+i*4 is not 16-byte aligned, so load it to ↙
    ↘ XMM0
        paddd   xmm1, xmm0
        movdqa  xmmword ptr [eax+edi*4], xmm1 ; ar3+i*4
        add     edi, 4
        cmp     edi, ecx
        jb      short loc_ED
        jmp     short loc_127

loc_109: ; CODE XREF: f(int,int *,int *,int *)+E3
        mov     ebx, [esp+10h+ar1]
        mov     esi, [esp+10h+ar2]

loc_111: ; CODE XREF: f(int,int *,int *,int *)+125
        movdqu  xmm0, xmmword ptr [ebx+edi*4]
        paddd   xmm0, xmmword ptr [esi+edi*4]
        movdqa  xmmword ptr [eax+edi*4], xmm0
        add     edi, 4
        cmp     edi, ecx
        jb      short loc_111

loc_127: ; CODE XREF: f(int,int *,int *,int *)+107
         ; f(int,int *,int *,int *)+164
        cmp     ecx, edx
        jnb     short loc_15B
        mov     esi, [esp+10h+ar1]
        mov     edi, [esp+10h+ar2]

loc_133: ; CODE XREF: f(int,int *,int *,int *)+13F
        mov     ebx, [esi+ecx*4]
        add     ebx, [edi+ecx*4]
        mov     [eax+ecx*4], ebx
        inc     ecx
        cmp     ecx, edx
        jb      short loc_133
        jmp     short loc_15B

loc_143: ; CODE XREF: f(int,int *,int *,int *)+17
         ; f(int,int *,int *,int *)+3A ...
        mov     esi, [esp+10h+ar1]
        mov     edi, [esp+10h+ar2]
        xor     ecx, ecx

loc_14D: ; CODE XREF: f(int,int *,int *,int *)+159
```

```
        mov     ebx, [esi+ecx*4]
        add     ebx, [edi+ecx*4]
        mov     [eax+ecx*4], ebx
        inc     ecx
        cmp     ecx, edx
        jb      short loc_14D

loc_15B: ; CODE XREF: f(int,int *,int *,int *)+A
          ; f(int,int *,int *,int *)+129 ...
        xor     eax, eax
        pop     ecx
        pop     ebx
        pop     esi
        pop     edi
        retn

loc_162: ; CODE XREF: f(int,int *,int *,int *)+8C
          ; f(int,int *,int *,int *)+9F
        xor     ecx, ecx
        jmp     short loc_127
?f@@YAHHPAH00@Z endp
```

The SSE2-related instructions are:

- MOVDQU (*Move Unaligned Double Quadword*)—just loads 16 bytes from memory into a XMM-register.
- PADDD (*Add Packed Integers*)—adds 4 pairs of 32-bit numbers and leaves the result in the first operand. By the way, no exception is raised in case of overflow and no flags are to be set, just the low 32 bits of the result are to be stored. If one of PADDD's operands is the address of a value in memory, then the address must be aligned on a 16-byte boundary. If it is not aligned, an exception will be triggered [181].
- MOVDQA (*Move Aligned Double Quadword*) is the same as MOVDQU, but requires the address of the value in memory to be aligned on a 16-bit boundary. If it is not aligned, exception will be raised. MOVDQA works faster than MOVDQU, but requires aforesaid.

So, these SSE2-instructions are to be executed only in case there are more than 4 pairs to work on and the pointer ar3 is aligned on a 16-byte boundary.

Also, if ar2 is aligned on a 16-byte boundary as well, this fragment of code is to be executed:

```
movdqu  xmm0, xmmword ptr [ebx+edi*4] ; ar1+i*4
paddd   xmm0, xmmword ptr [esi+edi*4] ; ar2+i*4
movdqa  xmmword ptr [eax+edi*4], xmm0 ; ar3+i*4
```

Otherwise, the value from ar2 is to be loaded into XMM0 using MOVDQU, which does not require aligned pointer, but may work slower:

```
movdqu  xmm1, xmmword ptr [ebx+edi*4] ; ar1+i*4
movdqu  xmm0, xmmword ptr [esi+edi*4] ; ar2+i*4 is not 16-byte aligned, so load it to XMM0
paddd   xmm1, xmm0
movdqa  xmmword ptr [eax+edi*4], xmm1 ; ar3+i*4
```

In all other cases, non-SSE2 code is to be executed.

GCC

GCC may also vectorize in simple cases[182], if the -O3 option is used and SSE2 support is turned on: -msse2.

What we get (GCC 4.4.1):

```
; f(int, int *, int *, int *)
            public _Z1fiPiS_S_
_Z1fiPiS_S_ proc near

var_18      = dword ptr -18h
var_14      = dword ptr -14h
```

[181] More about data alignment: Wikipedia: Data structure alignment
[182] More about GCC vectorization support: http://go.yurichev.com/17083

```
var_10      = dword ptr -10h
arg_0       = dword ptr  8
arg_4       = dword ptr  0Ch
arg_8       = dword ptr  10h
arg_C       = dword ptr  14h

            push    ebp
            mov     ebp, esp
            push    edi
            push    esi
            push    ebx
            sub     esp, 0Ch
            mov     ecx, [ebp+arg_0]
            mov     esi, [ebp+arg_4]
            mov     edi, [ebp+arg_8]
            mov     ebx, [ebp+arg_C]
            test    ecx, ecx
            jle     short loc_80484D8
            cmp     ecx, 6
            lea     eax, [ebx+10h]
            ja      short loc_80484E8

loc_80484C1: ; CODE XREF: f(int,int *,int *,int *)+4B
             ; f(int,int *,int *,int *)+61 ...
            xor     eax, eax
            nop
            lea     esi, [esi+0]

loc_80484C8: ; CODE XREF: f(int,int *,int *,int *)+36
            mov     edx, [edi+eax*4]
            add     edx, [esi+eax*4]
            mov     [ebx+eax*4], edx
            add     eax, 1
            cmp     eax, ecx
            jnz     short loc_80484C8

loc_80484D8: ; CODE XREF: f(int,int *,int *,int *)+17
             ; f(int,int *,int *,int *)+A5
            add     esp, 0Ch
            xor     eax, eax
            pop     ebx
            pop     esi
            pop     edi
            pop     ebp
            retn

            align 8

loc_80484E8: ; CODE XREF: f(int,int *,int *,int *)+1F
            test    bl, 0Fh
            jnz     short loc_80484C1
            lea     edx, [esi+10h]
            cmp     ebx, edx
            jbe     loc_8048578

loc_80484F8: ; CODE XREF: f(int,int *,int *,int *)+E0
            lea     edx, [edi+10h]
            cmp     ebx, edx
            ja      short loc_8048503
            cmp     edi, eax
            jbe     short loc_80484C1

loc_8048503: ; CODE XREF: f(int,int *,int *,int *)+5D
            mov     eax, ecx
            shr     eax, 2
            mov     [ebp+var_14], eax
            shl     eax, 2
            test    eax, eax
            mov     [ebp+var_10], eax
            jz      short loc_8048547
```

```
            mov     [ebp+var_18], ecx
            mov     ecx, [ebp+var_14]
            xor     eax, eax
            xor     edx, edx
            nop

loc_8048520: ; CODE XREF: f(int,int *,int *,int *)+9B
            movdqu  xmm1, xmmword ptr [edi+eax]
            movdqu  xmm0, xmmword ptr [esi+eax]
            add     edx, 1
            paddd   xmm0, xmm1
            movdqa  xmmword ptr [ebx+eax], xmm0
            add     eax, 10h
            cmp     edx, ecx
            jb      short loc_8048520
            mov     ecx, [ebp+var_18]
            mov     eax, [ebp+var_10]
            cmp     ecx, eax
            jz      short loc_80484D8

loc_8048547: ; CODE XREF: f(int,int *,int *,int *)+73
            lea     edx, ds:0[eax*4]
            add     esi, edx
            add     edi, edx
            add     ebx, edx
            lea     esi, [esi+0]

loc_8048558: ; CODE XREF: f(int,int *,int *,int *)+CC
            mov     edx, [edi]
            add     eax, 1
            add     edi, 4
            add     edx, [esi]
            add     esi, 4
            mov     [ebx], edx
            add     ebx, 4
            cmp     ecx, eax
            jg      short loc_8048558
            add     esp, 0Ch
            xor     eax, eax
            pop     ebx
            pop     esi
            pop     edi
            pop     ebp
            retn

loc_8048578: ; CODE XREF: f(int,int *,int *,int *)+52
            cmp     eax, esi
            jnb     loc_80484C1
            jmp     loc_80484F8
_Z1fiPiS_S_ endp
```

Almost the same, however, not as meticulously as Intel C++.

Memory copy example

Let's revisit the simple memcpy() example (1.16.2 on page 195):

```
#include <stdio.h>

void my_memcpy (unsigned char* dst, unsigned char* src, size_t cnt)
{
        size_t i;
        for (i=0; i<cnt; i++)
                dst[i]=src[i];
};
```

And that's what optimizations GCC 4.9.1 did:

Listing 1.390: Optimizing GCC 4.9.1 x64

```
my_memcpy:
; RDI = destination address
; RSI = source address
; RDX = size of block
        test    rdx, rdx
        je      .L41
        lea     rax, [rdi+16]
        cmp     rsi, rax
        lea     rax, [rsi+16]
        setae   cl
        cmp     rdi, rax
        setae   al
        or      cl, al
        je      .L13
        cmp     rdx, 22
        jbe     .L13
        mov     rcx, rsi
        push    rbp
        push    rbx
        neg     rcx
        and     ecx, 15
        cmp     rcx, rdx
        cmova   rcx, rdx
        xor     eax, eax
        test    rcx, rcx
        je      .L4
        movzx   eax, BYTE PTR [rsi]
        cmp     rcx, 1
        mov     BYTE PTR [rdi], al
        je      .L15
        movzx   eax, BYTE PTR [rsi+1]
        cmp     rcx, 2
        mov     BYTE PTR [rdi+1], al
        je      .L16
        movzx   eax, BYTE PTR [rsi+2]
        cmp     rcx, 3
        mov     BYTE PTR [rdi+2], al
        je      .L17
        movzx   eax, BYTE PTR [rsi+3]
        cmp     rcx, 4
        mov     BYTE PTR [rdi+3], al
        je      .L18
        movzx   eax, BYTE PTR [rsi+4]
        cmp     rcx, 5
        mov     BYTE PTR [rdi+4], al
        je      .L19
        movzx   eax, BYTE PTR [rsi+5]
        cmp     rcx, 6
        mov     BYTE PTR [rdi+5], al
        je      .L20
        movzx   eax, BYTE PTR [rsi+6]
        cmp     rcx, 7
        mov     BYTE PTR [rdi+6], al
        je      .L21
        movzx   eax, BYTE PTR [rsi+7]
        cmp     rcx, 8
        mov     BYTE PTR [rdi+7], al
        je      .L22
        movzx   eax, BYTE PTR [rsi+8]
        cmp     rcx, 9
        mov     BYTE PTR [rdi+8], al
        je      .L23
        movzx   eax, BYTE PTR [rsi+9]
        cmp     rcx, 10
        mov     BYTE PTR [rdi+9], al
        je      .L24
        movzx   eax, BYTE PTR [rsi+10]
        cmp     rcx, 11
        mov     BYTE PTR [rdi+10], al
```

```
        je      .L25
        movzx   eax, BYTE PTR [rsi+11]
        cmp     rcx, 12
        mov     BYTE PTR [rdi+11], al
        je      .L26
        movzx   eax, BYTE PTR [rsi+12]
        cmp     rcx, 13
        mov     BYTE PTR [rdi+12], al
        je      .L27
        movzx   eax, BYTE PTR [rsi+13]
        cmp     rcx, 15
        mov     BYTE PTR [rdi+13], al
        jne     .L28
        movzx   eax, BYTE PTR [rsi+14]
        mov     BYTE PTR [rdi+14], al
        mov     eax, 15
.L4:
        mov     r10, rdx
        lea     r9, [rdx-1]
        sub     r10, rcx
        lea     r8, [r10-16]
        sub     r9, rcx
        shr     r8, 4
        add     r8, 1
        mov     r11, r8
        sal     r11, 4
        cmp     r9, 14
        jbe     .L6
        lea     rbp, [rsi+rcx]
        xor     r9d, r9d
        add     rcx, rdi
        xor     ebx, ebx
.L7:
        movdqa  xmm0, XMMWORD PTR [rbp+0+r9]
        add     rbx, 1
        movups  XMMWORD PTR [rcx+r9], xmm0
        add     r9, 16
        cmp     rbx, r8
        jb      .L7
        add     rax, r11
        cmp     r10, r11
        je      .L1
.L6:
        movzx   ecx, BYTE PTR [rsi+rax]
        mov     BYTE PTR [rdi+rax], cl
        lea     rcx, [rax+1]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+1+rax]
        mov     BYTE PTR [rdi+1+rax], cl
        lea     rcx, [rax+2]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+2+rax]
        mov     BYTE PTR [rdi+2+rax], cl
        lea     rcx, [rax+3]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+3+rax]
        mov     BYTE PTR [rdi+3+rax], cl
        lea     rcx, [rax+4]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+4+rax]
        mov     BYTE PTR [rdi+4+rax], cl
        lea     rcx, [rax+5]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+5+rax]
        mov     BYTE PTR [rdi+5+rax], cl
```

```
        lea     rcx, [rax+6]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+6+rax]
        mov     BYTE PTR [rdi+6+rax], cl
        lea     rcx, [rax+7]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+7+rax]
        mov     BYTE PTR [rdi+7+rax], cl
        lea     rcx, [rax+8]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+8+rax]
        mov     BYTE PTR [rdi+8+rax], cl
        lea     rcx, [rax+9]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+9+rax]
        mov     BYTE PTR [rdi+9+rax], cl
        lea     rcx, [rax+10]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+10+rax]
        mov     BYTE PTR [rdi+10+rax], cl
        lea     rcx, [rax+11]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+11+rax]
        mov     BYTE PTR [rdi+11+rax], cl
        lea     rcx, [rax+12]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+12+rax]
        mov     BYTE PTR [rdi+12+rax], cl
        lea     rcx, [rax+13]
        cmp     rdx, rcx
        jbe     .L1
        movzx   ecx, BYTE PTR [rsi+13+rax]
        mov     BYTE PTR [rdi+13+rax], cl
        lea     rcx, [rax+14]
        cmp     rdx, rcx
        jbe     .L1
        movzx   edx, BYTE PTR [rsi+14+rax]
        mov     BYTE PTR [rdi+14+rax], dl
.L1:
        pop     rbx
        pop     rbp
.L41:
        rep ret
.L13:
        xor     eax, eax
.L3:
        movzx   ecx, BYTE PTR [rsi+rax]
        mov     BYTE PTR [rdi+rax], cl
        add     rax, 1
        cmp     rax, rdx
        jne     .L3
        rep ret
.L28:
        mov     eax, 14
        jmp     .L4
.L15:
        mov     eax, 1
        jmp     .L4
.L16:
        mov     eax, 2
        jmp     .L4
.L17:
        mov     eax, 3
```

```
        jmp     .L4
.L18:
        mov     eax, 4
        jmp     .L4
.L19:
        mov     eax, 5
        jmp     .L4
.L20:
        mov     eax, 6
        jmp     .L4
.L21:
        mov     eax, 7
        jmp     .L4
.L22:
        mov     eax, 8
        jmp     .L4
.L23:
        mov     eax, 9
        jmp     .L4
.L24:
        mov     eax, 10
        jmp     .L4
.L25:
        mov     eax, 11
        jmp     .L4
.L26:
        mov     eax, 12
        jmp     .L4
.L27:
        mov     eax, 13
        jmp     .L4
```

1.29.2 SIMD `strlen()` implementation

It has to be noted that the SIMD instructions can be inserted in C/C++ code via special macros[183]. For MSVC, some of them are located in the `intrin.h` file.

It is possible to implement the `strlen()` function[184] using SIMD instructions that works 2-2.5 times faster than the common implementation. This function loads 16 characters into a XMM-register and check each against zero [185].

```
size_t strlen_sse2(const char *str)
{
    register size_t len = 0;
    const char *s=str;
    bool str_is_aligned=(((unsigned int)str)&0xFFFFFFF0) == (unsigned int)str;

    if (str_is_aligned==false)
        return strlen (str);

    __m128i xmm0 = _mm_setzero_si128();
    __m128i xmm1;
    int mask = 0;

    for (;;)
    {
        xmm1 = _mm_load_si128((__m128i *)s);
        xmm1 = _mm_cmpeq_epi8(xmm1, xmm0);
        if ((mask = _mm_movemask_epi8(xmm1)) != 0)
        {
            unsigned long pos;
            _BitScanForward(&pos, mask);
            len += (size_t)pos;
```

[183] MSDN: MMX, SSE, and SSE2 Intrinsics
[184] strlen() —standard C library function for calculating string length
[185] The example is based on source code from: http://go.yurichev.com/17330.

```
            break;
        }
        s += sizeof(__m128i);
        len += sizeof(__m128i);
    };

    return len;
}
```

Let's compile it in MSVC 2010 with /Ox option:

Listing 1.391: Optimizing MSVC 2010

```
_pos$75552 = -4          ; size = 4
_str$ = 8                ; size = 4
?strlen_sse2@@YAIPBD@Z PROC ; strlen_sse2

    push     ebp
    mov      ebp, esp
    and      esp, -16            ; fffffff0H
    mov      eax, DWORD PTR _str$[ebp]
    sub      esp, 12             ; 0000000cH
    push     esi
    mov      esi, eax
    and      esi, -16            ; fffffff0H
    xor      edx, edx
    mov      ecx, eax
    cmp      esi, eax
    je       SHORT $LN4@strlen_sse
    lea      edx, DWORD PTR [eax+1]
    npad     3 ; align next label
$LL11@strlen_sse:
    mov      cl, BYTE PTR [eax]
    inc      eax
    test     cl, cl
    jne      SHORT $LL11@strlen_sse
    sub      eax, edx
    pop      esi
    mov      esp, ebp
    pop      ebp
    ret      0
$LN4@strlen_sse:
    movdqa   xmm1, XMMWORD PTR [eax]
    pxor     xmm0, xmm0
    pcmpeqb  xmm1, xmm0
    pmovmskb eax, xmm1
    test     eax, eax
    jne      SHORT $LN9@strlen_sse
$LL3@strlen_sse:
    movdqa   xmm1, XMMWORD PTR [ecx+16]
    add      ecx, 16                    ; 00000010H
    pcmpeqb  xmm1, xmm0
    add      edx, 16                    ; 00000010H
    pmovmskb eax, xmm1
    test     eax, eax
    je       SHORT $LL3@strlen_sse
$LN9@strlen_sse:
    bsf      eax, eax
    mov      ecx, eax
    mov      DWORD PTR _pos$75552[esp+16], eax
    lea      eax, DWORD PTR [ecx+edx]
    pop      esi
    mov      esp, ebp
    pop      ebp
    ret      0
?strlen_sse2@@YAIPBD@Z ENDP                ; strlen_sse2
```

How it works? First of all, we must understand goal of the function. It calculates C-string length, but we can use different terms: it's task is searching for zero byte, and then calculating its position relatively to string start.

First, we check if the `str` pointer is aligned on a 16-byte boundary. If not, we call the generic `strlen()` implementation.

Then, we load the next 16 bytes into the `XMM1` register using `MOVDQA`.

An observant reader might ask, why can't `MOVDQU` be used here since it can load data from the memory regardless pointer alignment?

Yes, it might be done in this way: if the pointer is aligned, load data using `MOVDQA`, if not —use the slower `MOVDQU`.

But here we are may hit another caveat:

In the Windows NT line of OS (but not limited to it), memory is allocated by pages of 4 KiB (4096 bytes). Each win32-process has 4 GiB available, but in fact, only some parts of the address space are connected to real physical memory. If the process is accessing an absent memory block, an exception is to be raised. That's how VM works[186].

So, a function loading 16 bytes at once may step over the border of an allocated memory block. Let's say that the OS has allocated 8192 (0x2000) bytes at address 0x008c0000. Thus, the block is the bytes starting from address 0x008c0000 to 0x008c1fff inclusive.

After the block, that is, starting from address 0x008c2000 there is nothing at all, e.g. the OS not allocated any memory there. Any attempt to access memory starting from that address will raise an exception.

And let's consider the example in which the program is holding a string that contains 5 characters almost at the end of a block, and that is not a crime.

0x008c1ff8	'h'
0x008c1ff9	'e'
0x008c1ffa	'l'
0x008c1ffb	'l'
0x008c1ffc	'o'
0x008c1ffd	'\x00'
0x008c1ffe	random noise
0x008c1fff	random noise

So, in normal conditions the program calls `strlen()`, passing it a pointer to the string `'hello'` placed in memory at address 0x008c1ff8. `strlen()` reads one byte at a time until 0x008c1ffd, where there's a zero byte, and then it stops.

Now if we implement our own `strlen()` reading 16 bytes at once, starting at any address, aligned or not, `MOVDQU` may attempt to load 16 bytes at once at address 0x008c1ff8 up to 0x008c2008, and then an exception will be raised. That situation is to be avoided, of course.

So then we'll work only with the addresses aligned on a 16 bytes boundary, which in combination with the knowledge that the OS' page size is usually aligned on a 16-byte boundary gives us some warranty that our function will not read from unallocated memory.

Let's get back to our function.

`_mm_setzero_si128()`—is a macro generating `pxor xmm0, xmm0` —it just clears the `XMM0` register.

`_mm_load_si128()`—is a macro for `MOVDQA`, it just loads 16 bytes from the address into the `XMM1` register.

`_mm_cmpeq_epi8()`—is a macro for `PCMPEQB`, an instruction that compares two XMM-registers bytewise.

And if some byte is equals to the one in the other register, there will be `0xff` at this point in the result or 0 if otherwise.

For example:

```
XMM1: 0x11223344556677880000000000000000
XMM0: 0x11ab3444007877881111111111111111
```

After the execution of `pcmpeqb xmm1, xmm0`, the `XMM1` register contains:

```
XMM1: 0xff0000ff0000ffff0000000000000000
```

In our case, this instruction compares each 16-byte block with a block of 16 zero-bytes, which has been set in the `XMM0` register by `pxor xmm0, xmm0`.

The next macro is `_mm_movemask_epi8()` —that is the `PMOVMSKB` instruction.

It is very useful with `PCMPEQB`.

186 wikipedia

```
pmovmskb eax, xmm1
```

This instruction sets first EAX bit to 1 if the most significant bit of the first byte in XMM1 is 1. In other words, if the first byte of the XMM1 register is 0xff, then the first bit of EAX is to be 1, too.

If the second byte in the XMM1 register is 0xff, then the second bit in EAX is to be set to 1. In other words, the instruction is answering the question "which bytes in XMM1 has the most significant bit set, or greater than 0x7f", and returns 16 bits in the EAX register. The other bits in the EAX register are to be cleared.

By the way, do not forget about this quirk of our algorithm. There might be 16 bytes in the input like:

15	14	13	12	11	10	9 … 3	2	1 … 0
'h'	'e'	'l'	'l'	'o'	0	garbage	0	garbage

It is the `'hello'` string, terminating zero, and some random noise in memory.

If we load these 16 bytes into XMM1 and compare them with the zeroed XMM0, we are getting something like [187]:

```
XMM1: 0x0000ff00000000000000ff0000000000
```

This means that the instruction found two zero bytes, and it is not surprising.

PMOVMSKB in our case will set EAX to
0b0010000000100000.

Obviously, our function must take only the first zero bit and ignore the rest.

The next instruction is BSF (*Bit Scan Forward*).

This instruction finds the first bit set to 1 and stores its position into the first operand.

```
EAX=0b0010000000100000
```

After the execution of `bsf eax, eax`, EAX contains 5, meaning 1 has been found at the 5th bit position (starting from zero).

MSVC has a macro for this instruction: `_BitScanForward`.

Now it is simple. If a zero byte has been found, its position is added to what we have already counted and now we have the return result.

Almost all.

By the way, it is also has to be noted that the MSVC compiler emitted two loop bodies side by side, for optimization.

By the way, SSE 4.2 (that appeared in Intel Core i7) offers more instructions where these string manipulations might be even easier: http://go.yurichev.com/17331

1.30 64 bits

1.30.1 x86-64

It is a 64-bit extension to the x86 architecture.

From the reverse engineer's perspective, the most important changes are:

- Almost all registers (except FPU and SIMD) were extended to 64 bits and got a R- prefix. 8 additional registers wer added. Now GPR's are: RAX, RBX, RCX, RDX, RBP, RSP, RSI, RDI, R8, R9, R10, R11, R12, R13, R14, R15.

  It is still possible to access the *older* register parts as usual. For example, it is possible to access the lower 32-bit part of the RAX register using EAX:

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RAX^{x64}							
				EAX			
						AX	
						AH	AL

[187] An order from MSB to LSB[188] is used here.

The new R8-R15 registers also have their *lower parts*: R8D-R15D (lower 32-bit parts), R8W-R15W (lower 16-bit parts), R8L-R15L (lower 8-bit parts).

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R8							
				R8D			
						R8W	
							R8L

The number of SIMD registers was doubled from 8 to 16: XMM0-XMM15.

- In Win64, the function calling convention is slightly different, somewhat resembling fastcall (6.1.3 on page 735). The first 4 arguments are stored in the RCX, RDX, R8, R9 registers, the rest —in the stack. The caller function must also allocate 32 bytes so the callee may save there 4 first arguments and use these registers for its own needs. Short functions may use arguments just from registers, but larger ones may save their values on the stack.

  System V AMD64 ABI (Linux, *BSD, Mac OS X)[Michael Matz, Jan Hubicka, Andreas Jaeger, Mark Mitchell, *System V Application Binary Interface. AMD64 Architecture Processor Supplement*, (2013)] [189]also somewhat resembles fastcall, it uses 6 registers RDI, RSI, RDX, RCX, R8, R9 for the first 6 arguments. All the rest are passed via the stack.

  See also the section on calling conventions (6.1 on page 734).

- The C/C++ *int* type is still 32-bit for compatibility.

- All pointers are 64-bit now.

Since now the number of registers is doubled, the compilers have more space for maneuvering called register allocation. For us this implies that the emitted code containing less number of local variables.

For example, the function that calculates the first S-box of the DES encryption algorithm processes 32/64/128/256 values at once (depending on DES_type type (uint32, uint64, SSE2 or AVX)) using the bitslice DES method (read more about this technique here (1.29 on page 406)):

```
/*
 * Generated S-box files.
 *
 * This software may be modified, redistributed, and used for any purpose,
 * so long as its origin is acknowledged.
 *
 * Produced by Matthew Kwan - March 1998
 */

#ifdef _WIN64
#define DES_type unsigned __int64
#else
#define DES_type unsigned int
#endif

void
s1 (
    DES_type    a1,
    DES_type    a2,
    DES_type    a3,
    DES_type    a4,
    DES_type    a5,
    DES_type    a6,
    DES_type    *out1,
    DES_type    *out2,
    DES_type    *out3,
    DES_type    *out4
) {
    DES_type    x1, x2, x3, x4, x5, x6, x7, x8;
    DES_type    x9, x10, x11, x12, x13, x14, x15, x16;
    DES_type    x17, x18, x19, x20, x21, x22, x23, x24;
    DES_type    x25, x26, x27, x28, x29, x30, x31, x32;
    DES_type    x33, x34, x35, x36, x37, x38, x39, x40;
    DES_type    x41, x42, x43, x44, x45, x46, x47, x48;
```

[189]Also available as https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf

```
    DES_type    x49, x50, x51, x52, x53, x54, x55, x56;

    x1 = a3 & ~a5;
    x2 = x1 ^ a4;
    x3 = a3 & ~a4;
    x4 = x3 | a5;
    x5 = a6 & x4;
    x6 = x2 ^ x5;
    x7 = a4 & ~a5;
    x8 = a3 ^ a4;
    x9 = a6 & ~x8;
    x10 = x7 ^ x9;
    x11 = a2 | x10;
    x12 = x6 ^ x11;
    x13 = a5 ^ x5;
    x14 = x13 & x8;
    x15 = a5 & ~a4;
    x16 = x3 ^ x14;
    x17 = a6 | x16;
    x18 = x15 ^ x17;
    x19 = a2 | x18;
    x20 = x14 ^ x19;
    x21 = a1 & x20;
    x22 = x12 ^ ~x21;
    *out2 ^= x22;
    x23 = x1 | x5;
    x24 = x23 ^ x8;
    x25 = x18 & ~x2;
    x26 = a2 & ~x25;
    x27 = x24 ^ x26;
    x28 = x6 | x7;
    x29 = x28 ^ x25;
    x30 = x9 ^ x24;
    x31 = x18 & ~x30;
    x32 = a2 & x31;
    x33 = x29 ^ x32;
    x34 = a1 & x33;
    x35 = x27 ^ x34;
    *out4 ^= x35;
    x36 = a3 & x28;
    x37 = x18 & ~x36;
    x38 = a2 | x3;
    x39 = x37 ^ x38;
    x40 = a3 | x31;
    x41 = x24 & ~x37;
    x42 = x41 | x3;
    x43 = x42 & ~a2;
    x44 = x40 ^ x43;
    x45 = a1 & ~x44;
    x46 = x39 ^ ~x45;
    *out1 ^= x46;
    x47 = x33 & ~x9;
    x48 = x47 ^ x39;
    x49 = x4 ^ x36;
    x50 = x49 & ~x5;
    x51 = x42 | x18;
    x52 = x51 ^ a5;
    x53 = a2 & ~x52;
    x54 = x50 ^ x53;
    x55 = a1 | x54;
    x56 = x48 ^ ~x55;
    *out3 ^= x56;
}
```

There are a lot of local variables. Of course, not all those going into the local stack. Let's compile it with MSVC 2008 with /Ox option:

Listing 1.392: Optimizing MSVC 2008

```
PUBLIC    _s1
```

```
; Function compile flags: /Ogtpy
_TEXT    SEGMENT
_x6$ = -20          ; size = 4
_x3$ = -16          ; size = 4
_x1$ = -12          ; size = 4
_x8$ = -8           ; size = 4
_x4$ = -4           ; size = 4
_a1$ = 8            ; size = 4
_a2$ = 12           ; size = 4
_a3$ = 16           ; size = 4
_x33$ = 20          ; size = 4
_x7$ = 20           ; size = 4
_a4$ = 20           ; size = 4
_a5$ = 24           ; size = 4
tv326 = 28          ; size = 4
_x36$ = 28          ; size = 4
_x28$ = 28          ; size = 4
_a6$ = 28           ; size = 4
_out1$ = 32         ; size = 4
_x24$ = 36          ; size = 4
_out2$ = 36         ; size = 4
_out3$ = 40         ; size = 4
_out4$ = 44         ; size = 4
_s1    PROC
    sub    esp, 20                      ; 00000014H
    mov    edx, DWORD PTR _a5$[esp+16]
    push   ebx
    mov    ebx, DWORD PTR _a4$[esp+20]
    push   ebp
    push   esi
    mov    esi, DWORD PTR _a3$[esp+28]
    push   edi
    mov    edi, ebx
    not    edi
    mov    ebp, edi
    and    edi, DWORD PTR _a5$[esp+32]
    mov    ecx, edx
    not    ecx
    and    ebp, esi
    mov    eax, ecx
    and    eax, esi
    and    ecx, ebx
    mov    DWORD PTR _x1$[esp+36], eax
    xor    eax, ebx
    mov    esi, ebp
    or     esi, edx
    mov    DWORD PTR _x4$[esp+36], esi
    and    esi, DWORD PTR _a6$[esp+32]
    mov    DWORD PTR _x7$[esp+32], ecx
    mov    edx, esi
    xor    edx, eax
    mov    DWORD PTR _x6$[esp+36], edx
    mov    edx, DWORD PTR _a3$[esp+32]
    xor    edx, ebx
    mov    ebx, esi
    xor    ebx, DWORD PTR _a5$[esp+32]
    mov    DWORD PTR _x8$[esp+36], edx
    and    ebx, edx
    mov    ecx, edx
    mov    edx, ebx
    xor    edx, ebp
    or     edx, DWORD PTR _a6$[esp+32]
    not    ecx
    and    ecx, DWORD PTR _a6$[esp+32]
    xor    edx, edi
    mov    edi, edx
    or     edi, DWORD PTR _a2$[esp+32]
    mov    DWORD PTR _x3$[esp+36], ebp
    mov    ebp, DWORD PTR _a2$[esp+32]
    xor    edi, ebx
```

```
    and     edi, DWORD PTR _a1$[esp+32]
    mov     ebx, ecx
    xor     ebx, DWORD PTR _x7$[esp+32]
    not     edi
    or      ebx, ebp
    xor     edi, ebx
    mov     ebx, edi
    mov     edi, DWORD PTR _out2$[esp+32]
    xor     ebx, DWORD PTR [edi]
    not     eax
    xor     ebx, DWORD PTR _x6$[esp+36]
    and     eax, edx
    mov     DWORD PTR [edi], ebx
    mov     ebx, DWORD PTR _x7$[esp+32]
    or      ebx, DWORD PTR _x6$[esp+36]
    mov     edi, esi
    or      edi, DWORD PTR _x1$[esp+36]
    mov     DWORD PTR _x28$[esp+32], ebx
    xor     edi, DWORD PTR _x8$[esp+36]
    mov     DWORD PTR _x24$[esp+32], edi
    xor     edi, ecx
    not     edi
    and     edi, edx
    mov     ebx, edi
    and     ebx, ebp
    xor     ebx, DWORD PTR _x28$[esp+32]
    xor     ebx, eax
    not     eax
    mov     DWORD PTR _x33$[esp+32], ebx
    and     ebx, DWORD PTR _a1$[esp+32]
    and     eax, ebp
    xor     eax, ebx
    mov     ebx, DWORD PTR _out4$[esp+32]
    xor     eax, DWORD PTR [ebx]
    xor     eax, DWORD PTR _x24$[esp+32]
    mov     DWORD PTR [ebx], eax
    mov     eax, DWORD PTR _x28$[esp+32]
    and     eax, DWORD PTR _a3$[esp+32]
    mov     ebx, DWORD PTR _x3$[esp+36]
    or      edi, DWORD PTR _a3$[esp+32]
    mov     DWORD PTR _x36$[esp+32], eax
    not     eax
    and     eax, edx
    or      ebx, ebp
    xor     ebx, eax
    not     eax
    and     eax, DWORD PTR _x24$[esp+32]
    not     ebp
    or      eax, DWORD PTR _x3$[esp+36]
    not     esi
    and     ebp, eax
    or      eax, edx
    xor     eax, DWORD PTR _a5$[esp+32]
    mov     edx, DWORD PTR _x36$[esp+32]
    xor     edx, DWORD PTR _x4$[esp+36]
    xor     ebp, edi
    mov     edi, DWORD PTR _out1$[esp+32]
    not     eax
    and     eax, DWORD PTR _a2$[esp+32]
    not     ebp
    and     ebp, DWORD PTR _a1$[esp+32]
    and     edx, esi
    xor     eax, edx
    or      eax, DWORD PTR _a1$[esp+32]
    not     ebp
    xor     ebp, DWORD PTR [edi]
    not     ecx
    and     ecx, DWORD PTR _x33$[esp+32]
    xor     ebp, ebx
    not     eax
```

```
    mov     DWORD PTR [edi], ebp
    xor     eax, ecx
    mov     ecx, DWORD PTR _out3$[esp+32]
    xor     eax, DWORD PTR [ecx]
    pop     edi
    pop     esi
    xor     eax, ebx
    pop     ebp
    mov     DWORD PTR [ecx], eax
    pop     ebx
    add     esp, 20
    ret     0
_s1     ENDP
```

5 variables were allocated in the local stack by the compiler.

Now let's try the same thing in the 64-bit version of MSVC 2008:

Listing 1.393: Optimizing MSVC 2008

```
a1$ = 56
a2$ = 64
a3$ = 72
a4$ = 80
x36$1$ = 88
a5$ = 88
a6$ = 96
out1$ = 104
out2$ = 112
out3$ = 120
out4$ = 128
s1    PROC
$LN3:
    mov     QWORD PTR [rsp+24], rbx
    mov     QWORD PTR [rsp+32], rbp
    mov     QWORD PTR [rsp+16], rdx
    mov     QWORD PTR [rsp+8], rcx
    push    rsi
    push    rdi
    push    r12
    push    r13
    push    r14
    push    r15
    mov     r15, QWORD PTR a5$[rsp]
    mov     rcx, QWORD PTR a6$[rsp]
    mov     rbp, r8
    mov     r10, r9
    mov     rax, r15
    mov     rdx, rbp
    not     rax
    xor     rdx, r9
    not     r10
    mov     r11, rax
    and     rax, r9
    mov     rsi, r10
    mov     QWORD PTR x36$1$[rsp], rax
    and     r11, r8
    and     rsi, r8
    and     r10, r15
    mov     r13, rdx
    mov     rbx, r11
    xor     rbx, r9
    mov     r9, QWORD PTR a2$[rsp]
    mov     r12, rsi
    or      r12, r15
    not     r13
    and     r13, rcx
    mov     r14, r12
    and     r14, rcx
    mov     rax, r14
    mov     r8, r14
```

```
    xor     r8, rbx
    xor     rax, r15
    not     rbx
    and     rax, rdx
    mov     rdi, rax
    xor     rdi, rsi
    or      rdi, rcx
    xor     rdi, r10
    and     rbx, rdi
    mov     rcx, rdi
    or      rcx, r9
    xor     rcx, rax
    mov     rax, r13
    xor     rax, QWORD PTR x36$1$[rsp]
    and     rcx, QWORD PTR a1$[rsp]
    or      rax, r9
    not     rcx
    xor     rcx, rax
    mov     rax, QWORD PTR out2$[rsp]
    xor     rcx, QWORD PTR [rax]
    xor     rcx, r8
    mov     QWORD PTR [rax], rcx
    mov     rax, QWORD PTR x36$1$[rsp]
    mov     rcx, r14
    or      rax, r8
    or      rcx, r11
    mov     r11, r9
    xor     rcx, rdx
    mov     QWORD PTR x36$1$[rsp], rax
    mov     r8, rsi
    mov     rdx, rcx
    xor     rdx, r13
    not     rdx
    and     rdx, rdi
    mov     r10, rdx
    and     r10, r9
    xor     r10, rax
    xor     r10, rbx
    not     rbx
    and     rbx, r9
    mov     rax, r10
    and     rax, QWORD PTR a1$[rsp]
    xor     rbx, rax
    mov     rax, QWORD PTR out4$[rsp]
    xor     rbx, QWORD PTR [rax]
    xor     rbx, rcx
    mov     QWORD PTR [rax], rbx
    mov     rbx, QWORD PTR x36$1$[rsp]
    and     rbx, rbp
    mov     r9, rbx
    not     r9
    and     r9, rdi
    or      r8, r11
    mov     rax, QWORD PTR out1$[rsp]
    xor     r8, r9
    not     r9
    and     r9, rcx
    or      rdx, rbp
    mov     rbp, QWORD PTR [rsp+80]
    or      r9, rsi
    xor     rbx, r12
    mov     rcx, r11
    not     rcx
    not     r14
    not     r13
    and     rcx, r9
    or      r9, rdi
    and     rbx, r14
    xor     r9, r15
    xor     rcx, rdx
```

```
    mov     rdx, QWORD PTR a1$[rsp]
    not     r9
    not     rcx
    and     r13, r10
    and     r9, r11
    and     rcx, rdx
    xor     r9, rbx
    mov     rbx, QWORD PTR [rsp+72]
    not     rcx
    xor     rcx, QWORD PTR [rax]
    or      r9, rdx
    not     r9
    xor     rcx, r8
    mov     QWORD PTR [rax], rcx
    mov     rax, QWORD PTR out3$[rsp]
    xor     r9, r13
    xor     r9, QWORD PTR [rax]
    xor     r9, r8
    mov     QWORD PTR [rax], r9
    pop     r15
    pop     r14
    pop     r13
    pop     r12
    pop     rdi
    pop     rsi
    ret     0
s1    ENDP
```

Nothing was allocated in the local stack by the compiler, x36 is synonym for a5.

By the way, there are CPUs with much more GPR's, e.g. Itanium (128 registers).

1.30.2 ARM

64-bit instructions appeared in ARMv8.

1.30.3 Float point numbers

How floating point numbers are processed in x86-64 is explained here: 1.31 on the next page.

1.30.4 64-bit architecture criticism

Some people has irritation sometimes: now one needs twice as much memory for storing pointers, including cache memory, despite the fact that x64 CPUs can address only 48 bits of external RAM.

> Pointers have gone out of favor to the point now where I had to flame about it because on my 64-bit computer that I have here, if I really care about using the capability of my machine I find that I'd better not use pointers because I have a machine that has 64-bit registers but it only has 2 gigabytes of RAM. So a pointer never has more than 32 significant bits to it. But every time I use a pointer it's costing me 64 bits and that doubles the size of my data structure. Worse, it goes into the cache and half of my cache is gone and that costs cash—cache is expensive.
>
> So if I'm really trying to push the envelope now, I have to use arrays instead of pointers. I make complicated macros so that it looks like I'm using pointers, but I'm not really.

(Donald Knuth in "Coders at Work: Reflections on the Craft of Programming ".)

Some people make their own memory allocators. It's interesting to know about CryptoMiniSat[190] case. This program rarely uses more than 4GiB of RAM, but it uses pointers heavily. So it requires less memory on 32-bit architecture than on 64-bit one. To mitigate this problem, author made his own allocator (in

[190] https://github.com/msoos/cryptominisat/

clauseallocator.(h|cpp) files), which allows to have access to allocated memory using 32-bit identifiers instead of 64-bit pointers.

1.31 Working with floating point numbers using SIMD

Of course, the FPU has remained in x86-compatible processors when the SIMD extensions were added.

The SIMD extensions (SSE2) offer an easier way to work with floating-point numbers.

The number format remains the same (IEEE 754).

So, modern compilers (including those generating for x86-64) usually use SIMD instructions instead of FPU ones.

It can be said that it's good news, because it's easier to work with them.

We are going to reuse the examples from the FPU section here: 1.19 on page 218.

1.31.1 Simple example

```
#include <stdio.h>

double f (double a, double b)
{
        return a/3.14 + b*4.1;
};

int main()
{
        printf ("%f\n", f(1.2, 3.4));
};
```

x64

Listing 1.394: Optimizing MSVC 2012 x64

```
__real@4010666666666666 DQ 04010666666666666r   ; 4.1
__real@40091eb851eb851f DQ 040091eb851eb851fr   ; 3.14

a$ = 8
b$ = 16
f       PROC
        divsd   xmm0, QWORD PTR __real@40091eb851eb851f
        mulsd   xmm1, QWORD PTR __real@4010666666666666
        addsd   xmm0, xmm1
        ret     0
f       ENDP
```

The input floating point values are passed in the XMM0-XMM3 registers, all the rest—via the stack [191].

a is passed in XMM0, b—via XMM1.

The XMM-registers are 128-bit (as we know from the section about SIMD: 1.29 on page 406), but the *double* values are 64 bit, so only lower register half is used.

DIVSD is an SSE-instruction that stands for “Divide Scalar Double-Precision Floating-Point Values”, it just divides one value of type *double* by another, stored in the lower halves of operands.

The constants are encoded by compiler in IEEE 754 format.

MULSD and ADDSD work just as the same, but do multiplication and addition.

The result of the function's execution in type *double* is left in the in XMM0 register.

That is how non-optimizing MSVC works:

[191] MSDN: Parameter Passing

Listing 1.395: MSVC 2012 x64

```
__real@4010666666666666 DQ 04010666666666666r   ; 4.1
__real@40091eb851eb851f DQ 040091eb851eb851fr   ; 3.14

a$ = 8
b$ = 16
f       PROC
        movsdx  QWORD PTR [rsp+16], xmm1
        movsdx  QWORD PTR [rsp+8], xmm0
        movsdx  xmm0, QWORD PTR a$[rsp]
        divsd   xmm0, QWORD PTR __real@40091eb851eb851f
        movsdx  xmm1, QWORD PTR b$[rsp]
        mulsd   xmm1, QWORD PTR __real@4010666666666666
        addsd   xmm0, xmm1
        ret     0
f       ENDP
```

Slightly redundant. The input arguments are saved in the "shadow space" (1.10.2 on page 100), but only their lower register halves, i.e., only 64-bit values of type *double*. GCC produces the same code.

x86

Let's also compile this example for x86. Despite the fact it's generating for x86, MSVC 2012 uses SSE2 instructions:

Listing 1.396: Non-optimizing MSVC 2012 x86

```
tv70 = -8          ; size = 8
_a$ = 8            ; size = 8
_b$ = 16           ; size = 8
_f      PROC
        push    ebp
        mov     ebp, esp
        sub     esp, 8
        movsd   xmm0, QWORD PTR _a$[ebp]
        divsd   xmm0, QWORD PTR __real@40091eb851eb851f
        movsd   xmm1, QWORD PTR _b$[ebp]
        mulsd   xmm1, QWORD PTR __real@4010666666666666
        addsd   xmm0, xmm1
        movsd   QWORD PTR tv70[ebp], xmm0
        fld     QWORD PTR tv70[ebp]
        mov     esp, ebp
        pop     ebp
        ret     0
_f      ENDP
```

Listing 1.397: Optimizing MSVC 2012 x86

```
tv67 = 8           ; size = 8
_a$ = 8            ; size = 8
_b$ = 16           ; size = 8
_f      PROC
        movsd   xmm1, QWORD PTR _a$[esp-4]
        divsd   xmm1, QWORD PTR __real@40091eb851eb851f
        movsd   xmm0, QWORD PTR _b$[esp-4]
        mulsd   xmm0, QWORD PTR __real@4010666666666666
        addsd   xmm1, xmm0
        movsd   QWORD PTR tv67[esp-4], xmm1
        fld     QWORD PTR tv67[esp-4]
        ret     0
_f      ENDP
```

It's almost the same code, however, there are some differences related to calling conventions: 1) the arguments are passed not in XMM registers, but in the stack, like in the FPU examples (1.19 on page 218); 2) the result of the function is returned in `ST(0)` — in order to do so, it's copied (through local variable `tv`) from one of the XMM registers to `ST(0)`.

Let's try the optimized example in OllyDbg:

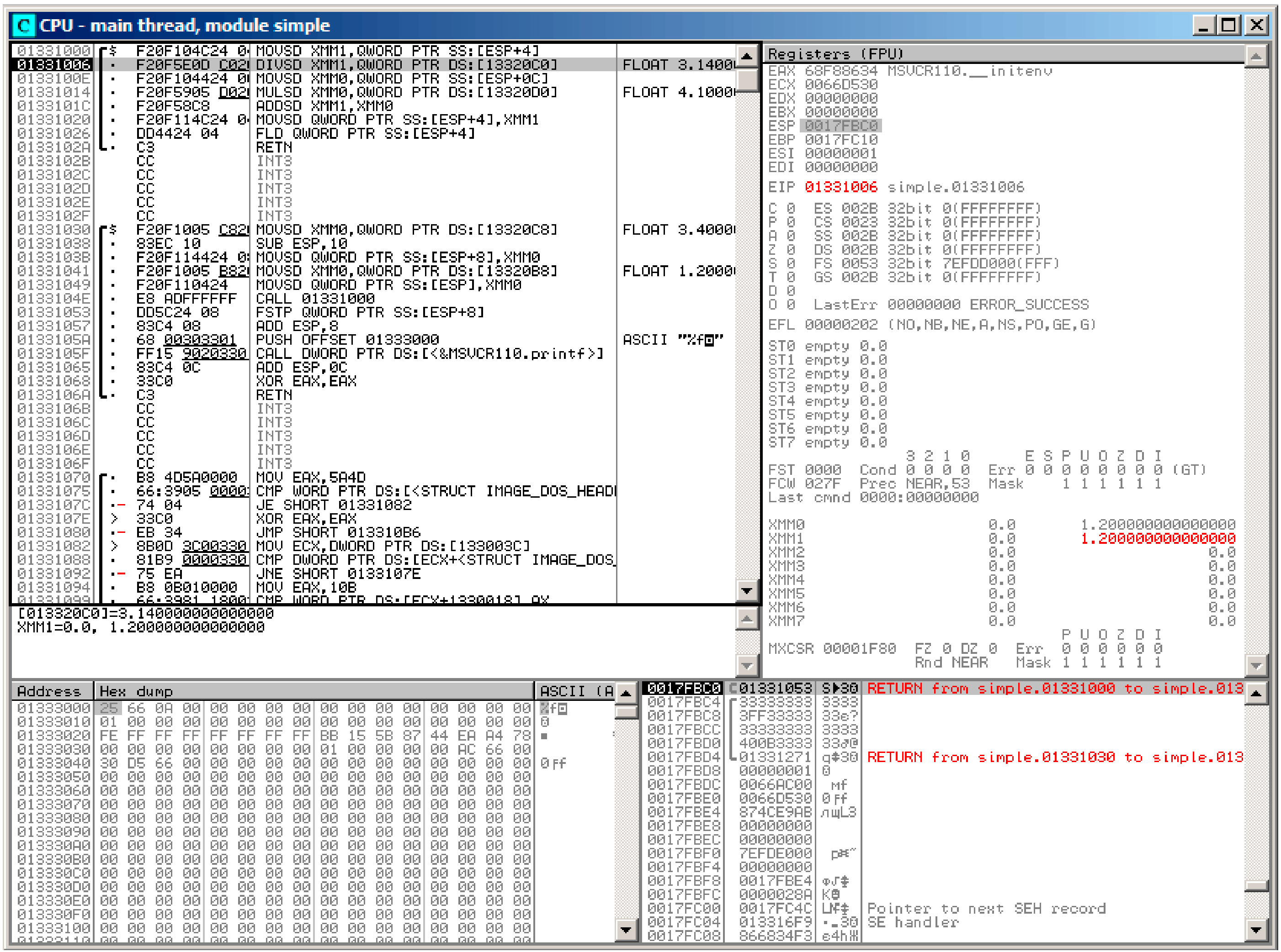


Figure 1.113: OllyDbg: MOVSD loads the value of a into XMM1

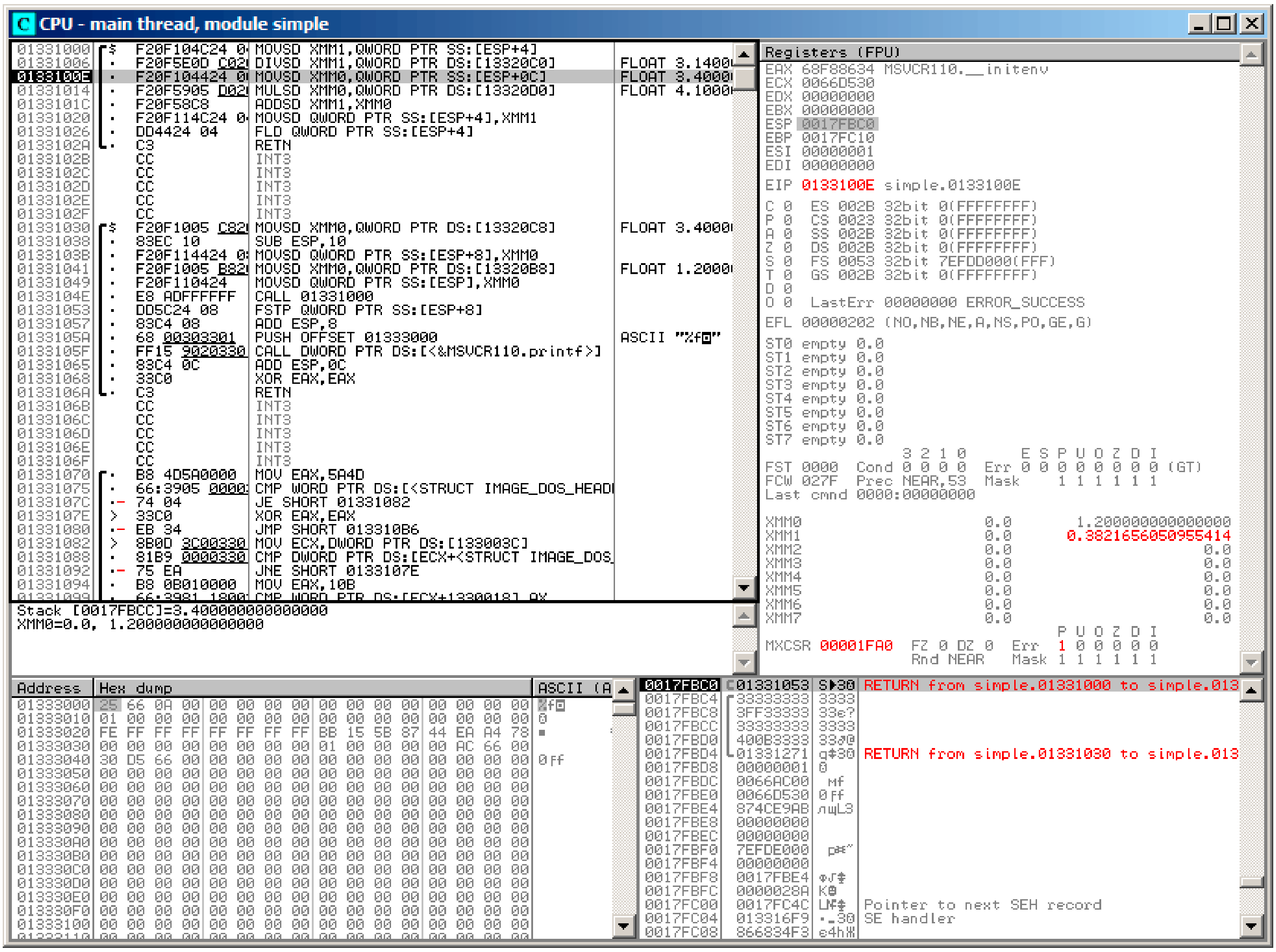


Figure 1.114: OllyDbg: DIVSD calculated quotient and stored it in XMM1

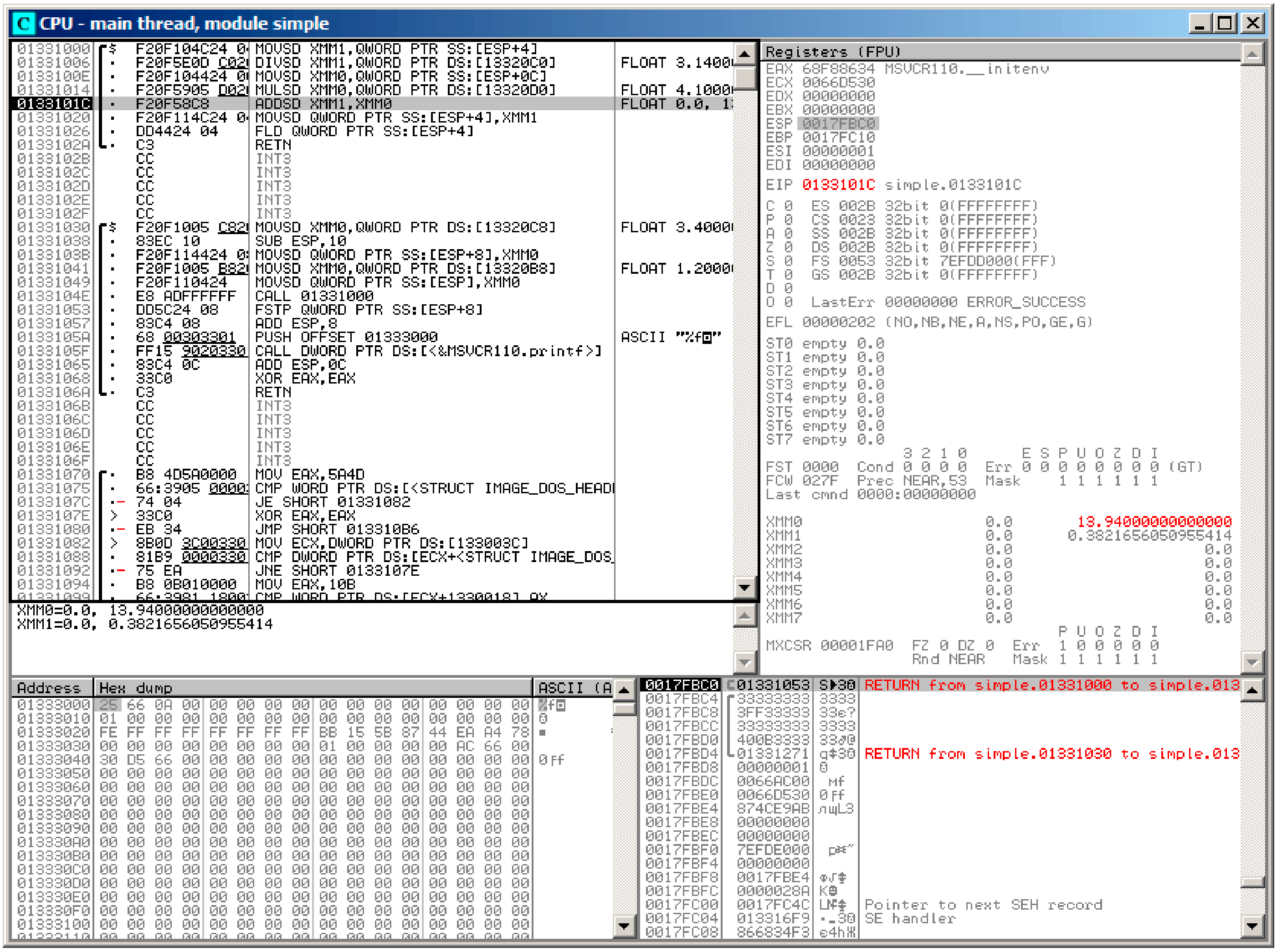


Figure 1.115: OllyDbg: MULSD calculated product and stored it in XMM0

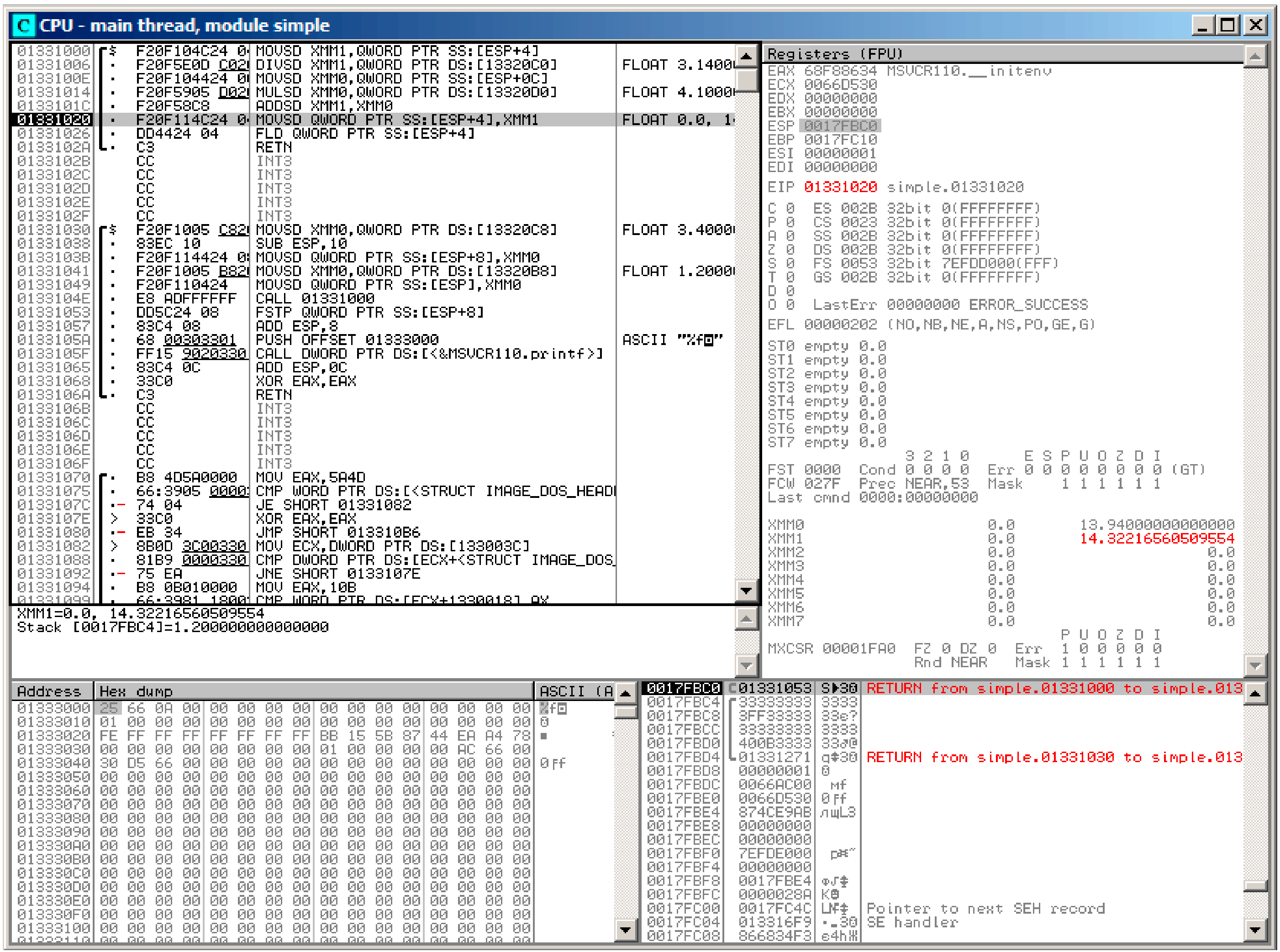


Figure 1.116: OllyDbg: ADDSD adds value in XMM0 to XMM1

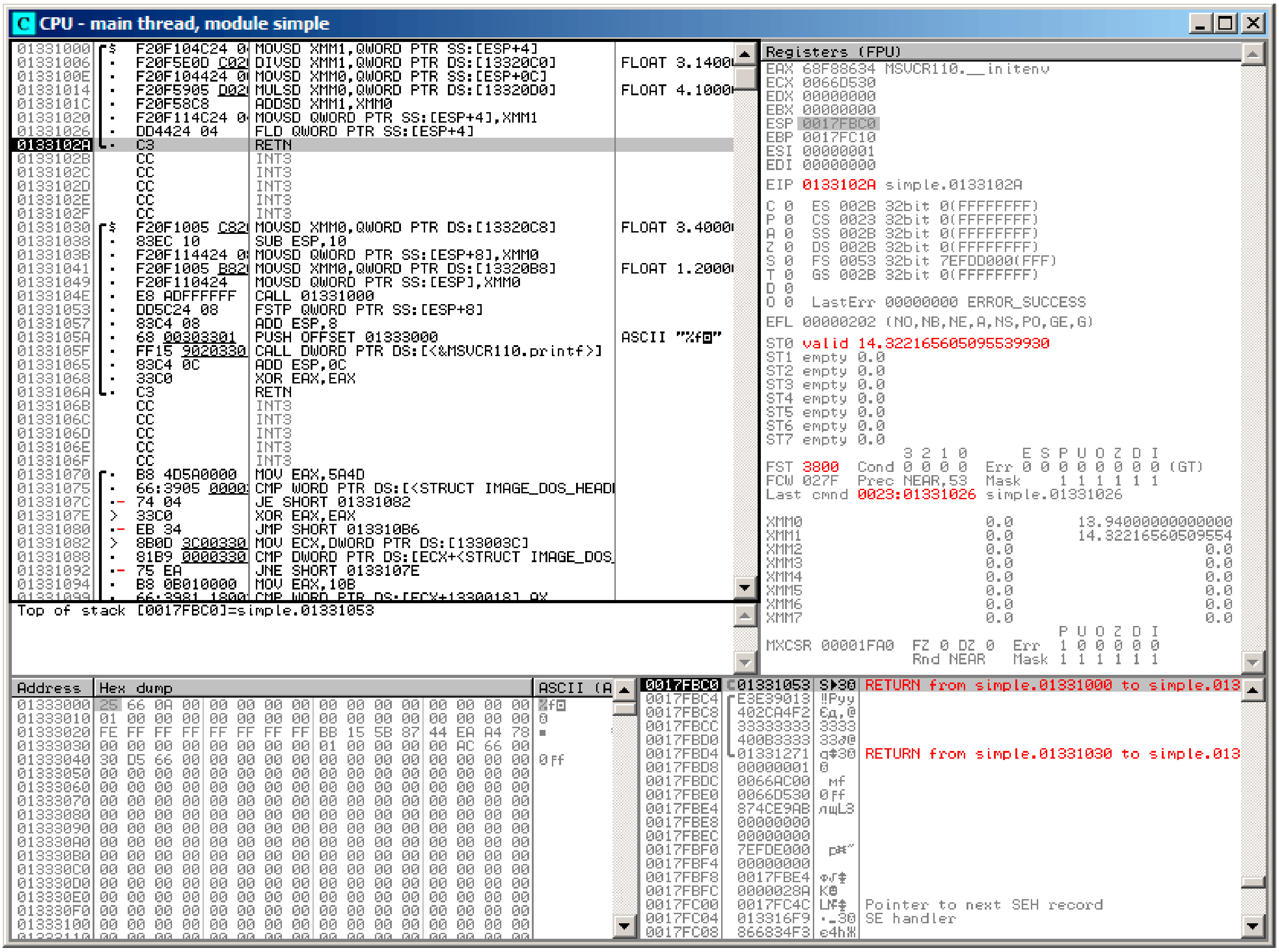


Figure 1.117: OllyDbg: FLD left function result in ST(0)

We see that OllyDbg shows the XMM registers as pairs of *double* numbers, but only the *lower* part is used.

Apparently, OllyDbg shows them in that format because the SSE2 instructions (suffixed with -SD) are executed right now.

But of course, it's possible to switch the register format and to see their contents as 4 *float*-numbers or just as 16 bytes.

1.31.2 Passing floating point number via arguments

```
#include <math.h>
#include <stdio.h>

int main ()
{
        printf ("32.01 ^ 1.54 = %lf\n", pow (32.01,1.54));

        return 0;
}
```

They are passed in the lower halves of the XMM0-XMM3 registers.

Listing 1.398: Optimizing MSVC 2012 x64

```
$SG1354 DB      '32.01 ^ 1.54 = %lf', 0aH, 00H

__real@40400147ae147ae1 DQ 040400147ae147ae1r   ; 32.01
__real@3ff8a3d70a3d70a4 DQ 03ff8a3d70a3d70a4r   ; 1.54

main    PROC
        sub     rsp, 40                                  ; 00000028H
        movsdx  xmm1, QWORD PTR __real@3ff8a3d70a3d70a4
        movsdx  xmm0, QWORD PTR __real@40400147ae147ae1
        call    pow
        lea     rcx, OFFSET FLAT:$SG1354
        movaps  xmm1, xmm0
        movd    rdx, xmm1
        call    printf
        xor     eax, eax
        add     rsp, 40                                  ; 00000028H
        ret     0
main    ENDP
```

There is no MOVSDX instruction in Intel and AMD manuals (12.1.4 on page 1013), there it is called just MOVSD. So there are two instructions sharing the same name in x86 (about the other see: .1.6 on page 1029). Apparently, Microsoft developers wanted to get rid of the mess, so they renamed it to MOVSDX. It just loads a value into the lower half of a XMM register.

pow() takes arguments from XMM0 and XMM1, and returns result in XMM0. It is then moved to RDX for printf(). Why? Maybe because printf()—is a variable arguments function?

Listing 1.399: Optimizing GCC 4.4.6 x64

```
.LC2:
        .string "32.01 ^ 1.54 = %lf\n"
main:
        sub     rsp, 8
        movsd   xmm1, QWORD PTR .LC0[rip]
        movsd   xmm0, QWORD PTR .LC1[rip]
        call    pow
        ; result is now in XMM0
        mov     edi, OFFSET FLAT:.LC2
        mov     eax, 1 ; number of vector registers passed
        call    printf
        xor     eax, eax
        add     rsp, 8
        ret
.LC0:
        .long   171798692
        .long   1073259479
.LC1:
        .long   2920577761
        .long   1077936455
```

GCC generates clearer output. The value for printf() is passed in XMM0. By the way, here is a case when 1 is written into EAX for printf()—this implies that one argument will be passed in vector registers, just as the standard requires [Michael Matz, Jan Hubicka, Andreas Jaeger, Mark Mitchell, *System V Application Binary Interface. AMD64 Architecture Processor Supplement*, (2013)] [192].

1.31.3 Comparison example

```
#include <stdio.h>

double d_max (double a, double b)
{
        if (a>b)
                return a;

        return b;
};

int main()
{
        printf ("%f\n", d_max (1.2, 3.4));
        printf ("%f\n", d_max (5.6, -4));
};
```

x64

Listing 1.400: Optimizing MSVC 2012 x64

```
a$ = 8
b$ = 16
d_max   PROC
        comisd  xmm0, xmm1
        ja      SHORT $LN2@d_max
        movaps  xmm0, xmm1
$LN2@d_max:
        fatret  0
d_max   ENDP
```

Optimizing MSVC generates a code very easy to understand.

COMISD is "Compare Scalar Ordered Double-Precision Floating-Point Values and Set EFLAGS". Essentially, that is what it does.

Non-optimizing MSVC generates more redundant code, but it is still not hard to understand:

Listing 1.401: MSVC 2012 x64

```
a$ = 8
b$ = 16
d_max   PROC
        movsdx  QWORD PTR [rsp+16], xmm1
        movsdx  QWORD PTR [rsp+8], xmm0
        movsdx  xmm0, QWORD PTR a$[rsp]
        comisd  xmm0, QWORD PTR b$[rsp]
        jbe     SHORT $LN1@d_max
        movsdx  xmm0, QWORD PTR a$[rsp]
        jmp     SHORT $LN2@d_max
$LN1@d_max:
        movsdx  xmm0, QWORD PTR b$[rsp]
$LN2@d_max:
        fatret  0
d_max   ENDP
```

However, GCC 4.4.6 did more optimizations and used the MAXSD ("Return Maximum Scalar Double-Precision Floating-Point Value") instruction, which just choose the maximum value!

[192] Also available as https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf

Listing 1.402: Optimizing GCC 4.4.6 x64

```
d_max:
        maxsd   xmm0, xmm1
        ret
```

x86

Let's compile this example in MSVC 2012 with optimization turned on:

Listing 1.403: Optimizing MSVC 2012 x86

```
_a$ = 8         ; size = 8
_b$ = 16        ; size = 8
_d_max  PROC
        movsd   xmm0, QWORD PTR _a$[esp-4]
        comisd  xmm0, QWORD PTR _b$[esp-4]
        jbe     SHORT $LN1@d_max
        fld     QWORD PTR _a$[esp-4]
        ret     0
$LN1@d_max:
        fld     QWORD PTR _b$[esp-4]
        ret     0
_d_max  ENDP
```

Almost the same, but the values of a and b are taken from the stack and the function result is left in ST(0).

If we load this example in OllyDbg, we can see how the COMISD instruction compares values and sets/clears the CF and PF flags:

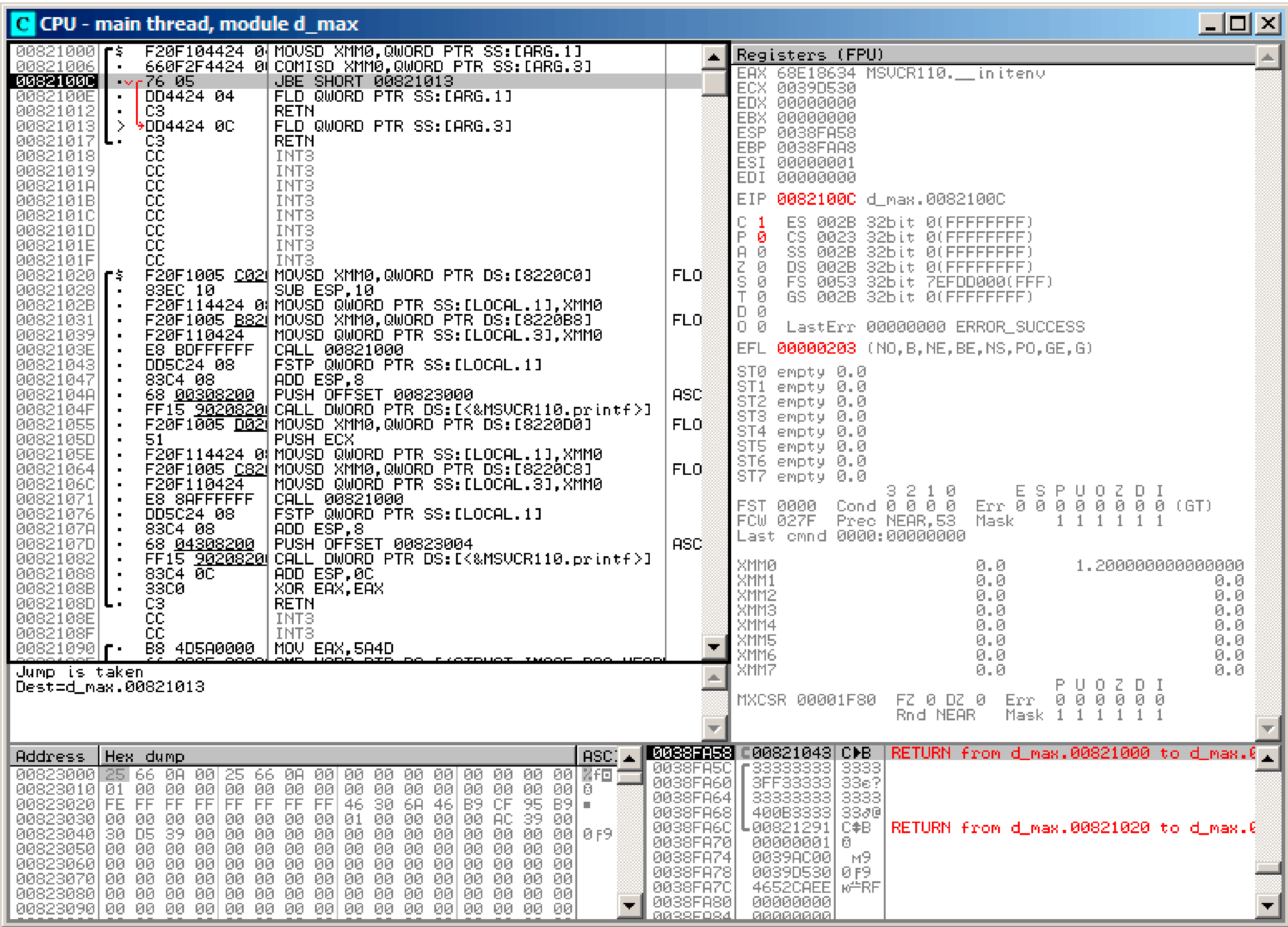


Figure 1.118: OllyDbg: COMISD changed CF and PF flags

1.31.4 Calculating machine epsilon: x64 and SIMD

Let's revisit the "calculating machine epsilon" example for *double* listing.1.25.2.

Now we compile it for x64:

Listing 1.404: Optimizing MSVC 2012 x64

```
v$ = 8
calculate_machine_epsilon PROC
        movsdx  QWORD PTR v$[rsp], xmm0
        movaps  xmm1, xmm0
        inc     QWORD PTR v$[rsp]
        movsdx  xmm0, QWORD PTR v$[rsp]
        subsd   xmm0, xmm1
        ret     0
calculate_machine_epsilon ENDP
```

There is no way to add 1 to a value in 128-bit XMM register, so it must be placed into memory.

There is, however, the ADDSD instruction (*Add Scalar Double-Precision Floating-Point Values*) which can add a value to the lowest 64-bit half of a XMM register while ignoring the higher one, but MSVC 2012 probably is not that good yet [193].

Nevertheless, the value is then reloaded to a XMM register and subtraction occurs. SUBSD is "Subtract Scalar Double-Precision Floating-Point Values", i.e., it operates on the lower 64-bit part of 128-bit XMM register. The result is returned in the XMM0 register.

1.31.5 Pseudo-random number generator example revisited

Let's revisit "pseudo-random number generator example" example listing.1.25.1.

If we compile this in MSVC 2012, it will use the SIMD instructions for the FPU.

Listing 1.405: Optimizing MSVC 2012

```
__real@3f800000 DD 03f800000r   ; 1

tv128 = -4
_tmp$ = -4
?float_rand@@YAMXZ PROC
        push    ecx
        call    ?my_rand@@YAIXZ
; EAX=pseudorandom value
        and     eax, 8388607    ; 007fffffH
        or      eax, 1065353216 ; 3f800000H
; EAX=pseudorandom value & 0x007fffff | 0x3f800000
; store it into local stack:
        mov     DWORD PTR _tmp$[esp+4], eax
; reload it as float point number:
        movss   xmm0, DWORD PTR _tmp$[esp+4]
; subtract 1.0:
        subss   xmm0, DWORD PTR __real@3f800000
; move value to ST0 by placing it in temporary variable...
        movss   DWORD PTR tv128[esp+4], xmm0
; ... and reloading it into ST0:
        fld     DWORD PTR tv128[esp+4]
        pop     ecx
        ret     0
?float_rand@@YAMXZ ENDP
```

All instructions have the -SS suffix, which stands for "Scalar Single".

"Scalar" implies that only one value is stored in the register.

"Single"[194] stands for *float* data type.

1.31.6 Summary

Only the lower half of XMM registers is used in all examples here, to store number in IEEE 754 format.

[193] As an exercise, you may try to rework this code to eliminate the usage of the local stack.
[194] I.e., single precision.

Essentially, all instructions prefixed by -SD ("Scalar Double-Precision")—are instructions working with floating point numbers in IEEE 754 format, stored in the lower 64-bit half of a XMM register.

And it is easier than in the FPU, probably because the SIMD extensions were evolved in a less chaotic way than the FPU ones in the past. The stack register model is not used.

If you would try to replace *double* with *float*

in these examples, the same instructions will be used, but prefixed with -SS ("Scalar Single-Precision"), for example, MOVSS, COMISS, ADDSS, etc.

"Scalar" implies that the SIMD register containing only one value instead of several.

Instructions working with several values in a register simultaneously have "Packed" in their name.

Needless to say, the SSE2 instructions work with 64-bit IEEE 754 numbers (*double*), while the internal representation of the floating-point numbers in FPU is 80-bit numbers.

Hence, the FPU may produce less round-off errors and as a consequence, FPU may give more precise calculation results.

1.32 ARM-specific details

1.32.1 Number sign (#) before number

The Keil compiler, IDA and objdump precede all numbers with the "#" number sign, for example: listing.1.16.1.

But when GCC 4.9 generates assembly language output, it doesn't, for example: listing.3.15.

The ARM listings in this book are somewhat mixed.

It's hard to say, which method is right. Supposedly, one has to obey the rules accepted in environment he/she works in.

1.32.2 Addressing modes

This instruction is possible in ARM64:

```
ldr     x0, [x29,24]
```

This means add 24 to the value in X29 and load the value from this address.

Please note that 24 is inside the brackets. The meaning is different if the number is outside the brackets:

```
ldr     w4, [x1],28
```

This means load the value at the address in X1, then add 28 to X1.

ARM allows you to add or subtract a constant to/from the address used for loading.

And it's possible to do that both before and after loading.

There is no such addressing mode in x86, but it is present in some other processors, even on PDP-11.

There is a legend that the pre-increment, post-increment, pre-decrement and post-decrement modes in PDP-11,

were "guilty" for the appearance of such C language (which developed on PDP-11) constructs as *ptr++, *++ptr, *ptr--, *--ptr.

By the way, this is one of the hard to memorize C features. This is how it is:

C term	ARM term	C statement	how it works
Post-increment	post-indexed addressing	`*ptr++`	use `*ptr` value, then increment `ptr` pointer
Post-decrement	post-indexed addressing	`*ptr--`	use `*ptr` value, then decrement `ptr` pointer
Pre-increment	pre-indexed addressing	`*++ptr`	increment `ptr` pointer, then use `*ptr` value
Pre-decrement	pre-indexed addressing	`*--ptr`	decrement `ptr` pointer, then use `*ptr` value

Pre-indexing is marked with an exclamation mark in the ARM assembly language. For example, see line 2 in listing.1.29.

Dennis Ritchie (one of the creators of the C language) mentioned that it presumably was invented by Ken Thompson (another C creator) because this processor feature was present in PDP-7 [195], [Dennis M. Ritchie, *The development of the C language*, (1993)][196].

Thus, C language compilers may use it, if it is present on the target processor.

That's very convenient for array processing.

1.32.3 Loading a constant into a register

32-bit ARM

As we already know, all instructions have a length of 4 bytes in ARM mode and 2 bytes in Thumb mode.

Then how can we load a 32-bit value into a register, if it's not possible to encode it in one instruction?

Let's try:

```
unsigned int f()
{
        return 0x12345678;
};
```

Listing 1.406: GCC 4.6.3 -O3 ARM mode

```
f:
        ldr     r0, .L2
        bx      lr
.L2:
        .word   305419896 ; 0x12345678
```

So, the `0x12345678` value is just stored aside in memory and loaded if needed.

But it's possible to get rid of the additional memory access.

Listing 1.407: GCC 4.6.3 -O3 -march=armv7-a (ARM mode)

```
movw    r0, #22136      ; 0x5678
movt    r0, #4660       ; 0x1234
bx      lr
```

We see that the value is loaded into the register by parts, the lower part first (using `MOVW`), then the higher (using `MOVT`).

This implies that 2 instructions are necessary in ARM mode for loading a 32-bit value into a register.

It's not a real problem, because in fact there are not many constants in real code (except of 0 and 1).

Does it mean that the two-instruction version is slower than one-instruction version?

Doubtfully. Most likely, modern ARM processors are able to detect such sequences and execute them fast.

On the other hand, IDA is able to detect such patterns in the code and disassembles this function as:

[195] http://yurichev.com/mirrors/C/c_dmr_postincrement.txt
[196] Also available as http://go.yurichev.com/17264

```
MOV    R0, 0x12345678
BX     LR
```

ARM64

```
uint64_t f()
{
        return 0x12345678ABCDEF01;
};
```

Listing 1.408: GCC 4.9.1 -O3

```
mov     x0, 61185   ; 0xef01
movk    x0, 0xabcd, lsl 16
movk    x0, 0x5678, lsl 32
movk    x0, 0x1234, lsl 48
ret
```

MOVK stands for "MOV Keep", i.e., it writes a 16-bit value into the register, not touching the rest of the bits. The LSL suffix shifts left the value by 16, 32 and 48 bits at each step. The shifting is done before loading.

This implies that 4 instructions are necessary to load a 64-bit value into a register.

Storing floating-point number into register

It's possible to store a floating-point number into a D-register using only one instruction.

For example:

```
double a()
{
        return 1.5;
};
```

Listing 1.409: GCC 4.9.1 -O3 + objdump

```
0000000000000000 <a>:
   0:   1e6f1000        fmov    d0, #1.500000000000000000e+000
   4:   d65f03c0        ret
```

The number 1.5 was indeed encoded in a 32-bit instruction. But how?

In ARM64, there are 8 bits in the FMOV instruction for encoding some floating-point numbers.

The algorithm is called VFPExpandImm() in [*ARM Architecture Reference Manual, ARMv8, for ARMv8-A architecture profile*, (2013)][197]. This is also called *minifloat*[198].

We can try different values: the compiler is able to encode 30.0 and 31.0, but it couldn't encode 32.0, as 8 bytes have to be allocated for this number in the IEEE 754 format:

```
double a()
{
        return 32;
};
```

Listing 1.410: GCC 4.9.1 -O3

```
a:
        ldr     d0, .LC0
        ret
.LC0:
        .word   0
        .word   1077936128
```

[197] Also available as http://yurichev.com/mirrors/ARMv8-A_Architecture_Reference_Manual_(Issue_A.a).pdf
[198] wikipedia

1.32.4 Relocs in ARM64

As we know, there are 4-byte instructions in ARM64, so it is impossible to write a large number into a register using a single instruction.

Nevertheless, an executable image can be loaded at any random address in memory, so that's why relocs exists. Read more about them (in relation to Win32 PE): 6.5.2 on page 759.

The address is formed using the ADRP and ADD instruction pair in ARM64.

The first loads a 4KiB-page address and the second one adds the remainder. Let's compile the example from "Hello, world!" (listing.1.8) in GCC (Linaro) 4.9 under win32:

Listing 1.411: GCC (Linaro) 4.9 and objdump of object file

```
...>aarch64-linux-gnu-gcc.exe hw.c -c

...>aarch64-linux-gnu-objdump.exe -d hw.o

...

0000000000000000 <main>:
   0:   a9bf7bfd        stp     x29, x30, [sp,#-16]!
   4:   910003fd        mov     x29, sp
   8:   90000000        adrp    x0, 0 <main>
   c:   91000000        add     x0, x0, #0x0
  10:   94000000        bl      0 <printf>
  14:   52800000        mov     w0, #0x0                        // #0
  18:   a8c17bfd        ldp     x29, x30, [sp],#16
  1c:   d65f03c0        ret

...>aarch64-linux-gnu-objdump.exe -r hw.o

...

RELOCATION RECORDS FOR [.text]:
OFFSET           TYPE              VALUE
0000000000000008 R_AARCH64_ADR_PREL_PG_HI21  .rodata
000000000000000c R_AARCH64_ADD_ABS_LO12_NC  .rodata
0000000000000010 R_AARCH64_CALL26  printf
```

So there are 3 relocs in this object file.

- The first one takes the page address, cuts the lowest 12 bits and writes the remaining high 21 bits to the ADRP instruction's bit fields. This is because we don't need to encode the low 12 bits, and the ADRP instruction has space only for 21 bits.
- The second one puts the 12 bits of the address relative to the page start into the ADD instruction's bit fields.
- The last, 26-bit one, is applied to the instruction at address 0x10 where the jump to the printf() function is.

  All ARM64 (and in ARM in ARM mode) instruction addresses have zeros in the two lowest bits (because all instructions have a size of 4 bytes), so one have to encode only the highest 26 bits of 28-bit address space (±128MB).

There are no such relocs in the executable file: because it's known where the "Hello!" string is located, in which page, and the address of puts() is also known.

So there are values set already in the ADRP, ADD and BL instructions (the linker has written them while linking):

Listing 1.412: objdump of executable file

```
0000000000400590 <main>:
  400590:       a9bf7bfd        stp     x29, x30, [sp,#-16]!
  400594:       910003fd        mov     x29, sp
  400598:       90000000        adrp    x0, 400000 <_init-0x3b8>
  40059c:       91192000        add     x0, x0, #0x648
  4005a0:       97fffa0         bl      400420 <puts@plt>
  4005a4:       52800000        mov     w0, #0x0                        // #0
  4005a8:       a8c17bfd        ldp     x29, x30, [sp],#16
```

```
  4005ac:       d65f03c0        ret

...

Contents of section .rodata:
 400640 01000200 00000000 48656c6c 6f210000  ........Hello!..
```

As an example, let's try to disassemble the BL instruction manually.
`0x97fffa0` is $0b10010111111111111111111110100000$. According to [*ARM Architecture Reference Manual, ARMv8, for ARMv8-A architecture profile*, (2013)C5.6.26], *imm26* is the last 26 bits:
$imm26 = 0b11111111111111111110100000$. It is `0x3FFFFA0`, but the MSB is 1, so the number is negative, and we can convert it manually to convenient form for us. By the rules of negation (2.2 on page 453), just invert all bits: (it is `0b1011111=0x5F`), and add 1 (`0x5F+1=0x60`). So the number in signed form is `-0x60`. Let's multiply `-0x60` by 4 (because address stored in opcode is divided by 4): it is `-0x180`. Now let's calculate destination address: `0x4005a0` + (`-0x180`) = `0x400420` (please note: we consider the address of the BL instruction, not the current value of PC, which may be different!). So the destination address is `0x400420`.

More about ARM64-related relocs: [*ELF for the ARM 64-bit Architecture (AArch64)*, (2013)][199].

1.33 MIPS-specific details

1.33.1 Loading a 32-bit constant into register

```
unsigned int f()
{
        return 0x12345678;
};
```

All instructions in MIPS, just like ARM, have a size of 32-bit, so it's not possible to embed a 32-bit constant into one instruction.

So one have to use at least two instructions: the first loads the high part of the 32-bit number and the second one applies an OR operation, which effectively sets the low 16-bit part of the target register:

Listing 1.413: GCC 4.4.5 -O3 (assembly output)

```
        li      $2,305397760  # 0x12340000
        j       $31
        ori     $2,$2,0x5678 ; branch delay slot
```

IDA is fully aware of such frequently encountered code patterns, so, for convenience it shows the last `ORI` instruction as the `LI` pseudo instruction, which allegedly loads a full 32-bit number into the $V0 register.

Listing 1.414: GCC 4.4.5 -O3 (IDA)

```
         lui     $v0, 0x1234
         jr      $ra
         li      $v0, 0x12345678 ; branch delay slot
```

The GCC assembly output has the LI pseudo instruction, but in fact, `LUI` ("Load Upper Immediate") is there, which stores a 16-bit value into the high part of the register.

Let's see in *objdump* output:

Listing 1.415: objdump

```
00000000 <f>:
   0:   3c021234        lui     v0,0x1234
   4:   03e00008        jr      ra
   8:   34425678        ori     v0,v0,0x5678
```

[199] Also available as http://go.yurichev.com/17288

Loading a 32-bit global variable into register

```
unsigned int global_var=0x12345678;

unsigned int f2()
{
        return global_var;
};
```

This is slightly different: LUI loads upper 16-bit from *global_var* into $2 (or $V0) and then LW loads lower 16-bits summing it with the contents of $2:

Listing 1.416: GCC 4.4.5 -O3 (assembly output)

```
f2:
        lui     $2,%hi(global_var)
        lw      $2,%lo(global_var)($2)
        j       $31
        nop     ; branch delay slot

        ...

global_var:
        .word   305419896
```

IDA is fully aware of often used LUI/LW instruction pair, so it coalesces both into a single LW instruction:

Listing 1.417: GCC 4.4.5 -O3 (IDA)

```
_f2:
                lw      $v0, global_var
                jr      $ra
                or      $at, $zero      ; branch delay slot

                ...

                .data
                .globl global_var
global_var:     .word 0x12345678         # DATA XREF: _f2
```

objdump's output is the same as GCC's assembly output. Let's also dump relocs of the object file:

Listing 1.418: objdump

```
objdump -D filename.o

...

0000000c <f2>:
   c:   3c020000        lui     v0,0x0
  10:   8c420000        lw      v0,0(v0)
  14:   03e00008        jr      ra
  18:   00200825        move    at,at   ; branch delay slot
  1c:   00200825        move    at,at

Disassembly of section .data:

00000000 <global_var>:
   0:   12345678        beq     s1,s4,159e4 <f2+0x159d8>

...

objdump -r filename.o

...

RELOCATION RECORDS FOR [.text]:
OFFSET   TYPE              VALUE
0000000c R_MIPS_HI16       global_var
00000010 R_MIPS_LO16       global_var
```

```
...
```

We can see that address of *global_var* is to be written right into `LUI` and `LW` instructions during executable file loading: high 16-bit part of *global_var* goes into the first one (`LUI`), lower 16-bit part goes into the second one (`LW`).

1.33.2 Further reading about MIPS

Dominic Sweetman, *See MIPS Run, Second Edition*, (2010).

Chapter 2

Important fundamentals

2.1 Integral datatypes

Integral datatype is a type for a value which can be converted to number. These are numbers, enumerations, booleans.

2.1.1 Bit

Obvious usage for bits are boolean values: 0 for *false* and 1 for *true*.

Set of booleans can be packed into word: there will be 32 booleans in 32-bit word, etc. This way is called *bitmap* or *bitfield*.

But it has obvious overhead: a bit jiggling, isolating, etc. While using word (or *int* type) for boolean variable is not economic, but highly efficient.

In C/C++ environment, 0 is for *false* and any non-zero value is for *true*. For example:

```
        if (1234)
                printf ("this will always be executed\n");
        else
                printf ("this will never\n");
```

This is popular way of enumerating characters in a C-string:

```
        char *input=...;

        while(*input) // execute body if *input character is non-zero
        {
                // do something with *input
                input++;
        };
```

2.1.2 Nibble AKA nybble

AKA half-byte, tetrade. Equals to 4 bits.

All these terms are still in use today.

Binary-coded decimal (BCD[1])

4-bit nibbles were used in 4-bit CPUs like legendary Intel 4004 (used in calculators).

It's interesting to know that there was *binary-coded decimal* (BCD) way of representing decimal digit using 4 bits. Decimal 0 is represented as 0b0000, decimal 9 as 0b1001 and higher values are not used. Decimal 1234 is represented as 0x1234. Of course, this way is not economical.

Nevertheless, it has one advantage: decimal to BCD-packed number conversion and back is extremely easy. BCD-numbers can be added, subtracted, etc., but an additional correction is needed. x86 CPUs has rare instructions for that: `AAA`/`DAA` (adjust after addition), `AAS`/`DAS` (adjust after subtraction), `AAM` (after multiplication), `AAD` (after division).

The need for CPUs to support BCD numbers is a reason why *half-carry flag* (on 8080/Z80) and *auxiliary flag* (AF on x86) are exist: this is carry-flag generated after proceeding of lower 4 bits. The flag is then used for adjustment instructions.

The fact of easy conversion had led to popularity of [Peter Abel, *IBM PC assembly language and programming* (1987)] book. But aside of this book, the author of these notes never seen BCD numbers in practice, except for *magic numbers* (5.6.1 on page 712), like when someone's birthday is encoded like 0x19791011—this is indeed packed BCD number.

BCD instructions in x86 were often used for other purposes, especially in undocumented ways, for example:

[1] Binary-Coded Decimal

```
        cmp al,10
        sbb al,69h
        das
```

This obscure code converts number in 0..15 range into ASCII character '0'..'9', 'A'..'F'.

Z80

Z80 was clone of 8-bit Intel 8080 CPU, and because of space constraints, it has 4-bit ALU, i.e., each operation over two 8-bit numbers had to be proceeded in two steps. One side-effect of this was easy and natural generation of *half-carry flag*.

2.1.3 Byte

Byte is primarily used for character storage. 8-bit bytes were not common as today. Punched tapes for teletypes had 5 and 6 possible holes, this is 5 or 6 bits for byte.

To emphasize the fact the byte has 8 bits, byte is sometimes called *octet*: at least *fetchmail* uses this terminology.

9-bit bytes used to exist in 36-bit architectures: 4 9-bit bytes would fit in a single word. Probably because of this fact, C/C++ standard tells that *char* has to have a room for *at least* 8 bits, but more bits are allowable.

For example, in the early C language manual[2], we can find this:

```
char  one byte character (PDP-11, IBM360: 8 bits; H6070: 9 bits)
```

By H6070 they probably meant Honeywell 6070, with 36-bit words.

Standard ASCII table

7-bit ASCII table is standard, which has only 128 possible characters. Early E-Mail transport software were operating only on 7-bit ASCII codes, so a MIME[3] standard needed to encode messages in non-Latin writing systems. 7-bit ASCII code was augmented by parity bit, resulting in 8 bits.

Data Encryption Standard (DES[4]) has a 56 bits key, this is 8 7-bit bytes, leaving a space to parity bit for each character.

There is no need to memorize whole ASCII table, but rather ranges. [0..0x1F] are control characters (non-printable). [0x20..0x7E] are printable ones. Codes starting at 0x80 are usually used for non-Latin writing systems and/or pseudographics.

Significant codes which will be easily memorized are: 0 (end of C-string, `'\0'` in C/C++); 0xA or 10 (*line feed*, `'\n'` in C/C++); 0xD or 13 (*carriage return*, `'\r'` in C/C++).

0x20 (space) is also often memorized.

8-bit CPUs

x86 has capability to work with byte(s) on register level (because they are descendants of 8-bit 8080 CPU), RISC CPUs like ARM and MIPS—not.

[2] https://yurichev.com/mirrors/C/bwk-tutor.html
[3] Multipurpose Internet Mail Extensions
[4] Data Encryption Standard

2.1.4 Wide char

This is an attempt to support multi-lingual environment by extending byte to 16-bit. Most well-known example is Windows NT kernel and win32 functions with *W* suffix. This is why each Latin character in plain English text string is interleaved with zero byte. This encoding is called UCS-2 or UTF-16

Usually, *wchar_t* is synonym to 16-bit *short* data type.

2.1.5 Signed integer vs unsigned

Some may argue, why unsigned data types exist at first place, since any unsigned number can be represented as signed. Yes, but absence of sign bit in a value extends its range twice. Hence, signed byte has range of -128..127, and unsigned one: 0..255. Another benefit of using unsigned data types is self-documenting: you define a variable which can't be assigned to negative values.

Unsigned data types are absent in Java, for which it's criticized. It's hard to implement cryptographical algorithms using boolean operations over signed data types.

Values like 0xFFFFFFFF (-1) are used often, mostly as error codes.

2.1.6 Word

Word word is somewhat ambiguous term and usually denotes a data type fitting in GPR. Bytes are practical for characters, but impractical for other arithmetical calculations.

Hence, many CPUs have GPRs with width of 16, 32 or 64 bits. Even 8-bit CPUs like 8080 and Z80 offer to work with 8-bit register pairs, each pair forming a 16-bit *pseudoregister* (*BC*, *DE*, *HL*, etc.). Z80 has some capability to work with register pairs, and this is, in a sense, some kind of 16-bit CPU emulation.

In general, if a CPU marketed as "n-bit CPU", this usually means it has n-bit GPRs.

There was a time when hard disks and RAM modules were marketed as having *n* kilo-words instead of *b* kilobytes/megabytes.

For example, *Apollo Guidance Computer*[5] has 2048 words of RAM. This was a 16-bit computer, so there was 4096 bytes of RAM.

TX-0[6] had 64K of 18-bit words of magnetic core memory, i.e., 64 kilo-words.

DECSYSTEM-2060[7] could have up to 4096 kilowords of *solid state memory* (i.e., hard disks, tapes, etc). This was 36-bit computer, so this is 18432 kilobytes or 18 megabytes.

---

int in C/C++ is almost always mapped to word. (Except of AMD64 architecture where *int* is still 32-bit one, perhaps, for the reason of better portability.)

int is 16-bit on PDP-11 and old MS-DOS compilers. *int* is 32-bit on VAX, on x86 starting at 80386, etc.

Even more than that, if type declaration for a variable is omitted in C/C++ program, *int* is used silently by default. Perhaps, this is inheritance of B programming language[8].

GPR is usually fastest container for variable, faster than packed bit, and sometimes even faster than byte (because there is no need to isolate a single bit/byte from GPR). Even if you use it as a container for loop counter in 0..99 range.

Word in assembly language is still 16-bit for x86, because it was so for 16-bit 8086. *Double word* is 32-bit, *quad word* is 64-bit. That's why 16-bit words are declared using `DW` in x86 assembly, 32-bit ones using `DD` and 64-bit ones using `DQ`.

Word is 32-bit for ARM, MIPS, etc., 16-bit data types are called *half-word* there. Hence, *double word* on 32-bit RISC is 64-bit data type.

[5] https://en.wikipedia.org/wiki/Apollo_Guidance_Computer
[6] https://en.wikipedia.org/wiki/TX-0
[7] https://en.wikipedia.org/wiki/DECSYSTEM-20
[8] http://yurichev.com/blog/typeless/

GDB has the following terminology: *halfword* for 16-bit, word for 32-bit and *giant word* for 64-bit.

16-bit C/C++ environment on PDP-11 and MS-DOS has *long* data type with width of 32 bits, perhaps, they meant *long word* or *long int*?

32-bit C/C++ environment has *long long* data type with width of 64 bits.

Now you see why the *word* word is ambiguous.

Should I use *int*?

Some people argue that *int* shouldn't be used at all, because it ambiguity can lead to bugs. For example, well-known *lzhuf* library uses *int* at one point and everything works fine on 16-bit architecture. But if ported to architecture with 32-bit *int*, it can crash: http://yurichev.com/blog/lzhuf/.

Less ambiguous types are defined in *stdint.h* file: *uint8_t*, *uint16_t*, *uint32_t*, *uint64_t*, etc.

Some people like Donald E. Knuth proposed[9] more sonorous words for these types: *byte/wyde/tetra-byte/octabyte*. But these names are less popular than clear terms with inclusion of *u* (*unsigned*) character and number right into the type name.

Word-oriented computers

Despite the ambiguity of the word term, modern computers are still word-oriented: RAM and all levels of cache are still organized by words, not by bytes. However, size in bytes is used in marketing.

Access to RAM/cache by address aligned by word boundary is often cheaper than non-aligned.

During data structures development, which are supposed to be fast and efficient, one should always take into consideration length of the word on the CPU to be executed on. Sometimes the compiler will do this for programmer, sometimes not.

2.1.7 Address register

For those who fostered on 32-bit and/or 64-bit x86, and/or RISC of 90s like ARM, MIPS, PowerPC, it's natural that address bus has the same width as GPR or word. Nevertheless, width of address bus can be different on other architectures.

8-bit Z80 can address 2^{16} bytes, using 8-bit registers pairs or dedicated registers (*IX*, *IY*). *SP* and *PC* registers are also 16-bit ones.

Cray-1 supercomputer has 64-bit GPRs, but 24-bit address registers, so it can address 2^{24} (16 megawords or 128 megabytes). RAM was very expensive in 1970s, and even in supercomputing environment it cannot be expected it could have more. So why to allocate 64-bit register for address or pointer?

8086/8088 CPUs had a really weird addressing scheme: values of two 16-bit registers were summed in a weird manner resulting in a 20-bit address. Perhaps, this was some kind of toy-level virtualization (11.6 on page 1003)? 8086 could run several programs (not simultaneously, though).

Early ARM1 has an interesting artifact:

> Another interesting thing about the register file is the PC register is missing a few bits. Since the ARM1 uses 26-bit addresses, the top 6 bits are not used. Because all instructions are aligned on a 32-bit boundary, the bottom two address bits in the PC are always zero. These 8 bits are not only unused, they are omitted from the chip entirely.

(http://www.righto.com/2015/12/reverse-engineering-arm1-ancestor-of.html)

Hence, it's physically not possible to push a value with one of two last bits set into PC register. Nor it's possible to set any bits in high 6 bits of PC.

x86-64 architecture has virtual 64-bit pointers/addresses, but internally, width of address bus is 48 bits (seems enough to address 256TB of RAM).

[9] http://www-cs-faculty.stanford.edu/~uno/news98.html

2.1.8 Numbers

What are numbers used for?

When you see some number(s) altering in a CPU register, you may be interested in what this number means. It's an important skill for a reverse engineer to determine possible data type from a set of changing numbers.

Boolean

If the number is switching from 0 to 1 and back, most chances that this value has boolean data type.

Loop counter, array index

Variable increasing from 0, like: 0, 1, 2, 3…—a good chance this is a loop counter and/or array index.

Signed numbers

If you see a variable which holds very low numbers and sometimes very high numbers, like 0, 1, 2, 3, and 0xFFFFFFFF, 0xFFFFFFFE, 0xFFFFFFFD, there's a good chance it is a signed variable in *two's complement* form (2.2 on the following page), and last 3 numbers are -1, -2, -3.

32-bit numbers

There are numbers so large[10], that there is even a special notation which exists to represent them (Knuth's up-arrow notation [11]). These numbers are so large so these are not practical for engineering, science and mathematics.

Almost all engineers and scientists are happy with IEEE 754 double precision floating point, which has maximal value around $1.8 \cdot 10^{308}$. (As a comparison, the number of atoms in the observable universe, is estimated to be between $4 \cdot 10^{79}$ and $4 \cdot 10^{81}$.)

In fact, upper bound in practical computing is much, much lower. If you get the source code of UNIX v6 for PDP-11 [12], 16-bit *int* is used everywhere while 32-bit *long* type is not used at all.

Same story was in MS-DOS era: 16-bit *int* was used almost for everything (array indices, loop counters), while 32-bit *long* was used rarely.

During advent of x86-64, it was decided for *int* to stay as 32 bit size integer, because, probably, usage of 64-bit *int* is even rarer.

I would say, 16-bit numbers in range 0..65535 are probably most used numbers in computing.

Given that, if you see unusually large 32-bit value like 0x87654321, this is a good chance this can be:

- this can still be a 16-bit number, but signed, between 0xFFFF8000 (-32768) and 0xFFFFFFFF (-1).
- address of memory cell (can be checked using memory map feature of debugger).
- packed bytes (can be checked visually).
- bit flags.
- something related to (amateur) cryptography.
- magic number (5.6.1 on page 712).
- IEEE 754 floating point number (can also be checked).

Almost same story for 64-bit values.

[10] https://en.wikipedia.org/wiki/Large_numbers
[11] https://en.wikipedia.org/wiki/Knuth%27s_up-arrow_notation
[12] http://minnie.tuhs.org/Archive/PDP-11/Distributions/research/Dennis_v6/

…so 16-bit *int* is enough for almost everything?

It's interesting to note: in [Michael Abrash, *Graphics Programming Black Book*, 1997 chapter 13] we can find that there are plenty cases in which 16-bit variables are just enough. In a meantime, Michael Abrash has a pity that 80386 and 80486 CPUs has so little available registers, so he offers to put two 16-bit values into one 32-bit register and then to rotate it using `ROR reg, 16` (on 80386 and later) (`ROL reg, 16` will also work) or BSWAP (on 80486 and later) instruction.

That reminds us Z80 with alternate pack of registers (suffixed with apostrophe), to which CPU can switch (and then switch back) using EXX instruction.

Size of buffer

When a programmer needs to declare the size of some buffer, values in form of 2^x are usually used (512 bytes, 1024, etc.). Values in 2^x form are easily recognizable (1.22.5 on page 322) in decimal, hexadecimal and binary base.

But needless to say, programmers are still humans with their decimal culture. And somehow, in DBMS area, size of textual database fields is often chosen as 10^x number, like 100, 200. They just think "Okay, 100 is enough, wait, 200 will be better". And they are right, of course.

Maximum width of *VARCHAR2* data type in Oracle RDBMS is 4000 characters, not 4096.

There is nothing wrong with this, this is just a place where numbers like 10^x can be encountered.

Address

It's always a good idea to keep in mind an approximate memory map of the process you currently debug. For example, many win32 executables started at 0x00401000, so an address like 0x00451230 is probably located inside executable section. You'll see addresses like these in the EIP register.

Stack is usually located somewhere below.

Many debuggers are able to show the memory map of the debuggee, for example: 1.9.3 on page 79.

If a value is increasing by step 4 on 32-bit architecture or by step 8 on 64-bit one, this probably sliding address of some elements of array.

It's important to know that win32 doesn't use addresses below 0x10000, so if you see some number below this constant, this cannot be an address (see also: `https://msdn.microsoft.com/en-us/library/ms810627.aspx`).

Anyway, many debuggers can show you if the value in a register can be an address to something. OllyDbg can also show an ASCII string if the value is an address of it.

Bit field

If you see a value where one (or more) bit(s) are flipping from time to time like 0xABCD1234 → 0xABCD1434 and back, this is probably a bit field (or bitmap).

Packed bytes

When *strcmp()* or *memcmp()* copies a buffer, it loads/stores 4 (or 8) bytes simultaneously, so if a string containing "4321", and it would be copied to another place, at one point you'll see 0x31323334 value in some register. This is 4 packed bytes into a 32-bit value.

2.2 Signed number representations

There are several methods for representing signed numbers[13], but "two's complement" is the most popular one in computers.

[13] wikipedia

Here is a table for some byte values:

binary	hexadecimal	unsigned	signed
01111111	0x7f	127	127
01111110	0x7e	126	126
...			
00000110	0x6	6	6
00000101	0x5	5	5
00000100	0x4	4	4
00000011	0x3	3	3
00000010	0x2	2	2
00000001	0x1	1	1
00000000	0x0	0	0
11111111	0xff	255	-1
11111110	0xfe	254	-2
11111101	0xfd	253	-3
11111100	0xfc	252	-4
11111011	0xfb	251	-5
11111010	0xfa	250	-6
...			
10000010	0x82	130	-126
10000001	0x81	129	-127
10000000	0x80	128	-128

The difference between signed and unsigned numbers is that if we represent `0xFFFFFFFE` and `0x00000002` as unsigned, then the first number (4294967294) is bigger than the second one (2). If we represent them both as signed, the first one becomes -2, and it is smaller than the second (2). That is the reason why conditional jumps (1.14 on page 124) are present both for signed (e.g. `JG`, `JL`) and unsigned (`JA`, `JB`) operations.

For the sake of simplicity, this is what one needs to know:

- Numbers can be signed or unsigned.
- C/C++ signed types:
  - `int64_t` (-9,223,372,036,854,775,808 .. 9,223,372,036,854,775,807) (- 9.2.. 9.2 quintillions) or `0x8000000000000000..0x7FFFFFFFFFFFFFFF`),
  - *int* (-2,147,483,648..2,147,483,647 (- 2.15.. 2.15Gb) or `0x80000000..0x7FFFFFFF`),
  - *char* (-128..127 or `0x80..0x7F`),
  - `ssize_t`.

  Unsigned:
  - `uint64_t` (0..18,446,744,073,709,551,615 (18 quintillions) or `0..0xFFFFFFFFFFFFFFFF`),
  - `unsigned int` (0..4,294,967,295 (4.3Gb) or `0..0xFFFFFFFF`),
  - `unsigned char` (0..255 or `0..0xFF`),
  - `size_t`.
- Signed types have the sign in the MSB: 1 means "minus", 0 means "plus".
- Promoting to a larger data types is simple: 1.28.5 on page 405.
- Negation is simple: just invert all bits and add 1.

  We can keep in mind that a number of inverse sign is located on the opposite side at the same proximity from zero. The addition of one is needed because zero is present in the middle.
- The addition and subtraction operations work well for both signed and unsigned values. But for multiplication and division operations, x86 has different instructions: `IDIV`/`IMUL` for signed and `DIV`/`MUL` for unsigned.
- Here are some more instructions that work with signed numbers: `CBW/CWD/CWDE/CDQ/CDQE` (.1.6 on page 1031), `MOVSX` (1.17.1 on page 201), `SAR` (.1.6 on page 1035).

A table of some negative and positive values (**??**) looks like thermometer with Celsius scale. This is why addition and subtraction works equally well for both signed and unsigned numbers: if the first addend is represented as mark on thermometer, and one need to add a second addend, and it's positive, we just shift mark up on thermometer by the value of second addend. If the second addend is negative, then we shift mark down to absolute value of the second addend.

Addition of two negative numbers works as follows. For example, we need to add -2 and -3 using 16-bit registers. -2 and -3 is 0xfffe and 0xfffd respectively. If we add these numbers as unsigned, we will get 0xfffe+0xfffd=0x1fffb. But we work on 16-bit registers, so the result is *cut off*, the first 1 is dropped, 0xfffb is left, and this is -5. This works because -2 (or 0xfffe) can be represented using plain English like this: "2 lacks in this value up to maximal value in 16-bit register + 1". -3 can be represented as "…3 lacks in this value up to …". Maximal value of 16-bit register + 1 is 0x10000. During addition of two numbers and *cutting off* by 2^{16} modulo, $2 + 3 = 5$ *will be lacking*.

2.2.1 Using IMUL over MUL

Example like listing.3.21.2 where two unsigned values are multiplied compiles into listing.3.21.2 where `IMUL` is used instead of `MUL`.

This is important property of both `MUL` and `IMUL` instructions. First of all, they both produce 64-bit value if two 32-bit values are multiplied, or 128-bit value if two 64-bit values are multiplied (biggest possible product in 32-bit environment is
`0xffffffff*0xffffffff=0xfffffffe00000001`). But C/C++ standards have no way to access higher half of result, and a product always has the same size as multiplicands. And both `MUL` and `IMUL` instructions works in the same way if higher half is ignored, i.e., they both generate the same lower half. This is important property of "two's complement" way of representing signed numbers.

So C/C++ compiler can use any of these instructions.

But `IMUL` is more versatile than `MUL` because it can take any register(s) as source, while `MUL` requires one of multiplicands stored in AX/EAX/RAX register. Even more than that: `MUL` stores result in `EDX:EAX` pair in 32-bit environment, or `RDX:RAX` in 64-bit one, so it always calculates the whole result. On contrary, it's possible to set a single destination register while using `IMUL` instead of pair, and then CPU will calculate only lower half, which works faster [see Torborn Granlund, *Instruction latencies and throughput for AMD and Intel x86 processors*[14]).

Given than, C/C++ compilers may generate `IMUL` instruction more often then `MUL`.

Nevertheless, using compiler intrinsic, it's still possible to do unsigned multiplication and get *full* result. This is sometimes called *extended multiplication*. MSVC has intrinsic for this called *__emul*[15] and another one: *_umul128*[16]. GCC offer *__int128* data type, and if 64-bit multiplicands are first promoted to 128-bit ones, then a product is stored into another *__int128* value, then result is shifted by 64 bits right, you'll get higher half of result[17].

MulDiv() function in Windows

Windows has MulDiv() function [18], fused multiply/divide function, it multiplies two 32-bit integers into intermediate 64-bit value and then divides it by a third 32-bit integer. It is easier than to use two compiler intrinsic, so Microsoft developers made a special function for it. And it seems, this is busy function, judging by its usage.

2.2.2 Couple of additions about two's complement form

> Exercise 2-1. Write a program to determine the ranges of `char`, `short`, `int`, and `long` variables, both `signed` and `unsigned`, by printing appropriate values from standard headers and by direct computation.
>
> Brian W. Kernighan, Dennis M. Ritchie, *The C Programming Language*, 2ed, (1988)

[14] `http://yurichev.com/mirrors/x86-timing.pdf`]
[15] `https://msdn.microsoft.com/en-us/library/d2s81xt0(v=vs.80).aspx`
[16] `https://msdn.microsoft.com/library/3dayytw9%28v=vs.100%29.aspx`
[17] Example: `http://stackoverflow.com/a/13187798`
[18] `https://msdn.microsoft.com/en-us/library/windows/desktop/aa383718(v=vs.85).aspx`

Getting maximum number of some word

Maximum unsigned number is just a number where all bits are set: *0xFF....FF* (this is -1 if the word is treated as signed integer). So you take a word, set all bits and get the value:

```
#include <stdio.h>

int main()
{
        unsigned int val=~0; // change to "unsigned char" to get maximal value for the unsigned
    ↳  8-bit byte
        // 0-1 will also work, or just -1
        printf ("%u\n", val); // %u for unsigned
};
```

This is 4294967295 for 32-bit integer.

Getting minimum number for some signed word

Minimum signed number is encoded as *0x80....00*, i.e., most significant bit is set, while others are cleared. Maximum signed number is encoded in the same way, but all bits are inverted: *0x7F....FF*.

Let's shift a lone bit left until it disappears:

```
#include <stdio.h>

int main()
{
        signed int val=1; // change to "signed char" to find values for signed byte
        while (val!=0)
        {
                printf ("%d %d\n", val, ~val);
                val=val<<1;
        };
};
```

Output is:

```
...

536870912 -536870913
1073741824 -1073741825
-2147483648 2147483647
```

Two last numbers are minimum and maximum signed 32-bit *int* respectively.

2.3 Integer overflow

I intentionally put this section after the section about signed number representation.

First, take a look at this implementation of *itoa()* function from [Brian W. Kernighan, Dennis M. Ritchie, *The C Programming Language*, 2ed, (1988)]:

```
void itoa(int n, char s[])
{
        int i, sign;
        if ((sign = n) < 0) /* record sign */
                n = -n; /* make n positive */
        i = 0;
        do { /* generate digits in reverse order */
                s[i++] = n % 10 + '0'; /* get next digit */
        } while ((n /= 10) > 0); /* delete it */
        if (sign < 0)
                s[i++] = '-';
        s[i] = '\0';
        strrev(s);
```

```
}
```

(The full source code: https://github.com/DennisYurichev/RE-for-beginners/blob/master/fundamentals
itoa_KR.c)

It has a subtle bug. Try to find it. You can download source code, compile it, etc. The answer on the next page.

From [Brian W. Kernighan, Dennis M. Ritchie, *The C Programming Language*, 2ed, (1988)]:

> Exercise 3-4. In a two's complement number representation, our version of *itoa* does not handle the largest negative number, that is, the value of *n* equal to $-(2^{wordsize-1})$. Explain why not. Modify it to print that value correctly, regardless of the machine on which it runs.

The answer is: the function cannot process largest negative number (INT_MIN or 0x80000000 or -2147483648) correctly.

How to change sign? Invert all bits and add 1. If to invert all bits in INT_MIN value (0x80000000), this is 0x7fffffff. Add 1 and this is 0x80000000 again. So changing sign has no effect. This is an important artifact of two's complement system.

Further reading:

- blexim – Basic Integer Overflows[19]
- Yannick Moy, Nikolaj Bjørner, and David Sielaff – Modular Bug-finding for Integer Overflows in the Large: Sound, Efficient, Bit-precise Static Analysis[20]

2.4 AND

2.4.1 Checking if a value is on 2^n boundary

If you need to check if your value is divisible by 2^n number (like 1024, 4096, etc.) without remainder, you can use a % operator in C/C++, but there is a simpler way. 4096 is 0x1000, so it always has $4 * 3 = 12$ lower bits cleared.

What you need is just:

```
if (value&0xFFF)
{
        printf ("value is not divisible by 0x1000 (or 4096)\n");
        printf ("by the way, remainder is %d\n", value&0xFFF);
}
else
        printf ("value is divisible by 0x1000 (or 4096)\n");
```

In other words, this code checks if there are any bit set among lower 12 bits. As a side effect, lower 12 bits is always a remainder from division a value by 4096 (because division by 2^n is merely a right shift, and shifted (and dropped) bits are bits of remainder).

Same story if you want to check if the number is odd or even:

```
if (value&1)
        // odd
else
        // even
```

This is merely the same as if to divide by 2 and get 1-bit remainder.

2.4.2 KOI-8R Cyrillic encoding

It was a time when 8-bit ASCII table wasn't supported by some Internet services, including email. Some supported, some others—not.

It was also a time, when non-Latin writing systems used second half of 8-bit ASCII table to accommodate non-Latin characters. There were several popular Cyrillic encodings, but KOI-8R (devised by Andrey "ache" Chernov) is somewhat unique in comparison with others.

[19] http://phrack.org/issues/60/10.html
[20] https://yurichev.com/mirrors/SMT/z3prefix.pdf

Figure 2.1: KOI8-R table

Someone may notice that Cyrillic characters are allocated almost in the same sequence as Latin ones. This leads to one important property: if all 8th bits in Cyrillic text encoded in KOI-8R are to be reset, a text transforms into transliterated text with Latin characters in place of Cyrillic. For example, Russian sentence:

> Мой дядя самых честных правил, Когда не в шутку занемог, Он уважать себя заставил, И лучше выдумать не мог.

...if encoded in KOI-8R and then 8th bit stripped, transforms into:

> mOJ DQDQ SAMYH ^ESTNYH PRAWIL, kOGDA NE W [UTKU ZANEMOG, oN UWAVATX SEBQ ZASTAWIL, i LU^[E WYDUMATX NE MOG.

...perhaps this is not very appealing æsthetically, but this text is still readable to Russian language natives.

Hence, Cyrillic text encoded in KOI-8R, passed through an old 7-bit service will survive into transliterated, but still readable text.

Stripping 8th bit is automatically transposes any character from the second half of the (any) 8-bit ASCII table to the first one, into the same place (take a look at red arrow right of table). If the character has already been placed in the first half (i.e., it has been in standard 7-bit ASCII table), it's not transposed.

Perhaps, transliterated text is still recoverable, if you'll add 8th bit to the characters which were seems transliterated.

Drawback is obvious: Cyrillic characters allocated in KOI-8R table are not in the same sequence as in Russian/Bulgarian/Ukrainian/etc. alphabet, and this isn't suitable for sorting, for example.

2.5 AND and OR as subtraction and addition

2.5.1 ZX Spectrum ROM text strings

Those who once investigated ZX Spectrum ROM internals, probably noticed that the last symbol of each text string is seemingly absent.

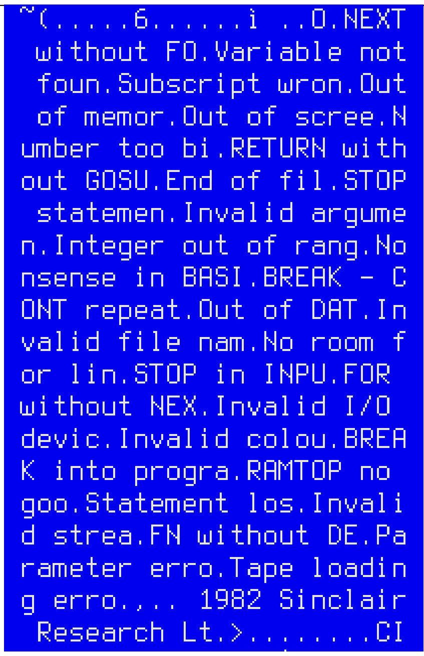


Figure 2.2: Part of ZX Spectrum ROM

There are present, in fact.

Here is excerpt of ZX Spectrum 128K ROM disassembled:

```
L048C:  DEFM "MERGE erro"           ; Report 'a'.
        DEFB 'r'+$80
L0497:  DEFM "Wrong file typ"       ; Report 'b'.
        DEFB 'e'+$80
L04A6:  DEFM "CODE erro"            ; Report 'c'.
        DEFB 'r'+$80
L04B0:  DEFM "Too many bracket"     ; Report 'd'.
        DEFB 's'+$80
L04C1:  DEFM "File already exist"   ; Report 'e'.
        DEFB 's'+$80
```

(http://www.matthew-wilson.net/spectrum/rom/128_ROM0.html)

Last character has most significant bit set, which marks string end. Presumably, it was done to save some space? Old 8-bit computers has very tight environment.

Characters of all messages are always in standard 7-bit ASCII table, so it's guaranteed 8th bit is never used for characters.

To print such string, we must check MSB of each byte, and if it's set, we must clear it, then print character, and then stop. Here is a C example:

```
unsigned char hw[]=
{
        'H',
        'e',
        'l',
        'l',
        'o'|0x80
};

void print_string()
{
        for (int i=0; ;i++)
        {
                if (hw[i]&0x80) // check MSB
                {
                        // clear MSB
                        // (in other words, clear all, but leave 7 lower bits intact)
                        printf ("%c", hw[i] & 0x7F);
                        // stop
```

```
                        break;
                };
                printf ("%c", hw[i]);
        };
};
```

Now what is interesting, since 8th bit is the most significant bit (in byte), we can check it, set it and remove it using arithmetical operations instead of logical.

I can rewrite my C example:

```
unsigned char hw[]=
{
        'H',
        'e',
        'l',
        'l',
        'o'+0x80
};

void print()
{
        for (int i=0; ;i++)
        {
                // hw[] must have 'unsigned char' type
                if (hw[i] >= 0x80) // check for MSB
                {
                        printf ("%c", hw[i]-0x80); // clear MSB
                        // stop
                        break;
                };
                printf ("%c", hw[i]);
        };
};
```

By default, *char* is signed type in C/C++, so to compare it with variable like 0x80 (which is negative (-128) if treated as signed), we must treat each character in text message as unsigned.

Now if 8th bit is set, the number is always larger or equal to 0x80. If 8th bit is clear, the number is always smaller than 0x80.

Even more than that: if 8th bit is set, it can be cleared by subtracting 0x80, nothing else. If it's not set beforehand, however, subtracting will destruct other bits.

Likewise, if 8th bit is clear, it's possible to set it by adding 0x80. But if it's set beforehand, addition operation will destruct some other bits.

In fact, this is valid for any bit. If the 4th bit is clear, you can set it just by adding 0x10: 0x100+0x10 = 0x110. If the 4th bit is set, you can clear it by subtracting 0x10: 0x1234-0x10 = 0x1224.

It works, because carry isn't happened during addition/subtraction. It will, however, happen, if the bit is already set there before addition, or absent before subtraction.

Likewise, addition/subtraction can be replaced using OR/AND operation if two conditions are met: 1) you want to add/subtract by a number in form of 2^n; 2) this bit in source value is clear/set.

For example, addition of 0x20 is the same as ORing value with 0x20 under condition that this bit is clear before: 0x1204|0x20 = 0x1204+0x20 = 0x1224.

Subtraction of 0x20 is the same as ANDing value with 0x20 (0x....FFDF), but if this bit is set before: 0x1234&(˜0x20) = 0x1234&0xFFDF = 0x1234-0x20 = 0x1214.

Again, it works because carry not happened when you add 2^n number and this bit isn't set before.

This property of boolean algebra is important, worth understanding and keeping it in mind.

Another example in this book: 3.16.3 on page 537.

2.6 XOR (exclusive OR)

XOR is widely used when one needs just to flip specific bit(s). Indeed, the XOR operation applied with 1 effectively inverts a bit:

input A	input B	output
0	0	0
0	1	1
1	0	1
1	1	0

And vice-versa, the XOR operation applied with 0 does nothing, i.e., it's an idle operation. This is a very important property of the XOR operation and it's highly recommended to memorize it.

2.6.1 Everyday speech

XOR operation present in common everyday speech. When someone asks "please buy apples or bananas", this usually means "buy the first object or the second, but not both"—this is exactly exclusive OR, because logical OR would mean "both objects are also fine".

Some people suggest "and/or" should be used in everyday speech to make emphasis that logical OR is used instead of exclusive OR: https://en.wikipedia.org/wiki/And/or.

2.6.2 Encryption

XOR is heavily used in both amateur (9.1) and *real* encryption (at least in *Feistel network*).

XOR is very useful here because: $cipher\_text = plain\_text \oplus key$ and then: $(plain\_text \oplus key) \oplus key = plain\_text$.

2.6.3 RAID4

RAID4 offers a very simple method to protect hard disks. For example, there are several disks (D_1, D_2, D_3, etc.) and one parity disk (P). Each bit/byte written to parity disk is calculated and written on-fly:

$$P = D_1 \oplus D_2 \oplus D_3 \tag{2.1}$$

If any of disks is failed, for example, D_2, it's restored using the very same way:

$$D_2 = D_1 \oplus P \oplus D_3 \tag{2.2}$$

If parity disk failed, it is restored using 2.1 way. If two of any disks are failed, then it wouldn't be possible to restore both.

RAID5 is more advanced, but this XOR property is still exploited there.

That's why RAID controllers has hardware "XOR accelerators" helping to XOR large chunks of written data on-fly. When computers get faster and faster, it now can be done at software level, using SIMD.

2.6.4 XOR swap algorithm

Hard to believe, but this code swaps values in EAX and EBX without aid of any other additional register or memory cell:

```
xor eax, ebx
xor ebx, eax
xor eax, ebx
```

Let's find out, how it works. First, we will rewrite it to step aside from x86 assembly language:

```
X = X XOR Y
Y = Y XOR X
X = X XOR Y
```

What X and Y has at each step? Just keep in mind the simple rule: $(X \oplus Y) \oplus Y = X$ for any values of X and Y.

Let's see, X after 1st step has $X \oplus Y$; Y after 2nd step has $Y \oplus (X \oplus Y) = X$; X after 3rd step has $(X \oplus Y) \oplus X = Y$.

Hard to say if anyone should use this trick, but it servers as a good demonstration example of XOR properties.

Wikipedia article (https://en.wikipedia.org/wiki/XOR_swap_algorithm) has also yet another explanation: addition and subtraction operations can be used instead of XOR:

```
X = X + Y
Y = X - Y
X = X - Y
```

Let's see: X after 1st step has $X+Y$; Y after 2nd step has $X+Y-Y = X$; X after 3rd step has $X+Y-X = Y$.

2.6.5 XOR linked list

Doubly linked list is a list in which each element has link to the previous element and to the next one. Hence, it's very easy to traverse list backwards or forward. `std::list` in C++ implements doubly linked list which also is examined in this book: 3.18.4.

So each element has two pointers. Is it possible, perhaps in environment of small RAM footprint, to preserve all functionality with one pointer instead of two? Yes, if it a value of $prev \oplus next$ will be stored in this memory cell, which is usually called "link".

Maybe, we could say that address to the previous element is "encrypted" using address of next element and otherwise: next element address is "encrypted" using previous element address.

When we traverse this list forward, we always know address of the previous element, so we can "decrypt" this field and get address of the next element. Likewise, it's possible to traverse this list backwards, "decrypting" this field using next element's address.

But it's not possible to find address of previous or next element of some specific element without knowing address of the first one.

Couple of things to complete this solution: first element will have address of next element without any XOR-ing, last element will have address of previous element without any XOR-ing.

Now let's sum it up. This is example of doubly linked list of 5 elements. A_x is address of element.

address	*link* field contents
A_0	A_1
A_1	$A_0 \oplus A_2$
A_2	$A_1 \oplus A_3$
A_3	$A_2 \oplus A_4$
A_4	A_3

And again, hard to say if anyone should use this tricky hacks, but this is also a good demonstration of XOR properties. As with XOR swap algorithm, Wikipedia article about it also offers way to use addition or subtraction instead of XOR: https://en.wikipedia.org/wiki/XOR_linked_list.

2.6.6 Zobrist hashing / tabulation hashing

If you work on a chess engine, you traverse a game tree many times per second, and often, you can encounter the same position, which has already been processed.

So you have to use a method to store already calculated positions somewhere. But chess position can require a lot of memory, and a hash function would be used instead.

Here is a way to compress a chess position into 64-bit value, called Zobrist hashing:

```
// we have 8*8 board and 12 pieces (6 for white side and 6 for black)

uint64_t table[12][8][8]; // filled with random values

int position[8][8]; // for each square on board. 0 - no piece. 1..12 - piece

uint64_t hash;

for (int row=0; row<8; row++)
        for (int col=0; col<8; col++)
        {
                int piece=position[row][col];

                if (piece!=0)
                        hash=hash^table[piece][row][col];
        };

return hash;
```

Now the most interesting part: if the next (modified) chess position differs only by one (moved) piece, you don't need to recalculate hash for the whole position, all you need is:

```
hash=...; // (already calculated)

// subtract information about the old piece:
hash=hash^table[old_piece][old_row][old_col];

// add information about the new piece:
hash=hash^table[new_piece][new_row][new_col];
```

2.6.7 By the way

The usual *OR* also sometimes called *inclusive OR* (or even *IOR*), as opposed to *exclusive OR*. One place is *operator* Python's library: it's called *operator.ior* here.

2.6.8 AND/OR/XOR as MOV

`OR reg, 0xFFFFFFFF` sets all bits to 1, hence, no matter what has been in register before, it will be set to -1. `OR reg, -1` is shorter than `MOV reg, -1`, so MSVC uses OR instead the latter, for example: 3.15.1 on page 527.

Likewise, `AND reg, 0` always resets all bits, hence, it acts like `MOV reg, 0`.

`XOR reg, reg`, no matter what has been in register beforehand, resets all bits, and also acts like `MOV reg, 0`.

2.7 Population count

`POPCNT` instruction is population count (AKA Hamming weight). It just counts number of bits set in an input value.

As a side effect, `POPCNT` instruction (or operation) can be used to determine, if the value has 2^n form. Since, 2^n number always has just one single bit, `POPCNT`'s result will always be just 1.

For example, I once wrote a base64 strings scanner for hunting something interesting in binary files[21]. And there is a lot of garbage and false positives, so I add an option to filter out data blocks which has size of 2^n bytes (i.e., 256 bytes, 512, 1024, etc.). The size of block is checked just like this:

```
if (popcnt(size)==1)
        // OK
...
```

[21] https://github.com/DennisYurichev/base64scanner

The instruction is also known as “NSA[22] instruction” due to rumors:

> This branch of cryptography is fast-paced and very politically charged. Most designs are secret; a majority of military encryptions systems in use today are based on LFSRs. In fact, most Cray computers (Cray 1, Cray X-MP, Cray Y-MP) have a rather curious instruction generally known as “population count.” It counts the 1 bits in a register and can be used both to efficiently calculate the Hamming distance between two binary words and to implement a vectorized version of a LFSR. I’ve heard this called the canonical NSA instruction, demanded by almost all computer contracts.

[Bruce Schneier, *Applied Cryptography*, (John Wiley & Sons, 1994)]

2.8 Endianness

The endianness is a way of representing values in memory.

2.8.1 Big-endian

The `0x12345678` value is represented in memory as:

address in memory	byte value
+0	0x12
+1	0x34
+2	0x56
+3	0x78

Big-endian CPUs include Motorola 68k, IBM POWER.

2.8.2 Little-endian

The `0x12345678` value is represented in memory as:

address in memory	byte value
+0	0x78
+1	0x56
+2	0x34
+3	0x12

Little-endian CPUs include Intel x86.

2.8.3 Example

Let’s take big-endian MIPS Linux installed and ready in QEMU [23].

And let’s compile this simple example:

```
#include <stdio.h>

int main()
{
        int v, i;

        v=123;

        printf ("%02X %02X %02X %02X\n",
                *(char*)&v,
                *(((char*)&v)+1),
                *(((char*)&v)+2),
```

[22] National Security Agency
[23] Available for download here: http://go.yurichev.com/17008

```
                *(((char*)&v)+3));
};
```

After running it we get:

```
root@debian-mips:~# ./a.out
00 00 00 7B
```

That is it. 0x7B is 123 in decimal. In little-endian architectures, 7B is the first byte (you can check on x86 or x86-64), but here it is the last one, because the highest byte goes first.

That's why there are separate Linux distributions for MIPS ("mips" (big-endian) and "mipsel" (little-endian)). It is impossible for a binary compiled for one endianness to work on an OS with different endianness.

There is another example of MIPS big-endiannes in this book: 1.24.4 on page 365.

2.8.4 Bi-endian

CPUs that may switch between endianness are ARM, PowerPC, SPARC, MIPS, IA64[24], etc.

2.8.5 Converting data

The BSWAP instruction can be used for conversion.

TCP/IP network data packets use the big-endian conventions, so that is why a program working on a little-endian architecture has to convert the values. The `htonl()` and `htons()` functions are usually used.

In TCP/IP, big-endian is also called "network byte order", while byte order on the computer "host byte order". "host byte order" is little-endian on Intel x86 and other little-endian architectures, but it is big-endian on IBM POWER, so `htonl()` and `htons()` don't shuffle any bytes on the latter.

2.9 Memory

There are 3 main types of memory:

- Global memory AKA "static memory allocation". No need to allocate explicitly, the allocation is performed just by declaring variables/arrays globally. These are global variables, residing in the data or constant segments. They are available globally (hence, considered as an anti-pattern). Not convenient for buffers/arrays, because they must have a fixed size. Buffer overflows that occur here usually overwrite variables or buffers residing next to them in memory. There's an example in this book: 1.9.3 on page 76.
- Stack AKA "allocate on stack". The allocation is performed just by declaring variables/arrays locally in the function. These are usually local variables for the function. Sometimes these local variable are also available to descending functions (to callee functions, if caller passes a pointer to a variable to the callee to be executed). Allocation and deallocation are very fast, it just SP needs to be shifted.

  But they're also not convenient for buffers/arrays, because the buffer size has to be fixed, unless `alloca()` (1.7.2 on page 35) (or a variable-length array) is used. Buffer overflows usually overwrite important stack structures: 1.20.2 on page 275.
- Heap AKA "dynamic memory allocation". Allocation/deallocation is performed by calling `malloc()/free()` or `new/delete` in C++. This is the most convenient method: the block size may be set at runtime.

  Resizing is possible (using `realloc()`), but can be slow. This is the slowest way to allocate memory: the memory allocator must support and update all control structures while allocating and deallocating. Buffer overflows usually overwrite these structures. Heap allocations are also source of memory leak problems: each memory block has to be deallocated explicitly, but one may forget about it, or do it incorrectly.

[24] Intel Architecture 64 (Itanium)

Another problem is the "use after free"—using a memory block after `free()` has been called on it, which is very dangerous.

Example in this book: 1.24.2 on page 348.

2.10 CPU

2.10.1 Branch predictors

Some latest compilers try to get rid of conditional jump instructions. Examples in this book are: 1.14.1 on page 135, 1.14.3 on page 143, 1.22.5 on page 330.

This is because the branch predictor is not always perfect, so the compilers try to do without conditional jumps, if possible.

Conditional instructions in ARM (like ADRcc) are one way, another one is the CMOVcc x86 instruction.

2.10.2 Data dependencies

Modern CPUs are able to execute instructions simultaneously (OOE[25]), but in order to do so, the results of one instruction in a group must not influence the execution of others. Hence, the compiler endeavors to use instructions with minimal influence on the CPU state.

That's why the LEA instruction is so popular, because it does not modify CPU flags, while other arithmetic instructions does.

2.11 Hash functions

A very simple example is CRC32, an algorithm that provides "stronger" checksum for integrity checking purposes. It is impossible to restore the original text from the hash value, it has much less information: But CRC32 is not cryptographically secure: it is known how to alter a text in a way that the resulting CRC32 hash value will be the one we need. Cryptographic hash functions are protected from this.

MD5, SHA1, etc. are such functions and they are widely used to hash user passwords in order to store them in a database. Indeed: an Internet forum database may not contain user passwords (a stolen database can compromise all users' passwords) but only hashes (so a cracker can't reveal the passwords). Besides, an Internet forum engine does not need to know your password exactly, it needs only to check if its hash is the same as the one in the database, and give you access if they match. One of the simplest password cracking methods is just to try hashing all possible passwords in order to see which matches the resulting value that we need. Other methods are much more complex.

2.11.1 How do one-way functions work?

A one-way function is a function which is able to transform one value into another, while it is impossible (or very hard) to reverse it. Some people have difficulties while understanding how this is possible at all. Here is a simple demonstration.

We have a vector of 10 numbers in range 0..9, each is present only once, for example:

```
4 6 0 1 3 5 7 8 9 2
```

The algorithm for the simplest possible one-way function is:

- take the number at zeroth position (4 in our case);
- take the number at first position (6 in our case);
- swap numbers at positions of 4 and 6.

Let's mark the numbers at positions 4 and 6:

[25] Out-of-Order Execution

```
4 6 0 1 3 5 7 8 9 2
        ^   ^
```

Let's swap them and we get this result:

```
4 6 0 1 7 5 3 8 9 2
```

While looking at the result, and even if we know the algorithm, we can't know unambiguously the initial state, because the first two numbers could be 0 and/or 1, and then they could participate in the swapping procedure.

This is an utterly simplified example for demonstration. Real one-way functions are much more complex.

Chapter 3

Slightly more advanced examples

3.1 Double negation

A popular way[1] to convert non-zero value into 1 (or boolean *true*) and zero value into 0 (or boolean *false*) is *!!statement*:

```
int convert_to_bool(int a)
{
        return !!a;
};
```

Optimizing GCC 5.4 x86:

```
convert_to_bool:
        mov     edx, DWORD PTR [esp+4]
        xor     eax, eax
        test    edx, edx
        setne   al
        ret
```

XOR always clears return value in EAX, even in case if SETNE will not trigger. I.e., XOR sets default return value to zero.

If the input value is not equal to zero (-NE suffix in SET instruction), 1 is set to AL, otherwise AL isn't touched.

Why SETNE operates on low 8-bit part of EAX register? Because the matter is just in the last bit (0 or 1), while other bits are cleared by XOR.

Therefore, that C/C++ code could be rewritten like this:

```
int convert_to_bool(int a)
{
        if (a!=0)
                return 1;
        else
                return 0;
};
```

...or even:

```
int convert_to_bool(int a)
{
        if (a)
                return 1;
        else
                return 0;
};
```

Compilers targeting CPUs lacking instruction similar to SET, in this case, generates branching instructions, etc.

[1]This way is also controversial, because it leads to hard-to-read code

3.2 strstr() example

Let's back to the fact that GCC sometimes can use part of string: 1.5.3 on page 18.

The *strstr()* C/C++ standard library function is used to find any occurrence in a string. This is what we will do:

```
#include <string.h>
#include <stdio.h>

int main()
{
        char *s="Hello, world!";
        char *w=strstr(s, "world");

        printf ("%p, [%s]\n", s, s);
        printf ("%p, [%s]\n", w, w);
};
```

The output is:

```
0x8048530, [Hello, world!]
0x8048537, [world!]
```

The difference between the address of the original string and the address of the substring that *strstr()* has returned is 7. Indeed, "Hello, " string has length of 7 characters.

The `printf()` function during second call has no idea there are some other characters before the passed string and it prints characters from the middle of original string till the end (marked by zero byte).

3.3 Temperature converting

Another very popular example in programming books for beginners is a small program that converts Fahrenheit temperature to Celsius or back.

$$C = \frac{5 \cdot (F - 32)}{9}$$

We can also add simple error handling: 1) we must check if the user has entered a correct number; 2) we must check if the Celsius temperature is not below -273 (which is below absolute zero, as we may recall from school physics lessons).

The `exit()` function terminates the program instantly, without returning to the caller function.

3.3.1 Integer values

```
#include <stdio.h>
#include <stdlib.h>

int main()
{
        int celsius, fahr;
        printf ("Enter temperature in Fahrenheit:\n");
        if (scanf ("%d", &fahr)!=1)
        {
                printf ("Error while parsing your input\n");
                exit(0);
        };

        celsius = 5 * (fahr-32) / 9;

        if (celsius<-273)
        {
                printf ("Error: incorrect temperature!\n");
```

```
                exit(0);
        };
        printf ("Celsius: %d\n", celsius);
};
```

Optimizing MSVC 2012 x86

Listing 3.1: Optimizing MSVC 2012 x86

```
$SG4228 DB      'Enter temperature in Fahrenheit:', 0aH, 00H
$SG4230 DB      '%d', 00H
$SG4231 DB      'Error while parsing your input', 0aH, 00H
$SG4233 DB      'Error: incorrect temperature!', 0aH, 00H
$SG4234 DB      'Celsius: %d', 0aH, 00H

_fahr$ = -4     ; size = 4
_main   PROC
        push    ecx
        push    esi
        mov     esi, DWORD PTR __imp__printf
        push    OFFSET $SG4228          ; 'Enter temperature in Fahrenheit:'
        call    esi                     ; call printf()
        lea     eax, DWORD PTR _fahr$[esp+12]
        push    eax
        push    OFFSET $SG4230          ; '%d'
        call    DWORD PTR __imp__scanf
        add     esp, 12
        cmp     eax, 1
        je      SHORT $LN2@main
        push    OFFSET $SG4231          ; 'Error while parsing your input'
        call    esi                     ; call printf()
        add     esp, 4
        push    0
        call    DWORD PTR __imp__exit
$LN9@main:
$LN2@main:
        mov     eax, DWORD PTR _fahr$[esp+8]
        add     eax, -32        ; ffffffe0H
        lea     ecx, DWORD PTR [eax+eax*4]
        mov     eax, 954437177  ; 38e38e39H
        imul    ecx
        sar     edx, 1
        mov     eax, edx
        shr     eax, 31         ; 0000001fH
        add     eax, edx
        cmp     eax, -273       ; fffffeefH
        jge     SHORT $LN1@main
        push    OFFSET $SG4233          ; 'Error: incorrect temperature!'
        call    esi     ; call printf()
        add     esp, 4
        push    0
        call    DWORD PTR __imp__exit
$LN10@main:
$LN1@main:
        push    eax
        push    OFFSET $SG4234          ; 'Celsius: %d'
        call    esi     ; call printf()
        add     esp, 8
        ; return 0 - by C99 standard
        xor     eax, eax
        pop     esi
        pop     ecx
        ret     0
$LN8@main:
_main   ENDP
```

What we can say about it:

- The address of `printf()` is first loaded in the ESI register, so the subsequent `printf()` calls are done just by the `CALL ESI` instruction. It's a very popular compiler technique, possible if several consequent calls to the same function are present in the code, and/or if there is a free register which can be used for this.
- We see the `ADD EAX, -32` instruction at the place where 32 has to be subtracted from the value. $EAX = EAX + (-32)$ is equivalent to $EAX = EAX - 32$ and somehow, the compiler decided to use ADD instead of SUB. Maybe it's worth it, it's hard to be sure.
- The LEA instruction is used when the value is to be multiplied by 5: `lea ecx, DWORD PTR [eax+eax*4]`. Yes, $i + i * 4$ is equivalent to $i * 5$ and LEA works faster then IMUL.
  By the way, the `SHL EAX, 2 / ADD EAX, EAX` instruction pair could be also used here instead— some compilers do it like.
- The division by multiplication trick (3.9 on page 497) is also used here.
- `main()` returns 0 if we don't have `return 0` at its end. The C99 standard tells us [*ISO/IEC 9899:TC3 (C C99 standard)*, (2007)5.1.2.2.3] that `main()` will return 0 in case the `return` statement is missing. This rule works only for the `main()` function.

  Though, MSVC doesn't officially support C99, but maybe it support it partially?

Optimizing MSVC 2012 x64

The code is almost the same, but we can find `INT 3` instructions after each `exit()` call.

```
        xor     ecx, ecx
        call    QWORD PTR __imp_exit
        int     3
```

`INT 3` is a debugger breakpoint.

It is known that `exit()` is one of the functions which can never return [2], so if it does, something really odd has happened and it's time to load the debugger.

3.3.2 Floating-point values

```
#include <stdio.h>
#include <stdlib.h>

int main()
{
        double celsius, fahr;
        printf ("Enter temperature in Fahrenheit:\n");
        if (scanf ("%lf", &fahr)!=1)
        {
                printf ("Error while parsing your input\n");
                exit(0);
        };

        celsius = 5 * (fahr-32) / 9;

        if (celsius<-273)
        {
                printf ("Error: incorrect temperature!\n");
                exit(0);
        };
        printf ("Celsius: %lf\n", celsius);
};
```

MSVC 2010 x86 uses FPU instructions...

Listing 3.2: Optimizing MSVC 2010 x86

```
$SG4038 DB      'Enter temperature in Fahrenheit:', 0aH, 00H
$SG4040 DB      '%lf', 00H
```

[2] another popular one is `longjmp()`

```
$SG4041 DB      'Error while parsing your input', 0aH, 00H
$SG4043 DB      'Error: incorrect temperature!', 0aH, 00H
$SG4044 DB      'Celsius: %lf', 0aH, 00H

__real@c071100000000000 DQ 0c071100000000000r   ; -273
__real@4022000000000000 DQ 04022000000000000r   ; 9
__real@4014000000000000 DQ 04014000000000000r   ; 5
__real@4040000000000000 DQ 04040000000000000r   ; 32

_fahr$ = -8     ; size = 8
_main   PROC
        sub     esp, 8
        push    esi
        mov     esi, DWORD PTR __imp__printf
        push    OFFSET $SG4038          ; 'Enter temperature in Fahrenheit:'
        call    esi                     ; call printf()
        lea     eax, DWORD PTR _fahr$[esp+16]
        push    eax
        push    OFFSET $SG4040          ; '%lf'
        call    DWORD PTR __imp__scanf
        add     esp, 12
        cmp     eax, 1
        je      SHORT $LN2@main
        push    OFFSET $SG4041          ; 'Error while parsing your input'
        call    esi                     ; call printf()
        add     esp, 4
        push    0
        call    DWORD PTR __imp__exit
$LN2@main:
        fld     QWORD PTR _fahr$[esp+12]
        fsub    QWORD PTR __real@4040000000000000 ; 32
        fmul    QWORD PTR __real@4014000000000000 ; 5
        fdiv    QWORD PTR __real@4022000000000000 ; 9
        fld     QWORD PTR __real@c071100000000000 ; -273
        fcomp   ST(1)
        fnstsw  ax
        test    ah, 65  ; 00000041H
        jne     SHORT $LN1@main
        push    OFFSET $SG4043          ; 'Error: incorrect temperature!'
        fstp    ST(0)
        call    esi             ; call printf()
        add     esp, 4
        push    0
        call    DWORD PTR __imp__exit
$LN1@main:
        sub     esp, 8
        fstp    QWORD PTR [esp]
        push    OFFSET $SG4044          ; 'Celsius: %lf'
        call    esi
        add     esp, 12
        ; return 0 - by C99 standard
        xor     eax, eax
        pop     esi
        add     esp, 8
        ret     0
$LN10@main:
_main   ENDP
```

…but MSVC 2012 uses SIMD instructions instead:

Listing 3.3: Optimizing MSVC 2010 x86

```
$SG4228 DB      'Enter temperature in Fahrenheit:', 0aH, 00H
$SG4230 DB      '%lf', 00H
$SG4231 DB      'Error while parsing your input', 0aH, 00H
$SG4233 DB      'Error: incorrect temperature!', 0aH, 00H
$SG4234 DB      'Celsius: %lf', 0aH, 00H
__real@c071100000000000 DQ 0c071100000000000r   ; -273
__real@4040000000000000 DQ 04040000000000000r   ; 32
__real@4022000000000000 DQ 04022000000000000r   ; 9
__real@4014000000000000 DQ 04014000000000000r   ; 5
```

```
_fahr$ = -8     ; size = 8
_main   PROC
        sub     esp, 8
        push    esi
        mov     esi, DWORD PTR __imp__printf
        push    OFFSET $SG4228          ; 'Enter temperature in Fahrenheit:'
        call    esi                     ; call printf()
        lea     eax, DWORD PTR _fahr$[esp+16]
        push    eax
        push    OFFSET $SG4230          ; '%lf'
        call    DWORD PTR __imp__scanf
        add     esp, 12
        cmp     eax, 1
        je      SHORT $LN2@main
        push    OFFSET $SG4231          ; 'Error while parsing your input'
        call    esi     ; call printf()
        add     esp, 4
        push    0
        call    DWORD PTR __imp__exit
$LN9@main:
$LN2@main:
        movsd   xmm1, QWORD PTR _fahr$[esp+12]
        subsd   xmm1, QWORD PTR __real@4040000000000000 ; 32
        movsd   xmm0, QWORD PTR __real@c071100000000000 ; -273
        mulsd   xmm1, QWORD PTR __real@4014000000000000 ; 5
        divsd   xmm1, QWORD PTR __real@4022000000000000 ; 9
        comisd  xmm0, xmm1
        jbe     SHORT $LN1@main
        push    OFFSET $SG4233          ; 'Error: incorrect temperature!'
        call    esi             ; call printf()
        add     esp, 4
        push    0
        call    DWORD PTR __imp__exit
$LN10@main:
$LN1@main:
        sub     esp, 8
        movsd   QWORD PTR [esp], xmm1
        push    OFFSET $SG4234          ; 'Celsius: %lf'
        call    esi                     ; call printf()
        add     esp, 12
        ; return 0 - by C99 standard
        xor     eax, eax
        pop     esi
        add     esp, 8
        ret     0
$LN8@main:
_main   ENDP
```

Of course, SIMD instructions are available in x86 mode, including those working with floating point numbers.

It's somewhat easier to use them for calculations, so the new Microsoft compiler uses them.

We can also see that the -273 value is loaded into XMM0 register too early. And that's OK, because the compiler may emit instructions not in the order they are in the source code.

3.4 Fibonacci numbers

Another widespread example used in programming textbooks is a recursive function that generates the Fibonacci numbers[3]. The sequence is very simple: each consecutive number is the sum of the previous two. The first two numbers are 0 and 1, or 1 and 1.

The sequence starts like this:

$$0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, 610, 987, 1597, 2584, 4181...$$

[3] http://go.yurichev.com/17332

3.4.1 Example #1

The implementation is simple. This program generates the sequence until 21.

```
#include <stdio.h>

void fib (int a, int b, int limit)
{
        printf ("%d\n", a+b);
        if (a+b > limit)
                return;
        fib (b, a+b, limit);
};

int main()
{
        printf ("0\n1\n1\n");
        fib (1, 1, 20);
};
```

Listing 3.4: MSVC 2010 x86

```
_a$ = 8                 ; size = 4
_b$ = 12                ; size = 4
_limit$ = 16            ; size = 4
_fib    PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _a$[ebp]
        add     eax, DWORD PTR _b$[ebp]
        push    eax
        push    OFFSET $SG2643
        call    DWORD PTR __imp__printf
        add     esp, 8
        mov     ecx, DWORD PTR _a$[ebp]
        add     ecx, DWORD PTR _b$[ebp]
        cmp     ecx, DWORD PTR _limit$[ebp]
        jle     SHORT $LN1@fib
        jmp     SHORT $LN2@fib
$LN1@fib:
        mov     edx, DWORD PTR _limit$[ebp]
        push    edx
        mov     eax, DWORD PTR _a$[ebp]
        add     eax, DWORD PTR _b$[ebp]
        push    eax
        mov     ecx, DWORD PTR _b$[ebp]
        push    ecx
        call    _fib
        add     esp, 12
$LN2@fib:
        pop     ebp
        ret     0
_fib    ENDP

_main   PROC
        push    ebp
        mov     ebp, esp
        push    OFFSET $SG2647 ; "0\n1\n1\n"
        call    DWORD PTR __imp__printf
        add     esp, 4
        push    20
        push    1
        push    1
        call    _fib
        add     esp, 12
        xor     eax, eax
        pop     ebp
        ret     0
_main   ENDP
```

We will illustrate the stack frames with this.

Let's load the example in OllyDbg and trace to the last call of f():

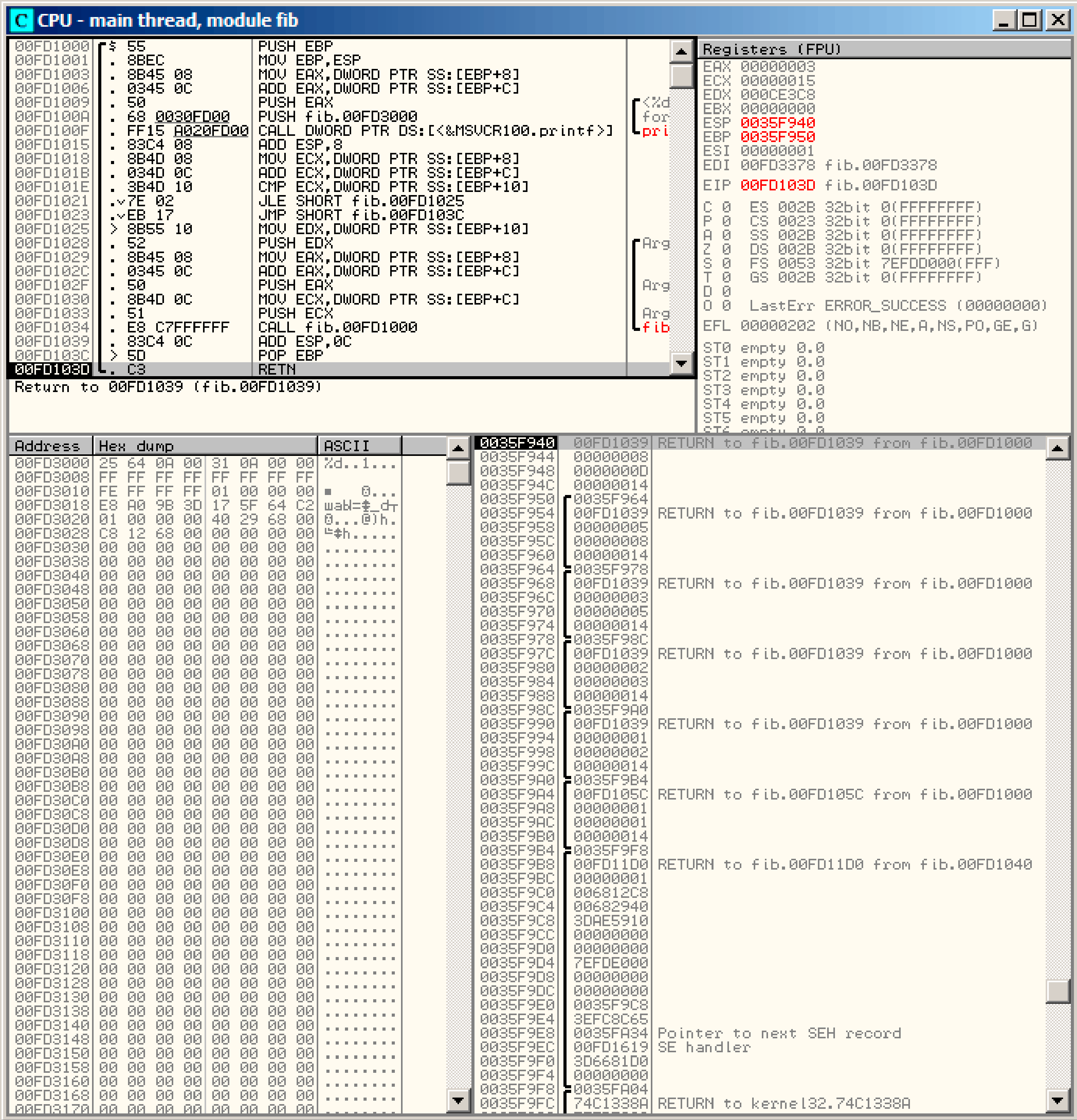


Figure 3.1: OllyDbg: last call of f()

Let's investigate the stack more closely. Comments were added by the author of this book [4]:

```
0035F940   00FD1039  RETURN to fib.00FD1039 from fib.00FD1000
0035F944   00000008  1st argument: a
0035F948   0000000D  2nd argument b
0035F94C   00000014  3rd argument: limit
0035F950  /0035F964  saved EBP register
0035F954  |00FD1039  RETURN to fib.00FD1039 from fib.00FD1000
0035F958  |00000005  1st argument: a
0035F95C  |00000008  2nd argument: b
0035F960  |00000014  3rd argument: limit
0035F964  ]0035F978  saved EBP register
0035F968  |00FD1039  RETURN to fib.00FD1039 from fib.00FD1000
0035F96C  |00000003  1st argument: a
0035F970  |00000005  2nd argument: b
0035F974  |00000014  3rd argument: limit
0035F978  ]0035F98C  saved EBP register
0035F97C  |00FD1039  RETURN to fib.00FD1039 from fib.00FD1000
0035F980  |00000002  1st argument: a
0035F984  |00000003  2nd argument: b
0035F988  |00000014  3rd argument: limit
0035F98C  ]0035F9A0  saved EBP register
0035F990  |00FD1039  RETURN to fib.00FD1039 from fib.00FD1000
0035F994  |00000001  1st argument: a
0035F998  |00000002  2nd argument: b
0035F99C  |00000014  3rd argument: limit
0035F9A0  ]0035F9B4  saved EBP register
0035F9A4  |00FD105C  RETURN to fib.00FD105C from fib.00FD1000
0035F9A8  |00000001  1st argument: a           \
0035F9AC  |00000001  2nd argument: b           | prepared in main() for f1()
0035F9B0  |00000014  3rd argument: limit       /
0035F9B4  ]0035F9F8  saved EBP register
0035F9B8  |00FD11D0  RETURN to fib.00FD11D0 from fib.00FD1040
0035F9BC  |00000001  main() 1st argument: argc  \
0035F9C0  |006812C8  main() 2nd argument: argv  | prepared in CRT for main()
0035F9C4  |00682940  main() 3rd argument: envp  /
```

The function is recursive [5], hence stack looks like a "sandwich".

We see that the *limit* argument is always the same (`0x14` or 20), but the a and b arguments are different for each call.

There are also the RA-s and the saved EBP values. OllyDbg is able to determine the EBP-based frames, so it draws these brackets. The values inside each bracket make the stack frame, in other words, the stack area which each function incarnation uses as scratch space.

We can also say that each function incarnation must not access stack elements beyond the boundaries of its frame (excluding function arguments), although it's technically possible.

It's usually true, unless the function has bugs.

Each saved EBP value is the address of the previous stack frame: this is the reason why some debuggers can easily divide the stack in frames and dump each function's arguments.

As we see here, each function incarnation prepares the arguments for the next function call.

At the end we see the 3 arguments for `main()`. `argc` is 1 (yes, indeed, we have ran the program without command-line arguments).

This easily to lead to a stack overflow: just remove (or comment out) the limit check and it will crash with exception `0xC00000FD` (stack overflow.)

3.4.2 Example #2

My function has some redundancy, so let's add a new local variable *next* and replace all "a+b" with it:

[4] By the way, it's possible to select several entries in OllyDbg and copy them to the clipboard (Ctrl-C). That's what was done by author for this example.

[5] i.e., it calls itself

```
#include <stdio.h>

void fib (int a, int b, int limit)
{
        int next=a+b;
        printf ("%d\n", next);
        if (next > limit)
                return;
        fib (b, next, limit);
};

int main()
{
        printf ("0\n1\n1\n");
        fib (1, 1, 20);
};
```

This is the output of non-optimizing MSVC, so the *next* variable is actually allocated in the local stack:

Listing 3.5: MSVC 2010 x86

```
_next$ = -4     ; size = 4
_a$ = 8         ; size = 4
_b$ = 12        ; size = 4
_limit$ = 16    ; size = 4
_fib    PROC
        push    ebp
        mov     ebp, esp
        push    ecx
        mov     eax, DWORD PTR _a$[ebp]
        add     eax, DWORD PTR _b$[ebp]
        mov     DWORD PTR _next$[ebp], eax
        mov     ecx, DWORD PTR _next$[ebp]
        push    ecx
        push    OFFSET $SG2751 ; '%d'
        call    DWORD PTR __imp__printf
        add     esp, 8
        mov     edx, DWORD PTR _next$[ebp]
        cmp     edx, DWORD PTR _limit$[ebp]
        jle     SHORT $LN1@fib
        jmp     SHORT $LN2@fib
$LN1@fib:
        mov     eax, DWORD PTR _limit$[ebp]
        push    eax
        mov     ecx, DWORD PTR _next$[ebp]
        push    ecx
        mov     edx, DWORD PTR _b$[ebp]
        push    edx
        call    _fib
        add     esp, 12
$LN2@fib:
        mov     esp, ebp
        pop     ebp
        ret     0
_fib    ENDP

_main   PROC
        push    ebp
        mov     ebp, esp
        push    OFFSET $SG2753 ; "0\n1\n1\n"
        call    DWORD PTR __imp__printf
        add     esp, 4
        push    20
        push    1
        push    1
        call    _fib
        add     esp, 12
        xor     eax, eax
        pop     ebp
        ret     0
```

```
_main   ENDP
```

Let's load it in OllyDbg once again:

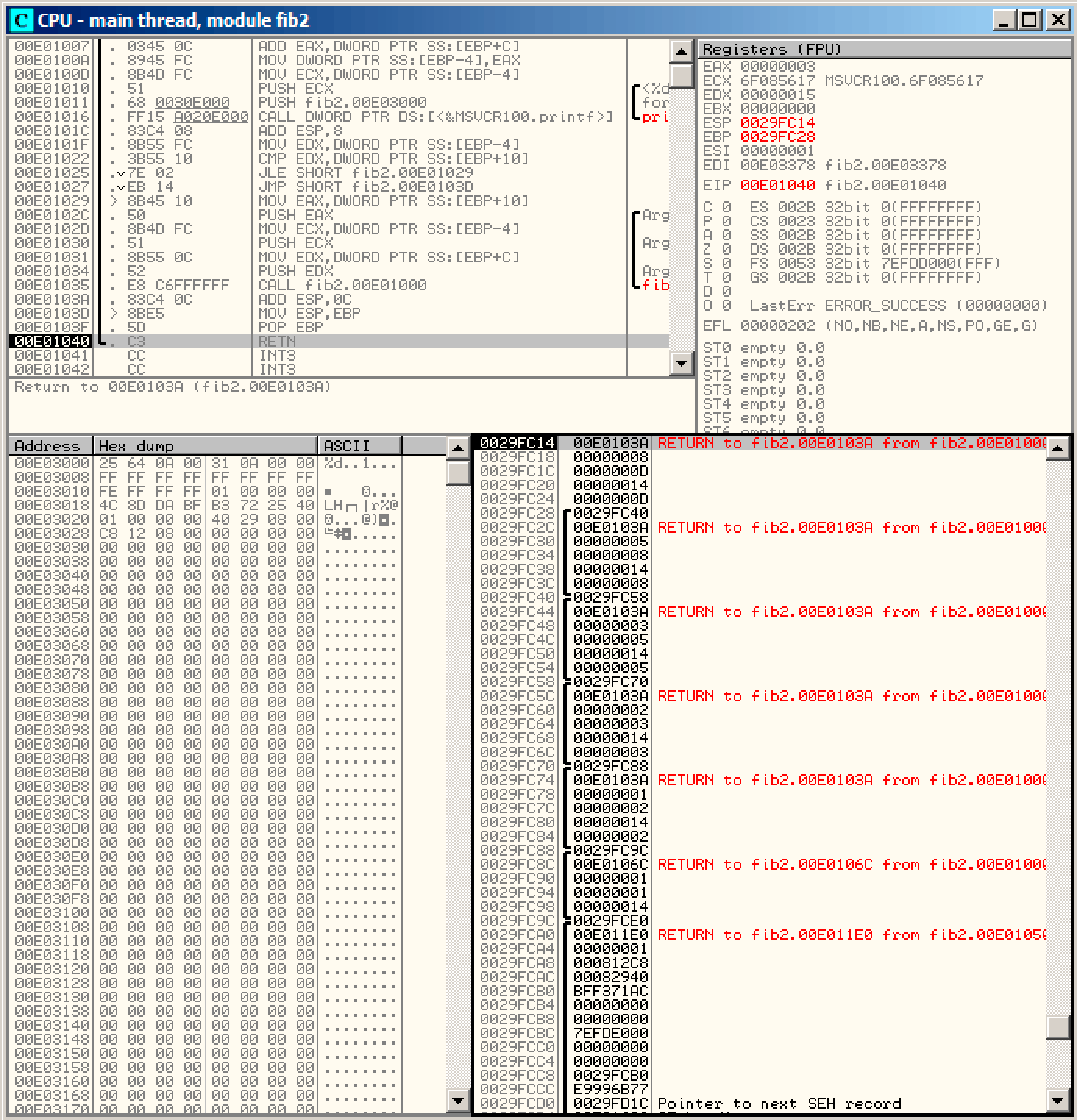


Figure 3.2: OllyDbg: last call of f()

Now the *next* variable is present in each frame.

Let's investigate the stack more closely. The author has again added his comments:

```
0029FC14   00E0103A  RETURN to fib2.00E0103A from fib2.00E01000
0029FC18   00000008  1st argument: a
0029FC1C   0000000D  2nd argument: b
0029FC20   00000014  3rd argument: limit
0029FC24   0000000D  "next" variable
0029FC28  /0029FC40  saved EBP register
0029FC2C  |00E0103A  RETURN to fib2.00E0103A from fib2.00E01000
0029FC30  |00000005  1st argument: a
0029FC34  |00000008  2nd argument: b
0029FC38  |00000014  3rd argument: limit
0029FC3C  |00000008  "next" variable
0029FC40  ]0029FC58  saved EBP register
0029FC44  |00E0103A  RETURN to fib2.00E0103A from fib2.00E01000
0029FC48  |00000003  1st argument: a
0029FC4C  |00000005  2nd argument: b
0029FC50  |00000014  3rd argument: limit
0029FC54  |00000005  "next" variable
0029FC58  ]0029FC70  saved EBP register
0029FC5C  |00E0103A  RETURN to fib2.00E0103A from fib2.00E01000
0029FC60  |00000002  1st argument: a
0029FC64  |00000003  2nd argument: b
0029FC68  |00000014  3rd argument: limit
0029FC6C  |00000003  "next" variable
0029FC70  ]0029FC88  saved EBP register
0029FC74  |00E0103A  RETURN to fib2.00E0103A from fib2.00E01000
0029FC78  |00000001  1st argument: a             \
0029FC7C  |00000002  2nd argument: b             | prepared in f1() for next f1() call
0029FC80  |00000014  3rd argument: limit         /
0029FC84  |00000002  "next" variable
0029FC88  ]0029FC9C  saved EBP register
0029FC8C  |00E0106C  RETURN to fib2.00E0106C from fib2.00E01000
0029FC90  |00000001  1st argument: a             \
0029FC94  |00000001  2nd argument: b             | prepared in main() for f1()
0029FC98  |00000014  3rd argument: limit         /
0029FC9C  ]0029FCE0  saved EBP register
0029FCA0  |00E011E0  RETURN to fib2.00E011E0 from fib2.00E01050
0029FCA4  |00000001  main() 1st argument: argc  \
0029FCA8  |000812C8  main() 2nd argument: argv  | prepared in CRT for main()
0029FCAC  |00082940  main() 3rd argument: envp  /
```

Here we see it: the *next* value is calculated in each function incarnation, then passed as argument b to the next incarnation.

3.4.3 Summary

Recursive functions are æsthetically nice, but technically may degrade performance because of their heavy stack usage. Everyone who writes performance critical code probably should avoid recursion.

For example, the author of this book once wrote a function to seek a particular node in a binary tree. As a recursive function it looked quite stylish but since additional time was spent at each function call for the prologue/epilogue, it was working a couple of times slower than an iterative (recursion-free) implementation.

By the way, that is the reason that some functional PL[6] compilers (where recursion is used heavily) use tail call. We talk about tail call when a function has only one single call to itself located at the end of it, like:

Listing 3.6: Scheme, example is copypasted from Wikipedia

```
;; factorial : number -> number
;; to calculate the product of all positive
;; integers less than or equal to n.
(define (factorial n)
 (if (= n 1)
     1
```

[6] LISP, Python, Lua, etc.

```
        (* n (factorial (- n 1)))))
```

Tail call is important because compiler can rework this code easily into iterative one, to get rid of recursion.

3.5 CRC32 calculation example

This is a very popular table-based CRC32 hash calculation technique[7].

```
/* By Bob Jenkins, (c) 2006, Public Domain */

#include <stdio.h>
#include <stddef.h>
#include <string.h>

typedef  unsigned long  ub4;
typedef  unsigned char  ub1;

static const ub4 crctab[256] = {
  0x00000000, 0x77073096, 0xee0e612c, 0x990951ba, 0x076dc419,
  0x706af48f, 0xe963a535, 0x9e6495a3, 0x0edb8832, 0x79dcb8a4,
  0xe0d5e91e, 0x97d2d988, 0x09b64c2b, 0x7eb17cbd, 0xe7b82d07,
  0x90bf1d91, 0x1db71064, 0x6ab020f2, 0xf3b97148, 0x84be41de,
  0x1adad47d, 0x6ddde4eb, 0xf4d4b551, 0x83d385c7, 0x136c9856,
  0x646ba8c0, 0xfd62f97a, 0x8a65c9ec, 0x14015c4f, 0x63066cd9,
  0xfa0f3d63, 0x8d080df5, 0x3b6e20c8, 0x4c69105e, 0xd56041e4,
  0xa2677172, 0x3c03e4d1, 0x4b04d447, 0xd20d85fd, 0xa50ab56b,
  0x35b5a8fa, 0x42b2986c, 0xdbbbc9d6, 0xacbcf940, 0x32d86ce3,
  0x45df5c75, 0xdcd60dcf, 0xabd13d59, 0x26d930ac, 0x51de003a,
  0xc8d75180, 0xbfd06116, 0x21b4f4b5, 0x56b3c423, 0xcfba9599,
  0xb8bda50f, 0x2802b89e, 0x5f058808, 0xc60cd9b2, 0xb10be924,
  0x2f6f7c87, 0x58684c11, 0xc1611dab, 0xb6662d3d, 0x76dc4190,
  0x01db7106, 0x98d220bc, 0xefd5102a, 0x71b18589, 0x06b6b51f,
  0x9fbfe4a5, 0xe8b8d433, 0x7807c9a2, 0x0f00f934, 0x9609a88e,
  0xe10e9818, 0x7f6a0dbb, 0x086d3d2d, 0x91646c97, 0xe6635c01,
  0x6b6b51f4, 0x1c6c6162, 0x856530d8, 0xf262004e, 0x6c0695ed,
  0x1b01a57b, 0x8208f4c1, 0xf50fc457, 0x65b0d9c6, 0x12b7e950,
  0x8bbeb8ea, 0xfcb9887c, 0x62dd1ddf, 0x15da2d49, 0x8cd37cf3,
  0xfbd44c65, 0x4db26158, 0x3ab551ce, 0xa3bc0074, 0xd4bb30e2,
  0x4adfa541, 0x3dd895d7, 0xa4d1c46d, 0xd3d6f4fb, 0x4369e96a,
  0x346ed9fc, 0xad678846, 0xda60b8d0, 0x44042d73, 0x33031de5,
  0xaa0a4c5f, 0xdd0d7cc9, 0x5005713c, 0x270241aa, 0xbe0b1010,
  0xc90c2086, 0x5768b525, 0x206f85b3, 0xb966d409, 0xce61e49f,
  0x5edef90e, 0x29d9c998, 0xb0d09822, 0xc7d7a8b4, 0x59b33d17,
  0x2eb40d81, 0xb7bd5c3b, 0xc0ba6cad, 0xedb88320, 0x9abfb3b6,
  0x03b6e20c, 0x74b1d29a, 0xead54739, 0x9dd277af, 0x04db2615,
  0x73dc1683, 0xe3630b12, 0x94643b84, 0x0d6d6a3e, 0x7a6a5aa8,
  0xe40ecf0b, 0x9309ff9d, 0x0a00ae27, 0x7d079eb1, 0xf00f9344,
  0x8708a3d2, 0x1e01f268, 0x6906c2fe, 0xf762575d, 0x806567cb,
  0x196c3671, 0x6e6b06e7, 0xfed41b76, 0x89d32be0, 0x10da7a5a,
  0x67dd4acc, 0xf9b9df6f, 0x8ebeeff9, 0x17b7be43, 0x60b08ed5,
  0xd6d6a3e8, 0xa1d1937e, 0x38d8c2c4, 0x4fdff252, 0xd1bb67f1,
  0xa6bc5767, 0x3fb506dd, 0x48b2364b, 0xd80d2bda, 0xaf0a1b4c,
  0x36034af6, 0x41047a60, 0xdf60efc3, 0xa867df55, 0x316e8eef,
  0x4669be79, 0xcb61b38c, 0xbc66831a, 0x256fd2a0, 0x5268e236,
  0xcc0c7795, 0xbb0b4703, 0x220216b9, 0x5505262f, 0xc5ba3bbe,
  0xb2bd0b28, 0x2bb45a92, 0x5cb36a04, 0xc2d7ffa7, 0xb5d0cf31,
  0x2cd99e8b, 0x5bdeae1d, 0x9b64c2b0, 0xec63f226, 0x756aa39c,
  0x026d930a, 0x9c0906a9, 0xeb0e363f, 0x72076785, 0x05005713,
  0x95bf4a82, 0xe2b87a14, 0x7bb12bae, 0x0cb61b38, 0x92d28e9b,
  0xe5d5be0d, 0x7cdcefb7, 0x0bdbdf21, 0x86d3d2d4, 0xf1d4e242,
  0x68ddb3f8, 0x1fda836e, 0x81be16cd, 0xf6b9265b, 0x6fb077e1,
  0x18b74777, 0x88085ae6, 0xff0f6a70, 0x66063bca, 0x11010b5c,
  0x8f659eff, 0xf862ae69, 0x616bffd3, 0x166ccf45, 0xa00ae278,
  0xd70dd2ee, 0x4e048354, 0x3903b3c2, 0xa7672661, 0xd06016f7,
  0x4969474d, 0x3e6e77db, 0xaed16a4a, 0xd9d65adc, 0x40df0b66,
  0x37d83bf0, 0xa9bcae53, 0xdebb9ec5, 0x47b2cf7f, 0x30b5ffe9,
```

[7] The source code has been taken from here: http://go.yurichev.com/17327

```
  0xbdbdf21c, 0xcabac28a, 0x53b39330, 0x24b4a3a6, 0xbad03605,
  0xcdd70693, 0x54de5729, 0x23d967bf, 0xb3667a2e, 0xc4614ab8,
  0x5d681b02, 0x2a6f2b94, 0xb40bbe37, 0xc30c8ea1, 0x5a05df1b,
  0x2d02ef8d
};

/* how to derive the values in crctab[] from polynomial 0xedb88320 */
void build_table()
{
  ub4 i, j;
  for (i=0; i<256; ++i) {
    j = i;
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    printf("0x%.8lx, ", j);
    if (i%6 == 5) printf("\n");
  }
}


/* the hash function */
ub4 crc(const void *key, ub4 len, ub4 hash)
{
  ub4  i;
  const ub1 *k = key;
  for (hash=len, i=0; i<len; ++i)
    hash = (hash >> 8) ^ crctab[(hash & 0xff) ^ k[i]];
  return hash;
}

/* To use, try "gcc -O crc.c -o crc; crc < crc.c" */
int main()
{
  char s[1000];
  while (gets(s)) printf("%.8lx\n", crc(s, strlen(s), 0));
  return 0;
}
```

We are interested in the `crc()` function only. By the way, pay attention to the two loop initializers in the `for()` statement: `hash=len, i=0`. The C/C++ standard allows this, of course. The emitted code will contain two operations in the loop initialization part instead of one.

Let's compile it in MSVC with optimization (`/Ox`). For the sake of brevity, only the `crc()` function is listed here, with my comments.

```
_key$ = 8               ; size = 4
_len$ = 12              ; size = 4
_hash$ = 16             ; size = 4
_crc    PROC
    mov    edx, DWORD PTR _len$[esp-4]
    xor    ecx, ecx ; i will be stored in ECX
    mov    eax, edx
    test   edx, edx
    jbe    SHORT $LN1@crc
    push   ebx
    push   esi
    mov    esi, DWORD PTR _key$[esp+4] ; ESI = key
    push   edi
$LL3@crc:

; work with bytes using only 32-bit registers. byte from address key+i we store into EDI

    movzx  edi, BYTE PTR [ecx+esi]
    mov    ebx, eax ; EBX = (hash = len)
```

```
    and    ebx, 255 ; EBX = hash & 0xff

; XOR EDI, EBX (EDI=EDI^EBX) - this operation uses all 32 bits of each register
; but other bits (8-31) are cleared all time, so its OK'
; these are cleared because, as for EDI, it was done by MOVZX instruction above
; high bits of EBX was cleared by AND EBX, 255 instruction above (255 = 0xff)

    xor    edi, ebx

; EAX=EAX>>8; bits 24-31 taken from nowhere will be cleared
    shr    eax, 8

; EAX=EAX^crctab[EDI*4] - choose EDI-th element from crctab[] table
    xor    eax, DWORD PTR _crctab[edi*4]
    inc    ecx             ; i++
    cmp    ecx, edx        ; i<len ?
    jb     SHORT $LL3@crc ; yes
    pop    edi
    pop    esi
    pop    ebx
$LN1@crc:
    ret    0
_crc    ENDP
```

Let's try the same in GCC 4.4.1 with -O3 option:

```
                public crc
crc             proc near

key             = dword ptr  8
hash            = dword ptr  0Ch

                push    ebp
                xor     edx, edx
                mov     ebp, esp
                push    esi
                mov     esi, [ebp+key]
                push    ebx
                mov     ebx, [ebp+hash]
                test    ebx, ebx
                mov     eax, ebx
                jz      short loc_80484D3
                nop                     ; padding
                lea     esi, [esi+0]    ; padding; works as NOP (ESI does not change here)

loc_80484B8:
                mov     ecx, eax        ; save previous state of hash to ECX
                xor     al, [esi+edx]   ; AL=*(key+i)
                add     edx, 1          ; i++
                shr     ecx, 8          ; ECX=hash>>8
                movzx   eax, al         ; EAX=*(key+i)
                mov     eax, dword ptr ds:crctab[eax*4] ; EAX=crctab[EAX]
                xor     eax, ecx        ; hash=EAX^ECX
                cmp     ebx, edx
                ja      short loc_80484B8

loc_80484D3:
                pop     ebx
                pop     esi
                pop     ebp
                retn
crc             endp
\
```

GCC has aligned the loop start on a 8-byte boundary by adding NOP and `lea esi, [esi+0]` (that is an *idle operation* too). Read more about it in npad section (.1.7 on page 1038).

3.6 Network address calculation example

As we know, a TCP/IP address (IPv4) consists of four numbers in the $0 \dots 255$ range, i.e., four bytes.

Four bytes can be fit in a 32-bit variable easily, so an IPv4 host address, network mask or network address can all be 32-bit integers.

From the user's point of view, the network mask is defined as four numbers and is formatted like 255.255.255.0 or so, but network engineers (sysadmins) use a more compact notation (CIDR[8]), like “/8”, “/16”, etc.

This notation just defines the number of bits the mask has, starting at the MSB.

Mask	Hosts	Usable	Netmask	Hex mask	
/30	4	2	255.255.255.252	0xfffffffc	
/29	8	6	255.255.255.248	0xfffffff8	
/28	16	14	255.255.255.240	0xfffffff0	
/27	32	30	255.255.255.224	0xffffffe0	
/26	64	62	255.255.255.192	0xffffffc0	
/24	256	254	255.255.255.0	0xffffff00	class C network
/23	512	510	255.255.254.0	0xfffffe00	
/22	1024	1022	255.255.252.0	0xfffffc00	
/21	2048	2046	255.255.248.0	0xfffff800	
/20	4096	4094	255.255.240.0	0xfffff000	
/19	8192	8190	255.255.224.0	0xffffe000	
/18	16384	16382	255.255.192.0	0xffffc000	
/17	32768	32766	255.255.128.0	0xffff8000	
/16	65536	65534	255.255.0.0	0xffff0000	class B network
/8	16777216	16777214	255.0.0.0	0xff000000	class A network

Here is a small example, which calculates the network address by applying the network mask to the host address.

```
#include <stdio.h>
#include <stdint.h>

uint32_t form_IP (uint8_t ip1, uint8_t ip2, uint8_t ip3, uint8_t ip4)
{
        return (ip1<<24) | (ip2<<16) | (ip3<<8) | ip4;
};

void print_as_IP (uint32_t a)
{
        printf ("%d.%d.%d.%d\n",
                (a>>24)&0xFF,
                (a>>16)&0xFF,
                (a>>8)&0xFF,
                (a)&0xFF);
};

// bit=31..0
uint32_t set_bit (uint32_t input, int bit)
{
        return input=input|(1<<bit);
};

uint32_t form_netmask (uint8_t netmask_bits)
{
        uint32_t netmask=0;
        uint8_t i;

        for (i=0; i<netmask_bits; i++)
                netmask=set_bit(netmask, 31-i);

        return netmask;
};

void calc_network_address (uint8_t ip1, uint8_t ip2, uint8_t ip3, uint8_t ip4, uint8_t ↙
    ↘ netmask_bits)
{
```

[8] Classless Inter-Domain Routing

```
        uint32_t netmask=form_netmask(netmask_bits);
        uint32_t ip=form_IP(ip1, ip2, ip3, ip4);
        uint32_t netw_adr;

        printf ("netmask=");
        print_as_IP (netmask);

        netw_adr=ip&netmask;

        printf ("network address=");
        print_as_IP (netw_adr);
};

int main()
{
        calc_network_address (10, 1, 2, 4, 24);    // 10.1.2.4, /24
        calc_network_address (10, 1, 2, 4, 8);     // 10.1.2.4, /8
        calc_network_address (10, 1, 2, 4, 25);    // 10.1.2.4, /25
        calc_network_address (10, 1, 2, 64, 26);   // 10.1.2.4, /26
};
```

3.6.1 calc_network_address()

`calc_network_address()` function is simplest one: it just ANDs the host address with the network mask, resulting in the network address.

Listing 3.7: Optimizing MSVC 2012 /Ob0

```
1  _ip1$ = 8              ; size = 1
2  _ip2$ = 12             ; size = 1
3  _ip3$ = 16             ; size = 1
4  _ip4$ = 20             ; size = 1
5  _netmask_bits$ = 24    ; size = 1
6  _calc_network_address PROC
7          push    edi
8          push    DWORD PTR _netmask_bits$[esp]
9          call    _form_netmask
10         push    OFFSET $SG3045 ; 'netmask='
11         mov     edi, eax
12         call    DWORD PTR __imp__printf
13         push    edi
14         call    _print_as_IP
15         push    OFFSET $SG3046 ; 'network address='
16         call    DWORD PTR __imp__printf
17         push    DWORD PTR _ip4$[esp+16]
18         push    DWORD PTR _ip3$[esp+20]
19         push    DWORD PTR _ip2$[esp+24]
20         push    DWORD PTR _ip1$[esp+28]
21         call    _form_IP
22         and     eax, edi        ; network address = host address & netmask
23         push    eax
24         call    _print_as_IP
25         add     esp, 36
26         pop     edi
27         ret     0
28 _calc_network_address ENDP
```

At line 22 we see the most important `AND`—here the network address is calculated.

3.6.2 form_IP()

The `form_IP()` function just puts all 4 bytes into a 32-bit value.

Here is how it is usually done:

- Allocate a variable for the return value. Set it to 0.

- Take the fourth (lowest) byte, apply OR operation to this byte and return the value. The return value contain the 4th byte now.
- Take the third byte, shift it left by 8 bits. You'll get a value like `0x0000bb00` where bb is your third byte. Apply the OR operation to the resulting value and returning value. The return value has contained `0x000000aa` so far, so ORing the values will produce a value like `0x0000bbaa`.
- Take the second byte, shift it left by 16 bits. You'll get a value like `0x00cc0000`, where cc is your second byte. Apply the OR operation to the resulting value and returning value. The return value has contained `0x0000bbaa` so far, so ORing the values will produce a value like `0x00ccbbaa`.
- Take the first byte, shift it left by 24 bits. You'll get a value like `0xdd000000`, where dd is your first byte. Apply the OR operation to the resulting value and returning value. The return value has contained `0x00ccbbaa` so far, so ORing the values will produce a value like `0xddccbbaa`.

And this is how it's done by non-optimizing MSVC 2012:

Listing 3.8: Non-optimizing MSVC 2012

```
; denote ip1 as "dd", ip2 as "cc", ip3 as "bb", ip4 as "aa".
_ip1$ = 8       ; size = 1
_ip2$ = 12      ; size = 1
_ip3$ = 16      ; size = 1
_ip4$ = 20      ; size = 1
_form_IP PROC
        push    ebp
        mov     ebp, esp
        movzx   eax, BYTE PTR _ip1$[ebp]
        ; EAX=000000dd
        shl     eax, 24
        ; EAX=dd000000
        movzx   ecx, BYTE PTR _ip2$[ebp]
        ; ECX=000000cc
        shl     ecx, 16
        ; ECX=00cc0000
        or      eax, ecx
        ; EAX=ddcc0000
        movzx   edx, BYTE PTR _ip3$[ebp]
        ; EDX=000000bb
        shl     edx, 8
        ; EDX=0000bb00
        or      eax, edx
        ; EAX=ddccbb00
        movzx   ecx, BYTE PTR _ip4$[ebp]
        ; ECX=000000aa
        or      eax, ecx
        ; EAX=ddccbbaa
        pop     ebp
        ret     0
_form_IP ENDP
```

Well, the order is different, but, of course, the order of the operations doesn't matter.

Optimizing MSVC 2012 does essentially the same, but in a different way:

Listing 3.9: Optimizing MSVC 2012 /Ob0

```
; denote ip1 as "dd", ip2 as "cc", ip3 as "bb", ip4 as "aa".
_ip1$ = 8       ; size = 1
_ip2$ = 12      ; size = 1
_ip3$ = 16      ; size = 1
_ip4$ = 20      ; size = 1
_form_IP PROC
        movzx   eax, BYTE PTR _ip1$[esp-4]
        ; EAX=000000dd
        movzx   ecx, BYTE PTR _ip2$[esp-4]
        ; ECX=000000cc
        shl     eax, 8
        ; EAX=0000dd00
        or      eax, ecx
        ; EAX=0000ddcc
        movzx   ecx, BYTE PTR _ip3$[esp-4]
```

```
        ; ECX=000000bb
        shl     eax, 8
        ; EAX=00ddcc00
        or      eax, ecx
        ; EAX=00ddccbb
        movzx   ecx, BYTE PTR _ip4$[esp-4]
        ; ECX=000000aa
        shl     eax, 8
        ; EAX=ddccbb00
        or      eax, ecx
        ; EAX=ddccbbaa
        ret     0
_form_IP ENDP
```

We could say that each byte is written to the lowest 8 bits of the return value, and then the return value is shifted left by one byte at each step.

Repeat 4 times for each input byte.

That's it! Unfortunately, there are probably no other ways to do it.

There are no popular CPUs or ISAs which has instruction for composing a value from bits or bytes.

It's all usually done by bit shifting and ORing.

3.6.3 print_as_IP()

`print_as_IP()` does the inverse: splitting a 32-bit value into 4 bytes.

Slicing works somewhat simpler: just shift input value by 24, 16, 8 or 0 bits, take the bits from zeroth to seventh (lowest byte), and that's it:

Listing 3.10: Non-optimizing MSVC 2012

```
_a$ = 8                 ; size = 4
_print_as_IP PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _a$[ebp]
        ; EAX=ddccbbaa
        and     eax, 255
        ; EAX=000000aa
        push    eax
        mov     ecx, DWORD PTR _a$[ebp]
        ; ECX=ddccbbaa
        shr     ecx, 8
        ; ECX=00ddccbb
        and     ecx, 255
        ; ECX=000000bb
        push    ecx
        mov     edx, DWORD PTR _a$[ebp]
        ; EDX=ddccbbaa
        shr     edx, 16
        ; EDX=0000ddcc
        and     edx, 255
        ; EDX=000000cc
        push    edx
        mov     eax, DWORD PTR _a$[ebp]
        ; EAX=ddccbbaa
        shr     eax, 24
        ; EAX=000000dd
        and     eax, 255 ; probably redundant instruction
        ; EAX=000000dd
        push    eax
        push    OFFSET $SG2973 ; '%d.%d.%d.%d'
        call    DWORD PTR __imp__printf
        add     esp, 20
        pop     ebp
        ret     0
_print_as_IP ENDP
```

Optimizing MSVC 2012 does almost the same, but without unnecessary reloading of the input value:

Listing 3.11: Optimizing MSVC 2012 /Ob0

```
_a$ = 8         ; size = 4
_print_as_IP PROC
        mov     ecx, DWORD PTR _a$[esp-4]
        ; ECX=ddccbbaa
        movzx   eax, cl
        ; EAX=000000aa
        push    eax
        mov     eax, ecx
        ; EAX=ddccbbaa
        shr     eax, 8
        ; EAX=00ddccbb
        and     eax, 255
        ; EAX=000000bb
        push    eax
        mov     eax, ecx
        ; EAX=ddccbbaa
        shr     eax, 16
        ; EAX=0000ddcc
        and     eax, 255
        ; EAX=000000cc
        push    eax
        ; ECX=ddccbbaa
        shr     ecx, 24
        ; ECX=000000dd
        push    ecx
        push    OFFSET $SG3020 ; '%d.%d.%d.%d'
        call    DWORD PTR __imp__printf
        add     esp, 20
        ret     0
_print_as_IP ENDP
```

3.6.4 form_netmask() and set_bit()

`form_netmask()` makes a network mask value from CIDR notation. Of course, it would be much effective to use here some kind of a precalculated table, but we consider it in this way intentionally, to demonstrate bit shifts.

We will also write a separate function `set_bit()`. It's a not very good idea to create a function for such primitive operation, but it would be easy to understand how it all works.

Listing 3.12: Optimizing MSVC 2012 /Ob0

```
_input$ = 8             ; size = 4
_bit$ = 12              ; size = 4
_set_bit PROC
        mov     ecx, DWORD PTR _bit$[esp-4]
        mov     eax, 1
        shl     eax, cl
        or      eax, DWORD PTR _input$[esp-4]
        ret     0
_set_bit ENDP

_netmask_bits$ = 8      ; size = 1
_form_netmask PROC
        push    ebx
        push    esi
        movzx   esi, BYTE PTR _netmask_bits$[esp+4]
        xor     ecx, ecx
        xor     bl, bl
        test    esi, esi
        jle     SHORT $LN9@form_netma
        xor     edx, edx
$LL3@form_netma:
        mov     eax, 31
        sub     eax, edx
```

```
        push    eax
        push    ecx
        call    _set_bit
        inc     bl
        movzx   edx, bl
        add     esp, 8
        mov     ecx, eax
        cmp     edx, esi
        jl      SHORT $LL3@form_netma
$LN9@form_netma:
        pop     esi
        mov     eax, ecx
        pop     ebx
        ret     0
_form_netmask ENDP
```

`set_bit()` is primitive: it just shift left 1 to number of bits we need and then ORs it with the “input” value. `form_netmask()` has a loop: it will set as many bits (starting from the MSB) as passed in the `netmask_bits` argument

3.6.5 Summary

That’s it! We run it and getting:

```
netmask=255.255.255.0
network address=10.1.2.0
netmask=255.0.0.0
network address=10.0.0.0
netmask=255.255.255.128
network address=10.1.2.0
netmask=255.255.255.192
network address=10.1.2.64
```

3.7 Loops: several iterators

In most cases loops have only one iterator, but there could be several in the resulting code.

Here is a very simple example:

```
#include <stdio.h>

void f(int *a1, int *a2, size_t cnt)
{
        size_t i;

        // copy from one array to another in some weird scheme
        for (i=0; i<cnt; i++)
                a1[i*3]=a2[i*7];
};
```

There are two multiplications at each iteration and they are costly operations. Can we optimize it somehow?

Yes, if we notice that both array indices are jumping on values that we can easily calculate without multiplication.

3.7.1 Three iterators

Listing 3.13: Optimizing MSVC 2013 x64

```
f       PROC
; RCX=a1
; RDX=a2
```

```
; R8=cnt
        test    r8, r8        ; cnt==0? exit then
        je      SHORT $LN1@f
        npad    11
$LL3@f:
        mov     eax, DWORD PTR [rdx]
        lea     rcx, QWORD PTR [rcx+12]
        lea     rdx, QWORD PTR [rdx+28]
        mov     DWORD PTR [rcx-12], eax
        dec     r8
        jne     SHORT $LL3@f
$LN1@f:
        ret     0
f       ENDP
```

Now there are 3 iterators: the *cnt* variable and two indices, which are increased by 12 and 28 at each iteration. We can rewrite this code in C/C++:

```
#include <stdio.h>

void f(int *a1, int *a2, size_t cnt)
{
        size_t i;
        size_t idx1=0; idx2=0;

        // copy from one array to another in some weird scheme
        for (i=0; i<cnt; i++)
        {
                a1[idx1]=a2[idx2];
                idx1+=3;
                idx2+=7;
        };
};
```

So, at the cost of updating 3 iterators at each iteration instead of one, we can remove two multiplication operations.

3.7.2 Two iterators

GCC 4.9 does even more, leaving only 2 iterators:

Listing 3.14: Optimizing GCC 4.9 x64

```
; RDI=a1
; RSI=a2
; RDX=cnt
f:
        test    rdx, rdx  ; cnt==0? exit then
        je      .L1
; calculate last element address in "a2" and leave it in RDX
        lea     rax, [0+rdx*4]
; RAX=RDX*4=cnt*4
        sal     rdx, 5
; RDX=RDX<<5=cnt*32
        sub     rdx, rax
; RDX=RDX-RAX=cnt*32-cnt*4=cnt*28
        add     rdx, rsi
; RDX=RDX+RSI=a2+cnt*28
.L3:
        mov     eax, DWORD PTR [rsi]
        add     rsi, 28
        add     rdi, 12
        mov     DWORD PTR [rdi-12], eax
        cmp     rsi, rdx
        jne     .L3
.L1:
        rep ret
```

There is no *counter* variable any more: GCC concluded that it is not needed.

The last element of the *a2* array is calculated before the loop begins (which is easy: $cnt * 7$) and that's how the loop is to be stopped: just iterate until the second index reaches this precalculated value.

You can read more about multiplication using shifts/additions/subtractions here: 1.18.1 on page 213.

This code can be rewritten into C/C++ like that:

```
#include <stdio.h>

void f(int *a1, int *a2, size_t cnt)
{
        size_t idx1=0; idx2=0;
        size_t last_idx2=cnt*7;

        // copy from one array to another in some weird scheme
        for (;;)
        {
                a1[idx1]=a2[idx2];
                idx1+=3;
                idx2+=7;
                if (idx2==last_idx2)
                        break;
        };
};
```

GCC (Linaro) 4.9 for ARM64 does the same, but it precalculates the last index of *a1* instead of *a2*, which, of course has the same effect:

Listing 3.15: Optimizing GCC (Linaro) 4.9 ARM64

```
; X0=a1
; X1=a2
; X2=cnt
f:
        cbz     x2, .L1             ; cnt==0? exit then
; calculate last element of "a1" array
        add     x2, x2, x2, lsl 1
; X2=X2+X2<<1=X2+X2*2=X2*3
        mov     x3, 0
        lsl     x2, x2, 2
; X2=X2<<2=X2*4=X2*3*4=X2*12
.L3:
        ldr     w4, [x1],28         ; load at X1, add 28 to X1 (post-increment)
        str     w4, [x0,x3]         ; store at X0+X3=a1+X3
        add     x3, x3, 12          ; shift X3
        cmp     x3, x2              ; end?
        bne     .L3
.L1:
        ret
```

GCC 4.4.5 for MIPS does the same:

Listing 3.16: Optimizing GCC 4.4.5 for MIPS (IDA)

```
; $a0=a1
; $a1=a2
; $a2=cnt
f:
; jump to loop check code:
                beqz    $a2, locret_24
; initialize counter (i) at 0:
                move    $v0, $zero ; branch delay slot, NOP

loc_8:
; load 32-bit word at $a1
                lw      $a3, 0($a1)
; increment counter (i):
                addiu   $v0, 1
; check for finish (compare "i" in $v0 and "cnt" in $a2):
                sltu    $v1, $v0, $a2
```

```
; store 32-bit word at $a0:
                sw      $a3, 0($a0)
; add 0x1C (28) to $a1 at each iteration:
                addiu   $a1, 0x1C
; jump to loop body if i<cnt:
                bnez    $v1, loc_8
; add 0xC (12) to $a0 at each iteration:
                addiu   $a0, 0xC ; branch delay slot

locret_24:
                jr      $ra
                or      $at, $zero ; branch delay slot, NOP
```

3.7.3 Intel C++ 2011 case

Compiler optimizations can also be weird, but nevertheless, still correct. Here is what the Intel C++ compiler 2011 does:

Listing 3.17: Optimizing Intel C++ 2011 x64

```
f       PROC
; parameter 1: rcx = a1
; parameter 2: rdx = a2
; parameter 3: r8  = cnt
.B1.1::
        test      r8, r8
        jbe       exit

.B1.2::
        cmp       r8, 6
        jbe       just_copy

.B1.3::
        cmp       rcx, rdx
        jbe       .B1.5

.B1.4::
        mov       r10, r8
        mov       r9, rcx
        shl       r10, 5
        lea       rax, QWORD PTR [r8*4]
        sub       r9, rdx
        sub       r10, rax
        cmp       r9, r10
        jge       just_copy2

.B1.5::
        cmp       rdx, rcx
        jbe       just_copy

.B1.6::
        mov       r9, rdx
        lea       rax, QWORD PTR [r8*8]
        sub       r9, rcx
        lea       r10, QWORD PTR [rax+r8*4]
        cmp       r9, r10
        jl        just_copy

just_copy2::
; R8 = cnt
; RDX = a2
; RCX = a1
        xor       r10d, r10d
        xor       r9d, r9d
        xor       eax, eax

.B1.8::
        mov       r11d, DWORD PTR [rax+rdx]
```

```
        inc     r10
        mov     DWORD PTR [r9+rcx], r11d
        add     r9, 12
        add     rax, 28
        cmp     r10, r8
        jb      .B1.8
        jmp     exit

just_copy::
; R8 = cnt
; RDX = a2
; RCX = a1
        xor     r10d, r10d
        xor     r9d, r9d
        xor     eax, eax

.B1.11::
        mov     r11d, DWORD PTR [rax+rdx]
        inc     r10
        mov     DWORD PTR [r9+rcx], r11d
        add     r9, 12
        add     rax, 28
        cmp     r10, r8
        jb      .B1.11

exit::
        ret
```

First, there are some decisions taken, then one of the routines is executed.

Looks like it is a check if arrays intersect.

This is very well known way of optimizing memory block copy routines. But copy routines are the same!

This is has to be an error of the Intel C++ optimizer, which still produces workable code, though.

We intentionally considering such example code in this book so the reader would understand that compiler output is weird at times, but still correct, because when the compiler was tested, it passed the tests.

3.8 Duff's device

Duff's device [9] is an unrolled loop with the possibility to jump to the middle of it. The unrolled loop is implemented using a fallthrough switch() statement. We would use here a slightly simplified version of Tom Duff's original code. Let's say, we have to write a function that clears a region in memory. One can come with a simple loop, clearing byte by byte. It's obviously slow, since all modern computers have much wider memory bus. So the better way is to clear the memory region using 4 or 8 bytes blocks. Since we are going to work with a 64-bit example here, we are going to clear the memory in 8 bytes blocks. So far so good. But what about the tail? Memory clearing routine can also be called for regions of size that's not a multiple of 8. So here is the algorithm:

- calculate the number of 8-bytes blocks, clear them using 8-bytes (64-bit) memory accesses;
- calculate the size of the tail, clear it using 1-byte memory accesses.

The second step can be implemented using a simple loop. But let's implement it as an unrolled loop:

```
#include <stdint.h>
#include <stdio.h>

void bzero(uint8_t* dst, size_t count)
{
        int i;

        if (count&(~7))
                // work out 8-byte blocks
                for (i=0; i<count>>3; i++)
                {
```

[9] wikipedia

```
                        *(uint64_t*)dst=0;
                        dst=dst+8;
                };

        // work out the tail
        switch(count & 7)
        {
        case 7: *dst++ = 0;
        case 6: *dst++ = 0;
        case 5: *dst++ = 0;
        case 4: *dst++ = 0;
        case 3: *dst++ = 0;
        case 2: *dst++ = 0;
        case 1: *dst++ = 0;
        case 0: // do nothing
                break;
        }
}
```

Let's first understand how the calculation is performed. The memory region size comes as a 64-bit value. And this value can be divided in two parts:

	7	6	5	4	3	2	1	0
...	B	B	B	B	B	S	S	S

("B" is number of 8-byte blocks and "S" is length of the tail in bytes).

When we divide the input memory region size by 8, the value is just shifted right by 3 bits. But to calculate the remainder, we can just to isolate the lowest 3 bits! So the number of 8-byte blocks is calculated as $count >> 3$ and remainder as $count \& 7$. We also have to find out if we are going to execute the 8-byte procedure at all, so we need to check if the value of $count$ is greater than 7. We do this by clearing the 3 lowest bits and comparing the resulting number with zero, because all we need here is to answer the question, is the high part of $count$ non-zero. Of course, this works because 8 is 2^3 and division by numbers that are 2^n is easy. It's not possible for other numbers. It's actually hard to say if these hacks are worth using, because they lead to hard-to-read code. However, these tricks are very popular and a practicing programmer, even if he/she is not using them, nevertheless has to understand them.

So the first part is simple: get the number of 8-byte blocks and write 64-bit zero values to memory. The second part is an unrolled loop implemented as fallthrough switch() statement.

First, let's express in plain English what we have to do here.

We have to "write as many zero bytes in memory, as $count \& 7$ value tells us". If it's 0, jump to the end, there is no work to do. If it's 1, jump to the place inside switch() statement where only one storage operation is to be executed. If it's 2, jump to another place, where two storage operation are to be executed, etc. 7 as input value leads to the execution of all 7 operations. There is no 8, because a memory region of 8 bytes is to be processed by the first part of our function. So we wrote an unrolled loop. It was definitely faster on older computers than normal loops (and conversely, latest CPUs works better for short loops than for unrolled ones). Maybe this is still meaningful on modern low-cost embedded MCU[10]s.

Let's see what the optimizing MSVC 2012 does:

```
dst$ = 8
count$ = 16
bzero   PROC
        test    rdx, -8
        je      SHORT $LN11@bzero
; work out 8-byte blocks
        xor     r10d, r10d
        mov     r9, rdx
        shr     r9, 3
        mov     r8d, r10d
        test    r9, r9
        je      SHORT $LN11@bzero
        npad    5
$LL19@bzero:
        inc     r8d
        mov     QWORD PTR [rcx], r10
        add     rcx, 8
```

[10]Microcontroller Unit

```
        movsxd  rax, r8d
        cmp     rax, r9
        jb      SHORT $LL19@bzero
$LN11@bzero:
; work out the tail
        and     edx, 7
        dec     rdx
        cmp     rdx, 6
        ja      SHORT $LN9@bzero
        lea     r8, OFFSET FLAT:__ImageBase
        mov     eax, DWORD PTR $LN22@bzero[r8+rdx*4]
        add     rax, r8
        jmp     rax
$LN8@bzero:
        mov     BYTE PTR [rcx], 0
        inc     rcx
$LN7@bzero:
        mov     BYTE PTR [rcx], 0
        inc     rcx
$LN6@bzero:
        mov     BYTE PTR [rcx], 0
        inc     rcx
$LN5@bzero:
        mov     BYTE PTR [rcx], 0
        inc     rcx
$LN4@bzero:
        mov     BYTE PTR [rcx], 0
        inc     rcx
$LN3@bzero:
        mov     BYTE PTR [rcx], 0
        inc     rcx
$LN2@bzero:
        mov     BYTE PTR [rcx], 0
$LN9@bzero:
        fatret  0
        npad    1
$LN22@bzero:
        DD      $LN2@bzero
        DD      $LN3@bzero
        DD      $LN4@bzero
        DD      $LN5@bzero
        DD      $LN6@bzero
        DD      $LN7@bzero
        DD      $LN8@bzero
bzero   ENDP
```

The first part of the function is predictable. The second part is just an unrolled loop and a jump passing control flow to the correct instruction inside it. There is no other code between the MOV/INC instruction pairs, so the execution is to fall until the very end, executing as many pairs as needed. By the way, we can observe that the MOV/INC pair consumes a fixed number of bytes (3+3). So the pair consumes 6 bytes. Knowing that, we can get rid of the switch() jumptable, we can just multiple the input value by 6 and jump to $current\_RIP + input\_value * 6$.

This can also be faster because we are not in need to fetch a value from the jumptable.

It's possible that 6 probably is not a very good constant for fast multiplication and maybe it's not worth it, but you get the idea[11].

That is what old-school demomakers did in the past with unrolled loops.

3.8.1 Should one use unrolled loops?

Unrolled loops can have benefits if there is no fast cache memory between RAM and CPU, and the CPU, in order to get the code of the next instruction, must load it from RAM each time. This is a case of modern low-cost MCU and old CPUs.

[11] As an exercise, you can try to rework the code to get rid of the jumptable. The instruction pair can be rewritten in a way that it will consume 4 bytes or maybe 8. 1 byte is also possible (using STOSB instruction).

Unrolled loops are slower than short loops if there is a fast cache between RAM and CPU and the body of loop can fit into cache, and CPU will load the code from it not touching the RAM. Fast loops are the loops which body's size can fit into L1 cache, but even faster loops are those small ones which can fit into micro-operation cache.

3.9 Division using multiplication

A very simple function:

```
int f(int a)
{
        return a/9;
};
```

3.9.1 x86

...is compiled in a very predictable way:

Listing 3.18: MSVC

```
_a$ = 8              ; size = 4
_f    PROC
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _a$[ebp]
    cdq             ; sign extend EAX to EDX:EAX
    mov    ecx, 9
    idiv   ecx
    pop    ebp
    ret    0
_f  ENDP
```

IDIV divides the 64-bit number stored in the EDX:EAX register pair by the value in the ECX. As a result, EAX will contain the quotient, and EDX— the remainder. The result is returned from the f() function in the EAX register, so the value is not moved after the division operation, it is in right place already.

Since IDIV uses the value in the EDX:EAX register pair, the CDQ instruction (before IDIV) extends the value in EAX to a 64-bit value taking its sign into account, just as MOVSX does.

If we turn optimization on (/Ox), we get:

Listing 3.19: Optimizing MSVC

```
_a$ = 8                      ; size = 4
_f    PROC

    mov    ecx, DWORD PTR _a$[esp-4]
    mov    eax, 954437177   ; 38e38e39H
    imul   ecx
    sar    edx, 1
    mov    eax, edx
    shr    eax, 31          ; 0000001fH
    add    eax, edx
    ret    0
_f    ENDP
```

This is division by multiplication. Multiplication operations work much faster. And it is possible to use this trick [12] to produce code which is effectively equivalent and faster.

This is also called “strength reduction” in compiler optimizations.

GCC 4.4.1 generates almost the same code even without additional optimization flags, just like MSVC with optimization turned on:

[12]Read more about division by multiplication in [Henry S. Warren, *Hacker's Delight*, (2002)10-3]

Listing 3.20: Non-optimizing GCC 4.4.1

```
        public f
f       proc near

arg_0   = dword ptr  8

        push    ebp
        mov     ebp, esp
        mov     ecx, [ebp+arg_0]
        mov     edx, 954437177 ; 38E38E39h
        mov     eax, ecx
        imul    edx
        sar     edx, 1
        mov     eax, ecx
        sar     eax, 1Fh
        mov     ecx, edx
        sub     ecx, eax
        mov     eax, ecx
        pop     ebp
        retn
f       endp
```

3.9.2 How it works

From school-level mathematics, we can remember that division by 9 can be replaced by multiplication by $\frac{1}{9}$. In fact, sometimes compilers do so for floating-point arithmetics, for example, FDIV instruction in x86 code can be replaced by FMUL. At least MSVC 6.0 will replace division by 9 by multiplication by $0.111111...$ and sometimes it's hard to be sure, what operation was in original source code.

But when we operate over integer values and integer CPU registers, we can't use fractions. However, we can rework fraction like that:

$$result = \frac{x}{9} = x \cdot \frac{1}{9} = x \cdot \frac{1 \cdot MagicNumber}{9 \cdot MagicNumber}$$

Given the fact that division by 2^n is very fast (using shifts), we now should find that $MagicNumber$, for which the following equation will be true: $2^n = 9 \cdot MagicNumber$.

Division by 2^{32} is somewhat hidden: lower 32-bit of product in EAX is not used (dropped), only higher 32-bit of product (in EDX) is used and then shifted by additional 1 bit.

In other words, the assembly code we have just seen multiplicates by $\frac{954437177}{2^{32+1}}$, or divides by $\frac{2^{32+1}}{954437177}$. To find divisor we just have to divide numerator by denominator. Using Wolfram Alpha, we can get 8.99999999.... as result (which is close to 9).

Read more about it in [Henry S. Warren, *Hacker's Delight*, (2002)10-3].

Couple of words about better understanding. Many people miss "hidden" division by 2^{32} or 2^{64}, when lower 32-bit part (or 64-bit part) of product is not used. Also, there is misconception that modulo inverse is used here. This is close, but not the same thing. Extended Euclidean algorithm is usually used to find *magic coefficient*, but in fact, this algorithm is rather used to solve the equation. You can solve it using any other method. Anyway, Extended Euclidean algorithm is probably the most efficient way to solve it. Also, needless to mention, the equation is unsolvable for some divisors, because this is diophantine equation (i.e., equation allowing result to be only integer), since we work on integer CPU registers, after all.

3.9.3 ARM

The ARM processor, just like in any other "pure" RISC processor lacks an instruction for division. It also lacks a single instruction for multiplication by a 32-bit constant (recall that a 32-bit constant cannot fit into a 32-bit opcode).

By taking advantage of this clever trick (or *hack*), it is possible to do division using only three instructions: addition, subtraction and bit shifts (1.22 on page 304).

Here is an example that divides a 32-bit number by 10, from [Advanced RISC Machines Ltd, *The ARM Cookbook*, (1994)3.3 Division by a Constant]. The output consists of the quotient and the remainder.

```
; takes argument in a1
; returns quotient in a1, remainder in a2
; cycles could be saved if only divide or remainder is required
    SUB    a2, a1, #10             ; keep (x-10) for later
    SUB    a1, a1, a1, lsr #2
    ADD    a1, a1, a1, lsr #4
    ADD    a1, a1, a1, lsr #8
    ADD    a1, a1, a1, lsr #16
    MOV    a1, a1, lsr #3
    ADD    a3, a1, a1, asl #2
    SUBS   a2, a2, a3, asl #1      ; calc (x-10) - (x/10)*10
    ADDPL  a1, a1, #1              ; fix-up quotient
    ADDMI  a2, a2, #10             ; fix-up remainder
    MOV    pc, lr
```

Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
__text:00002C58 39 1E 08 E3 E3 18 43 E3  MOV    R1, 0x38E38E39
__text:00002C60 10 F1 50 E7              SMMUL  R0, R0, R1
__text:00002C64 C0 10 A0 E1              MOV    R1, R0,ASR#1
__text:00002C68 A0 0F 81 E0              ADD    R0, R1, R0,LSR#31
__text:00002C6C 1E FF 2F E1              BX     LR
```

This code is almost the same as the one generated by the optimizing MSVC and GCC.

Apparently, LLVM uses the same algorithm for generating constants.

The observant reader may ask, how does MOV writes a 32-bit value in a register, when this is not possible in ARM mode.

it is impossible indeed, but, as we see, there are 8 bytes per instruction instead of the standard 4, in fact, there are two instructions.

The first instruction loads 0x8E39 into the low 16 bits of register and the second instruction is MOVT, it loads 0x383E into the high 16 bits of the register. IDA is fully aware of such sequences, and for the sake of compactness reduces them to one single "pseudo-instruction".

The SMMUL (*Signed Most Significant Word Multiply*) instruction two multiplies numbers, treating them as signed numbers and leaving the high 32-bit part of result in the R0 register, dropping the low 32-bit part of the result.

The"MOV R1, R0,ASR#1" instruction is an arithmetic shift right by one bit.

"ADD R0, R1, R0,LSR#31" is $R0 = R1 + R0 >> 31$

There is no separate shifting instruction in ARM mode. Instead, an instructions like (MOV, ADD, SUB, RSB)[13] can have a suffix added, that says if the second operand must be shifted, and if yes, by what value and how. ASR stands for *Arithmetic Shift Right*, LSR—*Logical Shift Right*.

Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```
MOV             R1, 0x38E38E39
SMMUL.W         R0, R0, R1
ASRS            R1, R0, #1
ADD.W           R0, R1, R0,LSR#31
BX              LR
```

There are separate instructions for shifting in Thumb mode, and one of them is used here—ASRS (arithmetic shift right).

[13] These instructions are also called "data processing instructions"

Non-optimizing Xcode 4.6.3 (LLVM) and Keil 6/2013

Non-optimizing LLVM does not generate the code we saw before in this section, but instead inserts a call to the library function *___divsi3*.

What about Keil: it inserts a call to the library function *__aeabi_idivmod* in all cases.

3.9.4 MIPS

For some reason, optimizing GCC 4.4.5 generate just a division instruction:

Listing 3.21: Optimizing GCC 4.4.5 (IDA)

```
f:
                li      $v0, 9
                bnez    $v0, loc_10
                div     $a0, $v0 ; branch delay slot
                break   0x1C00   ; "break 7" in assembly output and objdump

loc_10:
                mflo    $v0
                jr      $ra
                or      $at, $zero ; branch delay slot, NOP
```

Here we see here a new instruction: BREAK. It just raises an exception.

In this case, an exception is raised if the divisor is zero (it's not possible to divide by zero in conventional math).

But GCC probably did not do very well the optimization job and did not see that $V0 is never zero.

So the check is left here. So if $V0 is zero somehow, BREAK is to be executed, signaling to the OS about the exception.

Otherwise, MFLO executes, which takes the result of the division from the LO register and copies it in $V0.

By the way, as we may know, the MUL instruction leaves the high 32 bits of the result in register HI and the low 32 bits in register LO.

DIV leaves the result in the LO register, and remainder in the HI register.

If we alter the statement to "a % 9", the MFHI instruction is to be used here instead of MFLO.

3.9.5 Exercise

- http://challenges.re/27

3.10 String to number conversion (atoi())

Let's try to reimplement the standard atoi() C function.

3.10.1 Simple example

Here is the simplest possible way to read a number represented in ASCII encoding.

It's not error-prone: a character other than a digit leads to incorrect result.

```
#include <stdio.h>

int my_atoi (char *s)
{
        int rt=0;

        while (*s)
        {
```

```
                rt=rt*10 + (*s-'0');
                s++;
        };

        return rt;
};

int main()
{
        printf ("%d\n", my_atoi ("1234"));
        printf ("%d\n", my_atoi ("1234567890"));
};
```

So what the algorithm does is just reading digits from left to right.

The zero ASCII character is subtracted from each digit.

The digits from "0" to "9" are consecutive in the ASCII table, so we do not even need to know the exact value of the "0" character.

All we have to know is that "0" minus "0" is 0, "9" minus "0"'is 9 and so on.

Subtracting "0" from each character results in a number from 0 to 9 inclusive.

Any other character leads to an incorrect result, of course!

Each digit has to be added to the final result (in variable "rt"), but the final result is also multiplied by 10 at each digit.

In other words, the result is shifted left by one position in decimal form on each iteration.

The last digit is added, but there is no shift.

Optimizing MSVC 2013 x64

Listing 3.22: Optimizing MSVC 2013 x64

```
s$ = 8
my_atoi PROC
; load first character
        movzx   r8d, BYTE PTR [rcx]
; EAX is allocated for "rt" variable
; its 0 at start
        xor     eax, eax
; first character is zero-byte, i.e., string terminator?
; exit then.
        test    r8b, r8b
        je      SHORT $LN9@my_atoi
$LL2@my_atoi:
        lea     edx, DWORD PTR [rax+rax*4]
; EDX=RAX+RAX*4=rt+rt*4=rt*5
        movsx   eax, r8b
; EAX=input character
; load next character to R8D
        movzx   r8d, BYTE PTR [rcx+1]
; shift pointer in RCX to the next character:
        lea     rcx, QWORD PTR [rcx+1]
        lea     eax, DWORD PTR [rax+rdx*2]
; EAX=RAX+RDX*2=input character + rt*5*2=input character + rt*10
; correct digit by subtracting 48 (0x30 or '0')
        add     eax, -48                                ; ffffffffffffffd0H
; was the last character zero?
        test    r8b, r8b
; jump to loop begin, if not
        jne     SHORT $LL2@my_atoi
$LN9@my_atoi:
        ret     0
my_atoi ENDP
```

A character can be loaded in two places: the first character and all subsequent characters. This is arranged so for loop regrouping.

There is no instruction for multiplication by 10, two LEA instruction do this instead.

MSVC sometimes uses the ADD instruction with a negative constant instead of SUB. This is the case.

It's very hard to say why this is better then SUB. But MSVC does this often.

Optimizing GCC 4.9.1 x64

Optimizing GCC 4.9.1 is more concise, but there is one redundant RET instruction at the end. One would be enough.

Listing 3.23: Optimizing GCC 4.9.1 x64

```
my_atoi:
; load input character into EDX
        movsx   edx, BYTE PTR [rdi]
; EAX is allocated for "rt" variable
        xor     eax, eax
; exit, if loaded character is null byte
        test    dl, dl
        je      .L4
.L3:
        lea     eax, [rax+rax*4]
; EAX=RAX*5=rt*5
; shift pointer to the next character:
        add     rdi, 1
        lea     eax, [rdx-48+rax*2]
; EAX=input character - 48 + RAX*2 = input character - '0' + rt*10
; load next character:
        movsx   edx, BYTE PTR [rdi]
; goto loop begin, if loaded character is not null byte
        test    dl, dl
        jne     .L3
        rep ret
.L4:
        rep ret
```

Optimizing Keil 6/2013 (ARM mode)

Listing 3.24: Optimizing Keil 6/2013 (ARM mode)

```
my_atoi PROC
; R1 will contain pointer to character
        MOV      r1,r0
; R0 will contain "rt" variable
        MOV      r0,#0
        B        |L0.28|
|L0.12|
        ADD      r0,r0,r0,LSL #2
; R0=R0+R0<<2=rt*5
        ADD      r0,r2,r0,LSL #1
; R0=input character + rt*5<<1 = input character + rt*10
; correct whole thing by subtracting '0' from rt:
        SUB      r0,r0,#0x30
; shift pointer to the next character:
        ADD      r1,r1,#1
|L0.28|
; load input character to R2
        LDRB     r2,[r1,#0]
; is it null byte? if no, jump to loop body.
        CMP      r2,#0
        BNE      |L0.12|
; exit if null byte.
; "rt" variable is still in R0 register, ready to be used in caller function
        BX       lr
        ENDP
```

Optimizing Keil 6/2013 (Thumb mode)

Listing 3.25: Optimizing Keil 6/2013 (Thumb mode)

```
my_atoi PROC
; R1 will be pointer to the input character
        MOVS     r1,r0
; R0 is allocated to "rt" variable
        MOVS     r0,#0
        B        |L0.16|
|L0.6|
        MOVS     r3,#0xa
; R3=10
        MULS     r0,r3,r0
; R0=R3*R0=rt*10
; shift pointer to the next character:
        ADDS     r1,r1,#1
; correct whole thing by subtracting 0' character from it':
        SUBS     r0,r0,#0x30
        ADDS     r0,r2,r0
; rt=R2+R0=input character + (rt*10 - '0')
|L0.16|
; load input character to R2
        LDRB     r2,[r1,#0]
; is it zero?
        CMP      r2,#0
; jump to loop body if it is not
        BNE      |L0.6|
; rt variable in R0 now, ready to be used in caller function
        BX       lr
        ENDP
```

Interestingly, from school mathematics we may recall that the order of addition and subtraction operations doesn't matter.

That's our case: first, the $rt * 10 -' 0'$ expression is computed, then the input character value is added to it.

Indeed, the result is the same, but the compiler did some regrouping.

Optimizing GCC 4.9.1 ARM64

The ARM64 compiler can use the pre-increment instruction suffix:

Listing 3.26: Optimizing GCC 4.9.1 ARM64

```
my_atoi:
; load input character into W1
        ldrb    w1, [x0]
        mov     x2, x0
; X2=address of input string
; is loaded character zero?
; jump to exit if its so
; W1 will contain 0 in this case.
; it will be reloaded into W0 at L4.
        cbz     w1, .L4
; W0 will contain "rt" variable
; initialize it at zero:
        mov     w0, 0
.L3:
; subtract 48 or '0' from input variable and put result into W3:
        sub     w3, w1, #48
; load next character at address X2+1 into W1 with pre-increment:
        ldrb    w1, [x2,1]!
        add     w0, w0, w0, lsl 2
; W0=W0+W0<<2=W0+W0*4=rt*5
        add     w0, w3, w0, lsl 1
; W0=input digit + W0<<1 = input digit + rt*5*2 = input digit + rt*10
; if the character we just loaded is not null byte, jump to the loop begin
        cbnz    w1, .L3
```

```
; variable to be returned (rt) is in W0, ready to be used in caller function
        ret
.L4:
        mov     w0, w1
        ret
```

3.10.2 A slightly advanced example

My new code snippet is more advanced, now it checks for the “minus” sign at the first character and reports an error if a non-digit has been found in the input string:

```
#include <stdio.h>

int my_atoi (char *s)
{
        int negative=0;
        int rt=0;

        if (*s=='-')
        {
                negative=1;
                s++;
        };

        while (*s)
        {
                if (*s<'0' || *s>'9')
                {
                        printf ("Error! Unexpected char: '%c'\n", *s);
                        exit(0);
                };
                rt=rt*10 + (*s-'0');
                s++;
        };

        if (negative)
                return -rt;
        return rt;
};

int main()
{
        printf ("%d\n", my_atoi ("1234"));
        printf ("%d\n", my_atoi ("1234567890"));
        printf ("%d\n", my_atoi ("-1234"));
        printf ("%d\n", my_atoi ("-1234567890"));
        printf ("%d\n", my_atoi ("-a1234567890")); // error
};
```

Optimizing GCC 4.9.1 x64

Listing 3.27: Optimizing GCC 4.9.1 x64

```
.LC0:
        .string "Error! Unexpected char: '%c'\n"

my_atoi:
        sub     rsp, 8
        movsx   edx, BYTE PTR [rdi]
; check for minus sign
        cmp     dl, 45 ; '-'
        je      .L22
        xor     esi, esi
        test    dl, dl
        je      .L20
.L10:
```

```
; ESI=0 here if there was no minus sign and 1 if it was
        lea     eax, [rdx-48]
; any character other than digit will result in unsigned number greater than 9 after ↙
    ↘ subtraction
; so if it is not digit, jump to L4, where error will be reported:
        cmp     al, 9
        ja      .L4
        xor     eax, eax
        jmp     .L6
.L7:
        lea     ecx, [rdx-48]
        cmp     cl, 9
        ja      .L4
.L6:
        lea     eax, [rax+rax*4]
        add     rdi, 1
        lea     eax, [rdx-48+rax*2]
        movsx   edx, BYTE PTR [rdi]
        test    dl, dl
        jne     .L7
; if there was no minus sign, skip NEG instruction
; if it was, execute it.
        test    esi, esi
        je      .L18
        neg     eax
.L18:
        add     rsp, 8
        ret
.L22:
        movsx   edx, BYTE PTR [rdi+1]
        lea     rax, [rdi+1]
        test    dl, dl
        je      .L20
        mov     rdi, rax
        mov     esi, 1
        jmp     .L10
.L20:
        xor     eax, eax
        jmp     .L18
.L4:
; report error. character is in EDX
        mov     edi, 1
        mov     esi, OFFSET FLAT:.LC0 ; "Error! Unexpected char: '%c'\n"
        xor     eax, eax
        call    __printf_chk
        xor     edi, edi
        call    exit
```

If the “minus” sign has been encountered at the string start, the NEG instruction is to be executed at the end. It just negates the number.

There is one more thing that needs mentioning.

How would a common programmer check if the character is not a digit? Just how we have it in the source code:

```
if (*s<'0' || *s>'9')
    ...
```

There are two comparison operations.

What is interesting is that we can replace both operations by single one: just subtract “0” from character value,

treat result as unsigned value (this is important) and check if it’s greater than 9.

For example, let’s say that the user input contains the dot character (“.”) which has ASCII code 46. $46 - 48 = -2$ if we treat the result as a signed number.

Indeed, the dot character is located two places earlier than the “0” character in the ASCII table. But it is 0xFFFFFFFE (4294967294) if we treat the result as an unsigned value, and that’s definitely bigger than 9!

The compilers do this often, so it's important to recognize these tricks.

Another example of it in this book: 3.16.1 on page 535.

Optimizing MSVC 2013 x64 does the same tricks.

Optimizing Keil 6/2013 (ARM mode)

Listing 3.28: Optimizing Keil 6/2013 (ARM mode)

```
1  my_atoi PROC
2          PUSH     {r4-r6,lr}
3          MOV      r4,r0
4          LDRB     r0,[r0,#0]
5          MOV      r6,#0
6          MOV      r5,r6
7          CMP      r0,#0x2d '-'
8  ; R6 will contain 1 if minus was encountered, 0 if otherwise
9          MOVEQ    r6,#1
10         ADDEQ    r4,r4,#1
11         B        |L0.80|
12 |L0.36|
13         SUB      r0,r1,#0x30
14         CMP      r0,#0xa
15         BCC      |L0.64|
16         ADR      r0,|L0.220|
17         BL       __2printf
18         MOV      r0,#0
19         BL       exit
20 |L0.64|
21         LDRB     r0,[r4],#1
22         ADD      r1,r5,r5,LSL #2
23         ADD      r0,r0,r1,LSL #1
24         SUB      r5,r0,#0x30
25 |L0.80|
26         LDRB     r1,[r4,#0]
27         CMP      r1,#0
28         BNE      |L0.36|
29         CMP      r6,#0
30 ; negate result
31         RSBNE    r0,r5,#0
32         MOVEQ    r0,r5
33         POP      {r4-r6,pc}
34         ENDP
35
36 |L0.220|
37         DCB      "Error! Unexpected char: '%c'\n",0
```

There is no NEG instruction in 32-bit ARM, so the "Reverse Subtraction" operation (line 31) is used here.

It is triggered if the result of the CMP instruction (at line 29) has been "Not Equal" (hence -NE suffix).

So what RSBNE does is to subtract the resulting value from 0.

It works just like the regular subtraction operation, but swaps operands.

Subtracting any number from 0 results in negation: $0 - x = -x$.

Thumb mode code is mostly the same.

GCC 4.9 for ARM64 can use the NEG instruction, which is available in ARM64.

3.10.3 Exercise

Oh, by the way, security researchers deals often with unpredictable behavior of program while handling of incorrect data.

For example, while fuzzing. As an exercise, you may try to enter non-digit characters and see what happens.

Try to explain, what happened and why.

3.11 Inline functions

Inlined code is when the compiler, instead of placing a call instruction to a small or tiny function, just places its body right in-place.

Listing 3.29: A simple example
```
#include <stdio.h>

int celsius_to_fahrenheit (int celsius)
{
        return celsius * 9 / 5 + 32;
};

int main(int argc, char *argv[])
{
        int celsius=atol(argv[1]);
        printf ("%d\n", celsius_to_fahrenheit (celsius));
};
```

…is compiled in very predictable way, however, if we turn on GCC optimizations (`-O3`), we'll see:

Listing 3.30: Optimizing GCC 4.8.1
```
_main:
        push    ebp
        mov     ebp, esp
        and     esp, -16
        sub     esp, 16
        call    ___main
        mov     eax, DWORD PTR [ebp+12]
        mov     eax, DWORD PTR [eax+4]
        mov     DWORD PTR [esp], eax
        call    _atol
        mov     edx, 1717986919
        mov     DWORD PTR [esp], OFFSET FLAT:LC2 ; "%d\12\0"
        lea     ecx, [eax+eax*8]
        mov     eax, ecx
        imul    edx
        sar     ecx, 31
        sar     edx
        sub     edx, ecx
        add     edx, 32
        mov     DWORD PTR [esp+4], edx
        call    _printf
        leave
        ret
```

(Here the division is performed by multiplication(3.9 on page 497).)

Yes, our small function `celsius_to_fahrenheit()` has just been placed before the `printf()` call.

Why? It can be faster than executing this function's code plus the overhead of calling/returning.

Modern optimizing compilers are choosing small functions for inlining automatically. But it's possible to force compiler additionally to inline some function, if to mark it with the "inline" keyword in its declaration.

3.11.1 Strings and memory functions

Another very common automatic optimization tactic is the inlining of string functions like *strcpy()*, *strcmp()*, *strlen()*, *memset()*, *memcmp()*, *memcpy()*, etc..

Sometimes it's faster than to call a separate function.

These are very frequent patterns and it is highly advisable for reverse engineers to learn to detect automatically.

strcmp()

Listing 3.31: strcmp() example

```
bool is_bool (char *s)
{
        if (strcmp (s, "true")==0)
                return true;
        if (strcmp (s, "false")==0)
                return false;

        assert(0);
};
```

Listing 3.32: Optimizing GCC 4.8.1

```
.LC0:
        .string "true"
.LC1:
        .string "false"
is_bool:
.LFB0:
        push    edi
        mov     ecx, 5
        push    esi
        mov     edi, OFFSET FLAT:.LC0
        sub     esp, 20
        mov     esi, DWORD PTR [esp+32]
        repz cmpsb
        je      .L3
        mov     esi, DWORD PTR [esp+32]
        mov     ecx, 6
        mov     edi, OFFSET FLAT:.LC1
        repz cmpsb
        seta    cl
        setb    dl
        xor     eax, eax
        cmp     cl, dl
        jne     .L8
        add     esp, 20
        pop     esi
        pop     edi
        ret
.L8:
        mov     DWORD PTR [esp], 0
        call    assert
        add     esp, 20
        pop     esi
        pop     edi
        ret
.L3:
        add     esp, 20
        mov     eax, 1
        pop     esi
        pop     edi
        ret
```

Listing 3.33: Optimizing MSVC 2010

```
$SG3454 DB      'true', 00H
$SG3456 DB      'false', 00H

_s$ = 8         ; size = 4
?is_bool@@YA_NPAD@Z PROC ; is_bool
        push    esi
        mov     esi, DWORD PTR _s$[esp]
        mov     ecx, OFFSET $SG3454 ; 'true'
        mov     eax, esi
        npad    4 ; align next label
$LL6@is_bool:
```

```
        mov     dl, BYTE PTR [eax]
        cmp     dl, BYTE PTR [ecx]
        jne     SHORT $LN7@is_bool
        test    dl, dl
        je      SHORT $LN8@is_bool
        mov     dl, BYTE PTR [eax+1]
        cmp     dl, BYTE PTR [ecx+1]
        jne     SHORT $LN7@is_bool
        add     eax, 2
        add     ecx, 2
        test    dl, dl
        jne     SHORT $LL6@is_bool
$LN8@is_bool:
        xor     eax, eax
        jmp     SHORT $LN9@is_bool
$LN7@is_bool:
        sbb     eax, eax
        sbb     eax, -1
$LN9@is_bool:
        test    eax, eax
        jne     SHORT $LN2@is_bool

        mov     al, 1
        pop     esi

        ret     0
$LN2@is_bool:

        mov     ecx, OFFSET $SG3456 ; 'false'
        mov     eax, esi
$LL10@is_bool:
        mov     dl, BYTE PTR [eax]
        cmp     dl, BYTE PTR [ecx]
        jne     SHORT $LN11@is_bool
        test    dl, dl
        je      SHORT $LN12@is_bool
        mov     dl, BYTE PTR [eax+1]
        cmp     dl, BYTE PTR [ecx+1]
        jne     SHORT $LN11@is_bool
        add     eax, 2
        add     ecx, 2
        test    dl, dl
        jne     SHORT $LL10@is_bool
$LN12@is_bool:
        xor     eax, eax
        jmp     SHORT $LN13@is_bool
$LN11@is_bool:
        sbb     eax, eax
        sbb     eax, -1
$LN13@is_bool:
        test    eax, eax
        jne     SHORT $LN1@is_bool

        xor     al, al
        pop     esi

        ret     0
$LN1@is_bool:

        push    11
        push    OFFSET $SG3458
        push    OFFSET $SG3459
        call    DWORD PTR __imp___wassert
        add     esp, 12
        pop     esi

        ret     0
?is_bool@@YA_NPAD@Z ENDP ; is_bool
```

strlen()

Listing 3.34: strlen() example

```
int strlen_test(char *s1)
{
        return strlen(s1);
};
```

Listing 3.35: Optimizing MSVC 2010

```
_s1$ = 8 ; size = 4
_strlen_test PROC
        mov     eax, DWORD PTR _s1$[esp-4]
        lea     edx, DWORD PTR [eax+1]
$LL3@strlen_tes:
        mov     cl, BYTE PTR [eax]
        inc     eax
        test    cl, cl
        jne     SHORT $LL3@strlen_tes
        sub     eax, edx
        ret     0
_strlen_test ENDP
```

strcpy()

Listing 3.36: strcpy() example

```
void strcpy_test(char *s1, char *outbuf)
{
        strcpy(outbuf, s1);
};
```

Listing 3.37: Optimizing MSVC 2010

```
_s1$ = 8        ; size = 4
_outbuf$ = 12   ; size = 4
_strcpy_test PROC
        mov     eax, DWORD PTR _s1$[esp-4]
        mov     edx, DWORD PTR _outbuf$[esp-4]
        sub     edx, eax
        npad    6 ; align next label
$LL3@strcpy_tes:
        mov     cl, BYTE PTR [eax]
        mov     BYTE PTR [edx+eax], cl
        inc     eax
        test    cl, cl
        jne     SHORT $LL3@strcpy_tes
        ret     0
_strcpy_test ENDP
```

memset()

Example#1

Listing 3.38: 32 bytes

```
#include <stdio.h>

void f(char *out)
{
        memset(out, 0, 32);
};
```

Many compilers don't generate a call to memset() for short blocks, but rather insert a pack of MOVs:

Listing 3.39: Optimizing GCC 4.9.1 x64

```
f:
        mov     QWORD PTR [rdi], 0
        mov     QWORD PTR [rdi+8], 0
        mov     QWORD PTR [rdi+16], 0
        mov     QWORD PTR [rdi+24], 0
        ret
```

By the way, that remind us of unrolled loops: 1.16.1 on page 192.

Example#2

Listing 3.40: 67 bytes

```
#include <stdio.h>

void f(char *out)
{
        memset(out, 0, 67);
};
```

When the block size is not a multiple of 4 or 8, the compilers can behave differently.

For instance, MSVC 2012 continues to insert MOVs:

Listing 3.41: Optimizing MSVC 2012 x64

```
out$ = 8
f       PROC
        xor     eax, eax
        mov     QWORD PTR [rcx], rax
        mov     QWORD PTR [rcx+8], rax
        mov     QWORD PTR [rcx+16], rax
        mov     QWORD PTR [rcx+24], rax
        mov     QWORD PTR [rcx+32], rax
        mov     QWORD PTR [rcx+40], rax
        mov     QWORD PTR [rcx+48], rax
        mov     QWORD PTR [rcx+56], rax
        mov     WORD PTR [rcx+64], ax
        mov     BYTE PTR [rcx+66], al
        ret     0
f       ENDP
```

…while GCC uses REP STOSQ, concluding that this would be shorter than a pack of MOVs:

Listing 3.42: Optimizing GCC 4.9.1 x64

```
f:
        mov     QWORD PTR [rdi], 0
        mov     QWORD PTR [rdi+59], 0
        mov     rcx, rdi
        lea     rdi, [rdi+8]
        xor     eax, eax
        and     rdi, -8
        sub     rcx, rdi
        add     ecx, 67
        shr     ecx, 3
        rep stosq
        ret
```

memcpy()

Short blocks

The routine to copy short blocks is often implemented as a sequence of MOV instructions.

Listing 3.43: memcpy() example

```
void memcpy_7(char *inbuf, char *outbuf)
{
        memcpy(outbuf+10, inbuf, 7);
};
```

Listing 3.44: Optimizing MSVC 2010

```
_inbuf$ = 8     ; size = 4
_outbuf$ = 12   ; size = 4
_memcpy_7 PROC
        mov     ecx, DWORD PTR _inbuf$[esp-4]
        mov     edx, DWORD PTR [ecx]
        mov     eax, DWORD PTR _outbuf$[esp-4]
        mov     DWORD PTR [eax+10], edx
        mov     dx, WORD PTR [ecx+4]
        mov     WORD PTR [eax+14], dx
        mov     cl, BYTE PTR [ecx+6]
        mov     BYTE PTR [eax+16], cl
        ret     0
_memcpy_7 ENDP
```

Listing 3.45: Optimizing GCC 4.8.1

```
memcpy_7:
        push    ebx
        mov     eax, DWORD PTR [esp+8]
        mov     ecx, DWORD PTR [esp+12]
        mov     ebx, DWORD PTR [eax]
        lea     edx, [ecx+10]
        mov     DWORD PTR [ecx+10], ebx
        movzx   ecx, WORD PTR [eax+4]
        mov     WORD PTR [edx+4], cx
        movzx   eax, BYTE PTR [eax+6]
        mov     BYTE PTR [edx+6], al
        pop     ebx
        ret
```

That's usually done as follows: 4-byte blocks are copied first, then a 16-bit word (if needed), then the last byte (if needed).

Structures are also copied using MOV: 1.24.4 on page 361.

Long blocks

The compilers behave differently in this case.

Listing 3.46: memcpy() example

```
void memcpy_128(char *inbuf, char *outbuf)
{
        memcpy(outbuf+10, inbuf, 128);
};

void memcpy_123(char *inbuf, char *outbuf)
{
        memcpy(outbuf+10, inbuf, 123);
};
```

For copying 128 bytes, MSVC uses a single MOVSD instruction (because 128 divides evenly by 4):

Listing 3.47: Optimizing MSVC 2010

```
_inbuf$ = 8             ; size = 4
_outbuf$ = 12           ; size = 4
_memcpy_128 PROC
        push    esi
        mov     esi, DWORD PTR _inbuf$[esp]
```

```
        push    edi
        mov     edi, DWORD PTR _outbuf$[esp+4]
        add     edi, 10
        mov     ecx, 32
        rep movsd
        pop     edi
        pop     esi
        ret     0
_memcpy_128 ENDP
```

When copying 123 bytes, 30 32-bit words are copied first using MOVSD (that's 120 bytes), then 2 bytes are copied using MOVSW, then one more byte using MOVSB.

Listing 3.48: Optimizing MSVC 2010

```
_inbuf$ = 8             ; size = 4
_outbuf$ = 12           ; size = 4
_memcpy_123 PROC
        push    esi
        mov     esi, DWORD PTR _inbuf$[esp]
        push    edi
        mov     edi, DWORD PTR _outbuf$[esp+4]
        add     edi, 10
        mov     ecx, 30
        rep movsd
        movsw
        movsb
        pop     edi
        pop     esi
        ret     0
_memcpy_123 ENDP
```

GCC uses one big universal functions, that works for any block size:

Listing 3.49: Optimizing GCC 4.8.1

```
memcpy_123:
.LFB3:
        push    edi
        mov     eax, 123
        push    esi
        mov     edx, DWORD PTR [esp+16]
        mov     esi, DWORD PTR [esp+12]
        lea     edi, [edx+10]
        test    edi, 1
        jne     .L24
        test    edi, 2
        jne     .L25
.L7:
        mov     ecx, eax
        xor     edx, edx
        shr     ecx, 2
        test    al, 2
        rep movsd
        je      .L8
        movzx   edx, WORD PTR [esi]
        mov     WORD PTR [edi], dx
        mov     edx, 2
.L8:
        test    al, 1
        je      .L5
        movzx   eax, BYTE PTR [esi+edx]
        mov     BYTE PTR [edi+edx], al
.L5:
        pop     esi
        pop     edi
        ret
.L24:
        movzx   eax, BYTE PTR [esi]
        lea     edi, [edx+11]
        add     esi, 1
```

```
        test    edi, 2
        mov     BYTE PTR [edx+10], al
        mov     eax, 122
        je      .L7
.L25:
        movzx   edx, WORD PTR [esi]
        add     edi, 2
        add     esi, 2
        sub     eax, 2
        mov     WORD PTR [edi-2], dx
        jmp     .L7
.LFE3:
```

Universal memory copy functions usually work as follows: calculate how many 32-bit words can be copied, then copy them using MOVSD, then copy the remaining bytes.

More advanced and complex copy functions use SIMD instructions and also take the memory alignment in consideration.

As an example of SIMD strlen() function: 1.29.2 on page 416.

memcmp()

Listing 3.50: memcmp() example

```
int memcmp_1235(char *buf1, char *buf2)
{
        return memcmp(buf1, buf2, 1235);
};
```

For any block size, MSVC 2013 inserts the same universal function:

Listing 3.51: Optimizing MSVC 2010

```
_buf1$ = 8      ; size = 4
_buf2$ = 12     ; size = 4
_memcmp_1235 PROC
        mov     ecx, DWORD PTR _buf1$[esp-4]
        mov     edx, DWORD PTR _buf2$[esp-4]
        push    esi
        mov     esi, 1231
        npad    2
$LL5@memcmp_123:
        mov     eax, DWORD PTR [ecx]
        cmp     eax, DWORD PTR [edx]
        jne     SHORT $LN4@memcmp_123
        add     ecx, 4
        add     edx, 4
        sub     esi, 4
        jae     SHORT $LL5@memcmp_123
$LN4@memcmp_123:
        mov     al, BYTE PTR [ecx]
        cmp     al, BYTE PTR [edx]
        jne     SHORT $LN6@memcmp_123
        mov     al, BYTE PTR [ecx+1]
        cmp     al, BYTE PTR [edx+1]
        jne     SHORT $LN6@memcmp_123
        mov     al, BYTE PTR [ecx+2]
        cmp     al, BYTE PTR [edx+2]
        jne     SHORT $LN6@memcmp_123
        cmp     esi, -1
        je      SHORT $LN3@memcmp_123
        mov     al, BYTE PTR [ecx+3]
        cmp     al, BYTE PTR [edx+3]
        jne     SHORT $LN6@memcmp_123
$LN3@memcmp_123:
        xor     eax, eax
        pop     esi
        ret     0
```

```
$LN6@memcmp_123:
        sbb     eax, eax
        or      eax, 1
        pop     esi
        ret     0
_memcmp_1235 ENDP
```

strcat()

This is inlined strcat() as it has been generated by MSVC 6.0. There are 3 parts visible: 1) getting source string length (first `scasb`); 2) getting destination string length (second `scasb`); 3) copying source string into the end of destination string (`movsd`/`movsb` pair).

Listing 3.52: strcat()

```
                lea     edi, [src]
                or      ecx, 0FFFFFFFFh
                repne scasb
                not     ecx
                sub     edi, ecx
                mov     esi, edi
                mov     edi, [dst]
                mov     edx, ecx
                or      ecx, 0FFFFFFFFh
                repne scasb
                mov     ecx, edx
                dec     edi
                shr     ecx, 2
                rep movsd
                mov     ecx, edx
                and     ecx, 3
                rep movsb
```

IDA script

There is also a small IDA script for searching and folding such very frequently seen pieces of inline code: GitHub.

3.12 C99 restrict

Here is a reason why Fortran programs, in some cases, work faster than C/C++ ones.

```
void f1 (int* x, int* y, int* sum, int* product, int* sum_product, int* update_me, size_t s)
{
        for (int i=0; i<s; i++)
        {
                sum[i]=x[i]+y[i];
                product[i]=x[i]*y[i];
                update_me[i]=i*123; // some dummy value
                sum_product[i]=sum[i]+product[i];
        };
};
```

That's very simple example with one specific thing in it: the pointer to the `update_me` array could be a pointer to the `sum` array, `product` array, or even the `sum_product` array—nothing forbids that, right?

The compiler is fully aware of this, so it generates code with four stages in the loop body:

- calculate next `sum[i]`
- calculate next `product[i]`
- calculate next `update_me[i]`

- calculate next `sum_product[i]`—on this stage, we need to load from memory the already calculated `sum[i]` and `product[i]`

Is it possible to optimize the last stage? Since we have already calculated `sum[i]` and `product[i]` it is not necessary to load them again from memory.

Yes, but compiler is not sure that nothing has been overwritten at the 3rd stage! This is called "pointer aliasing", a situation when the compiler cannot be sure that a memory to which a pointer is pointing hasn't been changed.

restrict in the C99 standard [*ISO/IEC 9899:TC3 (C C99 standard)*, (2007) 6.7.3/1] is a promise, given by programmer to the compiler that the function arguments marked by this keyword always points to different memory locations and never intersects.

To be more precise and describe this formally, *restrict* shows that only this pointer is to be used to access an object, and no other pointer will be used for it.

It can be even said the object will be accessed only via one single pointer, if it is marked as *restrict*.

Let's add this keyword to each pointer argument:

```
void f2 (int* restrict x, int* restrict y, int* restrict sum, int* restrict product, int* ⤦
    ↳ restrict sum_product,
        int* restrict update_me, size_t s)
{
        for (int i=0; i<s; i++)
        {
                sum[i]=x[i]+y[i];
                product[i]=x[i]*y[i];
                update_me[i]=i*123; // some dummy value
                sum_product[i]=sum[i]+product[i];
        };
};
```

Let's see results:

Listing 3.53: GCC x64: f1()

```
f1:
        push    r15 r14 r13 r12 rbp rdi rsi rbx
        mov     r13, QWORD PTR 120[rsp]
        mov     rbp, QWORD PTR 104[rsp]
        mov     r12, QWORD PTR 112[rsp]
        test    r13, r13
        je      .L1
        add     r13, 1
        xor     ebx, ebx
        mov     edi, 1
        xor     r11d, r11d
        jmp     .L4
.L6:
        mov     r11, rdi
        mov     rdi, rax
.L4:
        lea     rax, 0[0+r11*4]
        lea     r10, [rcx+rax]
        lea     r14, [rdx+rax]
        lea     rsi, [r8+rax]
        add     rax, r9
        mov     r15d, DWORD PTR [r10]
        add     r15d, DWORD PTR [r14]
        mov     DWORD PTR [rsi], r15d         ; store to sum[]
        mov     r10d, DWORD PTR [r10]
        imul    r10d, DWORD PTR [r14]
        mov     DWORD PTR [rax], r10d         ; store to product[]
        mov     DWORD PTR [r12+r11*4], ebx    ; store to update_me[]
        add     ebx, 123
        mov     r10d, DWORD PTR [rsi]         ; reload sum[i]
        add     r10d, DWORD PTR [rax]         ; reload product[i]
        lea     rax, 1[rdi]
        cmp     rax, r13
        mov     DWORD PTR 0[rbp+r11*4], r10d  ; store to sum_product[]
```

```
        jne     .L6
.L1:
        pop     rbx rsi rdi rbp r12 r13 r14 r15
        ret
```

Listing 3.54: GCC x64: f2()

```
f2:
        push    r13 r12 rbp rdi rsi rbx
        mov     r13, QWORD PTR 104[rsp]
        mov     rbp, QWORD PTR 88[rsp]
        mov     r12, QWORD PTR 96[rsp]
        test    r13, r13
        je      .L7
        add     r13, 1
        xor     r10d, r10d
        mov     edi, 1
        xor     eax, eax
        jmp     .L10
.L11:
        mov     rax, rdi
        mov     rdi, r11
.L10:
        mov     esi, DWORD PTR [rcx+rax*4]
        mov     r11d, DWORD PTR [rdx+rax*4]
        mov     DWORD PTR [r12+rax*4], r10d  ; store to update_me[]
        add     r10d, 123
        lea     ebx, [rsi+r11]
        imul    r11d, esi
        mov     DWORD PTR [r8+rax*4], ebx    ; store to sum[]
        mov     DWORD PTR [r9+rax*4], r11d   ; store to product[]
        add     r11d, ebx
        mov     DWORD PTR 0[rbp+rax*4], r11d ; store to sum_product[]
        lea     r11, 1[rdi]
        cmp     r11, r13
        jne     .L11
.L7:
        pop     rbx rsi rdi rbp r12 r13
        ret
```

The difference between the compiled `f1()` and `f2()` functions is as follows: in `f1()`, `sum[i]` and `product[i]` are reloaded in the middle of the loop, and in `f2()` there is no such thing, the already calculated values are used, since we "promised" the compiler that no one and nothing will change the values in `sum[i]` and `product[i]` during the execution of the loop's body, so it is "sure" that there is no need to load the value from memory again.

Obviously, the second example works faster.

But what if the pointers in the function's arguments intersect somehow?

This is on the programmer's conscience, and the results will be incorrect.

Let's go back to Fortran.

Compilers of this programming language treats all pointers as such, so when it was not possible to set *restrict* in C, Fortran could generate faster code in these cases.

How practical is it?

In the cases when the function works with several big blocks in memory.

There are a lot of such in linear algebra, for instance.

Supercomputers/HPC[14] are very busy with linear algebra, so probably that is why, traditionally, Fortran is still used there [Eugene Loh, *The Ideal HPC Programming Language*, (2010)].

But when the number of iterations is not very big, certainly, the speed boost may not to be significant.

[14]High-Performance Computing

3.13 Branchless *abs()* function

Let's revisit an example we considered earlier 1.14.2 on page 141 and ask ourselves, is it possible to make a branchless version of the function in x86 code?

```
int my_abs (int i)
{
        if (i<0)
                return -i;
        else
                return i;
};
```

And the answer is yes.

3.13.1 Optimizing GCC 4.9.1 x64

We could see it if we compile it using optimizing GCC 4.9:

Listing 3.55: Optimizing GCC 4.9 x64

```
my_abs:
        mov     edx, edi
        mov     eax, edi
        sar     edx, 31
; EDX is 0xFFFFFFFF here if sign of input value is minus
; EDX is 0 if sign of input value is plus (including 0)
; the following two instructions have effect only if EDX is 0xFFFFFFFF
; or idle if EDX is 0
        xor     eax, edx
        sub     eax, edx
        ret
```

This is how it works:

Arithmetically shift the input value right by 31.

Arithmetical shift implies sign extension, so if the MSB is 1, all 32 bits are to be filled with 1, or with 0 if otherwise.

In other words, the `SAR REG, 31` instruction makes `0xFFFFFFFF` if the sign has been negative or 0 if positive.

After the execution of SAR, we have this value in EDX.

Then, if the value is `0xFFFFFFFF` (i.e., the sign is negative), the input value is inverted
(because `XOR REG, 0xFFFFFFFF` is effectively an inverse all bits operation).

Then, again, if the value is `0xFFFFFFFF` (i.e., the sign is negative), 1 is added to the final result (because subtracting -1 from some value resulting in incrementing it).

Inversion of all bits and incrementing is exactly how two's complement value is negated: 2.2 on page 452.

We may observe that the last two instruction do something if the sign of the input value is negative.

Otherwise (if the sign is positive) they do nothing at all, leaving the input value untouched.

The algorithm is explained in [Henry S. Warren, *Hacker's Delight*, (2002)2-4].

It's hard to say, how GCC did it, deduced it by itself or found a suitable pattern among known ones?

3.13.2 Optimizing GCC 4.9 ARM64

GCC 4.9 for ARM64 generates mostly the same, just decides to use the full 64-bit registers.

There are less instructions, because the input value can be shifted using a suffixed instruction ("asr") instead of using a separate instruction.

Listing 3.56: Optimizing GCC 4.9 ARM64

```
my_abs:
; sign-extend input 32-bit value to X0 64-bit register:
        sxtw    x0, w0
        eor     x1, x0, x0, asr 63
; X1=X0^(X0>>63) (shift is arithmetical)
        sub     x0, x1, x0, asr 63
; X0=X1-(X0>>63)=X0^(X0>>63)-(X0>>63) (all shifts are arithmetical)
        ret
```

3.14 Variadic functions

Functions like `printf()` and `scanf()` can have a variable number of arguments. How are these arguments accessed?

3.14.1 Computing arithmetic mean

Let's imagine that we want to calculate arithmetic mean, and for some weird reason we want to specify all the values as function arguments.

But it's impossible to get the number of arguments in a variadic function in C/C++, so let's denote the value of -1 as a terminator.

Using va_arg macro

There is the standard stdarg.h header file which define macros for dealing with such arguments.

The `printf()` and `scanf()` functions use them as well.

```
#include <stdio.h>
#include <stdarg.h>

int arith_mean(int v, ...)
{
        va_list args;
        int sum=v, count=1, i;
        va_start(args, v);

        while(1)
        {
                i=va_arg(args, int);
                if (i==-1) // terminator
                        break;
                sum=sum+i;
                count++;
        }

        va_end(args);
        return sum/count;
};

int main()
{
        printf ("%d\n", arith_mean (1, 2, 7, 10, 15, -1 /* terminator */));
};
```

The first argument has to be treated just like a normal argument.

All other arguments are loaded using the `va_arg` macro and then summed.

So what is inside?

cdecl calling conventions

Listing 3.57: Optimizing MSVC 6.0

```
_v$ = 8
_arith_mean PROC NEAR
        mov     eax, DWORD PTR _v$[esp-4] ; load 1st argument into sum
        push    esi
        mov     esi, 1                    ; count=1
        lea     edx, DWORD PTR _v$[esp]   ; address of the 1st argument
$L838:
        mov     ecx, DWORD PTR [edx+4]    ; load next argument
        add     edx, 4                    ; shift pointer to the next argument
        cmp     ecx, -1                   ; is it -1?
        je      SHORT $L856               ; exit if so
        add     eax, ecx                  ; sum = sum + loaded argument
        inc     esi                       ; count++
        jmp     SHORT $L838
$L856:
; calculate quotient

        cdq
        idiv    esi
        pop     esi
        ret     0
_arith_mean ENDP

$SG851  DB      '%d', 0aH, 00H

_main   PROC NEAR
        push    -1
        push    15
        push    10
        push    7
        push    2
        push    1
        call    _arith_mean
        push    eax
        push    OFFSET FLAT:$SG851 ; '%d'
        call    _printf
        add     esp, 32
        ret     0
_main   ENDP
```

The arguments, as we may see, are passed to `main()` one-by-one.

The first argument is pushed into the local stack as first.

The terminating value (-1) is pushed last.

The `arith_mean()` function takes the value of the first argument and stores it in the sum variable.

Then, it sets the EDX register to the address of the second argument, takes the value from it, adds it to sum, and does this in an infinite loop, until -1 is found.

When it's found, the sum is divided by the number of all values (excluding -1) and the quotient is returned.

So, in other words, the function treats the stack fragment as an array of integer values of infinite length.

Now we can understand why the *cdecl* calling convention forces us to push the first argument into the stack as last.

Because otherwise, it would not be possible to find the first argument, or, for printf-like functions, it would not be possible to find the address of the format-string.

Register-based calling conventions

The observant reader may ask, what about calling conventions where the first few arguments are passed in registers? Let's see:

Listing 3.58: Optimizing MSVC 2012 x64

```
$SG3013 DB      '%d', 0aH, 00H

v$ = 8
arith_mean PROC
        mov     DWORD PTR [rsp+8], ecx   ; 1st argument
        mov     QWORD PTR [rsp+16], rdx  ; 2nd argument
        mov     QWORD PTR [rsp+24], r8   ; 3rd argument
        mov     eax, ecx                 ; sum = 1st argument
        lea     rcx, QWORD PTR v$[rsp+8] ; pointer to the 2nd argument
        mov     QWORD PTR [rsp+32], r9   ; 4th argument
        mov     edx, DWORD PTR [rcx]     ; load 2nd argument
        mov     r8d, 1                   ; count=1
        cmp     edx, -1                  ; 2nd argument is -1?
        je      SHORT $LN8@arith_mean    ; exit if so
$LL3@arith_mean:
        add     eax, edx                 ; sum = sum + loaded argument
        mov     edx, DWORD PTR [rcx+8]   ; load next argument
        lea     rcx, QWORD PTR [rcx+8]   ; shift pointer to point to the argument after next
        inc     r8d                      ; count++
        cmp     edx, -1                  ; is loaded argument -1?
        jne     SHORT $LL3@arith_mean    ; go to loop begin if its not
$LN8@arith_mean:
; calculate quotient
        cdq
        idiv    r8d
        ret     0
arith_mean ENDP

main    PROC
        sub     rsp, 56
        mov     edx, 2
        mov     DWORD PTR [rsp+40], -1
        mov     DWORD PTR [rsp+32], 15
        lea     r9d, QWORD PTR [rdx+8]
        lea     r8d, QWORD PTR [rdx+5]
        lea     ecx, QWORD PTR [rdx-1]
        call    arith_mean
        lea     rcx, OFFSET FLAT:$SG3013
        mov     edx, eax
        call    printf
        xor     eax, eax
        add     rsp, 56
        ret     0
main    ENDP
```

We see that the first 4 arguments are passed in the registers and two more—in the stack.

The `arith_mean()` function first places these 4 arguments into the *Shadow Space* and then treats the *Shadow Space* and stack behind it as a single continuous array!

What about GCC? Things are slightly clumsier here, because now the function is divided in two parts: the first part saves the registers into the "red zone", processes that space, and the second part of the function processes the stack:

Listing 3.59: Optimizing GCC 4.9.1 x64

```
arith_mean:
        lea     rax, [rsp+8]
        ; save 6 input registers in
        ; red zone in the local stack
        mov     QWORD PTR [rsp-40], rsi
        mov     QWORD PTR [rsp-32], rdx
        mov     QWORD PTR [rsp-16], r8
        mov     QWORD PTR [rsp-24], rcx
        mov     esi, 8
        mov     QWORD PTR [rsp-64], rax
        lea     rax, [rsp-48]
        mov     QWORD PTR [rsp-8], r9
        mov     DWORD PTR [rsp-72], 8
        lea     rdx, [rsp+8]
```

```
        mov     r8d, 1
        mov     QWORD PTR [rsp-56], rax
        jmp     .L5
.L7:
        ; work out saved arguments
        lea     rax, [rsp-48]
        mov     ecx, esi
        add     esi, 8
        add     rcx, rax
        mov     ecx, DWORD PTR [rcx]
        cmp     ecx, -1
        je      .L4
.L8:
        add     edi, ecx
        add     r8d, 1
.L5:
        ; decide, which part we will work out now.
        ; is current argument number less or equal 6?
        cmp     esi, 47
        jbe     .L7             ; no, process saved arguments then
        ; work out arguments from stack
        mov     rcx, rdx
        add     rdx, 8
        mov     ecx, DWORD PTR [rcx]
        cmp     ecx, -1
        jne     .L8
.L4:
        mov     eax, edi
        cdq
        idiv    r8d
        ret

.LC1:
        .string "%d\n"
main:
        sub     rsp, 8
        mov     edx, 7
        mov     esi, 2
        mov     edi, 1
        mov     r9d, -1
        mov     r8d, 15
        mov     ecx, 10
        xor     eax, eax
        call    arith_mean
        mov     esi, OFFSET FLAT:.LC1
        mov     edx, eax
        mov     edi, 1
        xor     eax, eax
        add     rsp, 8
        jmp     __printf_chk
```

By the way, a similar usage of the *Shadow Space* is also considered here: 6.1.8 on page 740.

Using pointer to the first function argument

The example can be rewritten without va_arg macro:

```
#include <stdio.h>

int arith_mean(int v, ...)
{
        int *i=&v;
        int sum=*i, count=1;
        i++;

        while(1)
        {
                if ((*i)==-1) // terminator
```

```
                        break;
                sum=sum+(*i);
                count++;
                i++;
        }

        return sum/count;
};

int main()
{
        printf ("%d\n", arith_mean (1, 2, 7, 10, 15, -1 /* terminator */));
        // test: https://www.wolframalpha.com/input/?i=mean(1,2,7,10,15)
};
```

In other words, if an argument set is array of words (32-bit or 64-bit), we just enumerate array elements starting at first one.

3.14.2 *vprintf()* function case

Many programmers define their own logging functions which take a printf-like format string + a variable number of arguments.

Another popular example is the die() function, which prints some message and exits.

We need some way to pack input arguments of unknown number and pass them to the `printf()` function. But how?

That's why there are functions with "v" in name.

One of them is *vprintf()*: it takes a format-string and a pointer to a variable of type `va_list`:

```
#include <stdlib.h>
#include <stdarg.h>

void die (const char * fmt, ...)
{
        va_list va;
        va_start (va, fmt);

        vprintf (fmt, va);
        exit(0);
};
```

By closer examination, we can see that `va_list` is a pointer to an array. Let's compile:

Listing 3.60: Optimizing MSVC 2010

```
_fmt$ = 8
_die    PROC
        ; load 1st argument (format-string)
        mov     ecx, DWORD PTR _fmt$[esp-4]
        ; get pointer to the 2nd argument
        lea     eax, DWORD PTR _fmt$[esp]
        push    eax             ; pass a pointer
        push    ecx
        call    _vprintf
        add     esp, 8
        push    0
        call    _exit
$LN3@die:
        int     3
_die    ENDP
```

We see that all our function does is just taking a pointer to the arguments and passing it to *vprintf()*, and that function is treating it like an infinite array of arguments!

Listing 3.61: Optimizing MSVC 2012 x64

```
fmt$ = 48
```

```
die     PROC
        ; save first 4 arguments in Shadow Space
        mov     QWORD PTR [rsp+8], rcx
        mov     QWORD PTR [rsp+16], rdx
        mov     QWORD PTR [rsp+24], r8
        mov     QWORD PTR [rsp+32], r9
        sub     rsp, 40
        lea     rdx, QWORD PTR fmt$[rsp+8] ; pass pointer to the 1st argument
        ; RCX here is still points to the 1st argument (format-string) of die()
        ; so vprintf() will take it right from RCX
        call    vprintf
        xor     ecx, ecx
        call    exit
        int     3
die     ENDP
```

3.14.3 Pin case

It's interesting to note how some functions from Pin DBI[15] framework takes number of arguments:

```
            INS_InsertPredicatedCall(
                ins, IPOINT_BEFORE, (AFUNPTR)RecordMemRead,
                IARG_INST_PTR,
                IARG_MEMORYOP_EA, memOp,
                IARG_END);
```

(pinatrace.cpp)

And this is how INS_InsertPredicatedCall() function is declared:

```
extern VOID INS_InsertPredicatedCall(INS ins, IPOINT ipoint, AFUNPTR funptr, ...);
```

(pin_client.PH)

Hence, constants with names starting with IARG_ are some kinds of arguments to the function, which are handled inside of INS_InsertPredicatedCall(). You can pass as many arguments, as you need. Some commands has additional argument(s), some are not. Full list of arguments: https://software.intel.com/sites/landingpage/pintool/docs/58423/Pin/html/group__INST__ARGS.html. And it has to be a way to detect an end of arguments list, so the list must be terminated with IARG_END constant, without which, the function will (try to) handle random noise in the local stack, treating it as additional arguments.

Also, in [Brian W. Kernighan, Rob Pike, *Practice of Programming*, (1999)] we can find a nice example of C/C++ routines very similar to *pack/unpack*[16] in Python.

3.14.4 Format string exploit

It's a popular mistake, to write printf(string) instead of puts(string) or printf("%s", string). If the attacker can put his/her own text into string, he/she can crash process, or get insight into variables in the local stack.

Take a look at this:

```
#include <stdio.h>

int main()
{
        char *s1="hello";
        char *s2="world";
        char buf[128];

        // do something mundane here
        strcpy (buf, s1);
        strcpy (buf, " ");
        strcpy (buf, s2);
```

[15] Dynamic Binary Instrumentation
[16] https://docs.python.org/3/library/struct.html

```
        printf ("%s");
};
```

Please note, that `printf()` has no additional arguments besides single format string.

Now let's imagine, that was the attacker who put %s string into the last `printf()` first arguments. I compile this example using GCC 5.4.0 on x86 Ubuntu, and the resulting executable prints "world" string if it gets executed!

If I turn optimization on, `printf()` outputs some garbage, though—probably, strcpy() calls has been optimized and/or local variables as well. Also, result will be different for x64 code, different compiler, OS, etc.

Now, let's say, attacker could pass the following string to `printf()` call: `%x %x %x %x %x`. In may case, output is: "80485c6 b7751b48 1 0 80485c0" (these are just values from local stack). You see, there are 1 and 0 values, and some pointers (first is probably pointer to "world" string). So if the attacker passes `%s %s %s %s %s` string, the process will crash, because `printf()` treats 1 and/or 0 as pointer to string, tries to read characters from there and fails.

Even worse, there could be `sprintf (buf, string)` in code, where `buf` is a buffer in the local stack with size of 1024 bytes or so, attacker can craft `string` in such a way that `buf` will be overflown, maybe even in a way that would lead to code execution.

Many popular and well-known software was (or even still) vulnerable:

> QuakeWorld went up, got to around 4000 users, then the master server exploded.
> Disrupter and cohorts are working on more robust code now.
> If anyone did it on purpose, how about letting us know... (It wasn't all the people that tried %s as a name)

(John Carmack's .plan file, 17-Dec-1996[17])

Nowadays, almost all decent compilers warn about this.

Another problem is the lesser known %n `printf()` argument: whenever `printf()` reaches it in a format string, it writes the number of characters printed so far into the corresponding argument: http://stackoverflow.com/questions/3401156/what-is-the-use-of-the-n-format-specifier-in-c. Thus, an attacker could zap local variables by passing many %n commands in format string.

3.15 Strings trimming

A very common string processing task is to remove some characters at the start and/or at the end.

In this example, we are going to work with a function which removes all newline characters (CR[18]/LF[19]) from the end of the input string:

```
#include <stdio.h>
#include <string.h>

char* str_trim (char *s)
{
        char c;
        size_t str_len;

        // work as long as \r or \n is at the end of string
        // stop if some other character there or its an empty string
        // (at start or due to our operation)
        for (str_len=strlen(s); str_len>0 && (c=s[str_len-1]); str_len--)
        {
                if (c=='\r' || c=='\n')
                        s[str_len-1]=0;
                else
```

[17] https://github.com/ESWAT/john-carmack-plan-archive/blob/33ae52fdba46aa0d1abfed6fc7598233748541c0/by_day/johnc_plan_19961217.txt
[18] Carriage Return (13 or '\r' in C/C++)
[19] Line Feed (10 or '\n' in C/C++)

```
                                break;
        };
        return s;
};

int main()
{
        // test

        // strdup() is used to copy text string into data segment,
        // because it will crash on Linux otherwise,
        // where text strings are allocated in constant data segment,
        // and not modifiable.

        printf ("[%s]\n", str_trim (strdup("")));
        printf ("[%s]\n", str_trim (strdup("\n")));
        printf ("[%s]\n", str_trim (strdup("\r")));
        printf ("[%s]\n", str_trim (strdup("\n\r")));
        printf ("[%s]\n", str_trim (strdup("\r\n")));
        printf ("[%s]\n", str_trim (strdup("test1\r\n")));
        printf ("[%s]\n", str_trim (strdup("test2\n\r")));
        printf ("[%s]\n", str_trim (strdup("test3\n\r\n\r")));
        printf ("[%s]\n", str_trim (strdup("test4\n")));
        printf ("[%s]\n", str_trim (strdup("test5\r")));
        printf ("[%s]\n", str_trim (strdup("test6\r\r\r")));
};
```

The input argument is always returned on exit, this is convenient when you want to chain string processing functions, like it has done here in the `main()` function.

The second part of for() (`str_len>0 && (c=s[str_len-1])`) is the so called "short-circuit" in C/C++ and is very convenient [Dennis Yurichev, *C/C++ programming language notes*1.3.8].

The C/C++ compilers guarantee an evaluation sequence from left to right.

So if the first clause is false after evaluation, the second one is never to be evaluated.

3.15.1 x64: Optimizing MSVC 2013

Listing 3.62: Optimizing MSVC 2013 x64

```
s$ = 8
str_trim PROC

; RCX is the first function argument and it always holds pointer to the string
        mov     rdx, rcx
; this is strlen() function inlined right here:
; set RAX to 0xFFFFFFFFFFFFFFFF (-1)
        or      rax, -1
$LL14@str_trim:
        inc     rax
        cmp     BYTE PTR [rcx+rax], 0
        jne     SHORT $LL14@str_trim
; is the input string length zero? exit then:
        test    rax, rax
        je      SHORT $LN15@str_trim
; RAX holds string length
        dec     rcx
; RCX = s-1
        mov     r8d, 1
        add     rcx, rax
; RCX = s-1+strlen(s), i.e., this is the address of the last character in the string
        sub     r8, rdx
; R8 = 1-s
$LL6@str_trim:
; load the last character of the string:
; jump, if its code is 13 or 10:
        movzx   eax, BYTE PTR [rcx]
        cmp     al, 13
```

```
        je      SHORT $LN2@str_trim
        cmp     al, 10
        jne     SHORT $LN15@str_trim
$LN2@str_trim:
; the last character has a 13 or 10 code
; write zero at this place:
        mov     BYTE PTR [rcx], 0
; decrement address of the last character,
; so it will point to the character before the one which has just been erased:
        dec     rcx
        lea     rax, QWORD PTR [r8+rcx]
; RAX = 1 - s + address of the current last character
; thus we can determine if we reached the first character and we need to stop, if it is so
        test    rax, rax
        jne     SHORT $LL6@str_trim
$LN15@str_trim:
        mov     rax, rdx
        ret     0
str_trim ENDP
```

First, MSVC inlined the `strlen()` function code, because it concluded this is to be faster than the usual `strlen()` work + the cost of calling it and returning from it. This is called inlining: 3.11 on page 507.

The first instruction of the inlined `strlen()` is
`OR RAX, 0xFFFFFFFFFFFFFFFF`.

MSVC often uses `OR` instead of `MOV RAX, 0xFFFFFFFFFFFFFFFF`, because resulting opcode is shorter.

And of course, it is equivalent: all bits are set, and a number with all bits set is -1 in two's complement arithmetic: 2.2 on page 452.

Why would the -1 number be used in `strlen()`, one might ask. Due to optimizations, of course. Here is the code that MSVC generated:

Listing 3.63: Inlined `strlen()` by MSVC 2013 x64

```
; RCX = pointer to the input string
; RAX = current string length
        or      rax, -1
label:
        inc     rax
        cmp     BYTE PTR [rcx+rax], 0
        jne     SHORT label
; RAX = string length
```

Try to write shorter if you want to initialize the counter at 0! OK, let' try:

Listing 3.64: Our version of `strlen()`

```
; RCX = pointer to the input string
; RAX = current string length
        xor     rax, rax
label:
        cmp     byte ptr [rcx+rax], 0
        jz      exit
        inc     rax
        jmp     label
exit:
; RAX = string length
```

We failed. We have to use additional JMP instruction!

So what the MSVC 2013 compiler did is to move the `INC` instruction to the place before the actual character loading.

If the first character is 0, that's OK, RAX is 0 at this moment, so the resulting string length is 0.

The rest in this function seems easy to understand.

3.15.2 x64: Non-optimizing GCC 4.9.1

```
str_trim:
        push    rbp
        mov     rbp, rsp
        sub     rsp, 32
        mov     QWORD PTR [rbp-24], rdi
; for() first part begins here
        mov     rax, QWORD PTR [rbp-24]
        mov     rdi, rax
        call    strlen
        mov     QWORD PTR [rbp-8], rax   ; str_len
; for() first part ends here
        jmp     .L2
; for() body begins here
.L5:
        cmp     BYTE PTR [rbp-9], 13     ; c=='\r'?
        je      .L3
        cmp     BYTE PTR [rbp-9], 10     ; c=='\n'?
        jne     .L4
.L3:
        mov     rax, QWORD PTR [rbp-8]   ; str_len
        lea     rdx, [rax-1]             ; EDX=str_len-1
        mov     rax, QWORD PTR [rbp-24]  ; s
        add     rax, rdx                 ; RAX=s+str_len-1
        mov     BYTE PTR [rax], 0        ; s[str_len-1]=0
; for() body ends here
; for() third part begins here
        sub     QWORD PTR [rbp-8], 1     ; str_len--
; for() third part ends here
.L2:
; for() second part begins here
        cmp     QWORD PTR [rbp-8], 0     ; str_len==0?
        je      .L4                      ; exit then
; check second clause, and load "c"
        mov     rax, QWORD PTR [rbp-8]   ; RAX=str_len
        lea     rdx, [rax-1]             ; RDX=str_len-1
        mov     rax, QWORD PTR [rbp-24]  ; RAX=s
        add     rax, rdx                 ; RAX=s+str_len-1
        movzx   eax, BYTE PTR [rax]      ; AL=s[str_len-1]
        mov     BYTE PTR [rbp-9], al     ; store loaded char into "c"
        cmp     BYTE PTR [rbp-9], 0      ; is it zero?
        jne     .L5                      ; yes? exit then
; for() second part ends here
.L4:
; return "s"
        mov     rax, QWORD PTR [rbp-24]
        leave
        ret
```

Comments are added by the author of the book.

After the execution of `strlen()`, the control is passed to the L2 label, and there two clauses are checked, one after another.

The second will never be checked, if the first one (*str_len==0*) is false (this is “short-circuit”).

Now let’s see this function in short form:

- First for() part (call to `strlen()`)
- goto L2
- L5: for() body. goto exit, if needed
- for() third part (decrement of str_len)
- L2: for() second part: check first clause, then second. goto loop body begin or exit.
- L4: // exit
- return s

3.15.3 x64: Optimizing GCC 4.9.1

```
str_trim:
        push    rbx
        mov     rbx, rdi
; RBX will always be "s"
        call    strlen
; check for str_len==0 and exit if its so
        test    rax, rax
        je      .L9
        lea     rdx, [rax-1]
; RDX will always contain str_len-1 value, not str_len
; so RDX is more like buffer index variable
        lea     rsi, [rbx+rdx]      ; RSI=s+str_len-1
        movzx   ecx, BYTE PTR [rsi] ; load character
        test    cl, cl
        je      .L9                 ; exit if its zero
        cmp     cl, 10
        je      .L4
        cmp     cl, 13              ; exit if its not '\n' and not '\r'
        jne     .L9
.L4:
; this is weird instruction. we need RSI=s-1 here.
; its possible to get it by MOV RSI, EBX / DEC RSI
; but this is two instructions instead of one
        sub     rsi, rax
; RSI = s+str_len-1-str_len = s-1
; main loop begin
.L12:
        test    rdx, rdx
; store zero at address s-1+str_len-1+1 = s-1+str_len = s+str_len-1
        mov     BYTE PTR [rsi+1+rdx], 0
; check for str_len-1==0. exit if so.
        je      .L9
        sub     rdx, 1                   ; equivalent to str_len--
; load next character at address s+str_len-1
        movzx   ecx, BYTE PTR [rbx+rdx]
        test    cl, cl                   ; is it zero? exit then
        je      .L9
        cmp     cl, 10                   ; is it '\n'?
        je      .L12
        cmp     cl, 13                   ; is it '\r'?
        je      .L12
.L9:
; return "s"
        mov     rax, rbx
        pop     rbx
        ret
```

Now this is more complex.

The code before the loop's body start is executed only once, but it has the CR/LF characters check too! What is this code duplication for?

The common way to implement the main loop is probably this:

- (loop start) check for CR/LF characters, make decisions
- store zero character

But GCC has decided to reverse these two steps.

Of course, *store zero character* cannot be first step, so another check is needed:

- workout first character. match it to CR/LF, exit if character is not CR/LF
- (loop begin) store zero character
- check for CR/LF characters, make decisions

Now the main loop is very short, which is good for latest CPUs.

The code doesn't use the str_len variable, but str_len-1. So this is more like an index in a buffer.

Apparently, GCC notices that the str_len-1 statement is used twice.

So it's better to allocate a variable which always holds a value that's smaller than the current string length by one, and decrement it (this is the same effect as decrementing the str_len variable).

3.15.4 ARM64: Non-optimizing GCC (Linaro) 4.9

This implementation is straightforward:

Listing 3.65: Non-optimizing GCC (Linaro) 4.9

```
str_trim:
        stp     x29, x30, [sp, -48]!
        add     x29, sp, 0
        str     x0, [x29,24] ; copy input argument into local stack
        ldr     x0, [x29,24] ; s
        bl      strlen
        str     x0, [x29,40] ; str_len variable in local stack
        b       .L2
; main loop begin
.L5:
        ldrb    w0, [x29,39]
; W0=c
        cmp     w0, 13       ; is it '\r'?
        beq     .L3
        ldrb    w0, [x29,39]
; W0=c
        cmp     w0, 10       ; is it '\n'?
        bne     .L4          ; goto exit if it is not
.L3:
        ldr     x0, [x29,40]
; X0=str_len
        sub     x0, x0, #1
; X0=str_len-1
        ldr     x1, [x29,24]
; X1=s
        add     x0, x1, x0
; X0=s+str_len-1
        strb    wzr, [x0]    ; write byte at s+str_len-1
; decrement str_len:
        ldr     x0, [x29,40]
; X0=str_len
        sub     x0, x0, #1
; X0=str_len-1
        str     x0, [x29,40]
; save X0 (or str_len-1) to local stack
.L2:
        ldr     x0, [x29,40]
; str_len==0?
        cmp     x0, xzr
; goto exit then
        beq     .L4
        ldr     x0, [x29,40]
; X0=str_len
        sub     x0, x0, #1
; X0=str_len-1
        ldr     x1, [x29,24]
; X1=s
        add     x0, x1, x0
; X0=s+str_len-1
; load byte at address s+str_len-1 to W0
        ldrb    w0, [x0]
        strb    w0, [x29,39] ; store loaded byte to "c"
        ldrb    w0, [x29,39] ; reload it
; is it zero byte?
        cmp     w0, wzr
; goto exit, if its zero or to L5 if its not
        bne     .L5
.L4:
```

```
; return s
        ldr     x0, [x29,24]
        ldp     x29, x30, [sp], 48
        ret
```

3.15.5 ARM64: Optimizing GCC (Linaro) 4.9

This is a more advanced optimization.

The first character is loaded at the beginning, and compared against 10 (the LF character).

Characters are also loaded in the main loop, for the characters after first one.

This is somewhat similar to the 3.15.3 on page 529 example.

Listing 3.66: Optimizing GCC (Linaro) 4.9

```
str_trim:
        stp     x29, x30, [sp, -32]!
        add     x29, sp, 0
        str     x19, [sp,16]
        mov     x19, x0
; X19 will always hold value of "s"
        bl      strlen
; X0=str_len
        cbz     x0, .L9         ; goto L9 (exit) if str_len==0
        sub     x1, x0, #1
; X1=X0-1=str_len-1
        add     x3, x19, x1
; X3=X19+X1=s+str_len-1
        ldrb    w2, [x19,x1]    ; load byte at address X19+X1=s+str_len-1
; W2=loaded character
        cbz     w2, .L9         ; is it zero? jump to exit then
        cmp     w2, 10          ; is it '\n'?
        bne     .L15
.L12:
; main loop body. loaded character is always 10 or 13 at this moment!
        sub     x2, x1, x0
; X2=X1-X0=str_len-1-str_len=-1
        add     x2, x3, x2
; X2=X3+X2=s+str_len-1+(-1)=s+str_len-2
        strb    wzr, [x2,1]     ; store zero byte at address s+str_len-2+1=s+str_len-1
        cbz     x1, .L9         ; str_len-1==0? goto exit, if so
        sub     x1, x1, #1      ; str_len--
        ldrb    w2, [x19,x1]    ; load next character at address X19+X1=s+str_len-1
        cmp     w2, 10          ; is it '\n'?
        cbz     w2, .L9         ; jump to exit, if its zero
        beq     .L12            ; jump to begin loop, if its '\n'
.L15:
        cmp     w2, 13          ; is it '\r'?
        beq     .L12            ; yes, jump to the loop body begin
.L9:
; return "s"
        mov     x0, x19
        ldr     x19, [sp,16]
        ldp     x29, x30, [sp], 32
        ret
```

3.15.6 ARM: Optimizing Keil 6/2013 (ARM mode)

And again, the compiler took advantage of ARM mode's conditional instructions, so the code is much more compact.

Listing 3.67: Optimizing Keil 6/2013 (ARM mode)

```
str_trim PROC
        PUSH     {r4,lr}
```

```
; R0=s
        MOV      r4,r0
; R4=s
        BL       strlen       ; strlen() takes "s" value from R0
; R0=str_len
        MOV      r3,#0
; R3 will always hold 0
|L0.16|
        CMP      r0,#0        ; str_len==0?
        ADDNE    r2,r4,r0     ; (if str_len!=0) R2=R4+R0=s+str_len
        LDRBNE   r1,[r2,#-1]  ; (if str_len!=0) R1=load byte at address R2-1=s+str_len-1
        CMPNE    r1,#0        ; (if str_len!=0) compare loaded byte against 0
        BEQ      |L0.56|      ; jump to exit if str_len==0 or loaded byte is 0
        CMP      r1,#0xd      ; is loaded byte '\r'?
        CMPNE    r1,#0xa      ; (if loaded byte is not '\r') is loaded byte '\r'?
        SUBEQ    r0,r0,#1     ; (if loaded byte is '\r' or '\n') R0-- or str_len--
        STRBEQ   r3,[r2,#-1]  ; (if loaded byte is '\r' or '\n') store R3 (zero) at address R2-1=s+str_len-1
        BEQ      |L0.16|      ; jump to loop begin if loaded byte was '\r' or '\n'
|L0.56|
; return "s"
        MOV      r0,r4
        POP      {r4,pc}
        ENDP
```

3.15.7 ARM: Optimizing Keil 6/2013 (Thumb mode)

There are less conditional instructions in Thumb mode, so the code is simpler.

But there are is really weird thing with the 0x20 and 0x1F offsets (lines 22 and 23). Why did the Keil compiler do so? Honestly, it's hard to say.

It has to be a quirk of Keil's optimization process. Nevertheless, the code works correctly.

Listing 3.68: Optimizing Keil 6/2013 (Thumb mode)

```
1  str_trim PROC
2          PUSH     {r4,lr}
3          MOVS     r4,r0
4  ; R4=s
5          BL       strlen        ; strlen() takes "s" value from R0
6  ; R0=str_len
7          MOVS     r3,#0
8  ; R3 will always hold 0
9          B        |L0.24|
10 |L0.12|
11         CMP      r1,#0xd       ; is loaded byte '\r'?
12         BEQ      |L0.20|
13         CMP      r1,#0xa       ; is loaded byte '\n'?
14         BNE      |L0.38|       ; jump to exit, if no
15 |L0.20|
16         SUBS     r0,r0,#1      ; R0-- or str_len--
17         STRB     r3,[r2,#0x1f] ; store 0 at address R2+0x1F=s+str_len-0x20+0x1F=s+str_len-1
18 |L0.24|
19         CMP      r0,#0         ; str_len==0?
20         BEQ      |L0.38|       ; yes? jump to exit
21         ADDS     r2,r4,r0      ; R2=R4+R0=s+str_len
22         SUBS     r2,r2,#0x20   ; R2=R2-0x20=s+str_len-0x20
23         LDRB     r1,[r2,#0x1f] ; load byte at address R2+0x1F=s+str_len-0x20+0x1F=s+str_len-1 to R1
24         CMP      r1,#0         ; is loaded byte 0?
25         BNE      |L0.12|       ; jump to loop begin, if its not 0
26 |L0.38|
27 ; return "s"
28         MOVS     r0,r4
29         POP      {r4,pc}
30         ENDP
```

3.15.8 MIPS

Listing 3.69: Optimizing GCC 4.4.5 (IDA)

```
str_trim:
; IDA is not aware of local variable names, we gave them manually:
saved_GP          = -0x10
saved_S0           = -8
saved_RA           = -4

                lui     $gp, (__gnu_local_gp >> 16)
                addiu   $sp, -0x20
                la      $gp, (__gnu_local_gp & 0xFFFF)
                sw      $ra, 0x20+saved_RA($sp)
                sw      $s0, 0x20+saved_S0($sp)
                sw      $gp, 0x20+saved_GP($sp)
; call strlen(). input string address is still in $a0, strlen() will take it from there:
                lw      $t9, (strlen & 0xFFFF)($gp)
                or      $at, $zero ; load delay slot, NOP
                jalr    $t9
; input string address is still in $a0, put it to $s0:
                move    $s0, $a0   ; branch delay slot
; result of strlen() (i.e, length of string) is in $v0 now
; jump to exit if $v0==0 (i.e., if length of string is 0):
                beqz    $v0, exit
                or      $at, $zero ; branch delay slot, NOP
                addiu   $a1, $v0, -1
; $a1 = $v0-1 = str_len-1
                addu    $a1, $s0, $a1
; $a1 = input string address + $a1 = s+strlen-1
; load byte at address $a1:
                lb      $a0, 0($a1)
                or      $at, $zero ; load delay slot, NOP
; loaded byte is zero? jump to exit if its so:
                beqz    $a0, exit
                or      $at, $zero ; branch delay slot, NOP
                addiu   $v1, $v0, -2
; $v1 = str_len-2
                addu    $v1, $s0, $v1
; $v1 = $s0+$v1 = s+str_len-2
                li      $a2, 0xD
; skip loop body:
                b       loc_6C
                li      $a3, 0xA   ; branch delay slot
loc_5C:
; load next byte from memory to $a0:
                lb      $a0, 0($v1)
                move    $a1, $v1
; $a1=s+str_len-2
; jump to exit if loaded byte is zero:
                beqz    $a0, exit
; decrement str_len:
                addiu   $v1, -1    ; branch delay slot
loc_6C:
; at this moment, $a0=loaded byte, $a2=0xD (CR symbol) and $a3=0xA (LF symbol)
; loaded byte is CR? jump to loc_7C then:
                beq     $a0, $a2, loc_7C
                addiu   $v0, -1    ; branch delay slot
; loaded byte is LF? jump to exit if its not LF:
                bne     $a0, $a3, exit
                or      $at, $zero ; branch delay slot, NOP
loc_7C:
; loaded byte is CR at this moment
; jump to loc_5c (loop body begin) if str_len (in $v0) is not zero:
                bnez    $v0, loc_5C
; simultaneously, store zero at that place in memory:
                sb      $zero, 0($a1) ; branch delay slot
; "exit" label was named by me manually:
exit:
                lw      $ra, 0x20+saved_RA($sp)
```

```
                move    $v0, $s0
                lw      $s0, 0x20+saved_S0($sp)
                jr      $ra
                addiu   $sp, 0x20      ; branch delay slot
```

Registers prefixed with S- are also called “saved temporaries”, so $S0 value is saved in the local stack and restored upon finish.

3.16 toupper() function

Another very popular function transforms a symbol from lower case to upper case, if needed:

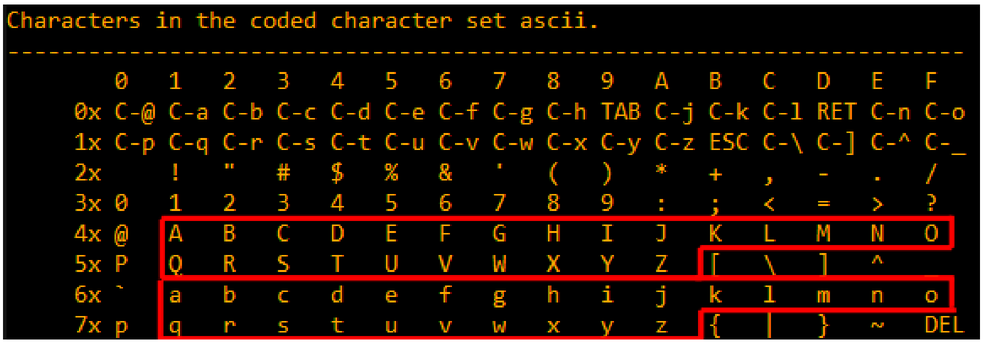
```
char toupper (char c)
{
        if(c>='a' && c<='z')
                return c-'a'+'A';
        else
                return c;
}
```

The `'a'+'A'` expression is left in the source code for better readability, it will be optimized by compiler, of course [20].

The ASCII code of “a” is 97 (or 0x61), and 65 (or 0x41) for “A”.

The difference (or distance) between them in the ASCII table is 32 (or 0x20).

For better understanding, the reader may take a look at the 7-bit standard ASCII table:


Characters in the coded character set ascii.

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0x	C-@	C-a	C-b	C-c	C-d	C-e	C-f	C-g	C-h	TAB	C-j	C-k	C-l	RET	C-n	C-o
1x	C-p	C-q	C-r	C-s	C-t	C-u	C-v	C-w	C-x	C-y	C-z	ESC	C-\	C-]	C-^	C-_
2x		!	"	#	$	%	&	'	(	)	*	+	,	-	.	/
3x	0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?
4x	@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
5x	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	^	
6x	`	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
7x	p	q	r	s	t	u	v	w	x	y	z	{	|	}	~	DEL

Figure 3.3: 7-bit ASCII table in Emacs

3.16.1 x64

Two comparison operations

Non-optimizing MSVC is straightforward: the code checks if the input symbol is in [97..122] range (or in [‘a’..‘z’] range) and subtracts 32 if it’s true.

There are also some minor compiler artifact:

Listing 3.70: Non-optimizing MSVC 2013 (x64)

```
c$ = 8
toupper PROC
        mov     BYTE PTR [rsp+8], cl
        movsx   eax, BYTE PTR c$[rsp]
        cmp     eax, 97
        jl      SHORT $LN2@toupper
        movsx   eax, BYTE PTR c$[rsp]
        cmp     eax, 122
        jg      SHORT $LN2@toupper
```

[20] However, to be meticulous, there still could be compilers which can’t optimize such expressions and will leave them right in the code.

```
10         movsx   eax, BYTE PTR c$[rsp]
11         sub     eax, 32
12         jmp     SHORT $LN3@toupper
13         jmp     SHORT $LN1@toupper      ; compiler artefact
14 $LN2@toupper:
15         movzx   eax, BYTE PTR c$[rsp]   ; unnecessary casting
16 $LN1@toupper:
17 $LN3@toupper:                           ; compiler artefact
18         ret     0
19 toupper ENDP
```

It's important to notice that the input byte is loaded into a 64-bit local stack slot at line 3.

All the remaining bits ([8..63]) are untouched, i.e., contain some random noise (you'll see it in debugger).

All instructions operate only on byte-level, so it's fine.

The last MOVZX instruction at line 15 takes the byte from the local stack slot and zero-extends it to a *int* 32-bit data type.

Non-optimizing GCC does mostly the same:

Listing 3.71: Non-optimizing GCC 4.9 (x64)

```
toupper:
        push    rbp
        mov     rbp, rsp
        mov     eax, edi
        mov     BYTE PTR [rbp-4], al
        cmp     BYTE PTR [rbp-4], 96
        jle     .L2
        cmp     BYTE PTR [rbp-4], 122
        jg      .L2
        movzx   eax, BYTE PTR [rbp-4]
        sub     eax, 32
        jmp     .L3
.L2:
        movzx   eax, BYTE PTR [rbp-4]
.L3:
        pop     rbp
        ret
```

One comparison operation

Optimizing MSVC does a better job, it generates only one comparison operation:

Listing 3.72: Optimizing MSVC 2013 (x64)

```
toupper PROC
        lea     eax, DWORD PTR [rcx-97]
        cmp     al, 25
        ja      SHORT $LN2@toupper
        movsx   eax, cl
        sub     eax, 32
        ret     0
$LN2@toupper:
        movzx   eax, cl
        ret     0
toupper ENDP
```

It was explained earlier how to replace the two comparison operations with a single one: 3.10.2 on page 505.

We will now rewrite this in C/C++:

```
int tmp=c-97;

if (tmp>25)
        return c;
else
        return c-32;
```

The *tmp* variable must be signed.

This makes two subtraction operations in case of a transformation plus one comparison.

In contrast the original algorithm uses two comparison operations plus one subtracting.

Optimizing GCC is even better, it gets rid of the jumps (which is good: 2.10.1 on page 466) by using the CMOVcc instruction:

Listing 3.73: Optimizing GCC 4.9 (x64)

```
1 toupper:
2         lea     edx, [rdi-97] ; 0x61
3         lea     eax, [rdi-32] ; 0x20
4         cmp     dl, 25
5         cmova   eax, edi
6         ret
```

At line 3 the code prepares the subtracted value in advance, as if the conversion will always happen.

At line 5 the subtracted value in EAX is replaced by the untouched input value if a conversion is not needed. And then this value (of course incorrect) is dropped.

Advance subtracting is a price the compiler pays for the absence of conditional jumps.

3.16.2 ARM

Optimizing Keil for ARM mode also generates only one comparison:

Listing 3.74: Optimizing Keil 6/2013 (ARM mode)

```
toupper PROC
        SUB      r1,r0,#0x61
        CMP      r1,#0x19
        SUBLS    r0,r0,#0x20
        ANDLS    r0,r0,#0xff
        BX       lr
        ENDP
```

The SUBLS and ANDLS instructions are executed only if the value in R1 is less than 0x19 (or equal). They also do the actual conversion.

Optimizing Keil for Thumb mode generates only one comparison operation as well:

Listing 3.75: Optimizing Keil 6/2013 (Thumb mode)

```
toupper PROC
        MOVS     r1,r0
        SUBS     r1,r1,#0x61
        CMP      r1,#0x19
        BHI      |L0.14|
        SUBS     r0,r0,#0x20
        LSLS     r0,r0,#24
        LSRS     r0,r0,#24
|L0.14|
        BX       lr
        ENDP
```

The last two LSLS and LSRS instructions work like `AND reg, 0xFF`: they are equivalent to the C/C++-expression $(i << 24) >> 24$.

Seems like that Keil for Thumb mode deduced that two 2-byte instructions are shorter than the code that loads the 0xFF constant into a register plus an AND instruction.

GCC for ARM64

Listing 3.76: Non-optimizing GCC 4.9 (ARM64)

```
toupper:
        sub     sp, sp, #16
```

```
        strb    w0, [sp,15]
        ldrb    w0, [sp,15]
        cmp     w0, 96
        bls     .L2
        ldrb    w0, [sp,15]
        cmp     w0, 122
        bhi     .L2
        ldrb    w0, [sp,15]
        sub     w0, w0, #32
        uxtb    w0, w0
        b       .L3
.L2:
        ldrb    w0, [sp,15]
.L3:
        add     sp, sp, 16
        ret
```

Listing 3.77: Optimizing GCC 4.9 (ARM64)

```
toupper:
        uxtb    w0, w0
        sub     w1, w0, #97
        uxtb    w1, w1
        cmp     w1, 25
        bhi     .L2
        sub     w0, w0, #32
        uxtb    w0, w0
.L2:
        ret
```

3.16.3 Using bit operations

Given the fact that 5th bit (counting from 0th) is always present after the check, subtracting is merely clearing this sole bit, but the very same effect can be achieved with ANDing (2.5 on page 458).

Even simpler, with XOR-ing:

```
char toupper (char c)
{
        if(c>='a' && c<='z')
                return c^0x20;
        else
                return c;
}
```

The code is close to what the optimized GCC has produced for the previous example (3.73 on the preceding page):

Listing 3.78: Optimizing GCC 5.4 (x86)

```
toupper:
        mov     edx, DWORD PTR [esp+4]
        lea     ecx, [edx-97]
        mov     eax, edx
        xor     eax, 32
        cmp     cl, 25
        cmova   eax, edx
        ret
```

...but XOR is used instead of SUB.

Flipping 5th bit is just moving a *cursor* in ASCII table up and down by two rows.

Some people say that lowercase/uppercase letters has been placed in the ASCII table in such a way deliberately, because:

> Very old keyboards used to do Shift just by toggling the 32 or 16 bit, depending on the key; this is why the relationship between small and capital letters in ASCII is so regular, and the relationship between numbers and symbols, and some pairs of symbols, is sort of regular if you squint at it.

(Eric S. Raymond, http://www.catb.org/esr/faqs/things-every-hacker-once-knew/)

Therefore, we can write this piece of code, which just flips the case of letters:

```
#include <stdio.h>

char flip (char c)
{
        if((c>='a' && c<='z') || (c>='A' && c<='Z'))
                return c^0x20;
        else
                return c;
}

int main()
{
        // will produce "hELLO, WORLD!"
        for (char *s="Hello, world!"; *s; s++)
                printf ("%c", flip(*s));
};
```

3.16.4 Summary

All these compiler optimizations are very popular nowadays and a practicing reverse engineer usually sees such code patterns often.

3.17 Obfuscation

The obfuscation is an attempt to hide the code (or its meaning) from reverse engineers.

3.17.1 Text strings

As we saw in (5.4 on page 704), text strings may be really helpful.

Programmers who are aware of this try to hide them, making it impossible to find the string in IDA or any hex editor.

Here is the simplest method.

This is how the string can be constructed:

```
mov     byte ptr [ebx], 'h'
mov     byte ptr [ebx+1], 'e'
mov     byte ptr [ebx+2], 'l'
mov     byte ptr [ebx+3], 'l'
mov     byte ptr [ebx+4], 'o'
mov     byte ptr [ebx+5], ' '
mov     byte ptr [ebx+6], 'w'
mov     byte ptr [ebx+7], 'o'
mov     byte ptr [ebx+8], 'r'
mov     byte ptr [ebx+9], 'l'
mov     byte ptr [ebx+10], 'd'
```

The string can also be compared with another one like this:

```
mov     ebx, offset username
cmp     byte ptr [ebx], 'j'
jnz     fail
cmp     byte ptr [ebx+1], 'o'
jnz     fail
cmp     byte ptr [ebx+2], 'h'
jnz     fail
cmp     byte ptr [ebx+3], 'n'
jnz     fail
jz      it_is_john
```

In both cases, it is impossible to find these strings straightforwardly in a hex editor.

By the way, this is a way to work with the strings when it is impossible to allocate space for them in the data segment, for example in a PIC[21] or in shellcode.

Another method is to use `sprintf()` for the construction:

```
sprintf(buf, "%s%c%s%c%s", "hel",'l',"o w",'o',"rld");
```

The code looks weird, but as a simple anti-reversing measure, it may be helpful.

Text strings may also be present in encrypted form, then every string usage is to be preceded by a string decrypting routine. For example: 8.5.2 on page 822.

3.17.2 Executable code

Inserting garbage

Executable code obfuscation implies inserting random garbage code between real one, which executes but does nothing useful.

A simple example:

Listing 3.79: original code

```
add     eax, ebx
mul     ecx
```

Listing 3.80: obfuscated code

```
xor     esi, 011223344h ; garbage
add     esi, eax        ; garbage
add     eax, ebx
mov     edx, eax        ; garbage
shl     edx, 4          ; garbage
mul     ecx
xor     esi, ecx        ; garbage
```

Here the garbage code uses registers which are not used in the real code (`ESI` and `EDX`). However, the intermediate results produced by the real code may be used by the garbage instructions for some extra mess—why not?

Replacing instructions with bloated equivalents

- `MOV op1, op2` can be replaced by the `PUSH op2 / POP op1` pair.
- `JMP label` can be replaced by the `PUSH label / RET` pair. IDA will not show the references to the label.
- `CALL label` can be replaced by the following instructions triplet:
  `PUSH label_after_CALL_instruction / PUSH label / RET`.
- `PUSH op` can also be replaced with the following instructions pair:
  `SUB ESP, 4 (or 8) / MOV [ESP], op`.

[21] Position Independent Code

Always executed/never executed code

If the developer is sure that ESI at always 0 at that point:

```
mov     esi, 1
...     ; some code not touching ESI
dec     esi
...     ; some code not touching ESI
cmp     esi, 0
jz      real_code
; fake luggage
real_code:
```

The reverse engineer needs some time to get into it.

This is also called an *opaque predicate*.

Another example (and again, the developer is sure that ESI is always zero):

```
add     eax, ebx        ; real code
mul     ecx             ; real code
add     eax, esi        ; opaque predicate. XOR, AND or SHL, etc, can be here instead of ADD.
```

Making a lot of mess

```
instruction 1
instruction 2
instruction 3
```

Can be replaced with:

```
begin:          jmp     ins1_label

ins2_label:     instruction 2
                jmp     ins3_label

ins3_label:     instruction 3
                jmp     exit:

ins1_label:     instruction 1
                jmp     ins2_label
exit:
```

Using indirect pointers

```
dummy_data1     db      100h dup (0)
message1        db      'hello world',0

dummy_data2     db      200h dup (0)
message2        db      'another message',0

func            proc
                ...
                mov     eax, offset dummy_data1 ; PE or ELF reloc here
                add     eax, 100h
                push    eax
                call    dump_string
                ...
                mov     eax, offset dummy_data2 ; PE or ELF reloc here
                add     eax, 200h
                push    eax
                call    dump_string
                ...
func            endp
```

IDA will show references only to dummy_data1 and dummy_data2, but not to the text strings.

Global variables and even functions may be accessed like that.

3.17.3 Virtual machine / pseudo-code

A programmer can construct his/her own PL or ISA and interpreter for it.

(Like the pre-5.0 Visual Basic, .NET or Java machines). The reverse engineer will have to spend some time to understand the meaning and details of all of the ISA's instructions.

He/she will also have to write a disassembler/decompiler of some sort.

3.17.4 Other things to mention

My own (yet weak) attempt to patch the Tiny C compiler to produce obfuscated code: http://go.yurichev.com/17220.

Using the MOV instruction for really complicated things: [Stephen Dolan, *mov is Turing-complete*, (2013)] [22].

3.17.5 Exercise

- http://challenges.re/29

3.18 C++

3.18.1 Classes

A simple example

Internally, the representation of C++ classes is almost the same as the structures.

Let's try an example with two variables, two constructors and one method:

```
#include <stdio.h>

class c
{
private:
    int v1;
    int v2;
public:
    c() // default ctor
    {
        v1=667;
        v2=999;
    };

    c(int a, int b) // ctor
    {
        v1=a;
        v2=b;
    };

    void dump()
    {
        printf ("%d; %d\n", v1, v2);
    };
};
```

[22] Also available as http://www.cl.cam.ac.uk/~sd601/papers/mov.pdf

```
int main()
{
    class c c1;
    class c c2(5,6);

    c1.dump();
    c2.dump();

    return 0;
};
```

MSVC: x86

Here is how the `main()` function looks like, translated into assembly language:

Listing 3.81: MSVC

```
_c2$ = -16 ; size = 8
_c1$ = -8  ; size = 8
_main PROC
    push ebp
    mov  ebp, esp
    sub  esp, 16
    lea  ecx, DWORD PTR _c1$[ebp]
    call ??0c@@QAE@XZ ; c::c
    push 6
    push 5
    lea  ecx, DWORD PTR _c2$[ebp]
    call ??0c@@QAE@HH@Z ; c::c
    lea  ecx, DWORD PTR _c1$[ebp]
    call ?dump@c@@QAEXXZ ; c::dump
    lea  ecx, DWORD PTR _c2$[ebp]
    call ?dump@c@@QAEXXZ ; c::dump
    xor  eax, eax
    mov  esp, ebp
    pop  ebp
    ret  0
_main ENDP
```

Here's what's going on. For each object (instance of class c) 8 bytes are allocated, exactly the size needed to store the 2 variables.

For *c1* a default argumentless constructor `??0c@@QAE@XZ` is called. For *c2* another constructor `??0c@@QAE@HH@Z` is called and two numbers are passed as arguments.

A pointer to the object (*this* in C++ terminology) is passed in the ECX register. This is called thiscall (3.18.1)—the method for passing a pointer to the object.

MSVC does it using the ECX register. Needless to say, it is not a standardized method, other compilers can do it differently, e.g., via the first function argument (like GCC).

Why do these functions have such odd names? That's name mangling.

A C++ class may contain several methods sharing the same name but having different arguments—that is polymorphism. And of course, different classes may have their own methods with the same name.

Name mangling enable us to encode the class name + method name + all method argument types in one ASCII string, which is then used as an internal function name. That's all because neither the linker, nor the DLL OS loader (mangled names may be among the DLL exports as well) knows anything about C++ or OOP[23].

The `dump()` function is called two times.

Now let's see the constructors' code:

Listing 3.82: MSVC

```
_this$ = -4       ; size = 4
??0c@@QAE@XZ PROC ; c::c, COMDAT
```

[23] Object-Oriented Programming

```
; _this$ = ecx
    push ebp
    mov  ebp, esp
    push ecx
    mov  DWORD PTR _this$[ebp], ecx
    mov  eax, DWORD PTR _this$[ebp]
    mov  DWORD PTR [eax], 667
    mov  ecx, DWORD PTR _this$[ebp]
    mov  DWORD PTR [ecx+4], 999
    mov  eax, DWORD PTR _this$[ebp]
    mov  esp, ebp
    pop  ebp
    ret  0
??0c@@QAE@XZ ENDP ; c::c

_this$ = -4 ; size = 4
_a$ = 8     ; size = 4
_b$ = 12    ; size = 4
??0c@@QAE@HH@Z PROC ; c::c, COMDAT
; _this$ = ecx
    push ebp
    mov  ebp, esp
    push ecx
    mov  DWORD PTR _this$[ebp], ecx
    mov  eax, DWORD PTR _this$[ebp]
    mov  ecx, DWORD PTR _a$[ebp]
    mov  DWORD PTR [eax], ecx
    mov  edx, DWORD PTR _this$[ebp]
    mov  eax, DWORD PTR _b$[ebp]
    mov  DWORD PTR [edx+4], eax
    mov  eax, DWORD PTR _this$[ebp]
    mov  esp, ebp
    pop  ebp
    ret  8
??0c@@QAE@HH@Z ENDP ; c::c
```

The constructors are just functions, they use a pointer to the structure in ECX, copying the pointer into their own local variable, however, it is not necessary.

From the C++ standard (C++11 12.1) we know that constructors are not required to return any values.

In fact, internally, the constructors return a pointer to the newly created object, i.e., *this*.

Now the dump() method:

Listing 3.83: MSVC

```
_this$ = -4          ; size = 4
?dump@c@@QAEXXZ PROC ; c::dump, COMDAT
; _this$ = ecx
    push ebp
    mov  ebp, esp
    push ecx
    mov  DWORD PTR _this$[ebp], ecx
    mov  eax, DWORD PTR _this$[ebp]
    mov  ecx, DWORD PTR [eax+4]
    push ecx
    mov  edx, DWORD PTR _this$[ebp]
    mov  eax, DWORD PTR [edx]
    push eax
    push OFFSET ??_C@_07NJBDCIEC@?$CFd?$DL?5?$CFd?6?$AA@
    call _printf
    add  esp, 12
    mov  esp, ebp
    pop  ebp
    ret  0
?dump@c@@QAEXXZ ENDP ; c::dump
```

Simple enough: dump() takes a pointer to the structure that contains the two *int*'s from ECX, takes both values from it and passes them to printf().

The code is much shorter if compiled with optimizations (/Ox):

Listing 3.84: MSVC

```
??0c@@QAE@XZ PROC ; c::c, COMDAT
; _this$ = ecx
    mov  eax, ecx
    mov  DWORD PTR [eax], 667
    mov  DWORD PTR [eax+4], 999
    ret  0
??0c@@QAE@XZ ENDP ; c::c

_a$ = 8  ; size = 4
_b$ = 12 ; size = 4
??0c@@QAE@HH@Z PROC ; c::c, COMDAT
; _this$ = ecx
    mov  edx, DWORD PTR _b$[esp-4]
    mov  eax, ecx
    mov  ecx, DWORD PTR _a$[esp-4]
    mov  DWORD PTR [eax], ecx
    mov  DWORD PTR [eax+4], edx
    ret  8
??0c@@QAE@HH@Z ENDP ; c::c

?dump@c@@QAEXXZ PROC ; c::dump, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx+4]
    mov  ecx, DWORD PTR [ecx]
    push eax
    push ecx
    push OFFSET ??_C@_07NJBDCIEC@?$CFd?$DL?5?$CFd?6?$AA@
    call _printf
    add  esp, 12
    ret  0
?dump@c@@QAEXXZ ENDP ; c::dump
```

That's all. The other thing we must note is that the stack pointer hasn't been corrected with `add esp, X` after the constructor has been called. At the same time, the constructor has `ret 8` instead of RET at the end.

This is all because the thiscall (3.18.1 on page 542) calling convention is used here, which together with the stdcall (6.1.2 on page 734) method offers the callee to correct the stack instead of the caller. The `ret x` instruction adds X to the value in ESP, then passes the control to the caller function.

See also the section about calling conventions (6.1 on page 734).

It also has to be noted that the compiler decides when to call the constructor and destructor—but we already know that from the C++ language basics.

MSVC: x86-64

As we already know, the first 4 function arguments in x86-64 are passed in RCX, RDX, R8 and R9 registers, all the rest—via the stack.

Nevertheless, the *this* pointer to the object is passed in RCX, the first argument of the method in RDX, etc. We can see this in the `c(int a, int b)` method internals:

Listing 3.85: Optimizing MSVC 2012 x64

```
; void dump()

?dump@c@@QEAAXXZ PROC ; c::dump
    mov    r8d, DWORD PTR [rcx+4]
    mov    edx, DWORD PTR [rcx]
    lea    rcx, OFFSET FLAT:??_C@_07NJBDCIEC@?$CFd?$DL?5?$CFd?6?$AA@ ; '%d; %d'
    jmp    printf
?dump@c@@QEAAXXZ ENDP ; c::dump

; c(int a, int b)

??0c@@QEAA@HH@Z PROC ; c::c
    mov    DWORD PTR [rcx], edx   ; 1st argument: a
```

```
    mov    DWORD PTR [rcx+4], r8d ; 2nd argument: b
    mov    rax, rcx
    ret    0
??0c@@QEAA@HH@Z ENDP ; c::c

; default ctor

??0c@@QEAA@XZ PROC ; c::c
    mov    DWORD PTR [rcx], 667
    mov    DWORD PTR [rcx+4], 999
    mov    rax, rcx
    ret    0
??0c@@QEAA@XZ ENDP ; c::c
```

The *int* data type is still 32-bit in x64 [24], so that is why 32-bit register parts are used here.

We also see JMP `printf` instead of RET in the `dump()` method, that *hack* we already saw earlier: 1.15.1 on page 154.

GCC: x86

It is almost the same story in GCC 4.4.1, with a few exceptions.

Listing 3.86: GCC 4.4.1

```
     public main
main proc near

var_20 = dword ptr -20h
var_1C = dword ptr -1Ch
var_18 = dword ptr -18h
var_10 = dword ptr -10h
var_8  = dword ptr -8

    push ebp
    mov  ebp, esp
    and  esp, 0FFFFFFF0h
    sub  esp, 20h
    lea  eax, [esp+20h+var_8]
    mov  [esp+20h+var_20], eax
    call _ZN1cC1Ev
    mov  [esp+20h+var_18], 6
    mov  [esp+20h+var_1C], 5
    lea  eax, [esp+20h+var_10]
    mov  [esp+20h+var_20], eax
    call _ZN1cC1Eii
    lea  eax, [esp+20h+var_8]
    mov  [esp+20h+var_20], eax
    call _ZN1c4dumpEv
    lea  eax, [esp+20h+var_10]
    mov  [esp+20h+var_20], eax
    call _ZN1c4dumpEv
    mov  eax, 0
    leave
    retn
main endp
```

Here we see another *name mangling* style, specific to GNU [25] It can also be noted that the pointer to the object is passed as the first function argument—invisible to programmer, of course.

First constructor:

```
                public _ZN1cC1Ev ; weak
_ZN1cC1Ev       proc near              ; CODE XREF: main+10
```

[24] Apparently, for easier porting of 32-bit C/C++ code to x64

[25] There is a good document about the various name mangling conventions in different compilers: [Agner Fog, *Calling conventions* (2015)].

```
arg_0           = dword ptr  8

                push    ebp
                mov     ebp, esp
                mov     eax, [ebp+arg_0]
                mov     dword ptr [eax], 667
                mov     eax, [ebp+arg_0]
                mov     dword ptr [eax+4], 999
                pop     ebp
                retn
_ZN1cC1Ev       endp
```

It just writes two numbers using the pointer passed in the first (and only) argument.

Second constructor:

```
                public _ZN1cC1Eii
_ZN1cC1Eii      proc near

arg_0           = dword ptr  8
arg_4           = dword ptr  0Ch
arg_8           = dword ptr  10h

                push    ebp
                mov     ebp, esp
                mov     eax, [ebp+arg_0]
                mov     edx, [ebp+arg_4]
                mov     [eax], edx
                mov     eax, [ebp+arg_0]
                mov     edx, [ebp+arg_8]
                mov     [eax+4], edx
                pop     ebp
                retn
_ZN1cC1Eii      endp
```

This is a function, the analog of which can look like this:

```
void ZN1cC1Eii (int *obj, int a, int b)
{
  *obj=a;
  *(obj+1)=b;
};
```

…and that is completely predictable.

Now the `dump()` function:

```
                public _ZN1c4dumpEv
_ZN1c4dumpEv    proc near

var_18          = dword ptr -18h
var_14          = dword ptr -14h
var_10          = dword ptr -10h
arg_0           = dword ptr  8

                push    ebp
                mov     ebp, esp
                sub     esp, 18h
                mov     eax, [ebp+arg_0]
                mov     edx, [eax+4]
                mov     eax, [ebp+arg_0]
                mov     eax, [eax]
                mov     [esp+18h+var_10], edx
                mov     [esp+18h+var_14], eax
                mov     [esp+18h+var_18], offset aDD ; "%d; %d\n"
                call    _printf
                leave
                retn
_ZN1c4dumpEv    endp
```

This function in its *internal representation* has only one argument, used as pointer to the object (*this*).

This function could be rewritten in C like this:

```
void ZN1c4dumpEv (int *obj)
{
  printf ("%d; %d\n", *obj, *(obj+1));
};
```

Thus, if we base our judgment on these simple examples, the difference between MSVC and GCC is the style of the encoding of function names (*name mangling*) and the method for passing a pointer to the object (via the ECX register or via the first argument).

GCC: x86-64

The first 6 arguments, as we already know, are passed in the RDI, RSI, RDX, RCX, R8 and R9 ([Michael Matz, Jan Hubicka, Andreas Jaeger, Mark Mitchell, *System V Application Binary Interface. AMD64 Architecture Processor Supplement*, (2013)] [26]) registers, and the pointer to *this* via the first one (RDI) and that is what we see here. The *int* data type is also 32-bit here.

The JMP instead of RET *hack* is also used here.

Listing 3.87: GCC 4.4.6 x64

```
; default ctor

_ZN1cC2Ev:
    mov  DWORD PTR [rdi], 667
    mov  DWORD PTR [rdi+4], 999
    ret

; c(int a, int b)

_ZN1cC2Eii:
    mov  DWORD PTR [rdi], esi
    mov  DWORD PTR [rdi+4], edx
    ret

; dump()

_ZN1c4dumpEv:
    mov  edx, DWORD PTR [rdi+4]
    mov  esi, DWORD PTR [rdi]
    xor  eax, eax
    mov  edi, OFFSET FLAT:.LC0 ; "%d; %d\n"
    jmp  printf
```

Class inheritance

Inherited classes are similar to the simple structures we already discussed, but extended in inheritable classes.

Let's take this simple example:

```
#include <stdio.h>

class object
{
    public:
        int color;
        object() { };
        object (int color) { this->color=color; };
        void print_color() { printf ("color=%d\n", color); };
};
```

[26] Also available as https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf

```
class box : public object
{
    private:
        int width, height, depth;
    public:
        box(int color, int width, int height, int depth)
        {
            this->color=color;
            this->width=width;
            this->height=height;
            this->depth=depth;
        };
        void dump()
        {
            printf ("this is box. color=%d, width=%d, height=%d, depth=%d\n", color, width, ↙
    ↘ height, depth);
        };
};

class sphere : public object
{
private:
    int radius;
public:
    sphere(int color, int radius)
    {
        this->color=color;
        this->radius=radius;
    };
    void dump()
    {
        printf ("this is sphere. color=%d, radius=%d\n", color, radius);
    };
};

int main()
{
    box b(1, 10, 20, 30);
    sphere s(2, 40);

    b.print_color();
    s.print_color();

    b.dump();
    s.dump();

    return 0;
};
```

Let's investigate the generated code of the `dump()` functions/methods and also `object::print_color()`, and see the memory layout for the structures-objects (for 32-bit code).

So, here are the `dump()` methods for several classes, generated by MSVC 2008 with `/Ox` and `/Ob0` options [27]

Listing 3.88: Optimizing MSVC 2008 /Ob0

```
??_C@_09GCEDOLPA@color?$DN?$CFd?6?$AA@ DB 'color=%d', 0aH, 00H ; `string'
?print_color@object@@QAEXXZ PROC ; object::print_color, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx]
    push eax

; 'color=%d', 0aH, 00H
    push OFFSET ??_C@_09GCEDOLPA@color?$DN?$CFd?6?$AA@
    call _printf
    add  esp, 8
    ret  0
?print_color@object@@QAEXXZ ENDP ; object::print_color
```

[27] The `/Ob0` option stands for disabling inline expansion since function inlining can make our experiment harder

Listing 3.89: Optimizing MSVC 2008 /Ob0

```
?dump@box@@QAEXXZ PROC ; box::dump, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx+12]
    mov  edx, DWORD PTR [ecx+8]
    push eax
    mov  eax, DWORD PTR [ecx+4]
    mov  ecx, DWORD PTR [ecx]
    push edx
    push eax
    push ecx

; 'this is box. color=%d, width=%d, height=%d, depth=%d', 0aH, 00H ; `string'
    push OFFSET ??_C@_0DG@NCNGAADL@this?5is?5box?4?5color?$DN?$CFd?0?5width?$DN?$CFd?0@
    call _printf
    add  esp, 20
    ret  0
?dump@box@@QAEXXZ ENDP ; box::dump
```

Listing 3.90: Optimizing MSVC 2008 /Ob0

```
?dump@sphere@@QAEXXZ PROC ; sphere::dump, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx+4]
    mov  ecx, DWORD PTR [ecx]
    push eax
    push ecx

; 'this is sphere. color=%d, radius=%d', 0aH, 00H
    push OFFSET ??_C@_0CF@EFEDJLDC@this?5is?5sphere?4?5color?$DN?$CFd?0?5radius@
    call _printf
    add  esp, 12
    ret  0
?dump@sphere@@QAEXXZ ENDP ; sphere::dump
```

So, here is the memory layout:

(base class *object*)

offset	description
+0x0	int color

(inherited classes)

box:

offset	description
+0x0	int color
+0x4	int width
+0x8	int height
+0xC	int depth

sphere:

offset	description
+0x0	int color
+0x4	int radius

Let's see `main()` function body:

Listing 3.91: Optimizing MSVC 2008 /Ob0

```
PUBLIC _main
_TEXT SEGMENT
_s$ = -24 ; size = 8
_b$ = -16 ; size = 16
_main PROC
    sub  esp, 24
    push 30
    push 20
    push 10
    push 1
```

```
    lea  ecx, DWORD PTR _b$[esp+40]
    call ??0box@@QAE@HHHH@Z ; box::box
    push 40
    push 2
    lea  ecx, DWORD PTR _s$[esp+32]
    call ??0sphere@@QAE@HH@Z ; sphere::sphere
    lea  ecx, DWORD PTR _b$[esp+24]
    call ?print_color@object@@QAEXXZ ; object::print_color
    lea  ecx, DWORD PTR _s$[esp+24]
    call ?print_color@object@@QAEXXZ ; object::print_color
    lea  ecx, DWORD PTR _b$[esp+24]
    call ?dump@box@@QAEXXZ ; box::dump
    lea  ecx, DWORD PTR _s$[esp+24]
    call ?dump@sphere@@QAEXXZ ; sphere::dump
    xor  eax, eax
    add  esp, 24
    ret  0
_main ENDP
```

The inherited classes must always add their fields after the base classes' fields, to make it possible for the base class methods to work with their own fields.

When the `object::print_color()` method is called, a pointers to both the *box* and *sphere* objects are passed as `this`, and it can work with these objects easily since the *color* field in these objects is always at the pinned address (at offset *+0x0*).

It can be said that the `object::print_color()` method is agnostic in relation to the input object type as long as the fields are *pinned* at the same addresses, and this condition is always true.

And if you create inherited class of the *box* class, the compiler will add the new fields after the *depth* field, leaving the *box* class fields at the pinned addresses.

Thus, the `box::dump()` method will work fine for accessing the *color*, *width*, *height* and *depths* fields, which are always pinned at known addresses.

The code generated by GCC is almost the same, with the sole exception of passing the `this` pointer (as it has been explained above, it is passed as the first argument instead of using the ECX register.

Encapsulation

Encapsulation is hiding the data in the *private* sections of the class, e.g. to allow access to them only from this class methods.

However, are there any marks in code the about the fact that some field is private and some other—not?

No, there are no such marks.

Let's try this simple example:

```
#include <stdio.h>

class box
{
    private:
        int color, width, height, depth;
    public:
        box(int color, int width, int height, int depth)
        {
            this->color=color;
            this->width=width;
            this->height=height;
            this->depth=depth;
        };
        void dump()
        {
            printf ("this is box. color=%d, width=%d, height=%d, depth=%d\n", color, width, ↙
    ↘ height, depth);
        };
};
```

Let's compile it again in MSVC 2008 with /Ox and /Ob0 options and see the box::dump() method code:

```
?dump@box@@QAEXXZ PROC ; box::dump, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx+12]
    mov  edx, DWORD PTR [ecx+8]
    push eax
    mov  eax, DWORD PTR [ecx+4]
    mov  ecx, DWORD PTR [ecx]
    push edx
    push eax
    push ecx
; 'this is box. color=%d, width=%d, height=%d, depth=%d', 0aH, 00H
    push OFFSET ??_C@_0DG@NCNGAADL@this?5is?5box?4?5color?$DN?$CFd?0?5width?$DN?$CFd?0@
    call _printf
    add  esp, 20
    ret  0
?dump@box@@QAEXXZ ENDP ; box::dump
```

Here is a memory layout of the class:

offset	description
+0x0	int color
+0x4	int width
+0x8	int height
+0xC	int depth

All fields are private and not allowed to be accessed from any other function, but knowing this layout, can we create code that modifies these fields?

To do this we'll add the hack_oop_encapsulation() function, which is not going to compile if it looked like this:

```
void hack_oop_encapsulation(class box * o)
{
    o->width=1; // that code can't be compiled':
                // "error C2248: 'box::width' : cannot access private member declared in class ↙
    ↘ 'box'"
};
```

Nevertheless, if we cast the *box* type to a *pointer to an int array*, and we modify the array of *int*-s that we have, we can succeed.

```
void hack_oop_encapsulation(class box * o)
{
    unsigned int *ptr_to_object=reinterpret_cast<unsigned int*>(o);
    ptr_to_object[1]=123;
};
```

This function's code is very simple—it can be said that the function takes a pointer to an array of *int*-s for input and writes *123* to the second *int*:

```
?hack_oop_encapsulation@@YAXPAVbox@@@Z PROC ; hack_oop_encapsulation
    mov eax, DWORD PTR _o$[esp-4]
    mov DWORD PTR [eax+4], 123
    ret 0
?hack_oop_encapsulation@@YAXPAVbox@@@Z ENDP ; hack_oop_encapsulation
```

Let's check how it works:

```
int main()
{
    box b(1, 10, 20, 30);

    b.dump();

    hack_oop_encapsulation(&b);

    b.dump();

```

```
    return 0;
};
```

Let's run:

```
this is box. color=1, width=10, height=20, depth=30
this is box. color=1, width=123, height=20, depth=30
```

We see that the encapsulation is just protection of class fields only in the compilation stage.

The C++ compiler is not allowing the generation of code that modifies protected fields straightforwardly, nevertheless, it is possible with the help of *dirty hacks*.

Multiple inheritance

Multiple inheritance is creating a class which inherits fields and methods from two or more classes.

Let's write a simple example again:

```
#include <stdio.h>

class box
{
    public:
        int width, height, depth;
        box() { };
        box(int width, int height, int depth)
        {
            this->width=width;
            this->height=height;
            this->depth=depth;
        };
        void dump()
        {
            printf ("this is box. width=%d, height=%d, depth=%d\n", width, height, depth);
        };
        int get_volume()
        {
            return width * height * depth;
        };
};

class solid_object
{
    public:
        int density;
        solid_object() { };
        solid_object(int density)
        {
            this->density=density;
        };
        int get_density()
        {
            return density;
        };
        void dump()
        {
            printf ("this is solid_object. density=%d\n", density);
        };
};

class solid_box: box, solid_object
{
    public:
        solid_box (int width, int height, int depth, int density)
        {
            this->width=width;
            this->height=height;
            this->depth=depth;
```

```
            this->density=density;
        };
        void dump()
        {
            printf ("this is solid_box. width=%d, height=%d, depth=%d, density=%d\n", width, ↙
    ↘ height, depth, density);
        };
        int get_weight() { return get_volume() * get_density(); };
};

int main()
{
    box b(10, 20, 30);
    solid_object so(100);
    solid_box sb(10, 20, 30, 3);

    b.dump();
    so.dump();
    sb.dump();
    printf ("%d\n", sb.get_weight());

    return 0;
};
```

Let's compile it in MSVC 2008 with the `/Ox` and `/Ob0` options and see the code of `box::dump()`, `solid_object::dump()` and `solid_box::dump()`:

Listing 3.92: Optimizing MSVC 2008 /Ob0

```
?dump@box@@QAEXXZ PROC ; box::dump, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx+8]
    mov  edx, DWORD PTR [ecx+4]
    push eax
    mov  eax, DWORD PTR [ecx]
    push edx
    push eax
; 'this is box. width=%d, height=%d, depth=%d', 0aH, 00H
    push OFFSET ??_C@_0CM@DIKPHDFI@this?5is?5box?4?5width?$DN?$CFd?0?5height?$DN?$CFd@
    call _printf
    add  esp, 16
    ret  0
?dump@box@@QAEXXZ ENDP ; box::dump
```

Listing 3.93: Optimizing MSVC 2008 /Ob0

```
?dump@solid_object@@QAEXXZ PROC ; solid_object::dump, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx]
    push eax
; 'this is solid_object. density=%d', 0aH
    push OFFSET ??_C@_0CC@KICFJINL@this?5is?5solid_object?4?5density?$DN?$CFd@
    call _printf
    add  esp, 8
    ret  0
?dump@solid_object@@QAEXXZ ENDP ; solid_object::dump
```

Listing 3.94: Optimizing MSVC 2008 /Ob0

```
?dump@solid_box@@QAEXXZ PROC ; solid_box::dump, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx+12]
    mov  edx, DWORD PTR [ecx+8]
    push eax
    mov  eax, DWORD PTR [ecx+4]
    mov  ecx, DWORD PTR [ecx]
    push edx
    push eax
    push ecx
; 'this is solid_box. width=%d, height=%d, depth=%d, density=%d', 0aH
```

```
    push OFFSET ??_C@_0DO@HNCNIHNN@this?5is?5solid_box?4?5width?$DN?$CFd?0?5hei@
    call _printf
    add  esp, 20
    ret  0
?dump@solid_box@@QAEXXZ ENDP ; solid_box::dump
```

So, the memory layout for all three classes is:

box class:

offset	description
+0x0	width
+0x4	height
+0x8	depth

solid_object class:

offset	description
+0x0	density

It can be said that the *solid_box* class memory layout is *united*:

solid_box class:

offset	description
+0x0	width
+0x4	height
+0x8	depth
+0xC	density

The code of the `box::get_volume()` and `solid_object::get_density()` methods is trivial:

Listing 3.95: Optimizing MSVC 2008 /Ob0

```
?get_volume@box@@QAEHXZ PROC ; box::get_volume, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx+8]
    imul eax, DWORD PTR [ecx+4]
    imul eax, DWORD PTR [ecx]
    ret  0
?get_volume@box@@QAEHXZ ENDP ; box::get_volume
```

Listing 3.96: Optimizing MSVC 2008 /Ob0

```
?get_density@solid_object@@QAEHXZ PROC ; solid_object::get_density, COMDAT
; _this$ = ecx
    mov eax, DWORD PTR [ecx]
    ret 0
?get_density@solid_object@@QAEHXZ ENDP ; solid_object::get_density
```

But the code of the `solid_box::get_weight()` method is much more interesting:

Listing 3.97: Optimizing MSVC 2008 /Ob0

```
?get_weight@solid_box@@QAEHXZ PROC ; solid_box::get_weight, COMDAT
; _this$ = ecx
    push esi
    mov  esi, ecx
    push edi
    lea  ecx, DWORD PTR [esi+12]
    call ?get_density@solid_object@@QAEHXZ ; solid_object::get_density
    mov  ecx, esi
    mov  edi, eax
    call ?get_volume@box@@QAEHXZ ; box::get_volume
    imul eax, edi
    pop  edi
    pop  esi
    ret  0
?get_weight@solid_box@@QAEHXZ ENDP ; solid_box::get_weight
```

`get_weight()` just calls two methods, but for `get_volume()` it just passes pointer to `this`, and for `get_density()` it passes a pointer to `this` incremented by 12 (or `0xC`) bytes, and there, in the `solid_box` class memory layout, the fields of the `solid_object` class start.

Thus, the `solid_object::get_density()` method will believe like it is dealing with the usual `solid_object` class, and the `box::get_volume()` method will work with its three fields, believing this is just the usual object of class box.

Thus, we can say, an object of a class, that inherits from several other classes, is representing in memory as a *united* class, that contains all inherited fields. And each inherited method is called with a pointer to the corresponding structure's part.

Virtual methods

Yet another simple example:

```
#include <stdio.h>

class object
{
    public:
        int color;
        object() { };
        object (int color) { this->color=color; };
        virtual void dump()
        {
            printf ("color=%d\n", color);
        };
};

class box : public object
{
    private:
        int width, height, depth;
    public:
        box(int color, int width, int height, int depth)
        {
            this->color=color;
            this->width=width;
            this->height=height;
            this->depth=depth;
        };
        void dump()
        {
            printf ("this is box. color=%d, width=%d, height=%d, depth=%d\n", color, width, ↙
    ↘ height, depth);
        };
};

class sphere : public object
{
    private:
        int radius;
    public:
        sphere(int color, int radius)
        {
            this->color=color;
            this->radius=radius;
        };
        void dump()
        {
            printf ("this is sphere. color=%d, radius=%d\n", color, radius);
        };
};

int main()
{
    box b(1, 10, 20, 30);
    sphere s(2, 40);

    object *o1=&b;
    object *o2=&s;
```

```
    o1->dump();
    o2->dump();
    return 0;
};
```

Class *object* has a virtual method `dump()` that is being replaced in the inheriting *box* and *sphere* classes.

If we are in an environment where it is not known the type of an object, as in the `main()` function in example, where the virtual method `dump()` is called, the information about its type must be stored somewhere, to be able to call the relevant virtual method.

Let's compile it in MSVC 2008 with the `/Ox` and `/Ob0` options and see the code of `main()`:

```
_s$ = -32 ; size = 12
_b$ = -20 ; size = 20
_main PROC
    sub  esp, 32
    push 30
    push 20
    push 10
    push 1
    lea  ecx, DWORD PTR _b$[esp+48]
    call ??0box@@QAE@HHHH@Z ; box::box
    push 40
    push 2
    lea  ecx, DWORD PTR _s$[esp+40]
    call ??0sphere@@QAE@HH@Z ; sphere::sphere
    mov  eax, DWORD PTR _b$[esp+32]
    mov  edx, DWORD PTR [eax]
    lea  ecx, DWORD PTR _b$[esp+32]
    call edx
    mov  eax, DWORD PTR _s$[esp+32]
    mov  edx, DWORD PTR [eax]
    lea  ecx, DWORD PTR _s$[esp+32]
    call edx
    xor  eax, eax
    add  esp, 32
    ret  0
_main ENDP
```

A pointer to the `dump()` function is taken somewhere from the object. Where could we store the address of the new method? Only somewhere in the constructors: there is no other place since nothing else is called in the `main()` function. [28]

Let's see the code of the constructor of the *box* class:

```
??_R0?AVbox@@@8 DD FLAT:??_7type_info@@6B@ ; box `RTTI Type Descriptor'
    DD    00H
    DB    '.?AVbox@@', 00H

??_R1A@?0A@EA@box@@8 DD FLAT:??_R0?AVbox@@@8 ; box::`RTTI Base Class Descriptor at (0,-1,0,64)'
    DD    01H
    DD    00H
    DD    0ffffffffH
    DD    00H
    DD    040H
    DD    FLAT:??_R3box@@8

??_R2box@@8 DD    FLAT:??_R1A@?0A@EA@box@@8 ; box::`RTTI Base Class Array'
    DD    FLAT:??_R1A@?0A@EA@object@@8

??_R3box@@8 DD    00H ; box::`RTTI Class Hierarchy Descriptor'
    DD    00H
    DD    02H
    DD    FLAT:??_R2box@@8

??_R4box@@6B@ DD 00H ; box::`RTTI Complete Object Locator'
    DD    00H
    DD    00H
```

[28] You can read more about pointers to functions in the relevant section:(1.27 on page 384)

```
    DD    FLAT:??_R0?AVbox@@@8
    DD    FLAT:??_R3box@@8

??_7box@@6B@ DD    FLAT:??_R4box@@6B@ ; box::`vftable'
    DD    FLAT:?dump@box@@UAEXXZ

_color$ = 8   ; size = 4
_width$ = 12  ; size = 4
_height$ = 16 ; size = 4
_depth$ = 20  ; size = 4
??0box@@QAE@HHHH@Z PROC ; box::box, COMDAT
; _this$ = ecx
    push esi
    mov  esi, ecx
    call ??0object@@QAE@XZ ; object::object
    mov  eax, DWORD PTR _color$[esp]
    mov  ecx, DWORD PTR _width$[esp]
    mov  edx, DWORD PTR _height$[esp]
    mov  DWORD PTR [esi+4], eax
    mov  eax, DWORD PTR _depth$[esp]
    mov  DWORD PTR [esi+16], eax
    mov  DWORD PTR [esi], OFFSET ??_7box@@6B@
    mov  DWORD PTR [esi+8], ecx
    mov  DWORD PTR [esi+12], edx
    mov  eax, esi
    pop  esi
    ret  16
??0box@@QAE@HHHH@Z ENDP ; box::box
```

Here we see a slightly different memory layout: the first field is a pointer to some table `` box::`vftable' `` (the name has been set by the MSVC compiler).

In this table we see a link to a table named `` box::`RTTI Complete Object Locator' `` and also a link to the `box::dump()` method.

These are called virtual methods table and RTTI[29]. The table of virtual methods has the addresses of methods and the RTTI table contains information about types.

By the way, the RTTI tables are used while calling *dynamic_cast* and *typeid* in C++. You can also see here the class name as a plain text string.

Thus, a method of the base *object* class may call the virtual method *object::dump()*, which in turn will call a method of an inherited class, since that information is present right in the object's structure.

Some additional CPU time is needed for doing look-ups in these tables and finding the right virtual method address, thus virtual methods are widely considered as slightly slower than common methods.

In GCC-generated code the RTTI tables are constructed slightly differently.

3.18.2 ostream

Let's start again with a "hello world" example, but now we are going to use *ostream*:

```
#include <iostream>

int main()
{
    std::cout << "Hello, world!\n";
}
```

Almost any C++ textbook tells us that the << operation can be defined (*overloaded*) for other types. That is what is done in *ostream*. We see that `operator<<` is called for *ostream*:

Listing 3.98: MSVC 2012 (reduced listing)

```
$SG37112 DB 'Hello, world!', 0aH, 00H
```

[29] Run-Time Type Information

```
_main PROC
    push OFFSET $SG37112
    push OFFSET ?cout@std@@3V?$basic_ostream@DU?$char_traits@D@std@@@1@A ; std::cout
    call ??$?6U?$char_traits@D@std@@@std@@YAAAV?$basic_ostream@DU?⤦
    ↳ $char_traits@D@std@@@0@AAV10@PBD@Z ; std::operator<<<std::char_traits<char> >
    add  esp, 8
    xor  eax, eax
    ret  0
_main ENDP
```

Let's modify the example:

```
#include <iostream>

int main()
{
    std::cout << "Hello, " << "world!\n";
}
```

And again, from many C++ textbooks we know that the result of each `operator<<` in ostream is forwarded to the next one. Indeed:

Listing 3.99: MSVC 2012

```
$SG37112 DB 'world!', 0aH, 00H
$SG37113 DB 'Hello, ', 00H

_main PROC
    push OFFSET $SG37113 ; 'Hello, '
    push OFFSET ?cout@std@@3V?$basic_ostream@DU?$char_traits@D@std@@@1@A ; std::cout
    call ??$?6U?$char_traits@D@std@@@std@@YAAAV?$basic_ostream@DU?⤦
    ↳ $char_traits@D@std@@@0@AAV10@PBD@Z ; std::operator<<<std::char_traits<char> >
    add  esp, 8

    push OFFSET $SG37112 ; 'world!'
    push eax             ; result of previous function execution
    call ??$?6U?$char_traits@D@std@@@std@@YAAAV?$basic_ostream@DU?⤦
    ↳ $char_traits@D@std@@@0@AAV10@PBD@Z ; std::operator<<<std::char_traits<char> >
    add  esp, 8

    xor  eax, eax
    ret  0
_main ENDP
```

If we would rename `operator<<` method name to `f()`, that code will looks like:

```
f(f(std::cout, "Hello, "), "world!");
```

GCC generates almost the same code as MSVC.

3.18.3 References

In C++, references are pointers (3.21 on page 611) as well, but they are called *safe*, because it is harder to make a mistake while dealing with them (C++11 8.3.2).

For example, reference must always be pointing to an object of the corresponding type and cannot be NULL [Marshall Cline, *C++ FAQ*8.6].

Even more than that, references cannot be changed, it is impossible to point them to another object (reseat) [Marshall Cline, *C++ FAQ*8.5].

If we are going to try to change the example with pointers (3.21 on page 611) to use references instead …

```
void f2 (int x, int y, int & sum, int & product)
{
        sum=x+y;
        product=x*y;
};
```

...then we can see that the compiled code is just the same as in the pointers example (3.21 on page 611):

Listing 3.100: Optimizing MSVC 2010

```
_x$ = 8         ; size = 4
_y$ = 12        ; size = 4
_sum$ = 16      ; size = 4
_product$ = 20  ; size = 4
?f2@@YAXHHAAH0@Z PROC   ; f2
        mov     ecx, DWORD PTR _y$[esp-4]
        mov     eax, DWORD PTR _x$[esp-4]
        lea     edx, DWORD PTR [eax+ecx]
        imul eax, ecx
        mov ecx, DWORD PTR _product$[esp-4]
        push esi
        mov     esi, DWORD PTR _sum$[esp]
        mov     DWORD PTR [esi], edx
        mov     DWORD PTR [ecx], eax
        pop     esi
        ret     0
?f2@@YAXHHAAH0@Z ENDP   ; f2
```

(The reason why C++ functions has such strange names is explained here: 3.18.1 on page 542.)

Hence, C++ references are as much efficient as usual pointers.

3.18.4 STL

N.B.: all examples here were checked only in 32-bit environment. x64 wasn't checked.

std::string

Internals

Many string libraries [Dennis Yurichev, *C/C++ programming language notes*2.2] implement a structure that contains a pointer to a string buffer, a variable that always contains the current string length (which is very convenient for many functions: [Dennis Yurichev, *C/C++ programming language notes*2.2.1]) and a variable containing the current buffer size.

The string in the buffer is usually terminated with zero, in order to be able to pass a pointer to the buffer into the functions that take usual C ASCIIZ strings.

It is not specified in the C++ standard how std::string has to be implemented, however, it is usually implemented as explained above.

The C++ string is not a class (as QString in Qt, for instance) but a template (basic_string), this is made in order to support various character types: at least *char* and *wchar_t*.

So, std::string is a class with *char* as its base type.

And std::wstring is a class with *wchar_t* as its base type.

MSVC

The MSVC implementation may store the buffer in place instead of using a pointer to a buffer (if the string is shorter than 16 symbols).

This implies that a short string is to occupy at least $16 + 4 + 4 = 24$ bytes in 32-bit environment or at least $16 + 8 + 8 = 32$

bytes in 64-bit one, and if the string is longer than 16 characters, we also have to add the length of the string itself.

Listing 3.101: example for MSVC

```
#include <string>
#include <stdio.h>
```

```
struct std_string
{
    union
    {
        char buf[16];
        char* ptr;
    } u;
    size_t size;     // AKA 'Mysize' in MSVC
    size_t capacity; // AKA 'Myres' in MSVC
};

void dump_std_string(std::string s)
{
    struct std_string *p=(struct std_string*)&s;
    printf ("[%s] size:%d capacity:%d\n", p->size>16 ? p->u.ptr : p->u.buf, p->size, p->↙
    ↘ capacity);
};

int main()
{
    std::string s1="short string";
    std::string s2="string longer that 16 bytes";

    dump_std_string(s1);
    dump_std_string(s2);

    // that works without using c_str()
    printf ("%s\n", &s1);
    printf ("%s\n", s2);
};
```

Almost everything is clear from the source code.

A couple of notes:

If the string is shorter than 16 symbols, a buffer for the string is not to be allocated in the heap.

This is convenient because in practice, a lot of strings are short indeed.

Looks like that Microsoft's developers chose 16 characters as a good balance.

One very important thing here can be seen at the end of main(): we're not using the c_str() method, nevertheless, if we compile and run this code, both strings will appear in the console!

This is why it works.

In the first case the string is shorter than 16 characters and the buffer with the string is located in the beginning of the std::string object (it can be treated as a structure). printf() treats the pointer as a pointer to the null-terminated array of characters, hence it works.

Printing the second string (longer than 16 characters) is even more dangerous: it is a typical programmer's mistake (or typo) to forget to write c_str().

This works because at the moment a pointer to buffer is located at the start of structure.

This may stay unnoticed for a long time, until a longer string appears there at some time, then the process will crash.

GCC

GCC's implementation of this structure has one more variable—reference count.

One interesting fact is that in GCC a pointer an instance of std::string instance points not to the beginning of the structure, but to the buffer pointer. In *libstdc++-v3\include\bits\basic_string.h* we can read that it was done for more convenient debugging:

```
   *  The reason you want _M_data pointing to the character %array and
   *  not the _Rep is so that the debugger can see the string
   *  contents. (Probably we should add a non-inline member to get
   *  the _Rep for the debugger to use, so users can check the actual
```

```
    *  string length.)
```

basic_string.h source code

We consider this in our example:

Listing 3.102: example for GCC

```
#include <string>
#include <stdio.h>

struct std_string
{
    size_t length;
    size_t capacity;
    size_t refcount;
};

void dump_std_string(std::string s)
{
    char *p1=*(char**)&s; // GCC type checking workaround
    struct std_string *p2=(struct std_string*)(p1-sizeof(struct std_string));
    printf ("[%s] size:%d capacity:%d\n", p1, p2->length, p2->capacity);
};

int main()
{
    std::string s1="short string";
    std::string s2="string longer that 16 bytes";

    dump_std_string(s1);
    dump_std_string(s2);

    // GCC type checking workaround:
    printf ("%s\n", *(char**)&s1);
    printf ("%s\n", *(char**)&s2);
};
```

A trickery has to be used to imitate the mistake we already have seen above because GCC has stronger type checking, nevertheless, printf() works here without c_str() as well.

A more advanced example

```
#include <string>
#include <stdio.h>

int main()
{
    std::string s1="Hello, ";
    std::string s2="world!\n";
    std::string s3=s1+s2;

    printf ("%s\n", s3.c_str());
}
```

Listing 3.103: MSVC 2012

```
$SG39512 DB 'Hello, ', 00H
$SG39514 DB 'world!', 0aH, 00H
$SG39581 DB '%s', 0aH, 00H

_s2$ = -72 ; size = 24
_s3$ = -48 ; size = 24
_s1$ = -24 ; size = 24
_main PROC
    sub  esp, 72

    push 7
```

```
    push OFFSET $SG39512
    lea  ecx, DWORD PTR _s1$[esp+80]
    mov  DWORD PTR _s1$[esp+100], 15
    mov  DWORD PTR _s1$[esp+96], 0
    mov  BYTE PTR _s1$[esp+80], 0
    call ?assign@?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@QAEAAV12@PBDI@Z ;↙
    ↳  std::basic_string<char,std::char_traits<char>,std::allocator<char> >::assign

    push 7
    push OFFSET $SG39514
    lea  ecx, DWORD PTR _s2$[esp+80]
    mov  DWORD PTR _s2$[esp+100], 15
    mov  DWORD PTR _s2$[esp+96], 0
    mov  BYTE PTR _s2$[esp+80], 0
    call ?assign@?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@QAEAAV12@PBDI@Z ;↙
    ↳  std::basic_string<char,std::char_traits<char>,std::allocator<char> >::assign

    lea  eax, DWORD PTR _s2$[esp+72]
    push eax
    lea  eax, DWORD PTR _s1$[esp+76]
    push eax
    lea  eax, DWORD PTR _s3$[esp+80]
    push eax
    call ??$?HDU?$char_traits@D@std@@V?$allocator@D@1@@std@@YA?AV?$basic_string@DU?↙
    ↳ $char_traits@D@std@@V?$allocator@D@2@@0@ABV10@0@Z ; std::operator+<char,std::char_traits<↙
    ↳ char>,std::allocator<char> >

    ; inlined c_str() method:
    cmp  DWORD PTR _s3$[esp+104], 16
    lea  eax, DWORD PTR _s3$[esp+84]
    cmovae eax, DWORD PTR _s3$[esp+84]

    push eax
    push OFFSET $SG39581
    call _printf
    add  esp, 20

    cmp  DWORD PTR _s3$[esp+92], 16
    jb   SHORT $LN119@main
    push DWORD PTR _s3$[esp+72]
    call ??3@YAXPAX@Z                ; operator delete
    add  esp, 4
$LN119@main:
    cmp  DWORD PTR _s2$[esp+92], 16
    mov  DWORD PTR _s3$[esp+92], 15
    mov  DWORD PTR _s3$[esp+88], 0
    mov  BYTE PTR _s3$[esp+72], 0
    jb   SHORT $LN151@main
    push DWORD PTR _s2$[esp+72]
    call ??3@YAXPAX@Z                ; operator delete
    add  esp, 4
$LN151@main:
    cmp  DWORD PTR _s1$[esp+92], 16
    mov  DWORD PTR _s2$[esp+92], 15
    mov  DWORD PTR _s2$[esp+88], 0
    mov  BYTE PTR _s2$[esp+72], 0
    jb   SHORT $LN195@main
    push DWORD PTR _s1$[esp+72]
    call ??3@YAXPAX@Z                ; operator delete
    add  esp, 4
$LN195@main:
    xor  eax, eax
    add  esp, 72
    ret  0
_main ENDP
```

The compiler does not construct strings statically: it would not be possible anyway if the buffer needs to be located in the heap.

Instead, the ASCIIZ strings are stored in the data segment, and later, at runtime, with the help of the “assign” method, the s1 and s2 strings are constructed. And with the help of `operator+`, the s3 string is constructed.

Please note that there is no call to the c_str() method, because its code is tiny enough so the compiler inlined it right there: if the string is shorter than 16 characters, a pointer to buffer is left in EAX, otherwise the address of the string buffer located in the heap is fetched.

Next, we see calls to the 3 destructors, they are called if the string is longer than 16 characters: then the buffers in the heap have to be freed. Otherwise, since all three std::string objects are stored in the stack, they are freed automatically, when the function ends.

As a consequence, processing short strings is faster, because of less heap accesses.

GCC code is even simpler (because the GCC way, as we saw above, is to not store shorter strings right in the structure):

Listing 3.104: GCC 4.8.1

```
.LC0:
    .string "Hello, "
.LC1:
    .string "world!\n"
main:
    push ebp
    mov  ebp, esp
    push edi
    push esi
    push ebx
    and  esp, -16
    sub  esp, 32
    lea  ebx, [esp+28]
    lea  edi, [esp+20]
    mov  DWORD PTR [esp+8], ebx
    lea  esi, [esp+24]
    mov  DWORD PTR [esp+4], OFFSET FLAT:.LC0
    mov  DWORD PTR [esp], edi

    call _ZNSsC1EPKcRKSaIcE

    mov  DWORD PTR [esp+8], ebx
    mov  DWORD PTR [esp+4], OFFSET FLAT:.LC1
    mov  DWORD PTR [esp], esi

    call _ZNSsC1EPKcRKSaIcE

    mov  DWORD PTR [esp+4], edi
    mov  DWORD PTR [esp], ebx

    call _ZNSsC1ERKSs

    mov  DWORD PTR [esp+4], esi
    mov  DWORD PTR [esp], ebx

    call _ZNSs6appendERKSs

    ; inlined c_str():
    mov  eax, DWORD PTR [esp+28]
    mov  DWORD PTR [esp], eax

    call puts

    mov  eax, DWORD PTR [esp+28]
    lea  ebx, [esp+19]
    mov  DWORD PTR [esp+4], ebx
    sub  eax, 12
    mov  DWORD PTR [esp], eax
    call _ZNSs4_Rep10_M_disposeERKSaIcE
    mov  eax, DWORD PTR [esp+24]
    mov  DWORD PTR [esp+4], ebx
    sub  eax, 12
    mov  DWORD PTR [esp], eax
    call _ZNSs4_Rep10_M_disposeERKSaIcE
```

```
    mov  eax, DWORD PTR [esp+20]
    mov  DWORD PTR [esp+4], ebx
    sub  eax, 12
    mov  DWORD PTR [esp], eax
    call _ZNSs4_Rep10_M_disposeERKSaIcE
    lea  esp, [ebp-12]
    xor  eax, eax
    pop  ebx
    pop  esi
    pop  edi
    pop  ebp
    ret
```

It can be seen that it's not a pointer to the object that is passed to destructors, but rather an address 12 bytes (or 3 words) before, i.e., a pointer to the real start of the structure.

std::string as a global variable

Experienced C++ programmers knows that global variables of STL[30] types can be defined without problems.

Yes, indeed:

```
#include <stdio.h>
#include <string>

std::string s="a string";

int main()
{
    printf ("%s\n", s.c_str());
};
```

But how and where `std::string` constructor will be called?

In fact, this variable is to be initialized even before `main()` start.

Listing 3.105: MSVC 2012: here is how a global variable is constructed and also its destructor is registered

```
??__Es@@YAXXZ PROC
    push 8
    push OFFSET $SG39512 ; 'a string'
    mov  ecx, OFFSET ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A ; s
    call ?assign@?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@QAEAAV12@PBDI@Z ;↙
    ↘ std::basic_string<char,std::char_traits<char>,std::allocator<char> >::assign
    push OFFSET ??__Fs@@YAXXZ ; `dynamic atexit destructor for 's''
    call _atexit
    pop  ecx
    ret  0
??__Es@@YAXXZ ENDP
```

Listing 3.106: MSVC 2012: here a global variable is used in `main()`

```
$SG39512 DB 'a string', 00H
$SG39519 DB '%s', 0aH, 00H

_main PROC
    cmp  DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A+20, 16
    mov  eax, OFFSET ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A ; s
    cmovae eax, DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A
    push eax
    push OFFSET $SG39519 ; '%s'
    call _printf
    add  esp, 8
    xor  eax, eax
    ret  0
_main ENDP
```

[30] (C++) Standard Template Library

Listing 3.107: MSVC 2012: this destructor function is called before exit

```
??__Fs@@YAXXZ PROC
    push ecx
    cmp  DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A+20, 16
    jb   SHORT $LN23@dynamic
    push esi
    mov  esi, DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A
    lea  ecx, DWORD PTR $T2[esp+8]
    call ??0?$_Wrap_alloc@V?$allocator@D@std@@@std@@QAE@XZ
    push OFFSET ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A ; s
    lea  ecx, DWORD PTR $T2[esp+12]
    call ??$destroy@PAD@?$_Wrap_alloc@V?$allocator@D@std@@@std@@QAEXPAPAD@Z
    lea  ecx, DWORD PTR $T1[esp+8]
    call ??0?$_Wrap_alloc@V?$allocator@D@std@@@std@@QAE@XZ
    push esi
    call ??3@YAXPAX@Z ; operator delete
    add  esp, 4
    pop  esi
$LN23@dynamic:
    mov  DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A+20, 15
    mov  DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A+16, 0
    mov  BYTE PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A, 0
    pop  ecx
    ret  0
??__Fs@@YAXXZ ENDP
```

In fact, a special function with all constructors of global variables is called from CRT, before main().

More than that: with the help of atexit() another function is registered, which contain calls to all destructors of such global variables.

GCC works likewise:

Listing 3.108: GCC 4.8.1

```
main:
    push ebp
    mov  ebp, esp
    and  esp, -16
    sub  esp, 16
    mov  eax, DWORD PTR s
    mov  DWORD PTR [esp], eax
    call puts
    xor  eax, eax
    leave
    ret
.LC0:
    .string "a string"
_GLOBAL__sub_I_s:
    sub  esp, 44
    lea  eax, [esp+31]
    mov  DWORD PTR [esp+8], eax
    mov  DWORD PTR [esp+4], OFFSET FLAT:.LC0
    mov  DWORD PTR [esp], OFFSET FLAT:s
    call _ZNSsC1EPKcRKSaIcE
    mov  DWORD PTR [esp+8], OFFSET FLAT:__dso_handle
    mov  DWORD PTR [esp+4], OFFSET FLAT:s
    mov  DWORD PTR [esp], OFFSET FLAT:_ZNSsD1Ev
    call __cxa_atexit
    add  esp, 44
    ret
.LFE645:
    .size  _GLOBAL__sub_I_s, .-_GLOBAL__sub_I_s
    .section .init_array,"aw"
    .align 4
    .long  _GLOBAL__sub_I_s
    .globl s
    .bss
    .align 4
    .type  s, @object
    .size  s, 4
```

```
s:
    .zero  4
    .hidden __dso_handle
```

But it does not create a separate function for this, each destructor is passed to atexit(), one by one.

std::list

This is the well-known doubly-linked list: each element has two pointers, to the previous and next elements.

This implies that the memory footprint is enlarged by 2 words for each element (8 bytes in 32-bit environment or 16 bytes in 64-bit).

C++ STL just adds the “next” and “previous” pointers to the existing structure of the type that you want to unite in a list.

Let’s work out an example with a simple 2-variable structure that we want to store in a list.

Although the C++ standard does not say how to implement it, both MSVC’s and GCC’s implementations are straightforward and similar, so here is only one source code for both:

```
#include <stdio.h>
#include <list>
#include <iostream>

struct a
{
    int x;
    int y;
};

struct List_node
{
    struct List_node* _Next;
    struct List_node* _Prev;
    int x;
    int y;
};

void dump_List_node (struct List_node *n)
{
    printf ("ptr=0x%p _Next=0x%p _Prev=0x%p x=%d y=%d\n",
        n, n->_Next, n->_Prev, n->x, n->y);
};

void dump_List_vals (struct List_node* n)
{
    struct List_node* current=n;

    for (;;)
    {
        dump_List_node (current);
        current=current->_Next;
        if (current==n) // end
            break;
    };
};

void dump_List_val (unsigned int *a)
{
#ifdef _MSC_VER
    // GCC implementation does not have "size" field
    printf ("_Myhead=0x%p, _Mysize=%d\n", a[0], a[1]);
#endif
    dump_List_vals ((struct List_node*)a[0]);
};

int main()
```

```
{
    std::list<struct a> l;

    printf ("* empty list:\n");
    dump_List_val((unsigned int*)(void*)&l);

    struct a t1;
    t1.x=1;
    t1.y=2;
    l.push_front (t1);
    t1.x=3;
    t1.y=4;
    l.push_front (t1);
    t1.x=5;
    t1.y=6;
    l.push_back (t1);

    printf ("* 3-elements list:\n");
    dump_List_val((unsigned int*)(void*)&l);

    std::list<struct a>::iterator tmp;
    printf ("node at .begin:\n");
    tmp=l.begin();
    dump_List_node ((struct List_node *)*(void**)&tmp);
    printf ("node at .end:\n");
    tmp=l.end();
    dump_List_node ((struct List_node *)*(void**)&tmp);

    printf ("* let's count from the beginning:\n");
    std::list<struct a>::iterator it=l.begin();
    printf ("1st element: %d %d\n", (*it).x, (*it).y);
    it++;
    printf ("2nd element: %d %d\n", (*it).x, (*it).y);
    it++;
    printf ("3rd element: %d %d\n", (*it).x, (*it).y);
    it++;
    printf ("element at .end(): %d %d\n", (*it).x, (*it).y);

    printf ("* let's count from the end:\n");
    std::list<struct a>::iterator it2=l.end();
    printf ("element at .end(): %d %d\n", (*it2).x, (*it2).y);
    it2--;
    printf ("3rd element: %d %d\n", (*it2).x, (*it2).y);
    it2--;
    printf ("2nd element: %d %d\n", (*it2).x, (*it2).y);
    it2--;
    printf ("1st element: %d %d\n", (*it2).x, (*it2).y);

    printf ("removing last element...\n");
    l.pop_back();
    dump_List_val((unsigned int*)(void*)&l);
};
```

GCC

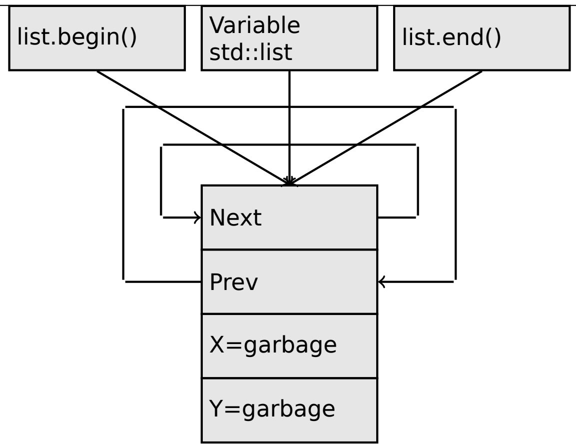
Let's start with GCC.

When we run the example, we'll see a long dump, let's work with it in pieces.

```
* empty list:
ptr=0x0028fe90 _Next=0x0028fe90 _Prev=0x0028fe90 x=3 y=0
```

Here we see an empty list.

Despite the fact it is empty, it has one element with garbage (AKA *dummy node*) in x and y. Both the "next" and "prev" pointers are pointing to the self node:



At this moment, the .begin and .end iterators are equal to each other.

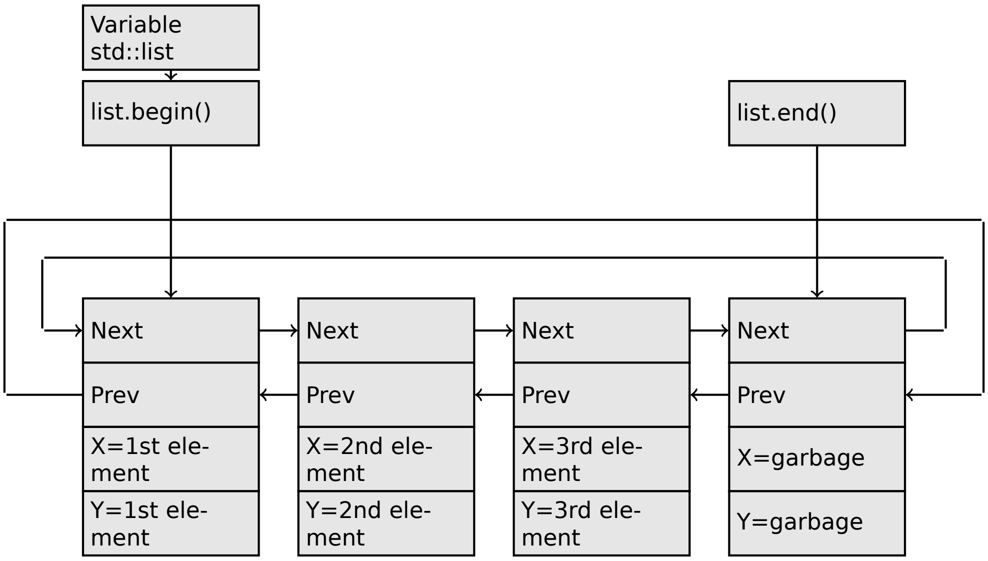
If we push 3 elements, the list internally will be:

```
* 3-elements list:
ptr=0x000349a0 _Next=0x00034988 _Prev=0x0028fe90 x=3 y=4
ptr=0x00034988 _Next=0x00034b40 _Prev=0x000349a0 x=1 y=2
ptr=0x00034b40 _Next=0x0028fe90 _Prev=0x00034988 x=5 y=6
ptr=0x0028fe90 _Next=0x000349a0 _Prev=0x00034b40 x=5 y=6
```

The last element is still at 0x0028fe90, it not to be moved until the list's disposal.

It still contain random garbage in x and y (5 and 6). By coincidence, these values are the same as in the last element, but it doesn't mean that they are meaningful.

Here is how these 3 elements are stored in memory:



The l variable always points to the first node.

The .begin() and .end() iterators are not variables, but functions, which when called return pointers to the corresponding nodes.

Having a dummy element (AKA *sentinel node*) is a very popular practice in implementing doubly-linked lists.

Without it, a lot of operations may become slightly more complex and, hence, slower.

The iterator is in fact just a pointer to a node. list.begin() and list.end() just return pointers.

```
node at .begin:
ptr=0x000349a0 _Next=0x00034988 _Prev=0x0028fe90 x=3 y=4
node at .end:
ptr=0x0028fe90 _Next=0x000349a0 _Prev=0x00034b40 x=5 y=6
```

The fact that the last element has a pointer to the first and the first element has a pointer to the last one remind us of circular lists.

This is very helpful here: having a pointer to the first list element, i.e., that is in the l variable, it is easy to get a pointer to the last one quickly, without the necessity to traverse the whole list.

Inserting an element at the end of the list is also quick, thanks to this feature.

`operator--` and `operator++` just set the current iterator's value to the `current_node->prev` or `current_node->next` values.

The reverse iterators (.rbegin, .rend) work just as the same, but in reverse.

`operator*` just returns a pointer to the point in the node structure, where the user's structure starts, i.e., a pointer to the first element of the structure (x).

The list insertion and deletion are trivial: just allocate a new node (or deallocate) and update all pointers to be valid.

That's why an iterator may become invalid after element deletion: it may still point to the node that has been already deallocated. This is also called a *dangling pointer*.

And of course, the information from the freed node (to which iterator still points) cannot be used anymore.

The GCC implementation (as of 4.8.1) doesn't store the current size of the list: this implies a slow .size() method: it has to traverse the whole list to count the elements, because it doesn't have any other way to get the information.

This means that this operation is $O(n)$, i.e., it steadily gets slower as the list grows.

Listing 3.109: Optimizing GCC 4.8.1 -fno-inline-small-functions

```
main proc near
    push ebp
    mov  ebp, esp
    push esi
    push ebx
    and  esp, 0FFFFFFF0h
    sub  esp, 20h
    lea  ebx, [esp+10h]
    mov  dword ptr [esp], offset s ; "* empty list:"
    mov  [esp+10h], ebx
    mov  [esp+14h], ebx
    call puts
    mov  [esp], ebx
    call _Z13dump_List_valPj ; dump_List_val(uint *)
    lea  esi, [esp+18h]
    mov  [esp+4], esi
    mov  [esp], ebx
    mov  dword ptr [esp+18h], 1 ; X for new element
    mov  dword ptr [esp+1Ch], 2 ; Y for new element
    call _ZNSt4listI1aSaIS0_EE10push_frontERKS0_ ; std::list<a,std::allocator<a>>::push_front(a↙
    ↳  const&)
    mov  [esp+4], esi
    mov  [esp], ebx
    mov  dword ptr [esp+18h], 3 ; X for new element
    mov  dword ptr [esp+1Ch], 4 ; Y for new element
    call _ZNSt4listI1aSaIS0_EE10push_frontERKS0_ ; std::list<a,std::allocator<a>>::push_front(a↙
    ↳  const&)
    mov  dword ptr [esp], 10h
    mov  dword ptr [esp+18h], 5 ; X for new element
    mov  dword ptr [esp+1Ch], 6 ; Y for new element
    call _Znwj           ; operator new(uint)
    cmp  eax, 0FFFFFFF8h
    jz   short loc_80002A6
    mov  ecx, [esp+1Ch]
    mov  edx, [esp+18h]
    mov  [eax+0Ch], ecx
    mov  [eax+8], edx

loc_80002A6: ; CODE XREF: main+86
    mov  [esp+4], ebx
    mov  [esp], eax
    call _ZNSt8__detail15_List_node_base7_M_hookEPS0_ ; std::__detail::_List_node_base::_M_hook↙
    ↳ (std::__detail::_List_node_base*)
    mov  dword ptr [esp], offset a3ElementsList ; "* 3-elements list:"
```

```
    call puts
    mov  [esp], ebx
    call _Z13dump_List_valPj ; dump_List_val(uint *)
    mov  dword ptr [esp], offset aNodeAt_begin ; "node at .begin:"
    call puts
    mov  eax, [esp+10h]
    mov  [esp], eax
    call _Z14dump_List_nodeP9List_node ; dump_List_node(List_node *)
    mov  dword ptr [esp], offset aNodeAt_end ; "node at .end:"
    call puts
    mov  [esp], ebx
    call _Z14dump_List_nodeP9List_node ; dump_List_node(List_node *)
    mov  dword ptr [esp], offset aLetSCountFromT ; "* let's count from the beginning:"
    call puts
    mov  esi, [esp+10h]
    mov  eax, [esi+0Ch]
    mov  [esp+0Ch], eax
    mov  eax, [esi+8]
    mov  dword ptr [esp+4], offset a1stElementDD ; "1st element: %d %d\n"
    mov  dword ptr [esp], 1
    mov  [esp+8], eax
    call __printf_chk
    mov  esi, [esi] ; operator++: get ->next pointer
    mov  eax, [esi+0Ch]
    mov  [esp+0Ch], eax
    mov  eax, [esi+8]
    mov  dword ptr [esp+4], offset a2ndElementDD ; "2nd element: %d %d\n"
    mov  dword ptr [esp], 1
    mov  [esp+8], eax
    call __printf_chk
    mov  esi, [esi] ; operator++: get ->next pointer
    mov  eax, [esi+0Ch]
    mov  [esp+0Ch], eax
    mov  eax, [esi+8]
    mov  dword ptr [esp+4], offset a3rdElementDD ; "3rd element: %d %d\n"
    mov  dword ptr [esp], 1
    mov  [esp+8], eax
    call __printf_chk
    mov  eax, [esi] ; operator++: get ->next pointer
    mov  edx, [eax+0Ch]
    mov  [esp+0Ch], edx
    mov  eax, [eax+8]
    mov  dword ptr [esp+4], offset aElementAt_endD ; "element at .end(): %d %d\n"
    mov  dword ptr [esp], 1
    mov  [esp+8], eax
    call __printf_chk
    mov  dword ptr [esp], offset aLetSCountFro_0 ; "* let's count from the end:"
    call puts
    mov  eax, [esp+1Ch]
    mov  dword ptr [esp+4], offset aElementAt_endD ; "element at .end(): %d %d\n"
    mov  dword ptr [esp], 1
    mov  [esp+0Ch], eax
    mov  eax, [esp+18h]
    mov  [esp+8], eax
    call __printf_chk
    mov  esi, [esp+14h]
    mov  eax, [esi+0Ch]
    mov  [esp+0Ch], eax
    mov  eax, [esi+8]
    mov  dword ptr [esp+4], offset a3rdElementDD ; "3rd element: %d %d\n"
    mov  dword ptr [esp], 1
    mov  [esp+8], eax
    call __printf_chk
    mov  esi, [esi+4] ; operator--: get ->prev pointer
    mov  eax, [esi+0Ch]
    mov  [esp+0Ch], eax
    mov  eax, [esi+8]
    mov  dword ptr [esp+4], offset a2ndElementDD ; "2nd element: %d %d\n"
    mov  dword ptr [esp], 1
    mov  [esp+8], eax
```

```
    call __printf_chk
    mov  eax, [esi+4] ; operator--: get ->prev pointer
    mov  edx, [eax+0Ch]
    mov  [esp+0Ch], edx
    mov  eax, [eax+8]
    mov  dword ptr [esp+4], offset a1stElementDD ; "1st element: %d %d\n"
    mov  dword ptr [esp], 1
    mov  [esp+8], eax
    call __printf_chk
    mov  dword ptr [esp], offset aRemovingLastEl ; "removing last element..."
    call puts
    mov  esi, [esp+14h]
    mov  [esp], esi
    call _ZNSt8__detail15_List_node_base9_M_unhookEv ; std::__detail::_List_node_base::↙
    ↳ _M_unhook(void)
    mov  [esp], esi ; void *
    call _ZdlPv ; operator delete(void *)
    mov  [esp], ebx
    call _Z13dump_List_valPj ; dump_List_val(uint *)
    mov  [esp], ebx
    call _ZNSt10_List_baseI1aSaIS0_EE8_M_clearEv ; std::_List_base<a,std::allocator<a>>::↙
    ↳ _M_clear(void)
    lea  esp, [ebp-8]
    xor  eax, eax
    pop  ebx
    pop  esi
    pop  ebp
    retn
main endp
```

Listing 3.110: The whole output

```
* empty list:
ptr=0x0028fe90 _Next=0x0028fe90 _Prev=0x0028fe90 x=3 y=0
* 3-elements list:
ptr=0x000349a0 _Next=0x00034988 _Prev=0x0028fe90 x=3 y=4
ptr=0x00034988 _Next=0x00034b40 _Prev=0x000349a0 x=1 y=2
ptr=0x00034b40 _Next=0x0028fe90 _Prev=0x00034988 x=5 y=6
ptr=0x0028fe90 _Next=0x000349a0 _Prev=0x00034b40 x=5 y=6
node at .begin:
ptr=0x000349a0 _Next=0x00034988 _Prev=0x0028fe90 x=3 y=4
node at .end:
ptr=0x0028fe90 _Next=0x000349a0 _Prev=0x00034b40 x=5 y=6
* let's count from the beginning:
1st element: 3 4
2nd element: 1 2
3rd element: 5 6
element at .end(): 5 6
* let's count from the end:
element at .end(): 5 6
3rd element: 5 6
2nd element: 1 2
1st element: 3 4
removing last element...
ptr=0x000349a0 _Next=0x00034988 _Prev=0x0028fe90 x=3 y=4
ptr=0x00034988 _Next=0x0028fe90 _Prev=0x000349a0 x=1 y=2
ptr=0x0028fe90 _Next=0x000349a0 _Prev=0x00034988 x=5 y=6
```

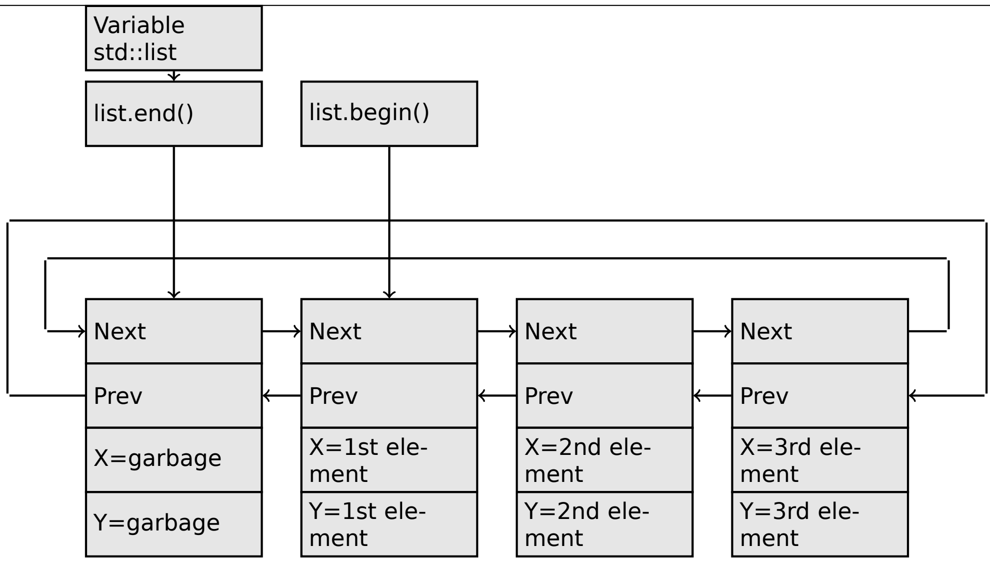
MSVC

MSVC's implementation (2012) is just the same, but it also stores the current size of the list.

This implies that the .size() method is very fast ($O(1)$): it just reads one value from memory.

On the other hand, the size variable must be updated at each insertion/deletion.

MSVC's implementation is also slightly different in the way it arranges the nodes:



GCC has its dummy element at the end of the list, while MSVC's is at the beginning.

Listing 3.111: Optimizing MSVC 2012 /Fa2.asm /GS- /Ob1

```
_l$ = -16 ; size = 8
_t1$ = -8 ; size = 8
_main    PROC
    sub  esp, 16
    push ebx
    push esi
    push edi
    push 0
    push 0
    lea  ecx, DWORD PTR _l$[esp+36]
    mov  DWORD PTR _l$[esp+40], 0
    ; allocate first garbage element
    call ?_Buynode0@?$_List_alloc@$0A@U?$_List_base_types@Ua@@V?↙
    ↳ $allocator@Ua@@@std@@@std@@@std@@QAEPAU?$_List_node@Ua@@PAX@2@PAU32@0@Z ; std::↙
    ↳ _List_alloc<0,std::_List_base_types<a,std::allocator<a> > >::_Buynode0
    mov  edi, DWORD PTR __imp__printf
    mov  ebx, eax
    push OFFSET $SG40685 ; '* empty list:'
    mov  DWORD PTR _l$[esp+32], ebx
    call edi  ; printf
    lea  eax, DWORD PTR _l$[esp+32]
    push eax
    call ?dump_List_val@@YAXPAI@Z ; dump_List_val
    mov  esi, DWORD PTR [ebx]
    add  esp, 8
    lea  eax, DWORD PTR _t1$[esp+28]
    push eax
    push DWORD PTR [esi+4]
    lea  ecx, DWORD PTR _l$[esp+36]
    push esi
    mov  DWORD PTR _t1$[esp+40], 1 ; data for a new node
    mov  DWORD PTR _t1$[esp+44], 2 ; data for a new node
    ; allocate new node
    call ??$_Buynode@ABUa@@@?$_List_buy@Ua@@V?$allocator@Ua@@@std@@@std@@QAEPAU?↙
    ↳ $_List_node@Ua@@PAX@1@PAU21@0ABUa@@@Z ; std::_List_buy<a,std::allocator<a> >::_Buynode<a ↙
    ↳ const &>
    mov  DWORD PTR [esi+4], eax
    mov  ecx, DWORD PTR [eax+4]
    mov  DWORD PTR _t1$[esp+28], 3 ; data for a new node
    mov  DWORD PTR [ecx], eax
    mov  esi, DWORD PTR [ebx]
    lea  eax, DWORD PTR _t1$[esp+28]
    push eax
    push DWORD PTR [esi+4]
    lea  ecx, DWORD PTR _l$[esp+36]
    push esi
    mov  DWORD PTR _t1$[esp+44], 4 ; data for a new node
```

```
    ; allocate new node
    call ??$_Buynode@ABUa@@@?$_List_buy@Ua@@V?$allocator@Ua@@@std@@@std@@QAEPAU?↙
    ↳ $_List_node@Ua@@PAX@1@PAU21@0ABUa@@@Z ; std::_List_buy<a,std::allocator<a> >::_Buynode<a ↙
    ↳ const &>
    mov  DWORD PTR [esi+4], eax
    mov  ecx, DWORD PTR [eax+4]
    mov  DWORD PTR _t1$[esp+28], 5 ; data for a new node
    mov  DWORD PTR [ecx], eax
    lea  eax, DWORD PTR _t1$[esp+28]
    push eax
    push DWORD PTR [ebx+4]
    lea  ecx, DWORD PTR _l$[esp+36]
    push ebx
    mov  DWORD PTR _t1$[esp+44], 6 ; data for a new node
    ; allocate new node
    call ??$_Buynode@ABUa@@@?$_List_buy@Ua@@V?$allocator@Ua@@@std@@@std@@QAEPAU?↙
    ↳ $_List_node@Ua@@PAX@1@PAU21@0ABUa@@@Z ; std::_List_buy<a,std::allocator<a> >::_Buynode<a ↙
    ↳ const &>
    mov  DWORD PTR [ebx+4], eax
    mov  ecx, DWORD PTR [eax+4]
    push OFFSET $SG40689 ; '* 3-elements list:'
    mov  DWORD PTR _l$[esp+36], 3
    mov  DWORD PTR [ecx], eax
    call edi ; printf
    lea  eax, DWORD PTR _l$[esp+32]
    push eax
    call ?dump_List_val@@YAXPAI@Z ; dump_List_val
    push OFFSET $SG40831 ; 'node at .begin:'
    call edi ; printf
    push DWORD PTR [ebx] ; get next field of node $l$ variable points to
    call ?dump_List_node@@YAXPAUList_node@@@Z ; dump_List_node
    push OFFSET $SG40835 ; 'node at .end:'
    call edi ; printf
    push ebx ; pointer to the node "l" variable points to!
    call ?dump_List_node@@YAXPAUList_node@@@Z ; dump_List_node
    push OFFSET $SG40839 ; '* let''s count from the begin:'
    call edi ; printf
    mov  esi, DWORD PTR [ebx] ; operator++: get ->next pointer
    push DWORD PTR [esi+12]
    push DWORD PTR [esi+8]
    push OFFSET $SG40846 ; '1st element: %d %d'
    call edi ; printf
    mov  esi, DWORD PTR [esi] ; operator++: get ->next pointer
    push DWORD PTR [esi+12]
    push DWORD PTR [esi+8]
    push OFFSET $SG40848 ; '2nd element: %d %d'
    call edi ; printf
    mov  esi, DWORD PTR [esi] ; operator++: get ->next pointer
    push DWORD PTR [esi+12]
    push DWORD PTR [esi+8]
    push OFFSET $SG40850 ; '3rd element: %d %d'
    call edi ; printf
    mov  eax, DWORD PTR [esi] ; operator++: get ->next pointer
    add  esp, 64
    push DWORD PTR [eax+12]
    push DWORD PTR [eax+8]
    push OFFSET $SG40852 ; 'element at .end(): %d %d'
    call edi ; printf
    push OFFSET $SG40853 ; '* let''s count from the end:'
    call edi ; printf
    push DWORD PTR [ebx+12] ; use x and y fields from the node "l" variable points to
    push DWORD PTR [ebx+8]
    push OFFSET $SG40860 ; 'element at .end(): %d %d'
    call edi ; printf
    mov  esi, DWORD PTR [ebx+4] ; operator--: get ->prev pointer
    push DWORD PTR [esi+12]
    push DWORD PTR [esi+8]
    push OFFSET $SG40862 ; '3rd element: %d %d'
    call edi ; printf
    mov  esi, DWORD PTR [esi+4] ; operator--: get ->prev pointer
```

```
    push DWORD PTR [esi+12]
    push DWORD PTR [esi+8]
    push OFFSET $SG40864 ; '2nd element: %d %d'
    call edi ; printf
    mov  eax, DWORD PTR [esi+4] ; operator--: get ->prev pointer
    push DWORD PTR [eax+12]
    push DWORD PTR [eax+8]
    push OFFSET $SG40866 ; '1st element: %d %d'
    call edi ; printf
    add  esp, 64
    push OFFSET $SG40867 ; 'removing last element...'
    call edi ; printf
    mov  edx, DWORD PTR [ebx+4]
    add  esp, 4

    ; prev=next?
    ; it is the only element, garbage one?
    ; if yes, do not delete it!
    cmp  edx, ebx
    je   SHORT $LN349@main
    mov  ecx, DWORD PTR [edx+4]
    mov  eax, DWORD PTR [edx]
    mov  DWORD PTR [ecx], eax
    mov  ecx, DWORD PTR [edx]
    mov  eax, DWORD PTR [edx+4]
    push edx
    mov  DWORD PTR [ecx+4], eax
    call ??3@YAXPAX@Z ; operator delete
    add  esp, 4
    mov  DWORD PTR _l$[esp+32], 2
$LN349@main:
    lea  eax, DWORD PTR _l$[esp+28]
    push eax
    call ?dump_List_val@@YAXPAI@Z ; dump_List_val
    mov  eax, DWORD PTR [ebx]
    add  esp, 4
    mov  DWORD PTR [ebx], ebx
    mov  DWORD PTR [ebx+4], ebx
    cmp  eax, ebx
    je   SHORT $LN412@main
$LL414@main:
    mov  esi, DWORD PTR [eax]
    push eax
    call ??3@YAXPAX@Z ; operator delete
    add  esp, 4
    mov  eax, esi
    cmp  esi, ebx
    jne  SHORT $LL414@main
$LN412@main:
    push  ebx
    call  ??3@YAXPAX@Z ; operator delete
    add   esp, 4
    xor   eax, eax
    pop   edi
    pop   esi
    pop   ebx
    add   esp, 16
    ret   0
_main ENDP
```

Unlike GCC, MSVC's code allocates the dummy element at the start of the function with the help of the "Buynode" function, it is also used to allocate the rest of the nodes (GCC's code allocates the first element in the local stack).

Listing 3.112: The whole output

```
* empty list:
_Myhead=0x003CC258, _Mysize=0
ptr=0x003CC258 _Next=0x003CC258 _Prev=0x003CC258 x=6226002 y=4522072
* 3-elements list:
```

```
_Myhead=0x003CC258, _Mysize=3
ptr=0x003CC258 _Next=0x003CC288 _Prev=0x003CC2A0 x=6226002 y=4522072
ptr=0x003CC288 _Next=0x003CC270 _Prev=0x003CC258 x=3 y=4
ptr=0x003CC270 _Next=0x003CC2A0 _Prev=0x003CC288 x=1 y=2
ptr=0x003CC2A0 _Next=0x003CC258 _Prev=0x003CC270 x=5 y=6
node at .begin:
ptr=0x003CC288 _Next=0x003CC270 _Prev=0x003CC258 x=3 y=4
node at .end:
ptr=0x003CC258 _Next=0x003CC288 _Prev=0x003CC2A0 x=6226002 y=4522072
* let's count from the beginning:
1st element: 3 4
2nd element: 1 2
3rd element: 5 6
element at .end(): 6226002 4522072
* let's count from the end:
element at .end(): 6226002 4522072
3rd element: 5 6
2nd element: 1 2
1st element: 3 4
removing last element...
_Myhead=0x003CC258, _Mysize=2
ptr=0x003CC258 _Next=0x003CC288 _Prev=0x003CC270 x=6226002 y=4522072
ptr=0x003CC288 _Next=0x003CC270 _Prev=0x003CC258 x=3 y=4
ptr=0x003CC270 _Next=0x003CC258 _Prev=0x003CC288 x=1 y=2
```

C++11 std::forward_list

The same thing as std::list, but singly-linked one, i.e., having only the “next” field at each node.

It has a smaller memory footprint, but also don’t offer the ability to traverse list backwards.

std::vector

We would call `std::vector` a safe wrapper of the PODT[31] C array. Internally it is somewhat similar to `std::string` (3.18.4 on page 559): it has a pointer to the allocated buffer, a pointer to the end of the array, and a pointer to the end of the allocated buffer.

The array’s elements lie in memory adjacently to each other, just like in a normal array (1.20 on page 267). In C++11 there is a new method called `.data()` , that returns a pointer to the buffer, like `.c_str()` in `std::string`.

The buffer allocated in the heap can be larger than the array itself.

Both MSVC’s and GCC’s implementations are similar, just the names of the structure’s fields are slightly different[32], so here is one source code that works for both compilers. Here is again the C-like code for dumping the structure of `std::vector`:

```
#include <stdio.h>
#include <vector>
#include <algorithm>
#include <functional>

struct vector_of_ints
{
    // MSVC names:
    int *Myfirst;
    int *Mylast;
    int *Myend;

    // GCC structure is the same, but names are: _M_start, _M_finish, _M_end_of_storage
};

void dump(struct vector_of_ints *in)
{
```

[31](C++) Plain Old Data Type
[32]GCC internals: http://go.yurichev.com/17086

```
    printf ("_Myfirst=%p, _Mylast=%p, _Myend=%p\n", in->Myfirst, in->Mylast, in->Myend);
    size_t size=(in->Mylast-in->Myfirst);
    size_t capacity=(in->Myend-in->Myfirst);
    printf ("size=%d, capacity=%d\n", size, capacity);
    for (size_t i=0; i<size; i++)
        printf ("element %d: %d\n", i, in->Myfirst[i]);
};

int main()
{
    std::vector<int> c;
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(1);
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(2);
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(3);
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(4);
    dump ((struct vector_of_ints*)(void*)&c);
    c.reserve (6);
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(5);
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(6);
    dump ((struct vector_of_ints*)(void*)&c);
    printf ("%d\n", c.at(5)); // with bounds checking
    printf ("%d\n", c[8]); // operator[], without bounds checking
};
```

Here is the output of this program when compiled in MSVC:

```
_Myfirst=00000000, _Mylast=00000000, _Myend=00000000
size=0, capacity=0
_Myfirst=0051CF48, _Mylast=0051CF4C, _Myend=0051CF4C
size=1, capacity=1
element 0: 1
_Myfirst=0051CF58, _Mylast=0051CF60, _Myend=0051CF60
size=2, capacity=2
element 0: 1
element 1: 2
_Myfirst=0051C278, _Mylast=0051C284, _Myend=0051C284
size=3, capacity=3
element 0: 1
element 1: 2
element 2: 3
_Myfirst=0051C290, _Mylast=0051C2A0, _Myend=0051C2A0
size=4, capacity=4
element 0: 1
element 1: 2
element 2: 3
element 3: 4
_Myfirst=0051B180, _Mylast=0051B190, _Myend=0051B198
size=4, capacity=6
element 0: 1
element 1: 2
element 2: 3
element 3: 4
_Myfirst=0051B180, _Mylast=0051B194, _Myend=0051B198
size=5, capacity=6
element 0: 1
element 1: 2
element 2: 3
element 3: 4
element 4: 5
_Myfirst=0051B180, _Mylast=0051B198, _Myend=0051B198
size=6, capacity=6
element 0: 1
element 1: 2
element 2: 3
```

```
element 3: 4
element 4: 5
element 5: 6
6
6619158
```

As it can be seen, there is no allocated buffer when `main()` starts. After the first `push_back()` call, a buffer is allocated. And then, after each `push_back()` call, both array size and buffer size (*capacity*) are increased. But the buffer address changes as well, because `push_back()` reallocates the buffer in the heap each time. It is costly operation, that's why it is very important to predict the size of the array in the future and reserve enough space for it with the `.reserve()` method.

The last number is garbage: there are no array elements at this point, so a random number is printed. This illustrates the fact that `operator[]` of `std::vector` does not check of the index is in the array's bounds. The slower `.at()` method, however, does this checking and throws an `std::out_of_range` exception in case of error.

Let's see the code:

Listing 3.113: MSVC 2012 /GS- /Ob1

```
$SG52650 DB '%d', 0aH, 00H
$SG52651 DB '%d', 0aH, 00H

_this$ = -4 ; size = 4
__Pos$ = 8  ; size = 4
?at@?$vector@HV?$allocator@H@std@@@std@@QAEAAHI@Z PROC ; std::vector<int,std::allocator<int> ↙
    ↳ >::at, COMDAT
; _this$ = ecx
    push ebp
    mov  ebp, esp
    push ecx
    mov  DWORD PTR _this$[ebp], ecx
    mov  eax, DWORD PTR _this$[ebp]
    mov  ecx, DWORD PTR _this$[ebp]
    mov  edx, DWORD PTR [eax+4]
    sub  edx, DWORD PTR [ecx]
    sar  edx, 2
    cmp  edx, DWORD PTR __Pos$[ebp]
    ja   SHORT $LN1@at
    push OFFSET ??_C@_0BM@NMJKDPPO@invalid?5vector?$DMT?$DO?5subscript?$AA@
    call DWORD PTR __imp_?_Xout_of_range@std@@YAXPBD@Z
$LN1@at:
    mov  eax, DWORD PTR _this$[ebp]
    mov  ecx, DWORD PTR [eax]
    mov  edx, DWORD PTR __Pos$[ebp]
    lea  eax, DWORD PTR [ecx+edx*4]
$LN3@at:
    mov  esp, ebp
    pop  ebp
    ret  4
?at@?$vector@HV?$allocator@H@std@@@std@@QAEAAHI@Z ENDP ; std::vector<int,std::allocator<int> ↙
    ↳ >::at

_c$ = -36 ; size = 12
$T1 = -24 ; size = 4
$T2 = -20 ; size = 4
$T3 = -16 ; size = 4
$T4 = -12 ; size = 4
$T5 = -8  ; size = 4
$T6 = -4  ; size = 4
_main PROC
    push ebp
    mov  ebp, esp
    sub  esp, 36
    mov  DWORD PTR _c$[ebp], 0     ; Myfirst
    mov  DWORD PTR _c$[ebp+4], 0   ; Mylast
    mov  DWORD PTR _c$[ebp+8], 0   ; Myend
    lea  eax, DWORD PTR _c$[ebp]
    push eax
    call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
```

```
    add  esp, 4
    mov  DWORD PTR $T6[ebp], 1
    lea  ecx, DWORD PTR $T6[ebp]
    push ecx
    lea  ecx, DWORD PTR _c$[ebp]
    call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::↙
    ↳ allocator<int> >::push_back
    lea  edx, DWORD PTR _c$[ebp]
    push edx
    call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
    add  esp, 4
    mov  DWORD PTR $T5[ebp], 2
    lea  eax, DWORD PTR $T5[ebp]
    push eax
    lea  ecx, DWORD PTR _c$[ebp]
    call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::↙
    ↳ allocator<int> >::push_back
    lea  ecx, DWORD PTR _c$[ebp]
    push ecx
    call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
    add  esp, 4
    mov  DWORD PTR $T4[ebp], 3
    lea  edx, DWORD PTR $T4[ebp]
    push edx
    lea  ecx, DWORD PTR _c$[ebp]
    call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::↙
    ↳ allocator<int> >::push_back
    lea  eax, DWORD PTR _c$[ebp]
    push eax
    call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
    add  esp, 4
    mov  DWORD PTR $T3[ebp], 4
    lea  ecx, DWORD PTR $T3[ebp]
    push ecx
    lea  ecx, DWORD PTR _c$[ebp]
    call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::↙
    ↳ allocator<int> >::push_back
    lea  edx, DWORD PTR _c$[ebp]
    push edx
    call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
    add  esp, 4
    push 6
    lea  ecx, DWORD PTR _c$[ebp]
    call ?reserve@?$vector@HV?$allocator@H@std@@@std@@QAEXI@Z ; std::vector<int,std::allocator<↙
    ↳ int> >::reserve
    lea  eax, DWORD PTR _c$[ebp]
    push eax
    call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
    add  esp, 4
    mov  DWORD PTR $T2[ebp], 5
    lea  ecx, DWORD PTR $T2[ebp]
    push ecx
    lea  ecx, DWORD PTR _c$[ebp]
    call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::↙
    ↳ allocator<int> >::push_back
    lea  edx, DWORD PTR _c$[ebp]
    push edx
    call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
    add  esp, 4
    mov  DWORD PTR $T1[ebp], 6
    lea  eax, DWORD PTR $T1[ebp]
    push eax
    lea  ecx, DWORD PTR _c$[ebp]
    call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::↙
    ↳ allocator<int> >::push_back
    lea  ecx, DWORD PTR _c$[ebp]
    push ecx
    call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
    add  esp, 4
    push 5
```

```
    lea  ecx, DWORD PTR _c$[ebp]
    call ?at@?$vector@HV?$allocator@H@std@@@std@@QAEAAHI@Z ; std::vector<int,std::allocator<int⤦
    ↳ > >::at
    mov  edx, DWORD PTR [eax]
    push edx
    push OFFSET $SG52650 ; '%d'
    call DWORD PTR __imp__printf
    add  esp, 8
    mov  eax, 8
    shl  eax, 2
    mov  ecx, DWORD PTR _c$[ebp]
    mov  edx, DWORD PTR [ecx+eax]
    push edx
    push OFFSET $SG52651 ; '%d'
    call DWORD PTR __imp__printf
    add  esp, 8
    lea  ecx, DWORD PTR _c$[ebp]
    call ?_Tidy@?$vector@HV?$allocator@H@std@@@std@@IAEXXZ ; std::vector<int,std::allocator<int⤦
    ↳ > >::_Tidy
    xor  eax, eax
    mov  esp, ebp
    pop  ebp
    ret  0
_main ENDP
```

We see how the `.at()` method checks the bounds and throws an exception in case of error. The number that the last `printf()` call prints is just taken from the memory, without any checks.

One may ask, why not use the variables like "size" and "capacity", like it was done in `std::string`. Supposedly, this was done for faster bounds checking.

The code GCC generates is in general almost the same, but the `.at()` method is inlined:

Listing 3.114: GCC 4.8.1 -fno-inline-small-functions -O1

```
main proc near
     push ebp
     mov  ebp, esp
     push edi
     push esi
     push ebx
     and  esp, 0FFFFFFF0h
     sub  esp, 20h
     mov  dword ptr [esp+14h], 0
     mov  dword ptr [esp+18h], 0
     mov  dword ptr [esp+1Ch], 0
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
     mov  dword ptr [esp+10h], 1
     lea  eax, [esp+10h]
     mov  [esp+4], eax
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(⤦
    ↳ int  const&)
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
     mov  dword ptr [esp+10h], 2
     lea  eax, [esp+10h]
     mov  [esp+4], eax
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(⤦
    ↳ int  const&)
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
     mov  dword ptr [esp+10h], 3
     lea  eax, [esp+10h]
```

```
     mov  [esp+4], eax
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(↙
    ↳ int  const&)
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
     mov  dword ptr [esp+10h], 4
     lea  eax, [esp+10h]
     mov  [esp+4], eax
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(↙
    ↳ int  const&)
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
     mov  ebx, [esp+14h]
     mov  eax, [esp+1Ch]
     sub  eax, ebx
     cmp  eax, 17h
     ja   short loc_80001CF
     mov  edi, [esp+18h]
     sub  edi, ebx
     sar  edi, 2
     mov  dword ptr [esp], 18h
     call _Znwj           ; operator new(uint)
     mov  esi, eax
     test edi, edi
     jz   short loc_80001AD
     lea  eax, ds:0[edi*4]
     mov  [esp+8], eax    ; n
     mov  [esp+4], ebx    ; src
     mov  [esp], esi      ; dest
     call memmove

loc_80001AD: ; CODE XREF: main+F8
     mov  eax, [esp+14h]
     test eax, eax
     jz   short loc_80001BD
     mov  [esp], eax      ; void *
     call _ZdlPv          ; operator delete(void *)

loc_80001BD: ; CODE XREF: main+117
     mov  [esp+14h], esi
     lea  eax, [esi+edi*4]
     mov  [esp+18h], eax
     add  esi, 18h
     mov  [esp+1Ch], esi

loc_80001CF: ; CODE XREF: main+DD
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
     mov  dword ptr [esp+10h], 5
     lea  eax, [esp+10h]
     mov  [esp+4], eax
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(↙
    ↳ int  const&)
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
     mov  dword ptr [esp+10h], 6
     lea  eax, [esp+10h]
     mov  [esp+4], eax
     lea  eax, [esp+14h]
     mov  [esp], eax
```

```
     call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(↙
    ↘ int  const&)
     lea  eax, [esp+14h]
     mov  [esp], eax
     call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
     mov  eax, [esp+14h]
     mov  edx, [esp+18h]
     sub  edx, eax
     cmp  edx, 17h
     ja   short loc_8000246
     mov  dword ptr [esp], offset aVector_m_range ; "vector::_M_range_check"
     call _ZSt20__throw_out_of_rangePKc ; std::__throw_out_of_range(char  const*)

loc_8000246:                        ; CODE XREF: main+19C
     mov  eax, [eax+14h]
     mov  [esp+8], eax
     mov  dword ptr [esp+4], offset aD ; "%d\n"
     mov  dword ptr [esp], 1
     call __printf_chk
     mov  eax, [esp+14h]
     mov  eax, [eax+20h]
     mov  [esp+8], eax
     mov  dword ptr [esp+4], offset aD ; "%d\n"
     mov  dword ptr [esp], 1
     call __printf_chk
     mov  eax, [esp+14h]
     test eax, eax
     jz   short loc_80002AC
     mov  [esp], eax      ; void *
     call _ZdlPv          ; operator delete(void *)
     jmp  short loc_80002AC

     mov  ebx, eax
     mov  edx, [esp+14h]
     test edx, edx
     jz   short loc_80002A4
     mov  [esp], edx      ; void *
     call _ZdlPv          ; operator delete(void *)

loc_80002A4: ; CODE XREF: main+1FE
     mov  [esp], ebx
     call _Unwind_Resume


loc_80002AC: ; CODE XREF: main+1EA
             ; main+1F4
     mov  eax, 0
     lea  esp, [ebp-0Ch]
     pop  ebx
     pop  esi
     pop  edi
     pop  ebp

locret_80002B8: ; DATA XREF: .eh_frame:08000510
                ; .eh_frame:080005BC
     retn
main endp
```

`.reserve()` is inlined as well. It calls `new()` if the buffer is too small for the new size, calls `memmove()` to copy the contents of the buffer, and calls `delete()` to free the old buffer.

Let's also see what the compiled program outputs if compiled with GCC:

```
_Myfirst=0x(nil), _Mylast=0x(nil), _Myend=0x(nil)
size=0, capacity=0
_Myfirst=0x8257008, _Mylast=0x825700c, _Myend=0x825700c
size=1, capacity=1
element 0: 1
_Myfirst=0x8257018, _Mylast=0x8257020, _Myend=0x8257020
size=2, capacity=2
```

```
element 0: 1
element 1: 2
_Myfirst=0x8257028, _Mylast=0x8257034, _Myend=0x8257038
size=3, capacity=4
element 0: 1
element 1: 2
element 2: 3
_Myfirst=0x8257028, _Mylast=0x8257038, _Myend=0x8257038
size=4, capacity=4
element 0: 1
element 1: 2
element 2: 3
element 3: 4
_Myfirst=0x8257040, _Mylast=0x8257050, _Myend=0x8257058
size=4, capacity=6
element 0: 1
element 1: 2
element 2: 3
element 3: 4
_Myfirst=0x8257040, _Mylast=0x8257054, _Myend=0x8257058
size=5, capacity=6
element 0: 1
element 1: 2
element 2: 3
element 3: 4
element 4: 5
_Myfirst=0x8257040, _Mylast=0x8257058, _Myend=0x8257058
size=6, capacity=6
element 0: 1
element 1: 2
element 2: 3
element 3: 4
element 4: 5
element 5: 6
6
0
```

We can spot that the buffer size grows in a different way that in MSVC.

Simple experimentation shows that in MSVC's implementation the buffer grows by ~50% each time it needs to be enlarged, while GCC's code enlarges it by 100% each time, i.e., doubles it.

std::map and std::set

The binary tree is another fundamental data structure.

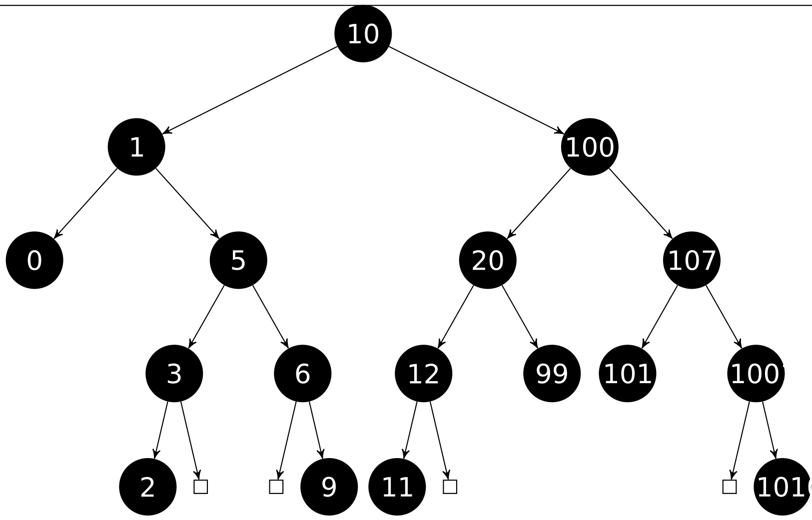
As its name states, this is a tree where each node has at most 2 links to other nodes. Each node has key and/or value: `std::set` provides only key at each node, `std::map` provides both key and value at each node.

Binary trees are usually the structure used in the implementation of "dictionaries" of key-values (AKA "associative arrays").

There are at least three important properties that a binary trees has:

- All keys are always stored in sorted form.
- Keys of any types can be stored easily. Binary tree algorithms are unaware of the key's type, only a key comparison function is required.
- Finding a specific key is relatively fast in comparison with lists and arrays.

Here is a very simple example: let's store these numbers in a binary tree: 0, 1, 2, 3, 5, 6, 9, 10, 11, 12, 20, 99, 100, 101, 107, 1001, 1010.



All keys that are smaller than the node key's value are stored on the left side.

All keys that are bigger than the node key's value are stored on the right side.

Hence, the lookup algorithm is straightforward: if the value that you are looking for is smaller than the current node's key value: move left, if it is bigger: move right, stop if the value required is equal to the node key's value.

That is why the searching algorithm may search for numbers, text strings, etc., as long as a key comparison function is provided.

All keys have unique values.

Having that, one needs $\approx \log_2 n$ steps in order to find a key in a balanced binary tree with n keys. This implies that ≈ 10 steps are needed ≈ 1000 keys, or ≈ 13 steps for ≈ 10000 keys.

Not bad, but the tree has always to be balanced for this: i.e., the keys has to be distributed evenly on all levels. The insertion and removal operations do some maintenance to keep the tree in a balanced state.

There are several popular balancing algorithms available, including the AVL tree and the red-black tree.

The latter extends each node with a "color" value to simplify the balancing process, hence, each node may be "red" or "black".

Both GCC's and MSVC's `std::map` and `std::set` template implementations use red-black trees.

`std::set` has only keys. `std::map` is the "extended" version of std::set: it also has a value at each node.

MSVC

```
#include <map>
#include <set>
#include <string>
#include <iostream>

// Structure is not packed! Each field occupies 4 bytes.
struct tree_node
{
    struct tree_node *Left;
    struct tree_node *Parent;
    struct tree_node *Right;
    char Color; // 0 - Red, 1 - Black
    char Isnil;
    //std::pair Myval;
    unsigned int first; // called Myval in std::set
    const char *second; // not present in std::set
};

struct tree_struct
{
    struct tree_node *Myhead;
    size_t Mysize;
};
```

```
void dump_tree_node (struct tree_node *n, bool is_set, bool traverse)
{
    printf ("ptr=0x%p Left=0x%p Parent=0x%p Right=0x%p Color=%d Isnil=%d\n",
            n, n->Left, n->Parent, n->Right, n->Color, n->Isnil);
    if (n->Isnil==0)
    {
        if (is_set)
            printf ("first=%d\n", n->first);
        else
            printf ("first=%d second=[%s]\n", n->first, n->second);
    }

    if (traverse)
    {
        if (n->Isnil==1)
            dump_tree_node (n->Parent, is_set, true);
        else
        {
            if (n->Left->Isnil==0)
                dump_tree_node (n->Left, is_set, true);
            if (n->Right->Isnil==0)
                dump_tree_node (n->Right, is_set, true);
        };
    };
};

const char* ALOT_OF_TABS="\t\t\t\t\t\t\t\t\t\t\t";

void dump_as_tree (int tabs, struct tree_node *n, bool is_set)
{
    if (is_set)
        printf ("%d\n", n->first);
    else
        printf ("%d [%s]\n", n->first, n->second);
    if (n->Left->Isnil==0)
    {
        printf ("%.*sL-------", tabs, ALOT_OF_TABS);
        dump_as_tree (tabs+1, n->Left, is_set);
    };
    if (n->Right->Isnil==0)
    {
        printf ("%.*sR-------", tabs, ALOT_OF_TABS);
        dump_as_tree (tabs+1, n->Right, is_set);
    };
};

void dump_map_and_set(struct tree_struct *m, bool is_set)
{
    printf ("ptr=0x%p, Myhead=0x%p, Mysize=%d\n", m, m->Myhead, m->Mysize);
    dump_tree_node (m->Myhead, is_set, true);
    printf ("As a tree:\n");
    printf ("root----");
    dump_as_tree (1, m->Myhead->Parent, is_set);
};

int main()
{
    // map

    std::map<int, const char*> m;

    m[10]="ten";
    m[20]="twenty";
    m[3]="three";
    m[101]="one hundred one";
    m[100]="one hundred";
    m[12]="twelve";
    m[107]="one hundred seven";
    m[0]="zero";
```

```
    m[1]="one";
    m[6]="six";
    m[99]="ninety-nine";
    m[5]="five";
    m[11]="eleven";
    m[1001]="one thousand one";
    m[1010]="one thousand ten";
    m[2]="two";
    m[9]="nine";
    printf ("dumping m as map:\n");
    dump_map_and_set ((struct tree_struct *)(void*)&m, false);

    std::map<int, const char*>::iterator it1=m.begin();
    printf ("m.begin():\n");
    dump_tree_node ((struct tree_node *)*(void**)&it1, false, false);
    it1=m.end();
    printf ("m.end():\n");
    dump_tree_node ((struct tree_node *)*(void**)&it1, false, false);

    // set

    std::set<int> s;
    s.insert(123);
    s.insert(456);
    s.insert(11);
    s.insert(12);
    s.insert(100);
    s.insert(1001);
    printf ("dumping s as set:\n");
    dump_map_and_set ((struct tree_struct *)(void*)&s, true);
    std::set<int>::iterator it2=s.begin();
    printf ("s.begin():\n");
    dump_tree_node ((struct tree_node *)*(void**)&it2, true, false);
    it2=s.end();
    printf ("s.end():\n");
    dump_tree_node ((struct tree_node *)*(void**)&it2, true, false);
};
```

Listing 3.115: MSVC 2012

```
dumping m as map:
ptr=0x0020FE04, Myhead=0x005BB3A0, Mysize=17
ptr=0x005BB3A0 Left=0x005BB4A0 Parent=0x005BB3C0 Right=0x005BB580 Color=1 Isnil=1
ptr=0x005BB3C0 Left=0x005BB4C0 Parent=0x005BB3A0 Right=0x005BB440 Color=1 Isnil=0
first=10 second=[ten]
ptr=0x005BB4C0 Left=0x005BB4A0 Parent=0x005BB3C0 Right=0x005BB520 Color=1 Isnil=0
first=1 second=[one]
ptr=0x005BB4A0 Left=0x005BB3A0 Parent=0x005BB4C0 Right=0x005BB3A0 Color=1 Isnil=0
first=0 second=[zero]
ptr=0x005BB520 Left=0x005BB400 Parent=0x005BB4C0 Right=0x005BB4E0 Color=0 Isnil=0
first=5 second=[five]
ptr=0x005BB400 Left=0x005BB5A0 Parent=0x005BB520 Right=0x005BB3A0 Color=1 Isnil=0
first=3 second=[three]
ptr=0x005BB5A0 Left=0x005BB3A0 Parent=0x005BB400 Right=0x005BB3A0 Color=0 Isnil=0
first=2 second=[two]
ptr=0x005BB4E0 Left=0x005BB3A0 Parent=0x005BB520 Right=0x005BB5C0 Color=1 Isnil=0
first=6 second=[six]
ptr=0x005BB5C0 Left=0x005BB3A0 Parent=0x005BB4E0 Right=0x005BB3A0 Color=0 Isnil=0
first=9 second=[nine]
ptr=0x005BB440 Left=0x005BB3E0 Parent=0x005BB3C0 Right=0x005BB480 Color=1 Isnil=0
first=100 second=[one hundred]
ptr=0x005BB3E0 Left=0x005BB460 Parent=0x005BB440 Right=0x005BB500 Color=0 Isnil=0
first=20 second=[twenty]
ptr=0x005BB460 Left=0x005BB540 Parent=0x005BB3E0 Right=0x005BB3A0 Color=1 Isnil=0
first=12 second=[twelve]
ptr=0x005BB540 Left=0x005BB3A0 Parent=0x005BB460 Right=0x005BB3A0 Color=0 Isnil=0
first=11 second=[eleven]
ptr=0x005BB500 Left=0x005BB3A0 Parent=0x005BB3E0 Right=0x005BB3A0 Color=1 Isnil=0
first=99 second=[ninety-nine]
ptr=0x005BB480 Left=0x005BB420 Parent=0x005BB440 Right=0x005BB560 Color=0 Isnil=0
```

```
first=107 second=[one hundred seven]
ptr=0x005BB420 Left=0x005BB3A0 Parent=0x005BB480 Right=0x005BB3A0 Color=1 Isnil=0
first=101 second=[one hundred one]
ptr=0x005BB560 Left=0x005BB3A0 Parent=0x005BB480 Right=0x005BB580 Color=1 Isnil=0
first=1001 second=[one thousand one]
ptr=0x005BB580 Left=0x005BB3A0 Parent=0x005BB560 Right=0x005BB3A0 Color=0 Isnil=0
first=1010 second=[one thousand ten]
As a tree:
root----10 [ten]
        L-------1 [one]
                L-------0 [zero]
                R-------5 [five]
                        L-------3 [three]
                                L-------2 [two]
                        R-------6 [six]
                                R-------9 [nine]
        R-------100 [one hundred]
                L-------20 [twenty]
                        L-------12 [twelve]
                                L-------11 [eleven]
                        R-------99 [ninety-nine]
                R-------107 [one hundred seven]
                        L-------101 [one hundred one]
                        R-------1001 [one thousand one]
                                R-------1010 [one thousand ten]
m.begin():
ptr=0x005BB4A0 Left=0x005BB3A0 Parent=0x005BB4C0 Right=0x005BB3A0 Color=1 Isnil=0
first=0 second=[zero]
m.end():
ptr=0x005BB3A0 Left=0x005BB4A0 Parent=0x005BB3C0 Right=0x005BB580 Color=1 Isnil=1

dumping s as set:
ptr=0x0020FDFC, Myhead=0x005BB5E0, Mysize=6
ptr=0x005BB5E0 Left=0x005BB640 Parent=0x005BB600 Right=0x005BB6A0 Color=1 Isnil=1
ptr=0x005BB600 Left=0x005BB660 Parent=0x005BB5E0 Right=0x005BB620 Color=1 Isnil=0
first=123
ptr=0x005BB660 Left=0x005BB640 Parent=0x005BB600 Right=0x005BB680 Color=1 Isnil=0
first=12
ptr=0x005BB640 Left=0x005BB5E0 Parent=0x005BB660 Right=0x005BB5E0 Color=0 Isnil=0
first=11
ptr=0x005BB680 Left=0x005BB5E0 Parent=0x005BB660 Right=0x005BB5E0 Color=0 Isnil=0
first=100
ptr=0x005BB620 Left=0x005BB5E0 Parent=0x005BB600 Right=0x005BB6A0 Color=1 Isnil=0
first=456
ptr=0x005BB6A0 Left=0x005BB5E0 Parent=0x005BB620 Right=0x005BB5E0 Color=0 Isnil=0
first=1001
As a tree:
root----123
        L-------12
                L-------11
                R-------100
        R-------456
                R-------1001
s.begin():
ptr=0x005BB640 Left=0x005BB5E0 Parent=0x005BB660 Right=0x005BB5E0 Color=0 Isnil=0
first=11
s.end():
ptr=0x005BB5E0 Left=0x005BB640 Parent=0x005BB600 Right=0x005BB6A0 Color=1 Isnil=1
```

The structure is not packed, so both *char* values occupy 4 bytes each.

As for `std::map`, `first` and `second` can be viewed as a single value of type `std::pair`. `std::set` has only one value at this address in the structure instead.

The current size of the tree is always present, as in the case of the implementation of `std::list` in MSVC (3.18.4 on page 571).

As in the case of `std::list`, the iterators are just pointers to nodes. The `.begin()` iterator points to the minimal key.

That pointer is not stored anywhere (as in lists), the minimal key of the tree is looked up every time.

operator-- and operator++ move the current node pointer to the predecessor or successor respectively, i.e., the nodes which have the previous or next key.

The algorithms for all these operations are explained in [Cormen, Thomas H. and Leiserson, Charles E. and Rivest, Ronald L. and Stein, Clifford, *Introduction to Algorithms, Third Edition*, (2009)].

The .end() iterator points to the dummy node, it has 1 in Isnil, which implies that the node has no key and/or value. It can be viewed as a "landing zone" in HDD[33] and often called *sentinel* [see N. Wirth, *Algorithms and Data Structures*, 1985] [34].

The "parent" field of the dummy node points to the root node, which serves as a vertex of the tree and contains information.

GCC

```
#include <stdio.h>
#include <map>
#include <set>
#include <string>
#include <iostream>

struct map_pair
{
    int key;
    const char *value;
};

struct tree_node
{
    int M_color; // 0 - Red, 1 - Black
    struct tree_node *M_parent;
    struct tree_node *M_left;
    struct tree_node *M_right;
};

struct tree_struct
{
    int M_key_compare;
    struct tree_node M_header;
    size_t M_node_count;
};

void dump_tree_node (struct tree_node *n, bool is_set, bool traverse, bool dump_keys_and_values↙
    ↳ )
{
    printf ("ptr=0x%p M_left=0x%p M_parent=0x%p M_right=0x%p M_color=%d\n",
            n, n->M_left, n->M_parent, n->M_right, n->M_color);

    void *point_after_struct=((char*)n)+sizeof(struct tree_node);

    if (dump_keys_and_values)
    {
        if (is_set)
            printf ("key=%d\n", *(int*)point_after_struct);
        else
        {
            struct map_pair *p=(struct map_pair *)point_after_struct;
            printf ("key=%d value=[%s]\n", p->key, p->value);
        };
    };

    if (traverse==false)
        return;

    if (n->M_left)
        dump_tree_node (n->M_left, is_set, traverse, dump_keys_and_values);
```

[33] Hard Disk Drive
[34] http://www.ethoberon.ethz.ch/WirthPubl/AD.pdf

```
    if (n->M_right)
        dump_tree_node (n->M_right, is_set, traverse, dump_keys_and_values);
};

const char* ALOT_OF_TABS="\t\t\t\t\t\t\t\t\t\t\t";

void dump_as_tree (int tabs, struct tree_node *n, bool is_set)
{
    void *point_after_struct=((char*)n)+sizeof(struct tree_node);

    if (is_set)
        printf ("%d\n", *(int*)point_after_struct);
    else
    {
        struct map_pair *p=(struct map_pair *)point_after_struct;
        printf ("%d [%s]\n", p->key, p->value);
    }

    if (n->M_left)
    {
        printf ("%.*sL-------", tabs, ALOT_OF_TABS);
        dump_as_tree (tabs+1, n->M_left, is_set);
    };
    if (n->M_right)
    {
        printf ("%.*sR-------", tabs, ALOT_OF_TABS);
        dump_as_tree (tabs+1, n->M_right, is_set);
    };
};

void dump_map_and_set(struct tree_struct *m, bool is_set)
{
    printf ("ptr=0x%p, M_key_compare=0x%x, M_header=0x%p, M_node_count=%d\n",
        m, m->M_key_compare, &m->M_header, m->M_node_count);
    dump_tree_node (m->M_header.M_parent, is_set, true, true);
    printf ("As a tree:\n");
    printf ("root----");
    dump_as_tree (1, m->M_header.M_parent, is_set);
};

int main()
{
    // map

    std::map<int, const char*> m;

    m[10]="ten";
    m[20]="twenty";
    m[3]="three";
    m[101]="one hundred one";
    m[100]="one hundred";
    m[12]="twelve";
    m[107]="one hundred seven";
    m[0]="zero";
    m[1]="one";
    m[6]="six";
    m[99]="ninety-nine";
    m[5]="five";
    m[11]="eleven";
    m[1001]="one thousand one";
    m[1010]="one thousand ten";
    m[2]="two";
    m[9]="nine";

    printf ("dumping m as map:\n");
    dump_map_and_set ((struct tree_struct *)(void*)&m, false);

    std::map<int, const char*>::iterator it1=m.begin();
    printf ("m.begin():\n");
    dump_tree_node ((struct tree_node *)*(void**)&it1, false, false, true);
```

```
    it1=m.end();
    printf ("m.end():\n");
    dump_tree_node ((struct tree_node *)*(void**)&it1, false, false, false);

    // set

    std::set<int> s;
    s.insert(123);
    s.insert(456);
    s.insert(11);
    s.insert(12);
    s.insert(100);
    s.insert(1001);
    printf ("dumping s as set:\n");
    dump_map_and_set ((struct tree_struct *)(void*)&s, true);
    std::set<int>::iterator it2=s.begin();
    printf ("s.begin():\n");
    dump_tree_node ((struct tree_node *)*(void**)&it2, true, false, true);
    it2=s.end();
    printf ("s.end():\n");
    dump_tree_node ((struct tree_node *)*(void**)&it2, true, false, false);
};
```

Listing 3.116: GCC 4.8.1

```
dumping m as map:
ptr=0x0028FE3C, M_key_compare=0x402b70, M_header=0x0028FE40, M_node_count=17
ptr=0x007A4988 M_left=0x007A4C00 M_parent=0x0028FE40 M_right=0x007A4B80 M_color=1
key=10 value=[ten]
ptr=0x007A4C00 M_left=0x007A4BE0 M_parent=0x007A4988 M_right=0x007A4C60 M_color=1
key=1 value=[one]
ptr=0x007A4BE0 M_left=0x00000000 M_parent=0x007A4C00 M_right=0x00000000 M_color=1
key=0 value=[zero]
ptr=0x007A4C60 M_left=0x007A4B40 M_parent=0x007A4C00 M_right=0x007A4C20 M_color=0
key=5 value=[five]
ptr=0x007A4B40 M_left=0x007A4CE0 M_parent=0x007A4C60 M_right=0x00000000 M_color=1
key=3 value=[three]
ptr=0x007A4CE0 M_left=0x00000000 M_parent=0x007A4B40 M_right=0x00000000 M_color=0
key=2 value=[two]
ptr=0x007A4C20 M_left=0x00000000 M_parent=0x007A4C60 M_right=0x007A4D00 M_color=1
key=6 value=[six]
ptr=0x007A4D00 M_left=0x00000000 M_parent=0x007A4C20 M_right=0x00000000 M_color=0
key=9 value=[nine]
ptr=0x007A4B80 M_left=0x007A49A8 M_parent=0x007A4988 M_right=0x007A4BC0 M_color=1
key=100 value=[one hundred]
ptr=0x007A49A8 M_left=0x007A4BA0 M_parent=0x007A4B80 M_right=0x007A4C40 M_color=0
key=20 value=[twenty]
ptr=0x007A4BA0 M_left=0x007A4C80 M_parent=0x007A49A8 M_right=0x00000000 M_color=1
key=12 value=[twelve]
ptr=0x007A4C80 M_left=0x00000000 M_parent=0x007A4BA0 M_right=0x00000000 M_color=0
key=11 value=[eleven]
ptr=0x007A4C40 M_left=0x00000000 M_parent=0x007A49A8 M_right=0x00000000 M_color=1
key=99 value=[ninety-nine]
ptr=0x007A4BC0 M_left=0x007A4B60 M_parent=0x007A4B80 M_right=0x007A4CA0 M_color=0
key=107 value=[one hundred seven]
ptr=0x007A4B60 M_left=0x00000000 M_parent=0x007A4BC0 M_right=0x00000000 M_color=1
key=101 value=[one hundred one]
ptr=0x007A4CA0 M_left=0x00000000 M_parent=0x007A4BC0 M_right=0x007A4CC0 M_color=1
key=1001 value=[one thousand one]
ptr=0x007A4CC0 M_left=0x00000000 M_parent=0x007A4CA0 M_right=0x00000000 M_color=0
key=1010 value=[one thousand ten]
As a tree:
root----10 [ten]
        L-------1 [one]
                L-------0 [zero]
                R-------5 [five]
                        L-------3 [three]
                                L-------2 [two]
                        R-------6 [six]
                                R-------9 [nine]
```

```
        R-------100 [one hundred]
                L-------20 [twenty]
                        L-------12 [twelve]
                                L-------11 [eleven]
                        R-------99 [ninety-nine]
                R-------107 [one hundred seven]
                        L-------101 [one hundred one]
                        R-------1001 [one thousand one]
                                R-------1010 [one thousand ten]
m.begin():
ptr=0x007A4BE0 M_left=0x00000000 M_parent=0x007A4C00 M_right=0x00000000 M_color=1
key=0 value=[zero]
m.end():
ptr=0x0028FE40 M_left=0x007A4BE0 M_parent=0x007A4988 M_right=0x007A4CC0 M_color=0

dumping s as set:
ptr=0x0028FE20, M_key_compare=0x8, M_header=0x0028FE24, M_node_count=6
ptr=0x007A1E80 M_left=0x01D5D890 M_parent=0x0028FE24 M_right=0x01D5D850 M_color=1
key=123
ptr=0x01D5D890 M_left=0x01D5D870 M_parent=0x007A1E80 M_right=0x01D5D8B0 M_color=1
key=12
ptr=0x01D5D870 M_left=0x00000000 M_parent=0x01D5D890 M_right=0x00000000 M_color=0
key=11
ptr=0x01D5D8B0 M_left=0x00000000 M_parent=0x01D5D890 M_right=0x00000000 M_color=0
key=100
ptr=0x01D5D850 M_left=0x00000000 M_parent=0x007A1E80 M_right=0x01D5D8D0 M_color=1
key=456
ptr=0x01D5D8D0 M_left=0x00000000 M_parent=0x01D5D850 M_right=0x00000000 M_color=0
key=1001
As a tree:
root----123
        L-------12
                L-------11
                R-------100
        R-------456
                R-------1001
s.begin():
ptr=0x01D5D870 M_left=0x00000000 M_parent=0x01D5D890 M_right=0x00000000 M_color=0
key=11
s.end():
ptr=0x0028FE24 M_left=0x01D5D870 M_parent=0x007A1E80 M_right=0x01D5D8D0 M_color=0
```

GCC's implementation is very similar [35]. The only difference is the absence of the `Isnil` field, so the structure occupies slightly less space in memory than its implementation in MSVC.

The dummy node is also used as a place to point the `.end()` iterator also has no key and/or value.

Rebalancing demo (GCC)

Here is also a demo showing us how a tree is rebalanced after some insertions.

Listing 3.117: GCC

```
#include <stdio.h>
#include <map>
#include <set>
#include <string>
#include <iostream>

struct map_pair
{
    int key;
    const char *value;
};

struct tree_node
{
```

[35] http://go.yurichev.com/17084

```
    int M_color; // 0 - Red, 1 - Black
    struct tree_node *M_parent;
    struct tree_node *M_left;
    struct tree_node *M_right;
};

struct tree_struct
{
    int M_key_compare;
    struct tree_node M_header;
    size_t M_node_count;
};

const char* ALOT_OF_TABS="\t\t\t\t\t\t\t\t\t\t\t";

void dump_as_tree (int tabs, struct tree_node *n)
{
    void *point_after_struct=((char*)n)+sizeof(struct tree_node);

    printf ("%d\n", *(int*)point_after_struct);

    if (n->M_left)
    {
        printf ("%.*sL-------", tabs, ALOT_OF_TABS);
        dump_as_tree (tabs+1, n->M_left);
    };
    if (n->M_right)
    {
        printf ("%.*sR-------", tabs, ALOT_OF_TABS);
        dump_as_tree (tabs+1, n->M_right);
    };
};

void dump_map_and_set(struct tree_struct *m)
{
    printf ("root----");
    dump_as_tree (1, m->M_header.M_parent);
};

int main()
{
    std::set<int> s;
    s.insert(123);
    s.insert(456);
    printf ("123, 456 has been inserted\n");
    dump_map_and_set ((struct tree_struct *)(void*)&s);
    s.insert(11);
    s.insert(12);
    printf ("\n");
    printf ("11, 12 has been inserted\n");
    dump_map_and_set ((struct tree_struct *)(void*)&s);
    s.insert(100);
    s.insert(1001);
    printf ("\n");
    printf ("100, 1001 has been inserted\n");
    dump_map_and_set ((struct tree_struct *)(void*)&s);
    s.insert(667);
    s.insert(1);
    s.insert(4);
    s.insert(7);
    printf ("\n");
    printf ("667, 1, 4, 7 has been inserted\n");
    dump_map_and_set ((struct tree_struct *)(void*)&s);
    printf ("\n");
};
```

Listing 3.118: GCC 4.8.1

```
123, 456 has been inserted
root----123
```

```
        R-------456

11, 12 has been inserted
root----123
        L-------11
                R-------12
        R-------456

100, 1001 has been inserted
root----123
        L-------12
                L-------11
                R-------100
        R-------456
                R-------1001

667, 1, 4, 7 has been inserted
root----12
        L-------4
                L-------1
                R-------11
                        L-------7
        R-------123
                L-------100
                R-------667
                        L-------456
                        R-------1001
```

3.18.5 Memory

Sometimes you may hear from C++ programmers "allocate memory on stack" and/or "allocate memory on heap".

Allocating object *on stack*:

```
void f()
{
        ...

        Class o=Class(...);

        ...
};
```

The memory for object (or structure) is allocated in stack, using simple SP shift. The memory is deallocated upon function exit, or, more precisely, at the end of *scope*—SP is returning to its state (same as at the start of function) and destructor of *Class* is called. In the same manner, memory for allocated structure in C is deallocated upon function exit.

Allocating object *on heap*:

```
void f1()
{
        ...

        Class *o=new Class(...);

        ...
};

void f2()
{
        ...

        delete o;

        ...
};
```

This is the same as allocating memory for a structure using *malloc()* call. In fact, *new* in C++ is wrapper for *malloc()*, and *delete* is wrapper for *free()*. Since memory block has been allocated in heap, it must be deallocated explicitly, using *delete*. Class destructor will be automatically called right before that moment.

Which method is better? Allocating *on stack* is very fast, and good for small, short-lived object, which will be used only in the current function.

Allocating *on heap* is slower, and better for long-lived object, which will be used across many functions. Also, objects allocated in heap are prone to memory leakage, because they must to be freed explicitly, but one can forget about it.

Anyway, this is matter of taste.

3.19 Negative array indices

It's possible to address the space *before* an array by supplying a negative index, e.g., $array[-1]$.

3.19.1 Addressing string from the end

Python PL allows to address arrays and strings from the end. For example, *string[-1]* returns the last character, *string[-2]* returns penultimate, etc. Hard to believe, but this is also possible in C/C++:

```
#include <string.h>
#include <stdio.h>

int main()
{
        char *s="Hello, world!";
        char *s_end=s+strlen(s);

        printf ("last character: %c\n", s_end[-1]);
        printf ("penultimate character: %c\n", s_end[-2]);
};
```

It works, but *s_end* must always has an address of terminating zero byte at the end of *s* string. If *s* string's size get changed, *s_end* must be updated.

The trick is dubious, but again, this is a demonstration of negative indices.

3.19.2 Addressing some kind of block from the end

Let's first recall why stack grows backwards (1.7.1 on page 30). There is some kind of block in memory and you want to store both heap and stack there, and you are not sure, how big they both can grow during runtime.

You can set a *heap* pointer to the beginning of the block, then you can set a *stack* pointer to the end of the block (*heap* + *size_of_block*), and then you can address *nth* element of stack like *stack[-n]*. For example, *stack[-1]* for 1st element, *stack[-2]* for 2nd, etc.

This will work in the same fashion, as our trick of addressing string from the end.

You can easily check if the structures has not begun to overlap each other: just be sure that address of the last element in *heap* is below the address of the last element of *stack*.

Unfortunately, -0 as index will not work, since two's complement way of representing negative numbers (2.2 on page 452) don't allow negative zero, so it cannot be distinguished from positive zero.

This method is also mentioned in "Transaction processing", Jim Gray, 1993, "The Tuple-Oriented File System" chapter, p. 755.

3.19.3 Arrays started at 1

Fortran and Mathematica defined first element of array as 1th, probably because this is tradition in mathematics. Other PLs like C/C++ defined it as 0th. Which is better? Edsger W. Dijkstra argued that latter is better [36].

But programmers may still have a habit after Fortran, so using this little trick, it's possible to address the first element in C/C++ using index 1:

```
#include <stdio.h>

int main()
{
        int random_value=0x11223344;
        unsigned char array[10];
        int i;
        unsigned char *fakearray=&array[-1];

        for (i=0; i<10; i++)
                array[i]=i;

        printf ("first element %d\n", fakearray[1]);
        printf ("second element %d\n", fakearray[2]);
        printf ("last element %d\n", fakearray[10]);

        printf ("array[-1]=%02X, array[-2]=%02X, array[-3]=%02X, array[-4]=%02X\n",
                array[-1],
                array[-2],
                array[-3],
                array[-4]);
};
```

Listing 3.119: Non-optimizing MSVC 2010

```
$SG2751 DB      'first element %d', 0aH, 00H
$SG2752 DB      'second element %d', 0aH, 00H
$SG2753 DB      'last element %d', 0aH, 00H
$SG2754 DB      'array[-1]=%02X, array[-2]=%02X, array[-3]=%02X, array[-4'
        DB      ']=%02X', 0aH, 00H

_fakearray$ = -24               ; size = 4
_random_value$ = -20    ; size = 4
_array$ = -16           ; size = 10
_i$ = -4                ; size = 4
_main   PROC
        push    ebp
        mov     ebp, esp
        sub     esp, 24
        mov     DWORD PTR _random_value$[ebp], 287454020 ; 11223344H
        ; set fakearray[] one byte earlier before array[]
        lea     eax, DWORD PTR _array$[ebp]
        add     eax, -1 ; eax=eax-1
        mov     DWORD PTR _fakearray$[ebp], eax
        mov     DWORD PTR _i$[ebp], 0
        jmp     SHORT $LN3@main
        ; fill array[] with 0..9
$LN2@main:
        mov     ecx, DWORD PTR _i$[ebp]
        add     ecx, 1
        mov     DWORD PTR _i$[ebp], ecx
$LN3@main:
        cmp     DWORD PTR _i$[ebp], 10
        jge     SHORT $LN1@main
        mov     edx, DWORD PTR _i$[ebp]
        mov     al, BYTE PTR _i$[ebp]
        mov     BYTE PTR _array$[ebp+edx], al
        jmp     SHORT $LN2@main
$LN1@main:
```

[36] See https://www.cs.utexas.edu/users/EWD/transcriptions/EWD08xx/EWD831.html

```
        mov     ecx, DWORD PTR _fakearray$[ebp]
        ; ecx=address of fakearray[0], ecx+1 is fakearray[1] or array[0]
        movzx   edx, BYTE PTR [ecx+1]
        push    edx
        push    OFFSET $SG2751 ; 'first element %d'
        call    _printf
        add     esp, 8
        mov     eax, DWORD PTR _fakearray$[ebp]
        ; eax=address of fakearray[0], eax+2 is fakearray[2] or array[1]
        movzx   ecx, BYTE PTR [eax+2]
        push    ecx
        push    OFFSET $SG2752 ; 'second element %d'
        call    _printf
        add     esp, 8
        mov     edx, DWORD PTR _fakearray$[ebp]
        ; edx=address of fakearray[0], edx+10 is fakearray[10] or array[9]
        movzx   eax, BYTE PTR [edx+10]
        push    eax
        push    OFFSET $SG2753 ; 'last element %d'
        call    _printf
        add     esp, 8
        ; subtract 4, 3, 2 and 1 from pointer to array[0] in order to find values before array[]
        lea     ecx, DWORD PTR _array$[ebp]
        movzx   edx, BYTE PTR [ecx-4]
        push    edx
        lea     eax, DWORD PTR _array$[ebp]
        movzx   ecx, BYTE PTR [eax-3]
        push    ecx
        lea     edx, DWORD PTR _array$[ebp]
        movzx   eax, BYTE PTR [edx-2]
        push    eax
        lea     ecx, DWORD PTR _array$[ebp]
        movzx   edx, BYTE PTR [ecx-1]
        push    edx
        push    OFFSET $SG2754 ; 'array[-1]=%02X, array[-2]=%02X, array[-3]=%02X, array[-4]=%02X'
        call    _printf
        add     esp, 20
        xor     eax, eax
        mov     esp, ebp
        pop     ebp
        ret     0
_main   ENDP
```

So we have `array[]` of ten elements, filled with $0 \dots 9$ bytes.

Then we have the `fakearray[]` pointer, which points one byte before `array[]`.

`fakearray[1]` points exactly to `array[0]`. But we are still curious, what is there before `array[]`? We have added `random_value` before `array[]` and set it to `0x11223344`. The non-optimizing compiler allocated the variables in the order they were declared, so yes, the 32-bit `random_value` is right before the array.

We ran it, and:

```
first element 0
second element 1
last element 9
array[-1]=11, array[-2]=22, array[-3]=33, array[-4]=44
```

Here is the stack fragment we will copypaste from OllyDbg's stack window (with comments added by the author):

Listing 3.120: Non-optimizing MSVC 2010

```
CPU Stack
Address   Value
001DFBCC  /001DFBD3 ; fakearray pointer
001DFBD0  |11223344 ; random_value
001DFBD4  |03020100 ; 4 bytes of array[]
001DFBD8  |07060504 ; 4 bytes of array[]
```

```
001DFBDC  |00CB0908 ; random garbage + 2 last bytes of array[]
001DFBE0  |0000000A ; last i value after loop was finished
001DFBE4  |001DFC2C ; saved EBP value
001DFBE8  \00CB129D ; Return Address
```

The pointer to the `fakearray[]` (`0x001DFBD3`) is indeed the address of `array[]` in the stack (`0x001DFBD4`), but minus 1 byte.

It's still very hackish and dubious trick. Doubtfully anyone should use it in production code, but as a demonstration, it fits perfectly here.

3.20 Packing 12-bit values into array using bit operations (x64, ARM/ARM64, MIPS)

(This part has been first appeared in my blog at 4-Sep-2015.)

3.20.1 Introduction

File Allocation Table (FAT) was a widely popular filesystem. Hard to believe, but it's still used on flash drives, perhaps, for the reason of simplicity and compatibility. The FAT table itself is array of elements, each of which points to the next cluster number of a file (FAT supports files scattered across the whole disk). That implies that maximum of each element is maximum number of clusters on the disk. In MS-DOS era, most hard disks has FAT16 filesystem, because cluster number could be packed into 16-bit value. Hard disks then become cheaper, and FAT32 emerged, where 32-bit value was allocated for cluster number. But there were also a times, when floppy diskettes were not that cheap and has no much space, so FAT12 were used on them, for the reason of packing all filesystem structures as tight as possible.

So the FAT table in FAT12 filesystem is an array where each two subsequent 12-bit elements are stored into 3 bytes (triplet). Here is how 6 12-bit values (AAA, BBB, CCC, DDD, EEE and FFF) are packed into 9 bytes:

```
 +0 +1 +2 +3 +4 +5 +6 +7 +8
|AA|AB|BB|CC|CD|DD|EE|EF|FF|...
```

Pushing values into array and pulling them back can be good example of bit twiddling operations (in both C/C++ and low-level machine code), so that's why I'll use FAT12 as an example here.

3.20.2 Data structure

We can quickly observe that each byte triplet will store 2 12-bit values: the first one is located at the left side, second one is at right:

```
 +0 +1 +2
|11|12|22|...
```

We will pack nibbles (4 bit chunks) in the following way (1 - highest nibble, 3 - lowest):

(Even)

```
 +0 +1 +2
|12|3.|..|...
```

(Odd)

```
 +0 +1 +2
|..|.1|23|...
```

3.20.3 The algorithm

So the algorithm can be as follows: if the element's index is even, put it at left side, if the index is odd, place it at right side. The middle byte: if the element's index is even, place part of it in high 4 bits, if it's odd, place its part in low 4 bits. But first, find the right triplet, this is easy: $\frac{index}{2}$. Finding the address of right byte in array of bytes is also easy: $\frac{index}{2} \cdot 3$ or $index \cdot \frac{3}{2}$ or just $index \cdot 1.5$.

Pulling values from array: if index is even, get leftmost and middle bytes and combine its parts. If index is odd, get middle and rightmost bytes and combine them. Do not forget to isolate unneeded bits in middle byte.

Pushing values is almost the same, but be careful not to overwrite some *other's* bits in the middle byte, correcting only *yours*.

3.20.4 The C/C++ code

```
#include <stdio.h>
#include <stdint.h>
#include <assert.h>

#define ARRAY_SIZE (0x1000/2*3)
uint8_t array[ARRAY_SIZE]; // big enough array of triplets

unsigned int get_from_array (unsigned int idx)
{
        // find right triple in array:
        int triple=(idx>>1);
        int array_idx=triple*3;
        //assert (array_idx<ARRAY_SIZE);

        if (idx&1)
        {
                // this is odd element

                // compose value using middle and rightmost bytes:
                return ((array[array_idx+1]&0xF) << 8)|array[array_idx+2];
        }
        else
        {
                // this is even element

                // compose value using rightmost and middle bytes:
                return array[array_idx]<<4 | ((array[array_idx+1]>>4)&0xF);
        };
};

void put_to_array (unsigned int idx, unsigned int val)
{
        //assert (val<=0xFFF);

        // find right triple in array:
        int triple=(idx>>1);
        int array_idx=triple*3;
        //assert (array_idx<ARRAY_SIZE);

        if (idx&1)
        {
                // this is odd element
                // put value into middle and rightmost bytes:

                // decompose value to be stored:
                uint8_t val_lowest_byte=val&0xFF; // isolate lowest 8 bits
                uint8_t val_highest_nibble=val>>8; // no need to apply &0xF, we already know ↙
    ↘ the val<=0xFFF

                // clear low 4 bits in the middle byte:
                array[array_idx+1]=array[array_idx+1]&0xF0;
```

```
                array[array_idx+1]=array[array_idx+1]|val_highest_nibble;
                array[array_idx+2]=val_lowest_byte;
        }
        else
        {
                // this is even element
                // put value into leftmost and middle bytes:

                // decompose value to be stored:
                uint8_t val_highest_byte=val>>4;
                uint8_t val_lowest_nibble=val&0xF;

                array[array_idx]=val_highest_byte;

                // clear high 4 bits in the middle byte:
                array[array_idx+1]=array[array_idx+1]&0xF;
                array[array_idx+1]=array[array_idx+1]|val_lowest_nibble<<4;
        };
};

int main()
{
        int i;

        // test
        for (i=0; i<0x1000; i++)
        {
                put_to_array(i, i);
        };

        for (i=0; i<0x1000; i++)
        {
                assert(get_from_array(i)==i);
        };
        //put_to_array(0x1000, 1); // will fail due to assert()

        // print triples:
        for (int i=0;i<0x1000/2;i++)
                printf ("0x%02X%02X%02X\n",array[i*3],array[i*3+1],array[i*3+2]);
};
```

During test, all 12-bit elements are filled with values in 0..0xFFF range. And here is a dump of all triplets, each line has 3 bytes:

```
0x000001
0x002003
0x004005
0x006007
0x008009
0x00A00B
0x00C00D
0x00E00F
0x010011
0x012013
0x014015

...

0xFECFED
0xFEEFEF
0xFF0FF1
0xFF2FF3
0xFF4FF5
0xFF6FF7
0xFF8FF9
0xFFAFFB
0xFFCFFD
0xFFEFFF
```

Here is also GDB byte-level output of 300 bytes (or 100 triplets) started at 512/2*3, i.e., it's address where

512th element (0x200) is beginning. I added square brackets in my text editor to show triplets explicitly. Take a notice at the middle bytes, where the last element is ended and the next is started. In other words, each middle byte has lowest 4 bits of even element and highest 4 bits of odd element.

```
(gdb) x/300xb array+512/2*3
0x601380 <array+768>: [ 0x20    0x02    0x01 ][ 0x20    0x22    0x03 ][ 0x20    0x42
0x601388 <array+776>:   0x05 ][ 0x20    0x62    0x07 ][ 0x20    0x82    0x09 ][ 0x20
0x601390 <array+784>:   0xa2    0x0b ][ 0x20    0xc2    0x0d ][ 0x20    0xe2    0x0f ]
0x601398 <array+792>: [ 0x21    0x02    0x11 ][ 0x21    0x22    0x13 ][ 0x21    0x42
0x6013a0 <array+800>:   0x15 ][ 0x21    0x62    0x17 ][ 0x21    0x82    0x19 ][ 0x21
0x6013a8 <array+808>:   0xa2    0x1b ][ 0x21    0xc2    0x1d ][ 0x21    0xe2    0x1f ]
0x6013b0 <array+816>: [ 0x22    0x02    0x21 ][ 0x22    0x22    0x23 ][ 0x22    0x42
0x6013b8 <array+824>:   0x25 ][ 0x22    0x62    0x27 ][ 0x22    0x82    0x29 ][ 0x22
0x6013c0 <array+832>:   0xa2    0x2b ][ 0x22    0xc2    0x2d ][ 0x22    0xe2    0x2f ]
0x6013c8 <array+840>: [ 0x23    0x02    0x31 ][ 0x23    0x22    0x33 ][ 0x23    0x42
0x6013d0 <array+848>:   0x35 ][ 0x23    0x62    0x37 ][ 0x23    0x82    0x39 ][ 0x23
0x6013d8 <array+856>:   0xa2    0x3b ][ 0x23    0xc2    0x3d ][ 0x23    0xe2    0x3f ]
0x6013e0 <array+864>: [ 0x24    0x02    0x41 ][ 0x24    0x22    0x43 ][ 0x24    0x42
0x6013e8 <array+872>:   0x45 ][ 0x24    0x62    0x47 ][ 0x24    0x82    0x49 ][ 0x24
0x6013f0 <array+880>:   0xa2    0x4b ][ 0x24    0xc2    0x4d ][ 0x24    0xe2    0x4f ]
0x6013f8 <array+888>: [ 0x25    0x02    0x51 ][ 0x25    0x22    0x53 ][ 0x25    0x42
0x601400 <array+896>:   0x55 ][ 0x25    0x62    0x57 ][ 0x25    0x82    0x59 ][ 0x25
0x601408 <array+904>:   0xa2    0x5b ][ 0x25    0xc2    0x5d ][ 0x25    0xe2    0x5f ]
0x601410 <array+912>: [ 0x26    0x02    0x61 ][ 0x26    0x22    0x63 ][ 0x26    0x42
0x601418 <array+920>:   0x65 ][ 0x26    0x62    0x67 ][ 0x26    0x82    0x69 ][ 0x26
0x601420 <array+928>:   0xa2    0x6b ][ 0x26    0xc2    0x6d ][ 0x26    0xe2    0x6f ]
0x601428 <array+936>: [ 0x27    0x02    0x71 ][ 0x27    0x22    0x73 ][ 0x27    0x42
0x601430 <array+944>:   0x75 ][ 0x27    0x62    0x77 ][ 0x27    0x82    0x79 ][ 0x27
0x601438 <array+952>:   0xa2    0x7b ][ 0x27    0xc2    0x7d ][ 0x27    0xe2    0x7f ]
0x601440 <array+960>: [ 0x28    0x02    0x81 ][ 0x28    0x22    0x83 ][ 0x28    0x42
0x601448 <array+968>:   0x85 ][ 0x28    0x62    0x87 ][ 0x28    0x82    0x89 ][ 0x28
0x601450 <array+976>:   0xa2    0x8b ][ 0x28    0xc2    0x8d ][ 0x28    0xe2    0x8f ]
0x601458 <array+984>: [ 0x29    0x02    0x91 ][ 0x29    0x22    0x93 ][ 0x29    0x42
0x601460 <array+992>:   0x95 ][ 0x29    0x62    0x97 ][ 0x29    0x82    0x99 ][ 0x29
0x601468 <array+1000>:  0xa2    0x9b ][ 0x29    0xc2    0x9d ][ 0x29    0xe2    0x9f ]
0x601470 <array+1008>:[ 0x2a    0x02    0xa1 ][ 0x2a    0x22    0xa3 ][ 0x2a    0x42
0x601478 <array+1016>:  0xa5 ][ 0x2a    0x62    0xa7 ][ 0x2a    0x82    0xa9 ][ 0x2a
0x601480 <array+1024>:  0xa2    0xab ][ 0x2a    0xc2    0xad ][ 0x2a    0xe2    0xaf ]
0x601488 <array+1032>:[ 0x2b    0x02    0xb1 ][ 0x2b    0x22    0xb3 ][ 0x2b    0x42
0x601490 <array+1040>:  0xb5 ][ 0x2b    0x62    0xb7 ][ 0x2b    0x82    0xb9 ][ 0x2b
0x601498 <array+1048>:  0xa2    0xbb ][ 0x2b    0xc2    0xbd ][ 0x2b    0xe2    0xbf ]
0x6014a0 <array+1056>:[ 0x2c    0x02    0xc1 ][ 0x2c    0x22    0xc3 ][ 0x2c    0x42
0x6014a8 <array+1064>:  0xc5 ][ 0x2c    0x62    0xc7 ]
```

3.20.5 How it works

Let array be a global buffer to make simpler access to it.

Getter

Let's first start at the function getting values from the array, because it's simpler.

The method of finding triplet's number is just division input index by 2, but we can do it just by shifting right by 1 bit. This is a very common way of dividing/multiplication by numbers in form of 2^n.

I can demonstrate how it works. Let's say, you want to divide 123 by 10. Just drop last digit (3, which is remainder of division) and 12 is left. Division by 2 is just dropping least significant bit. Dropping can be done by shifting right.

Now the functions must decide if the input index even (so 12-bit value is placed at the left) or odd (at the right). Simplest way to do so is to isolate lowest bit (x&1). If it's zero, our value is even, otherwise it's odd.

This fact can be illustrated easily, take a look at the lowest bit:

```
decimal binary even/odd
```

```
0       0000   even
1       0001   odd
2       0010   even
3       0011   odd
4       0100   even
5       0101   odd
6       0110   even
7       0111   odd
8       1000   even
9       1001   odd
10      1010   even
11      1011   odd
12      1100   even
13      1101   odd
14      1110   even
15      1111   odd
...
```

Zero is also even number, it's so in two's complement system, where it's located between two odd numbers (-1 and 1).

For math geeks, I could also say that even or odd sign is also remainder of division by 2. Division of a number by 2 is merely dropping the last bit, which is remainder of division. Well, we do not have to do shifts here, just isolate lowest bit.

If the element is odd, we take middle and right bytes (*array[array_idx+1]* and *array[array_idx+2]*). Lowest 4 bits of the middle byte is isolated. Right byte is taken as a whole. Now we have to combine these parts into 12-bit value. To do so, shift 4 bits from the middle byte by 8 bits left, so these 4 bits will be allocated right behind highest 8th bit of byte. Then, using OR operation, we just add these parts.

If the element is even, high 8 bits of 12-bit value is located in left byte, while lowest 4 bits are located in the high 4 bits of middle byte. We isolate highest 4 bits in the middle byte by shifting it 4 bits right and then applying AND operation, just to be sure that nothing is left there. We also take left byte and shift its value 4 bits left, because it has bits from 11th to 4th (inclusive, starting at 0), Using OR operation, we combine these two parts.

Setter

Setter calculates triplet's address in the same way. It also operates on left/right bytes in the same way. But it's not correct just to write to the middle byte, because write operation will destroy the information related to the other element. So the common way is to load byte, drop bits where you'll write, write it there, but leave other part intact. Using AND operation (& in C/C++), we drop everything except *our* part. Using OR operation (| in C/C++), we then update the middle byte.

3.20.6 Optimizing GCC 4.8.2 for x86-64

Let's see what optimizing GCC 4.8.2 for Linux x64 will do. I added comments. Sometimes readers are confused because instructions order is not logical. It's OK, because optimizing compilers take CPU out-of-order-execution mechanisms into considerations, and sometimes, swapped instructions performing better.

Getter

```
get_from_array:
; EDI=idx
; make a copy:
        mov     eax, edi
; calculate idx>>1:
        shr     eax
; determine if the element even or odd by isolation of the lowest bit:
        and     edi, 1
; calculate (idx>>1)*3.
; multiplication is slow in geenral, and can be replaced by one shifting and addition operation
; LEA is capable to do both:
        lea     edx, [rax+rax*2]
```

```
; EDX now is (idx>>1)*3
; point EAX to the middle byte:
        lea     eax, [rdx+1]
; sign-extend EAX value to RDX:
        cdqe
; get middle byte into EAX:
        movzx   eax, BYTE PTR array[rax]
; finally check the value of the lowest bit in index.
; jump if index is odd (NE is the same as NZ (Not Zero)):
        jne     .L9

; this is even element, go on
; sign-extend EDX to RDX:
        movsx   rdx, edx
; shift middle byte 4 bits right:
        shr     al, 4
; AL now has 4 highest bits of middle byte
; load left byte into EDX:
        movzx   edx, BYTE PTR array[rdx]
; sign-extend AL (where high 4 bits of middle byte are now)
        movzx   eax, al
; EAX has 4 high bits bits of middle byte
; EDX now has left byte
; shift left byte 4 bits left:
        sal     edx, 4
; 4 lowest bits in EDX after shifting is cleared to zero
; finally merge values:
        or      eax, edx
        ret
.L9:
; this is odd element, go on
; calculate address of right byte:
        add     edx, 2
; isolate lowest 4 bits in middle byte:
        and     eax, 15 ; 15=0xF
; sign-extend EDX (where address of right byte is) to RDX:
        movsx   rdx, edx
; shift 4 bits we got from middle bytes 8 bits left:
        sal     eax, 8
; load right byte:
        movzx   edx, BYTE PTR array[rdx]
; merge values:
        or      eax, edx
        ret
```

Setter

```
put_to_array:
; EDI=idx
; ESI=val
; copy idx to EAX:
        mov     eax, edi
; calculate idx>>1 and put it to EAX:
        shr     eax
; isolate lowest bit in idx:
        and     edi, 1
; calculate (idx>>2)*3 and put it to EAX:
        lea     eax, [rax+rax*2]
; jump if index is odd (NE is the same as NZ (Not Zero)):
        jne     .L5

; this is even element, go on
; sign-extend address of triplet in EAX to RDX:
        movsx   rdx, eax
; copy val value to ECX:
        mov     ecx, esi
; calculate address of middle byte:
        add     eax, 1
```

```
; sign-extend address in EAX to RDX:
        cdqe
; prepare left byte in ECX by shifting it:
        shr     ecx, 4
; prepare 4 bits for middle byte:
        sal     esi, 4
; put left byte:
        mov     BYTE PTR array[rdx], cl
; load middle byte (its address still in RAX):
        movzx   edx, BYTE PTR array[rax]
; drop high 4 bits:
        and     edx, 15 ; 15=0xF
; merge our data and low 4 bits which were there before:
        or      esi, edx
; put middle byte back:
        mov     BYTE PTR array[rax], sil
        ret
.L5:
; this is odd element, go on
; calculate address of middle byte and put it to ECX:
        lea     ecx, [rax+1]
; copy val value from ESI to EDI:
        mov     edi, esi
; calculate address of right byte:
        add     eax, 2
; get high 4 bits of input value by shifting it 8 bits right:
        shr     edi, 8
; sign-extend address in EAX into RAX:
        cdqe
; sign-extend address of middle byte in ECX to RCX:
        movsx   rcx, ecx
; load middle byte into EDX:
        movzx   edx, BYTE PTR array[rcx]
; drop low 4 bits in middle byte:
        and     edx, -16 ; -16=0xF0
; merge data from input val with what was in middle byte before:
        or      edx, edi
; store middle byte:
        mov     BYTE PTR array[rcx], dl
; store right byte. val is still in ESI and SIL is a part of ESI register which has lowest 8 ↙
    ↘ bits:
        mov     BYTE PTR array[rax], sil
        ret
```

Other comments

All addresses in Linux x64 are 64-bit ones, so during pointer arithmetic, all values should also be 64-bit. The code calculating offsets inside of array operates on 32-bit values (input *idx* argument has type of *int*, which has width of 32 bits), and so these values must be converted to 64-bit addresses before actual memory load/store. So there are a lot of sign-extending instructions (like CDQE, MOVSX) used for conversion. Why to extend sign? By C/C++ standards, pointer arithmetic can operate on negative values (it's possible to access array using negative index like *array[-123]*, see: 3.19 on page 593). Since GCC compiler cannot be sure if all indices are always positive, it adds sign-extending instructions.

3.20.7 Optimizing Keil 5.05 (Thumb mode)

Getter

The following code has final OR operation in the function epilogue. Indeed, it executes at the end of both branches, so it's possible to save some space.

```
get_from_array PROC
; R0 = idx
        PUSH     {r4,r5,lr}
        LSRS     r1,r0,#1
```

```
; R1 = R0>>1 = idx>>1
; R1 is now number of triplet
        LSLS     r2,r1,#1
; R2 = R1<<1 = (R0>>1)<<1 = R0&(~1) = idx&(~1)
; the operation (x>>1)<<1 looks senseless, but it's intended to clear the lowest bit in x (or ↙
    ↘ idx)
        LSLS     r5,r0,#31
; R5 = R0<<31 = idx<<31
; thus, R5 will contain 0x80000000 in case of even idx or zero if odd
        ADDS     r4,r1,r2
; R4 = R1+R2 = idx>>1 + idx&(~1) = offset of triplet begin (or offset of left byte)
; the expression looks tricky, but it's equal to multiplication by 1.5
        LSRS     r0,r0,#1
; R0 = R0>>1 = idx>>1
; load pointer to array:
        LDR      r3,|array|
; R3 = offset of array table
        LSLS     r1,r0,#1
; R1 = R0<<1 = (idx>>1)<<1 = idx&(~1)
        ADDS     r0,r0,r1
; R0 = idx>>1 + idx&(~1) = idx*1.5 = offset of triple begin
        ADDS     r1,r3,r0
; R1 = R3+R0 = offset of array + idx*1.5
; in other words, R1 now contains absolute address of triplet
; load middle byte (at address R1+1):
        LDRB     r2,[r1,#1]
; R2 = middle byte
; finally check if the idx even or odd:
        CMP      r5,#0
; jump if even:
        BEQ      |L0.92|
; idx is odd, go on:
        LSLS     r0,r2,#28
; R0 = R2<<28 = middle_byte<<28
; load right byte at R1+2:
        LDRB     r1,[r1,#2]
; R1 = right byte
        LSRS     r0,r0,#20
; R0 = R0>>20 = (R2<<28)>>20
; this is the same as R2<<8, but Keil compiler generates more complex code in order to drop all↙
    ↘  bits behind these 4
        B        |L0.98|
|L0.92|
; idx is even, go on:
; load left byte. R3=array now and R4=address of it
        LDRB     r0,[r3,r4]
; R0 = left byte
        LSLS     r0,r0,#4
; R0 = left_byte<<4
; shift middle_byte in R2 4 bits right:
        LSRS     r1,r2,#4
; R1=middle_byte>>4
|L0.98|
; function epilogue:
; current R0 value is shifted left byte or part of middle byte
; R1 is shifted part of middle byte or right byte
; now merge values and leave merged result in R0:
        ORRS     r0,r0,r1
; R0 = R0|R1
        POP      {r4,r5,pc}
        ENDP
```

There are at least of redundancy: *idx*1.5* is calculated twice. As an exercise, reader may try to rework assembly function to make it shorter. Do not forget about testing!

Another thing to mention is that it’s hard to generate big constants in 16-bit Thumb instructions, so Keil compiler often generates tricky code using shifting instructions to achieve the same effect. For example, it’s tricky to generate `AND Rdest, Rsrc, 1` or `TST Rsrc, 1` code in Thumb mode, so Keil generates the code which shifts input *idx* by 31 bits left and then check, if the resulting value zero or not.

Setter

The first half of setter code is very similar to getter, address of triplet is calculated first, then the jump is occurred in order to dispatch to the right handler's code.

```
put_to_array PROC
        PUSH     {r4,r5,lr}
; R0 = idx
; R1 = val
        LSRS     r2,r0,#1
; R2 = R0>>1 = idx>>1
        LSLS     r3,r2,#1
; R3 = R2<<1 = (idx>>1)<<1 = idx&(~1)
        LSLS     r4,r0,#31
; R4 = R0<<31 = idx<<31
        ADDS     r3,r2,r3
; R3 = R2+R3 = idx>>1 + idx&(~1) = idx*1.5
        LSRS     r0,r0,#1
; R0 = R0>>1 = idx>>1
        LDR      r2,|array|
; R2 = address of array
        LSLS     r5,r0,#1
; R5 = R0<<1 = (idx>>1)<<1 = idx&(~1)
        ADDS     r0,r0,r5
; R0 = R0+R5 = idx>>1 + idx&(~1) = idx*1.5
        ADDS     r0,r2,r0
; R0 = R2+R0 = array + idx*1.5, in other words, this is address of triplet
; finally test shifted lowest bit in idx:
        CMP      r4,#0
; jump if idx is even:
        BEQ      |L0.40|
; idx is odd, go on:
; load middle byte at R0+1:
        LDRB     r3,[r0,#1]
; R3 = middle_byte
        LSRS     r2,r1,#8
; R2 = R1>>8 = val>>8
        LSRS     r3,r3,#4
; R3 = R3>>4 = middle_byte>>4
        LSLS     r3,r3,#4
; R3 = R3<<4 = (middle_byte>>4)<<4
; this two shift operations are used to drop low 4 bits in middle_byte
; merge high 4 bits in middle byte (in R3) with val>>8 (in R2):
        ORRS     r3,r3,r2
; R3 = updated middle byte
; store it at R0+1:
        STRB     r3,[r0,#1]
; store low 8 bits of val (val&0xFF) at R0+2:
        STRB     r1,[r0,#2]
        POP      {r4,r5,pc}
|L0.40|
; idx is even, go on:
        LSRS     r4,r1,#4
; R4 = R1>>4 = val>>4
; store val>>4 at R2+R3 (address of left byte or beginning of triplet):
        STRB     r4,[r2,r3]
; load middle byte at R0+1:
        LDRB     r3,[r0,#1]
; R3 = middle byte
        LSLS     r2,r1,#4
; R2 = R1<<4 = val<<4
        LSLS     r1,r3,#28
; R1 = R3<<28 = middle_byte<<28
        LSRS     r1,r1,#28
; R1 = R1>>28 = (middle_byte<<28)>>28
; these two shifting operation are used to drop all bits in register except lowest 4
; merge lowest 4 bits (in R1) and val<<4 (in R2):
        ORRS     r1,r1,r2
; store it at R0+1:
        STRB     r1,[r0,#1]
```

```
        POP      {r4,r5,pc}
        ENDP
```

3.20.8 Optimizing Keil 5.05 (ARM mode)

Getter

Getter function for ARM mode has no conditional branches at all! Thanks to the suffixes (like *-EQ*, *-NE*), which can be supplied to many instructions in ARM mode, so the instruction will be only executed if the corresponding flag(s) are set.

Many arithmetical instructions in ARM mode can have shifting suffix like LSL #1 (it means, the last operand is shifted left by 1 bit).

```
get_from_array PROC
; R0 = idx
        LSR      r1,r0,#1
; R1 = R0>>1 = idx>>1
; check lowest bit in idx and set flags:
        TST      r0,#1
        ADD      r2,r1,r1,LSL #1
; R2 = R1+R1<<1 = R1+R1*2 = R1*3
; thanks to shifting suffix, a single instruction in ARM mode can multiplicate by 3
        LDR      r1,|array|
; R1 = address of array
        LSR      r0,r0,#1
; R0 = R0>>1 = idx>>1
        ADD      r0,r0,r0,LSL #1
; R0 = R0+R0<<1 = R0+R0*2 = R0*3 = (idx>>1)*3 = idx*1.5
        ADD      r0,r0,r1
; R0 = R0+R1 = array + idx*1.5, this is absolute address of triplet
; load middle byte at R0+1:
        LDRB     r3,[r0,#1]
; R3 = middle byte

; the following 3 instructions executed if index is odd, otherwise all of them are skipped:
; load right byte at R0+2:
        LDRBNE   r0,[r0,#2]
; R0 = right byte
        ANDNE    r1,r3,#0xf
; R1 = R3&0xF = middle_byte&0xF
        ORRNE    r0,r0,r1,LSL #8
; R0 = R0|(R1<<8) = right_byte | (middle_byte&0xF)<<8
; this is the result returned

; the following 3 instructions executed if index is even, otherwise all of them are skipped:
; load at R1+R2 = array + (idx>>1)*3 = array + idx*1.5
        LDRBEQ   r0,[r1,r2]
; R0 = left byte
        LSLEQ    r0,r0,#4
; R0 = R0<<4 = left_byte << 4
        ORREQ    r0,r0,r3,LSR #4
; R0 = R0 | R3>>4 = left_byte << 4 | middle_byte >> 4
; this is the result returned
        BX       lr
        ENDP
```

Setter

```
put_to_array PROC
; R0 = idx
; R1 = val
        LSR      r2,r0,#1
; R2 = R0>>1 = idx>>1
; check the lowest bit of idx and set flags:
```

```
        TST      r0,#1
        LDR      r12,|array|
; R12 = address of array
        LSR      r0,r0,#1
; R0 = R0>>1 = idx>>1
        ADD      r0,r0,r0,LSL #1
; R0 = R0+R0<<1 = R0+R0*2 = R0*3 = (idx>>1)*3 = idx/2*3 = idx*1.5
        ADD      r3,r2,r2,LSL #1
; R3 = R2+R2<<1 = R2+R2*2 = R2*3 = (idx>>1)*3 = idx/2*3 = idx*1.5
        ADD      r0,r0,r12
; R0 = R0+R12 = idx*1.5 + array
; jump if idx is even:
        BEQ      |L0.56|
; idx is odd, go on:
; load middle byte at R0+1:
        LDRB     r3,[r0,#1]
; R3 = middle byte
        AND      r3,r3,#0xf0
; R3 = R3&0xF0 = middle_byte&0xF0
        ORR      r2,r3,r1,LSR #8
; R2 = R3 | R1>>8 = middle_byte&0xF0 | val>>8
; store middle_byte&0xF0 | val>>8 at R0+1 (at the place of middle byte):
        STRB     r2,[r0,#1]
; store low 8 bits of val (or val&0xFF) at R0+2 (at the place of right byte):
        STRB     r1,[r0,#2]
        BX       lr
|L0.56|
; idx is even, go on:
        LSR      r2,r1,#4
; R2 = R1>>4 = val>>4
; store val>>4 at R12+R3 or array + idx*1.5 (place of left byte):
        STRB     r2,[r12,r3]
; load byte at R0+1 (middle byte):
        LDRB     r2,[r0,#1]
; R2 = middle_byte
; drop high 4 bits of middle byte:
        AND      r2,r2,#0xf
; R2 = R2&0xF = middle_byte&0xF
; update middle byte:
        ORR      r1,r2,r1,LSL #4
; R1 = R2 | R1<<4 = middle_byte&0xF | val<<4
; store updated middle byte at R0+1:
        STRB     r1,[r0,#1]
        BX       lr
ENDP
```

Value of *idx*1.5* is calculated twice, this is redundancy Keil compiler produced can be eliminated. You can rework assembly function as well to make it shorter. Do not forget about tests!

3.20.9 (32-bit ARM) Comparison of code density in Thumb and ARM modes

Thumb mode in ARM CPUs was introduced to make instructions shorter (16-bits) instead of 32-bit instructions in ARM mode. But as we can see, it's hard to say, if it was worth it: code in ARM mode is always shorter (however, instructions are longer).

3.20.10 Optimizing GCC 4.9.3 for ARM64

Getter

```
<get_from_array>:
; W0 = idx
   0:           lsr     w2, w0, #1
; W2 = W0>>1 = idx>>1
   4:           lsl     w1, w2, #2
; W1 = W2<<2 = (W0>>1)<<2 = (idx&(~1))<<1
```

```
   8:           sub     w1, w1, w2
; W1 = W1-W2 = (idx&(~1))<<1 - idx>>1 = idx*1.5
; now test lowest bit of idx and jump if it is present.
; (ARM64 has single instruction for these operations: TBNZ (Test and Branch Not Zero)).
   c:           tbnz    w0, #0, 30 <get_from_array+0x30>

; idx is even, go on:
  10:           adrp    x2, page of array
  14:           add     w3, w1, #0x1
; W3 = W1+1 = idx*1.5 + 1, i.e., offset of middle byte
  18:           add     x2, x2, offset of array within page
; load left byte at X2+W1 = array + idx*1.5 with sign-extension ("sxtw")
  1c:           ldrb    w0, [x2,w1,sxtw]
; load middle byte at X2+W3 = array + idx*1.5 + 1 with sign-extension ("sxtw")
  20:           ldrb    w1, [x2,w3,sxtw]
; W0 = left byte
; W1 = middle byte
  24:           lsl     w0, w0, #4
; W0 = W0<<4 = left_byte << 4
; merge parts:
  28:           orr     w0, w0, w1, lsr #4
; W0 = W0 | W1>>4 = left_byte << 4 | middle_byte >> 4
; value in W0 is returned
  2c:           ret

; idx is odd, go on:
  30:           adrp    x2, page of array
  34:           add     w0, w1, #0x1
; W0 = W1+1 = idx*1.5+1, i.e., offset of middle byte
  38:           add     x2, x2, address of array within page
  3c:           add     w1, w1, #0x2
; W1 = W1+2 = idx*1.5+2, i.e., offset of right byte
; load middle byte at X2+W0 = array+idx*1.5+1 with sign-extension ("sxtw")
  40:           ldrb    w0, [x2,w0,sxtw]
; load right byte at X2+W1 = array+idx*1.5+2 with sign-extension ("sxtw")
  44:           ldrb    w1, [x2,w1,sxtw]
; W0 = middle byte
; W1 = right byte
  48:           ubfiz   w0, w0, #8, #4
; W0 = middle_byte<<8
; now merge parts:
  4c:           orr     w0, w0, w1
; W0 = W0 | W1 = middle_byte<<8 | right_byte
; value in W0 is returned
  50:           ret
```

ARM64 has new cool instruction UBFIZ (*Unsigned bitfield insert in zero, with zeros to left and right*), which can be used to place specified number of bits from one register to another. It's alias of another instruction, UBFM (*Unsigned bitfield move, with zeros to left and right*). UBFM is the instruction used internally in ARM64 instead of LSL/LSR (bit shifts).

Setter

```
<put_to_array>:
W0 = idx
W1 = val
  54:           lsr     w3, w0, #1
; W3 = W0>>1 = idx>>1
  58:           lsl     w2, w3, #2
; W2 = W3<<2 = (W0>>1)<<2 = (idx&(~1))<<1
  5c:           sub     w2, w2, w3
; W2 = W2-W3 = (idx&(~1))<<1 - idx>>1 = idx*1.5
; jump if lowest bit in idx is 1:
  60:           tbnz    w0, #0, 94 <put_to_array+0x40>

; idx is even, go on:
  64:           adrp    x0, page of array
  68:           add     w3, w2, #0x1
```

```
; W3 = W2+1 = idx*1.5+1, i.e., offset of middle byte
  6c:           add     x0, x0, offset of array within page
; X0 = address of array
  70:           lsr     w4, w1, #4
; W4 = W1>>4 = val>>4
  74:           sxtw    x3, w3
; X3 = sign-extended 32-bit W3 (idx*1.5+1) to 64-bit
; sign-extension is needed here because the value will be used as offset within array,
; and negative offsets are possible in standard C/C++
  78:           ubfiz   w1, w1, #4, #4
; W1 = W1<<4 = val<<4
; store W4 (val>>4) at X0+W2 = array + idx*1.5, i.e., address of left byte:
  7c:           strb    w4, [x0,w2,sxtw]
; load middle byte at X0+X3 = array+idx*1.5+1
  80:           ldrb    w2, [x0,x3]
; W2 = middle byte
  84:           and     w2, w2, #0xf
; W2 = W2&0xF = middle_byte&0xF (high 4 bits in middle byte are dropped)
; merge parts of new version of middle byte:
  88:           orr     w1, w2, w1
; W1 = W2|W1 = middle_byte&0xF | val<<4
; store W2 (new middle byte) at X0+X3 = array+idx*1.5+1
  8c:           strb    w1, [x0,x3]
  90:           ret

; idx is odd, go on:
  94:           add     w4, w2, #0x1
; W4 = W2+1 = idx*1.5+1, i.e., offset of middle byte
  98:           adrp    x0, page of array
  9c:           add     x0, x0, offset of array within page
; X0 = address of array
  a0:           add     w2, w2, #0x2
; W2 = W2+2 = idx*1.5+2, i.e., offset of right byte
  a4:           sxtw    x4, w4
; X4 = sign-extended 64-bit version of 32-bit W4
; load at X0+X4 = array+idx*1.5+1:
  a8:           ldrb    w3, [x0,x4]
; W3 = middle byte
  ac:           and     w3, w3, #0xfffffff0
; W3 = W3&0xFFFFFFF0 = middle_byte&0xFFFFFFF0, i.e., clear lowest 4 bits
  b0:           orr     w3, w3, w1, lsr #8
; W3 = W3|W1>>8 = middle_byte&0xFFFFFFF0 | val>>8
; store new version of middle byte at X0+X4=array+idx*1.5+1:
  b4:           strb    w3, [x0,x4]
; now store lowest 8 bits of val (in W1) at X0+W2=array+idx*1.5+2, i.e., place of right byte
; SXTW suffix means W2 will be sign-extended to 64-bit value before summing with X0
  b8:           strb    w1, [x0,w2,sxtw]
  bc:           ret
```

3.20.11 Optimizing GCC 4.4.5 for MIPS

Needless to keep in mind that each instruction after jump/branch instruction is executed first. It's called *branch delay slot* in RISC CPUs lingo. To make things simpler, just swap instructions (mentally) in each instruction pair which is started with branch or jump instruction.

MIPS has no flags (apparently, to simplify data dependencies), so branch instructions (like BNE) does both comparison and branching.

There is also GP (Global Pointer) set up code in the function prologue, which can be ignored so far.

Getter

```
get_from_array:
; $4 = idx
        srl     $2,$4,1
; $2 = $4>>1 = idx>>1
```

```
        lui     $28,%hi(__gnu_local_gp)
        sll     $3,$2,1
; $3 = $2<<1 = (idx>>1)<<1 = idx&(~1)
        andi    $4,$4,0x1
; $4 = $4&1 = idx&1
        addiu   $28,$28,%lo(__gnu_local_gp)

; jump if $4 (idx&1) is not zero (if idx is odd):
        bne     $4,$0,$L6
; $2 = $3+$2 = idx>>1 + idx&(~1) = idx*1.5
        addu    $2,$3,$2 ; branch delay slot - this instruction executed before BNE

; idx is even, go on:
        lw      $3,%got(array)($28)
; $3 = array
        nop
        addu    $2,$3,$2
; $2 = $3+$2 = array + idx*1.5
; load byte at $2+0 = array + idx*1.5 (left byte):
        lbu     $3,0($2)
; $3 = left byte
; load byte at $2+1 = array + idx*1.5+1 (middle byte):
        lbu     $2,1($2)
; $2 = middle byte
        sll     $3,$3,4
; $3 = $3<<4 = left_byte<<4
        srl     $2,$2,4
; $2 = $2>>4 = middle_byte>>4
        j       $31
        or      $2,$2,$3 ; branch delay slot - this instruction executed before J
; $2 = $2|$3 = middle_byte>>4 | left_byte<<4
; $2=returned result

$L6:
; idx is odd, go on:
        lw      $3,%got(array)($28)
; $3 = array
        nop
        addu    $2,$3,$2
; $2 = $3+$2 = array + idx*1.5
; load byte at $2+1 = array + idx*1.5 + 1 (middle byte)
        lbu     $4,1($2)
; $4 = middle byte
; load byte at $2+1 = array + idx*1.5 + 2 (right byte)
        lbu     $3,2($2)
; $3 = right byte
        andi    $2,$4,0xf
; $2 = $4&0xF = middle_byte&0xF
        sll     $2,$2,8
; $2 = $2<<8 = middle_byte&0xF << 8
        j       $31
        or      $2,$2,$3 ; branch delay slot - this instruction executed before J
; $2 = $2|$3 = middle_byte&0xF << 8 | right byte
; $2=returned result
```

Setter

```
put_to_array:
; $4=idx
; $5=val
        srl     $2,$4,1
; $2 = $4>>1 = idx>>1
        lui     $28,%hi(__gnu_local_gp)
        sll     $3,$2,1
; $3 = $2<<1 = (idx>>1)<<1 = idx&(~1)
        andi    $4,$4,0x1
; $4 = $4&1 = idx&1
        addiu   $28,$28,%lo(__gnu_local_gp)
```

```
; jump if $4=idx&1 is not zero (i.e., if idx is odd):
        bne     $4,$0,$L11
        addu    $2,$3,$2 ; branch delay slot, this instruction is executed before BNE
; $2 = $3+$2 = idx&(~1) + idx>>1 = idx*1.5

; idx is even, go on
        lw      $3,%got(array)($28)
; $3 = array
        addiu   $4,$2,1
; $4 = $2+1 = idx*1.5+1, i.e., offset of middle byte in array
        srl     $6,$5,4
; $6 = $5>>4 = val>>4
        addu    $2,$3,$2
; $2 = $3+$2 = array + idx*1.5 (offset of left byte)
; store $6 (val>>4) as left byte:
        sb      $6,0($2)
        addu    $2,$3,$4
; $2 = $3+$4 = array + idx*1.5 + 1 (absolute address of middle byte)
; load middle byte at $2+0 = array + idx*1.5 + 1
        lbu     $3,0($2)
; $3 = middle byte
        andi    $5,$5,0xf
; $5 = $5&0xF = val&0xF
        andi    $3,$3,0xf
; $3 = $3&0xF = middle_byte&0xF
        sll     $5,$5,4
; $5 = $5<<4 = (val&0xF)<<4
        or      $5,$3,$5
; $5 = $3|$5 = middle_byte&0xF | (val&0xF)<<4 (new version of middle byte)
        j       $31
; store $5 (new middle byte) at $2 (array + idx*1.5 + 1)
        sb      $5,0($2) ; branch delay slot, this instruction is executed before J

$L11:
; idx is odd, go on
        lw      $4,%got(array)($28)
; $4 = array
        addiu   $3,$2,1
; $3 = $2+1 = idx*1.5+1 (offset of middle byte)
        addu    $3,$4,$3
; $3 = $4+$3 = array + idx*1.5+1
; load middle byte at $3 (array + idx*1.5+1)
        lbu     $6,0($3)
; $6 = middle byte
        srl     $7,$5,8
; $7 = $5>>8 = val>>8
        andi    $6,$6,0xf0
; $6 = $6&0xF0 = middle_byte&0xF0
        or      $6,$6,$7
; $6 = $6|$7 = middle_byte&0xF0 | val>>8
        addu    $2,$4,$2
; store updated middle byte at $3 (array + idx*1.5+1)
        sb      $6,0($3)
        j       $31
; store low 8 bits of val at $2+2=idx*1.5+2 (place of right byte)
        sb      $5,2($2) ; branch delay slot, this instruction is executed before J
```

3.20.12 Difference from the real FAT12

The real FAT12 table is slightly different: https://en.wikipedia.org/wiki/Design_of_the_FAT_file_system#Cluster_map.

For even elements:

```
 +0 +1 +2
|23|.1|..|..
```

For odd elements:

```
 +0 +1 +2
|..|3.|12|..
```

Here are FAT12-related functions in Linux Kernel:
fat12_ent_get(), fat12_ent_put().

Nevertheless, I did as I did because values are better visible and recognizable in byte-level GDB dump, for the sake of demonstration.

3.20.13 Exercise

Perhaps, there could be a way to store data in a such way, so getter/setter functions would be faster. If we would place values in this way:

(Even elements)

```
 +0 +1 +2
|23|1.|..|..
```

(Odd elements)

```
 +0 +1 +2
|..|.1|23|..
```

This schema of storing data will allow to eliminate at least one shift operation. As an exercise, you may rework my C/C++ code in that way and see what compiler will produce.

3.20.14 Summary

Bit shifts (<< and >> in C/C++, SHL/SHR/SAL/SAR in x86, LSL/LSR in ARM, SLL/SRL in MIPS) are used to place bit(s) to specific place.

AND operation (& in C/C++, `AND` in x86/ARM) is used to drop unneeded bits, also during isolation.

OR operation (| in C/C++, `OR` in x86/ARM) is used to merge or combine several values into one. One input value must have zero space at the place where another value has its information-caring bits.

ARM64 has new instructions `UBFM`, `UFBIZ` to move specific bits from one register to another.

3.20.15 Conclusion

FAT12 is hardly used somewhere nowadays, but if you have space constraints and you have to store values limited to 12 bits, you may consider tightly-packed array in the manner it's done in FAT12 table.

3.21 More about pointers

> The way C handles pointers, for example, was a brilliant innovation; it solved a lot of problems that we had before in data structuring and made the programs look good afterwards.
>
> Donald Knuth, interview (1993)

For those, who still have hard time understanding C/C++ pointers, here are more examples. Some of them are weird and serves only demonstration purpose: use them in production code only if you really know what you're doing.

3.21.1 Working with addresses instead of pointers

Pointer is just an address in memory. But why we write `char* string` instead of something like `address string`? Pointer variable is supplied with a type of the value to which pointer points. So then compiler will be able to catch data typization bugs during compilation.

To be pedantic, data typing in programming languages is all about preventing bugs and self-documentation. It's possible to use maybe two of data types like *int* (or *int64_t*) and byte—these are the only types which are available to assembly language programmers. But it's just very hard task to write big and practical assembly programs without nasty bugs. Any small typo can lead to hard-to-find bug.

Data type information is absent in a compiled code (and this is one of the main problems for decompilers), and I can demonstrate this.

This is what sane C/C++ programmer can write:

```
#include <stdio.h>
#include <stdint.h>

void print_string (char *s)
{
        printf ("(address: 0x%llx)\n", s);
        printf ("%s\n", s);
};

int main()
{
        char *s="Hello, world!";

        print_string (s);
};
```

This is what I can write:

```
#include <stdio.h>
#include <stdint.h>

void print_string (uint64_t address)
{
        printf ("(address: 0x%llx)\n", address);
        puts ((char*)address);
};

int main()
{
        char *s="Hello, world!";

        print_string ((uint64_t)s);
};
```

I use *uint64_t* because I run this example on Linux x64. *int* would work for 32-bit OS-es. First, a pointer to character (the very first in the greeting string) is casted to *uint64_t*, then it's passed further. `print_string()` function casts back incoming *uint64_t* value into pointer to a character.

What is interesting is that GCC 4.8.4 produces identical assembly output for both versions:

```
gcc 1.c -S -masm=intel -O3 -fno-inline
```

```
.LC0:
        .string "(address: 0x%llx)\n"
print_string:
        push    rbx
        mov     rdx, rdi
        mov     rbx, rdi
        mov     esi, OFFSET FLAT:.LC0
        mov     edi, 1
        xor     eax, eax
        call    __printf_chk
        mov     rdi, rbx
        pop     rbx
```

```
        jmp     puts
.LC1:
        .string "Hello, world!"
main:
        sub     rsp, 8
        mov     edi, OFFSET FLAT:.LC1
        call    print_string
        add     rsp, 8
        ret
```

(I've removed all insignificant GCC directives.)

I also tried UNIX *diff* utility and it shows no differences at all.

Let's continue to abuse C/C++ programming traditions heavily. Someone may write this:

```
#include <stdio.h>
#include <stdint.h>

uint8_t load_byte_at_address (uint8_t* address)
{
        return *address;
        //this is also possible: return address[0];
};

void print_string (char *s)
{
        char* current_address=s;
        while (1)
        {
                char current_char=load_byte_at_address(current_address);
                if (current_char==0)
                        break;
                printf ("%c", current_char);
                current_address++;
        };
};

int main()
{
        char *s="Hello, world!";

        print_string (s);
};
```

It can be rewritten like this:

```
#include <stdio.h>
#include <stdint.h>

uint8_t load_byte_at_address (uint64_t address)
{
        return *(uint8_t*)address;
        //this is also possible: return address[0];
};

void print_string (uint64_t address)
{
        uint64_t current_address=address;
        while (1)
        {
                char current_char=load_byte_at_address(current_address);
                if (current_char==0)
                        break;
                printf ("%c", current_char);
                current_address++;
        };
};

int main()
{
```

```
        char *s="Hello, world!";

        print_string ((uint64_t)s);
};
```

Both source codes resulting in the same assembly output:

```
gcc 1.c -S -masm=intel -O3 -fno-inline
```

```
load_byte_at_address:
        movzx   eax, BYTE PTR [rdi]
        ret
print_string:
.LFB15:
        push    rbx
        mov     rbx, rdi
        jmp     .L4
.L7:
        movsx   edi, al
        add     rbx, 1
        call    putchar
.L4:
        mov     rdi, rbx
        call    load_byte_at_address
        test    al, al
        jne     .L7
        pop     rbx
        ret
.LC0:
        .string "Hello, world!"
main:
        sub     rsp, 8
        mov     edi, OFFSET FLAT:.LC0
        call    print_string
        add     rsp, 8
        ret
```

(I have also removed all insignificant GCC directives.)

No difference: C/C++ pointers are essentially addresses, but supplied with type information, in order to prevent possible mistakes at the time of compilation. Types are not checked during runtime—it would be huge (and unneeded) overhead.

3.21.2 Passing values as pointers; tagged unions

Here is an example on how to pass values in pointers:

```
#include <stdio.h>
#include <stdint.h>

uint64_t multiply1 (uint64_t a, uint64_t b)
{
        return a*b;
};

uint64_t* multiply2 (uint64_t *a, uint64_t *b)
{
        return (uint64_t*)((uint64_t)a*(uint64_t)b);
};

int main()
{
        printf ("%d\n", multiply1(123, 456));
        printf ("%d\n", (uint64_t)multiply2((uint64_t*)123, (uint64_t*)456));
};
```

It works smoothly and GCC 4.8.4 compiles both multiply1() and multiply2() functions identically!

```
multiply1:
        mov     rax, rdi
        imul    rax, rsi
        ret

multiply2:
        mov     rax, rdi
        imul    rax, rsi
        ret
```

As long as you do not dereference pointer (in other words, you don't read any data from the address stored in pointer), everything will work fine. Pointer is a variable which can store anything, like usual variable.

Signed multiplication instruction (IMUL) is used here instead of unsigned one (MUL), read more about it here: 2.2.1.

By the way, it's well-known hack to abuse pointers a little called *tagged pointers*. In short, if all your pointers points to blocks of memory with size of, let's say, 16 bytes (or it is always aligned on 16-byte boundary), 4 lowest bits of pointer is always zero bits and this space can be used somehow. It's very popular in LISP compilers and interpreters. They store cell/object type in these unused bits, this can save some memory. Even more, you can judge about cell/object type using just pointer, with no additional memory access. Read more about it: [Dennis Yurichev, *C/C++ programming language notes*1.3].

3.21.3 Pointers abuse in Windows kernel

The resource section of PE executable file in Windows OS is a section containing pictures, icons, strings, etc. Early Windows versions allowed to address resources only by IDs, but then Microsoft added a way to address them using strings.

So then it would be possible to pass ID or string to FindResource() function. Which is declared like this:

```
HRSRC WINAPI FindResource(
  _In_opt_ HMODULE hModule,
  _In_     LPCTSTR lpName,
  _In_     LPCTSTR lpType
);
```

lpName and *lpType* has *char** or *wchar** types, and when someone still wants to pass ID, he/she have to use MAKEINTRESOURCE macro, like this:

```
result = FindResource(..., MAKEINTRESOURCE(1234), ...);
```

It's interesting fact that MAKEINTRESOURCE is merely casting integer to pointer. In MSVC 2013, in the file *Microsoft SDKs\Windows\v7.1A\Include\Ks.h* we can find this:

```
...

#if (!defined( MAKEINTRESOURCE ))
#define MAKEINTRESOURCE( res ) ((ULONG_PTR) (USHORT) res)
#endif

...
```

Sounds insane. Let's peek into ancient leaked Windows NT4 source code. In *private/windows/base/client/module.c* we can find *FindResource()* source code:

```
HRSRC
FindResourceA(
    HMODULE hModule,
    LPCSTR lpName,
    LPCSTR lpType
    )

...

{
    NTSTATUS Status;
```

```
    ULONG IdPath[ 3 ];
    PVOID p;

    IdPath[ 0 ] = 0;
    IdPath[ 1 ] = 0;
    try {
        if ((IdPath[ 0 ] = BaseDllMapResourceIdA( lpType )) == -1) {
            Status = STATUS_INVALID_PARAMETER;
            }
        else
        if ((IdPath[ 1 ] = BaseDllMapResourceIdA( lpName )) == -1) {
            Status = STATUS_INVALID_PARAMETER;
...
```

Let's proceed to *BaseDllMapResourceIdA()* in the same source file:

```
ULONG
BaseDllMapResourceIdA(
    LPCSTR lpId
    )
{
    NTSTATUS Status;
    ULONG Id;
    UNICODE_STRING UnicodeString;
    ANSI_STRING AnsiString;
    PWSTR s;

    try {
        if ((ULONG)lpId & LDR_RESOURCE_ID_NAME_MASK) {
            if (*lpId == '#') {
                Status = RtlCharToInteger( lpId+1, 10, &Id );
                if (!NT_SUCCESS( Status ) || Id & LDR_RESOURCE_ID_NAME_MASK) {
                    if (NT_SUCCESS( Status )) {
                        Status = STATUS_INVALID_PARAMETER;
                        }
                    BaseSetLastNTError( Status );
                    Id = (ULONG)-1;
                    }
                }
            else {
                RtlInitAnsiString( &AnsiString, lpId );
                Status = RtlAnsiStringToUnicodeString( &UnicodeString,
                                                       &AnsiString,
                                                       TRUE
                                                     );
                if (!NT_SUCCESS( Status )){
                    BaseSetLastNTError( Status );
                    Id = (ULONG)-1;
                    }
                else {
                    s = UnicodeString.Buffer;
                    while (*s != UNICODE_NULL) {
                        *s = RtlUpcaseUnicodeChar( *s );
                        s++;
                        }

                    Id = (ULONG)UnicodeString.Buffer;
                    }
                }
            }
        else {
            Id = (ULONG)lpId;
            }
        }
    except (EXCEPTION_EXECUTE_HANDLER) {
        BaseSetLastNTError( GetExceptionCode() );
        Id =  (ULONG)-1;
        }
    return Id;
}
```

lpId is ANDed with *LDR_RESOURCE_ID_NAME_MASK*. Which we can find in *public/sdk/inc/ntldr.h*:

```
...

#define LDR_RESOURCE_ID_NAME_MASK 0xFFFF0000

...
```

So *lpId* is ANDed with *0xFFFF0000* and if some bits beyond lowest 16 bits are still present, first half of function is executed (*lpId* is treated as an address of string). Otherwise—second half (*lpId* is treated as 16-bit value).

Still, this code can be found in Windows 7 kernel32.dll file:

```
....

.text:0000000078D24510 ; __int64 __fastcall BaseDllMapResourceIdA(PCSZ SourceString)
.text:0000000078D24510 BaseDllMapResourceIdA proc near         ; CODE XREF: FindResourceExA+34
.text:0000000078D24510                                         ; FindResourceExA+4B
.text:0000000078D24510
.text:0000000078D24510 var_38          = qword ptr -38h
.text:0000000078D24510 var_30          = qword ptr -30h
.text:0000000078D24510 var_28          = _UNICODE_STRING ptr -28h
.text:0000000078D24510 DestinationString= _STRING ptr -18h
.text:0000000078D24510 arg_8           = dword ptr  10h
.text:0000000078D24510
.text:0000000078D24510 ; FUNCTION CHUNK AT .text:0000000078D42FB4 SIZE 000000D5 BYTES
.text:0000000078D24510
.text:0000000078D24510                 push    rbx
.text:0000000078D24512                 sub     rsp, 50h
.text:0000000078D24516                 cmp     rcx, 10000h
.text:0000000078D2451D                 jnb     loc_78D42FB4
.text:0000000078D24523                 mov     [rsp+58h+var_38], rcx
.text:0000000078D24528                 jmp     short $+2
.text:0000000078D2452A ; ↙
    ↳ ---------------------------------------------------------------------------
.text:0000000078D2452A
.text:0000000078D2452A loc_78D2452A:                           ; CODE XREF: ↙
    ↳ BaseDllMapResourceIdA+18
.text:0000000078D2452A                                         ; BaseDllMapResourceIdA+1EAD0
.text:0000000078D2452A                 jmp     short $+2
.text:0000000078D2452C ; ↙
    ↳ ---------------------------------------------------------------------------
.text:0000000078D2452C
.text:0000000078D2452C loc_78D2452C:                           ; CODE XREF: ↙
    ↳ BaseDllMapResourceIdA:loc_78D2452A
.text:0000000078D2452C                                         ; BaseDllMapResourceIdA+1EB74
.text:0000000078D2452C                 mov     rax, rcx
.text:0000000078D2452F                 add     rsp, 50h
.text:0000000078D24533                 pop     rbx
.text:0000000078D24534                 retn
.text:0000000078D24534 ; ↙
    ↳ ---------------------------------------------------------------------------
.text:0000000078D24535                 align 20h
.text:0000000078D24535 BaseDllMapResourceIdA endp

....

.text:0000000078D42FB4 loc_78D42FB4:                           ; CODE XREF: ↙
    ↳ BaseDllMapResourceIdA+D
.text:0000000078D42FB4                 cmp     byte ptr [rcx], '#'
.text:0000000078D42FB7                 jnz     short loc_78D43005
.text:0000000078D42FB9                 inc     rcx
.text:0000000078D42FBC                 lea     r8, [rsp+58h+arg_8]
.text:0000000078D42FC1                 mov     edx, 0Ah
.text:0000000078D42FC6                 call    cs:__imp_RtlCharToInteger
.text:0000000078D42FCC                 mov     ecx, [rsp+58h+arg_8]
.text:0000000078D42FD0                 mov     [rsp+58h+var_38], rcx
.text:0000000078D42FD5                 test    eax, eax
.text:0000000078D42FD7                 js      short loc_78D42FE6
.text:0000000078D42FD9                 test    rcx, 0FFFFFFFFFFFF0000h
```

```
.text:0000000078D42FE0                 jz      loc_78D2452A

....
```

If value in input pointer is greater than 0x10000, jump to string processing is occurred. Otherwise, input value of *lpId* is returned as is. *0xFFFF0000* mask is not used here any more, because this is 64-bit code after all, but still, *0xFFFFFFFFFFFF0000* could work here.

Attentive reader may ask, what if address of input string is lower than 0x10000? This code relied on the fact that in Windows there are nothing on addresses below 0x10000, at least in Win32 realm.

Raymond Chen writes about this:

> How does MAKEINTRESOURCE work? It just stashes the integer in the bottom 16 bits of a pointer, leaving the upper bits zero. This relies on the convention that the first 64KB of address space is never mapped to valid memory, a convention that is enforced starting in Windows 7.

In short words, this is dirty hack and probably one should use it only if there is a real necessity. Perhaps, *FindResource()* function in past had *SHORT* type for its arguments, and then Microsoft has added a way to pass strings there, but older code must also be supported.

Now here is my short distilled example:

```
#include <stdio.h>
#include <stdint.h>

void f(char* a)
{
        if (((uint64_t)a)>0x10000)
                printf ("Pointer to string has been passed: %s\n", a);
        else
                printf ("16-bit value has been passed: %d\n", (uint64_t)a);
};

int main()
{
        f("Hello!"); // pass string
        f((char*)1234); // pass 16-bit value
};
```

It works!

Pointers abuse in Linux kernel

As it has been noted in comments on Hacker News, Linux kernel also has something like that.

For example, this function can return both error code and pointer:

```
struct kernfs_node *kernfs_create_link(struct kernfs_node *parent,
                                       const char *name,
                                       struct kernfs_node *target)
{
        struct kernfs_node *kn;
        int error;

        kn = kernfs_new_node(parent, name, S_IFLNK|S_IRWXUGO, KERNFS_LINK);
        if (!kn)
                return ERR_PTR(-ENOMEM);

        if (kernfs_ns_enabled(parent))
                kn->ns = target->ns;
        kn->symlink.target_kn = target;
        kernfs_get(target);     /* ref owned by symlink */

        error = kernfs_add_one(kn);
        if (!error)
                return kn;
```

```
        kernfs_put(kn);
        return ERR_PTR(error);
}
```

(https://github.com/torvalds/linux/blob/fceef393a538134f03b778c5d2519e670269342f/fs/kernfs/symlink.c#L25)

ERR_PTR is a macro to cast integer to pointer:

```
static inline void * __must_check ERR_PTR(long error)
{
        return (void *) error;
}
```

(https://github.com/torvalds/linux/blob/61d0b5a4b2777dcf5daef245e212b3c1fa8091ca/tools/virtio/linux/err.h)

This header file also has a macro helper to distinguish error code from pointer:

```
#define IS_ERR_VALUE(x) unlikely((x) >= (unsigned long)-MAX_ERRNO)
```

This means, error codes are the "pointers" which are very close to -1 and, hopefully, there are nothing in kernel memory on the addresses like 0xFFFFFFFFFFFFFFFF, 0xFFFFFFFFFFFFFFFE, 0xFFFFFFFFFFFFFFFD, etc.

Much more popular solution is to return *NULL* in case of error and to pass error code via additional argument. Linux kernel authors don't do that, but everyone who use these functions must always keep in mind that returning pointer must always be checked with *IS_ERR_VALUE* before dereferencing.

For example:

```
        fman->cam_offset = fman_muram_alloc(fman->muram, fman->cam_size);
        if (IS_ERR_VALUE(fman->cam_offset)) {
                dev_err(fman->dev, "%s: MURAM alloc for DMA CAM failed\n",
                        __func__);
                return -ENOMEM;
        }
```

(https://github.com/torvalds/linux/blob/aa00edc1287a693eadc7bc67a3d73555d969b35d/drivers/net/ethernet/freescale/fman/fman.c#L826)

Pointers abuse in UNIX userland

mmap() function returns -1 in case of error (or `MAP_FAILED`, which equals to -1). Some people say, mmap() can map a memory at zeroth address in rare situations, so it can't use 0 or NULL as error code.

3.21.4 Null pointers

"Null pointer assignment" error of MS-DOS era

Some oldschoolers may recall a weird error message of MS-DOS era: "Null pointer assignment". What does it mean?

It's not possible to write a memory at zero address in *NIX and Windows OSes, but it was possible to do so in MS-DOS due to absence of memory protection whatsoever.

So I've pulled my ancient Turbo C++ 3.0 (later it was renamed to Borland C++) from early 1990s and tried to compile this:

```
#include <stdio.h>

int main()
{
        int *ptr=NULL;
        *ptr=1234;
        printf ("Now let's read at NULL\n");
```

```
        printf ("%d\n", *ptr);
};
```

Hard to believe, but it works, with error upon exit, though:

Listing 3.121: Ancient Turbo C 3.0

```
C:\TC30\BIN\1
Now let's read at NULL
1234
Null pointer assignment

C:\TC30\BIN>_
```

Let’s dig deeper into the source code of CRT of Borland C++ 3.1, file *c0.asm*:

```
;       _checknull()    check for null pointer zapping copyright message

...

;       Check for null pointers before exit

__checknull     PROC    DIST
                PUBLIC  __checknull

IF      LDATA  EQ  false
  IFNDEF  __TINY__
                push    si
                push    di
                mov     es, cs:DGROUP@@
                xor     ax, ax
                mov     si, ax
                mov     cx, lgth_CopyRight
ComputeChecksum label   near
                add     al, es:[si]
                adc     ah, 0
                inc     si
                loop    ComputeChecksum
                sub     ax, CheckSum
                jz      @@SumOK
                mov     cx, lgth_NullCheck
                mov     dx, offset DGROUP: NullCheck
                call    ErrorDisplay
@@SumOK:        pop     di
                pop     si
  ENDIF
ENDIF

_DATA           SEGMENT

;       Magic symbol used by the debug info to locate the data segment
                public DATASEG@
DATASEG@        label   byte

;       The CopyRight string must NOT be moved or changed without
;       changing the null pointer check logic

CopyRight       db      4 dup(0)
                db      'Borland C++ - Copyright 1991 Borland Intl.',0
lgth_CopyRight  equ     $ - CopyRight

IF      LDATA  EQ  false
IFNDEF  __TINY__
CheckSum        equ     00D5Ch
NullCheck       db      'Null pointer assignment', 13, 10
lgth_NullCheck  equ     $ - NullCheck
ENDIF
ENDIF

...
```

The MS-DOS memory model was really weird (11.6) and probably not worth looking into it unless you're fan of retrocomputing or retrogaming. One thing we have to keep in mind is that memory segment (included data segment) in MS-DOS is a memory segment in which code or data is stored, but unlike "serious" OSes, it's started at address 0.

And in Borland C++ CRT, the data segment is started with 4 zero bytes and the copyright string "Borland C++ - Copyright 1991 Borland Intl.". The integrity of the 4 zero bytes and text string is checked upon exit, and if it's corrupted, the error message is displayed.

But why? Writing at null pointer is common mistake in C/C++, and if you do so in *NIX or Windows, your application will crash. MS-DOS has no memory protection, so CRT has to check this post-factum and warn about it upon exit. If you see this message, this means, your program at some point has written at address 0.

Our program did so. And this is why 1234 number has been read correctly: because it was written at the place of the first 4 zero bytes. Checksum is incorrect upon exit (because the number has been left there), so error message has been displayed.

Am I right? I've rewritten the program to check my assumptions:

```
#include <stdio.h>

int main()
{
        int *ptr=NULL;
        *ptr=1234;
        printf ("Now let's read at NULL\n");
        printf ("%d\n", *ptr);
        *ptr=0; // psst, cover our tracks!
};
```

This program executes without error message upon exit.

Though method to warn about null pointer assignment is relevant for MS-DOS, perhaps, it can still be used today in low-cost MCUs with no memory protection and/or MMU[37].

Why would anyone write at address 0?

But why would sane programmer write a code which writes something at address 0? It can be done accidentally: for example, a pointer must be initialized to newly allocated memory block and then passed to some function which returns data through pointer.

```
int *ptr=NULL;

... we forgot to allocate memory and initialize ptr

strcpy (ptr, buf); // strcpy() terminates silently because MS-DOS has no memory protection
```

Even worse:

```
int *ptr=malloc(1000);

... we forgot to check if memory has been really allocated: this is MS-DOS after all and ↙
    ↘ computers had small amount of RAM,
... and RAM shortage was very common.
... if malloc() returned NULL, the ptr will also be NULL.

strcpy (ptr, buf); // strcpy() terminates silently because MS-DOS has no memory protection
```

NULL in C/C++

NULL in C/C++ is just a macro which is often defined like this:

```
#define NULL  ((void*)0)
```

[37] Memory Management Unit

(libio.h file)

*void** is a data type reflecting the fact it's the pointer, but to a value of unknown data type (*void*).

NULL is usually used to show absence of an object. For example, you have a single-linked list, and each node has a value (or pointer to a value) and *next* pointer. To show that there are no next node, 0 is stored to *next* field. Other solutions are just worse. Perhaps, you may have some crazy environment where you need to allocate memory blocks at zero address. How would you indicate absence of the next node? Some kind of *magic number*? Maybe -1? Or maybe using additional bit?

In Wikipedia we may find this:

> In fact, quite contrary to the zero page's original preferential use, some modern operating systems such as FreeBSD, Linux and Microsoft Windows[2] actually make the zero page inaccessible to trap uses of NULL pointers.

(https://en.wikipedia.org/wiki/Zero_page)

Null pointer to function

It's possible to call function by its address. For example, I compile this by MSVC 2010 and run it in Windows 7:

```
#include <windows.h>
#include <stdio.h>

int main()
{
        printf ("0x%x\n", &MessageBoxA);
};
```

The result is *0x7578feae* and doesn't changing after several times I run it, because user32.dll (where MessageBoxA function resides) is always loads at the same address. And also because ASLR[38] is not enabled (result would be different each time in that case).

Let's call *MessageBoxA()* by address:

```
#include <windows.h>
#include <stdio.h>

typedef int (*msgboxtype)(HWND hWnd, LPCTSTR lpText, LPCTSTR lpCaption,  UINT uType);

int main()
{
        msgboxtype msgboxaddr=0x7578feae;

        // force to load DLL into process memory,
        // since our code doesn't use any function from user32.dll,
        // and DLL is not imported
        LoadLibrary ("user32.dll");

        msgboxaddr(NULL, "Hello, world!", "hello", MB_OK);
};
```

Weird, but works in Windows 7 x86.

This is commonly used in shellcodes, because it's hard to call DLL functions by name from there. And ASLR is a countermeasure.

Now what is really weird, some embedded C programmers may be familiar with a code like that:

```
int reset()
{
        void (*foo)(void) = 0;
        foo();
};
```

[38] Address Space Layout Randomization

Who will want to call a function at address 0? This is portable way to jump at zero address. Many low-cost cheap microcontrollers also have no memory protection or MMU and after reset, they start to execute code at address 0, where some kind of initialization code is stored. So jumping to address 0 is a way to reset itself. One could use inline assembly, but if it's not possible, this portable method can be used.

It even compiles correctly by my GCC 4.8.4 on Linux x64:

```
reset:
        sub     rsp, 8
        xor     eax, eax
        call    rax
        add     rsp, 8
        ret
```

The fact that stack pointer is shifted is not a problem: initialization code in microcontrollers usually completely ignores registers and RAM state and boots from scratch.

And of course, this code will crash on *NIX or Windows because of memory protection and even in absence of protection, there are no code at address 0.

GCC even has non-standard extension, allowing to jump to a specific address rather than call a function there: http://gcc.gnu.org/onlinedocs/gcc/Labels-as-Values.html.

3.21.5 Array as function argument

Someone may ask, what is the difference between declaring function argument type as array and as pointer?

As it seems, there are no difference at all:

```
void write_something1(int a[16])
{
        a[5]=0;
};

void write_something2(int *a)
{
        a[5]=0;
};

int f()
{
        int a[16];
        write_something1(a);
        write_something2(a);
};
```

Optimizing GCC 4.8.4:

```
write_something1:
        mov     DWORD PTR [rdi+20], 0
        ret

write_something2:
        mov     DWORD PTR [rdi+20], 0
        ret
```

But you may still declare array instead of pointer for self-documenting purposes, if the size of array is always fixed. And maybe, some static analysis tool will be able to warn you about possible buffer overflow. Or is it possible with some tools today?

Some people, including Linus Torvalds, criticizes this C/C++ feature: https://lkml.org/lkml/2015/9/3/428.

C99 standard also have *static* keyword [*ISO/IEC 9899:TC3 (C C99 standard)*, (2007) 6.7.5.3]:

> If the keyword static also appears within the [and] of the array type derivation, then for each call to the function, the value of the corresponding actual argument shall provide access to the first element of an array with at least as many elements as specified by the size expression.

3.21.6 Pointer to function

A function name in C/C++ without brackets, like "printf" is a pointer to function of *void (*)()* type. Let's try to read function's contents and patch it:

```
#include <memory.h>
#include <stdio.h>

void print_something ()
{
        printf ("we are in %s()\n", __FUNCTION__);
};

int main()
{
        print_something();
        printf ("first 3 bytes: %x %x %x...\n",
                        *(unsigned char*)print_something,
                        *((unsigned char*)print_something+1),
                        *((unsigned char*)print_something+2));

        *(unsigned char*)print_something=0xC3; // opecode of RET
        printf ("going to call patched print_something():\n");
        print_something();
        printf ("it must exit at this point\n");

};
```

It tells, that the first 3 bytes of functions are `55 89 e5`. Indeed, these are opcodes of `PUSH EBP` and `MOV EBP, ESP` instructions (these are x86 opcodes). But then our program crashes, because *text* section is readonly.

We can recompile our example and make *text* section writable [39]:

```
gcc --static -g -Wl,--omagic -o example example.c
```

That works!

```
we are in print_something()
first 3 bytes: 55 89 e5...
going to call patched print_something():
it must exit at this point
```

3.21.7 Pointer as object identificator

Both assembly language and C has no OOP features, but it's possible to write a code in OOP style (just treat structure as an object).

It's interesting, that sometimes, pointer to an object (or its address) is called as ID (in sense of data hiding/encapsulation).

For example, LoadLibrary(), according to MSDN[40], returns "handle to the module" [41]. Then you pass this "handle" to other functions like GetProcAddress(). But in fact, LoadLibrary() returns pointer to DLL file mapped into memory [42]. You can read two bytes from the address LoadLibrary() returns, and that would be "MZ" (first two bytes of any .EXE/.DLL file in Windows).

[39] `http://stackoverflow.com/questions/27581279/make-text-segment-writable-elf`
[40] Microsoft Developer Network
[41] `https://msdn.microsoft.com/ru-ru/library/windows/desktop/ms684175(v=vs.85).aspx`
[42] `https://blogs.msdn.microsoft.com/oldnewthing/20041025-00/?p=37483`

Apparently, Microsoft “hides” that fact to provide better forward compatibility. Also, HMODULE and HINSTANCE data types had another meaning in 16-bit Windows.

Probably, this is reason why `printf()` has “%p” modifier, which is used for printing pointers (32-bit integers on 32-bit architectures, 64-bit on 64-bit, etc) in hexadecimal form. Address of a structure dumped into debug log may help in finding it in another place of log.

Here is also from SQLite source code:

```
...

struct Pager {
  sqlite3_vfs *pVfs;          /* OS functions to use for IO */
  u8 exclusiveMode;           /* Boolean. True if locking_mode==EXCLUSIVE */
  u8 journalMode;             /* One of the PAGER_JOURNALMODE_* values */
  u8 useJournal;              /* Use a rollback journal on this file */
  u8 noSync;                  /* Do not sync the journal if true */

....

static int pagerLockDb(Pager *pPager, int eLock){
  int rc = SQLITE_OK;

  assert( eLock==SHARED_LOCK || eLock==RESERVED_LOCK || eLock==EXCLUSIVE_LOCK );
  if( pPager->eLock<eLock || pPager->eLock==UNKNOWN_LOCK ){
    rc = sqlite3OsLock(pPager->fd, eLock);
    if( rc==SQLITE_OK && (pPager->eLock!=UNKNOWN_LOCK||eLock==EXCLUSIVE_LOCK) ){
      pPager->eLock = (u8)eLock;
      IOTRACE(("LOCK %p %d\n", pPager, eLock))
    }
  }
  return rc;
}

...

  PAGER_INCR(sqlite3_pager_readdb_count);
  PAGER_INCR(pPager->nRead);
  IOTRACE(("PGIN %p %d\n", pPager, pgno));
  PAGERTRACE(("FETCH %d page %d hash(%08x)\n",
               PAGERID(pPager), pgno, pager_pagehash(pPg)));

...
```

3.22 Loop optimizations

3.22.1 Weird loop optimization

This is a simplest ever memcpy() function implementation:

```
void memcpy (unsigned char* dst, unsigned char* src, size_t cnt)
{
        size_t i;
        for (i=0; i<cnt; i++)
                dst[i]=src[i];
};
```

At least MSVC 6.0 from the end of 1990s till MSVC 2013 can produce a really weird code (this listing is generated by MSVC 2013 x86):

```
_dst$ = 8               ; size = 4
_src$ = 12              ; size = 4
_cnt$ = 16              ; size = 4
_memcpy PROC
        mov     edx, DWORD PTR _cnt$[esp-4]
        test    edx, edx
```

```
        je      SHORT $LN1@f
        mov     eax, DWORD PTR _dst$[esp-4]
        push    esi
        mov     esi, DWORD PTR _src$[esp]
        sub     esi, eax
; ESI=src-dst, i.e., pointers difference
$LL8@f:
        mov     cl, BYTE PTR [esi+eax] ; load byte at "esi+dst" or at "src-dst+dst" at the ↙
    ↳ beginning or at just "src"
        lea     eax, DWORD PTR [eax+1] ; dst++
        mov     BYTE PTR [eax-1], cl   ; store the byte at "(dst++)--" or at just "dst" at the ↙
    ↳ beginning
        dec     edx                    ; decrement counter until we finished
        jne     SHORT $LL8@f
        pop     esi
$LN1@f:
        ret     0
_memcpy ENDP
```

This is weird, because how humans work with two pointers? They store two addresses in two registers or two memory cells. MSVC compiler in this case stores two pointers as one pointer (*sliding dst* in EAX) and difference between *src* and *dst* pointers (left unchanged over the span of loop body execution in ESI). (By the way, this is a rare case when ptrdiff_t data type can be used.) When it needs to load a byte from *src*, it loads it at *diff* + *sliding dst* and stores byte at just *sliding dst*.

This has to be some optimization trick. But I've rewritten this function to:

```
_f2     PROC
        mov     edx, DWORD PTR _cnt$[esp-4]
        test    edx, edx
        je      SHORT $LN1@f
        mov     eax, DWORD PTR _dst$[esp-4]
        push    esi
        mov     esi, DWORD PTR _src$[esp]
        ; eax=dst; esi=src
$LL8@f:
        mov     cl, BYTE PTR [esi+edx]
        mov     BYTE PTR [eax+edx], cl
        dec     edx
        jne     SHORT $LL8@f
        pop     esi
$LN1@f:
        ret     0
_f2     ENDP
```

...and it works as efficient as the *optimized* version on my Intel Xeon E31220 @ 3.10GHz. Maybe, this optimization was targeted some older x86 CPUs of 1990s era, since this trick is used at least by ancient MS VC 6.0?

Any idea?

Hex-Rays 2.2 have a hard time recognizing patterns like that (hopefully, temporary?):

```
void __cdecl f1(char *dst, char *src, size_t size)
{
  size_t counter; // edx@1
  char *sliding_dst; // eax@2
  char tmp; // cl@3

  counter = size;
  if ( size )
  {
    sliding_dst = dst;
    do
    {
      tmp = (sliding_dst++)[src - dst];         // difference (src-dst) is calculated once, ↙
    ↳ before loop body
      *(sliding_dst - 1) = tmp;
      --counter;
    }
```

```
    while ( counter );
  }
}
```

Nevertheless, this optimization trick is often used by MSVC (not just in DIY[43] homebrew *memcpy()* routines, but in many loops which uses two or more arrays), so it's worth for reverse engineers to keep it in mind.

3.22.2 Another loop optimization

If you process all elements of some array which happens to be located in global memory, compiler can optimize it. For example, let's calculate a sum of all elements of array of 128 *int*'s:

```
#include <stdio.h>

int a[128];

int sum_of_a()
{
        int rt=0;

        for (int i=0; i<128; i++)
                rt=rt+a[i];

        return rt;
};

int main()
{
        // initialize
        for (int i=0; i<128; i++)
                a[i]=i;

        // calculate the sum
        printf ("%d\n", sum_of_a());
};
```

Optimizing GCC 5.3.1 (x86) can produce this (IDA):

```
.text:080484B0 sum_of_a        proc near
.text:080484B0                 mov     edx, offset a
.text:080484B5                 xor     eax, eax
.text:080484B7                 mov     esi, esi
.text:080484B9                 lea     edi, [edi+0]
.text:080484C0
.text:080484C0 loc_80484C0:            ; CODE XREF: sum_of_a+1B
.text:080484C0                 add     eax, [edx]
.text:080484C2                 add     edx, 4
.text:080484C5                 cmp     edx, offset __libc_start_main@@GLIBC_2_0
.text:080484CB                 jnz     short loc_80484C0
.text:080484CD                 rep retn
.text:080484CD sum_of_a        endp
.text:080484CD

...

.bss:0804A040                 public a
.bss:0804A040 a               dd 80h dup(?) ; DATA XREF: main:loc_8048338
.bss:0804A040                               ; main+19
.bss:0804A040 _bss            ends
.bss:0804A040
extern:0804A240 ; ===========================================================================
extern:0804A240
extern:0804A240 ; Segment type: Externs
extern:0804A240 ; extern
extern:0804A240                 extrn __libc_start_main@@GLIBC_2_0:near
extern:0804A240                                 ; DATA XREF: main+25
```

[43] Do It Yourself

```
extern:0804A240                                ; main+5D
extern:0804A244                    extrn __printf_chk@@GLIBC_2_3_4:near
extern:0804A248                    extrn __libc_start_main:near
extern:0804A248                                ; CODE XREF: ___libc_start_main
extern:0804A248                                ; DATA XREF: .got.plt:off_804A00C
```

What the heck is `__libc_start_main@@GLIBC_2_0` at `0x080484C5`? This is a label just after end of `a[]` array. The function can be rewritten like this:

```
int sum_of_a_v2()
{
        int *tmp=a;
        int rt=0;

        do
        {
                rt=rt+(*tmp);
                tmp++;
        }
        while (tmp<(a+128));

        return rt;
};
```

First version has *i* counter, and the address of each element of array is to be calculated at each iteration. The second version is more optimized: the pointer to each element of array is always ready and is sliding 4 bytes forward at each iteration. How to check if the loop is ended? Just compare the pointer with the address just behind array's end, which is, in our case, is happens to be address of imported `__libc_start_main()` function from Glibc 2.0. Sometimes code like this is confusing, and this is very popular optimizing trick, so that's why I made this example.

My second version is very close to what GCC did, and when I compile it, the code is almost the same as in first version, but two first instructions are swapped:

```
.text:080484D0                  public sum_of_a_v2
.text:080484D0 sum_of_a_v2      proc near
.text:080484D0                  xor     eax, eax
.text:080484D2                  mov     edx, offset a
.text:080484D7                  mov     esi, esi
.text:080484D9                  lea     edi, [edi+0]
.text:080484E0
.text:080484E0 loc_80484E0:             ; CODE XREF: sum_of_a_v2+1B
.text:080484E0                  add     eax, [edx]
.text:080484E2                  add     edx, 4
.text:080484E5                  cmp     edx, offset __libc_start_main@@GLIBC_2_0
.text:080484EB                  jnz     short loc_80484E0
.text:080484ED                  rep retn
.text:080484ED sum_of_a_v2      endp
```

Needless to say, this optimization is possible if the compiler can calculate address of the end of array during compilation time. This happens if the array is global and it's size is fixed.

However, if the address of array is unknown during compilation, but size is fixed, address of the label just behind array's end can be calculated at the beginning of the loop.

3.23 More about structures

3.23.1 Sometimes a C structure can be used instead of array

Arithmetic mean

```
#include <stdio.h>

int mean(int *a, int len)
{
        int sum=0;
```

```
        for (int i=0; i<len; i++)
                sum=sum+a[i];
        return sum/len;
};

struct five_ints
{
        int a0;
        int a1;
        int a2;
        int a3;
        int a4;
};

int main()
{
        struct five_ints a;
        a.a0=123;
        a.a1=456;
        a.a2=789;
        a.a3=10;
        a.a4=100;
        printf ("%d\n", mean(&a, 5));
        // test: https://www.wolframalpha.com/input/?i=mean(123,456,789,10,100)
};
```

This works: *mean()* function will never access behind the end of *five_ints* structure, because 5 is passed, meaining, only 5 integers will be accessed.

Putting string into structure

```
#include <stdio.h>

struct five_chars
{
        char a0;
        char a1;
        char a2;
        char a3;
        char a4;
} __attribute__ ((aligned (1),packed));

int main()
{
        struct five_chars a;
        a.a0='h';
        a.a1='i';
        a.a2='!';
        a.a3='\n';
        a.a4=0;
        printf (&a); // prints "hi!"
};
```

((aligned (1),packed)) attribute must be used, because otherwise, each structure field will be aligned on 4-byte or 8-byte boundary.

Summary

This is just another example of how structures and arrays are stored in memory. Perhaps, no sane programmer will do something like in this example, except in case of some specific hack. Or maybe in case of source code obfuscation?

3.23.2 Unsized array in C structure

In some win32 structures we can find ones with last field defined as an array of one element:

```
typedef struct _SYMBOL_INFO {
  ULONG   SizeOfStruct;
  ULONG   TypeIndex;

  ...

  ULONG   MaxNameLen;
  TCHAR   Name[1];
} SYMBOL_INFO, *PSYMBOL_INFO;
```

(https://msdn.microsoft.com/en-us/library/windows/desktop/ms680686(v=vs.85).aspx)

This is a hack, meaning, the last field is array of unknown size, which is to be calculated at the time of structure allocation.

Why: *Name* field may be short, so why to define it with some kind of *MAX_NAME* constant which can be 128, 256, or even bigger?

Why not to use pointer instead? Then you have to allocate two blocks: one for structure and the other one for string. This may be slower and may require larger memory overhead. Also, you need dereference pointer (i.e., read address of the string from the structure)—not a big deal, but some people say this is still surplus cost.

This is also known as *struct hack*: http://c-faq.com/struct/structhack.html.

Example:

```
#include <stdio.h>

struct st
{
        int a;
        int b;
        char s[];
};

void f (struct st *s)
{
        printf ("%d %d %s\n", s->a, s->b, s->s);
        // f() can't replace s[] with bigger string - size of allocated block is unknown at ↙
    ↘ this point
};

int main()
{
#define STRING "Hello!"
        struct st *s=malloc(sizeof(struct st)+strlen(STRING)+1); // incl. terminating zero
        s->a=1;
        s->b=2;
        strcpy (s->s, STRING);
        f(s);
};
```

In short, it works because C has no array boundary checks. Any array is treated as having infinite size.

Problem: after allocation, the whole size of allocated block for structure is unknown (except for memory manager), so you can't just replace string with larger string. You would still be able to do so if the field would be declared as something like *s[MAX_NAME]*.

In other words, you have a structure plus an array (or string) fused together in the single allocated memory block. Another problem is what you obviously can't declare two such arrays in single structure, or to declare another field after such array.

Older compilers require to declare array with at least one element: *s[1]*, newer allows to declare it as variable-sized array: *s[]*. This is also called *flexible array member*[44] in C99 standard.

[44] https://en.wikipedia.org/wiki/Flexible_array_member

Read more about it in GCC documentation[45], MSDN documentation[46].

Dennis Ritchie (one of C creators) called this trick “unwarranted chumminess with the C implementation” (perhaps, acknowledging hackish nature of the trick).

Like it or not, use it or not: it is still another demonstration on how structures are stored in memory, that’s why I write about it.

3.23.3 Version of C structure

Many Windows programmers have seen this is MSDN:

```
SizeOfStruct
    The size of the structure, in bytes. This member must be set to sizeof(SYMBOL_INFO).
```

(https://msdn.microsoft.com/en-us/library/windows/desktop/ms680686(v=vs.85).aspx)

Some structures like *SYMBOL_INFO* has started with this field indeed. Why? This is some kind of structure version.

Imagine you have a function which draws circle. It takes a single argument—a pointer to a structure with only two fields: X and Y. And then color displays flooded a market, sometimes in 1980s. And you want to add *color* argument to the function. But, let’s say, you cannot add another argument to it (a lot of software use your API[47] and cannot be recompiled). And if the old piece of software uses your API with color display, let your function draw a circle in (default) black and white colors.

Another day you add another feature: circle now can be filled, and brush type can be set.

Here is one solution to the problem:

```
#include <stdio.h>

struct ver1
{
        size_t SizeOfStruct;
        int coord_X;
        int coord_Y;
};

struct ver2
{
        size_t SizeOfStruct;
        int coord_X;
        int coord_Y;
        int color;
};

struct ver3
{
        size_t SizeOfStruct;
        int coord_X;
        int coord_Y;
        int color;
        int fill_brush_type; // 0 - do not fill circle
};

void draw_circle(struct ver3 *s) // latest struct version is used here
{
        // we presume SizeOfStruct, coord_X and coord_Y fields are always present
        printf ("We are going to draw a circle at %d:%d\n", s->coord_X, s->coord_Y);

        if (s->SizeOfStruct>=sizeof(int)*4)
        {
                // this is at least ver2, color field is present
                printf ("We are going to set color %d\n", s->color);
        }
```

[45] https://gcc.gnu.org/onlinedocs/gcc/Zero-Length.html
[46] https://msdn.microsoft.com/en-us/library/b6fae073.aspx
[47] Application Programming Interface

```
        if (s->SizeOfStruct>=sizeof(int)*5)
        {
                // this is at least ver3, fill_brush_type field is present
                printf ("We are going to fill it using brush type %d\n", s->fill_brush_type);
        }
};

// early software version
void call_as_ver1()
{
        struct ver1 s;
        s.SizeOfStruct=sizeof(s);
        s.coord_X=123;
        s.coord_Y=456;
        printf ("** %s()\n", __FUNCTION__);
        draw_circle(&s);
};

// next software version
void call_as_ver2()
{
        struct ver2 s;
        s.SizeOfStruct=sizeof(s);
        s.coord_X=123;
        s.coord_Y=456;
        s.color=1;
        printf ("** %s()\n", __FUNCTION__);
        draw_circle(&s);
};

// latest, most advanced version
void call_as_ver3()
{
        struct ver3 s;
        s.SizeOfStruct=sizeof(s);
        s.coord_X=123;
        s.coord_Y=456;
        s.color=1;
        s.fill_brush_type=3;
        printf ("** %s()\n", __FUNCTION__);
        draw_circle(&s);
};

int main()
{
        call_as_ver1();
        call_as_ver2();
        call_as_ver3();
};
```

In other words, *SizeOfStruct* field takes a role of *version of structure* field. It could be enumerate type (1, 2, 3, etc.), but to set *SizeOfStruct* field to *sizeof(struct...)* is less prone to mistakes/bugs.

In C++, this problem is solved using *inheritance* (3.18.1 on page 547). You just extend your base class (let's call it *Circle*), and then you will have *ColoredCircle* and then *FilledColoredCircle*, and so on. A current *version* of an object (or, more precisely, current *type*) will be determined using C++ RTTI.

So when you see *SizeOfStruct* somewhere in MSDN—perhaps this structure was extended at least once in past.

3.23.4 High-score file in "Block out" game and primitive serialization

Many videogames has high-score file, sometimes called "Hall of fame". Ancient "Block out"[48] game (3D tetris from 1989) isn't exception, here is what we see at the end:

[48] http://www.bestoldgames.net/eng/old-games/blockout.php

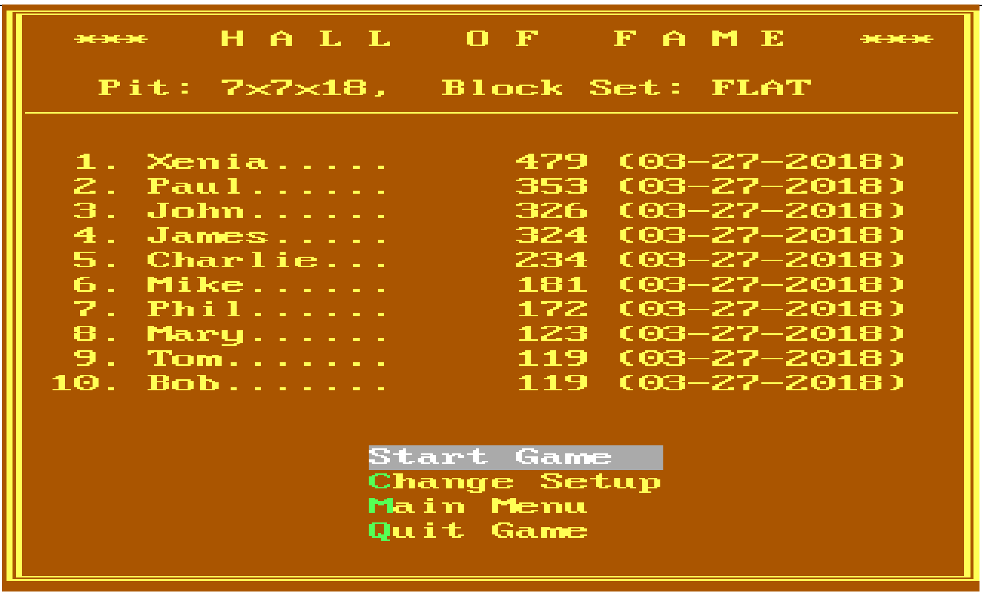


Figure 3.4: High score table

Now we can see that the file has changed after we added our name is *BLSCORE.DAT*.

```
% xxd -g 1 BLSCORE.DAT

00000000: 0a 00 58 65 6e 69 61 2e 2e 2e 2e 2e 00 df 01 00  ..Xenia.........
00000010: 00 30 33 2d 32 37 2d 32 30 31 38 00 50 61 75 6c  .03-27-2018.Paul
00000020: 2e 2e 2e 2e 2e 2e 00 61 01 00 00 30 33 2d 32 37  .......a...03-27
00000030: 2d 32 30 31 38 00 4a 6f 68 6e 2e 2e 2e 2e 2e 2e  -2018.John......
00000040: 00 46 01 00 00 30 33 2d 32 37 2d 32 30 31 38 00  .F...03-27-2018.
00000050: 4a 61 6d 65 73 2e 2e 2e 2e 2e 00 44 01 00 00 30  James......D...0
00000060: 33 2d 32 37 2d 32 30 31 38 00 43 68 61 72 6c 69  3-27-2018.Charli
00000070: 65 2e 2e 2e 00 ea 00 00 00 30 33 2d 32 37 2d 32  e........03-27-2
00000080: 30 31 38 00 4d 69 6b 65 2e 2e 2e 2e 2e 2e 00 b5  018.Mike........
00000090: 00 00 00 30 33 2d 32 37 2d 32 30 31 38 00 50 68  ...03-27-2018.Ph
000000a0: 69 6c 2e 2e 2e 2e 2e 2e 00 ac 00 00 00 30 33 2d  il..........03-
000000b0: 32 37 2d 32 30 31 38 00 4d 61 72 79 2e 2e 2e 2e  27-2018.Mary....
000000c0: 2e 2e 00 7b 00 00 00 30 33 2d 32 37 2d 32 30 31  ...{...03-27-201
000000d0: 38 00 54 6f 6d 2e 2e 2e 2e 2e 2e 2e 00 77 00 00  8.Tom........w..
000000e0: 00 30 33 2d 32 37 2d 32 30 31 38 00 42 6f 62 2e  .03-27-2018.Bob.
000000f0: 2e 2e 2e 2e 2e 2e 00 77 00 00 00 30 33 2d 32 37  .......w...03-27
00000100: 2d 32 30 31 38 00                                -2018.
```

All entries are clearly visible. The very first byte is probably number of entries. Second is zero and, in fact, number of entries can be 16-bit value spanning over first two bytes.

Next, after "Xenia" name we see 0xDF and 0x01 bytes. Xenia has score of 479, and this is exactly 0x1DF in hexadecimal radix. So a high score value is probably 16-bit integer, or maybe 32-bit integer: there are two more zero bytes after.

Now let's think about the fact that both array elements and structure elements are always placed in memory in adjacently to each other. That enables us to write the whole array/structure to the file using simple *write()* or *fwrite()* function, and then restore it using *read()* or *fread()*, as simple as that. This is what is called *serialization* nowadays.

Read

Now let's write C program to read highscore file:

```
#include <assert.h>
#include <stdio.h>
#include <stdint.h>
#include <string.h>

struct entry
{
```

```
        char name[11]; // incl. terminating zero
        uint32_t score;
        char date[11]; // incl. terminating zero
} __attribute__ ((aligned (1),packed));

struct highscore_file
{
        uint8_t count;
        uint8_t unknown;
        struct entry entries[10];
} __attribute__ ((aligned (1), packed));

struct highscore_file file;

int main(int argc, char* argv[])
{
        FILE* f=fopen(argv[1], "rb");
        assert (f!=NULL);
        size_t got=fread(&file, 1, sizeof(struct highscore_file), f);
        assert (got==sizeof(struct highscore_file));
        fclose(f);
        for (int i=0; i<file.count; i++)
        {
                printf ("name=%s score=%d date=%s\n",
                                file.entries[i].name,
                                file.entries[i].score,
                                file.entries[i].date);
        };
};
```

We need GCC *((aligned (1),packed))* attribute so that all structure fields will be packed on 1-byte boundary.

Of course it works:

```
name=Xenia..... score=479 date=03-27-2018
name=Paul...... score=353 date=03-27-2018
name=John...... score=326 date=03-27-2018
name=James..... score=324 date=03-27-2018
name=Charlie... score=234 date=03-27-2018
name=Mike...... score=181 date=03-27-2018
name=Phil...... score=172 date=03-27-2018
name=Mary...... score=123 date=03-27-2018
name=Tom....... score=119 date=03-27-2018
name=Bob....... score=119 date=03-27-2018
```

(Needless to say, each name is padded with dots, both on screen and in the file, perhaps, for æsthetical reasons.)

Write

Let's check if we right about width of score value. Is it really has 32 bits?

```
int main(int argc, char* argv[])
{
        FILE* f=fopen(argv[1], "rb");
        assert (f!=NULL);
        size_t got=fread(&file, 1, sizeof(struct highscore_file), f);
        assert (got==sizeof(struct highscore_file));
        fclose(f);

        strcpy (file.entries[1].name, "Mallory...");
        file.entries[1].score=12345678;
        strcpy (file.entries[1].date, "08-12-2016");

        f=fopen(argv[1], "wb");
        assert (f!=NULL);
        got=fwrite(&file, 1, sizeof(struct highscore_file), f);
        assert (got==sizeof(struct highscore_file));
        fclose(f);
```

```
};
```

Let's run Blockout:

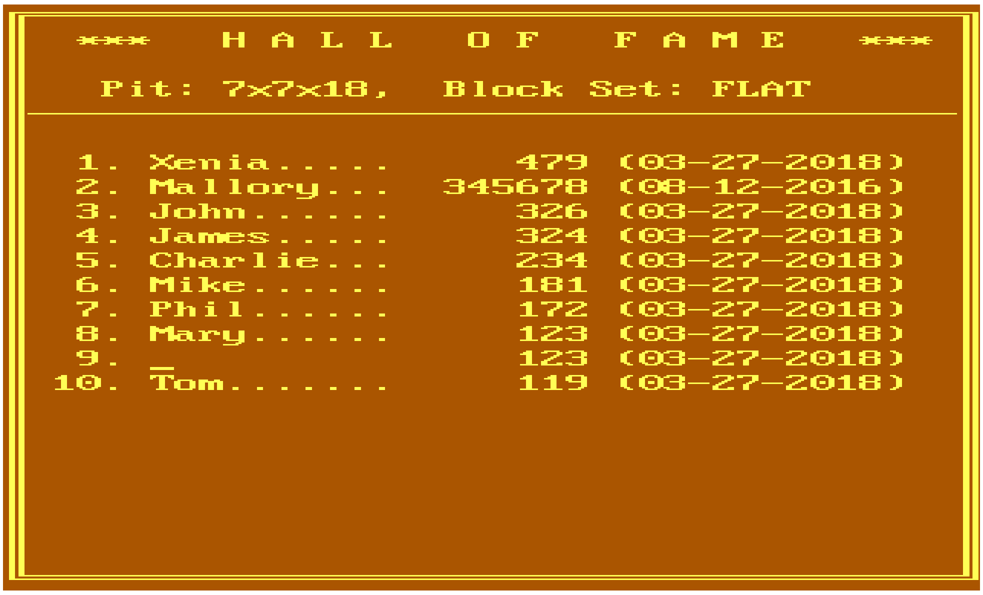


Figure 3.5: High score table

First two digits (1 or 2) are choked. Perhaps, this is formatting issues... but the number is almost correct. Now I'm changing it to 999999 and run again:

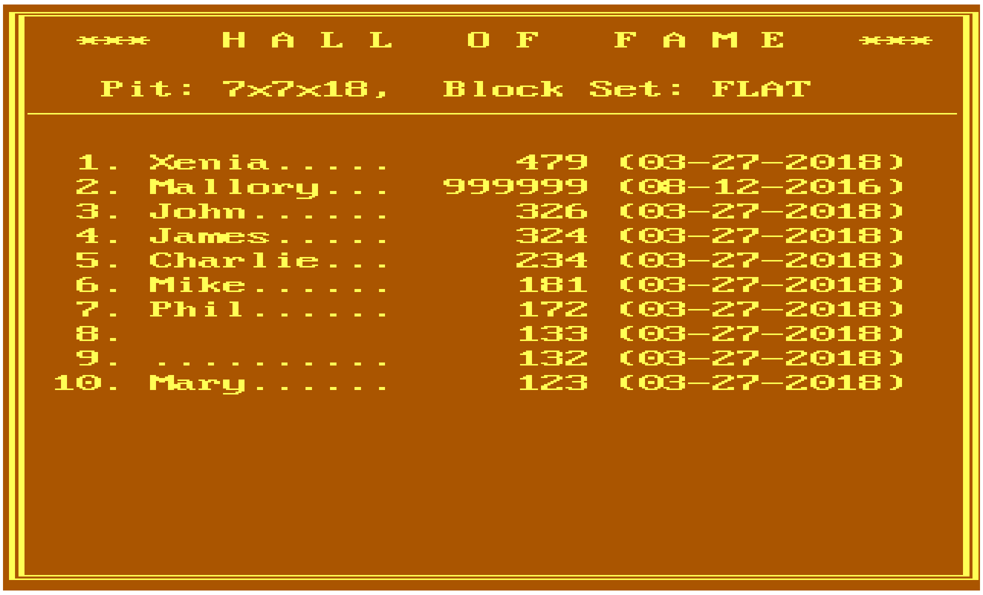


Figure 3.6: High score table

Now it's correct. Yes, high score value is 32-bit integer.

Is it serialization?

...almost. Serialization like this is highly popular in scientific and engineering software, where efficiency and speed is much more important than converting into XML[49] or JSON[50] and back.

One important thing is that you obviously cannot serialize pointers, because each time you load the file into memory, all the structures may be allocated in different places.

[49] Extensible Markup Language
[50] JavaScript Object Notation

But: if you work on some kind of low-cost MCU with simple OS on it and you have your structures allocated at always same places in memory, perhaps you can save and restore pointers as well.

Random noise

When I prepared this example, I had to run “Block out” many times and played for it a bit to fill high-score table with random names.

And when there were just 3 entries in the file, I saw this:

```
00000000: 03 00 54 6f 6d 61 73 2e 2e 2e 2e 2e 00 da 2a 00  ..Tomas.......*.
00000010: 00 30 38 2d 31 32 2d 32 30 31 36 00 43 68 61 72  .08-12-2016.Char
00000020: 6c 69 65 2e 2e 2e 00 8b 1e 00 00 30 38 2d 31 32  lie........08-12
00000030: 2d 32 30 31 36 00 4a 6f 68 6e 2e 2e 2e 2e 2e 2e  -2016.John......
00000040: 00 80 00 00 00 30 38 2d 31 32 2d 32 30 31 36 00  .....08-12-2016.
00000050: 00 00 57 c8 a2 01 06 01 ba f9 47 c7 05 00 f8 4f  ..W.......G....O
00000060: 06 01 06 01 a6 32 00 00 00 00 00 00 00 00 00 00  .....2..........
00000070: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
00000080: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
00000090: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
000000a0: 00 00 00 00 00 00 00 00 00 00 93 c6 a2 01 46 72  ..............Fr
000000b0: 8c f9 f6 c5 05 00 f8 4f 00 02 06 01 a6 32 06 01  .......O.....2..
000000c0: 00 00 98 f9 f2 c0 05 00 f8 4f 00 02 a6 32 a2 f9  .........O...2..
000000d0: 80 c1 a6 32 a6 32 f4 4f aa f9 39 c1 a6 32 06 01  ...2.2.O..9..2..
000000e0: b4 f9 2b c5 a6 32 e1 4f c7 c8 a2 01 82 72 c6 f9  ..+..2.O.....r..
000000f0: 30 c0 05 00 00 00 00 00 00 00 a6 32 d4 f9 76 2d  0..........2..v-
00000100: a6 32 00 00 00 00                                .2....
```

The first byte has value of 3, meaning there are 3 entries. And there are 3 entries present. But then we see a random noise at the second half of file.

The noise is probably has its origins in uninitialized data. Perhaps, “Block out” allocated memory for 10 entries somewhere in heap, where, obviously, some pseudorandom noise (left from something else) was present. Then it set first/second byte, fill 3 entries, and then it never touched 7 entries left, so they are written to the file as is.

When “Block out” loads high score file at the next run, it reads number of entries from the first/second byte (3) and then completely ignores what is after it.

This is common problem. Not a problem in strict sense: it’s not a bug, but information can be exposed outwards.

Microsoft Word versions from 1990s has been often left pieces of previously edited texts into the *.doc* files. It was some kind of amusement back then, to get a *.doc* file from someone, then open it in a hexadecimal editor and read something else, what has been edited on that computer before.

The problem can be even much more serious: Heartbleed bug[51] in OpenSSL.

Homework

“Block out” has several polycubes (flat/basic/extended), size of pit can be configured, etc. And it seems, for each configuration, “Block out” has its own high score table. I’ve noticed that some information is probably stored in *BLSCORE.IDX* file. This can be a homework for hardcore “Block out” fans—to understand its structure as well.

The “Block out” files are here: `http://beginners.re/examples/blockout.zip` (including the binary high score files I’ve used in this example). You can use DosBox to run it.

3.24 memmove() and memcpy()

The difference between these standard functions is that *memcpy()* blindly copies a block to another place, while *memmove()* correctly handles overlapping blocks. For example, you want to tug a string two bytes forward:

[51] https://en.wikipedia.org/wiki/Heartbleed

```
`|.|.|h|e|l|l|o|...` -> `|h|e|l|l|o|...`
```

memcpy() which copies 32-bit or 64-bit words at once, or even SIMD, will obviously fail here, a byte-wise copy routine must be used instead.

Now even more advanced example, insert two bytes in front of string:

```
`|h|e|l|l|o|...` -> `|.|.|h|e|l|l|o|...`
```

Now even byte-wise memory copy routine will fail, you have to copy bytes starting at the end.

That's a rare case where DF x86 flag is to be set before REP MOVSB instruction: DF defines direction, and now we must move backwardly.

The typical *memmove()* routine works like this: 1) if source is below destination, copy forward; 2) if source is above destination, copy backward.

This is *memmove()* from uClibc:

```
void *memmove(void *dest, const void *src, size_t n)
{
        int eax, ecx, esi, edi;
        __asm__ __volatile__(
                "       movl    %%eax, %%edi\n"
                "       cmpl    %%esi, %%eax\n"
                "       je      2f\n" /* (optional) src == dest -> NOP */
                "       jb      1f\n" /* src > dest -> simple copy */
                "       leal    -1(%%esi,%%ecx), %%esi\n"
                "       leal    -1(%%eax,%%ecx), %%edi\n"
                "       std\n"
                "1:     rep; movsb\n"
                "       cld\n"
                "2:\n"
                : "=&c" (ecx), "=&S" (esi), "=&a" (eax), "=&D" (edi)
                : "0" (n), "1" (src), "2" (dest)
                : "memory"
        );
        return (void*)eax;
}
```

In the first case, REP MOVSB is called with DF flag cleared. In the second, DF is set, then cleared.

More complex algorithm has the following piece in it:

"if difference between *source* and *destination* is larger than width of word, copy using words rather than bytes, and use byte-wise copy to copy unaligned parts".

This how it happens in Glibc 2.24 in non-optimized C part.

Given all that, *memmove()* may be slower than *memcpy()*. But some people, including Linus Torvalds, argue[52] that *memcpy()* should be an alias (or synonym) of *memmove()*, and the latter function must just check at start, if the buffers are overlapping or not, and then behave as *memcpy()* or *memmove()*. Nowadays, check for overlapping buffers is very cheap, after all.

3.24.1 Anti-debugging trick

I've heard about anti-debugging trick where all you need is just set DF to crash the process: the very next *memcpy()* routine will lead to crash because it copies backwardly. But I can't check this: it seems all memory copy routines clear/set DF as they want to. On the other hand, *memmove()* from uClibc I cited here, has no explicit clear of DF (it assumes DF is always clear?), so it can really crash.

3.25 setjmp/longjmp

setjmp/longjmp is a mechanism in C which is very similar to throw/catch mechanism in C++ and other higher-level PLs. Here is an example from zlib:

[52] https://bugzilla.redhat.com/show_bug.cgi?id=638477#c132

```
...

    /* return if bits() or decode() tries to read past available input */
    if (setjmp(s.env) != 0)             /* if came back here via longjmp(), */
        err = 2;                        /*  then skip decomp(), return error */
    else
        err = decomp(&s); /* decompress */

...

    /* load at least need bits into val */
    val = s->bitbuf;
    while (s->bitcnt < need) {
        if (s->left == 0) {
            s->left = s->infun(s->inhow, &(s->in));
            if (s->left == 0) longjmp(s->env, 1); /* out of input */

...

        if (s->left == 0) {
            s->left = s->infun(s->inhow, &(s->in));
            if (s->left == 0) longjmp(s->env, 1); /* out of input */
```

(zlib/contrib/blast/blast.c)

Call to `setjmp()` saves current PC, SP and other registers into env structure, then it returns 0.

In case of error, `longjmp()` *teleporting* you into the point after right after `setjmp()` call, as if `setjmp()` call returned non-null value (which was passed to `longjmp()`). This reminds as `fork()` syscall in UNIX.

Now let's take a look on distilled example:

```
#include <stdio.h>
#include <setjmp.h>

jmp_buf env;

void f2()
{
        printf ("%s() begin\n", __FUNCTION__);
        // something odd happened here
        longjmp (env, 1234);
        printf ("%s() end\n", __FUNCTION__);
};

void f1()
{
        printf ("%s() begin\n", __FUNCTION__);
        f2();
        printf ("%s() end\n", __FUNCTION__);
};

int main()
{
        int err=setjmp(env);
        if (err==0)
        {
                f1();
        }
        else
        {
                printf ("Error %d\n", err);
        };
};
```

If we run it, we will see:

```
f1() begin
f2() begin
Error 1234
```

jmp_buf structure usually comes undocumented, to preserve forward compatibility.

Let's see how setjmp() implemented in MSVC 2013 x64:

```
                ...

                ; RCX = address of jmp_buf

                mov     [rcx], rax
                mov     [rcx+8], rbx
                mov     [rcx+18h], rbp
                mov     [rcx+20h], rsi
                mov     [rcx+28h], rdi
                mov     [rcx+30h], r12
                mov     [rcx+38h], r13
                mov     [rcx+40h], r14
                mov     [rcx+48h], r15
                lea     r8, [rsp+arg_0]
                mov     [rcx+10h], r8
                mov     r8, [rsp+0]     ; get saved RA from stack
                mov     [rcx+50h], r8   ; save it
                stmxcsr dword ptr [rcx+58h]
                fnstcw  word ptr [rcx+5Ch]
                movdqa  xmmword ptr [rcx+60h], xmm6
                movdqa  xmmword ptr [rcx+70h], xmm7
                movdqa  xmmword ptr [rcx+80h], xmm8
                movdqa  xmmword ptr [rcx+90h], xmm9
                movdqa  xmmword ptr [rcx+0A0h], xmm10
                movdqa  xmmword ptr [rcx+0B0h], xmm11
                movdqa  xmmword ptr [rcx+0C0h], xmm12
                movdqa  xmmword ptr [rcx+0D0h], xmm13
                movdqa  xmmword ptr [rcx+0E0h], xmm14
                movdqa  xmmword ptr [rcx+0F0h], xmm15
                retn
```

It just populates jmp_buf structure with current values of almost all registers. Also, current value of RA is taken from the stack and saved in jmp_buf: it will be used as new value of PC in future.

Now longjmp():

```
                ...

                ; RCX = address of jmp_buf

                mov     rax, rdx
                mov     rbx, [rcx+8]
                mov     rsi, [rcx+20h]
                mov     rdi, [rcx+28h]
                mov     r12, [rcx+30h]
                mov     r13, [rcx+38h]
                mov     r14, [rcx+40h]
                mov     r15, [rcx+48h]
                ldmxcsr dword ptr [rcx+58h]
                fnclex
                fldcw   word ptr [rcx+5Ch]
                movdqa  xmm6, xmmword ptr [rcx+60h]
                movdqa  xmm7, xmmword ptr [rcx+70h]
                movdqa  xmm8, xmmword ptr [rcx+80h]
                movdqa  xmm9, xmmword ptr [rcx+90h]
                movdqa  xmm10, xmmword ptr [rcx+0A0h]
                movdqa  xmm11, xmmword ptr [rcx+0B0h]
                movdqa  xmm12, xmmword ptr [rcx+0C0h]
                movdqa  xmm13, xmmword ptr [rcx+0D0h]
                movdqa  xmm14, xmmword ptr [rcx+0E0h]
                movdqa  xmm15, xmmword ptr [rcx+0F0h]
                mov     rdx, [rcx+50h]  ; get PC (RIP)
                mov     rbp, [rcx+18h]
                mov     rsp, [rcx+10h]
                jmp     rdx             ; jump to saved PC
```

```
                ...
```

It just restores (almost) all registers, takes RA from structure and jumps there. This effectively works as if setjmp() returned to caller. Also, RAX is set to be equal to the second argument of longjmp(). This works as if setjmp() returned non-zero value at first place.

As a side effect of SP restoration, all values in stack which has been set and used between setjmp() and longjmp() calls are just dropped. They will not be used anymore. Hence, longjmp() usually jumps backwards [53].

This implies that, unlike in throw/catch mechanism in C++, no memory will be freed, no destructors will be called, etc. Hence, this technique sometimes can be dangerous. Nevertheless, it's still quite popular. It's still used in Oracle RDBMS.

It also has unexpected side-effect: if some buffer has been overflown inside of a function (maybe due to remote attack), and a function wants to report error, and it calls longjmp(), overwritten stack part just gets unused.

As an exercise, you can try to understand, why not all registers are saved. Why XMM0-XMM5 and other registers are skipped?

3.26 Other weird stack hacks

3.26.1 Accessing arguments/local variables of caller

From C/C++ basics we know that this is impossible for a function to access arguments of caller function or its local variables.

Nevertheless, it's possible using dirty hacks. For example:

```
#include <stdio.h>

void f(char *text)
{
        // print stack
        int *tmp=&text;
        for (int i=0; i<20; i++)
        {
                printf ("0x%x\n", *tmp);
                tmp++;
        };
};

void draw_text(int X, int Y, char* text)
{
        f(text);

        printf ("We are going to draw [%s] at %d:%d\n", text, X, Y);
};

int main()
{
        printf ("address of main()=0x%x\n", &main);
        printf ("address of draw_text()=0x%x\n", &draw_text);
        draw_text(100, 200, "Hello!");
};
```

On 32-bit Ubuntu 16.04 and GCC 5.4.0, I got this:

```
address of main()=0x80484f8
address of draw_text()=0x80484cb
0x8048645       first argument to f()
0x8048628
0xbfd8ab98
```

[53] However, there are some people who can use it for much more complicated things, imitating coroutines, etc: https://www.embeddedrelated.com/showarticle/455.php, http://fanf.livejournal.com/105413.html

```
0xb7634590
0xb779eddc
0xb77e4918
0xbfd8aba8
0x8048547       return address into the middle of main()
0x64            first argument to draw_text()
0xc8            second argument to draw_text()
0x8048645       third argument to draw_text()
0x8048581
0xb779d3dc
0xbfd8abc0
0x0
0xb7603637
0xb779d000
0xb779d000
0x0
0xb7603637
```

(Comments are mine.)

Since *f()* starting to enumerate stack elements at its first argument, the first stack element is indeed a pointer to “Hello!” string. We see its address is also used as third argument to *draw_text()* function.

In *f()* we could read all functions arguments and local variables if we know exact stack layout, but it’s always changed, from compiler to compiler. Various optimization levels affects stack layout greatly.

But if we can somehow detect information we need, we can use it and even modify it. As an example, I’ll rework *f()* function:

```
void f(char *text)
{
        ...

        // find 100, 200 values pair and modify the second on
        tmp=&text;
        for (int i=0; i<20; i++)
        {
                if (*tmp==100 && *(tmp+1)==200)
                {
                        printf ("found\n");
                        *(tmp+1)=210; // change 200 to 210
                        break;
                };
                tmp++;
        };
};
```

Holy moly, it works:

```
found
We are going to draw [Hello!] at 100:210
```

Summary

It’s extremely dirty hack, intended to demonstrate stack internals. I never ever seen or heard that anyone used this in a real code. But still, this is a good example.

Exercise

The example has been compiled without optimization on 32-bit Ubuntu using GCC 5.4.0 and it works. But when I turn on `-O3` maximum optimization, it’s failed. Try to find why.

Use your favorite compiler and OS, try various optimization levels, find if it’s works and if it’s not, find why.

3.26.2 Returning string

This is classic bug from Brian W. Kernighan, Rob Pike, *Practice of Programming*, (1999):

```
#include <stdio.h>

char* amsg(int n, char* s)
{
        char buf[100];

        sprintf (buf, "error %d: %s\n", n, s) ;

        return buf;
};

int main()
{
        amsg ("%s\n", interim (1234, "something wrong!"));
};
```

It would crash. First, let's understand, why.

This is a stack state before amsg() return:

```
(lower addresses)

[amsg(): 100 bytes]
[RA]                    <- current SP
[two amsg arguments]
[something else]
[main() local variables]

(upper addresses)
```

When amsg() returns control flow to `main()`, so far so good. But `printf()` is called from `main()`, which is, in turn, use stack for its own needs, zapping 100-byte buffer. A random garbage will be printed at the best.

Hard to believe, but I know how to fix this problem:

```
#include <stdio.h>

char* amsg(int n, char* s)
{
        char buf[100];

        sprintf (buf, "error %d: %s\n", n, s) ;

        return buf;
};

char* interim (int n, char* s)
{
        char large_buf[8000];
        // make use of local array.
        // it will be optimized away otherwise, as useless.
        large_buf[0]=0;
        return amsg (n, s);
};

int main()
{
        printf ("%s\n", interim (1234, "something wrong!"));
};
```

It will work if compiled by MSVC 2013 with no optimizations and with `/GS-` option[54]. MSVC will warn: "warning C4172: returning address of local variable or temporary", but the code will run and message will be printed. Let's see stack state at the moment when amsg() returns control to interim():

[54]Turn off buffer security check

```
(lower addresses)

[amsg(): 100 bytes]
[RA]                                     <- current SP
[two amsg() arguments]
[interim() stuff, incl. 8000 bytes]
[something else]
[main() local variables]

(upper addresses)
```

Now the stack state at the moment when interim() returns control to `main()`:

```
(lower addresses)

[amsg(): 100 bytes]
[RA]
[two amsg() arguments]
[interim() stuff, incl. 8000 bytes]
[something else]                         <- current SP
[main() local variables]

(upper addresses)
```

So when `main()` calls `printf()`, it uses stack at the place where interim()'s buffer was allocated, and doesn't zap 100 bytes with error message inside, because 8000 bytes (or maybe much less) is just enough for everything `printf()` and other descending functions do!

It may also work if there are many functions between, like: `main()` → f1() → f2() → f3() ... → amsg(), and then the result of amsg() is used in `main()`. The distance between SP in `main()` and address of `buf[]` must be long enough,

This is why bugs like these are dangerous: sometimes your code works (and bug can be hiding unnoticed), sometimes not. Bugs like these are jokingly called heisenbugs or schrödinbugs[55].

3.27 OpenMP

OpenMP is one of the simplest ways to parallelize simple algorithms.

As an example, let's try to build a program to compute a cryptographic *nonce*.

In my simplistic example, the *nonce* is a number added to the plain unencrypted text in order to produce a hash with some specific features.

For example, at some step, the Bitcoin protocol requires to find such *nonce* so the resulting hash contains a specific number of consecutive zeros. This is also called "proof of work" [56] (i.e., the system proves that it did some intensive calculations and spent some time for it).

My example is not related to Bitcoin in any way, it will try to add numbers to the "hello, world!_" string in order to find such number that when "hello, world!_<number>" is hashed with the SHA512 algorithm, it will contain at least 3 zero bytes.

Let's limit our brute-force to the interval in 0..INT32_MAX-1 (i.e., `0x7FFFFFFE` or 2147483646).

The algorithm is pretty straightforward:

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <time.h>
#include "sha512.h"

int found=0;
int32_t checked=0;

int32_t* __min;
```

[55] https://en.wikipedia.org/wiki/Heisenbug
[56] wikipedia

```
int32_t* __max;

time_t start;

#ifdef __GNUC__
#define min(X,Y) ((X) < (Y) ? (X) : (Y))
#define max(X,Y) ((X) > (Y) ? (X) : (Y))
#endif

void check_nonce (int32_t nonce)
{
        uint8_t buf[32];
        struct sha512_ctx ctx;
        uint8_t res[64];

        // update statistics
        int t=omp_get_thread_num();

        if (__min[t]==-1)
                __min[t]=nonce;
        if (__max[t]==-1)
                __max[t]=nonce;

        __min[t]=min(__min[t], nonce);
        __max[t]=max(__max[t], nonce);

        // idle if valid nonce found
        if (found)
                return;

        memset (buf, 0, sizeof(buf));
        sprintf (buf, "hello, world!_%d", nonce);

        sha512_init_ctx (&ctx);
        sha512_process_bytes (buf, strlen(buf), &ctx);
        sha512_finish_ctx (&ctx, &res);
        if (res[0]==0 && res[1]==0 && res[2]==0)
        {
                printf ("found (thread %d): [%s]. seconds spent=%d\n", t, buf, time(NULL)-start↙
    ↳ );
                found=1;
        };
        #pragma omp atomic
        checked++;

        #pragma omp critical
        if ((checked % 100000)==0)
                printf ("checked=%d\n", checked);
};

int main()
{
        int32_t i;
        int threads=omp_get_max_threads();
        printf ("threads=%d\n", threads);

        __min=(int32_t*)malloc(threads*sizeof(int32_t));
        __max=(int32_t*)malloc(threads*sizeof(int32_t));
        for (i=0; i<threads; i++)
                __min[i]=__max[i]=-1;

        start=time(NULL);

        #pragma omp parallel for
        for (i=0; i<INT32_MAX; i++)
                check_nonce (i);

        for (i=0; i<threads; i++)
                printf ("__min[%d]=0x%08x __max[%d]=0x%08x\n", i, __min[i], i, __max[i]);
```

```
        free(__min); free(__max);
};
```

The check_nonce() function just adds a number to the string, hashes it with the SHA512 algorithm and checks for 3 zero bytes in the result.

A very important part of the code is:

```
        #pragma omp parallel for
        for (i=0; i<INT32_MAX; i++)
                check_nonce (i);
```

Yes, that simple, without #pragma we just call check_nonce() for each number from 0 to INT32_MAX (0x7fffffff or 2147483647). With #pragma, the compiler adds some special code which slices the loop interval into smaller ones, to run them on all CPU cores available [57].

The example can be compiled [58] in MSVC 2012:

```
cl openmp_example.c sha512.obj /openmp /O1 /Zi /Faopenmp_example.asm
```

Or in GCC:

```
gcc -fopenmp 2.c sha512.c -S -masm=intel
```

3.27.1 MSVC

Now this is how MSVC 2012 generates the main loop:

Listing 3.122: MSVC 2012

```
        push    OFFSET _main$omp$1
        push    0
        push    1
        call    __vcomp_fork
        add     esp, 16
```

All functions prefixed by vcomp are OpenMP-related and are stored in the vcomp*.dll file. So here a group of threads is started.

Let's take a look on _mainomp1:

Listing 3.123: MSVC 2012

```
$T1 = -8        ; size = 4
$T2 = -4        ; size = 4
_main$omp$1 PROC
        push    ebp
        mov     ebp, esp
        push    ecx
        push    ecx
        push    esi
        lea     eax, DWORD PTR $T2[ebp]
        push    eax
        lea     eax, DWORD PTR $T1[ebp]
        push    eax
        push    1
        push    1
        push    2147483646      ; 7ffffffeH
        push    0
        call    __vcomp_for_static_simple_init
        mov     esi, DWORD PTR $T1[ebp]
        add     esp, 24
        jmp     SHORT $LN6@main$omp$1
$LL2@main$omp$1:
        push    esi
        call    _check_nonce
```

[57] N.B.: This is intentionally simplest possible example, but in practice, the usage of OpenMP can be harder and more complex

[58] sha512.(c|h) and u64.h files can be taken from the OpenSSL library: http://go.yurichev.com/17324

```
        pop     ecx
        inc     esi
$LN6@main$omp$1:
        cmp     esi, DWORD PTR $T2[ebp]
        jle     SHORT $LL2@main$omp$1
        call    __vcomp_for_static_end
        pop     esi
        leave
        ret     0
_main$omp$1 ENDP
```

This function is to be started n times in parallel, where n is the number of CPU cores. vcomp_for_static_simple_init() calculates the interval for the for() construct for the current thread, depending on the current thread's number.

The loop's start and end values are stored in the $T1 and $T2 local variables. You may also notice 7ffffffeh (or 2147483646) as an argument to the vcomp_for_static_simple_init() function—this is the number of iterations for the whole loop, to be divided evenly.

Then we see a new loop with a call to the check_nonce() function, which does all the work.

Let's also add some code at the beginning of the check_nonce() function to gather statistics about the arguments with which the function has been called.

This is what we see when we run it:

```
threads=4
...
checked=2800000
checked=3000000
checked=3200000
checked=3300000
found (thread 3): [hello, world!_1611446522]. seconds spent=3
__min[0]=0x00000000 __max[0]=0x1fffffff
__min[1]=0x20000000 __max[1]=0x3fffffff
__min[2]=0x40000000 __max[2]=0x5fffffff
__min[3]=0x60000000 __max[3]=0x7ffffffe
```

Yes, the result is correct, the first 3 bytes are zeros:

```
C:\...\sha512sum test
000000f4a8fac5a4ed38794da4c1e39f54279ad5d9bb3c5465cdf57adaf60403
df6e3fe6019f5764fc9975e505a7395fed780fee50eb38dd4c0279cb114672e2 *test
```

The running time is $\approx 2..3$ seconds on 4-core Intel Xeon E3-1220 3.10 GHz. In the task manager we see 5 threads: 1 main thread + 4 more. No further optimizations are done to keep this example as small and clear as possible. But probably it can be done much faster. My CPU has 4 cores, that is why OpenMP started exactly 4 threads.

By looking at the statistics table we can clearly see how the loop has been sliced into 4 even parts. Oh well, almost even, if we don't consider the last bit.

There are also pragmas for atomic operations.

Let's see how this code is compiled:

```
        #pragma omp atomic
        checked++;

        #pragma omp critical
        if ((checked % 100000)==0)
                printf ("checked=%d\n", checked);
```

Listing 3.124: MSVC 2012

```
        push    edi
        push    OFFSET _checked
        call    __vcomp_atomic_add_i4
; Line 55
        push    OFFSET _$vcomp$critsect$
        call    __vcomp_enter_critsect
```

```
        add     esp, 12
; Line 56
        mov     ecx, DWORD PTR _checked
        mov     eax, ecx
        cdq
        mov     esi, 100000     ; 000186a0H
        idiv    esi
        test    edx, edx
        jne     SHORT $LN1@check_nonc
; Line 57
        push    ecx
        push    OFFSET ??_C@_0M@NPNHLIOO@checked?$DN?$CFd?6?$AA@
        call    _printf
        pop     ecx
        pop     ecx
$LN1@check_nonc:
        push    DWORD PTR _$vcomp$critsect$
        call    __vcomp_leave_critsect
        pop     ecx
```

As it turns out, the `vcomp_atomic_add_i4()` function in the vcomp*.dll is just a tiny function with the LOCK XADD instruction[59] in it.

`vcomp_enter_critsect()` eventually calling win32 API function `EnterCriticalSection()` [60].

3.27.2 GCC

GCC 4.8.1 produces a program which shows exactly the same statistics table,

so, GCC's implementation divides the loop in parts in the same fashion.

Listing 3.125: GCC 4.8.1

```
        mov     edi, OFFSET FLAT:main._omp_fn.0
        call    GOMP_parallel_start
        mov     edi, 0
        call    main._omp_fn.0
        call    GOMP_parallel_end
```

Unlike MSVC's implementation, what GCC code does is to start 3 threads, and run the fourth in the current thread. So there are 4 threads instead of the 5 in MSVC.

Here is the `main._omp_fn.0` function:

Listing 3.126: GCC 4.8.1

```
main._omp_fn.0:
        push    rbp
        mov     rbp, rsp
        push    rbx
        sub     rsp, 40
        mov     QWORD PTR [rbp-40], rdi
        call    omp_get_num_threads
        mov     ebx, eax
        call    omp_get_thread_num
        mov     esi, eax
        mov     eax, 2147483647 ; 0x7FFFFFFF
        cdq
        idiv    ebx
        mov     ecx, eax
        mov     eax, 2147483647 ; 0x7FFFFFFF
        cdq
        idiv    ebx
        mov     eax, edx
        cmp     esi, eax
        jl      .L15
```

[59]Read more about LOCK prefix: .1.6 on page 1026

[60]You can read more about critical sections here: 6.5.4 on page 787

```
.L18:
        imul    esi, ecx
        mov     edx, esi
        add     eax, edx
        lea     ebx, [rax+rcx]
        cmp     eax, ebx
        jge     .L14
        mov     DWORD PTR [rbp-20], eax
.L17:
        mov     eax, DWORD PTR [rbp-20]
        mov     edi, eax
        call    check_nonce
        add     DWORD PTR [rbp-20], 1
        cmp     DWORD PTR [rbp-20], ebx
        jl      .L17
        jmp     .L14
.L15:
        mov     eax, 0
        add     ecx, 1
        jmp     .L18
.L14:
        add     rsp, 40
        pop     rbx
        pop     rbp
        ret
```

Here we see the division clearly: by calling `omp_get_num_threads()` and `omp_get_thread_num()`

we get the number of threads running, and also the current thread's number, and then determine the loop's interval. Then we run `check_nonce()`.

GCC also inserted the `LOCK ADD`

instruction right in the code, unlike MSVC, which generated a call to a separate DLL function:

Listing 3.127: GCC 4.8.1

```
        lock add        DWORD PTR checked[rip], 1
        call    GOMP_critical_start
        mov     ecx, DWORD PTR checked[rip]
        mov     edx, 351843721
        mov     eax, ecx
        imul    edx
        sar     edx, 13
        mov     eax, ecx
        sar     eax, 31
        sub     edx, eax
        mov     eax, edx
        imul    eax, eax, 100000
        sub     ecx, eax
        mov     eax, ecx
        test    eax, eax
        jne     .L7
        mov     eax, DWORD PTR checked[rip]
        mov     esi, eax
        mov     edi, OFFSET FLAT:.LC2 ; "checked=%d\n"
        mov     eax, 0
        call    printf
.L7:
        call    GOMP_critical_end
```

The functions prefixed with GOMP are from GNU OpenMP library. Unlike vcomp*.dll, its source code is freely available: GitHub.

3.28 Another heisenbug

Sometimes, array (or buffer) can overflow due to *fencepost error*:

```
#include <stdio.h>

int array1[128];
int important_var1;
int important_var2;
int important_var3;
int important_var4;
int important_var5;

int main()
{
        important_var1=1;
        important_var2=2;
        important_var3=3;
        important_var4=4;
        important_var5=5;

        array1[0]=123;
        array1[128]=456; // BUG

        printf ("important_var1=%d\n", important_var1);
        printf ("important_var2=%d\n", important_var2);
        printf ("important_var3=%d\n", important_var3);
        printf ("important_var4=%d\n", important_var4);
        printf ("important_var5=%d\n", important_var5);
};
```

This is what this program printed in my case (non-optimized GCC 5.4 x86 on Linux):

```
important_var1=1
important_var2=456
important_var3=3
important_var4=4
important_var5=5
```

As it happens, `important_var2` has been placed by compiler right after `array1[]`:

Listing 3.128: objdump -x

```
0804a040 g     O .bss   00000200              array1
...
0804a240 g     O .bss   00000004              important_var2
0804a244 g     O .bss   00000004              important_var4
...
0804a248 g     O .bss   00000004              important_var1
0804a24c g     O .bss   00000004              important_var3
0804a250 g     O .bss   00000004              important_var5
```

Other compiler can arrange variables in another order, and another variable would be zapped. This is also *heisenbug* (3.26.2 on page 643)—bug may appear or may left unnoticed depending on compiler version and optimization switches.

It all variables and arrays are allocated in local stack, stack protection may be triggered, or may not. However, Valgrind can find bugs like these.

3.29 Windows 16-bit

16-bit Windows programs are rare nowadays, but can be used in the cases of retrocomputing or dongle hacking (8.5 on page 815).

16-bit Windows versions were up to 3.11. 95/98/ME also support 16-bit code, as well as the 32-bit versions of the Windows NT line. The 64-bit versions of Windows NT line do not support 16-bit executable code at all.

The code resembles MS-DOS's one.

Executable files are of type NE-type (so-called "new executable").

All examples considered here were compiled by the OpenWatcom 1.9 compiler, using these switches:

```
wcl.exe -i=C:/WATCOM/h/win/ -s -os -bt=windows -bcl=windows example.c
```

3.29.1 Example#1

```
#include <windows.h>

int PASCAL WinMain( HINSTANCE hInstance,
                    HINSTANCE hPrevInstance,
                    LPSTR lpCmdLine,
                    int nCmdShow )
{
        MessageBeep(MB_ICONEXCLAMATION);
        return 0;
};
```

```
WinMain         proc near
                push    bp
                mov     bp, sp
                mov     ax, 30h ; '0'   ; MB_ICONEXCLAMATION constant
                push    ax
                call    MESSAGEBEEP
                xor     ax, ax          ; return 0
                pop     bp
                retn    0Ah
WinMain         endp
```

Seems to be easy, so far.

3.29.2 Example #2

```
#include <windows.h>

int PASCAL WinMain( HINSTANCE hInstance,
                    HINSTANCE hPrevInstance,
                    LPSTR lpCmdLine,
                    int nCmdShow )
{
        MessageBox (NULL, "hello, world", "caption", MB_YESNOCANCEL);
        return 0;
};
```

```
WinMain         proc near
                push    bp
                mov     bp, sp
                xor     ax, ax          ; NULL
                push    ax
                push    ds
                mov     ax, offset aHelloWorld ; 0x18. "hello, world"
                push    ax
                push    ds
                mov     ax, offset aCaption ; 0x10. "caption"
                push    ax
                mov     ax, 3           ; MB_YESNOCANCEL
                push    ax
                call    MESSAGEBOX
                xor     ax, ax          ; return 0
                pop     bp
                retn    0Ah
WinMain         endp

dseg02:0010 aCaption        db 'caption',0
dseg02:0018 aHelloWorld     db 'hello, world',0
```

Couple important things here: the PASCAL calling convention dictates passing the first argument first (MB_YESNOCANCEL), and the last argument—last (NULL). This convention also tells the callee to restore the stack pointer: hence the RETN instruction has 0Ah as argument, which implies that the pointer has to be increased by 10 bytes when the function exits. It is like stdcall (6.1.2 on page 734), but the arguments are passed in "natural" order.

The pointers are passed in pairs: first the data segment is passed, then the pointer inside the segment. There is only one segment in this example, so DS always points to the data segment of the executable.

3.29.3 Example #3

```
#include <windows.h>

int PASCAL WinMain( HINSTANCE hInstance,
                    HINSTANCE hPrevInstance,
                    LPSTR lpCmdLine,
                    int nCmdShow )
{
    int result=MessageBox (NULL, "hello, world", "caption", MB_YESNOCANCEL);

    if (result==IDCANCEL)
        MessageBox (NULL, "you pressed cancel", "caption", MB_OK);
    else if (result==IDYES)
        MessageBox (NULL, "you pressed yes", "caption", MB_OK);
    else if (result==IDNO)
        MessageBox (NULL, "you pressed no", "caption", MB_OK);

    return 0;
};
```

```
WinMain         proc near
                push    bp
                mov     bp, sp
                xor     ax, ax       ; NULL
                push    ax
                push    ds
                mov     ax, offset aHelloWorld ; "hello, world"
                push    ax
                push    ds
                mov     ax, offset aCaption ; "caption"
                push    ax
                mov     ax, 3           ; MB_YESNOCANCEL
                push    ax
                call    MESSAGEBOX
                cmp     ax, 2           ; IDCANCEL
                jnz     short loc_2F
                xor     ax, ax
                push    ax
                push    ds
                mov     ax, offset aYouPressedCanc ; "you pressed cancel"
                jmp     short loc_49
loc_2F:
                cmp     ax, 6           ; IDYES
                jnz     short loc_3D
                xor     ax, ax
                push    ax
                push    ds
                mov     ax, offset aYouPressedYes ; "you pressed yes"
                jmp     short loc_49
loc_3D:
                cmp     ax, 7           ; IDNO
                jnz     short loc_57
                xor     ax, ax
                push    ax
                push    ds
                mov     ax, offset aYouPressedNo ; "you pressed no"
loc_49:
                push    ax
```

```
                push    ds
                mov     ax, offset aCaption ; "caption"
                push    ax
                xor     ax, ax
                push    ax
                call    MESSAGEBOX
loc_57:
                xor     ax, ax
                pop     bp
                retn    0Ah
WinMain         endp
```

Somewhat extended example from the previous section.

3.29.4 Example #4

```
#include <windows.h>

int PASCAL func1 (int a, int b, int c)
{
        return a*b+c;
};

long PASCAL func2 (long a, long b, long c)
{
        return a*b+c;
};

long PASCAL func3 (long a, long b, long c, int d)
{
        return a*b+c-d;
};

int PASCAL WinMain( HINSTANCE hInstance,
                    HINSTANCE hPrevInstance,
                    LPSTR lpCmdLine,
                    int nCmdShow )
{
        func1 (123, 456, 789);
        func2 (600000, 700000, 800000);
        func3 (600000, 700000, 800000, 123);
        return 0;
};
```

```
func1           proc near

c               = word ptr  4
b               = word ptr  6
a               = word ptr  8

                push    bp
                mov     bp, sp
                mov     ax, [bp+a]
                imul    [bp+b]
                add     ax, [bp+c]
                pop     bp
                retn    6
func1           endp

func2           proc near

arg_0           = word ptr  4
arg_2           = word ptr  6
arg_4           = word ptr  8
arg_6           = word ptr  0Ah
arg_8           = word ptr  0Ch
arg_A           = word ptr  0Eh
```

```
                push    bp
                mov     bp, sp
                mov     ax, [bp+arg_8]
                mov     dx, [bp+arg_A]
                mov     bx, [bp+arg_4]
                mov     cx, [bp+arg_6]
                call    sub_B2 ; long 32-bit multiplication
                add     ax, [bp+arg_0]
                adc     dx, [bp+arg_2]
                pop     bp
                retn    12
func2           endp

func3           proc near

arg_0           = word ptr  4
arg_2           = word ptr  6
arg_4           = word ptr  8
arg_6           = word ptr  0Ah
arg_8           = word ptr  0Ch
arg_A           = word ptr  0Eh
arg_C           = word ptr  10h

                push    bp
                mov     bp, sp
                mov     ax, [bp+arg_A]
                mov     dx, [bp+arg_C]
                mov     bx, [bp+arg_6]
                mov     cx, [bp+arg_8]
                call    sub_B2 ; long 32-bit multiplication
                mov     cx, [bp+arg_2]
                add     cx, ax
                mov     bx, [bp+arg_4]
                adc     bx, dx          ; BX=high part, CX=low part
                mov     ax, [bp+arg_0]
                cwd                     ; AX=low part d, DX=high part d
                sub     cx, ax
                mov     ax, cx
                sbb     bx, dx
                mov     dx, bx
                pop     bp
                retn    14
func3           endp

WinMain         proc near
                push    bp
                mov     bp, sp
                mov     ax, 123
                push    ax
                mov     ax, 456
                push    ax
                mov     ax, 789
                push    ax
                call    func1
                mov     ax, 9      ; high part of 600000
                push    ax
                mov     ax, 27C0h  ; low part of 600000
                push    ax
                mov     ax, 0Ah    ; high part of 700000
                push    ax
                mov     ax, 0AE60h ; low part of 700000
                push    ax
                mov     ax, 0Ch    ; high part of 800000
                push    ax
                mov     ax, 3500h  ; low part of 800000
                push    ax
                call    func2
                mov     ax, 9      ; high part of 600000
                push    ax
```

```
                mov     ax, 27C0h  ; low part of 600000
                push    ax
                mov     ax, 0Ah    ; high part of 700000
                push    ax
                mov     ax, 0AE60h ; low part of 700000
                push    ax
                mov     ax, 0Ch    ; high part of 800000
                push    ax
                mov     ax, 3500h  ; low part of 800000
                push    ax
                mov     ax, 7Bh    ; 123
                push    ax
                call    func3
                xor     ax, ax     ; return 0
                pop     bp
                retn    0Ah
WinMain         endp
```

32-bit values (the `long` data type implies 32 bits, while *int* is 16-bit) in 16-bit code (both MS-DOS and Win16) are passed in pairs. It is just like when 64-bit values are used in a 32-bit environment (1.28 on page 396).

sub_B2 here is a library function written by the compiler's developers that does "long multiplication", i.e., multiplies two 32-bit values. Other compiler functions that do the same are listed here: .5 on page 1043, .4 on page 1043.

The ADD/ADC instruction pair is used for addition of compound values: ADD may set/clear the CF flag, and ADC uses it after.

The SUB/SBB instruction pair is used for subtraction: SUB may set/clear the CF flag, SBB uses it after.

32-bit values are returned from functions in the `DX:AX` register pair.

Constants are also passed in pairs in `WinMain()` here.

The *int*-typed 123 constant is first converted according to its sign into a 32-bit value using the CWD instruction.

3.29.5 Example #5

```
#include <windows.h>

int PASCAL string_compare (char *s1, char *s2)
{
        while (1)
        {
                if (*s1!=*s2)
                        return 0;
                if (*s1==0 || *s2==0)
                        return 1; // end of string
                s1++;
                s2++;
        };

};

int PASCAL string_compare_far (char far *s1, char far *s2)
{
        while (1)
        {
                if (*s1!=*s2)
                        return 0;
                if (*s1==0 || *s2==0)
                        return 1; // end of string
                s1++;
                s2++;
        };

};
```

```
void PASCAL remove_digits (char *s)
{
        while (*s)
        {
                if (*s>='0' && *s<='9')
                        *s='-';
                s++;
        };
};

char str[]="hello 1234 world";

int PASCAL WinMain( HINSTANCE hInstance,
                    HINSTANCE hPrevInstance,
                    LPSTR lpCmdLine,
                    int nCmdShow )
{
        string_compare ("asd", "def");
        string_compare_far ("asd", "def");
        remove_digits (str);
        MessageBox (NULL, str, "caption", MB_YESNOCANCEL);
        return 0;
};
```

```
string_compare  proc near

arg_0 = word ptr  4
arg_2 = word ptr  6

      push    bp
      mov     bp, sp
      push    si
      mov     si, [bp+arg_0]
      mov     bx, [bp+arg_2]

loc_12: ; CODE XREF: string_compare+21j
      mov     al, [bx]
      cmp     al, [si]
      jz      short loc_1C
      xor     ax, ax
      jmp     short loc_2B


loc_1C: ; CODE XREF: string_compare+Ej
      test    al, al
      jz      short loc_22
      jnz     short loc_27

loc_22: ; CODE XREF: string_compare+16j
      mov     ax, 1
      jmp     short loc_2B


loc_27: ; CODE XREF: string_compare+18j
      inc     bx
      inc     si
      jmp     short loc_12


loc_2B: ; CODE XREF: string_compare+12j
        ; string_compare+1Dj
      pop     si
      pop     bp
      retn    4
string_compare  endp

string_compare_far proc near ; CODE XREF: WinMain+18p

arg_0 = word ptr  4
```

```
arg_2 = word ptr  6
arg_4 = word ptr  8
arg_6 = word ptr  0Ah

      push    bp
      mov     bp, sp
      push    si
      mov     si, [bp+arg_0]
      mov     bx, [bp+arg_4]

loc_3A: ; CODE XREF: string_compare_far+35j
      mov     es, [bp+arg_6]
      mov     al, es:[bx]
      mov     es, [bp+arg_2]
      cmp     al, es:[si]
      jz      short loc_4C
      xor     ax, ax
      jmp     short loc_67


loc_4C: ; CODE XREF: string_compare_far+16j
      mov     es, [bp+arg_6]
      cmp     byte ptr es:[bx], 0
      jz      short loc_5E
      mov     es, [bp+arg_2]
      cmp     byte ptr es:[si], 0
      jnz     short loc_63

loc_5E: ; CODE XREF: string_compare_far+23j
      mov     ax, 1
      jmp     short loc_67


loc_63: ; CODE XREF: string_compare_far+2Cj
      inc     bx
      inc     si
      jmp     short loc_3A


loc_67: ; CODE XREF: string_compare_far+1Aj
        ; string_compare_far+31j
      pop     si
      pop     bp
      retn    8
string_compare_far endp

remove_digits   proc near ; CODE XREF: WinMain+1Fp

arg_0 = word ptr  4

      push    bp
      mov     bp, sp
      mov     bx, [bp+arg_0]

loc_72: ; CODE XREF: remove_digits+18j
      mov     al, [bx]
      test    al, al
      jz      short loc_86
      cmp     al, 30h ; '0'
      jb      short loc_83
      cmp     al, 39h ; '9'
      ja      short loc_83
      mov     byte ptr [bx], 2Dh ; '-'

loc_83: ; CODE XREF: remove_digits+Ej
        ; remove_digits+12j
      inc     bx
      jmp     short loc_72
```

```
loc_86: ; CODE XREF: remove_digits+Aj
        pop     bp
        retn    2
remove_digits   endp

WinMain proc near ; CODE XREF: start+EDp
        push    bp
        mov     bp, sp
        mov     ax, offset aAsd ; "asd"
        push    ax
        mov     ax, offset aDef ; "def"
        push    ax
        call    string_compare
        push    ds
        mov     ax, offset aAsd ; "asd"
        push    ax
        push    ds
        mov     ax, offset aDef ; "def"
        push    ax
        call    string_compare_far
        mov     ax, offset aHello1234World ; "hello 1234 world"
        push    ax
        call    remove_digits
        xor     ax, ax
        push    ax
        push    ds
        mov     ax, offset aHello1234World ; "hello 1234 world"
        push    ax
        push    ds
        mov     ax, offset aCaption ; "caption"
        push    ax
        mov     ax, 3 ; MB_YESNOCANCEL
        push    ax
        call    MESSAGEBOX
        xor     ax, ax
        pop     bp
        retn    0Ah
WinMain endp
```

Here we see a difference between the so-called “near” pointers and the “far” pointers: another weird artifact of segmented memory in 16-bit 8086.

You can read more about it here: 11.6 on page 1003.

“near” pointers are those which point within the current data segment. Hence, the `string_compare()` function takes only two 16-bit pointers, and accesses the data from the segment that DS points to (The `mov al, [bx]` instruction actually works like `mov al, ds:[bx]`—DS is implicit here).

“far” pointers are those which may point to data in another memory segment.
Hence `string_compare_far()` takes the 16-bit pair as a pointer, loads the high part of it in the ES segment register and accesses the data through it
(`mov al, es:[bx]`). “far” pointers are also used in my
`MessageBox()` win16 example: 3.29.2 on page 650. Indeed, the Windows kernel is not aware which data segment to use when accessing text strings, so it need the complete information.

The reason for this distinction is that a compact program may use just one 64kb data segment, so it doesn’t need to pass the high part of the address, which is always the same. A bigger program may use several 64kb data segments, so it needs to specify the segment of the data each time.

It’s the same story for code segments. A compact program may have all executable code within one 64kb-segment, then all functions in it will be called using the CALL NEAR instruction, and the code flow will be returned using RETN. But if there are several code segments, then the address of the function is to be specified by a pair, it is to be called using the CALL FAR instruction, and the code flow is to be returned using RETF.

This is what is set in the compiler by specifying “memory model”.

The compilers targeting MS-DOS and Win16 have specific libraries for each memory model: they differ by pointer types for code and data.

3.29.6 Example #6

```
#include <windows.h>
#include <time.h>
#include <stdio.h>

char strbuf[256];

int PASCAL WinMain( HINSTANCE hInstance,
                    HINSTANCE hPrevInstance,
                    LPSTR lpCmdLine,
                    int nCmdShow )
{

        struct tm *t;
        time_t unix_time;

        unix_time=time(NULL);

        t=localtime (&unix_time);

        sprintf (strbuf, "%04d-%02d-%02d %02d:%02d:%02d", t->tm_year+1900, t->tm_mon, t->↙
    ↳ tm_mday,
                t->tm_hour, t->tm_min, t->tm_sec);

        MessageBox (NULL, strbuf, "caption", MB_OK);
        return 0;
};
```

```
WinMain         proc near

var_4           = word ptr -4
var_2           = word ptr -2

                push    bp
                mov     bp, sp
                push    ax
                push    ax
                xor     ax, ax
                call    time_
                mov     [bp+var_4], ax   ; low part of UNIX time
                mov     [bp+var_2], dx   ; high part of UNIX time
                lea     ax, [bp+var_4]   ; take a pointer of high part
                call    localtime_
                mov     bx, ax           ; t
                push    word ptr [bx]    ; second
                push    word ptr [bx+2]  ; minute
                push    word ptr [bx+4]  ; hour
                push    word ptr [bx+6]  ; day
                push    word ptr [bx+8]  ; month
                mov     ax, [bx+0Ah]     ; year
                add     ax, 1900
                push    ax
                mov     ax, offset a04d02d02d02d02 ; "%04d-%02d-%02d %02d:%02d:%02d"
                push    ax
                mov     ax, offset strbuf
                push    ax
                call    sprintf_
                add     sp, 10h
                xor     ax, ax            ; NULL
                push    ax
                push    ds
                mov     ax, offset strbuf
                push    ax
                push    ds
                mov     ax, offset aCaption ; "caption"
                push    ax
                xor     ax, ax          ; MB_OK
                push    ax
```

```
                call    MESSAGEBOX
                xor     ax, ax
                mov     sp, bp
                pop     bp
                retn    0Ah
WinMain         endp
```

UNIX time is a 32-bit value, so it is returned in the DX:AX register pair and stored in two local 16-bit variables. Then a pointer to the pair is passed to the `localtime()` function. The `localtime()` function has a `struct tm` allocated somewhere in the guts of the C library, so only a pointer to it is returned.

By the way, this also implies that the function cannot be called again until its results are used.

For the `time()` and `localtime()` functions, a Watcom calling convention is used here: the first four arguments are passed in the AX, DX, BX and CX, registers, and the rest arguments are via the stack.

The functions using this convention are also marked by underscore at the end of their name.

`sprintf()` does not use the PASCAL calling convention, nor the Watcom one,
so the arguments are passed in the normal *cdecl* way (6.1.1 on page 734).

Global variables

This is the same example, but now these variables are global:

```
#include <windows.h>
#include <time.h>
#include <stdio.h>

char strbuf[256];
struct tm *t;
time_t unix_time;

int PASCAL WinMain( HINSTANCE hInstance,
                    HINSTANCE hPrevInstance,
                    LPSTR lpCmdLine,
                    int nCmdShow )
{

        unix_time=time(NULL);

        t=localtime (&unix_time);

        sprintf (strbuf, "%04d-%02d-%02d %02d:%02d:%02d", t->tm_year+1900, t->tm_mon, t->↙
    ↳ tm_mday,
                t->tm_hour, t->tm_min, t->tm_sec);

        MessageBox (NULL, strbuf, "caption", MB_OK);
        return 0;
};
```

```
unix_time_low   dw 0
unix_time_high  dw 0
t               dw 0

WinMain         proc near
                push    bp
                mov     bp, sp
                xor     ax, ax
                call    time_
                mov     unix_time_low, ax
                mov     unix_time_high, dx
                mov     ax, offset unix_time_low
                call    localtime_
                mov     bx, ax
                mov     t, ax                   ; will not be used in future...
                push    word ptr [bx]           ; seconds
                push    word ptr [bx+2]         ; minutes
                push    word ptr [bx+4]         ; hour
```

```
                push    word ptr [bx+6]     ; day
                push    word ptr [bx+8]     ; month
                mov     ax, [bx+0Ah]        ; year
                add     ax, 1900
                push    ax
                mov     ax, offset a04d02d02d02d02 ; "%04d-%02d-%02d %02d:%02d:%02d"
                push    ax
                mov     ax, offset strbuf
                push    ax
                call    sprintf_
                add     sp, 10h
                xor     ax, ax          ; NULL
                push    ax
                push    ds
                mov     ax, offset strbuf
                push    ax
                push    ds
                mov     ax, offset aCaption ; "caption"
                push    ax
                xor     ax, ax          ; MB_OK
                push    ax
                call    MESSAGEBOX
                xor     ax, ax          ; return 0
                pop     bp
                retn    0Ah
WinMain         endp
```

`t` is not to be used, but the compiler emitted the code which stores the value.

Because it is not sure, maybe that value will eventually be used in some other module.

Chapter 4

Java

4.1 Java

4.1.1 Introduction

There are some well-known decompilers for Java (or JVM bytecode in general) [1].

The reason is the decompilation of JVM-bytecode is somewhat easier than for lower level x86 code:

- There is much more information about the data types.
- The JVM memory model is much more rigorous and outlined.
- The Java compiler don't do any optimizations (the JVM JIT[2] does them at runtime), so the bytecode in the class files is usually pretty readable.

When can the knowledge of JVM be useful?

- Quick-and-dirty patching tasks of class files without the need to recompile the decompiler's results.
- Analyzing obfuscated code.
- Building your own obfuscator.
- Building a compiler codegenerator (back-end) targeting JVM (like Scala, Clojure, etc. [3]).

Let's start with some simple pieces of code. JDK 1.7 is used everywhere, unless mentioned otherwise.

This is the command used to decompile class files everywhere:
`javap -c -verbose`.

This is the book I used while preparing all examples: [Tim Lindholm, Frank Yellin, Gilad Bracha, Alex Buckley, *The Java(R) Virtual Machine Specification / Java SE 7 Edition*] [4].

4.1.2 Returning a value

Probably the simplest Java function is the one which returns some value.

Oh, and we must keep in mind that there are no "free" functions in Java in common sense, they are "methods".

Each method is related to some class, so it's not possible to define a method outside of a class.

But we'll call them "functions" anyway, for simplicity.

```
public class ret
{
        public static int main(String[] args)
        {
                return 0;
```

[1] For example, JAD: http://varaneckas.com/jad/
[2] Just-In-Time compilation
[3] Full list: http://en.wikipedia.org/wiki/List_of_JVM_languages
[4] Also available as https://docs.oracle.com/javase/specs/jvms/se7/jvms7.pdf; http://docs.oracle.com/javase/specs/jvms/se7/html/

```
        }
}
```

Let's compile it:

```
javac ret.java
```

...and decompile it using the standard Java utility:

```
javap -c -verbose ret.class
```

And we get:

Listing 4.1: JDK 1.7 (excerpt)

```
  public static int main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=1, args_size=1
         0: iconst_0
         1: ireturn
```

The Java developers decided that 0 is one of the busiest constants in programming, so there is a separate short one-byte `iconst_0` instruction which pushes 0

[5]. There are also `iconst_1` (which pushes 1), `iconst_2`, etc., up to `iconst_5`.

There is also `iconst_m1` which pushes -1.

The stack is used in JVM for passing data to called functions and also for return values. So `iconst_0` pushes 0 into the stack. `ireturn` returns an integer value (*i* in name means *integer*) from the TOS[6].

Let's rewrite our example slightly, now we return 1234:

```
public class ret
{
        public static int main(String[] args)
        {
                return 1234;
        }
}
```

...we get:

Listing 4.2: JDK 1.7 (excerpt)

```
  public static int main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=1, args_size=1
         0: sipush        1234
         3: ireturn
```

`sipush` (*short integer*) pushes 1234 into the stack. *short* in name implies a 16-bit value is to be pushed. The number 1234 indeed fits well in a 16-bit value.

What about larger values?

```
public class ret
{
        public static int main(String[] args)
        {
                return 12345678;
        }
}
```

[5]Just like in MIPS, where a separate register for zero constant exists: 1.5.5 on page 26.
[6]Top of Stack

Listing 4.3: Constant pool

```
...
   #2 = Integer            12345678
...
```

```
  public static int main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=1, args_size=1
         0: ldc           #2                  // int 12345678
         2: ireturn
```

It's not possible to encode a 32-bit number in a JVM instruction opcode, the developers didn't leave such possibility.

So the 32-bit number 12345678 is stored in so called "constant pool" which is, let's say, the library of most used constants (including strings, objects, etc.).

This way of passing constants is not unique to JVM.

MIPS, ARM and other RISC CPUs also can't encode a 32-bit number in a 32-bit opcode, so the RISC CPU code (including MIPS and ARM) has to construct the value in several steps, or to keep it in the data segment: 1.32.3 on page 440, 1.33.1 on page 443.

MIPS code also traditionally has a constant pool, named "literal pool", the segments are called ".lit4" (for 32-bit single precision floating point number constants) and ".lit8" (for 64-bit double precision floating point number constants).

Let's try some other data types!

Boolean:

```
public class ret
{
        public static boolean main(String[] args)
        {
                return true;
        }
}
```

```
  public static boolean main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=1, args_size=1
         0: iconst_1
         1: ireturn
```

This JVM bytecode is no different from one returning integer 1.

32-bit data slots in the stack are also used here for boolean values, like in C/C++.

But one could not use returned boolean value as integer or vice versa — type information is stored in the class file and checked at runtime.

It's the same story with a 16-bit *short*:

```
public class ret
{
        public static short main(String[] args)
        {
                return 1234;
        }
}
```

```
  public static short main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=1, args_size=1
         0: sipush        1234
         3: ireturn
```

…and *char*!

```
public class ret
{
        public static char main(String[] args)
        {
                return 'A';
        }
}
```

```
  public static char main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=1, args_size=1
         0: bipush        65
         2: ireturn
```

bipush means "push byte". Needless to say that a *char* in Java is 16-bit UTF-16 character, and it's equivalent to *short*, but the ASCII code of the "A" character is 65, and it's possible to use the instruction for pushing a byte in the stack.

Let's also try a *byte*:

```
public class retc
{
        public static byte main(String[] args)
        {
                return 123;
        }
}
```

```
  public static byte main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=1, args_size=1
         0: bipush        123
         2: ireturn
```

One may ask, why bother with a 16-bit *short* data type which internally works as a 32-bit integer?

Why use a *char* data type if it is the same as a *short* data type?

The answer is simple: for data type control and source code readability.

A *char* may essentially be the same as a *short*, but we quickly grasp that it's a placeholder for an UTF-16 character, and not for some other integer value.

When using *short*, we show everyone that the variable's range is limited by 16 bits.

It's a very good idea to use the *boolean* type where needed to, instead of the C-style *int*.

There is also a 64-bit integer data type in Java:

```
public class ret3
{
        public static long main(String[] args)
        {
                return 1234567890123456789L;
        }
}
```

Listing 4.4: Constant pool

```
...
   #2 = Long               1234567890123456789l
...
```

```
  public static long main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=1, args_size=1
```

```
         0: ldc2_w        #2                  // long 1234567890123456789l
         3: lreturn
```

The 64-bit number is also stored in a constant pool, `ldc2_w` loads it and `lreturn` (*long return*) returns it.

The `ldc2_w` instruction is also used to load double precision floating point numbers (which also occupy 64 bits) from a constant pool:

```
public class ret
{
        public static double main(String[] args)
        {
                return 123.456d;
        }
}
```

Listing 4.5: Constant pool

```
...
   #2 = Double             123.456d
...
```

```
  public static double main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=1, args_size=1
         0: ldc2_w        #2                  // double 123.456d
         3: dreturn
```

`dreturn` stands for "return double".

And finally, a single precision floating point number:

```
public class ret
{
        public static float main(String[] args)
        {
                return 123.456f;
        }
}
```

Listing 4.6: Constant pool

```
...
   #2 = Float              123.456f
...
```

```
  public static float main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=1, args_size=1
         0: ldc           #2                  // float 123.456f
         2: freturn
```

The `ldc` instruction used here is the same one as for loading 32-bit integer numbers from a constant pool.

`freturn` stands for "return float".

Now what about function that return nothing?

```
public class ret
{
        public static void main(String[] args)
        {
                return;
        }
}
```

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=0, locals=1, args_size=1
         0: return
```

This means that the `return` instruction is used to return control without returning an actual value.

Knowing all this, it's very easy to deduce the function's (or method's) returning type from the last instruction.

4.1.3 Simple calculating functions

Let's continue with a simple calculating functions.

```
public class calc
{
        public static int half(int a)
        {
                return a/2;
        }
}
```

Here's the output when the `iconst_2` instruction is used:

```
  public static int half(int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=1, args_size=1
         0: iload_0
         1: iconst_2
         2: idiv
         3: ireturn
```

`iload_0` takes the zeroth function argument and pushes it to the stack.

`iconst_2` pushes 2 in the stack. After the execution of these two instructions, this is how stack looks like:

```
      +---+
TOS ->| 2 |
      +---+
      | a |
      +---+
```

`idiv` just takes the two values at the TOS, divides one by the other and leaves the result at TOS:

```
      +--------+
TOS ->| result |
      +--------+
```

`ireturn` takes it and returns.

Let's proceed with double precision floating point numbers:

```
public class calc
{
        public static double half_double(double a)
        {
                return a/2.0;
        }
}
```

Listing 4.7: Constant pool

```
...
   #2 = Double             2.0d
...
```

```
  public static double half_double(double);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=4, locals=2, args_size=1
         0: dload_0
         1: ldc2_w        #2                  // double 2.0d
         4: ddiv
         5: dreturn
```

It's the same, but the `ldc2_w` instruction is used to load the constant 2.0 from the constant pool.

Also, the other three instructions have the *d* prefix, meaning they work with *double* data type values.

Let's now use a function with two arguments:

```
public class calc
{
        public static int sum(int a, int b)
        {
                return a+b;
        }
}
```

```
  public static int sum(int, int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=2, args_size=2
         0: iload_0
         1: iload_1
         2: iadd
         3: ireturn
```

`iload_0` loads the first function argument (a), `iload_1`—second (b).

Here is the stack after the execution of both instructions:

```
      +---+
TOS ->| b |
      +---+
      | a |
      +---+
```

`iadd` adds the two values and leaves the result at TOS:

```
      +--------+
TOS ->| result |
      +--------+
```

Let's extend this example to the *long* data type:

```
        public static long lsum(long a, long b)
        {
                return a+b;
        }
```

...we got:

```
  public static long lsum(long, long);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=4, locals=4, args_size=2
         0: lload_0
         1: lload_2
         2: ladd
         3: lreturn
```

The second `lload` instruction takes the second argument from the 2nd slot.

That's because a 64-bit *long* value occupies exactly two 32-bit slots.

Slightly more advanced example:

```
public class calc
{
        public static int mult_add(int a, int b, int c)
        {
                return a*b+c;
        }
}
```

```
  public static int mult_add(int, int, int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=3, args_size=3
         0: iload_0
         1: iload_1
         2: imul
         3: iload_2
         4: iadd
         5: ireturn
```

The first step is multiplication. The product is left at the TOS:

```
      +---------+
TOS ->| product |
      +---------+
```

`iload_2` loads the third argument (c) in the stack:

```
      +---------+
TOS ->|    c    |
      +---------+
      | product |
      +---------+
```

Now the `iadd` instruction can add the two values.

4.1.4 JVM memory model

x86 and other low-level environments use the stack for argument passing and as a local variables storage. JVM is slightly different.

It has:

- Local variable array (LVA[7]). Used as storage for incoming function arguments and local variables.

  Instructions like `iload_0` load values from it.

  `istore` stores values in it. At the beginning the function arguments are stored: starting at 0 or at 1 (if the zeroth argument is occupied by *this* pointer).

  Then the local variables are allocated.

  Each slot has size of 32-bit.

  Hence, values of *long* and *double* data types occupy two slots.

- Operand stack (or just "stack"). It's used for computations and passing arguments while calling other functions.

  Unlike low-level environments like x86, it's not possible to access the stack without using instructions which explicitly pushes or pops values to/from it.

- Heap. It is used as storage for objects and arrays.

These 3 areas are isolated from each other.

[7] (Java) Local Variable Array

4.1.5 Simple function calling

`Math.random()` returns a pseudorandom number in range of [0.0 …1.0), but let's say that for some reason we need to devise a function that returns a number in range of [0.0 …0.5):

```
public class HalfRandom
{
        public static double f()
        {
                return Math.random()/2;
        }
}
```

Listing 4.8: Constant pool

```
...
   #2 = Methodref          #18.#19    //  java/lang/Math.random:()D
   #3 = Double             2.0d
...
  #12 = Utf8               ()D
...
  #18 = Class              #22        //  java/lang/Math
  #19 = NameAndType        #23:#12    //  random:()D
  #22 = Utf8               java/lang/Math
  #23 = Utf8               random
```

```
  public static double f();
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=4, locals=0, args_size=0
         0: invokestatic  #2          // Method java/lang/Math.random:()D
         3: ldc2_w        #3          // double 2.0d
         6: ddiv
         7: dreturn
```

`invokestatic` calls the `Math.random()` function and leaves the result at the TOS.

Then the result is divided by 2.0 and returned.

But how is the function name encoded?

It's encoded in the constant pool using a `Methodref` expression.

It defines the class and method names.

The first field of `Methodref` points to a `Class` expression which, in turn, points to the usual text string ("java/lang/Math").

The second `Methodref` expression points to a `NameAndType` expression which also has two links to the strings.

The first string is "random", which is the name of the method.

The second string is "()D", which encodes the function's type. It means that it returns a *double* value (hence the *D* in the string).

This is the way 1) JVM can check data for type correctness; 2) Java decompilers can restore data types from a compiled class file.

Now let's try the "Hello, world!" example:

```
public class HelloWorld
{
        public static void main(String[] args)
        {
                System.out.println("Hello, World");
        }
}
```

Listing 4.9: Constant pool

```
...
```

```
   #2 = Fieldref           #16.#17        //  java/lang/System.out:Ljava/io/PrintStream;
   #3 = String             #18            //  Hello, World
   #4 = Methodref          #19.#20        //  java/io/PrintStream.println:(Ljava/lang/String;)V
...
  #16 = Class              #23            //  java/lang/System
  #17 = NameAndType        #24:#25        //  out:Ljava/io/PrintStream;
  #18 = Utf8               Hello, World
  #19 = Class              #26            //  java/io/PrintStream
  #20 = NameAndType        #27:#28        //  println:(Ljava/lang/String;)V
...
  #23 = Utf8               java/lang/System
  #24 = Utf8               out
  #25 = Utf8               Ljava/io/PrintStream;
  #26 = Utf8               java/io/PrintStream
  #27 = Utf8               println
  #28 = Utf8               (Ljava/lang/String;)V
...
```

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=1, args_size=1
         0: getstatic     #2        // Field java/lang/System.out:Ljava/io/PrintStream;
         3: ldc           #3        // String Hello, World
         5: invokevirtual #4        // Method java/io/PrintStream.println:(Ljava/lang/String;)V
         8: return
```

`ldc` at offset 3 takes a pointer to the "Hello, World" string in the constant pool and pushes in the stack.

It's called a *reference* in the Java world, but it's rather a pointer, or an address [8].

The familiar `invokevirtual` instruction takes the information about the `println` function (or method) from the constant pool and calls it.

As we may know, there are several `println` methods, one for each data type.

Our case is the version of `println` intended for the *String* data type.

But what about the first `getstatic` instruction?

This instruction takes a *reference* (or address of) a field of the object `System.out` and pushes it in the stack.

This value is acts like the *this* pointer for the `println` method.

Thus, internally, the `println` method takes two arguments for input: 1) *this*, i.e., a pointer to an object; 2) the address of the "Hello, World" string.

Indeed, `println()` is called as a method within an initialized `System.out` object.

For convenience, the `javap` utility writes all this information in the comments.

4.1.6 Calling beep()

This is a simple calling of two functions without arguments:

```
        public static void main(String[] args)
        {
                java.awt.Toolkit.getDefaultToolkit().beep();
        };
```

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=1, args_size=1
         0: invokestatic  #2      // Method java/awt/Toolkit.getDefaultToolkit:()Ljava/awt/↙
    ↳ Toolkit;
```

[8]About difference in pointers and *reference*'s in C++ see: 3.18.3 on page 558.

```
        3: invokevirtual #3      // Method java/awt/Toolkit.beep:()V
        6: return
```

First `invokestatic` at offset 0 calls
`java.awt.Toolkit.getDefaultToolkit()`, which returns a reference to an object of class `Toolkit`.
The `invokevirtual` instruction at offset 3 calls the `beep()` method of this class.

4.1.7 Linear congruential PRNG

Let's try a simple pseudorandom numbers generator, which we already considered once in the book (1.23 on page 338):

```
public class LCG
{
        public static int rand_state;

        public void my_srand (int init)
        {
                rand_state=init;
        }

        public static int RNG_a=1664525;
        public static int RNG_c=1013904223;

        public int my_rand ()
        {
                rand_state=rand_state*RNG_a;
                rand_state=rand_state+RNG_c;
                return rand_state & 0x7fff;
        }
}
```

There are couple of class fields which are initialized at start.

But how? In `javap` output we can find the class constructor:

```
  static {};
    flags: ACC_STATIC
    Code:
      stack=1, locals=0, args_size=0
         0: ldc           #5          // int 1664525
         2: putstatic     #3          // Field RNG_a:I
         5: ldc           #6          // int 1013904223
         7: putstatic     #4          // Field RNG_c:I
        10: return
```

That's the way variables are initialized.

RNG_a occupies the 3rd slot in the class and RNG_c—4th, and `putstatic` puts the constants there.

The `my_srand()` function just stores the input value in `rand_state`:

```
  public void my_srand(int);
    flags: ACC_PUBLIC
    Code:
      stack=1, locals=2, args_size=2
         0: iload_1
         1: putstatic     #2          // Field rand_state:I
         4: return
```

`iload_1` takes the input value and pushes it into stack. But why not `iload_0`?

It's because this function may use fields of the class, and so *this* is also passed to the function as a zeroth argument.

The field `rand_state` occupies the 2nd slot in the class, so `putstatic` copies the value from the TOS into the 2nd slot.

Now `my_rand()`:

```
  public int my_rand();
    flags: ACC_PUBLIC
    Code:
      stack=2, locals=1, args_size=1
         0: getstatic     #2          // Field rand_state:I
         3: getstatic     #3          // Field RNG_a:I
         6: imul
         7: putstatic     #2          // Field rand_state:I
        10: getstatic     #2          // Field rand_state:I
        13: getstatic     #4          // Field RNG_c:I
        16: iadd
        17: putstatic     #2          // Field rand_state:I
        20: getstatic     #2          // Field rand_state:I
        23: sipush        32767
        26: iand
        27: ireturn
```

It just loads all the values from the object's fields, does the operations and updates `rand_state`'s value using the `putstatic` instruction.

At offset 20, `rand_state` is reloaded again (because it has been dropped from the stack before, by `putstatic`).

This looks like non-efficient code, but be sure, the JVM is usually good enough to optimize such things really well.

4.1.8 Conditional jumps

Now let's proceed to conditional jumps.

```
public class abs
{
        public static int abs(int a)
        {
                if (a<0)
                        return -a;
                return a;
        }
}
```

```
  public static int abs(int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=1, args_size=1
         0: iload_0
         1: ifge          7
         4: iload_0
         5: ineg
         6: ireturn
         7: iload_0
         8: ireturn
```

`ifge` jumps to offset 7 if the value at TOS is greater or equal to 0.

Don't forget, any `ifXX` instruction pops the value (to be compared) from the stack.

ineg just negates value at TOS.

Another example:

```
        public static int min (int a, int b)
        {
                if (a>b)
                        return b;
                return a;
        }
```

We get:

```
  public static int min(int, int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=2, args_size=2
         0: iload_0
         1: iload_1
         2: if_icmple     7
         5: iload_1
         6: ireturn
         7: iload_0
         8: ireturn
```

`if_icmple` pops two values and compares them. If the second one is lesser than (or equal to) the first, a jump to offset 7 is performed.

When we define `max()` function …

```
        public static int max (int a, int b)
        {
                if (a>b)
                        return a;
                return b;
        }
```

…the resulting code is the same, but the last two `iload` instructions (at offsets 5 and 7) are swapped:

```
  public static int max(int, int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=2, args_size=2
         0: iload_0
         1: iload_1
         2: if_icmple     7
         5: iload_0
         6: ireturn
         7: iload_1
         8: ireturn
```

A more advanced example:

```
public class cond
{
        public static void f(int i)
        {
                if (i<100)
                        System.out.print("<100");
                if (i==100)
                        System.out.print("==100");
                if (i>100)
                        System.out.print(">100");
                if (i==0)
                        System.out.print("==0");
        }
}
```

```
  public static void f(int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=1, args_size=1
         0: iload_0
         1: bipush        100
         3: if_icmpge     14
         6: getstatic     #2        // Field java/lang/System.out:Ljava/io/PrintStream;
         9: ldc           #3        // String <100
        11: invokevirtual #4        // Method java/io/PrintStream.print:(Ljava/lang/String;)V
        14: iload_0
        15: bipush        100
        17: if_icmpne     28
        20: getstatic     #2        // Field java/lang/System.out:Ljava/io/PrintStream;
```

```
        23: ldc           #5        // String ==100
        25: invokevirtual #4        // Method java/io/PrintStream.print:(Ljava/lang/String;)V
        28: iload_0
        29: bipush        100
        31: if_icmple     42
        34: getstatic     #2        // Field java/lang/System.out:Ljava/io/PrintStream;
        37: ldc           #6        // String >100
        39: invokevirtual #4        // Method java/io/PrintStream.print:(Ljava/lang/String;)V
        42: iload_0
        43: ifne          54
        46: getstatic     #2        // Field java/lang/System.out:Ljava/io/PrintStream;
        49: ldc           #7        // String ==0
        51: invokevirtual #4        // Method java/io/PrintStream.print:(Ljava/lang/String;)V
        54: return
```

`if_icmpge` pops two values and compares them. If the second one is larger than the first, a jump to offset 14 is performed.

`if_icmpne` and `if_icmple` work just the same, but implement different conditions.

There is also a `ifne` instruction at offset 43.

Its name is misnomer, it would've be better to name it `ifnz` (jump if the value at TOS is not zero).

And that is what it does: it jumps to offset 54 if the input value is not zero.

If zero,the execution flow proceeds to offset 46, where the "==0" string is printed.

N.B.: JVM has no unsigned data types, so the comparison instructions operate only on signed integer values.

4.1.9 Passing arguments

Let's extend our `min()`/`max()` example:

```
public class minmax
{
        public static int min (int a, int b)
        {
                if (a>b)
                        return b;
                return a;
        }

        public static int max (int a, int b)
        {
                if (a>b)
                        return a;
                return b;
        }

        public static void main(String[] args)
        {
                int a=123, b=456;
                int max_value=max(a, b);
                int min_value=min(a, b);
                System.out.println(min_value);
                System.out.println(max_value);
        }
}
```

Here is `main()` function code:

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=5, args_size=1
         0: bipush        123
         2: istore_1
         3: sipush        456
```

```
         6: istore_2
         7: iload_1
         8: iload_2
         9: invokestatic  #2       // Method max:(II)I
        12: istore_3
        13: iload_1
        14: iload_2
        15: invokestatic  #3       // Method min:(II)I
        18: istore        4
        20: getstatic     #4       // Field java/lang/System.out:Ljava/io/PrintStream;
        23: iload         4
        25: invokevirtual #5       // Method java/io/PrintStream.println:(I)V
        28: getstatic     #4       // Field java/lang/System.out:Ljava/io/PrintStream;
        31: iload_3
        32: invokevirtual #5       // Method java/io/PrintStream.println:(I)V
        35: return
```

Arguments are passed to the other function in the stack, and the return value is left on TOS.

4.1.10 Bitfields

All bit-wise operations work just like in any other ISA:

```
        public static int set (int a, int b)
        {
                return a | 1<<b;
        }

        public static int clear (int a, int b)
        {
                return a & (~(1<<b));
        }
```

```
  public static int set(int, int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=3, locals=2, args_size=2
         0: iload_0
         1: iconst_1
         2: iload_1
         3: ishl
         4: ior
         5: ireturn

  public static int clear(int, int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=3, locals=2, args_size=2
         0: iload_0
         1: iconst_1
         2: iload_1
         3: ishl
         4: iconst_m1
         5: ixor
         6: iand
         7: ireturn
```

`iconst_m1` loads -1 in the stack, it's the same as the `0xFFFFFFFF` number.

XORing with `0xFFFFFFFF` has the same effect of inverting all bits (2.6 on page 461).

Let's extend all data types to 64-bit *long*:

```
        public static long lset (long a, int b)
        {
                return a | 1<<b;
        }
```

```
        public static long lclear (long a, int b)
        {
                return a & (~(1<<b));
        }
```

```
  public static long lset(long, int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=4, locals=3, args_size=2
         0: lload_0
         1: iconst_1
         2: iload_2
         3: ishl
         4: i2l
         5: lor
         6: lreturn

  public static long lclear(long, int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=4, locals=3, args_size=2
         0: lload_0
         1: iconst_1
         2: iload_2
         3: ishl
         4: iconst_m1
         5: ixor
         6: i2l
         7: land
         8: lreturn
```

The code is the same, but instructions with *l* prefix are used, which operate on 64-bit values.

Also, the second argument of the function still is of type *int*, and when the 32-bit value in it needs to be promoted to 64-bit value the `i2l` instruction is used, which essentially extend the value of an *integer* type to a *long* one.

4.1.11 Loops

```
public class Loop
{
        public static void main(String[] args)
        {
                for (int i = 1; i <= 10; i++)
                {
                        System.out.println(i);
                }
        }
}
```

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=2, args_size=1
         0: iconst_1
         1: istore_1
         2: iload_1
         3: bipush        10
         5: if_icmpgt     21
         8: getstatic     #2          // Field java/lang/System.out:Ljava/io/PrintStream;
        11: iload_1
        12: invokevirtual #3          // Method java/io/PrintStream.println:(I)V
        15: iinc          1, 1
        18: goto          2
        21: return
```

`iconst_1` loads 1 into TOS, `istore_1` stores it in the LVA at slot 1.

Why not the zeroth slot? Because the `main()` function has one argument (array of `String`) and a pointer to it (or *reference*) is now in the zeroth slot.

So, the *i* local variable will always be in 1st slot.

Instructions at offsets 3 and 5 compare *i* with 10.

If *i* is larger, execution flow passes to offset 21, where the function ends.

If it's not, `println` is called.

i is then reloaded at offset 11, for `println`.

By the way, we call the `println` method for an *integer*, and we see this in the comments: "(I)V" (*I* means *integer* and *V* means the return type is *void*).

When `println` finishes, *i* is incremented at offset 15.

The first operand of the instruction is the number of a slot (1), the second is the number (1) to add to the variable.

`goto` is just GOTO, it jumps to the beginning of the loop's body offset 2.

Let's proceed with a more complex example:

```
public class Fibonacci
{
        public static void main(String[] args)
        {
                int limit = 20, f = 0, g = 1;

                for (int i = 1; i <= limit; i++)
                {
                        f = f + g;
                        g = f - g;
                        System.out.println(f);
                }
        }
}
```

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=5, args_size=1
         0: bipush        20
         2: istore_1
         3: iconst_0
         4: istore_2
         5: iconst_1
         6: istore_3
         7: iconst_1
         8: istore        4
        10: iload         4
        12: iload_1
        13: if_icmpgt     37
        16: iload_2
        17: iload_3
        18: iadd
        19: istore_2
        20: iload_2
        21: iload_3
        22: isub
        23: istore_3
        24: getstatic     #2         // Field java/lang/System.out:Ljava/io/PrintStream;
        27: iload_2
        28: invokevirtual #3         // Method java/io/PrintStream.println:(I)V
        31: iinc          4, 1
        34: goto          10
        37: return
```

Here is a map of the LVA slots:

- 0 — the sole argument of `main()`

- 1 — *limit*, always contains 20
- 2 — *f*
- 3 — *g*
- 4 — *i*

We can see that the Java compiler allocates variables in LVA slots in the same order they were declared in the source code.

There are separate `istore` instructions for accessing slots 0, 1, 2 and 3, but not for 4 and larger, so there is `istore` with an additional operand at offset 8 which takes the slot number as an operand.

It's the same with `iload` at offset 10.

But isn't it dubious to allocate another slot for the *limit* variable, which always contains 20 (so it's a constant in essence), and reload its value so often?

JVM JIT compiler is usually good enough to optimize such things.

Manual intervention in the code is probably not worth it.

4.1.12 switch()

The switch() statement is implemented with the `tableswitch` instruction:

```
        public static void f(int a)
        {
                switch (a)
                {
                case 0: System.out.println("zero"); break;
                case 1: System.out.println("one\n"); break;
                case 2: System.out.println("two\n"); break;
                case 3: System.out.println("three\n"); break;
                case 4: System.out.println("four\n"); break;
                default: System.out.println("something unknown\n"); break;
                };
        }
```

As simple, as possible:

```
  public static void f(int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=1, args_size=1
         0: iload_0
         1: tableswitch   { // 0 to 4
                       0: 36
                       1: 47
                       2: 58
                       3: 69
                       4: 80
                 default: 91
            }
        36: getstatic     #2     // Field java/lang/System.out:Ljava/io/PrintStream;
        39: ldc           #3     // String zero
        41: invokevirtual #4     // Method java/io/PrintStream.println:(Ljava/lang/String;)V
        44: goto          99
        47: getstatic     #2     // Field java/lang/System.out:Ljava/io/PrintStream;
        50: ldc           #5     // String one\n
        52: invokevirtual #4     // Method java/io/PrintStream.println:(Ljava/lang/String;)V
        55: goto          99
        58: getstatic     #2     // Field java/lang/System.out:Ljava/io/PrintStream;
        61: ldc           #6     // String two\n
        63: invokevirtual #4     // Method java/io/PrintStream.println:(Ljava/lang/String;)V
        66: goto          99
        69: getstatic     #2     // Field java/lang/System.out:Ljava/io/PrintStream;
        72: ldc           #7     // String three\n
        74: invokevirtual #4     // Method java/io/PrintStream.println:(Ljava/lang/String;)V
        77: goto          99
```

```
        80: getstatic     #2      // Field java/lang/System.out:Ljava/io/PrintStream;
        83: ldc           #8      // String four\n
        85: invokevirtual #4      // Method java/io/PrintStream.println:(Ljava/lang/String;)V
        88: goto          99
        91: getstatic     #2      // Field java/lang/System.out:Ljava/io/PrintStream;
        94: ldc           #9      // String something unknown\n
        96: invokevirtual #4      // Method java/io/PrintStream.println:(Ljava/lang/String;)V
        99: return
```

4.1.13 Arrays

Simple example

Let's first create an array of 10 integers and fill it:

```
        public static void main(String[] args)
        {
                int a[]=new int[10];
                for (int i=0; i<10; i++)
                        a[i]=i;
                dump (a);
        }
```

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=3, locals=3, args_size=1
         0: bipush        10
         2: newarray       int
         4: astore_1
         5: iconst_0
         6: istore_2
         7: iload_2
         8: bipush        10
        10: if_icmpge     23
        13: aload_1
        14: iload_2
        15: iload_2
        16: iastore
        17: iinc          2, 1
        20: goto          7
        23: aload_1
        24: invokestatic  #4      // Method dump:([I)V
        27: return
```

The `newarray` instruction creates an array object of 10 *int* elements.

The array's size is set with `bipush` and left at TOS.

The array's type is set in `newarray` instruction's operand.

After `newarray`'s execution, a *reference* (or pointer) to the newly created array in the heap is left at the TOS.

`astore_1` stores the *reference* to the 1st slot in LVA.

The second part of the `main()` function is the loop which stores *i* into the corresponding array element.

`aload_1` gets a *reference* of the array and places it in the stack.

`iastore` then stores the integer value from the stack in the array, *reference* of which is currently in TOS.

The third part of the `main()` function calls the `dump()` function.

An argument for it is prepared by `aload_1` (offset 23).

Now let's proceed to the `dump()` function:

```
        public static void dump(int a[])
        {
                for (int i=0; i<a.length; i++)
                        System.out.println(a[i]);
        }
```

```
  public static void dump(int[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=3, locals=2, args_size=1
         0: iconst_0
         1: istore_1
         2: iload_1
         3: aload_0
         4: arraylength
         5: if_icmpge     23
         8: getstatic     #2      // Field java/lang/System.out:Ljava/io/PrintStream;
        11: aload_0
        12: iload_1
        13: iaload
        14: invokevirtual #3      // Method java/io/PrintStream.println:(I)V
        17: iinc          1, 1
        20: goto          2
        23: return
```

The incoming `reference` to the array is in the zeroth slot.

The `a.length` expression in the source code is converted to an `arraylength` instruction: it takes a *reference* to the array and leaves the array size at TOS.

`iaload` at offset 13 is used to load array elements, it requires to array *reference* be present in the stack (prepared by `aload_0` at 11), and also an index (prepared by `iload_1` at offset 12).

Needless to say, instructions prefixed with *a* may be mistakenly comprehended as *array* instructions.

It's not correct. These instructions works with *references* to objects.

And arrays and strings are objects too.

Summing elements of array

Another example:

```
public class ArraySum
{
        public static int f (int[] a)
        {
                int sum=0;
                for (int i=0; i<a.length; i++)
                        sum=sum+a[i];
                return sum;
        }
}
```

```
  public static int f(int[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=3, locals=3, args_size=1
         0: iconst_0
         1: istore_1
         2: iconst_0
         3: istore_2
         4: iload_2
         5: aload_0
         6: arraylength
         7: if_icmpge     22
        10: iload_1
        11: aload_0
```

```
        12: iload_2
        13: iaload
        14: iadd
        15: istore_1
        16: iinc          2, 1
        19: goto          4
        22: iload_1
        23: ireturn
```

LVA slot 0 contains a *reference* to the input array.

LVA slot 1 contains the local variable *sum*.

The only argument of the main() function is an array too

We'll be using the only argument of the main() function, which is an array of strings:

```
public class UseArgument
{
        public static void main(String[] args)
        {
                System.out.print("Hi, ");
                System.out.print(args[1]);
                System.out.println(". How are you?");
        }
}
```

The zeroth argument is the program's name (like in C/C++, etc.), so the 1st argument supplied by the user is 1st.

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=3, locals=1, args_size=1
         0: getstatic     #2      // Field java/lang/System.out:Ljava/io/PrintStream;
         3: ldc           #3      // String Hi,
         5: invokevirtual #4      // Method java/io/PrintStream.print:(Ljava/lang/String;)V
         8: getstatic     #2      // Field java/lang/System.out:Ljava/io/PrintStream;
        11: aload_0
        12: iconst_1
        13: aaload
        14: invokevirtual #4      // Method java/io/PrintStream.print:(Ljava/lang/String;)V
        17: getstatic     #2      // Field java/lang/System.out:Ljava/io/PrintStream;
        20: ldc           #5      // String . How are you?
        22: invokevirtual #6      // Method java/io/PrintStream.println:(Ljava/lang/String;)V
        25: return
```

aload_0 at 11 loads a *reference* of the zeroth LVA slot (1st and only main() argument).

iconst_1 and aaload at 12 and 13 take a *reference* to the first (counting at 0) element of array.

The *reference* to the string object is at TOS at offset 14, and it is taken from there by println method.

Pre-initialized array of strings

```
class Month
{
        public static String[] months =
        {
                "January",
                "February",
                "March",
                "April",
                "May",
                "June",
                "July",
                "August",
```

```
                "September",
                "October",
                "November",
                "December"
        };

        public String get_month (int i)
        {
                return months[i];
        };
}
```

The get_month() function is simple: Функция get_month() проста:

```
  public java.lang.String get_month(int);
    flags: ACC_PUBLIC
    Code:
      stack=2, locals=2, args_size=2
         0: getstatic     #2         // Field months:[Ljava/lang/String;
         3: iload_1
         4: aaload
         5: areturn
```

aaload operates on an array of *references*.

Java String are objects, so the *a*-instructions are used to operate on them.

areturn returns a *reference* to a String object.

How is the months[] array initialized?

```
  static {};
    flags: ACC_STATIC
    Code:
      stack=4, locals=0, args_size=0
         0: bipush        12
         2: anewarray     #3         // class java/lang/String
         5: dup
         6: iconst_0
         7: ldc           #4         // String January
         9: aastore
        10: dup
        11: iconst_1
        12: ldc           #5         // String February
        14: aastore
        15: dup
        16: iconst_2
        17: ldc           #6         // String March
        19: aastore
        20: dup
        21: iconst_3
        22: ldc           #7         // String April
        24: aastore
        25: dup
        26: iconst_4
        27: ldc           #8         // String May
        29: aastore
        30: dup
        31: iconst_5
        32: ldc           #9         // String June
        34: aastore
        35: dup
        36: bipush        6
        38: ldc           #10        // String July
        40: aastore
        41: dup
        42: bipush        7
        44: ldc           #11        // String August
        46: aastore
        47: dup
        48: bipush        8
```

```
        50: ldc           #12        // String September
        52: aastore
        53: dup
        54: bipush        9
        56: ldc           #13        // String October
        58: aastore
        59: dup
        60: bipush        10
        62: ldc           #14        // String November
        64: aastore
        65: dup
        66: bipush        11
        68: ldc           #15        // String December
        70: aastore
        71: putstatic     #2         // Field months:[Ljava/lang/String;
        74: return
```

anewarray creates a new array of *references* (hence *a* prefix).

The object's type is defined in the anewarray's operand, it is the "java/lang/String" string.

The bipush 12 before anewarray sets the array's size.

We see here a new instruction for us: dup.

It's a standard instruction in stack computers (including the Forth programming language) which just duplicates the value at TOS.

By the way, FPU 80x87 is also a stack computer and it has similar instruction – FDUP.

It is used here to duplicate a *reference* to an array, because the aastore instruction pops the *reference* to array from the stack, but subsequent aastore will need it again.

The Java compiler concluded that it's better to generate a dup instead of generating a getstatic instruction before each array store operation (i.e., 11 times).

aastore puts a *reference* (to string) into the array at an index which is taken from TOS.

Finally, putstatic puts *reference* to the newly created array into the second field of our object, i.e., *months* field.

Variadic functions

Variadic functions actually use arrays:

```
        public static void f(int... values)
        {
                for (int i=0; i<values.length; i++)
                        System.out.println(values[i]);
        }

        public static void main(String[] args)
        {
                f (1,2,3,4,5);
        }
```

```
  public static void f(int...);
    flags: ACC_PUBLIC, ACC_STATIC, ACC_VARARGS
    Code:
      stack=3, locals=2, args_size=1
         0: iconst_0
         1: istore_1
         2: iload_1
         3: aload_0
         4: arraylength
         5: if_icmpge     23
         8: getstatic     #2       // Field java/lang/System.out:Ljava/io/PrintStream;
        11: aload_0
        12: iload_1
        13: iaload
```

```
        14: invokevirtual #3       // Method java/io/PrintStream.println:(I)V
        17: iinc          1, 1
        20: goto          2
        23: return
```

f() just takes an array of integers using aload_0 at offset 3.

Then it gets the array's size, etc.

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=4, locals=1, args_size=1
         0: iconst_5
         1: newarray       int
         3: dup
         4: iconst_0
         5: iconst_1
         6: iastore
         7: dup
         8: iconst_1
         9: iconst_2
        10: iastore
        11: dup
        12: iconst_2
        13: iconst_3
        14: iastore
        15: dup
        16: iconst_3
        17: iconst_4
        18: iastore
        19: dup
        20: iconst_4
        21: iconst_5
        22: iastore
        23: invokestatic  #4       // Method f:([I)V
        26: return
```

The array is constructed in main() using the newarray instruction, then it's filled, and f() is called.

Oh, by the way, array object is not destroyed at the end of main().

There are no destructors in Java at all, because the JVM has a garbage collector which does this automatically, when it feels it needs to.

What about the format() method?

It takes two arguments at input: a string and an array of objects:

```
        public PrintStream format(String format, Object... args)
```

(http://docs.oracle.com/javase/tutorial/java/data/numberformat.html)

Let's see:

```
        public static void main(String[] args)
        {
                int i=123;
                double d=123.456;
                System.out.format("int: %d double: %f.%n", i, d);
        }
```

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=7, locals=4, args_size=1
         0: bipush        123
         2: istore_1
         3: ldc2_w        #2         // double 123.456d
         6: dstore_2
         7: getstatic     #4         // Field java/lang/System.out:Ljava/io/PrintStream;
```

```
        10: ldc           #5         // String int: %d double: %f.%n
        12: iconst_2
        13: anewarray     #6         // class java/lang/Object
        16: dup
        17: iconst_0
        18: iload_1
        19: invokestatic  #7         // Method java/lang/Integer.valueOf:(I)Ljava/lang/Integer;
        22: aastore
        23: dup
        24: iconst_1
        25: dload_2
        26: invokestatic  #8         // Method java/lang/Double.valueOf:(D)Ljava/lang/Double;
        29: aastore
        30: invokevirtual #9         // Method java/io/PrintStream.format:(Ljava/lang/String;[↙
    ↘ Ljava/lang/Object;)Ljava/io/PrintStream;
        33: pop
        34: return
```

So values of the *int* and *double* types are first promoted to `Integer` and `Double` objects using the `valueOf` methods.

The `format()` method needs objects of type `Object` at input, and since the `Integer` and `Double` classes are derived from the root `Object` class, they suitable for elements in the input array.

On the other hand, an array is always homogeneous, i.e., it can't hold elements of different types, which makes it impossible to push *int* and *double* values in it.

An array of `Object` objects is created at offset 13, an `Integer` object is added to the array at offset 22, and a `Double` object is added to the array at offset 29.

The penultimate `pop` instruction discards the element at TOS, so when `return` is executed, the stack becomes empty (or balanced).

Two-dimensional arrays

Two-dimensional arrays in Java are just one-dimensional arrays of *references* to another one-dimensional arrays.

Let's create a two-dimensional array:

```
        public static void main(String[] args)
        {
                int[][] a = new int[5][10];
                a[1][2]=3;
        }
```

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=3, locals=2, args_size=1
         0: iconst_5
         1: bipush        10
         3: multianewarray #2,  2      // class "[[I"
         7: astore_1
         8: aload_1
         9: iconst_1
        10: aaload
        11: iconst_2
        12: iconst_3
        13: iastore
        14: return
```

It's created using the `multianewarray` instruction: the object's type and dimensionality are passed as operands.

The array's size (10*5) is left in stack (using the instructions `iconst_5` and `bipush`).

A *reference* to row #1 is loaded at offset 10 (`iconst_1` and `aaload`).

The column is chosen using `iconst_2` at offset 11.

The value to be written is set at offset 12.

`iastore` at 13 writes the array's element.

How it is an element accessed?

```
	public static int get12 (int[][] in)
	{
		return in[1][2];
	}
```

```
  public static int get12(int[][]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=1, args_size=1
         0: aload_0
         1: iconst_1
         2: aaload
         3: iconst_2
         4: iaload
         5: ireturn
```

A *Reference* to the array's row is loaded at offset 2, the column is set at offset 3, then `iaload` loads the array's element.

Three-dimensional arrays

Three-dimensional arrays are just one-dimensional arrays of *references* to one-dimensional arrays of *references*.

```
	public static void main(String[] args)
	{
		int[][][] a = new int[5][10][15];

		a[1][2][3]=4;

		get_elem(a);
	}
```

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=3, locals=2, args_size=1
         0: iconst_5
         1: bipush        10
         3: bipush        15
         5: multianewarray #2,  3     // class "[[[I"
         9: astore_1
        10: aload_1
        11: iconst_1
        12: aaload
        13: iconst_2
        14: aaload
        15: iconst_3
        16: iconst_4
        17: iastore
        18: aload_1
        19: invokestatic  #3          // Method get_elem:([[[I)I
        22: pop
        23: return
```

Now it takes two `aaload` instructions to find right *reference*:

```
	public static int get_elem (int[][][] a)
	{
		return a[1][2][3];
	}
```

```
public static int get_elem(int[][][]);
  flags: ACC_PUBLIC, ACC_STATIC
  Code:
    stack=2, locals=1, args_size=1
       0: aload_0
       1: iconst_1
       2: aaload
       3: iconst_2
       4: aaload
       5: iconst_3
       6: iaload
       7: ireturn
```

Summary

Is it possible to do a buffer overflow in Java?

No, because the array's length is always present in an array object, array bounds are controlled, and an exception is to be raised in case of out-of-bounds access.

There are no multi-dimensional arrays in Java in the C/C++ sense, so Java is not very suited for fast scientific computations.

4.1.14 Strings

First example

Strings are objects and are constructed in the same way as other objects (and arrays).

```
        public static void main(String[] args)
        {
                System.out.println("What is your name?");
                String input = System.console().readLine();
                System.out.println("Hello, "+input);
        }
```

```
public static void main(java.lang.String[]);
  flags: ACC_PUBLIC, ACC_STATIC
  Code:
    stack=3, locals=2, args_size=1
       0: getstatic     #2        // Field java/lang/System.out:Ljava/io/PrintStream;
       3: ldc           #3        // String What is your name?
       5: invokevirtual #4        // Method java/io/PrintStream.println:(Ljava/lang/String;)V
       8: invokestatic  #5        // Method java/lang/System.console:()Ljava/io/Console;
      11: invokevirtual #6        // Method java/io/Console.readLine:()Ljava/lang/String;
      14: astore_1
      15: getstatic     #2        // Field java/lang/System.out:Ljava/io/PrintStream;
      18: new           #7        // class java/lang/StringBuilder
      21: dup
      22: invokespecial #8        // Method java/lang/StringBuilder."<init>":()V
      25: ldc           #9        // String Hello,
      27: invokevirtual #10       // Method java/lang/StringBuilder.append:(Ljava/lang/String↙
  ↳ ;)Ljava/lang/StringBuilder;
      30: aload_1
      31: invokevirtual #10       // Method java/lang/StringBuilder.append:(Ljava/lang/String↙
  ↳ ;)Ljava/lang/StringBuilder;
      34: invokevirtual #11       // Method java/lang/StringBuilder.toString:()Ljava/lang/↙
  ↳ String;
      37: invokevirtual #4        // Method java/io/PrintStream.println:(Ljava/lang/String;)V
      40: return
```

The readLine() method is called at offset 11, a *reference* to string (which is supplied by the user) is then stored at TOS.

At offset 14 the *reference* to string is stored in slot 1 of LVA.

The string the user entered is reloaded at offset 30 and concatenated with the "Hello, " string using the `StringBuilder` class.

The constructed string is then printed using `println` at offset 37.

Second example

Another example:

```
public class strings
{
        public static char test (String a)
        {
                return a.charAt(3);
        };

        public static String concat (String a, String b)
        {
                return a+b;
        }
}
```

```
  public static char test(java.lang.String);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=1, args_size=1
         0: aload_0
         1: iconst_3
         2: invokevirtual #2        // Method java/lang/String.charAt:(I)C
         5: ireturn
```

The string concatenation is performed using `StringBuilder`:

```
  public static java.lang.String concat(java.lang.String, java.lang.String);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=2, args_size=2
         0: new           #3        // class java/lang/StringBuilder
         3: dup
         4: invokespecial #4        // Method java/lang/StringBuilder."<init>":()V
         7: aload_0
         8: invokevirtual #5        // Method java/lang/StringBuilder.append:(Ljava/lang/String↙
    ↳ ;)Ljava/lang/StringBuilder;
        11: aload_1
        12: invokevirtual #5        // Method java/lang/StringBuilder.append:(Ljava/lang/String↙
    ↳ ;)Ljava/lang/StringBuilder;
        15: invokevirtual #6        // Method java/lang/StringBuilder.toString:()Ljava/lang/↙
    ↳ String;
        18: areturn
```

Another example:

```
        public static void main(String[] args)
        {
                String s="Hello!";
                int n=123;
                System.out.println("s=" + s + " n=" + n);
        }
```

And again, the strings are constructed using the `StringBuilder` class and its append method, then the constructed string is passed to `println`:

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=3, locals=3, args_size=1
         0: ldc           #2        // String Hello!
         2: astore_1
```

```
         3: bipush        123
         5: istore_2
         6: getstatic     #3        // Field java/lang/System.out:Ljava/io/PrintStream;
         9: new           #4        // class java/lang/StringBuilder
        12: dup
        13: invokespecial #5        // Method java/lang/StringBuilder."<init>":()V
        16: ldc           #6        // String s=
        18: invokevirtual #7        // Method java/lang/StringBuilder.append:(Ljava/lang/String↙
    ↘ ;)Ljava/lang/StringBuilder;
        21: aload_1
        22: invokevirtual #7        // Method java/lang/StringBuilder.append:(Ljava/lang/String↙
    ↘ ;)Ljava/lang/StringBuilder;
        25: ldc           #8        // String  n=
        27: invokevirtual #7        // Method java/lang/StringBuilder.append:(Ljava/lang/String↙
    ↘ ;)Ljava/lang/StringBuilder;
        30: iload_2
        31: invokevirtual #9        // Method java/lang/StringBuilder.append:(I)Ljava/lang/↙
    ↘ StringBuilder;
        34: invokevirtual #10       // Method java/lang/StringBuilder.toString:()Ljava/lang/↙
    ↘ String;
        37: invokevirtual #11       // Method java/io/PrintStream.println:(Ljava/lang/String;)V
        40: return
```

4.1.15 Exceptions

Let's rework our *Month* example (4.1.13 on page 681) a bit:

Listing 4.10: IncorrectMonthException.java

```
public class IncorrectMonthException extends Exception
{
        private int index;

        public IncorrectMonthException(int index)
        {
                this.index = index;
        }
        public int getIndex()
        {
                return index;
        }
}
```

Listing 4.11: Month2.java

```
class Month2
{
        public static String[] months =
        {
                "January",
                "February",
                "March",
                "April",
                "May",
                "June",
                "July",
                "August",
                "September",
                "October",
                "November",
                "December"
        };

        public static String get_month (int i) throws IncorrectMonthException
        {
                if (i<0 || i>11)
                        throw new IncorrectMonthException(i);
                return months[i];
```

```
        };

        public static void main (String[] args)
        {
                try
                {
                        System.out.println(get_month(100));
                }
                catch(IncorrectMonthException e)
                {
                        System.out.println("incorrect month index: "+ e.getIndex());
                        e.printStackTrace();
                }
        };
}
```

Essentially, `IncorrectMonthException.class` has just an object constructor and one getter method.

The `IncorrectMonthException` class is derived from `Exception`, so the `IncorrectMonthException` constructor first calls the constructor of the `Exception` class, then it puts incoming integer value into the sole `IncorrectMonthException` class field:

```
  public IncorrectMonthException(int);
    flags: ACC_PUBLIC
    Code:
      stack=2, locals=2, args_size=2
         0: aload_0
         1: invokespecial #1        // Method java/lang/Exception."<init>":()V
         4: aload_0
         5: iload_1
         6: putfield      #2        // Field index:I
         9: return
```

`getIndex()` is just a getter. A *reference* to `IncorrectMonthException` is passed in the zeroth LVA slot (*this*), `aload_0` takes it, `getfield` loads an integer value from the object, `ireturn` returns it.

```
  public int getIndex();
    flags: ACC_PUBLIC
    Code:
      stack=1, locals=1, args_size=1
         0: aload_0
         1: getfield      #2        // Field index:I
         4: ireturn
```

Now let's take a look at `get_month()` in `Month2.class`:

Listing 4.12: Month2.class

```
  public static java.lang.String get_month(int) throws IncorrectMonthException;
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=3, locals=1, args_size=1
         0: iload_0
         1: iflt          10
         4: iload_0
         5: bipush        11
         7: if_icmple     19
        10: new           #2        // class IncorrectMonthException
        13: dup
        14: iload_0
        15: invokespecial #3        // Method IncorrectMonthException."<init>":(I)V
        18: athrow
        19: getstatic     #4        // Field months:[Ljava/lang/String;
        22: iload_0
        23: aaload
        24: areturn
```

`iflt` at offset 1 is *if less than*.

In case of invalid index, a new object is created using the new instruction at offset 10.

The object's type is passed as an operand to the instruction (which is `IncorrectMonthException`).

Then its constructor is called, and index is passed via TOS (offset 15).

When the control flow is offset 18, the object is already constructed, so now the `athrow` instruction takes a *reference* to the newly constructed object and signals to JVM to find the appropriate exception handler.

The `athrow` instruction doesn't return the control flow here, so at offset 19 there is another basic block, not related to exceptions business, where we can get from offset 7.

How do handlers work?

`main()` in `Month2.class`:

Listing 4.13: Month2.class

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=3, locals=2, args_size=1
         0: getstatic     #5        // Field java/lang/System.out:Ljava/io/PrintStream;
         3: bipush        100
         5: invokestatic  #6        // Method get_month:(I)Ljava/lang/String;
         8: invokevirtual #7        // Method java/io/PrintStream.println:(Ljava/lang/String;)V
        11: goto          47
        14: astore_1
        15: getstatic     #5        // Field java/lang/System.out:Ljava/io/PrintStream;
        18: new           #8        // class java/lang/StringBuilder
        21: dup
        22: invokespecial #9        // Method java/lang/StringBuilder."<init>":()V
        25: ldc           #10       // String incorrect month index:
        27: invokevirtual #11       // Method java/lang/StringBuilder.append:(Ljava/lang/String↙
    ↘ ;)Ljava/lang/StringBuilder;
        30: aload_1
        31: invokevirtual #12       // Method IncorrectMonthException.getIndex:()I
        34: invokevirtual #13       // Method java/lang/StringBuilder.append:(I)Ljava/lang/↙
    ↘ StringBuilder;
        37: invokevirtual #14       // Method java/lang/StringBuilder.toString:()Ljava/lang/↙
    ↘ String;
        40: invokevirtual #7        // Method java/io/PrintStream.println:(Ljava/lang/String;)V
        43: aload_1
        44: invokevirtual #15       // Method IncorrectMonthException.printStackTrace:()V
        47: return
      Exception table:
         from    to  target type
             0    11    14   Class IncorrectMonthException
```

Here is the `Exception table`, which defines that from offsets 0 to 11 (inclusive) an exception `IncorrectMonthException` may happen, and if it does, the control flow is to be passed to offset 14.

Indeed, the main program ends at offset 11.

At offset 14 the handler starts. It's not possible to get here, there are no conditional/unconditional jumps to this area.

But JVM will transfer the execution flow here in case of an exception.

The very first `astore_1` (at 14) takes the incoming *reference* to the exception object and stores it in LVA slot 1.

Later, the `getIndex()` method (of this exception object) will be called at offset 31.

The *reference* to the current exception object is passed right before that (offset 30).

The rest of the code is does just string manipulation: first the integer value returned by `getIndex()` is converted to string by the `toString()` method, then it's concatenated with the "incorrect month index: " text string (like we saw before), then `println()` and `printStackTrace()` are called.

After `printStackTrace()` finishes, the exception is handled and we can continue with the normal execution.

At offset 47 there is a `return` which finishes the `main()` function, but there could be any other code which would execute as if no exceptions were raised.

Here is an example on how IDA shows exception ranges:

Listing 4.14: from some random .class file found on the author's computer

```
    .catch java/io/FileNotFoundException from met001_335 to met001_360\
 using met001_360
    .catch java/io/FileNotFoundException from met001_185 to met001_214\
 using met001_214
    .catch java/io/FileNotFoundException from met001_181 to met001_192\
 using met001_195
    .catch java/io/FileNotFoundException from met001_155 to met001_176\
 using met001_176
    .catch java/io/FileNotFoundException from met001_83 to met001_129 using \
met001_129
    .catch java/io/FileNotFoundException from met001_42 to met001_66 using \
met001_69
    .catch java/io/FileNotFoundException from met001_begin to met001_37\
 using met001_37
```

4.1.16 Classes

Simple class:

Listing 4.15: test.java

```
public class test
{
        public static int a;
        private static int b;

        public test()
        {
            a=0;
            b=0;
        }
        public static void set_a (int input)
        {
                a=input;
        }
        public static int get_a ()
        {
                return a;
        }
        public static void set_b (int input)
        {
                b=input;
        }
        public static int get_b ()
        {
                return b;
        }
}
```

The constructor just sets both fields to zero:

```
  public test();
    flags: ACC_PUBLIC
    Code:
      stack=1, locals=1, args_size=1
         0: aload_0
         1: invokespecial #1         // Method java/lang/Object."<init>":()V
         4: iconst_0
         5: putstatic     #2         // Field a:I
         8: iconst_0
         9: putstatic     #3         // Field b:I
        12: return
```

Setter of a:

```
  public static void set_a(int);
    flags: ACC_PUBLIC, ACC_STATIC
```

```
    Code:
      stack=1, locals=1, args_size=1
         0: iload_0
         1: putstatic     #2          // Field a:I
         4: return
```

Getter of a:

```
  public static int get_a();
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=0, args_size=0
         0: getstatic     #2          // Field a:I
         3: ireturn
```

Setter of b:

```
  public static void set_b(int);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=1, args_size=1
         0: iload_0
         1: putstatic     #3          // Field b:I
         4: return
```

Getter of b:

```
  public static int get_b();
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=1, locals=0, args_size=0
         0: getstatic     #3          // Field b:I
         3: ireturn
```

There is no difference in the code which works with public and private fields.

But this type information is present in the `.class` file, and it's not possible to access private fields from everywhere.

Let's create an object and call its method:

Listing 4.16: ex1.java

```
public class ex1
{
        public static void main(String[] args)
        {
                test obj=new test();
                obj.set_a (1234);
                System.out.println(obj.a);
        }
}
```

```
  public static void main(java.lang.String[]);
    flags: ACC_PUBLIC, ACC_STATIC
    Code:
      stack=2, locals=2, args_size=1
         0: new           #2         // class test
         3: dup
         4: invokespecial #3         // Method test."<init>":()V
         7: astore_1
         8: aload_1
         9: pop
        10: sipush        1234
        13: invokestatic  #4         // Method test.set_a:(I)V
        16: getstatic     #5         // Field java/lang/System.out:Ljava/io/PrintStream;
        19: aload_1
        20: pop
        21: getstatic     #6         // Field test.a:I
        24: invokevirtual #7         // Method java/io/PrintStream.println:(I)V
        27: return
```

The new instruction creates an object, but doesn't call the constructor (it is called at offset 4).

The `set_a()` method is called at offset 16.

The a field is accessed using the `getstatic` instruction at offset 21.

4.1.17 Simple patching

First example

Let's proceed with a simple code patching task.

```
public class nag
{
        public static void nag_screen()
        {
                System.out.println("This program is not registered");
        };
        public static void main(String[] args)
        {
                System.out.println("Greetings from the mega-software");
                nag_screen();
        }
}
```

How would we remove the printing of “This program is not registered” string?

Let's load the .class file into IDA:

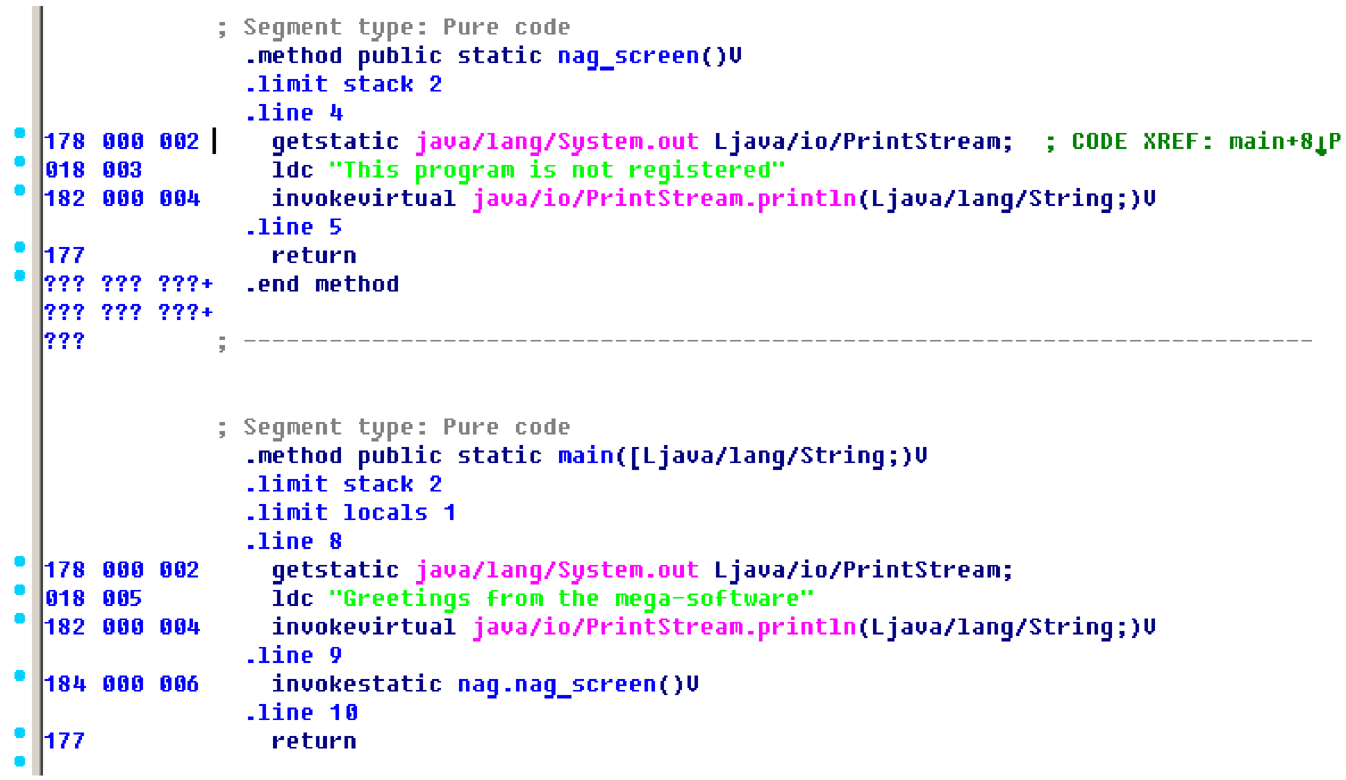


Figure 4.1: IDA

Let's patch the first byte of the function to 177 (which is the `return` instruction's opcode):

```
                ; Segment type: Pure code
                  .method public static nag_screen()V
                  .limit stack 2
                  .line 4

                nag_screen:                                   ; CODE XREF: main+8↓P
177                 return
000                 0 ; 0x00
002                 2 ; 0x02
018 003             ldc "This program is not registered"
182 000 004         invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
                  .line 5
177                 return
??? ??? ???+      .end method
??? ??? ???+
???             ; ---------------------------------------------------------------------------
```

Figure 4.2: IDA

But that doesn't work (JRE 1.7):

```
Exception in thread "main" java.lang.VerifyError: Expecting a stack map frame
Exception Details:
  Location:
    nag.nag_screen()V @1: nop
  Reason:
    Error exists in the bytecode
  Bytecode:
    0000000: b100 0212 03b6 0004 b1

        at java.lang.Class.getDeclaredMethods0(Native Method)
        at java.lang.Class.privateGetDeclaredMethods(Class.java:2615)
        at java.lang.Class.getMethod0(Class.java:2856)
        at java.lang.Class.getMethod(Class.java:1668)
        at sun.launcher.LauncherHelper.getMainMethod(LauncherHelper.java:494)
        at sun.launcher.LauncherHelper.checkAndLoadMain(LauncherHelper.java:486)
```

Perhaps JVM has some other checks related to the stack maps.

OK, let's patch it differently by removing the call to nag():

```
                ; Segment type: Pure code
                  .method public static main([Ljava/lang/String;)V
                  .limit stack 2
                  .limit locals 1
                  .line 8
178 000 002         getstatic java/lang/System.out Ljava/io/PrintStream;
018 005             ldc "Greetings from the mega-software"
182 000 004         invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
                  .line 9
000                 nop
000                 nop
000                 nop
                  .line 10
177                 return

                ; ===========================================================================
```

Figure 4.3: IDA

0 is the opcode for NOP.

Now that works!

Second example

Another simple crackme example:

```
public class password
{
        public static void main(String[] args)
        {
                System.out.println("Please enter the password");
                String input = System.console().readLine();
                if (input.equals("secret"))
                        System.out.println("password is correct");
                else
                        System.out.println("password is not correct");
        }
}
```

Let's load it in IDA:

Figure 4.4: IDA

We see here the `ifeq` instruction which does the job.

Its name stands for *if equal*, and this is misnomer, a better name would be `ifz` (*if zero*), i.e, if value at TOS is zero, then do the jump.

In our example, it jumps if the password is not correct (the `equals` method returns `False`, which is 0).

The very first idea is to patch this instruction.

There are two bytes in `ifeq` opcode, which encode the jump offset.

To make this instruction a NOP, we must set the 3rd byte to the value of 3 (because by adding 3 to the current address we will always jump to the next instruction, since the `ifeq` instruction's length is 3 bytes):

```
                ; Segment type: Pure code
                  .method public static main([Ljava/lang/String;)V
                  .limit stack 2
                  .limit locals 2
                  .line 3
178 000 002         getstatic java/lang/System.out Ljava/io/PrintStream;
018 003             ldc "Please enter the password"
182 000 004         invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
                  .line 4
184 000 005         invokestatic java/lang/System.console()Ljava/io/Console;
182 000 006         invokevirtual java/io/Console.readLine()Ljava/lang/String;
076                 astore_1 ; met002_slot001
                  .line 5
043                 aload_1 ; met002_slot001
018 007             ldc "secret"
182 000 008         invokevirtual java/lang/String.equals(Ljava/lang/Object;)Z
153 000 003         ifeq met002_24
                  .line 6

                met002_24:                                    ; CODE XREF: main+21↑j
178 000 002         getstatic java/lang/System.out Ljava/io/PrintStream;
018 009             ldc "password is correct"
182 000 004         invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
167 000 011         goto met002_43
                  .line 8
178 000 002         .stack use locals
                      locals Object java/lang/String
                    .end stack
                    getstatic java/lang/System.out Ljava/io/PrintStream;
018 010             ldc "password is not correct"
182 000 004         invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
                  .line 9
```

Figure 4.5: IDA

That doesn't work (JRE 1.7):

```
Exception in thread "main" java.lang.VerifyError: Expecting a stackmap frame at branch target ↙
    ↳ 24
Exception Details:
  Location:
    password.main([Ljava/lang/String;)V @21: ifeq
  Reason:
    Expected stackmap frame at this location.
  Bytecode:
    0000000: b200 0212 03b6 0004 b800 05b6 0006 4c2b
    0000010: 1207 b600 0899 0003 b200 0212 09b6 0004
    0000020: a700 0bb2 0002 120a b600 04b1
  Stackmap Table:
    append_frame(@35,Object[#20])
    same_frame(@43)

        at java.lang.Class.getDeclaredMethods0(Native Method)
        at java.lang.Class.privateGetDeclaredMethods(Class.java:2615)
        at java.lang.Class.getMethod0(Class.java:2856)
        at java.lang.Class.getMethod(Class.java:1668)
        at sun.launcher.LauncherHelper.getMainMethod(LauncherHelper.java:494)
        at sun.launcher.LauncherHelper.checkAndLoadMain(LauncherHelper.java:486)
```

But it must be mentioned that it worked in JRE 1.6.

We can also try to replace to all 3 `ifeq` opcode bytes with zero bytes (NOP), and it still won't work.

Seems like there are more stack map checks in JRE 1.7.

OK, we'll replace the whole call to the `equals` method with the `iconst_1` instruction plus a pack of NOPs:

```
                ; Segment type: Pure code
                  .method public static main([Ljava/lang/String;)V
                  .limit stack 2
                  .limit locals 2
                  .line 3
178 000 002         getstatic java/lang/System.out Ljava/io/PrintStream;
018 003             ldc "Please enter the password"
182 000 004         invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
                  .line 4
184 000 005         invokestatic java/lang/System.console()Ljava/io/Console;
182 000 006         invokevirtual java/io/Console.readLine()Ljava/lang/String;
076                 astore_1 ; met002_slot001
                  .line 5
004                 iconst_1
000                 nop
000                 nop
000                 nop
000                 nop
000                 nop
153 000 014         ifeq met002_35
                  .line 6
178 000 002         getstatic java/lang/System.out Ljava/io/PrintStream;
018 009             ldc "password is correct"
182 000 004         invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
167 000 011         goto met002_43
                  .line 8

                met002_35:                                          ; CODE XREF: main+21↑j
178 000 002         .stack use locals
                      locals Object java/lang/String
                    .end stack
```

Figure 4.6: IDA

1 needs always to be in the TOS when the `ifeq` instruction is executed, so `ifeq` would never jump.

This works.

4.1.18 Summary

What is missing in Java in comparison to C/C++?

- Structures: use classes.
- Unions: use class hierarchies.
- Unsigned data types. By the way, this makes cryptographic algorithms somewhat harder to implement in Java.
- Function pointers.

Chapter 5

Finding important/interesting stuff in the code

Minimalism it is not a prominent feature of modern software.

But not because the programmers are writing a lot, but because a lot of libraries are commonly linked statically to executable files. If all external libraries were shifted into an external DLL files, the world would be different. (Another reason for C++ are the STL and other template libraries.)

Thus, it is very important to determine the origin of a function, if it is from standard library or well-known library (like Boost[1], libpng[2]), or if it is related to what we are trying to find in the code.

It is just absurd to rewrite all code in C/C++ to find what we're looking for.

One of the primary tasks of a reverse engineer is to find quickly the code he/she needs.

The IDA disassembler allow us to search among text strings, byte sequences and constants. It is even possible to export the code to .lst or .asm text files and then use `grep`, awk, etc.

When you try to understand what some code is doing, this easily could be some open-source library like libpng. So when you see some constants or text strings which look familiar, it is always worth to *google* them. And if you find the opensource project where they are used, then it's enough just to compare the functions. It may solve some part of the problem.

For example, if a program uses XML files, the first step may be determining which XML library is used for processing, since the standard (or well-known) libraries are usually used instead of self-made one.

For example, the author of these lines once tried to understand how the compression/decompression of network packets works in SAP 6.0. It is a huge software, but a detailed .PDB with debugging information is present, and that is convenient. He finally came to the idea that one of the functions, that was called *CsDecomprLZC*, was doing the decompression of network packets. Immediately he tried to google its name and he quickly found the function was used in MaxDB (it is an open-source SAP project) [3].

`http://www.google.com/search?q=CsDecomprLZC`

Astoundingly, MaxDB and SAP 6.0 software shared likewise code for the compression/decompression of network packets.

5.1 Identification of executable files

5.1.1 Microsoft Visual C++

MSVC versions and DLLs that can be imported:

---

[1] `http://go.yurichev.com/17036`
[2] `http://go.yurichev.com/17037`
[3] More about it in relevant section (8.10.1 on page 884)

Marketing ver.	Internal ver.	CL.EXE ver.	DLLs imported	Release date
6	6.0	12.00	msvcrt.dll msvcp60.dll	June 1998
.NET (2002)	7.0	13.00	msvcr70.dll msvcp70.dll	February 13, 2002
.NET 2003	7.1	13.10	msvcr71.dll msvcp71.dll	April 24, 2003
2005	8.0	14.00	msvcr80.dll msvcp80.dll	November 7, 2005
2008	9.0	15.00	msvcr90.dll msvcp90.dll	November 19, 2007
2010	10.0	16.00	msvcr100.dll msvcp100.dll	April 12, 2010
2012	11.0	17.00	msvcr110.dll msvcp110.dll	September 12, 2012
2013	12.0	18.00	msvcr120.dll msvcp120.dll	October 17, 2013

msvcp*.dll has C++-related functions, so if it is imported, this is probably a C++ program.

Name mangling

The names usually start with the `?` symbol.

You can read more about MSVC's name mangling here: 3.18.1 on page 542.

5.1.2 GCC

Aside from *NIX targets, GCC is also present in the win32 environment, in the form of Cygwin and MinGW.

Name mangling

Names usually start with the `_Z` symbols.

You can read more about GCC's name mangling here: 3.18.1 on page 542.

Cygwin

cygwin1.dll is often imported.

MinGW

msvcrt.dll may be imported.

5.1.3 Intel Fortran

libifcoremd.dll, libifportmd.dll and libiomp5md.dll (OpenMP support) may be imported.

libifcoremd.dll has a lot of functions prefixed with `for_`, which means *Fortran*.

5.1.4 Watcom, OpenWatcom

Name mangling

Names usually start with the `W` symbol.

For example, that is how the method named "method" of the class "class" that does not have any arguments and returns *void* is encoded:

```
W?method$_class$n__v
```

5.1.5 Borland

Here is an example of Borland Delphi's and C++Builder's name mangling:

```
@TApplication@IdleAction$qv
@TApplication@ProcessMDIAccels$qp6tagMSG
@TModule@$bctr$qpcpvt1
@TModule@$bdtr$qv
@TModule@ValidWindow$qp14TWindowsObject
@TrueColorTo8BitN$qpviiiiiit1iiiiii
@TrueColorTo16BitN$qpviiiiiit1iiiiii
@DIB24BitTo8BitBitmap$qpviiiiiit1iiiii
@TrueBitmap@$bctr$qpcl
@TrueBitmap@$bctr$qpvl
@TrueBitmap@$bctr$qiilll
```

The names always start with the `@` symbol, then we have the class name came, method name, and encoded the types of the arguments of the method.

These names can be in the .exe imports, .dll exports, debug data, etc.

Borland Visual Component Libraries (VCL) are stored in .bpl files instead of .dll ones, for example, vcl50.dll, rtl60.dll.

Another DLL that might be imported: BORLNDMM.DLL.

Delphi

Almost all Delphi executables has the "Boolean" text string at the beginning of the code segment, along with other type names.

This is a very typical beginning of the `CODE` segment of a Delphi program, this block came right after the win32 PE file header:

```
00000400  04 10 40 00 03 07 42 6f  6f 6c 65 61 6e 01 00 00  |..@...Boolean...|
00000410  00 00 01 00 00 00 00 10  40 00 05 46 61 6c 73 65  |........@..False|
00000420  04 54 72 75 65 8d 40 00  2c 10 40 00 09 08 57 69  |.True.@.,.@...Wi|
00000430  64 65 43 68 61 72 03 00  00 00 00 ff ff 00 00 90  |deChar..........|
00000440  44 10 40 00 02 04 43 68  61 72 01 00 00 00 00 ff  |D.@...Char......|
00000450  00 00 00 90 58 10 40 00  01 08 53 6d 61 6c 6c 69  |....X.@...Smalli|
00000460  6e 74 02 00 80 ff ff ff  7f 00 00 90 70 10 40 00  |nt..........p.@.|
00000470  01 07 49 6e 74 65 67 65  72 04 00 00 00 80 ff ff  |..Integer.......|
00000480  ff 7f 8b c0 88 10 40 00  01 04 42 79 74 65 01 00  |......@...Byte..|
00000490  00 00 00 ff 00 00 00 90  9c 10 40 00 01 04 57 6f  |..........@...Wo|
000004a0  72 64 03 00 00 00 00 ff  ff 00 00 90 b0 10 40 00  |rd............@.|
000004b0  01 08 43 61 72 64 69 6e  61 6c 05 00 00 00 00 ff  |..Cardinal......|
000004c0  ff ff ff 90 c8 10 40 00  10 05 49 6e 74 36 34 00  |......@...Int64.|
000004d0  00 00 00 00 00 00 80 ff  ff ff ff ff ff ff 7f 90  |................|
000004e0  e4 10 40 00 04 08 45 78  74 65 6e 64 65 64 02 90  |..@...Extended..|
000004f0  f4 10 40 00 04 06 44 6f  75 62 6c 65 01 8d 40 00  |..@...Double..@.|
00000500  04 11 40 00 04 08 43 75  72 72 65 6e 63 79 04 90  |..@...Currency..|
00000510  14 11 40 00 0a 06 73 74  72 69 6e 67 20 11 40 00  |..@...string .@.|
00000520  0b 0a 57 69 64 65 53 74  72 69 6e 67 30 11 40 00  |..WideString0.@.|
00000530  0c 07 56 61 72 69 61 6e  74 8d 40 00 40 11 40 00  |..Variant.@.@.@.|
00000540  0c 0a 4f 6c 65 56 61 72  69 61 6e 74 98 11 40 00  |..OleVariant..@.|
00000550  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
00000560  00 00 00 00 00 00 00 00  00 00 00 00 98 11 40 00  |..............@.|
00000570  04 00 00 00 00 00 00 00  18 4d 40 00 24 4d 40 00  |.........M@.$M@.|
00000580  28 4d 40 00 2c 4d 40 00  20 4d 40 00 68 4a 40 00  |(M@.,M@. M@.hJ@.|
00000590  84 4a 40 00 c0 4a 40 00  07 54 4f 62 6a 65 63 74  |.J@..J@..TObject|
000005a0  a4 11 40 00 07 07 54 4f  62 6a 65 63 74 98 11 40  |..@...TObject..@|
000005b0  00 00 00 00 00 00 00 06  53 79 73 74 65 6d 00 00  |........System..|
000005c0  c4 11 40 00 0f 0a 49 49  6e 74 65 72 66 61 63 65  |..@...IInterface|
000005d0  00 00 00 00 01 00 00 00  00 00 00 00 00 c0 00 00  |................|
```

```
000005e0  00 00 00 00 46 06 53 79  73 74 65 6d 03 00 ff ff  |....F.System....|
000005f0  f4 11 40 00 0f 09 49 44  69 73 70 61 74 63 68 c0  |..@...IDispatch.|
00000600  11 40 00 01 00 04 02 00  00 00 00 00 c0 00 00 00  |.@..............|
00000610  00 00 00 46 06 53 79 73  74 65 6d 04 00 ff ff 90  |...F.System.....|
00000620  cc 83 44 24 04 f8 e9 51  6c 00 00 83 44 24 04 f8  |..D$...Ql...D$..|
00000630  e9 6f 6c 00 00 83 44 24  04 f8 e9 79 6c 00 00 cc  |.ol...D$...yl...|
00000640  cc 21 12 40 00 2b 12 40  00 35 12 40 00 01 00 00  |.!.@.+.@.5.@....|
00000650  00 00 00 00 00 00 00 00  00 c0 00 00 00 00 00 00  |................|
00000660  46 41 12 40 00 08 00 00  00 00 00 00 00 8d 40 00  |FA.@..........@.|
00000670  bc 12 40 00 4d 12 40 00  00 00 00 00 00 00 00 00  |..@.M.@.........|
00000680  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
00000690  bc 12 40 00 0c 00 00 00  4c 11 40 00 18 4d 40 00  |..@.....L.@..M@.|
000006a0  50 7e 40 00 5c 7e 40 00  2c 4d 40 00 20 4d 40 00  |P~@.\~@.,M@. M@.|
000006b0  6c 7e 40 00 84 4a 40 00  c0 4a 40 00 11 54 49 6e  |l~@..J@..J@..TIn|
000006c0  74 65 72 66 61 63 65 64  4f 62 6a 65 63 74 8b c0  |terfacedObject..|
000006d0  d4 12 40 00 07 11 54 49  6e 74 65 72 66 61 63 65  |..@...TInterface|
000006e0  64 4f 62 6a 65 63 74 bc  12 40 00 a0 11 40 00 00  |dObject..@...@..|
000006f0  00 06 53 79 73 74 65 6d  00 00 8b c0 00 13 40 00  |..System......@.|
00000700  11 0b 54 42 6f 75 6e 64  41 72 72 61 79 04 00 00  |..TBoundArray...|
00000710  00 00 00 00 00 03 00 00  00 6c 10 40 00 06 53 79  |.........l.@..Sy|
00000720  73 74 65 6d 28 13 40 00  04 09 54 44 61 74 65 54  |stem(.@...TDateT|
00000730  69 6d 65 01 ff 25 48 e0  c4 00 8b c0 ff 25 44 e0  |ime..%H......%D.|
```

The first 4 bytes of the data segment (DATA) can be `00 00 00 00`, `32 13 8B C0` or `FF FF FF FF`.

This information can be useful when dealing with packed/encrypted Delphi executables.

5.1.6 Other known DLLs

- vcomp*.dll—Microsoft's implementation of OpenMP.

5.2 Communication with outer world (function level)

It's often advisable to track function arguments and return values in debugger or DBI. For example, the author once tried to understand meaning of some obscure function, which happens to be incorrectly implemented bubble sort[4]. (It worked correctly, but slower.) Meanwhile, watching inputs and outputs of this function helps instantly to understand what it does.

Often, when you see division by multiplication (3.9 on page 497), but forgot all details about its mechanics, you can just observe input and output and quickly find divisor.

5.3 Communication with the outer world (win32)

Sometimes it's enough to observe some function's inputs and outputs in order to understand what it does. That way you can save time.

Files and registry access: for the very basic analysis, Process Monitor[5] utility from SysInternals can help.

For the basic analysis of network accesses, Wireshark[6] can be useful.

But then you will have to look inside anyway.

The first thing to look for is which functions from the OS's APIs and standard libraries are used.

If the program is divided into a main executable file and a group of DLL files, sometimes the names of the functions in these DLLs can help.

If we are interested in exactly what can lead to a call to `MessageBox()` with specific text, we can try to find this text in the data segment, find the references to it and find the points from which the control may be passed to the `MessageBox()` call we're interested in.

[4] https://yurichev.com/blog/weird_sort/
[5] http://go.yurichev.com/17301
[6] http://go.yurichev.com/17303

If we are talking about a video game and we're interested in which events are more or less random in it, we may try to find the `rand()` function or its replacements (like the Mersenne twister algorithm) and find the places from which those functions are called, and more importantly, how are the results used. One example: 8.2.

But if it is not a game, and `rand()` is still used, it is also interesting to know why. There are cases of unexpected `rand()` usage in data compression algorithms (for encryption imitation): blog.yurichev.com.

5.3.1 Often used functions in the Windows API

These functions may be among the imported. It is worth to note that not every function might be used in the code that was written by the programmer. A lot of functions might be called from library functions and CRT code.

Some functions may have the `-A` suffix for the ASCII version and `-W` for the Unicode version.

- Registry access (advapi32.dll): RegEnumKeyEx, RegEnumValue, RegGetValue, RegOpenKeyEx, RegQueryValueEx.
- Access to text .ini-files (kernel32.dll): GetPrivateProfileString.
- Dialog boxes (user32.dll): MessageBox, MessageBoxEx, CreateDialog, SetDlgItemText, GetDlgItemText.
- Resources access (6.5.2 on page 763): (user32.dll): LoadMenu.
- TCP/IP networking (ws2_32.dll): WSARecv, WSASend.
- File access (kernel32.dll): CreateFile, ReadFile, ReadFileEx, WriteFile, WriteFileEx.
- High-level access to the Internet (wininet.dll): WinHttpOpen.
- Checking the digital signature of an executable file (wintrust.dll): WinVerifyTrust.
- The standard MSVC library (if it's linked dynamically) (msvcr*.dll): assert, itoa, ltoa, open, printf, read, strcmp, atol, atoi, fopen, fread, fwrite, memcmp, rand, strlen, strstr, strchr.

5.3.2 Extending trial period

Registry access functions are frequent targets for those who try to crack trial period of some software, which may save installation date/time into registry.

Another popular target are GetLocalTime() and GetSystemTime() functions: a trial software, at each startup, must check current date/time somehow anyway.

5.3.3 Removing nag dialog box

A popular way to find out what causing popping nag dialog box is intercepting MessageBox(), CreateDialog() and CreateWindow() functions.

5.3.4 tracer: Intercepting all functions in specific module

There are INT3 breakpoints in the tracer, that are triggered only once, however, they can be set for all functions in a specific DLL.

```
--one-time-INT3-bp:somedll.dll!.*
```

Or, let's set INT3 breakpoints on all functions with the `xml` prefix in their name:

```
--one-time-INT3-bp:somedll.dll!xml.*
```

On the other side of the coin, such breakpoints are triggered only once. Tracer will show the call of a function, if it happens, but only once. Another drawback—it is impossible to see the function's arguments.

Nevertheless, this feature is very useful when you know that the program uses a DLL, but you do not know which functions are actually used. And there are a lot of functions.

For example, let's see, what does the uptime utility from cygwin use:

```
tracer -l:uptime.exe --one-time-INT3-bp:cygwin1.dll!.*
```

Thus we may see all that cygwin1.dll library functions that were called at least once, and where from:

```
One-time INT3 breakpoint: cygwin1.dll!__main (called from uptime.exe!OEP+0x6d (0x40106d))
One-time INT3 breakpoint: cygwin1.dll!_geteuid32 (called from uptime.exe!OEP+0xba3 (0x401ba3))
One-time INT3 breakpoint: cygwin1.dll!_getuid32 (called from uptime.exe!OEP+0xbaa (0x401baa))
One-time INT3 breakpoint: cygwin1.dll!_getegid32 (called from uptime.exe!OEP+0xcb7 (0x401cb7))
One-time INT3 breakpoint: cygwin1.dll!_getgid32 (called from uptime.exe!OEP+0xcbe (0x401cbe))
One-time INT3 breakpoint: cygwin1.dll!sysconf (called from uptime.exe!OEP+0x735 (0x401735))
One-time INT3 breakpoint: cygwin1.dll!setlocale (called from uptime.exe!OEP+0x7b2 (0x4017b2))
One-time INT3 breakpoint: cygwin1.dll!_open64 (called from uptime.exe!OEP+0x994 (0x401994))
One-time INT3 breakpoint: cygwin1.dll!_lseek64 (called from uptime.exe!OEP+0x7ea (0x4017ea))
One-time INT3 breakpoint: cygwin1.dll!read (called from uptime.exe!OEP+0x809 (0x401809))
One-time INT3 breakpoint: cygwin1.dll!sscanf (called from uptime.exe!OEP+0x839 (0x401839))
One-time INT3 breakpoint: cygwin1.dll!uname (called from uptime.exe!OEP+0x139 (0x401139))
One-time INT3 breakpoint: cygwin1.dll!time (called from uptime.exe!OEP+0x22e (0x40122e))
One-time INT3 breakpoint: cygwin1.dll!localtime (called from uptime.exe!OEP+0x236 (0x401236))
One-time INT3 breakpoint: cygwin1.dll!sprintf (called from uptime.exe!OEP+0x25a (0x40125a))
One-time INT3 breakpoint: cygwin1.dll!setutent (called from uptime.exe!OEP+0x3b1 (0x4013b1))
One-time INT3 breakpoint: cygwin1.dll!getutent (called from uptime.exe!OEP+0x3c5 (0x4013c5))
One-time INT3 breakpoint: cygwin1.dll!endutent (called from uptime.exe!OEP+0x3e6 (0x4013e6))
One-time INT3 breakpoint: cygwin1.dll!puts (called from uptime.exe!OEP+0x4c3 (0x4014c3))
```

5.4 Strings

5.4.1 Text strings

C/C++

The normal C strings are zero-terminated (ASCIIZ-strings).

The reason why the C string format is as it is (zero-terminated) is apparently historical. In [Dennis M. Ritchie, *The Evolution of the Unix Time-sharing System*, (1979)] we read:

> A minor difference was that the unit of I/O was the word, not the byte, because the PDP-7 was a word-addressed machine. In practice this meant merely that all programs dealing with character streams ignored null characters, because null was used to pad a file to an even number of characters.

In Hiew or FAR Manager these strings looks like this:

```
int main()
{
        printf ("Hello, world!\n");
};
```

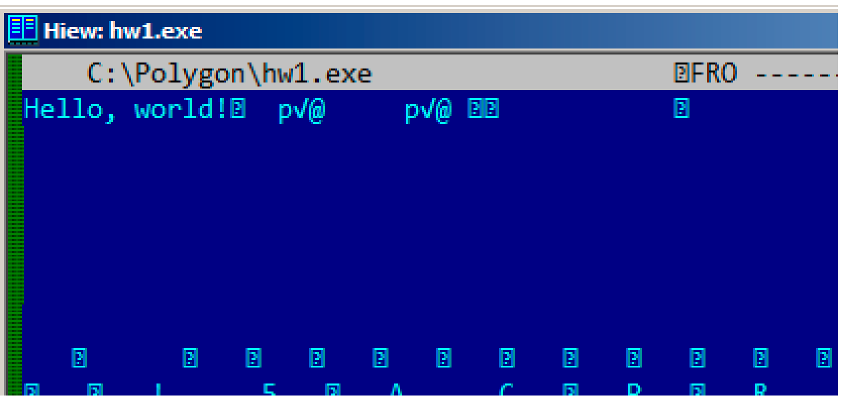


Figure 5.1: Hiew

Borland Delphi

The string in Pascal and Borland Delphi is preceded by an 8-bit or 32-bit string length.

For example:

Listing 5.1: Delphi

```
CODE:00518AC8                  dd 19h
CODE:00518ACC aLoading___Plea db 'Loading... , please wait.',0

...

CODE:00518AFC                  dd 10h
CODE:00518B00 aPreparingRun__ db 'Preparing run...',0
```

Unicode

Often, what is called Unicode is a methods for encoding strings where each character occupies 2 bytes or 16 bits. This is a common terminological mistake. Unicode is a standard for assigning a number to each character in the many writing systems of the world, but does not describe the encoding method.

The most popular encoding methods are: UTF-8 (is widespread in Internet and *NIX systems) and UTF-16LE (is used in Windows).

UTF-8

UTF-8 is one of the most successful methods for encoding characters. All Latin symbols are encoded just like in ASCII, and the symbols beyond the ASCII table are encoded using several bytes. 0 is encoded as before, so all standard C string functions work with UTF-8 strings just like any other string.

Let's see how the symbols in various languages are encoded in UTF-8 and how it looks like in FAR, using the 437 codepage [7]:

```
How much? 100€?

(English) I can eat glass and it doesn't hurt me.
(Greek) Μπορώ να φάω σπασμένα γυαλιά χωρίς να πάθω τίποτα.
(Hungarian) Meg tudom enni az üveget, nem lesz tőle bajom.
(Icelandic) Ég get etið gler án þess að meiða mig.
(Polish) Mogę jeść szkło i mi nie szkodzi.
(Russian) Я могу есть стекло, оно мне не вредит.
(Arabic): أنا قادر على أكل الزجاج و هذا لا يؤلمني.
(Hebrew): אני יכול לאכול זכוכית וזה לא מזיק לי.
(Chinese) 我能吞下玻璃而不伤身体。
(Japanese) 私はガラスを食べられます。それは私を傷つけません。
(Hindi) मैं काँच खा सकता हूँ और मुझे उससे कोई चोट नहीं पहुंचती.
```

[7] The example and translations was taken from here: http://go.yurichev.com/17304

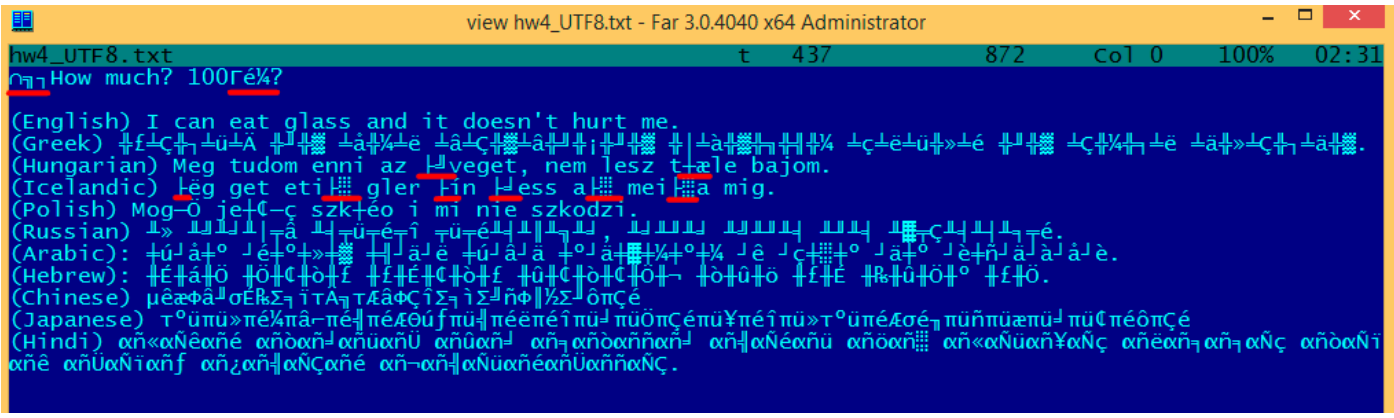


Figure 5.2: FAR: UTF-8

As you can see, the English language string looks the same as it is in ASCII.

The Hungarian language uses some Latin symbols plus symbols with diacritic marks.

These symbols are encoded using several bytes, these are underscored with red. It's the same story with the Icelandic and Polish languages.

There is also the "Euro" currency symbol at the start, which is encoded with 3 bytes.

The rest of the writing systems here have no connection with Latin.

At least in Russian, Arabic, Hebrew and Hindi we can see some recurring bytes, and that is not surprise: all symbols from a writing system are usually located in the same Unicode table, so their code begins with the same numbers.

At the beginning, before the "How much?" string we see 3 bytes, which are in fact the BOM[8]. The BOM defines the encoding system to be used.

UTF-16LE

Many win32 functions in Windows have the suffixes -A and -W. The first type of functions works with normal strings, the other with UTF-16LE strings (*wide*).

In the second case, each symbol is usually stored in a 16-bit value of type *short*.

The Latin symbols in UTF-16 strings look in Hiew or FAR like they are interleaved with zero byte:

```
int wmain()
{
        wprintf (L"Hello, world!\n");
};
```

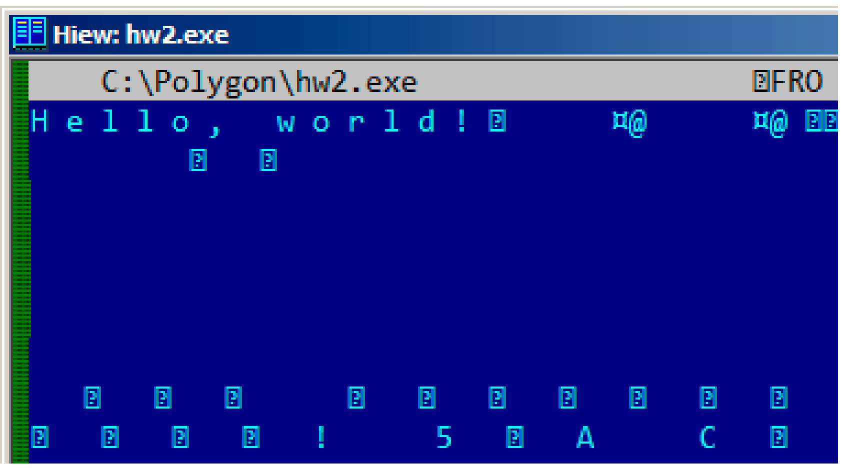


Figure 5.3: Hiew

[8] Byte Order Mark

We can see this often in Windows NT system files:

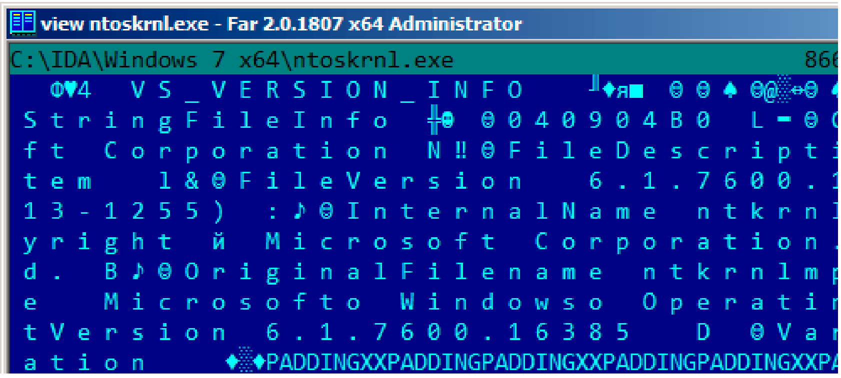


Figure 5.4: Hiew

Strings with characters that occupy exactly 2 bytes are called "Unicode" in IDA:

```
.data:0040E000 aHelloWorld:
.data:0040E000                  unicode 0, <Hello, world!>
.data:0040E000                  dw 0Ah, 0
```

Here is how the Russian language string is encoded in UTF-16LE:

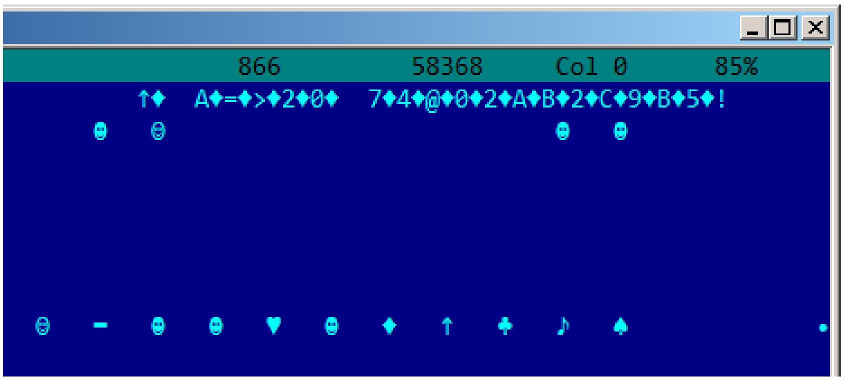


Figure 5.5: Hiew: UTF-16LE

What we can easily spot is that the symbols are interleaved by the diamond character (which has the ASCII code of 4). Indeed, the Cyrillic symbols are located in the fourth Unicode plane [9]. Hence, all Cyrillic symbols in UTF-16LE are located in the `0x400-0x4FF` range.

Let's go back to the example with the string written in multiple languages. Here is how it looks like in UTF-16LE.

[9] wikipedia

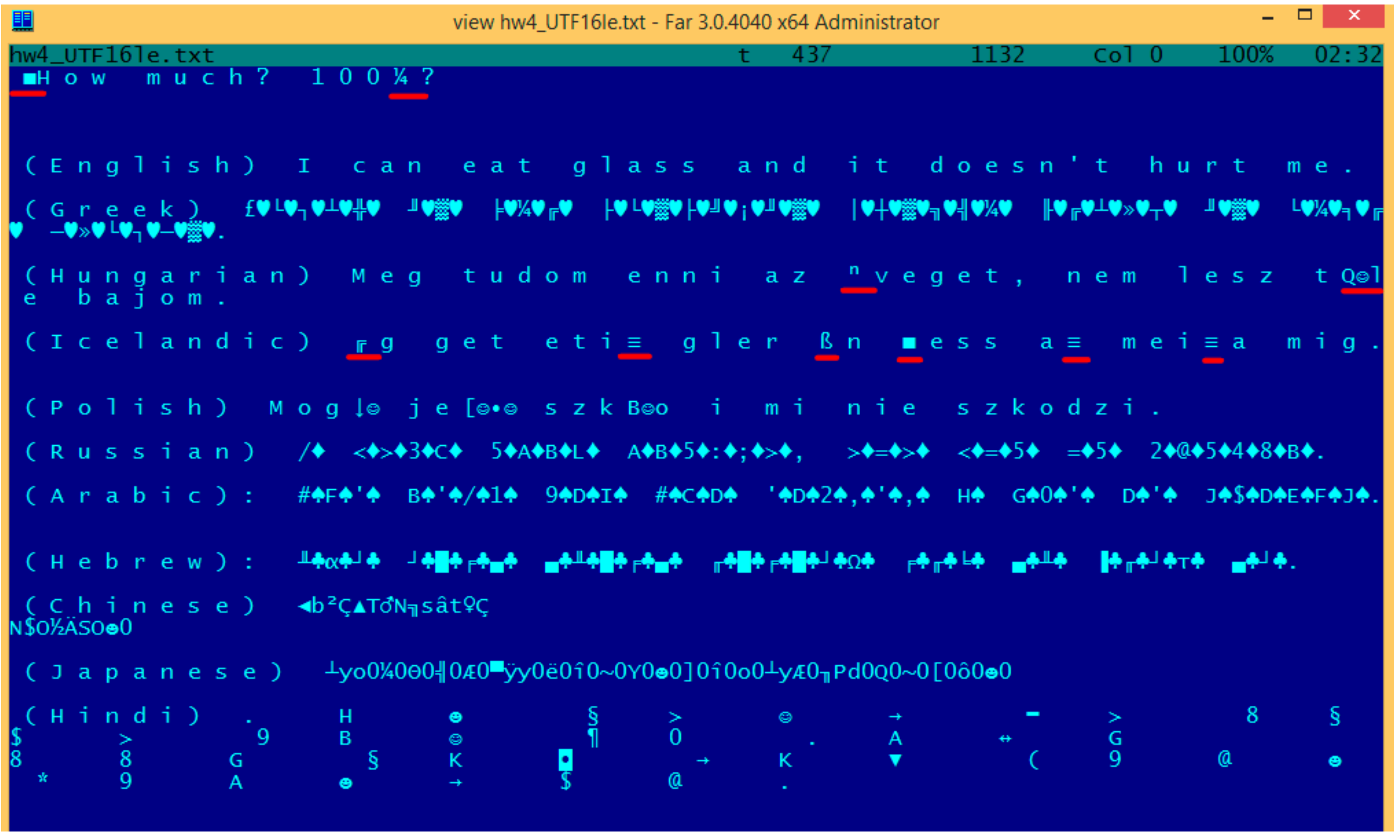


Figure 5.6: FAR: UTF-16LE

Here we can also see the BOM at the beginning. All Latin characters are interleaved with a zero byte.

Some characters with diacritic marks (Hungarian and Icelandic languages) are also underscored in red.

Base64

The base64 encoding is highly popular for the cases when you have to transfer binary data as a text string.

In essence, this algorithm encodes 3 binary bytes into 4 printable characters: all 26 Latin letters (both lower and upper case), digits, plus sign ("+") and slash sign ("/"), 64 characters in total.

One distinctive feature of base64 strings is that they often (but not always) ends with 1 or 2 padding equality symbol(s) ("="), for example:

```
AVjbbVSVfcUMu1xvjaMgjNtueRwBbxnyJw8dpGnLW8ZW8aKG3v4Y0icuQT+qEJAp9lAOuWs=
```

```
WVjbbVSVfcUMu1xvjaMgjNtueRwBbxnyJw8dpGnLW8ZW8aKG3v4Y0icuQT+qEJAp9lAOuQ==
```

The equality sign ("=") is never encounter in the middle of base64-encoded strings.

Now example of manual encoding. Let's encode 0x00, 0x11, 0x22, 0x33 hexadecimal bytes into base64 string:

```
$ echo -n "\x00\x11\x22\x33" | base64
ABEiMw==
```

Let's put all 4 bytes in binary form, then regroup them into 6-bit groups:

```
|  00   ||  11   ||  22   ||  33   ||       ||       |
00000000000100010010001000110011????????????????
| A   || B   || E   || i   || M   || w   || =   || =   |
```

Three first bytes (0x00, 0x11, 0x22) can be encoded into 4 base64 characters ("ABEi"), but the last one (0x33) — cannot be, so it's encoded using two characters ("Mw") and padding symbol ("=") is added twice to pad the last group to 4 characters. Hence, length of all correct base64 strings are always divisible by 4.

Base64 is often used when binary data needs to be stored in XML. "Armored" (i.e., in text form) PGP keys and signatures are encoded using base64.

Some people tries to use base64 to obfuscate strings: http://blog.sec-consult.com/2016/01/deliberately-html [10].

There are utilities for scanning an arbitrary binary files for base64 strings. One such utility is base64scanner[11].

Another encoding system which was much more popular in UseNet and FidoNet is Uuencoding. Binary files are still encoded in Uuencode format in Phrack magazine. It offers mostly the same features, but is different from base64 in the sense that file name is also stored in header.

By the way: there is also close sibling to base64: base32, alphabet of which has 10 digits and 26 Latin characters. One well-known usage of it is onion addresses [12], like: http://3g2upl4pq6kufc4m.onion/. URL can't have mixed-case Latin characters, so apparently, this is why Tor developers used base32.

5.4.2 Finding strings in binary

> Actually, the best form of Unix documentation is frequently running the **strings** command over a program's object code. Using **strings**, you can get a complete list of the program's hard-coded file name, environment variables, undocumented options, obscure error messages, and so forth.
>
> The Unix-Haters Handbook

The standard UNIX *strings* utility is quick-n-dirty way to see strings in file. For example, these are some strings from OpenSSH 7.2 sshd executable file:

```
...
0123
0123456789
0123456789abcdefABCDEF.:/
%02x
...
%.100s, line %lu: Bad permitopen specification <%.100s>
%.100s, line %lu: invalid criteria
%.100s, line %lu: invalid tun device
...
%.200s/.ssh/environment
...
2886173b9c9b6fdbdeda7a247cd636db38deaa.debug
$2a$06$r3.juUaHZDlIbQaO2dS9FuYxL1W9M81R1Tc92PoSNmzvpEqLkLGrK
...
3des-cbc
...
Bind to port %s on %s.
Bind to port %s on %s failed: %.200s.
/bin/login
/bin/sh
/bin/sh /etc/ssh/sshrc
...
D$4PQWR1
D$4PUj
D$4PV
D$4PVj
D$4PW
D$4PWj
D$4X
D$4XZj
D$4Y
...
diffie-hellman-group-exchange-sha1
```

[10] http://archive.is/nDCas
[11] https://github.com/DennisYurichev/base64scanner
[12] https://trac.torproject.org/projects/tor/wiki/doc/HiddenServiceNames

```
diffie-hellman-group-exchange-sha256
digests
D$iPV
direct-streamlocal
direct-streamlocal@openssh.com
...
FFFFFFFFFFFFFFFFC90FDAA22168C234C4C6628B80DC1CD129024E088A6...
...
```

There are options, error messages, file paths, imported dynamic modules and functions, some other strange strings (keys?) There is also unreadable noise—x86 code sometimes has chunks consisting of printable ASCII characters, up to 8 characters.

Of course, OpenSSH is open-source program. But looking at readable strings inside of some unknown binary is often a first step of analysis.

grep can be applied as well.

Hiew has the same capability (Alt-F6), as well as Sysinternals ProcessMonitor.

5.4.3 Error/debug messages

Debugging messages are very helpful if present. In some sense, the debugging messages are reporting what's going on in the program right now. Often these are `printf()`-like functions, which write to log-files, or sometimes do not writing anything but the calls are still present since the build is not a debug one but *release* one.

If local or global variables are dumped in debug messages, it might be helpful as well since it is possible to get at least the variable names. For example, one of such function in Oracle RDBMS is `ksdwrt()`.

Meaningful text strings are often helpful. The IDA disassembler may show from which function and from which point this specific string is used. Funny cases sometimes happen[13].

The error messages may help us as well. In Oracle RDBMS, errors are reported using a group of functions. You can read more about them here: blog.yurichev.com.

It is possible to find quickly which functions report errors and in which conditions.

By the way, this is often the reason for copy-protection systems to inarticulate cryptic error messages or just error numbers. No one is happy when the software cracker quickly understand why the copy-protection is triggered just by the error message.

One example of encrypted error messages is here: 8.5.2 on page 822.

5.4.4 Suspicious magic strings

Some magic strings which are usually used in backdoors looks pretty suspicious.

For example, there was a backdoor in the TP-Link WR740 home router[14]. The backdoor can activated using the following URL:
`http://192.168.0.1/userRpmNatDebugRpm26525557/start_art.html`.

Indeed, the "userRpmNatDebugRpm26525557" string is present in the firmware.

This string was not googleable until the wide disclosure of information about the backdoor.

You would not find this in any RFC[15].

You would not find any computer science algorithm which uses such strange byte sequences.

And it doesn't look like an error or debugging message.

So it's a good idea to inspect the usage of such weird strings.

[13] blog.yurichev.com
[14] `http://sekurak.pl/tp-link-httptftp-backdoor/`
[15] Request for Comments

Sometimes, such strings are encoded using base64.

So it's a good idea to decode them all and to scan them visually, even a glance should be enough.

More precise, this method of hiding backdoors is called "security through obscurity".

5.5 Calls to assert()

Sometimes the presence of the `assert()` macro is useful too: commonly this macro leaves source file name, line number and condition in the code.

The most useful information is contained in the assert's condition, we can deduce variable names or structure field names from it. Another useful piece of information are the file names—we can try to deduce what type of code is there. Also it is possible to recognize well-known open-source libraries by the file names.

Listing 5.2: Example of informative assert() calls

```
.text:107D4B29 mov  dx, [ecx+42h]
.text:107D4B2D cmp  edx, 1
.text:107D4B30 jz   short loc_107D4B4A
.text:107D4B32 push 1ECh
.text:107D4B37 push offset aWrite_c ; "write.c"
.text:107D4B3C push offset aTdTd_planarcon ; "td->td_planarconfig == PLANARCONFIG_CON"...
.text:107D4B41 call ds:_assert

...

.text:107D52CA mov  edx, [ebp-4]
.text:107D52CD and  edx, 3
.text:107D52D0 test edx, edx
.text:107D52D2 jz   short loc_107D52E9
.text:107D52D4 push 58h
.text:107D52D6 push offset aDumpmode_c ; "dumpmode.c"
.text:107D52DB push offset aN30     ; "(n & 3) == 0"
.text:107D52E0 call ds:_assert

...

.text:107D6759 mov  cx, [eax+6]
.text:107D675D cmp  ecx, 0Ch
.text:107D6760 jle  short loc_107D677A
.text:107D6762 push 2D8h
.text:107D6767 push offset aLzw_c   ; "lzw.c"
.text:107D676C push offset aSpLzw_nbitsBit ; "sp->lzw_nbits <= BITS_MAX"
.text:107D6771 call ds:_assert
```

It is advisable to "google" both the conditions and file names, which can lead us to an open-source library. For example, if we "google" "sp->lzw_nbits <= BITS_MAX", this predictably gives us some open-source code that's related to the LZW compression.

5.6 Constants

Humans, including programmers, often use round numbers like 10, 100, 1000, in real life as well as in the code.

The practicing reverse engineer usually know them well in hexadecimal representation: 10=0xA, 100=0x64, 1000=0x3E8, 10000=0x2710.

The constants `0xAAAAAAAA` (0b10101010101010101010101010101010) and `0x55555555` (0b01010101010101010101010101010101) are also popular—those are composed of alternating bits.

That may help to distinguish some signal from a signal where all bits are turned on (0b1111 …) or off (0b0000 …). For example, the 0x55AA constant is used at least in the boot sector, MBR[16], and in the ROM of IBM-compatible extension cards.

Some algorithms, especially cryptographical ones use distinct constants, which are easy to find in code using IDA.

For example, the MD5[17] algorithm initializes its own internal variables like this:

```
var int h0 := 0x67452301
var int h1 := 0xEFCDAB89
var int h2 := 0x98BADCFE
var int h3 := 0x10325476
```

If you find these four constants used in the code in a row, it is highly probable that this function is related to MD5.

Another example are the CRC16/CRC32 algorithms, whose calculation algorithms often use precomputed tables like this one:

Listing 5.3: linux/lib/crc16.c

```
/** CRC table for the CRC-16. The poly is 0x8005 (x^16 + x^15 + x^2 + 1) */
u16 const crc16_table[256] = {
        0x0000, 0xC0C1, 0xC181, 0x0140, 0xC301, 0x03C0, 0x0280, 0xC241,
        0xC601, 0x06C0, 0x0780, 0xC741, 0x0500, 0xC5C1, 0xC481, 0x0440,
        0xCC01, 0x0CC0, 0x0D80, 0xCD41, 0x0F00, 0xCFC1, 0xCE81, 0x0E40,
        ...
```

See also the precomputed table for CRC32: 3.5 on page 482.

In tableless CRC algorithms well-known polynomials are used, for example, 0xEDB88320 for CRC32.

5.6.1 Magic numbers

A lot of file formats define a standard file header where a *magic number(s)*[18] is used, single one or even several.

For example, all Win32 and MS-DOS executables start with the two characters "MZ"[19].

At the beginning of a MIDI file the "MThd" signature must be present. If we have a program which uses MIDI files for something, it's very likely that it must check the file for validity by checking at least the first 4 bytes.

This could be done like this: (*buf* points to the beginning of the loaded file in memory)

```
cmp [buf], 0x6468544D ; "MThd"
jnz _error_not_a_MIDI_file
```

…or by calling a function for comparing memory blocks like memcmp() or any other equivalent code up to a CMPSB (.1.6 on page 1032) instruction.

When you find such point you already can say where the loading of the MIDI file starts, also, we could see the location of the buffer with the contents of the MIDI file, what is used from the buffer, and how.

Dates

Often, one may encounter number like 0x19870116, which is clearly looks like a date (year 1987, 1th month (January), 16th day). This may be someone's birthday (a programmer, his/her relative, child), or some other important date. The date may also be written in a reverse order, like 0x16011987. American-style dates are also popular, like 0x01161987.

Well-known example is 0x19540119 (magic number used in UFS2 superblock structure), which is a birthday of Marshall Kirk McKusick, prominent FreeBSD contributor.

[16] Master Boot Record
[17] wikipedia
[18] wikipedia
[19] wikipedia

Stuxnet uses the number "19790509" (not as 32-bit number, but as string, though), and this led to speculation that the malware is connected to Israel [20]

Also, numbers like those are very popular in amateur-grade cryptography, for example, excerpt from the *secret function* internals from HASP3 dongle [21]:

```
void xor_pwd(void)
{
        int i;

        pwd^=0x09071966;
        for(i=0;i<8;i++)
        {
                al_buf[i]= pwd & 7; pwd = pwd >> 3;
        }
};

void emulate_func2(unsigned short seed)
{
        int i, j;
        for(i=0;i<8;i++)
        {
                ch[i] = 0;

                for(j=0;j<8;j++)
                {
                        seed *= 0x1989;
                        seed += 5;
                        ch[i] |= (tab[(seed>>9)&0x3f]) << (7-j);
                }
        }
}
```

DHCP

This applies to network protocols as well. For example, the DHCP protocol's network packets contains the so-called *magic cookie*: `0x63538263`. Any code that generates DHCP packets somewhere must embed this constant into the packet. If we find it in the code we may find where this happens and, not only that. Any program which can receive DHCP packet must verify the *magic cookie*, comparing it with the constant.

For example, let's take the dhcpcore.dll file from Windows 7 x64 and search for the constant. And we can find it, twice: it seems that the constant is used in two functions with descriptive names `DhcpExtractOptionsForValidation()` and `DhcpExtractFullOptions()`:

Listing 5.4: dhcpcore.dll (Windows 7 x64)

```
.rdata:000007FF6483CBE8 dword_7FF6483CBE8 dd 63538263h          ; DATA XREF: ↙
    ↘ DhcpExtractOptionsForValidation+79
.rdata:000007FF6483CBEC dword_7FF6483CBEC dd 63538263h          ; DATA XREF: ↙
    ↘ DhcpExtractFullOptions+97
```

And here are the places where these constants are accessed:

Listing 5.5: dhcpcore.dll (Windows 7 x64)

```
.text:000007FF6480875F  mov     eax, [rsi]
.text:000007FF64808761  cmp     eax, cs:dword_7FF6483CBE8
.text:000007FF64808767  jnz     loc_7FF64817179
```

And:

Listing 5.6: dhcpcore.dll (Windows 7 x64)

```
.text:000007FF648082C7  mov     eax, [r12]
.text:000007FF648082CB  cmp     eax, cs:dword_7FF6483CBEC
.text:000007FF648082D1  jnz     loc_7FF648173AF
```

[20] This is a date of execution of Habib Elghanian, persian jew.
[21] https://web.archive.org/web/20160311231616/http://www.woodmann.com/fravia/bayu3.htm

5.6.2 Specific constants

Sometimes, there is a specific constant for some type of code. For example, the author once dug into a code, where number 12 was encountered suspiciously often. Size of many arrays is 12, or multiple of 12 (24, etc). As it turned out, that code takes 12-channel audio file at input and process it.

And vice versa: for example, if a program works with text field which has length of 120 bytes, there has to be a constant 120 or 119 somewhere in the code. If UTF-16 is used, then $2 \cdot 120$. If a code works with network packets of fixed size, it's good idea to search for this constant in the code as well.

This is also true for amateur cryptography (license keys, etc). If encrypted block has size of n bytes, you may want to try to find occurences of this number throughout the code. Also, if you see a piece of code which is been repeated n times in loop during execution, this may be encryption/decryption routine.

5.6.3 Searching for constants

It is easy in IDA: Alt-B or Alt-I. And for searching for a constant in a big pile of files, or for searching in non-executable files, there is a small utility called *binary grep*[22].

5.7 Finding the right instructions

If the program is utilizing FPU instructions and there are very few of them in the code, one can try to check each one manually with a debugger.

For example, we may be interested how Microsoft Excel calculates the formulae entered by user. For example, the division operation.

If we load excel.exe (from Office 2010) version 14.0.4756.1000 into IDA, make a full listing and to find every FDIV instruction (except the ones which use constants as a second operand—obviously, they do not suit us):

```
cat EXCEL.lst | grep fdiv | grep -v dbl_ > EXCEL.fdiv
```

…then we see that there are 144 of them.

We can enter a string like =(1/3) in Excel and check each instruction.

By checking each instruction in a debugger or tracer (one may check 4 instruction at a time), we get lucky and the sought-for instruction is just the 14th:

```
.text:3011E919 DC 33          fdiv    qword ptr [ebx]
```

```
PID=13944|TID=28744|(0) 0x2f64e919 (Excel.exe!BASE+0x11e919)
EAX=0x02088006 EBX=0x02088018 ECX=0x00000001 EDX=0x00000001
ESI=0x02088000 EDI=0x00544804 EBP=0x0274FA3C ESP=0x0274F9F8
EIP=0x2F64E919
FLAGS=PF IF
FPU ControlWord=IC RC=NEAR PC=64bits PM UM OM ZM DM IM
FPU StatusWord=
FPU ST(0): 1.000000
```

ST(0) holds the first argument (1) and second one is in [EBX].

The instruction after FDIV (FSTP) writes the result in memory:

```
.text:3011E91B DD 1E          fstp    qword ptr [esi]
```

If we set a breakpoint on it, we can see the result:

[22] GitHub

```
PID=32852|TID=36488|(0) 0x2f40e91b (Excel.exe!BASE+0x11e91b)
EAX=0x00598006 EBX=0x00598018 ECX=0x00000001 EDX=0x00000001
ESI=0x00598000 EDI=0x00294804 EBP=0x026CF93C ESP=0x026CF8F8
EIP=0x2F40E91B
FLAGS=PF IF
FPU ControlWord=IC RC=NEAR PC=64bits PM UM OM ZM DM IM
FPU StatusWord=C1 P
FPU ST(0): 0.333333
```

Also as a practical joke, we can modify it on the fly:

```
tracer -l:excel.exe bpx=excel.exe!BASE+0x11E91B,set(st0,666)
```

```
PID=36540|TID=24056|(0) 0x2f40e91b (Excel.exe!BASE+0x11e91b)
EAX=0x00680006 EBX=0x00680018 ECX=0x00000001 EDX=0x00000001
ESI=0x00680000 EDI=0x00395404 EBP=0x0290FD9C ESP=0x0290FD58
EIP=0x2F40E91B
FLAGS=PF IF
FPU ControlWord=IC RC=NEAR PC=64bits PM UM OM ZM DM IM
FPU StatusWord=C1 P
FPU ST(0): 0.333333
Set ST0 register to 666.000000
```

Excel shows 666 in the cell, finally convincing us that we have found the right point.

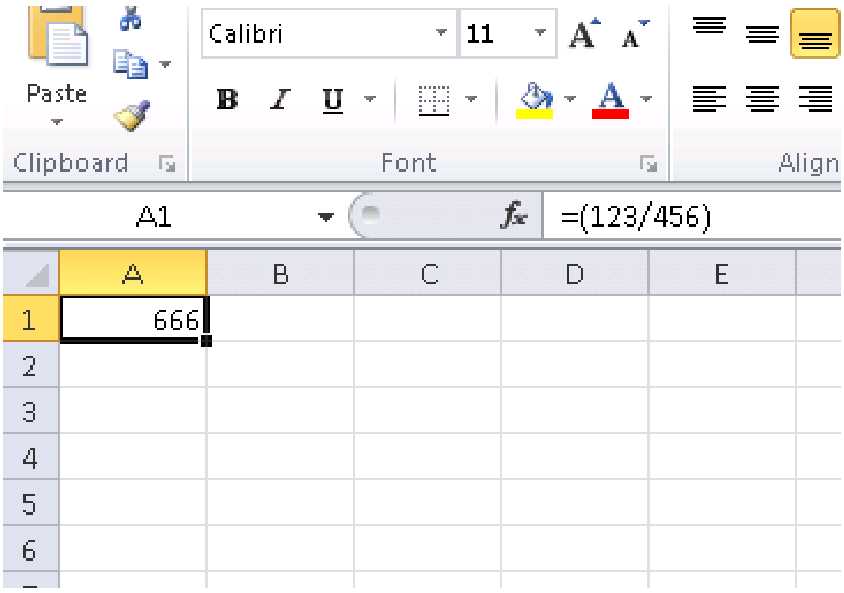


Figure 5.7: The practical joke worked

If we try the same Excel version, but in x64, we will find only 12 FDIV instructions there, and the one we looking for is the third one.

```
tracer.exe -l:excel.exe bpx=excel.exe!BASE+0x1B7FCC,set(st0,666)
```

It seems that a lot of division operations of *float* and *double* types, were replaced by the compiler with SSE instructions like DIVSD (DIVSD is present 268 times in total).

5.8 Suspicious code patterns

5.8.1 XOR instructions

Instructions like XOR op, op (for example, XOR EAX, EAX) are usually used for setting the register value to zero, but if the operands are different, the "exclusive or" operation is executed.

This operation is rare in common programming, but widespread in cryptography, including amateur one. It's especially suspicious if the second operand is a big number.

This may point to encrypting/decrypting, checksum computing, etc.

One exception to this observation worth noting is the "canary" (1.20.3 on page 283). Its generation and checking are often done using the XOR instruction.

This AWK script can be used for processing IDA listing (.lst) files:

```
gawk -e '$2=="xor" { tmp=substr($3, 0, length($3)-1); if (tmp!=$4) if($4!="esp") if ($4!="ebp")⤦
    ⤥ { print $1, $2, tmp, ",", $4 } }' filename.lst
```

It is also worth noting that this kind of script can also match incorrectly disassembled code (5.11.1 on page 726).

5.8.2 Hand-written assembly code

Modern compilers do not emit the LOOP and RCL instructions. On the other hand, these instructions are well-known to coders who like to code directly in assembly language. If you spot these, it can be said that there is a high probability that this fragment of code was hand-written. Such instructions are marked as (M) in the instructions list in this appendix: .1.6 on page 1026.

Also the function prologue/epilogue are not commonly present in hand-written assembly.

Commonly there is no fixed system for passing arguments to functions in the hand-written code.

Example from the Windows 2003 kernel (ntoskrnl.exe file):

```
MultiplyTest proc near               ; CODE XREF: Get386Stepping
             xor     cx, cx
loc_620555:                          ; CODE XREF: MultiplyTest+E
             push    cx
             call    Multiply
             pop     cx
             jb      short locret_620563
             loop    loc_620555
             clc
locret_620563:                       ; CODE XREF: MultiplyTest+C
             retn
MultiplyTest endp

Multiply     proc near               ; CODE XREF: MultiplyTest+5
             mov     ecx, 81h
             mov     eax, 417A000h
             mul     ecx
             cmp     edx, 2
             stc
             jnz     short locret_62057F
             cmp     eax, 0FE7A000h
             stc
             jnz     short locret_62057F
             clc
locret_62057F:                       ; CODE XREF: Multiply+10
                                     ; Multiply+18
             retn
Multiply     endp
```

Indeed, if we look in the WRK[23] v1.2 source code, this code can be found easily in file *WRK-v1.2\base\ntos\ke\i386\cpu.asm*.

[23] Windows Research Kernel

5.9 Using magic numbers while tracing

Often, our main goal is to understand how the program uses a value that has been either read from file or received via network. The manual tracing of a value is often a very labor-intensive task. One of the simplest techniques for this (although not 100% reliable) is to use your own *magic number*.

This resembles X-ray computed tomography is some sense: a radiocontrast agent is injected into the patient's blood, which is then used to improve the visibility of the patient's internal structure in to the X-rays. It is well known how the blood of healthy humans percolates in the kidneys and if the agent is in the blood, it can be easily seen on tomography, how blood is percolating, and are there any stones or tumors.

We can take a 32-bit number like `0x0badf00d`, or someone's birth date like `0x11101979` and write this 4-byte number to some point in a file used by the program we investigate.

Then, while tracing this program with tracer in *code coverage* mode, with the help of *grep* or just by searching in the text file (of tracing results), we can easily see where the value has been used and how.

Example of *grepable* tracer results in *cc* mode:

```
0x150bf66 (_kziaia+0x14), e=       1 [MOV EBX, [EBP+8]] [EBP+8]=0xf59c934
0x150bf69 (_kziaia+0x17), e=       1 [MOV EDX, [69AEB08h]] [69AEB08h]=0
0x150bf6f (_kziaia+0x1d), e=       1 [FS: MOV EAX, [2Ch]]
0x150bf75 (_kziaia+0x23), e=       1 [MOV ECX, [EAX+EDX*4]] [EAX+EDX*4]=0xf1ac360
0x150bf78 (_kziaia+0x26), e=       1 [MOV [EBP-4], ECX] ECX=0xf1ac360
```

This can be used for network packets as well. It is important for the *magic number* to be unique and not to be present in the program's code.

Aside of the tracer, DosBox (MS-DOS emulator) in heavydebug mode is able to write information about all registers' states for each executed instruction of the program to a plain text file[24], so this technique may be useful for DOS programs as well.

5.10 Loops

Whenever your program works with some kind of file, or buffer of some size, it has to be some kind of decrypting/processing loop inside of the code.

This is a real example of tracer tool output. There was a code which loads some kind of encryted file of 258 bytes. I run it with the intention to get each instruction counts (a DBI tool will serve much better these days). And I quickly found a piece of code, which executed 259/258 times:

```
...

0x45a6b5 e=   1 [FS: MOV [0], EAX] EAX=0x218fb08
0x45a6bb e=   1 [MOV [EBP-254h], ECX] ECX=0x218fbd8
0x45a6c1 e=   1 [MOV EAX, [EBP-254h]] [EBP-254h]=0x218fbd8
0x45a6c7 e=   1 [CMP [EAX+14h], 0] [EAX+14h]=0x102
0x45a6cb e=   1 [JZ 45A9F2h] ZF=false
0x45a6d1 e=   1 [MOV [EBP-0Dh], 1]
0x45a6d5 e=   1 [XOR ECX, ECX] ECX=0x218fbd8
0x45a6d7 e=   1 [MOV [EBP-14h], CX] CX=0
0x45a6db e=   1 [MOV [EBP-18h], 0]
0x45a6e2 e=   1 [JMP 45A6EDh]
0x45a6e4 e= 258 [MOV EDX, [EBP-18h]] [EBP-18h]=0..5 (248 items skipped) 0xfd..0x101
0x45a6e7 e= 258 [ADD EDX, 1] EDX=0..5 (248 items skipped) 0xfd..0x101
0x45a6ea e= 258 [MOV [EBP-18h], EDX] EDX=1..6 (248 items skipped) 0xfe..0x102
0x45a6ed e= 259 [MOV EAX, [EBP-254h]] [EBP-254h]=0x218fbd8
0x45a6f3 e= 259 [MOV ECX, [EBP-18h]] [EBP-18h]=0..5 (249 items skipped) 0xfe..0x102
0x45a6f6 e= 259 [CMP ECX, [EAX+14h]] ECX=0..5 (249 items skipped) 0xfe..0x102 [EAX+14h]=0x102
0x45a6f9 e= 259 [JNB 45A727h] CF=false,true
0x45a6fb e= 258 [MOV EDX, [EBP-254h]] [EBP-254h]=0x218fbd8
0x45a701 e= 258 [MOV EAX, [EDX+10h]] [EDX+10h]=0x21ee4c8
0x45a704 e= 258 [MOV ECX, [EBP-18h]] [EBP-18h]=0..5 (248 items skipped) 0xfd..0x101
0x45a707 e= 258 [ADD ECX, 1] ECX=0..5 (248 items skipped) 0xfd..0x101
0x45a70a e= 258 [IMUL ECX, ECX, 1Fh] ECX=1..6 (248 items skipped) 0xfe..0x102
```

[24] See also my blog post about this DosBox feature: blog.yurichev.com

```
0x45a70d e= 258 [MOV EDX, [EBP-18h]] [EBP-18h]=0..5 (248 items skipped) 0xfd..0x101
0x45a710 e= 258 [MOVZX EAX, [EAX+EDX]] [EAX+EDX]=1..6 (156 items skipped) 0xf3, 0xf8, 0xf9, 0↙
    ↳ xfc, 0xfd
0x45a714 e= 258 [XOR EAX, ECX] EAX=1..6 (156 items skipped) 0xf3, 0xf8, 0xf9, 0xfc, 0xfd ECX=0↙
    ↳ x1f, 0x3e, 0x5d, 0x7c, 0x9b (248 items skipped) 0x1ec2, 0x1ee1, 0x1f00, 0x1f1f, 0x1f3e
0x45a716 e= 258 [MOV ECX, [EBP-254h]] [EBP-254h]=0x218fbd8
0x45a71c e= 258 [MOV EDX, [ECX+10h]] [ECX+10h]=0x21ee4c8
0x45a71f e= 258 [MOV ECX, [EBP-18h]] [EBP-18h]=0..5 (248 items skipped) 0xfd..0x101
0x45a722 e= 258 [MOV [EDX+ECX], AL] AL=0..5 (77 items skipped) 0xe2, 0xee, 0xef, 0xf7, 0xfc
0x45a725 e= 258 [JMP 45A6E4h]
0x45a727 e=   1 [PUSH 5]
0x45a729 e=   1 [MOV ECX, [EBP-254h]] [EBP-254h]=0x218fbd8
0x45a72f e=   1 [CALL 45B500h]
0x45a734 e=   1 [MOV ECX, EAX] EAX=0x218fbd8
0x45a736 e=   1 [CALL 45B710h]
0x45a73b e=   1 [CMP EAX, 5] EAX=5

...
```

As it turns out, this is the decrypting loop.

5.10.1 Some binary file patterns

All examples here were prepared on the Windows with active code page 437 [25] in console. Binary files internally may look visually different if another code page is set.

[25] https://en.wikipedia.org/wiki/Code_page_437

Arrays

Sometimes, we can clearly spot an array of 16/32/64-bit values visually, in hex editor.

Here is an example of array of 16-bit values. We see that the first byte in pair is 7 or 8, and the second looks random:

Figure 5.8: FAR: array of 16-bit values

I used a file containing 12-channel signal digitized using 16-bit ADC[26].

[26] Analog-to-Digital Converter

And here is an example of very typical MIPS code.

As we may recall, every MIPS (and also ARM in ARM mode or ARM64) instruction has size of 32 bits (or 4 bytes), so such code is array of 32-bit values.

By looking at this screenshot, we may see some kind of pattern.

Vertical red lines are added for clarity:

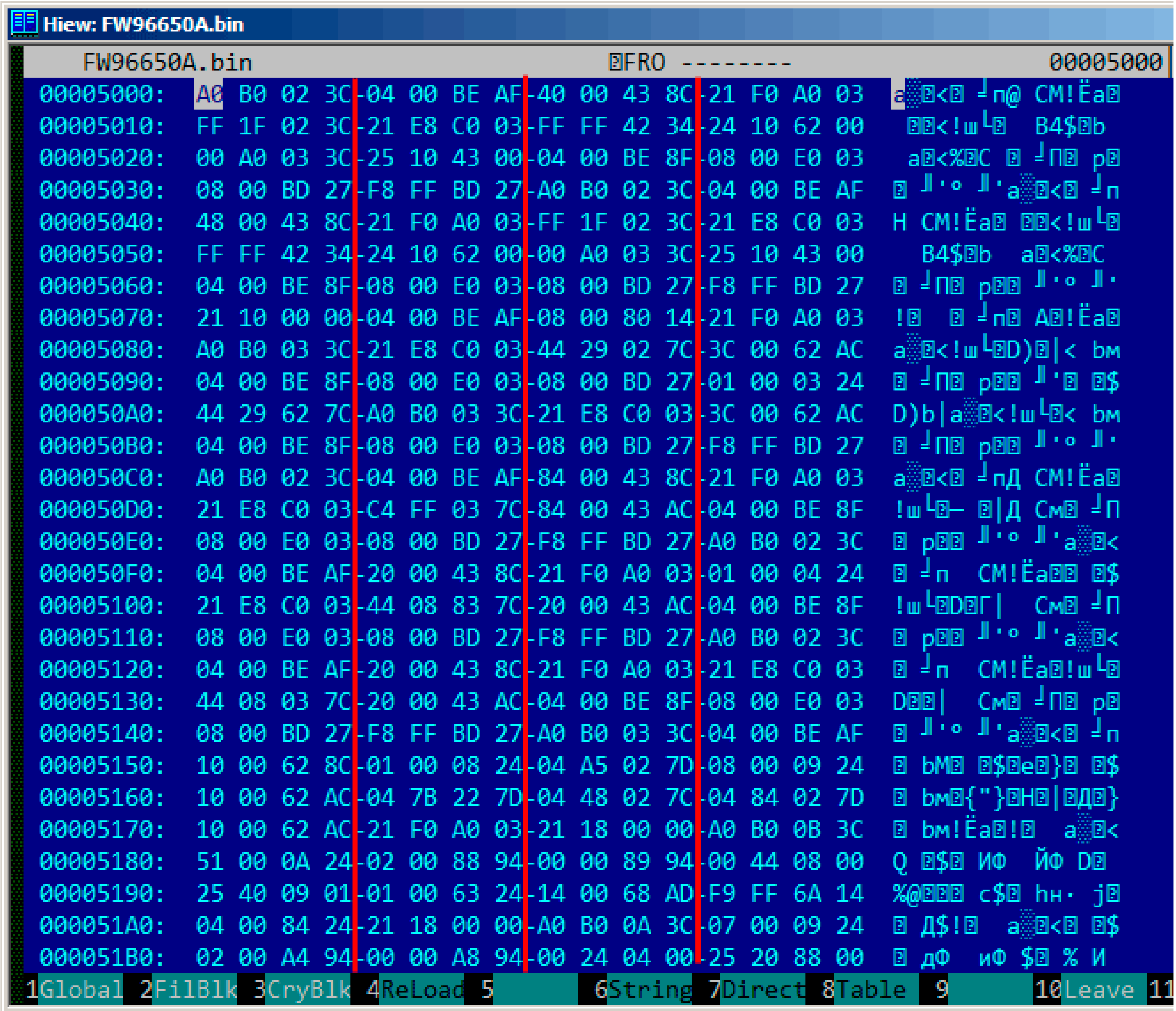


Figure 5.9: Hiew: very typical MIPS code

Another example of such pattern here is book: 9.5 on page 973.

Sparse files

This is sparse file with data scattered amidst almost empty file. Each space character here is in fact zero byte (which is looks like space). This is a file to program FPGA (Altera Stratix GX device). Of course, files like these can be compressed easily, but formats like this one are very popular in scientific and engineering software where efficient access is important while compactness is not.

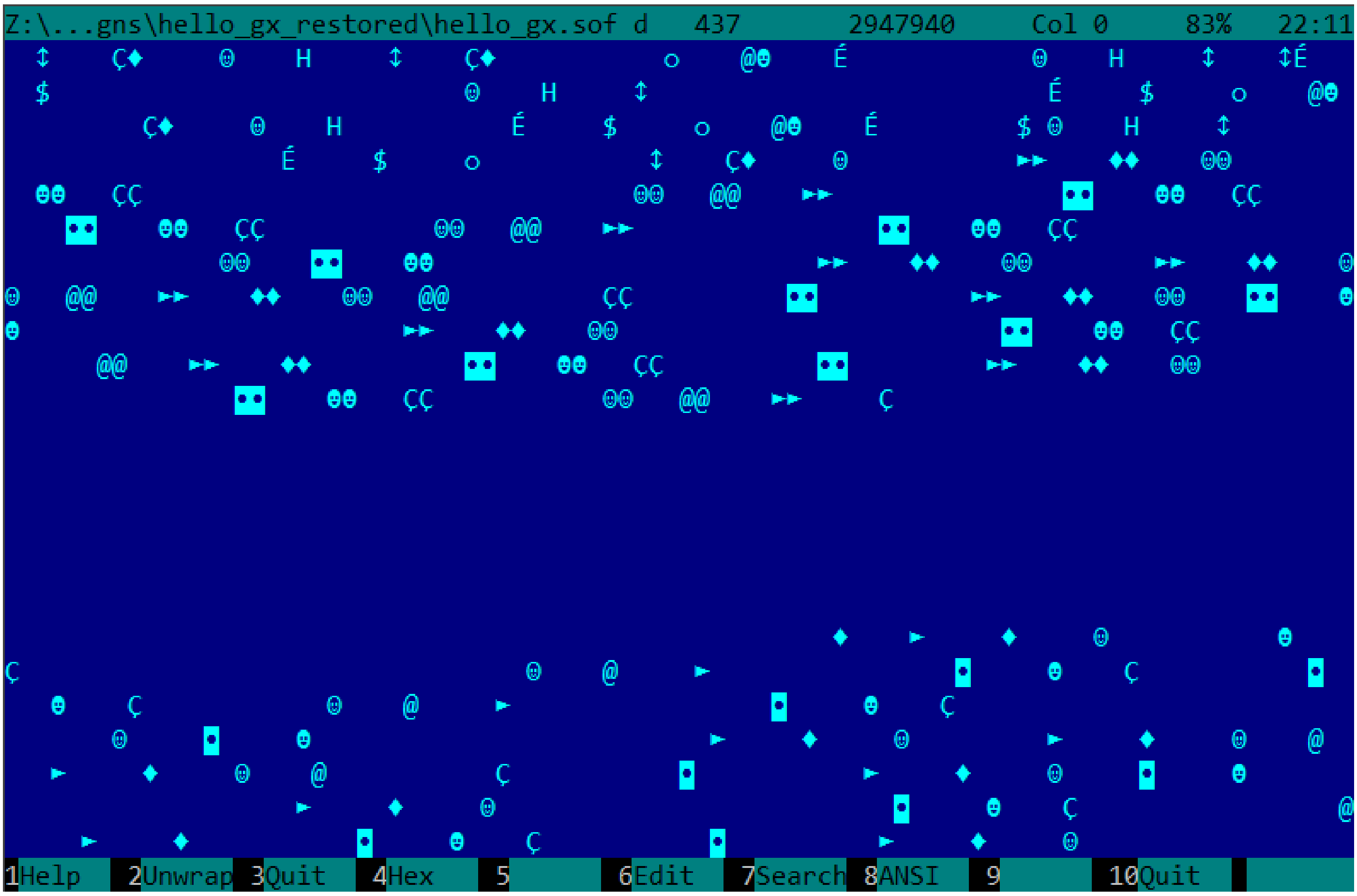


Figure 5.10: FAR: Sparse file

Compressed file

This file is just some compressed archive. It has relatively high entropy and visually looks just chaotic. This is how compressed and/or encrypted files looks like.

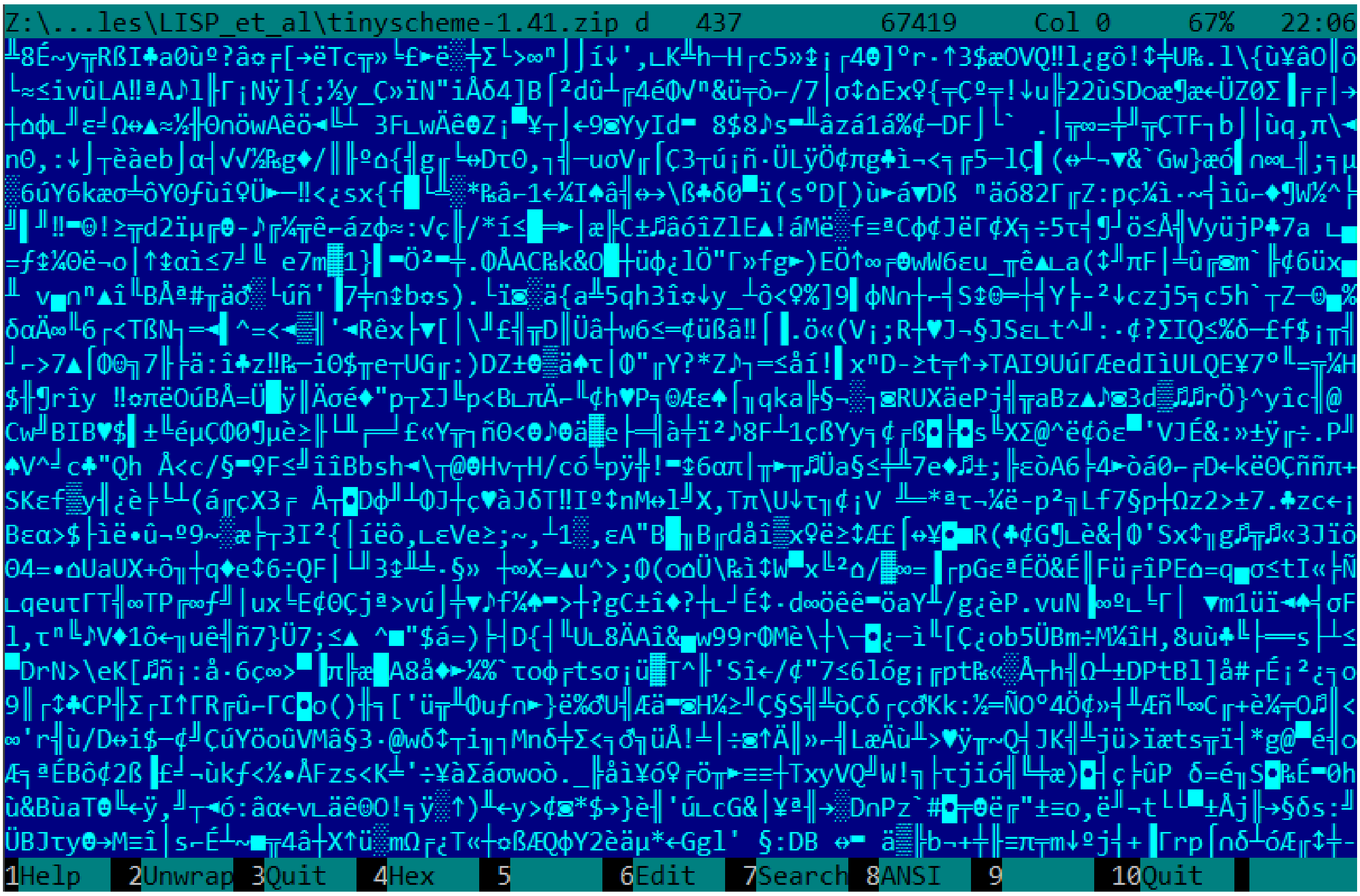


Figure 5.11: FAR: Compressed file

CDFS[27]

OS installations are usually distributed as ISO files which are copies of CD/DVD discs. Filesystem used is named CDFS, here is you see file names mixed with some additional data. This can be file sizes, pointers to another directories, file attributes, etc. This is how typical filesystems may look internally.

Figure 5.12: FAR: ISO file: Ubuntu 15 installation CD[28]

[27] Compact Disc File System

32-bit x86 executable code

This is how 32-bit x86 executable code looks like. It has not very high entropy, because some bytes occurred more often than others.

Figure 5.13: FAR: Executable 32-bit x86 code

BMP graphics files

BMP files are not compressed, so each byte (or group of bytes) describes each pixel. I've found this picture somewhere inside my installed Windows 8.1:

Figure 5.14: Example picture

You see that this picture has some pixels which unlikely can be compressed very good (around center), but there are long one-color lines at top and bottom. Indeed, lines like these also looks as lines during viewing the file:

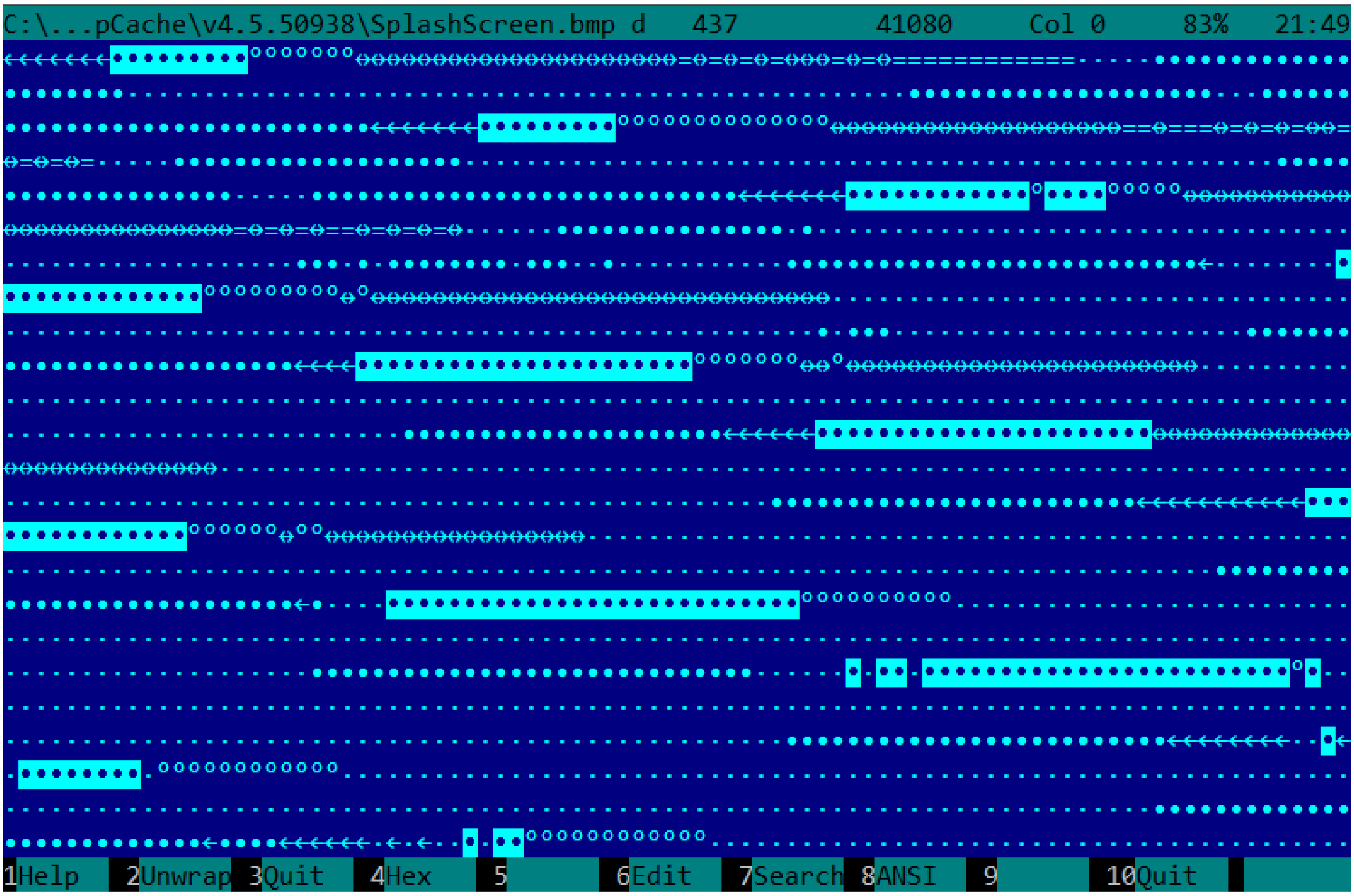


Figure 5.15: BMP file fragment

5.10.2 Memory "snapshots" comparing

The technique of the straightforward comparison of two memory snapshots in order to see changes was often used to hack 8-bit computer games and for hacking "high score" files.

For example, if you had a loaded game on an 8-bit computer (there isn't much memory on these, but the game usually consumes even less memory) and you know that you have now, let's say, 100 bullets, you can do a "snapshot" of all memory and back it up to some place. Then shoot once, the bullet count goes to 99, do a second "snapshot" and then compare both: it must be a byte somewhere which has been 100 at the beginning, and now it is 99.

Considering the fact that these 8-bit games were often written in assembly language and such variables were global, it can be said for sure which address in memory has holding the bullet count. If you searched for all references to the address in the disassembled game code, it was not very hard to find a piece of code decrementing the bullet count, then to write a NOP instruction there, or a couple of NOP-s, and then have a game with 100 bullets forever. Games on these 8-bit computers were commonly loaded at the constant address, also, there were not much different versions of each game (commonly just one version was popular for a long span of time), so enthusiastic gamers knew which bytes must be overwritten (using the BASIC's instruction POKE) at which address in order to hack it. This led to "cheat" lists that contained POKE instructions, published in magazines related to 8-bit games. See also: wikipedia.

Likewise, it is easy to modify "high score" files, this does not work with just 8-bit games. Notice your score count and back up the file somewhere. When the "high score" count gets different, just compare the two files, it can even be done with the DOS utility FC[29] ("high score" files are often in binary form).

There will be a point where a couple of bytes are different and it is easy to see which ones are holding the score number. However, game developers are fully aware of such tricks and may defend the program against it.

Somewhat similar example in this book is: 9.3 on page 961.

Windows registry

It is also possible to compare the Windows registry before and after a program installation.

It is a very popular method of finding which registry elements are used by the program. Perhaps, this is the reason why the "windows registry cleaner" shareware is so popular.

Blink-comparator

Comparison of files or memory snapshots remind us blink-comparator [30]: a device used by astronomers in past, intended to find moving celestial objects.

Blink-comparator allows to switch quickly between two photographies shot in different time, so astronomer would spot the difference visually.

By the way, Pluto was discovered by blink-comparator in 1930.

5.11 ISA detection

Often, you can deal with a binary file for an unknown ISA. Perhaps, easiest way to detect ISA is to try various ones in IDA, objdump or another disassembler.

To achieve this, one should understand a difference between incorrectly disassembled code and correctly one.

5.11.1 Incorrectly disassembled code

Practicing reverse engineers often have to deal with incorrectly disassembled code.

[29] MS-DOS utility for comparing binary files
[30] http://go.yurichev.com/17348

Disassembling from an incorrect start (x86)

Unlike ARM and MIPS (where any instruction has a length of 2 or 4 bytes), x86 instructions have variable size, so any disassembler that starts in the middle of a x86 instruction may produce incorrect results.

As an example:

```
add     [ebp-31F7Bh], cl
dec     dword ptr [ecx-3277Bh]
dec     dword ptr [ebp-2CF7Bh]
inc     dword ptr [ebx-7A76F33Ch]
fdiv    st(4), st
db 0FFh
dec     dword ptr [ecx-21F7Bh]
dec     dword ptr [ecx-22373h]
dec     dword ptr [ecx-2276Bh]
dec     dword ptr [ecx-22B63h]
dec     dword ptr [ecx-22F4Bh]
dec     dword ptr [ecx-23343h]
jmp     dword ptr [esi-74h]
xchg    eax, ebp
clc
std
db 0FFh
db 0FFh
mov     word ptr [ebp-214h], cs ; <- disassembler finally found right track here
mov     word ptr [ebp-238h], ds
mov     word ptr [ebp-23Ch], es
mov     word ptr [ebp-240h], fs
mov     word ptr [ebp-244h], gs
pushf
pop     dword ptr [ebp-210h]
mov     eax, [ebp+4]
mov     [ebp-218h], eax
lea     eax, [ebp+4]
mov     [ebp-20Ch], eax
mov     dword ptr [ebp-2D0h], 10001h
mov     eax, [eax-4]
mov     [ebp-21Ch], eax
mov     eax, [ebp+0Ch]
mov     [ebp-320h], eax
mov     eax, [ebp+10h]
mov     [ebp-31Ch], eax
mov     eax, [ebp+4]
mov     [ebp-314h], eax
call    ds:IsDebuggerPresent
mov     edi, eax
lea     eax, [ebp-328h]
push    eax
call    sub_407663
pop     ecx
test    eax, eax
jnz     short loc_402D7B
```

There are incorrectly disassembled instructions at the beginning, but eventually the disassembler gets on the right track.

How does random noise looks disassembled?

Common properties that can be spotted easily are:

- Unusually big instruction dispersion. The most frequent x86 instructions are PUSH, MOV, CALL, but here we see instructions from all instruction groups: FPU instructions, IN/OUT instructions, rare and system instructions, everything mixed up in one single place.
- Big and random values, offsets and immediates.
- Jumps having incorrect offsets, often jumping in the middle of another instructions.

Listing 5.7: random noise (x86)

```
    mov     bl, 0Ch
    mov     ecx, 0D38558Dh
    mov     eax, ds:2C869A86h
    db      67h
    mov     dl, 0CCh
    insb
    movsb
    push    eax
    xor     [edx-53h], ah
    fcom    qword ptr [edi-45A0EF72h]
    pop     esp
    pop     ss
    in      eax, dx
    dec     ebx
    push    esp
    lds     esp, [esi-41h]
    retf
    rcl     dword ptr [eax], cl
    mov     cl, 9Ch
    mov     ch, 0DFh
    push    cs
    insb
    mov     esi, 0D9C65E4Dh
    imul    ebp, [ecx], 66h
    pushf
    sal     dword ptr [ebp-64h], cl
    sub     eax, 0AC433D64h
    out     8Ch, eax
    pop     ss
    sbb     [eax], ebx
    aas
    xchg    cl, [ebx+ebx*4+14B31Eh]
    jecxz   short near ptr loc_58+1
    xor     al, 0C6h
    inc     edx
    db      36h
    pusha
    stosb
    test    [ebx], ebx
    sub     al, 0D3h ; 'L'
    pop     eax
    stosb

loc_58: ; CODE XREF: seg000:0000004A
    test    [esi], eax
    inc     ebp
    das
    db      64h
    pop     ecx
    das
    hlt

    pop     edx
    out     0B0h, al
    lodsb
    push    ebx
    cdq
    out     dx, al
    sub     al, 0Ah
    sti
    outsd
    add     dword ptr [edx], 96FCBE4Bh
    and     eax, 0E537EE4Fh
    inc     esp
    stosd
    cdq
    push    ecx
    in      al, 0CBh
    mov     ds:0D114C45Ch, al
```

```
    mov     esi, 659D1985h
```

Listing 5.8: random noise (x86-64)

```
    lea     esi, [rax+rdx*4+43558D29h]

loc_AF3: ; CODE XREF: seg000:0000000000000B46
    rcl     byte ptr [rsi+rax*8+29BB423Ah], 1
    lea     ecx, cs:0FFFFFFFFB2A6780Fh
    mov     al, 96h
    mov     ah, 0CEh
    push    rsp
    lods    byte ptr [esi]

    db  2Fh ; /

    pop     rsp
    db      64h
    retf    0E993h

    cmp     ah, [rax+4Ah]
    movzx   rsi, dword ptr [rbp-25h]
    push    4Ah
    movzx   rdi, dword ptr [rdi+rdx*8]

    db  9Ah

    rcr     byte ptr [rax+1Dh], cl
    lodsd
    xor     [rbp+6CF20173h], edx
    xor     [rbp+66F8B593h], edx
    push    rbx
    sbb     ch, [rbx-0Fh]
    stosd
    int     87h
    db      46h, 4Ch
    out     33h, rax
    xchg    eax, ebp
    test    ecx, ebp
    movsd
    leave
    push    rsp

    db  16h

    xchg    eax, esi
    pop     rdi

loc_B3D: ; CODE XREF: seg000:0000000000000B5F
    mov     ds:93CA685DF98A90F9h, eax
    jnz     short near ptr loc_AF3+6
    out     dx, eax
    cwde
    mov     bh, 5Dh ; ']'
    movsb
    pop     rbp
```

Listing 5.9: random noise (ARM (ARM mode))

```
BLNE    0xFE16A9D8
BGE     0x1634D0C
SVCCS   0x450685
STRNVT  R5, [PC],#-0x964
LDCGE   p6, c14, [R0],#0x168
STCCSL  p9, c9, [LR],#0x14C
CMNHIP  PC, R10,LSL#22
FLDMIADNV LR!, {D4}
MCR     p5, 2, R2,c15,c6, 4
BLGE    0x1139558
BLGT    0xFF9146E4
```

```
STRNEB  R5, [R4],#0xCA2
STMNEIB R5, {R0,R4,R6,R7,R9-SP,PC}
STMIA   R8, {R0,R2-R4,R7,R8,R10,SP,LR}^
STRB    SP, [R8],PC,ROR#18
LDCCS   p9, c13, [R6,#0x1BC]
LDRGE   R8, [R9,#0x66E]
STRNEB  R5, [R8],#-0x8C3
STCCSL  p15, c9, [R7,#-0x84]
RSBLS   LR, R2, R11,ASR LR
SVCGT   0x9B0362
SVCGT   0xA73173
STMNEDB R11!, {R0,R1,R4-R6,R8,R10,R11,SP}
STR     R0, [R3],#-0xCE4
LDCGT   p15, c8, [R1,#0x2CC]
LDRCCB  R1, [R11],-R7,ROR#30
BLLT    0xFED9D58C
BL      0x13E60F4
LDMVSIB R3!, {R1,R4-R7}^
USATNE  R10, #7, SP,LSL#11
LDRGEB  LR, [R1],#0xE56
STRPLT  R9, [LR],#0x567
LDRLT   R11, [R1],#-0x29B
SVCNV   0x12DB29
MVNNVS  R5, SP,LSL#25
LDCL    p8, c14, [R12,#-0x288]
STCNEL  p2, c6, [R6,#-0xBC]!
SVCNV   0x2E5A2F
BLX     0x1A8C97E
TEQGE   R3, #0x1100000
STMLSIA R6, {R3,R6,R10,R11,SP}
BICPLS  R12, R2, #0x5800
BNE     0x7CC408
TEQGE   R2, R4,LSL#20
SUBS    R1, R11, #0x28C
BICVS   R3, R12, R7,ASR R0
LDRMI   R7, [LR],R3,LSL#21
BLMI    0x1A79234
STMVCDB R6, {R0-R3,R6,R7,R10,R11}
EORMI   R12, R6, #0xC5
MCRRCS  p1, 0xF, R1,R3,c2
```

Listing 5.10: random noise (ARM (Thumb mode))

```
    LSRS    R3, R6, #0x12
    LDRH    R1, [R7,#0x2C]
    SUBS    R0, #0x55 ; 'U'
    ADR     R1, loc_3C
    LDR     R2, [SP,#0x218]
    CMP     R4, #0x86
    SXTB    R7, R4
    LDR     R4, [R1,#0x4C]
    STR     R4, [R4,R2]
    STR     R0, [R6,#0x20]
    BGT     0xFFFFFF72
    LDRH    R7, [R2,#0x34]
    LDRSH   R0, [R2,R4]
    LDRB    R2, [R7,R2]

    DCB 0x17
    DCB 0xED

    STRB    R3, [R1,R1]
    STR     R5, [R0,#0x6C]
    LDMIA   R3, {R0-R5,R7}
    ASRS    R3, R2, #3
    LDR     R4, [SP,#0x2C4]
    SVC     0xB5
    LDR     R6, [R1,#0x40]
    LDR     R5, =0xB2C5CA32
    STMIA   R6, {R1-R4,R6}
```

```
    LDR     R1, [R3,#0x3C]
    STR     R1, [R5,#0x60]
    BCC     0xFFFFFF70
    LDR     R4, [SP,#0x1D4]
    STR     R5, [R5,#0x40]
    ORRS    R5, R7

loc_3C ; DATA XREF: ROM:00000006
    B       0xFFFFFF98
```

Listing 5.11: random noise (MIPS little endian)

```
    lw      $t9, 0xCB3($t5)
    sb      $t5, 0x3855($t0)
    sltiu   $a2, $a0, -0x657A
    ldr     $t4, -0x4D99($a2)
    daddi   $s0, $s1, 0x50A4
    lw      $s7, -0x2353($s4)
    bgtzl   $a1, 0x17C5C

    .byte 0x17
    .byte 0xED
    .byte 0x4B  # K
    .byte 0x54  # T

    lwc2    $31, 0x66C5($sp)
    lwu     $s1, 0x10D3($a1)
    ldr     $t6, -0x204B($zero)
    lwc1    $f30, 0x4DBE($s2)
    daddiu  $t1, $s1, 0x6BD9
    lwu     $s5, -0x2C64($v1)
    cop0    0x13D642D
    bne     $gp, $t4, 0xFFFF9EF0
    lh      $ra, 0x1819($s1)
    sdl     $fp, -0x6474($t8)
    jal     0x78C0050
    ori     $v0, $s2, 0xC634
    blez    $gp, 0xFFFEA9D4
    swl     $t8, -0x2CD4($s2)
    sltiu   $a1, $k0, 0x685
    sdc1    $f15, 0x5964($at)
    sw      $s0, -0x19A6($a1)
    sltiu   $t6, $a3, -0x66AD
    lb      $t7, -0x4F6($t3)
    sd      $fp, 0x4B02($a1)
```

It is also important to keep in mind that cleverly constructed unpacking and decryption code (including self-modifying) may looks like noise as well, but still execute correctly.

5.11.2 Correctly disassembled code

Each ISA has a dozen of a most used instructions, all the rest are used much less often.

As of x86, it is interesting to know that the fact that function calls (PUSH/CALL/ADD) and MOV instructions are the most frequently executed pieces of code in almost all programs we use. In other words, CPU is very busy passing information between levels of abstractions, or, it can be said, it's very busy switching between these levels. Regardless type of ISA. This is a cost of splitting problems into several levels of abstractions (so humans could work with them easier).

5.12 Text strings right in the middle of compressed data

You can download Linux kernels and find English words right in the middle of compressed data:

```
% wget https://www.kernel.org/pub/linux/kernel/v4.x/linux-4.10.2.tar.gz
```

```
% xxd -g 1 -seek 0x515c550 -l 0x30 linux-4.10.2.tar.gz

0515c550: c5 59 43 cf 41 27 85 54 35 4a 57 90 73 89 b7 6a  .YC.A'.T5JW.s..j
0515c560: 15 af 03 db 20 df 6a 51 f9 56 49 52 55 53 3d da  .... .jQ.VIRUS=.
0515c570: 0e b9 29 24 cc 6a 38 e2 78 66 09 33 72 aa 88 df  ..)$.j8.xf.3r...
```

```
% wget https://cdn.kernel.org/pub/linux/kernel/v2.3/linux-2.3.3.tar.bz2

% xxd -g 1 -seek 0xa93086 -l 0x30 linux-2.3.3.tar.bz2

00a93086: 4d 45 54 41 4c cd 44 45 2d 2c 41 41 54 94 8b a1  METAL.DE-,AAT...
00a93096: 5d 2b d8 d0 bd d8 06 91 74 ab 41 a0 0a 8a 94 68  ]+......t.A....h
00a930a6: 66 56 86 81 68 0d 0e 25 6b b6 80 a4 28 1a 00 a4  fV..h..%k...(...
```

One of Linux kernel patches in compressed form has the “Linux” word itself:

```
% wget https://cdn.kernel.org/pub/linux/kernel/v4.x/testing/patch-4.6-rc4.gz

% xxd -g 1 -seek 0x4d03f -l 0x30 patch-4.6-rc4.gz

0004d03f: c7 40 24 bd ae ef ee 03 2c 95 dc 65 eb 31 d3 f1  .@$.....,..e.1..
0004d04f: 4c 69 6e 75 78 f2 f3 70 3c 3a bd 3e bd f8 59 7e  Linux..p<:.>..Y~
0004d05f: cd 76 55 74 2b cb d5 af 7a 35 56 d7 5e 07 5a 67  .vUt+...z5V.^.Zg
```

Other English words I’ve found in other compressed Linux kernel trees:

```
linux-4.6.2.tar.gz: [maybe] at 0x68e78ec
linux-4.10.14.tar.xz: [OCEAN] at 0x6bf0a8
linux-4.7.8.tar.gz: [FUNNY] at 0x29e6e20
linux-4.6.4.tar.gz: [DRINK] at 0x68dc314
linux-2.6.11.8.tar.bz2: [LUCKY] at 0x1ab5be7
linux-3.0.68.tar.gz: [BOOST] at 0x11238c7
linux-3.0.16.tar.bz2: [APPLE] at 0x34c091
linux-3.0.26.tar.xz: [magic] at 0x296f7d9
linux-3.11.8.tar.bz2: [TRUTH] at 0xf635ba
linux-3.10.11.tar.bz2: [logic] at 0x4a7f794
```

There is a nice illustration of apophenia and pareidolia There is a nice illustration of apophenia and pareidolia (human’s mind ability to see faces in clouds, etc) in Lurkmore, Russian counterpart of Encyclopedia Dramatica. As they wrote in the article about electronic voice phenomenon[31], you can open any long enough compressed file in hex editor and find well-known 3-letter Russian obscene word, and you’ll find it a lot: but that means nothing, just a mere coincidence.

And I was interested in calculation, how big compressed file must be to contain all possible 3-letter, 4-letter, etc, words? In my naive calculations, I’ve got this: probability of the first specific byte in the middle of compressed data stream with maximal entropy is $\frac{1}{256}$, probability of the 2nd is also $\frac{1}{256}$, and probability of specific byte pair is $\frac{1}{256 \cdot 256} = \frac{1}{256^2}$. Probabilty of specific triple is $\frac{1}{256^3}$. If the file has maximal entropy (which is almost unachievable, but …) and we live in an ideal world, you’ve got to have a file of size just $256^3 = 16777216$, which is 16-17MB. You can check: get any compressed file, and use *rafind2* to search for any 3-letter word (not just that Russian obscene one).

It took ≈ 8-9 GB of my downloaded movies/TV series files to find the word “beer” in them (case sensitive). Perhaps, these movies wasn’t compressed good enough? This is also true for a well-known 4-letter English obscene word.

My approach is naive, so I googled for mathematically grounded one, and have find this question: “Time until a consecutive sequence of ones in a random bit sequence” [32]. The answer is: $(p^{-n}-1)/(1-p)$, where p is probability of each event and n is number of consecutive events. Plug $\frac{1}{256}$ and 3 and you’ll get almost the same as my naive calculations.

So any 3-letter word can be found in the compressed file (with ideal entropy) of length $256^3 = \approx 17MB$, any 4-letter word — $256^4 = 4.7GB$ (size of DVD). Any 5-letter word — $256^5 = \approx 1TB$.

For the piece of text you are reading now, I mirrored the whole kernel.org website (hopefully, sysadmins can forgive me), and it has ≈ 430GB of compressed Linux Kernel source trees. It has enough compressed

[31] http://archive.is/gYnFL
[32] http://math.stackexchange.com/questions/27989/time-until-a-consecutive-sequence-of-ones-in-a-random-bit-sequence/27991#27991

data to contain these words, however, I cheated a bit: I searched for both lowercase and uppercase strings, thus compressed data set I need is almost halved.

This is quite interesting thing to think about: 1TB of compressed data with maximal entropy has all possible 5-byte chains, but the data is encoded not in chains itself, but in the order of chains (no matter of compression algorithm, etc).

Now the information for gamblers: one should throw a dice ≈ 42 times to get a pair of six, but no one will tell you, when exactly this will happen. I don't remember, how many times coin was tossed in the "Rosencrantz & Guildenstern Are Dead" movie, but one should toss it ≈ 2048 times and at some point, you'll get 10 heads in a row, and at some other point, 10 tails in a row. Again, no one will tell you, when exactly this will happen.

Compressed data can also be treated as a stream of random data, so we can use the same mathematics to determine probabilities, etc.

If you can live with strings of mixed case, like "bEeR", probabilities and compressed data sets are much lower: $128^3 = 2MB$ for all 3-letter words of mixed case, $128^4 = 268MB$ for all 4-letter words, $128^5 = 34GB$ for all 5-letter words, etc.

Moral of the story: whenever you search for some patterns, you can find it in the middle of compressed blob, but that means nothing else then coincidence. In philosophical sense, this is a case of selection/confirmation bias: you find what you search for in "The Library of Babel"[33].

5.13 Other things

5.13.1 General idea

A reverse engineer should try to be in programmer's shoes as often as possible. To take his/her viewpoint and ask himself, how would one solve some task the specific case.

5.13.2 Order of functions in binary code

All functions located in a single .c or .cpp-file are compiled into corresponding object (.o) file. Later, linker puts all object files it needs together, not changing order or functions in them. As a consequence, if you see two or more consecutive functions, it means, that they were placed together in a single source code file (unless you're on border of two object files, of course.) This means these functions have something in common, that they are from the same API level, from same library, etc.

5.13.3 Tiny functions

Tiny functions like empty functions (1.3 on page 5) or function which returns just "true" (1) or "false" (0) (1.4 on page 7) are very common, and almost all decent compilers tend to put only one such function into resulting executable code even if there were several similar functions in source code. So, whenever you see a tiny function consisting just of `mov eax, 1 / ret` which is referenced (and can be called) from many places, which are seems unconnected to each other, this may be a result of such optimization.

5.13.4 C++

RTTI (3.18.1 on page 557)-data may be also useful for C++ class identification.

[33] Short story by Jorge Luis Borges

Chapter 6

OS-specific

6.1 Arguments passing methods (calling conventions)

6.1.1 cdecl

This is the most popular method for passing arguments to functions in the C/C++ languages.

The glscaller also must return the value of the stack pointer (ESP) to its initial state after the callee function exits.

Listing 6.1: cdecl

```
push arg3
push arg2
push arg1
call function
add esp, 12 ; returns ESP
```

6.1.2 stdcall

It's almost the same as *cdecl*, with the exception that the callee must set ESP to the initial state by executing the `RET x` instruction instead of `RET`,
where `x = arguments number * sizeof(int)`[1]. The caller is not adjusting the stack pointer, there are no `add esp, x` instruction.

Listing 6.2: stdcall

```
push arg3
push arg2
push arg1
call function

function:
... do something ...
ret 12
```

The method is ubiquitous in win32 standard libraries, but not in win64 (see below about win64).

For example, we can take the function from 1.86 on page 97 and change it slightly by adding the `__stdcall` modifier:

```
int __stdcall f2 (int a, int b, int c)
{
        return a*b+c;
};
```

It is to be compiled in almost the same way as 1.87 on page 97, but you will see `RET 12` instead of `RET`. SP is not updated in the caller.

[1]The size of an *int* type variable is 4 in x86 systems and 8 in x64 systems

As a consequence, the number of function arguments can be easily deduced from the RETN n instruction: just divide n by 4.

Listing 6.3: MSVC 2010

```
_a$ = 8         ; size = 4
_b$ = 12        ; size = 4
_c$ = 16        ; size = 4
_f2@12  PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _a$[ebp]
        imul    eax, DWORD PTR _b$[ebp]
        add     eax, DWORD PTR _c$[ebp]
        pop     ebp
        ret     12
_f2@12  ENDP

; ...
        push    3
        push    2
        push    1
        call    _f2@12
        push    eax
        push    OFFSET $SG81369
        call    _printf
        add     esp, 8
```

Functions with variable number of arguments

printf()-like functions are, probably, the only case of functions with a variable number of arguments in C/C++, but it is easy to illustrate an important difference between *cdecl* and *stdcall* with their help. Let's start with the idea that the compiler knows the argument count of each printf() function call.

However, the called printf(), which is already compiled and located in MSVCRT.DLL (if we talk about Windows), does not have any information about how much arguments were passed, however it can determine it from the format string.

Thus, if printf() would be a *stdcall* function and restored stack pointer to its initial state by counting the number of arguments in the format string, this could be a dangerous situation, when one programmer's typo can provoke a sudden program crash. Thus it is not suitable for such functions to use *stdcall*, *cdecl* is better.

6.1.3 fastcall

That's the general naming for the method of passing some arguments via registers and the rest via the stack. It worked faster than *cdecl*/*stdcall* on older CPUs (because of smaller stack pressure). It may not help to gain any significant performance on latest (much more complex) CPUs, however.

It is not standardized, so the various compilers can do it differently. It's a well known caveat: if you have two DLLs and the one uses another one, and they are built by different compilers with different *fastcall* calling conventions, you can expect problems.

Both MSVC and GCC pass the first and second arguments via ECX and EDX and the rest of the arguments via the stack.

The stack pointer must be restored to its initial state by the callee (like in *stdcall*).

Listing 6.4: fastcall

```
push arg3
mov edx, arg2
mov ecx, arg1
call function

function:
.. do something ..
ret 4
```

For example, we may take the function from 1.86 on page 97 and change it slightly by adding a `__fastcall` modifier:

```
int __fastcall f3 (int a, int b, int c)
{
        return a*b+c;
};
```

Here is how it is to be compiled:

Listing 6.5: Optimizing MSVC 2010 /Ob0

```
_c$ = 8         ; size = 4
@f3@12  PROC
; _a$ = ecx
; _b$ = edx
        mov     eax, ecx
        imul    eax, edx
        add     eax, DWORD PTR _c$[esp-4]
        ret     4
@f3@12  ENDP

; ...

        mov     edx, 2
        push    3
        lea     ecx, DWORD PTR [edx-1]
        call    @f3@12
        push    eax
        push    OFFSET $SG81390
        call    _printf
        add     esp, 8
```

We see that the callee returns SP by using the RETN instruction with an operand.

Which implies that the number of arguments can be deduced easily here as well.

GCC regparm

It is the evolution of *fastcall*[2] in some sense. With the `-mregparm` option it is possible to set how many arguments are to be passed via registers (3 is the maximum). Thus, the EAX, EDX and ECX registers are to be used.

Of course, if the number the of arguments is less than 3, not all 3 registers are to be used.

The caller restores the stack pointer to its initial state.

For example, see (1.22.1 on page 306).

Watcom/OpenWatcom

Here it is called “register calling convention”. The first 4 arguments are passed via the EAX, EDX, EBX and ECX registers. All the rest—via the stack.

These functions has an underscore appended to the function name in order to distinguish them from those having a different calling convention.

6.1.4 thiscall

This is passing the object’s *this* pointer to the function-method, in C++.

In MSVC, *this* is usually passed in the ECX register.

In GCC, the *this* pointer is passed as the first function-method argument. Thus it will be visible that all functions in assembly code have an extra argument, in comparison with the source code.

For an example, see (3.18.1 on page 542).

[2] http://go.yurichev.com/17040

6.1.5 x86-64

Windows x64

The method of for passing arguments in Win64 somewhat resembles `fastcall`. The first 4 arguments are passed via RCX, RDX, R8 and R9, the rest—via the stack. The caller also must prepare space for 32 bytes or 4 64-bit values, so then the callee can save there the first 4 arguments. Short functions may use the arguments' values just from the registers, but larger ones may save their values for further use.

The caller also must return the stack pointer into its initial state.

This calling convention is also used in Windows x86-64 system DLLs (instead of *stdcall* in win32).

Example:

```
#include <stdio.h>

void f1(int a, int b, int c, int d, int e, int f, int g)
{
        printf ("%d %d %d %d %d %d %d\n", a, b, c, d, e, f, g);
};

int main()
{
        f1(1,2,3,4,5,6,7);
};
```

Listing 6.6: MSVC 2012 /0b

```
$SG2937 DB      '%d %d %d %d %d %d %d', 0aH, 00H

main    PROC
        sub     rsp, 72

        mov     DWORD PTR [rsp+48], 7
        mov     DWORD PTR [rsp+40], 6
        mov     DWORD PTR [rsp+32], 5
        mov     r9d, 4
        mov     r8d, 3
        mov     edx, 2
        mov     ecx, 1
        call    f1

        xor     eax, eax
        add     rsp, 72
        ret     0
main    ENDP

a$ = 80
b$ = 88
c$ = 96
d$ = 104
e$ = 112
f$ = 120
g$ = 128
f1      PROC
$LN3:
        mov     DWORD PTR [rsp+32], r9d
        mov     DWORD PTR [rsp+24], r8d
        mov     DWORD PTR [rsp+16], edx
        mov     DWORD PTR [rsp+8], ecx
        sub     rsp, 72

        mov     eax, DWORD PTR g$[rsp]
        mov     DWORD PTR [rsp+56], eax
        mov     eax, DWORD PTR f$[rsp]
        mov     DWORD PTR [rsp+48], eax
        mov     eax, DWORD PTR e$[rsp]
        mov     DWORD PTR [rsp+40], eax
        mov     eax, DWORD PTR d$[rsp]
```

```
        mov     DWORD PTR [rsp+32], eax
        mov     r9d, DWORD PTR c$[rsp]
        mov     r8d, DWORD PTR b$[rsp]
        mov     edx, DWORD PTR a$[rsp]
        lea     rcx, OFFSET FLAT:$SG2937
        call    printf

        add     rsp, 72
        ret     0
f1      ENDP
```

Here we clearly see how 7 arguments are passed: 4 via registers and the remaining 3 via the stack.

The code of the f1() function's prologue saves the arguments in the "scratch space"—a space in the stack intended exactly for this purpose.

This is arranged so because the compiler cannot be sure that there will be enough registers to use without these 4, which will otherwise be occupied by the arguments until the function's execution end.

The "scratch space" allocation in the stack is the caller's duty.

Listing 6.7: Optimizing MSVC 2012 /0b

```
$SG2777 DB      '%d %d %d %d %d %d %d', 0aH, 00H

a$ = 80
b$ = 88
c$ = 96
d$ = 104
e$ = 112
f$ = 120
g$ = 128
f1      PROC
$LN3:
        sub     rsp, 72

        mov     eax, DWORD PTR g$[rsp]
        mov     DWORD PTR [rsp+56], eax
        mov     eax, DWORD PTR f$[rsp]
        mov     DWORD PTR [rsp+48], eax
        mov     eax, DWORD PTR e$[rsp]
        mov     DWORD PTR [rsp+40], eax
        mov     DWORD PTR [rsp+32], r9d
        mov     r9d, r8d
        mov     r8d, edx
        mov     edx, ecx
        lea     rcx, OFFSET FLAT:$SG2777
        call    printf

        add     rsp, 72
        ret     0
f1      ENDP

main    PROC
        sub     rsp, 72

        mov     edx, 2
        mov     DWORD PTR [rsp+48], 7
        mov     DWORD PTR [rsp+40], 6
        lea     r9d, QWORD PTR [rdx+2]
        lea     r8d, QWORD PTR [rdx+1]
        lea     ecx, QWORD PTR [rdx-1]
        mov     DWORD PTR [rsp+32], 5
        call    f1

        xor     eax, eax
        add     rsp, 72
        ret     0
main    ENDP
```

If we compile the example with optimizations, it is to be almost the same, but the "scratch space" will not be used, because it won't be needed.

Also take a look on how MSVC 2012 optimizes the loading of primitive values into registers by using LEA (.1.6 on page 1028). MOV would be 1 byte longer here (5 instead of 4).

Another example of such thing is: 8.1.1 on page 797.

Windows x64: Passing *this* (C/C++)

The *this* pointer is passed in RCX, the first argument of the method is in RDX, etc. For an example see: 3.18.1 on page 544.

Linux x64

The way arguments are passed in Linux for x86-64 is almost the same as in Windows, but 6 registers are used instead of 4 (RDI, RSI, RDX, RCX, R8, R9) and there is no "scratch space", although the callee may save the register values in the stack, if it needs/wants to.

Listing 6.8: Optimizing GCC 4.7.3

```
.LC0:
        .string "%d %d %d %d %d %d %d\n"
f1:
        sub     rsp, 40
        mov     eax, DWORD PTR [rsp+48]
        mov     DWORD PTR [rsp+8], r9d
        mov     r9d, ecx
        mov     DWORD PTR [rsp], r8d
        mov     ecx, esi
        mov     r8d, edx
        mov     esi, OFFSET FLAT:.LC0
        mov     edx, edi
        mov     edi, 1
        mov     DWORD PTR [rsp+16], eax
        xor     eax, eax
        call    __printf_chk
        add     rsp, 40
        ret
main:
        sub     rsp, 24
        mov     r9d, 6
        mov     r8d, 5
        mov     DWORD PTR [rsp], 7
        mov     ecx, 4
        mov     edx, 3
        mov     esi, 2
        mov     edi, 1
        call    f1
        add     rsp, 24
        ret
```

N.B.: here the values are written into the 32-bit parts of the registers (e.g., EAX) but not in the whole 64-bit register (RAX). This is because each write to the low 32-bit part of a register automatically clears the high 32 bits. Supposedly, it was decided in AMD to do so to simplify porting code to x86-64.

6.1.6 Return values of *float* and *double* type

In all conventions except in Win64, the values of type *float* or *double* are returned via the FPU register ST(0).

In Win64, the values of *float* and *double* types are returned in the low 32 or 64 bits of the XMM0 register.

6.1.7 Modifying arguments

Sometimes, C/C++ programmers (not limited to these PLs, though), may ask, what can happen if they modify the arguments?

The answer is simple: the arguments are stored in the stack, that is where the modification takes place.

The calling functions is not using them after the callee's exit (the author of these lines has never seen any such case in his practice).

```
#include <stdio.h>

void f(int a, int b)
{
        a=a+b;
        printf ("%d\n", a);
};
```

Listing 6.9: MSVC 2012

```
_a$ = 8                                                         ; size = 4
_b$ = 12                                                        ; size = 4
_f      PROC
        push    ebp
        mov     ebp, esp
        mov     eax, DWORD PTR _a$[ebp]
        add     eax, DWORD PTR _b$[ebp]
        mov     DWORD PTR _a$[ebp], eax
        mov     ecx, DWORD PTR _a$[ebp]
        push    ecx
        push    OFFSET $SG2938 ; '%d', 0aH
        call    _printf
        add     esp, 8
        pop     ebp
        ret     0
_f      ENDP
```

So yes, one can modify the arguments easily. Of course, if it is not *references* in C++ (3.18.3 on page 558), and if you don't modify data to which a pointer points to, then the effect will not propagate outside the current function.

Theoretically, after the callee's return, the caller could get the modified argument and use it somehow. Maybe if it is written directly in assembly language.

For example, code like this will be generated by usual C/C++ compiler:

```
        push    456     ; will be b
        push    123     ; will be a
        call    f       ; f() modifies its first argument
        add     esp, 2*4
```

We can rewrite this code like:

```
        push    456     ; will be b
        push    123     ; will be a
        call    f       ; f() modifies its first argument
        pop     eax
        add     esp, 4
        ; EAX=1st argument of f() modified in f()
```

Hard to imagine, why anyone would need this, but this is possible in practice. Nevertheless, the C/C++ languages standards don't offer any way to do so.

6.1.8 Taking a pointer to function argument

…even more than that, it's possible to take a pointer to the function's argument and pass it to another function:

```
#include <stdio.h>

// located in some other file
void modify_a (int *a);

void f (int a)
{
        modify_a (&a);
        printf ("%d\n", a);
};
```

It's hard to understand how it works until we can see the code:

Listing 6.10: Optimizing MSVC 2010

```
$SG2796 DB      '%d', 0aH, 00H

_a$ = 8
_f      PROC
        lea     eax, DWORD PTR _a$[esp-4] ; just get the address of value in local stack
        push    eax                       ; and pass it to modify_a()
        call    _modify_a
        mov     ecx, DWORD PTR _a$[esp]   ; reload it from the local stack
        push    ecx                       ; and pass it to printf()
        push    OFFSET $SG2796 ; '%d'
        call    _printf
        add     esp, 12
        ret     0
_f      ENDP
```

The address of the place in the stack where a has been passed is just passed to another function. It modifies the value addressed by the pointer and then `printf()` prints the modified value.

The observant reader might ask, what about calling conventions where the function's arguments are passed in registers?

That's a situation where the *Shadow Space* is used.

The input value is copied from the register to the *Shadow Space* in the local stack, and then this address is passed to the other function:

Listing 6.11: Optimizing MSVC 2012 x64

```
$SG2994 DB      '%d', 0aH, 00H

a$ = 48
f       PROC
        mov     DWORD PTR [rsp+8], ecx   ; save input value in Shadow Space
        sub     rsp, 40
        lea     rcx, QWORD PTR a$[rsp]   ; get address of value and pass it to modify_a()
        call    modify_a
        mov     edx, DWORD PTR a$[rsp]   ; reload value from Shadow Space and pass it to printf
    ()
        lea     rcx, OFFSET FLAT:$SG2994 ; '%d'
        call    printf
        add     rsp, 40
        ret     0
f       ENDP
```

GCC also stores the input value in the local stack:

Listing 6.12: Optimizing GCC 4.9.1 x64

```
.LC0:
        .string "%d\n"
f:
        sub     rsp, 24
        mov     DWORD PTR [rsp+12], edi  ; store input value to the local stack
        lea     rdi, [rsp+12]            ; take an address of the value and pass it to modify_a
    ()
        call    modify_a
```

```
        mov     edx, DWORD PTR [rsp+12]  ; reload value from the local stack and pass it to ↙
    ↘ printf()
        mov     esi, OFFSET FLAT:.LC0    ; '%d'
        mov     edi, 1
        xor     eax, eax
        call    __printf_chk
        add     rsp, 24
        ret
```

GCC for ARM64 does the same, but this space is called *Register Save Area* here:

Listing 6.13: Optimizing GCC 4.9.1 ARM64

```
f:
        stp     x29, x30, [sp, -32]!
        add     x29, sp, 0          ; setup FP
        add     x1, x29, 32         ; calculate address of variable in Register Save Area
        str     w0, [x1,-4]!        ; store input value there
        mov     x0, x1              ; pass address of variable to the modify_a()
        bl      modify_a
        ldr     w1, [x29,28]        ; load value from the variable and pass it to printf()
        adrp    x0, .LC0 ; '%d'
        add     x0, x0, :lo12:.LC0
        bl      printf              ; call printf()
        ldp     x29, x30, [sp], 32
        ret
.LC0:
        .string "%d\n"
```

By the way, a similar usage of the *Shadow Space* is also considered here: 3.14.1 on page 520.

6.2 Thread Local Storage

TLS is a data area, specific to each thread. Every thread can store what it needs there. One well-known example is the C standard global variable *errno*.

Multiple threads may simultaneously call functions which return an error code in *errno*, so a global variable will not work correctly here for multi-threaded programs, so *errno* must be stored in the TLS.

In the C++11 standard, a new *thread_local* modifier was added, showing that each thread has its own version of the variable, it can be initialized, and it is located in the TLS [3]:

Listing 6.14: C++11

```
#include <iostream>
#include <thread>

thread_local int tmp=3;

int main()
{
        std::cout << tmp << std::endl;
};
```

Compiled in MinGW GCC 4.8.1, but not in MSVC 2012.

If we talk about PE files, in the resulting executable file, the *tmp* variable is to be allocated in the section devoted to the TLS.

6.2.1 Linear congruential generator revisited

The pseudorandom number generator we considered earlier 1.23 on page 338 has a flaw: it's not thread-safe, because it has an internal state variable which can be read and/or modified in different threads simultaneously.

[3] C11 also has thread support, optional though

Win32

Uninitialized TLS data

One solution is to add `__declspec( thread )` modifier to the global variable, then it will be allocated in the TLS (line 9):

```
1 #include <stdint.h>
2 #include <windows.h>
3 #include <winnt.h>
4 
5 // from the Numerical Recipes book:
6 #define RNG_a 1664525
7 #define RNG_c 1013904223
8 
9 __declspec( thread ) uint32_t rand_state;
10 
11 void my_srand (uint32_t init)
12 {
13         rand_state=init;
14 }
15 
16 int my_rand ()
17 {
18         rand_state=rand_state*RNG_a;
19         rand_state=rand_state+RNG_c;
20         return rand_state & 0x7fff;
21 }
22 
23 int main()
24 {
25         my_srand(0x12345678);
26         printf ("%d\n", my_rand());
27 };
```

Hiew shows us that there is a new PE section in the executable file: `.tls`.

Listing 6.15: Optimizing MSVC 2013 x86

```
_TLS    SEGMENT
_rand_state DD  01H DUP (?)
_TLS    ENDS

_DATA   SEGMENT
$SG84851 DB     '%d', 0aH, 00H
_DATA   ENDS
_TEXT   SEGMENT

_init$ = 8      ; size = 4
_my_srand PROC
; FS:0=address of TIB
        mov     eax, DWORD PTR fs:__tls_array  ; displayed in IDA as FS:2Ch
; EAX=address of TLS of process
        mov     ecx, DWORD PTR __tls_index
        mov     ecx, DWORD PTR [eax+ecx*4]
; ECX=current TLS segment
        mov     eax, DWORD PTR _init$[esp-4]
        mov     DWORD PTR _rand_state[ecx], eax
        ret     0
_my_srand ENDP

_my_rand PROC
; FS:0=address of TIB
        mov     eax, DWORD PTR fs:__tls_array  ; displayed in IDA as FS:2Ch
; EAX=address of TLS of process
        mov     ecx, DWORD PTR __tls_index
        mov     ecx, DWORD PTR [eax+ecx*4]
; ECX=current TLS segment
        imul    eax, DWORD PTR _rand_state[ecx], 1664525
        add     eax, 1013904223         ; 3c6ef35fH
```

```
        mov     DWORD PTR _rand_state[ecx], eax
        and     eax, 32767                ; 00007fffH
        ret     0
_my_rand ENDP

_TEXT   ENDS
```

rand_state is now in the TLS segment, and each thread has its own version of this variable.

Here is how it's accessed: load the address of the TIB from FS:2Ch, then add an additional index (if needed), then calculate the address of the TLS segment.

Then it's possible to access the rand_state variable through the ECX register, which points to an unique area in each thread.

The FS: selector is familiar to every reverse engineer, it is specially used to always point to TIB, so it would be fast to load the thread-specific data.

The GS: selector is used in Win64 and the address of the TLS is 0x58:

Listing 6.16: Optimizing MSVC 2013 x64

```
_TLS    SEGMENT
rand_state DD   01H DUP (?)
_TLS    ENDS

_DATA   SEGMENT
$SG85451 DB     '%d', 0aH, 00H
_DATA   ENDS

_TEXT   SEGMENT

init$ = 8
my_srand PROC
        mov     edx, DWORD PTR _tls_index
        mov     rax, QWORD PTR gs:88 ; 58h
        mov     r8d, OFFSET FLAT:rand_state
        mov     rax, QWORD PTR [rax+rdx*8]
        mov     DWORD PTR [r8+rax], ecx
        ret     0
my_srand ENDP

my_rand PROC
        mov     rax, QWORD PTR gs:88 ; 58h
        mov     ecx, DWORD PTR _tls_index
        mov     edx, OFFSET FLAT:rand_state
        mov     rcx, QWORD PTR [rax+rcx*8]
        imul    eax, DWORD PTR [rcx+rdx], 1664525 ; 0019660dH
        add     eax, 1013904223         ; 3c6ef35fH
        mov     DWORD PTR [rcx+rdx], eax
        and     eax, 32767              ; 00007fffH
        ret     0
my_rand ENDP

_TEXT   ENDS
```

Initialized TLS data

Let's say, we want to set some fixed value to rand_state, so in case the programmer forgets to, the rand_state variable would be initialized to some constant anyway (line 9):

```
1 #include <stdint.h>
2 #include <windows.h>
3 #include <winnt.h>
4
5 // from the Numerical Recipes book:
6 #define RNG_a 1664525
7 #define RNG_c 1013904223
8
```

```
__declspec( thread ) uint32_t rand_state=1234;

void my_srand (uint32_t init)
{
        rand_state=init;
}

int my_rand ()
{
        rand_state=rand_state*RNG_a;
        rand_state=rand_state+RNG_c;
        return rand_state & 0x7fff;
}

int main()
{
        printf ("%d\n", my_rand());
};
```

The code is not different from what we already saw, but in IDA we see:

```
.tls:00404000 ; Segment type: Pure data
.tls:00404000 ; Segment permissions: Read/Write
.tls:00404000 _tls            segment para public 'DATA' use32
.tls:00404000                 assume cs:_tls
.tls:00404000                 ;org 404000h
.tls:00404000 TlsStart        db    0         ; DATA XREF: .rdata:TlsDirectory
.tls:00404001                 db    0
.tls:00404002                 db    0
.tls:00404003                 db    0
.tls:00404004                 dd 1234
.tls:00404008 TlsEnd          db    0         ; DATA XREF: .rdata:TlsEnd_ptr
...
```

1234 is there and every time a new thread starts, a new TLS is allocated for it, and all this data, including 1234, will be copied there.

This is a typical scenario:

- Thread A is started. A TLS is created for it, 1234 is copied to `rand_state`.
- The `my_rand()` function is called several times in thread A. `rand_state` is different from 1234.
- Thread B is started. A TLS is created for it, 1234 is copied to `rand_state`, while thread A has a different value in the same variable.

TLS callbacks

But what if the variables in the TLS have to be filled with some data that must be prepared in some unusual way?

Let's say, we've got the following task: the programmer can forget to call the `my_srand()` function to initialize the PRNG, but the generator has to be initialized at start with something truly random, instead of 1234. This is a case in which TLS callbacks can be used.

The following code is not very portable due to the hack, but nevertheless, you get the idea.

What we do here is define a function (`tls_callback()`) which is to be called *before* the process and/or thread start.

The function initializes the PRNG with the value returned by `GetTickCount()` function.

```
#include <stdint.h>
#include <windows.h>
#include <winnt.h>

// from the Numerical Recipes book:
#define RNG_a 1664525
#define RNG_c 1013904223
```

```
__declspec( thread ) uint32_t rand_state;

void my_srand (uint32_t init)
{
        rand_state=init;
}

void NTAPI tls_callback(PVOID a, DWORD dwReason, PVOID b)
{
        my_srand (GetTickCount());
}

#pragma data_seg(".CRT$XLB")
PIMAGE_TLS_CALLBACK p_thread_callback = tls_callback;
#pragma data_seg()

int my_rand ()
{
        rand_state=rand_state*RNG_a;
        rand_state=rand_state+RNG_c;
        return rand_state & 0x7fff;
}

int main()
{
        // rand_state is already initialized at the moment (using GetTickCount())
        printf ("%d\n", my_rand());
};
```

Let's see it in IDA:

Listing 6.17: Optimizing MSVC 2013

```
.text:00401020 TlsCallback_0   proc near               ; DATA XREF: .rdata:TlsCallbacks
.text:00401020                 call    ds:GetTickCount
.text:00401026                 push    eax
.text:00401027                 call    my_srand
.text:0040102C                 pop     ecx
.text:0040102D                 retn    0Ch
.text:0040102D TlsCallback_0   endp

...

.rdata:004020C0 TlsCallbacks    dd offset TlsCallback_0 ; DATA XREF: .rdata:TlsCallbacks_ptr

...

.rdata:00402118 TlsDirectory    dd offset TlsStart
.rdata:0040211C TlsEnd_ptr      dd offset TlsEnd
.rdata:00402120 TlsIndex_ptr    dd offset TlsIndex
.rdata:00402124 TlsCallbacks_ptr dd offset TlsCallbacks
.rdata:00402128 TlsSizeOfZeroFill dd 0
.rdata:0040212C TlsCharacteristics dd 300000h
```

TLS callback functions are sometimes used in unpacking routines to obscure their processing.

Some people may be confused and be in the dark that some code executed right before the OEP[4].

Linux

Here is how a thread-local global variable is declared in GCC:

```
__thread uint32_t rand_state=1234;
```

This is not the standard C/C++ modifier, but a rather GCC-specific one [5].

[4] Original Entry Point
[5] http://go.yurichev.com/17062

The GS: selector is also used to access the TLS, but in a somewhat different way:

Listing 6.18: Optimizing GCC 4.8.1 x86

```
.text:08048460 my_srand        proc near
.text:08048460
.text:08048460 arg_0           = dword ptr  4
.text:08048460
.text:08048460                 mov     eax, [esp+arg_0]
.text:08048464                 mov     gs:0FFFFFFFCh, eax
.text:0804846A                 retn
.text:0804846A my_srand        endp

.text:08048470 my_rand         proc near
.text:08048470                 imul    eax, gs:0FFFFFFFCh, 19660Dh
.text:0804847B                 add     eax, 3C6EF35Fh
.text:08048480                 mov     gs:0FFFFFFFCh, eax
.text:08048486                 and     eax, 7FFFh
.text:0804848B                 retn
.text:0804848B my_rand         endp
```

More about it: [Ulrich Drepper, *ELF Handling For Thread-Local Storage*, (2013)][6].

6.3 System calls (syscall-s)

As we know, all running processes inside an OS are divided into two categories: those having full access to the hardware ("kernel space") and those that do not ("user space").

The OS kernel and usually the drivers are in the first category.

All applications are usually in the second category.

For example, Linux kernel is in *kernel space*, but Glibc in *user space*.

This separation is crucial for the safety of the OS: it is very important not to give to any process the possibility to screw up something in other processes or even in the OS kernel. On the other hand, a failing driver or error inside the OS's kernel usually leads to a kernel panic or BSOD[7].

The protection in the x86 processors allows to separate everything into 4 levels of protection (rings), but both in Linux and in Windows only two are used: ring0 ("kernel space") and ring3 ("user space").

System calls (syscall-s) are a point where these two areas are connected.

It can be said that this is the main API provided to applications.

As in Windows NT, the syscalls table resides in the SSDT[8].

The usage of syscalls is very popular among shellcode and computer viruses authors, because it is hard to determine the addresses of needed functions in the system libraries, but it is easier to use syscalls. However, much more code has to be written due to the lower level of abstraction of the API.

It is also worth noting that the syscall numbers may be different in various OS versions.

6.3.1 Linux

In Linux, a syscall is usually called via `int 0x80`. The call's number is passed in the EAX register, and any other parameters —in the other registers.

Listing 6.19: A simple example of the usage of two syscalls

```
section .text
global  _start

_start:
        mov     edx,len ; buffer len
        mov     ecx,msg ; buffer
```

[6]Also available as http://go.yurichev.com/17272
[7]Blue Screen of Death
[8]System Service Dispatch Table

```
        mov     ebx,1   ; file descriptor. 1 is for stdout
        mov     eax,4   ; syscall number. 4 is for sys_write
        int     0x80

        mov     eax,1   ; syscall number. 1 is for sys_exit
        int     0x80

section .data

msg     db  'Hello, world!',0xa
len     equ $ - msg
```

Compilation:

```
nasm -f elf32 1.s
ld 1.o
```

The full list of syscalls in Linux: http://go.yurichev.com/17319.

For system calls interception and tracing in Linux, strace(7.2.3 on page 791) can be used.

6.3.2 Windows

Here they are called via `int 0x2e` or using the special x86 instruction SYSENTER.

The full list of syscalls in Windows: http://go.yurichev.com/17320.

Further reading:

"Windows Syscall Shellcode" by Piotr Bania: http://go.yurichev.com/17321.

6.4 Linux

6.4.1 Position-independent code

While analyzing Linux shared (.so) libraries, one may frequently spot this code pattern:

Listing 6.20: libc-2.17.so x86

```
.text:0012D5E3 __x86_get_pc_thunk_bx proc near         ; CODE XREF: sub_17350+3
.text:0012D5E3                                         ; sub_173CC+4 ...
.text:0012D5E3                 mov     ebx, [esp+0]
.text:0012D5E6                 retn
.text:0012D5E6 __x86_get_pc_thunk_bx endp

...

.text:000576C0 sub_576C0       proc near               ; CODE XREF: tmpfile+73

...

.text:000576C0                 push    ebp
.text:000576C1                 mov     ecx, large gs:0
.text:000576C8                 push    edi
.text:000576C9                 push    esi
.text:000576CA                 push    ebx
.text:000576CB                 call    __x86_get_pc_thunk_bx
.text:000576D0                 add     ebx, 157930h
.text:000576D6                 sub     esp, 9Ch

...

.text:000579F0                 lea     eax, (a__gen_tempname - 1AF000h)[ebx] ; "__gen_tempname"
.text:000579F6                 mov     [esp+0ACh+var_A0], eax
.text:000579FA                 lea     eax, (a__SysdepsPosix - 1AF000h)[ebx] ; "../sysdeps/↙
    ↳ posix/tempname.c"
.text:00057A00                 mov     [esp+0ACh+var_A8], eax
```

```
.text:00057A04                 lea     eax, (aInvalidKindIn_ - 1AF000h)[ebx] ; "! \"invalid ↙
    ↘ KIND in __gen_tempname\""
.text:00057A0A                 mov     [esp+0ACh+var_A4], 14Ah
.text:00057A12                 mov     [esp+0ACh+var_AC], eax
.text:00057A15                 call    __assert_fail
```

All pointers to strings are corrected by some constants and the value in EBX, which is calculated at the beginning of each function.

This is the so-called PIC, it is intended to be executable if placed at any random point of memory, that is why it cannot contain any absolute memory addresses.

PIC was crucial in early computer systems and is still crucial today in embedded systems without virtual memory support (where all processes are placed in a single continuous memory block).

It is also still used in *NIX systems for shared libraries, since they are shared across many processes while loaded in memory only once. But all these processes can map the same shared library at different addresses, so that is why a shared library has to work correctly without using any absolute addresses.

Let's do a simple experiment:

```
#include <stdio.h>

int global_variable=123;

int f1(int var)
{
    int rt=global_variable+var;
    printf ("returning %d\n", rt);
    return rt;
};
```

Let's compile it in GCC 4.7.3 and see the resulting .so file in IDA:

```
gcc -fPIC -shared -O3 -o 1.so 1.c
```

Listing 6.21: GCC 4.7.3

```
.text:00000440                 public __x86_get_pc_thunk_bx
.text:00000440 __x86_get_pc_thunk_bx proc near         ; CODE XREF: _init_proc+4
.text:00000440                                         ; deregister_tm_clones+4 ...
.text:00000440                 mov     ebx, [esp+0]
.text:00000443                 retn
.text:00000443 __x86_get_pc_thunk_bx endp

.text:00000570                 public f1
.text:00000570 f1              proc near
.text:00000570
.text:00000570 var_1C          = dword ptr -1Ch
.text:00000570 var_18          = dword ptr -18h
.text:00000570 var_14          = dword ptr -14h
.text:00000570 var_8           = dword ptr -8
.text:00000570 var_4           = dword ptr -4
.text:00000570 arg_0           = dword ptr  4
.text:00000570
.text:00000570                 sub     esp, 1Ch
.text:00000573                 mov     [esp+1Ch+var_8], ebx
.text:00000577                 call    __x86_get_pc_thunk_bx
.text:0000057C                 add     ebx, 1A84h
.text:00000582                 mov     [esp+1Ch+var_4], esi
.text:00000586                 mov     eax, ds:(global_variable_ptr - 2000h)[ebx]
.text:0000058C                 mov     esi, [eax]
.text:0000058E                 lea     eax, (aReturningD - 2000h)[ebx] ; "returning %d\n"
.text:00000594                 add     esi, [esp+1Ch+arg_0]
.text:00000598                 mov     [esp+1Ch+var_18], eax
.text:0000059C                 mov     [esp+1Ch+var_1C], 1
.text:000005A3                 mov     [esp+1Ch+var_14], esi
.text:000005A7                 call    ___printf_chk
.text:000005AC                 mov     eax, esi
.text:000005AE                 mov     ebx, [esp+1Ch+var_8]
.text:000005B2                 mov     esi, [esp+1Ch+var_4]
```

```
.text:000005B6                 add     esp, 1Ch
.text:000005B9                 retn
.text:000005B9 f1              endp
```

That's it: the pointers to *«returning %d\n»* and *global_variable* are to be corrected at each function execution.

The `__x86_get_pc_thunk_bx()` function returns in EBX the address of the point after a call to itself (`0x57C` here).

That's a simple way to get the value of the program counter (EIP) at some point. The `0x1A84` constant is related to the difference between this function's start and the so-called *Global Offset Table Procedure Linkage Table* (GOT PLT), the section right after the *Global Offset Table* (GOT), where the pointer to *global_variable* is. IDA shows these offsets in their processed form to make them easier to understand, but in fact the code is:

```
.text:00000577                 call    __x86_get_pc_thunk_bx
.text:0000057C                 add     ebx, 1A84h
.text:00000582                 mov     [esp+1Ch+var_4], esi
.text:00000586                 mov     eax, [ebx-0Ch]
.text:0000058C                 mov     esi, [eax]
.text:0000058E                 lea     eax, [ebx-1A30h]
```

Here EBX points to the `GOT PLT` section and to calculate a pointer to *global_variable* (which is stored in the `GOT`), `0xC` must be subtracted.

To calculate pointer to the *«returning %d\n»* string, `0x1A30` must be subtracted.

By the way, that is the reason why the AMD64 instruction set supports RIP[9]-relative addressing — to simplify PIC-code.

Let's compile the same C code using the same GCC version, but for x64.

IDA would simplify the resulting code but would suppress the RIP-relative addressing details, so we are going to use *objdump* instead of IDA to see everything:

```
0000000000000720 <f1>:
 720:   48 8b 05 b9 08 20 00    mov    rax,QWORD PTR [rip+0x2008b9]        # 200fe0 <_DYNAMIC+0↙
    ↳ x1d0>
 727:   53                      push   rbx
 728:   89 fb                   mov    ebx,edi
 72a:   48 8d 35 20 00 00 00    lea    rsi,[rip+0x20]        # 751 <_fini+0x9>
 731:   bf 01 00 00 00          mov    edi,0x1
 736:   03 18                   add    ebx,DWORD PTR [rax]
 738:   31 c0                   xor    eax,eax
 73a:   89 da                   mov    edx,ebx
 73c:   e8 df fe ff ff          call   620 <__printf_chk@plt>
 741:   89 d8                   mov    eax,ebx
 743:   5b                      pop    rbx
 744:   c3                      ret
```

`0x2008b9` is the difference between the address of the instruction at `0x720` and *global_variable*, and `0x20` is the difference between the address of the instruction at `0x72A` and the *«returning %d\n»* string.

As you might see, the need to recalculate addresses frequently makes execution slower (it is better in x64, though).

So it is probably better to link statically if you care about performance [see: Agner Fog, *Optimizing software in C++* (2015)].

Windows

The PIC mechanism is not used in Windows DLLs. If the Windows loader needs to load DLL on another base address, it "patches" the DLL in memory (at the *FIXUP* places) in order to correct all addresses.

This implies that several Windows processes cannot share an once loaded DLL at different addresses in different process' memory blocks — since each instance that's loaded in memory is *fixed* to work only at these addresses..

[9]program counter in AMD64

6.4.2 *LD_PRELOAD* hack in Linux

This allows us to load our own dynamic libraries before others, even before system ones, like libc.so.6.

This, in turn, allows us to “substitute” our written functions before the original ones in the system libraries. For example, it is easy to intercept all calls to time(), read(), write(), etc.

Let’s see if we can fool the *uptime* utility. As we know, it tells how long the computer has been working. With the help of strace(7.2.3 on page 791), it is possible to see that the utility takes this information the `/proc/uptime` file:

```
$ strace uptime
...
open("/proc/uptime", O_RDONLY)          = 3
lseek(3, 0, SEEK_SET)                   = 0
read(3, "416166.86 414629.38\n", 2047)  = 20
...
```

It is not a real file on disk, it is a virtual one and its contents are generated on fly in the Linux kernel. There are just two numbers:

```
$ cat /proc/uptime
416690.91 415152.03
```

What we can learn from Wikipedia [10]:

> The first number is the total number of seconds the system has been up. The second number is how much of that time the machine has spent idle, in seconds.

Let’s try to write our own dynamic library with the open(), read(), close() functions working as we need.

At first, our open() will compare the name of the file to be opened with what we need and if it is so, it will write down the descriptor of the file opened.

Second, read(), if called for this file descriptor, will substitute the output, and in the rest of the cases will call the original read() from libc.so.6. And also close(), will note if the file we are currently following is to be closed.

We are going to use the dlopen() and dlsym() functions to determine the original function addresses in libc.so.6.

We need them because we must pass control to the “real” functions.

On the other hand, if we intercepted strcmp() and monitored each string comparisons in the program, then we would have to implement our version of strcmp(), and not use the original function [11], that would be easier.

```
#include <stdio.h>
#include <stdarg.h>
#include <stdlib.h>
#include <stdbool.h>
#include <unistd.h>
#include <dlfcn.h>
#include <string.h>

void *libc_handle = NULL;
int (*open_ptr)(const char *, int) = NULL;
int (*close_ptr)(int) = NULL;
ssize_t (*read_ptr)(int, void*, size_t) = NULL;

bool inited = false;

_Noreturn void die (const char * fmt, ...)
{
        va_list va;
        va_start (va, fmt);
```

[10] wikipedia
[11] For example, here is how simple strcmp() interception works in this article [12] written by Yong Huang

```
        vprintf (fmt, va);
        exit(0);
};

static void find_original_functions ()
{
        if (inited)
                return;

        libc_handle = dlopen ("libc.so.6", RTLD_LAZY);
        if (libc_handle==NULL)
                die ("can't open libc.so.6\n");

        open_ptr = dlsym (libc_handle, "open");
        if (open_ptr==NULL)
                die ("can't find open()\n");

        close_ptr = dlsym (libc_handle, "close");
        if (close_ptr==NULL)
                die ("can't find close()\n");

        read_ptr = dlsym (libc_handle, "read");
        if (read_ptr==NULL)
                die ("can't find read()\n");

        inited = true;
}

static int opened_fd=0;

int open(const char *pathname, int flags)
{
        find_original_functions();

        int fd=(*open_ptr)(pathname, flags);
        if (strcmp(pathname, "/proc/uptime")==0)
                opened_fd=fd; // that's our file! record its file descriptor
        else
                opened_fd=0;
        return fd;
};

int close(int fd)
{
        find_original_functions();

        if (fd==opened_fd)
                opened_fd=0; // the file is not opened anymore
        return (*close_ptr)(fd);
};

ssize_t read(int fd, void *buf, size_t count)
{
        find_original_functions();

        if (opened_fd!=0 && fd==opened_fd)
        {
                // that's our file!
                return snprintf (buf, count, "%d %d", 0x7fffffff, 0x7fffffff)+1;
        };
        // not our file, go to real read() function
        return (*read_ptr)(fd, buf, count);
};
```

(Source code at GitHub)

Let's compile it as common dynamic library:

```
gcc -fpic -shared -Wall -o fool_uptime.so fool_uptime.c -ldl
```

Let's run *uptime* while loading our library before the others:

```
LD_PRELOAD=`pwd`/fool_uptime.so uptime
```

And we see:

```
 01:23:02 up 24855 days,  3:14,  3 users,  load average: 0.00, 0.01, 0.05
```

If the *LD_PRELOAD*

environment variable always points to the filename and path of our library, it is to be loaded for all starting programs.

More examples:

- Very simple interception of the strcmp() (Yong Huang) http://go.yurichev.com/17143
- Kevin Pulo—Fun with LD_PRELOAD. A lot of examples and ideas. yurichev.com
- File functions interception for compression/decompression files on fly (zlibc). http://go.yurichev.com/17146

6.5 Windows NT

6.5.1 CRT (win32)

Does the program execution start right at the `main()` function? No, it does not.

If we would open any executable file in IDA or HIEW, we can see OEP pointing to some another code block.

This code is doing some maintenance and preparations before passing control flow to our code. It is called startup-code or CRT code (C RunTime).

The `main()` function takes an array of the arguments passed on the command line, and also one with environment variables. But in fact a generic string is passed to the program, the CRT code finds the spaces in it and cuts it in parts. The CRT code also prepares the environment variables array envp.

As for GUI[13] win32 applications, `WinMain` is used instead of `main()`, having its own arguments:

```
int CALLBACK WinMain(
  _In_  HINSTANCE hInstance,
  _In_  HINSTANCE hPrevInstance,
  _In_  LPSTR lpCmdLine,
  _In_  int nCmdShow
);
```

The CRT code prepares them as well.

Also, the number returned by the `main()` function is the exit code.

It may be passed in CRT to the `ExitProcess()` function, which takes the exit code as an argument.

Usually, each compiler has its own CRT code.

Here is a typical CRT code for MSVC 2008.

```
___tmainCRTStartup proc near

var_24 = dword ptr -24h
var_20 = dword ptr -20h
var_1C = dword ptr -1Ch
ms_exc = CPPEH_RECORD ptr -18h

       push    14h
       push    offset stru_4092D0
       call    __SEH_prolog4
       mov     eax, 5A4Dh
```

[13] Graphical User Interface

```
        cmp     ds:400000h, ax
        jnz     short loc_401096
        mov     eax, ds:40003Ch
        cmp     dword ptr [eax+400000h], 4550h
        jnz     short loc_401096
        mov     ecx, 10Bh
        cmp     [eax+400018h], cx
        jnz     short loc_401096
        cmp     dword ptr [eax+400074h], 0Eh
        jbe     short loc_401096
        xor     ecx, ecx
        cmp     [eax+4000E8h], ecx
        setnz   cl
        mov     [ebp+var_1C], ecx
        jmp     short loc_40109A


loc_401096: ; CODE XREF: ___tmainCRTStartup+18
            ; ___tmainCRTStartup+29 ...
        and     [ebp+var_1C], 0

loc_40109A: ; CODE XREF: ___tmainCRTStartup+50
        push    1
        call    __heap_init
        pop     ecx
        test    eax, eax
        jnz     short loc_4010AE
        push    1Ch
        call    _fast_error_exit
        pop     ecx

loc_4010AE: ; CODE XREF: ___tmainCRTStartup+60
        call    __mtinit
        test    eax, eax
        jnz     short loc_4010BF
        push    10h
        call    _fast_error_exit
        pop     ecx

loc_4010BF: ; CODE XREF: ___tmainCRTStartup+71
        call    sub_401F2B
        and     [ebp+ms_exc.disabled], 0
        call    __ioinit
        test    eax, eax
        jge     short loc_4010D9
        push    1Bh
        call    __amsg_exit
        pop     ecx

loc_4010D9: ; CODE XREF: ___tmainCRTStartup+8B
        call    ds:GetCommandLineA
        mov     dword_40B7F8, eax
        call    ___crtGetEnvironmentStringsA
        mov     dword_40AC60, eax
        call    __setargv
        test    eax, eax
        jge     short loc_4010FF
        push    8
        call    __amsg_exit
        pop     ecx

loc_4010FF: ; CODE XREF: ___tmainCRTStartup+B1
        call    __setenvp
        test    eax, eax
        jge     short loc_401110
        push    9
        call    __amsg_exit
        pop     ecx

loc_401110: ; CODE XREF: ___tmainCRTStartup+C2
```

```
82         push    1
83         call    __cinit
84         pop     ecx
85         test    eax, eax
86         jz      short loc_401123
87         push    eax
88         call    __amsg_exit
89         pop     ecx
90
91 loc_401123: ; CODE XREF: ___tmainCRTStartup+D6
92         mov     eax, envp
93         mov     dword_40AC80, eax
94         push    eax             ; envp
95         push    argv            ; argv
96         push    argc            ; argc
97         call    _main
98         add     esp, 0Ch
99         mov     [ebp+var_20], eax
100        cmp     [ebp+var_1C], 0
101        jnz     short $LN28
102        push    eax             ; uExitCode
103        call    $LN32
104
105 $LN28:      ; CODE XREF: ___tmainCRTStartup+105
106        call    __cexit
107        jmp     short loc_401186
108
109
110 $LN27:      ; DATA XREF: .rdata:stru_4092D0
111        mov     eax, [ebp+ms_exc.exc_ptr] ; Exception filter 0 for function 401044
112        mov     ecx, [eax]
113        mov     ecx, [ecx]
114        mov     [ebp+var_24], ecx
115        push    eax
116        push    ecx
117        call    __XcptFilter
118        pop     ecx
119        pop     ecx
120
121 $LN24:
122        retn
123
124
125 $LN14:      ; DATA XREF: .rdata:stru_4092D0
126        mov     esp, [ebp+ms_exc.old_esp] ; Exception handler 0 for function 401044
127        mov     eax, [ebp+var_24]
128        mov     [ebp+var_20], eax
129        cmp     [ebp+var_1C], 0
130        jnz     short $LN29
131        push    eax             ; int
132        call    __exit
133
134
135 $LN29:      ; CODE XREF: ___tmainCRTStartup+135
136        call    __c_exit
137
138 loc_401186: ; CODE XREF: ___tmainCRTStartup+112
139        mov     [ebp+ms_exc.disabled], 0FFFFFFFEh
140        mov     eax, [ebp+var_20]
141        call    __SEH_epilog4
142        retn
```

Here we can see calls to `GetCommandLineA()` (line 62), then to `setargv()` (line 66) and `setenvp()` (line 74), which apparently fill the global variables `argc`, `argv`, `envp`.

Finally, `main()` is called with these arguments (line 97).

There are also calls to functions with self-describing names like `heap_init()` (line 35), `ioinit()` (line 54).

The heap is indeed initialized in the CRT. If you try to use `malloc()` in a program without CRT, it will exit abnormally with the following error:

```
runtime error R6030
- CRT not initialized
```

Global object initializations in C++ is also occur in the CRT before the execution of main(): 3.18.4 on page 564.

The value that main() returns is passed to cexit(), or in $LN32, which in turn calls doexit().

Is it possible to get rid of the CRT? Yes, if you know what you are doing.

The MSVC's linker has the /ENTRY option for setting an entry point.

```
#include <windows.h>

int main()
{
        MessageBox (NULL, "hello, world", "caption", MB_OK);
};
```

Let's compile it in MSVC 2008.

```
cl no_crt.c user32.lib /link /entry:main
```

We are getting a runnable .exe with size 2560 bytes, that has a PE header in it, instructions calling MessageBox, two strings in the data segment, the MessageBox function imported from user32.dll and nothing else.

This works, but you cannot write WinMain with its 4 arguments instead of main().

To be precise, you can, but the arguments are not prepared at the moment of execution.

By the way, it is possible to make the .exe even shorter by aligning the PE sections at less than the default 4096 bytes.

```
cl no_crt.c user32.lib /link /entry:main /align:16
```

Linker says:

```
LINK : warning LNK4108: /ALIGN specified without /DRIVER; image may not run
```

We get an .exe that's 720 bytes. It can be executed in Windows 7 x86, but not in x64 (an error message will be shown when you try to execute it).

With even more efforts, it is possible to make the executable even shorter, but as you can see, compatibility problems arise quickly.

6.5.2 Win32 PE

PE is an executable file format used in Windows. The difference between .exe, .dll and .sys is that .exe and .sys usually do not have exports, only imports.

A DLL[14], just like any other PE-file, has an entry point (OEP) (the function DllMain() is located there) but this function usually does nothing. .sys is usually a device driver. As of drivers, Windows requires the checksum to be present in the PE file and for it to be correct [15].

Starting at Windows Vista, a driver's files must also be signed with a digital signature. It will fail to load otherwise.

Every PE file begins with tiny DOS program that prints a message like "This program cannot be run in DOS mode."—if you run this program in DOS or Windows 3.1 (OS-es which are not aware of the PE format), this message will be printed.

[14] Dynamic-Link Library
[15] For example, Hiew(7.1 on page 789) can calculate it

Terminology

- Module—a separate file, .exe or .dll.
- Process—a program loaded into memory and currently running. Commonly consists of one .exe file and bunch of .dll files.
- Process memory—the memory a process works with. Each process has its own. There usually are loaded modules, memory of the stack, heap(s), etc.
- VA[16]—an address which is to be used in program while runtime.
- Base address (of module)—the address within the process memory at which the module is to be loaded. OS loader may change it, if the base address is already occupied by another module just loaded before.
- RVA[17]—the VA-address minus the base address.

  Many addresses in PE-file tables use RVA-addresses.
- IAT[18]—an array of addresses of imported symbols [19]. Sometimes, the `IMAGE_DIRECTORY_ENTRY_IAT` data directory points at the IAT. It is worth noting that IDA (as of 6.1) may allocate a pseudo-section named `.idata` for IAT, even if the IAT is a part of another section!
- INT[20]—an array of names of symbols to be imported[21].

Base address

The problem is that several module authors can prepare DLL files for others to use and it is not possible to reach an agreement which addresses is to be assigned to whose modules.

So that is why if two necessary DLLs for a process have the same base address, one of them will be loaded at this base address, and the other—at some other free space in process memory, and each virtual addresses in the second DLL will be corrected.

With MSVC the linker often generates the .exe files with a base address of `0x400000` [22], and with the code section starting at `0x401000`. This means that the RVA of the start of the code section is `0x1000`.

DLLs are often generated by MSVC's linker with a base address of `0x10000000` [23].

There is also another reason to load modules at various base addresses, in this case random ones. It is ASLR[24].

A shellcode trying to get executed on a compromised system must call system functions, hence, know their addresses.

In older OS (in Windows NT line: before Windows Vista), system DLL (like kernel32.dll, user32.dll) were always loaded at known addresses, and if we also recall that their versions rarely changed, the addresses of functions were fixed and shellcode could call them directly.

In order to avoid this, the ASLR method loads your program and all modules it needs at random base addresses, different every time.

ASLR support is denoted in a PE file by setting the flag

`IMAGE_DLL_CHARACTERISTICS_DYNAMIC_BASE` [see Mark Russinovich, *Microsoft Windows Internals*].

Subsystem

There is also a *subsystem* field, usually it is:

- native[25] (.sys-driver),

[16] Virtual Address
[17] Relative Virtual Address
[18] Import Address Table
[19] Matt Pietrek, *An In-Depth Look into the Win32 Portable Executable File Format*, (2002)]
[20] Import Name Table
[21] Matt Pietrek, *An In-Depth Look into the Win32 Portable Executable File Format*, (2002)]
[22] The origin of this address choice is described here: MSDN
[23] This can be changed by the /BASE linker option
[24] wikipedia
[25] Meaning, the module use Native API instead of Win32

- console (console application) or
- GUI (non-console).

OS version

A PE file also specifies the minimal Windows version it needs in order to be loadable.

The table of version numbers stored in the PE file and corresponding Windows codenames is here[26].

For example, MSVC 2005 compiles .exe files for running on Windows NT4 (version 4.00), but MSVC 2008 does not (the generated files have a version of 5.00, at least Windows 2000 is needed to run them).

MSVC 2012 generates .exe files of version 6.00 by default, targeting at least Windows Vista. However, by changing the compiler's options[27], it is possible to force it to compile for Windows XP.

Sections

Division in sections, as it seems, is present in all executable file formats.

It is devised in order to separate code from data, and data—from constant data.

- Either the *IMAGE_SCN_CNT_CODE* or *IMAGE_SCN_MEM_EXECUTE* flags will be set on the code section—this is executable code.
- On data section—*IMAGE_SCN_CNT_INITIALIZED_DATA*, *IMAGE_SCN_MEM_READ* and *IMAGE_SCN_MEM_WRITE* flags.
- On an empty section with uninitialized data—*IMAGE_SCN_CNT_UNINITIALIZED_DATA*, *IMAGE_SCN_MEM_READ* and *IMAGE_SCN_MEM_WRITE*.
- On a constant data section (one that's protected from writing), the flags *IMAGE_SCN_CNT_INITIALIZED_DATA* and *IMAGE_SCN_MEM_READ* can be set, but not *IMAGE_SCN_MEM_WRITE*. A process going to crash if it tries to write to this section.

Each section in PE-file may have a name, however, it is not very important. Often (but not always) the code section is named `.text`, the data section—`.data`, the constant data section — `.rdata` *(readable data)*. Other popular section names are:

- `.idata`—imports section. IDA may create a pseudo-section named like this: 6.5.2 on the previous page.
- `.edata`—exports section (rare)
- `.pdata`—section holding all information about exceptions in Windows NT for MIPS, IA64 and x64: 6.5.3 on page 783
- `.reloc`—relocs section
- `.bss`—uninitialized data (BSS)
- `.tls`—thread local storage (TLS)
- `.rsrc`—resources
- `.CRT`—may present in binary files compiled by ancient MSVC versions

PE file packers/encryptors often garble section names or replace the names with their own.

MSVC allows you to declare data in arbitrarily named section [28].

Some compilers and linkers can add a section with debugging symbols and other debugging information (MinGW for instance). However it is not so in latest versions of MSVC (separate PDB files are used there for this purpose).

That is how a PE section is described in the file:

[26] wikipedia
[27] MSDN
[28] MSDN

```
typedef struct _IMAGE_SECTION_HEADER {
  BYTE  Name[IMAGE_SIZEOF_SHORT_NAME];
  union {
    DWORD PhysicalAddress;
    DWORD VirtualSize;
  } Misc;
  DWORD VirtualAddress;
  DWORD SizeOfRawData;
  DWORD PointerToRawData;
  DWORD PointerToRelocations;
  DWORD PointerToLinenumbers;
  WORD  NumberOfRelocations;
  WORD  NumberOfLinenumbers;
  DWORD Characteristics;
} IMAGE_SECTION_HEADER, *PIMAGE_SECTION_HEADER;
```

[29]

A word about terminology: *PointerToRawData* is called “Offset” in Hiew and *VirtualAddress* is called “RVA” there.

Data section

Data section in file can be smaller than in memory. For example, some variables can be initialized, some are not. Compiler and linker will collect them all into one section, but the first part of it is initialized and allocated in file, while another is absent in file (of course, to make it smaller). *VirtualSize* will be equal to the size of section in memory, and *SizeOfRawData* — to size of section in file.

IDA can show the border between initialized and not initialized parts like that:

```
...

.data:10017FFA                 db    0
.data:10017FFB                 db    0
.data:10017FFC                 db    0
.data:10017FFD                 db    0
.data:10017FFE                 db    0
.data:10017FFF                 db    0
.data:10018000                 db    ? ;
.data:10018001                 db    ? ;
.data:10018002                 db    ? ;
.data:10018003                 db    ? ;
.data:10018004                 db    ? ;
.data:10018005                 db    ? ;

...
```

Relocations (relocs)

AKA FIXUP-s (at least in Hiew).

They are also present in almost all executable file formats [30]. Exceptions are shared dynamic libraries compiled with PIC, or any other PIC-code.

What are they for?

Obviously, modules can be loaded on various base addresses, but how to deal with global variables, for example? They must be accessed by address. One solution is position-independent code (6.4.1 on page 748). But it is not always convenient.

That is why a relocations table is present. There the addresses of points that must be corrected are enumerated, in case of loading at a different base address.

For example, there is a global variable at address `0x410000` and this is how it is accessed:

[29] MSDN
[30] Even in .exe files for MS-DOS

```
A1 00 00 41 00         mov         eax,[000410000]
```

The base address of the module is `0x400000`, the RVA of the global variable is `0x10000`.

If the module is loaded at base address `0x500000`, the real address of the global variable must be `0x510000`.

As we can see, the address of variable is encoded in the instruction `MOV`, after the byte `0xA1`.

That is why the address of the 4 bytes after `0xA1`, is written in the relocs table.

If the module is loaded at a different base address, the OS loader enumerates all addresses in the table,

finds each 32-bit word the address points to, subtracts the original base address from it (we get the RVA here), and adds the new base address to it.

If a module is loaded at its original base address, nothing happens.

All global variables can be treated like that.

Relocs may have various types, however, in Windows for x86 processors, the type is usually *IMAGE_REL_BASED_HIGHLOW*.

By the way, relocs are darkened in Hiew, for example: fig.1.21.

OllyDbg underlines the places in memory to which relocs are to be applied, for example: fig.1.52.

Exports and imports

As we all know, any executable program must use the OS's services and other DLL-libraries somehow.

It can be said that functions from one module (usually DLL) must be connected somehow to the points of their calls in other modules (.exe-file or another DLL).

For this, each DLL has an "exports" table, which consists of functions plus their addresses in a module.

And every .exe file or DLL has "imports", a table of functions it needs for execution including list of DLL filenames.

After loading the main .exe-file, the OS loader processes imports table: it loads the additional DLL-files, finds function names among the DLL exports and writes their addresses down in the IAT of the main .exe-module.

As we can see, during loading the loader must compare a lot of function names, but string comparison is not a very fast procedure, so there is a support for "ordinals" or "hints", which are function numbers stored in the table, instead of their names.

That is how they can be located faster when loading a DLL. Ordinals are always present in the "export" table.

For example, a program using the MFC[31] library usually loads mfc*.dll by ordinals, and in such programs there are no MFC function names in INT.

When loading such programs in IDA, it will ask for a path to the mfc*.dll files in order to determine the function names.

If you don't tell IDA the path to these DLLs, there will be *mfc80_123* instead of function names.

Imports section

Often a separate section is allocated for the imports table and everything related to it (with name like `.idata`), however, this is not a strict rule.

Imports are also a confusing subject because of the terminological mess. Let's try to collect all information in one place.

[31] Microsoft Foundation Classes

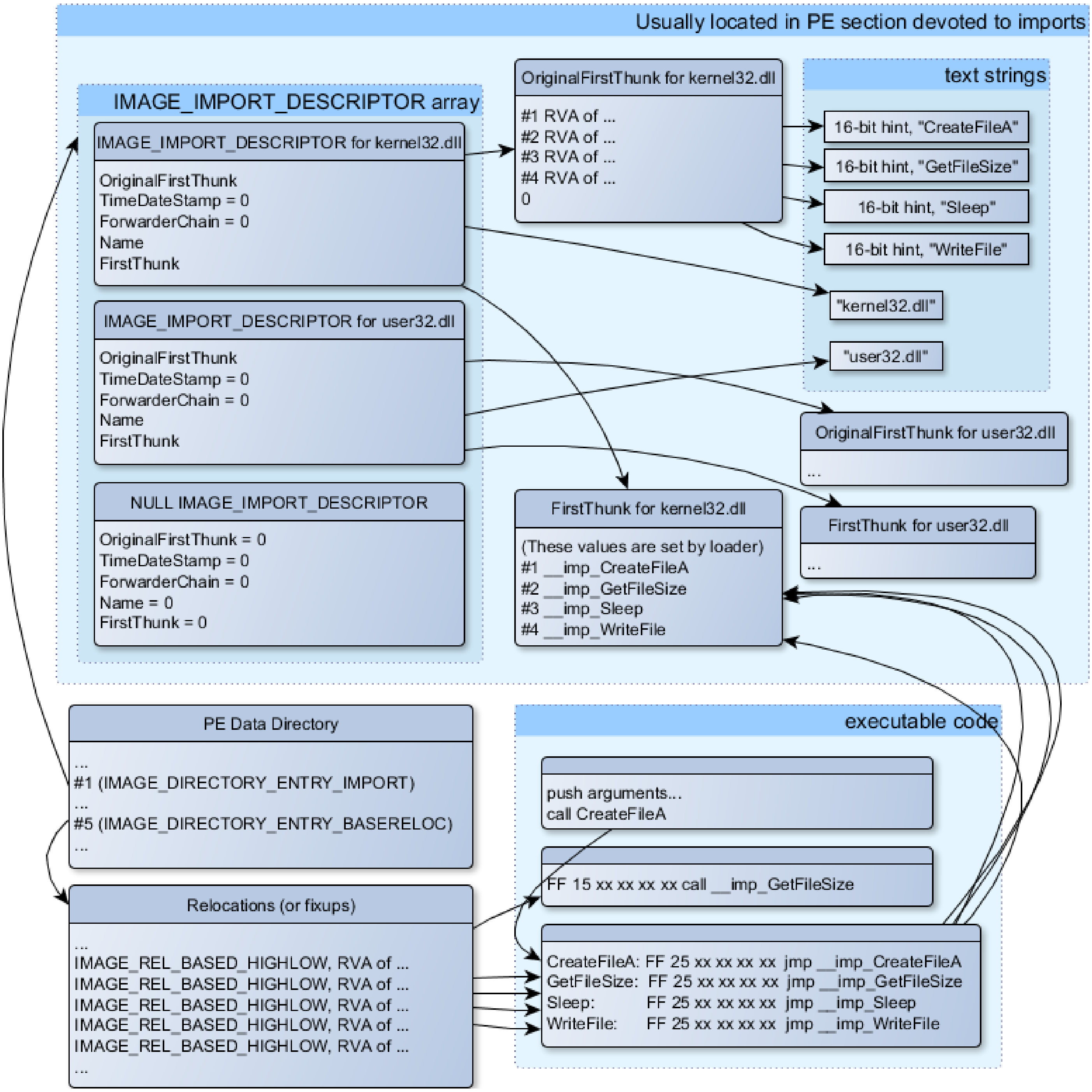


Figure 6.1: A scheme that unites all PE-file structures related to imports

The main structure is the array *IMAGE_IMPORT_DESCRIPTOR*. Each element for each DLL being imported.

Each element holds the RVA address of the text string (DLL name) (*Name*).

OriginalFirstThunk is the RVA address of the INT table. This is an array of RVA addresses, each of which points to a text string with a function name. Each string is prefixed by a 16-bit integer (“hint”)—“ordinal” of function.

While loading, if it is possible to find a function by ordinal, then the strings comparison will not occur. The array is terminated by zero.

There is also a pointer to the IAT table named *FirstThunk*, it is just the RVA address of the place where the loader writes the addresses of the resolved functions.

The points where the loader writes addresses are marked by IDA like this: *__imp_CreateFileA*, etc.

There are at least two ways to use the addresses written by the loader.

- The code will have instructions like *call __imp_CreateFileA*, and since the field with the address of the imported function is a global variable in some sense, the address of the *call* instruction (plus 1 or 2) is to be added to the relocs table, for the case when the module is loaded at a different base address.

But, obviously, this may enlarge relocs table significantly.

Because there are might be a lot of calls to imported functions in the module.

Furthermore, large relocs table slows down the process of loading modules.

- For each imported function, there is only one jump allocated, using the JMP instruction plus a reloc to it. Such points are also called "thunks".

  All calls to the imported functions are just CALL instructions to the corresponding "thunk". In this case, additional relocs are not necessary because these CALL-s have relative addresses and do not need to be corrected.

These two methods can be combined.

Possible, the linker creates individual "thunk"s if there are too many calls to the function, but not done by default.

By the way, the array of function addresses to which FirstThunk is pointing is not necessary to be located in the IAT section. For example, the author of these lines once wrote the PE_add_import[32] utility for adding imports to an existing .exe-file.

Some time earlier, in the previous versions of the utility, at the place of the function you want to substitute with a call to another DLL, my utility wrote the following code:

```
MOV EAX, [yourdll.dll!function]
JMP EAX
```

FirstThunk points to the first instruction. In other words, when loading yourdll.dll, the loader writes the address of the *function* function right in the code.

It also worth noting that a code section is usually write-protected, so my utility adds the *IMAGE_SCN_MEM_WRITE* flag for code section. Otherwise, the program to crash while loading with error code 5 (access denied).

One might ask: what if I supply a program with a set of DLL files which is not supposed to change (including addresses of all DLL functions), is it possible to speed up the loading process?

Yes, it is possible to write the addresses of the functions to be imported into the FirstThunk arrays in advance. The *Timestamp* field is present in the *IMAGE_IMPORT_DESCRIPTOR* structure.

If a value is present there, then the loader compares this value with the date-time of the DLL file.

If the values are equal, then the loader does not do anything, and the loading of the process can be faster. This is called "old-style binding" [33].

The BIND.EXE utility in Windows SDK is for this. For speeding up the loading of your program, Matt Pietrek in Matt Pietrek, *An In-Depth Look into the Win32 Portable Executable File Format*, (2002)][34], suggests to do the binding shortly after your program installation on the computer of the end user.

PE-files packers/encryptors may also compress/encrypt imports table.

In this case, the Windows loader, of course, will not load all necessary DLLs.

Therefore, the packer/encryptor does this on its own, with the help of *LoadLibrary()* and the *GetProcAddress()* functions.

That is why these two functions are often present in IAT in packed files.

In the standard DLLs from the Windows installation, IAT often is located right at the beginning of the PE file. Supposedly, it is made so for optimization.

While loading, the .exe file is not loaded into memory as a whole (recall huge install programs which are started suspiciously fast), it is "mapped", and loaded into memory in parts as they are accessed.

Probably, Microsoft developers decided it will be faster.

[32] yurichev.com
[33] MSDN. There is also the "new-style binding".
[34] Also available as `http://go.yurichev.com/17318`

Resources

Resources in a PE file are just a set of icons, pictures, text strings, dialog descriptions.

Perhaps they were separated from the main code, so all these things could be multilingual, and it would be simpler to pick text or picture for the language that is currently set in the OS.

As a side effect, they can be edited easily and saved back to the executable file, even if one does not have special knowledge, by using the ResHack editor, for example (6.5.2).

.NET

.NET programs are not compiled into machine code but into a special bytecode. Strictly speaking, there is bytecode instead of the usual x86 code in the .exe file, however, the entry point (OEP) points to this tiny fragment of x86 code:

```
jmp         mscoree.dll!_CorExeMain
```

The .NET loader is located in mscoree.dll, which processes the PE file.

It was so in all pre-Windows XP OSes. Starting from XP, the OS loader is able to detect the .NET file and run it without executing that JMP instruction [35].

TLS

This section holds initialized data for the TLS(6.2 on page 742) (if needed). When a new thread start, its TLS data is initialized using the data from this section.

Aside from that, the PE file specification also provides initialization of the TLS section, the so-called TLS callbacks.

If they are present, they are to be called before the control is passed to the main entry point (OEP).

This is used widely in the PE file packers/encryptors.

Tools

- objdump (present in cygwin) for dumping all PE-file structures.
- Hiew(7.1 on page 789) as editor.
- pefile—Python-library for PE-file processing [36].
- ResHack AKA Resource Hacker—resources editor[37].
- PE_add_import[38]— simple tool for adding symbol(s) to PE executable import table.
- PE_patcher[39]—simple tool for patching PE executables.
- PE_search_str_refs[40]—simple tool for searching for a function in PE executables which use some text string.

Further reading

- Daniel Pistelli—The .NET File Format [41]

[35] MSDN
[36] http://go.yurichev.com/17052
[37] http://go.yurichev.com/17052
[38] http://go.yurichev.com/17049
[39] yurichev.com
[40] yurichev.com
[41] http://go.yurichev.com/17056

6.5.3 Windows SEH

Let's forget about MSVC

In Windows, the SEH is intended for exceptions handling, nevertheless, it is language-agnostic, not related to C++ or OOP in any way.

Here we are going to take a look at SEH in its isolated (from C++ and MSVC extensions) form.

Each running process has a chain of SEH handlers, each TIB has the address of the most recently defined handler.

When an exception occurs (division by zero, incorrect address access, user exception triggered by calling the `RaiseException()` function), the OS finds the last handler in the TIB and calls it, passing exception kind and all information about the CPU state (register values, etc.) at the moment of the exception.

The exception handler considering the exception, does it see something familiar? If so, it handles the exception.

If not, it signals to the OS that it cannot handle it and the OS calls the next handler in the chain, until a handler which is able to handle the exception is be found.

At the very end of the chain there a standard handler that shows the well-known dialog box, informing the user about a process crash, some technical information about the CPU state at the time of the crash, and offering to collect all information and send it to developers in Microsoft.

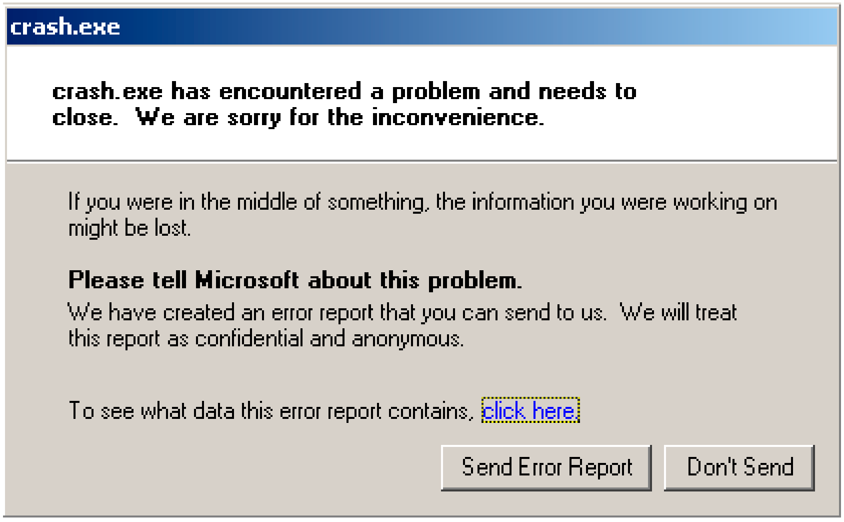


Figure 6.2: Windows XP

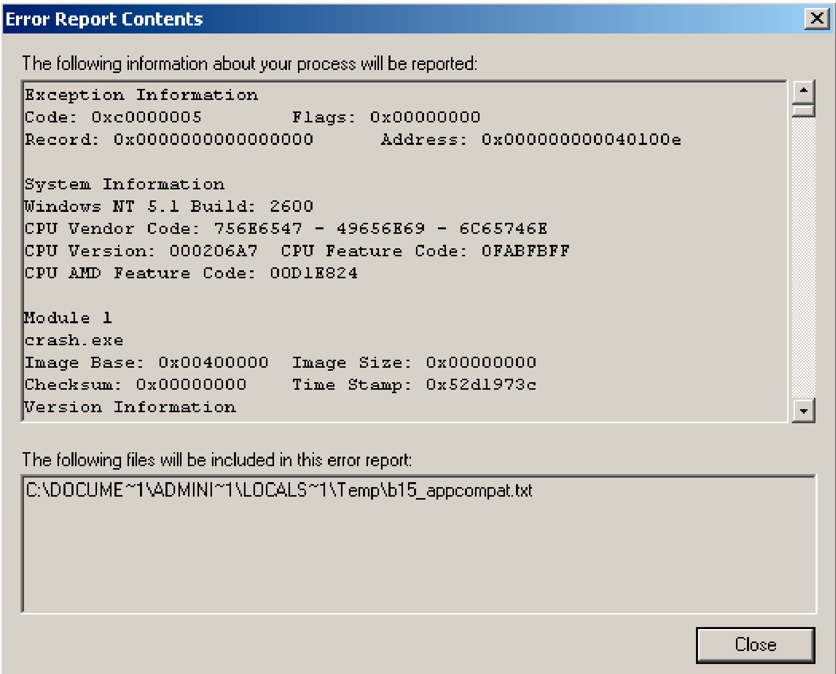


Figure 6.3: Windows XP

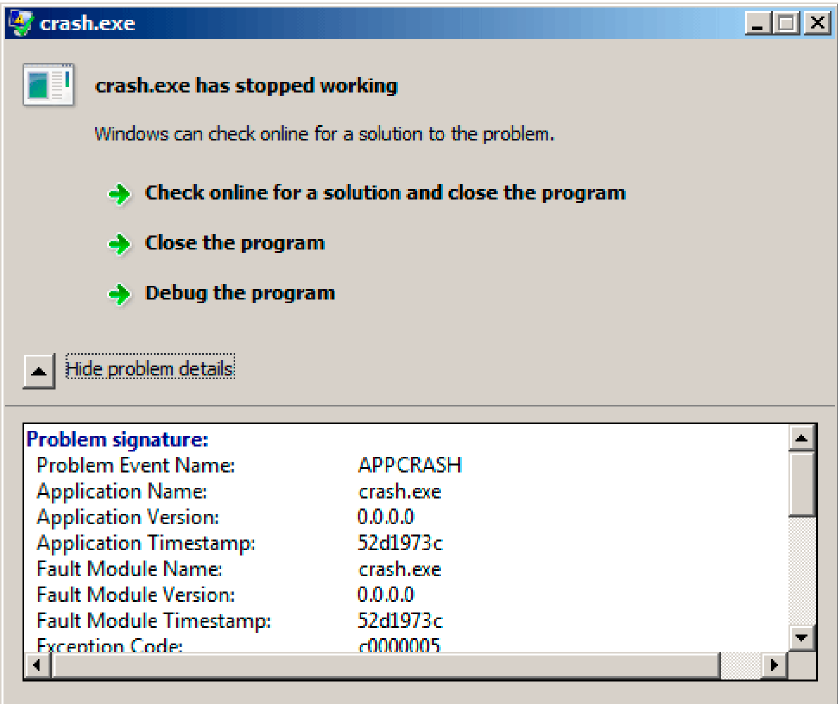


Figure 6.4: Windows 7

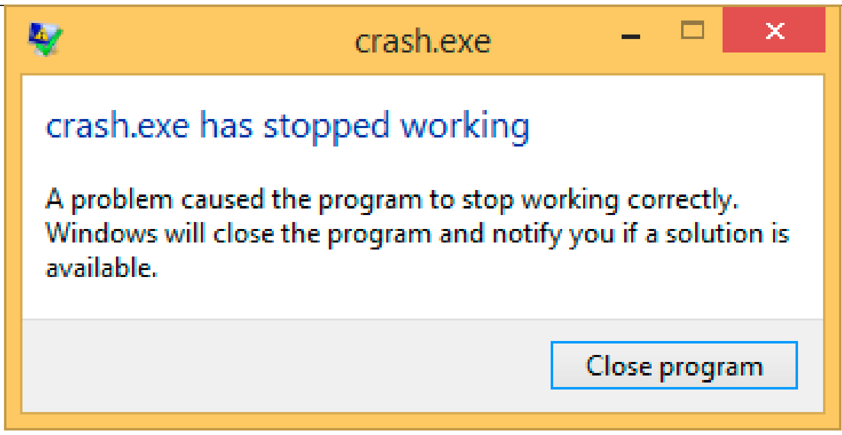


Figure 6.5: Windows 8.1

Earlier, this handler was called Dr. Watson [42].

By the way, some developers make their own handler that sends information about the program crash to themselves. It is registered with the help of `SetUnhandledExceptionFilter()` and to be called if the OS does not have any other way to handle the exception. An example is Oracle RDBMS—it saves huge dumps reporting all possible information about the CPU and memory state.

Let's write our own primitive exception handler. This example is based on the example from [Matt Pietrek, *A Crash Course on the Depths of Win32™ Structured Exception Handling*, (1997)][43]. It must be compiled with the SAFESEH option: `cl seh1.cpp /link /safeseh:no`. More about SAFESEH here: MSDN.

```
#include <windows.h>
#include <stdio.h>

DWORD new_value=1234;

EXCEPTION_DISPOSITION __cdecl except_handler(
                struct _EXCEPTION_RECORD *ExceptionRecord,
                void * EstablisherFrame,
                struct _CONTEXT *ContextRecord,
                void * DispatcherContext )
{
        unsigned i;

        printf ("%s\n", __FUNCTION__);
        printf ("ExceptionRecord->ExceptionCode=0x%p\n", ExceptionRecord->ExceptionCode);
        printf ("ExceptionRecord->ExceptionFlags=0x%p\n", ExceptionRecord->ExceptionFlags);
        printf ("ExceptionRecord->ExceptionAddress=0x%p\n", ExceptionRecord->ExceptionAddress);

        if (ExceptionRecord->ExceptionCode==0xE1223344)
        {
                printf ("That's for us\n");
                // yes, we "handled" the exception
                return ExceptionContinueExecution;
        }
        else if (ExceptionRecord->ExceptionCode==EXCEPTION_ACCESS_VIOLATION)
        {
                printf ("ContextRecord->Eax=0x%08X\n", ContextRecord->Eax);
                // will it be possible to 'fix' it?
                printf ("Trying to fix wrong pointer address\n");
                ContextRecord->Eax=(DWORD)&new_value;
                // yes, we "handled" the exception
                return ExceptionContinueExecution;
        }
        else
        {
                printf ("We do not handle this\n");
                // someone else's problem
                return ExceptionContinueSearch;
        };
```

[42] wikipedia
[43] Also available as http://go.yurichev.com/17293

```
}

int main()
{
        DWORD handler = (DWORD)except_handler; // take a pointer to our handler

        // install exception handler
        __asm
        {                               // make EXCEPTION_REGISTRATION record:
                push    handler         // address of handler function
                push    FS:[0]          // address of previous handler
                mov     FS:[0],ESP      // add new EXECEPTION_REGISTRATION
        }

        RaiseException (0xE1223344, 0, 0, NULL);

        // now do something very bad
        int* ptr=NULL;
        int val=0;
        val=*ptr;
        printf ("val=%d\n", val);

        // deinstall exception handler
        __asm
        {                               // remove our EXECEPTION_REGISTRATION record
                mov     eax,[ESP]       // get pointer to previous record
                mov     FS:[0], EAX     // install previous record
                add     esp, 8          // clean our EXECEPTION_REGISTRATION off stack
        }

        return 0;
}
```

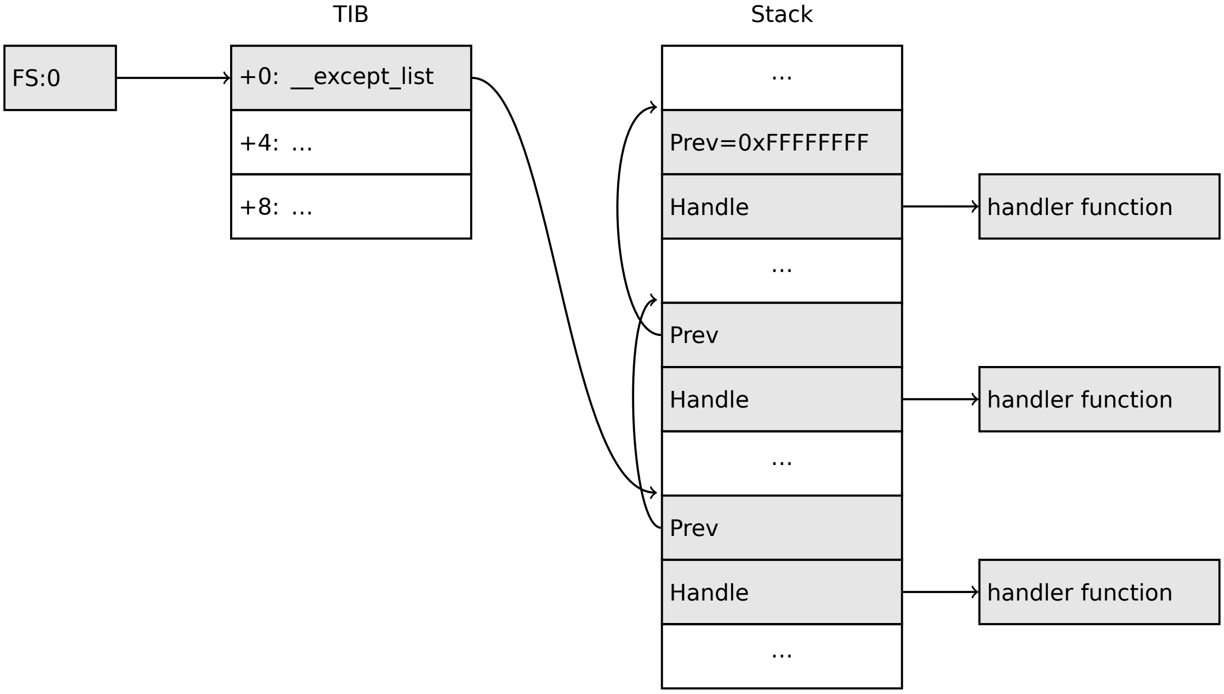
The FS: segment register is pointing to the TIB in win32.

The very first element in the TIB is a pointer to the last handler in the chain. We save it in the stack and store the address of our handler there. The structure is named `_EXCEPTION_REGISTRATION`, it is a simple singly-linked list and its elements are stored right in the stack.

Listing 6.22: MSVC/VC/crt/src/exsup.inc

```
\_EXCEPTION\_REGISTRATION struc
     prev    dd      ?
     handler dd      ?
\_EXCEPTION\_REGISTRATION ends
```

So each “handler” field points to a handler and an each “prev” field points to the previous record in the chain of exception handlers. The last record has `0xFFFFFFFF` (-1) in the “prev” field.



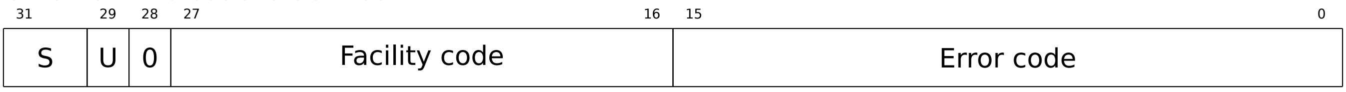
After our handler is installed, we call `RaiseException()` [44]. This is an user exception. The handler checks the code. If the code is `0xE1223344`, it returning `ExceptionContinueExecution`, which means that handler corrected the CPU state (it is usually a correction of the EIP/ESP registers) and the OS can resume the execution of the thread. If you alter slightly the code so the handler returns `ExceptionContinueSearch`,

then the OS will call the other handlers, and it's unlikely that one who can handle it will be found, since no one will have any information about it (rather about its code). You will see the standard Windows dialog about a process crash.

What is the difference between a system exceptions and a user one? Here are the system ones:

as defined in WinBase.h	as defined in ntstatus.h	value
EXCEPTION_ACCESS_VIOLATION	STATUS_ACCESS_VIOLATION	0xC0000005
EXCEPTION_DATATYPE_MISALIGNMENT	STATUS_DATATYPE_MISALIGNMENT	0x80000002
EXCEPTION_BREAKPOINT	STATUS_BREAKPOINT	0x80000003
EXCEPTION_SINGLE_STEP	STATUS_SINGLE_STEP	0x80000004
EXCEPTION_ARRAY_BOUNDS_EXCEEDED	STATUS_ARRAY_BOUNDS_EXCEEDED	0xC000008C
EXCEPTION_FLT_DENORMAL_OPERAND	STATUS_FLOAT_DENORMAL_OPERAND	0xC000008D
EXCEPTION_FLT_DIVIDE_BY_ZERO	STATUS_FLOAT_DIVIDE_BY_ZERO	0xC000008E
EXCEPTION_FLT_INEXACT_RESULT	STATUS_FLOAT_INEXACT_RESULT	0xC000008F
EXCEPTION_FLT_INVALID_OPERATION	STATUS_FLOAT_INVALID_OPERATION	0xC0000090
EXCEPTION_FLT_OVERFLOW	STATUS_FLOAT_OVERFLOW	0xC0000091
EXCEPTION_FLT_STACK_CHECK	STATUS_FLOAT_STACK_CHECK	0xC0000092
EXCEPTION_FLT_UNDERFLOW	STATUS_FLOAT_UNDERFLOW	0xC0000093
EXCEPTION_INT_DIVIDE_BY_ZERO	STATUS_INTEGER_DIVIDE_BY_ZERO	0xC0000094
EXCEPTION_INT_OVERFLOW	STATUS_INTEGER_OVERFLOW	0xC0000095
EXCEPTION_PRIV_INSTRUCTION	STATUS_PRIVILEGED_INSTRUCTION	0xC0000096
EXCEPTION_IN_PAGE_ERROR	STATUS_IN_PAGE_ERROR	0xC0000006
EXCEPTION_ILLEGAL_INSTRUCTION	STATUS_ILLEGAL_INSTRUCTION	0xC000001D
EXCEPTION_NONCONTINUABLE_EXCEPTION	STATUS_NONCONTINUABLE_EXCEPTION	0xC0000025
EXCEPTION_STACK_OVERFLOW	STATUS_STACK_OVERFLOW	0xC00000FD
EXCEPTION_INVALID_DISPOSITION	STATUS_INVALID_DISPOSITION	0xC0000026
EXCEPTION_GUARD_PAGE	STATUS_GUARD_PAGE_VIOLATION	0x80000001
EXCEPTION_INVALID_HANDLE	STATUS_INVALID_HANDLE	0xC0000008
EXCEPTION_POSSIBLE_DEADLOCK	STATUS_POSSIBLE_DEADLOCK	0xC0000194
CONTROL_C_EXIT	STATUS_CONTROL_C_EXIT	0xC000013A

That is how the code is defined:



S is a basic status code: 11—error; 10—warning; 01—informational; 00—success. U—whether the code is user code.

[44] MSDN

That is why we chose 0xE1223344—E_{16} (1110_2) 0xE (1110b) means that it is 1) user exception; 2) error.

But to be honest, this example works fine without these high bits.

Then we try to read a value from memory at address 0.

Of course, there is nothing at this address in win32, so an exception is raised.

The very first handler is to be called—yours, and it will know about it first, by checking the code if it's equal to the `EXCEPTION_ACCESS_VIOLATION` constant.

The code that's reading from memory at address 0 is looks like this:

Listing 6.23: MSVC 2010

```
        ...
        xor     eax, eax
        mov     eax, DWORD PTR [eax] ; exception will occur here
        push    eax
        push    OFFSET msg
        call    _printf
        add     esp, 8
        ...
```

Will it be possible to fix this error "on the fly" and to continue with program execution?

Yes, our exception handler can fix the EAX value and let the OS execute this instruction once again. So that is what we do. `printf()` prints 1234, because after the execution of our handler EAX is not 0, but contains the address of the global variable `new_value`. The execution will resume.

That is what is going on: the memory manager in the CPU signals about an error, the CPU suspends the thread, finds the exception handler in the Windows kernel, which, in turn, starts to call all handlers in the SEH chain, one by one.

We use MSVC 2010 here, but of course, there is no any guarantee that EAX will be used for this pointer.

This address replacement trick is showy, and we considering it here as an illustration of SEH's internals. Nevertheless, it's hard to recall any case where it is used for "on-the-fly" error fixing.

Why SEH-related records are stored right in the stack instead of some other place?

Supposedly because the OS is not needing to care about freeing this information, these records are simply disposed when the function finishes its execution. This is somewhat like alloca(): (1.7.2 on page 35).

Now let's get back to MSVC

Supposedly, Microsoft programmers needed exceptions in C, but not in C++ (for use in Windows NT kernel, which is written in C), so they added a non-standard C extension to MSVC[45]. It is not related to C++ PL exceptions.

```
__try
{
    ...
}
__except(filter code)
{
    handler code
}
```

"Finally" block may be instead of handler code:

```
__try
{
    ...
}
__finally
{
    ...
}
```

[45] MSDN

The filter code is an expression, telling whether this handler code corresponds to the exception raised.

If your code is too big and cannot fit into one expression, a separate filter function can be defined.

There are a lot of such constructs in the Windows kernel. Here are a couple of examples from there (WRK):

Listing 6.24: WRK-v1.2/base/ntos/ob/obwait.c

```
try {

    KeReleaseMutant( (PKMUTANT)SignalObject,
                     MUTANT_INCREMENT,
                     FALSE,
                     TRUE );

} except((GetExceptionCode () == STATUS_ABANDONED ||
          GetExceptionCode () == STATUS_MUTANT_NOT_OWNED)?
             EXCEPTION_EXECUTE_HANDLER :
             EXCEPTION_CONTINUE_SEARCH) {
    Status = GetExceptionCode();

    goto WaitExit;
}
```

Listing 6.25: WRK-v1.2/base/ntos/cache/cachesub.c

```
try {

    RtlCopyBytes( (PVOID)((PCHAR)CacheBuffer + PageOffset),
                  UserBuffer,
                  MorePages ?
                    (PAGE_SIZE - PageOffset) :
                    (ReceivedLength - PageOffset) );

} except( CcCopyReadExceptionFilter( GetExceptionInformation(),
                                                             &Status ) ) {
```

Here is also a filter code example:

Listing 6.26: WRK-v1.2/base/ntos/cache/copysup.c

```
LONG
CcCopyReadExceptionFilter(
    IN PEXCEPTION_POINTERS ExceptionPointer,
    IN PNTSTATUS ExceptionCode
    )

/*++

Routine Description:

    This routine serves as an exception filter and has the special job of
    extracting the "real" I/O error when Mm raises STATUS_IN_PAGE_ERROR
    beneath us.

Arguments:

    ExceptionPointer - A pointer to the exception record that contains
                       the real Io Status.

    ExceptionCode - A pointer to an NTSTATUS that is to receive the real
                    status.

Return Value:

    EXCEPTION_EXECUTE_HANDLER

--*/

{
```

```
    *ExceptionCode = ExceptionPointer->ExceptionRecord->ExceptionCode;

    if ( (*ExceptionCode == STATUS_IN_PAGE_ERROR) &&
         (ExceptionPointer->ExceptionRecord->NumberParameters >= 3) ) {

        *ExceptionCode = (NTSTATUS) ExceptionPointer->ExceptionRecord->ExceptionInformation[2];
    }

    ASSERT( !NT_SUCCESS(*ExceptionCode) );

    return EXCEPTION_EXECUTE_HANDLER;
}
```

Internally, SEH is an extension of the OS-supported exceptions. But the handler function is `_except_handler3` (for SEH3) or `_except_handler4` (for SEH4).

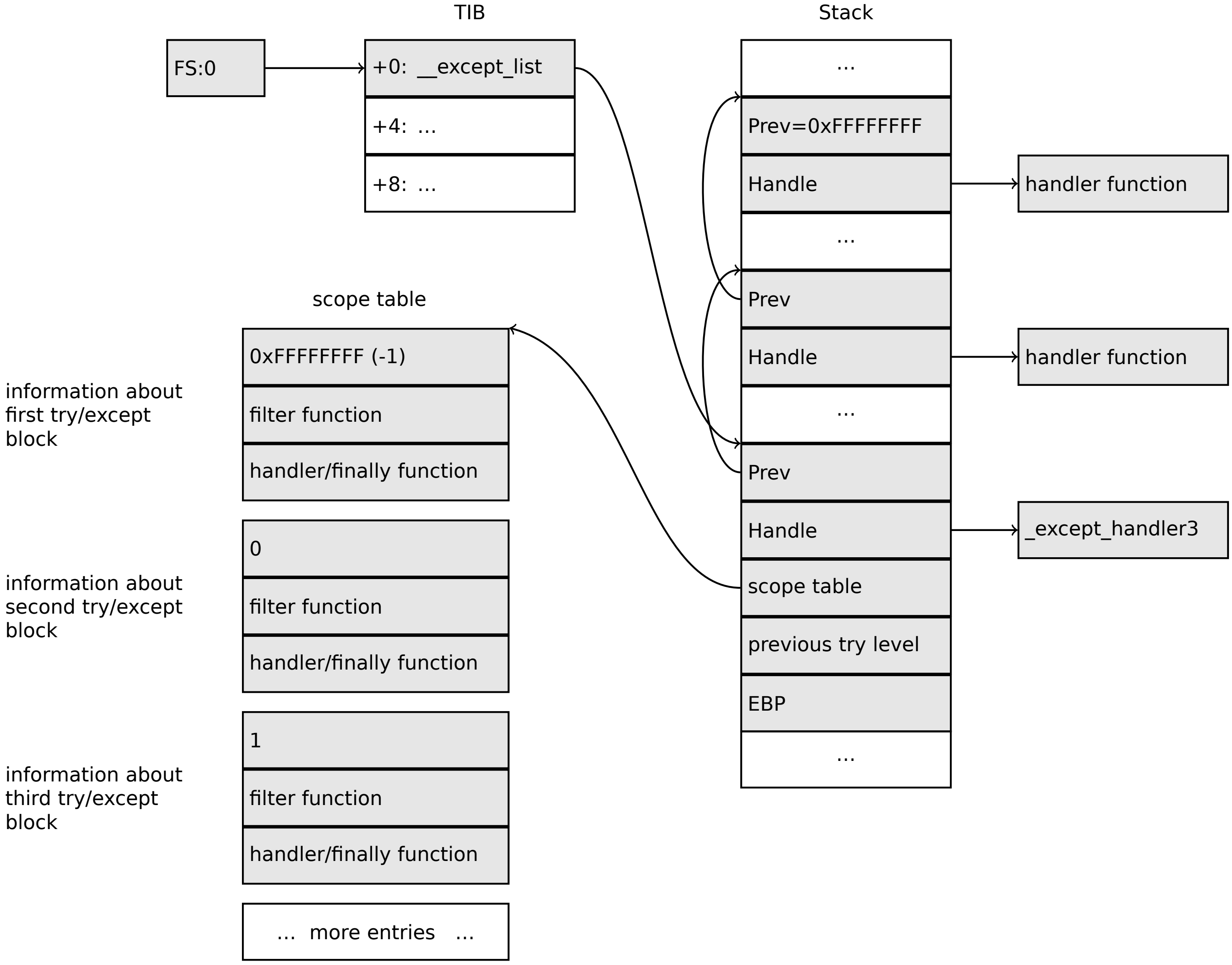
The code of this handler is MSVC-related, it is located in its libraries, or in msvcr*.dll. It is very important to know that SEH is a MSVC thing.

Other win32-compilers may offer something completely different.

SEH3

SEH3 has `_except_handler3` as a handler function, and extends the `_EXCEPTION_REGISTRATION` table, adding a pointer to the *scope table* and *previous try level* variable. SEH4 extends the *scope table* by 4 values for buffer overflow protection.

The *scope table* is a table that consists of pointers to the filter and handler code blocks, for each nested level of *try/except*.



Again, it is very important to understand that the OS takes care only of the *prev/handle* fields, and nothing more.
It is the job of the `_except_handler3` function to read the other fields and *scope table*, and decide which handler to execute and when.

The source code of the `_except_handler3` function is closed.

However, Sanos OS, which has a win32 compatibility layer, has the same functions reimplemented, which are somewhat equivalent to those in Windows [46]. Another reimplementation is present in Wine[47] and ReactOS[48].

If the *filter* pointer is NULL, the *handler* pointer is the pointer to the *finally* code block.

During execution, the *previous try level* value in the stack changes, so `_except_handler3` can get information about the current level of nestedness, in order to know which *scope table* entry to use.

SEH3: one try/except block example

```
#include <stdio.h>
#include <windows.h>
#include <excpt.h>

int main()
{
    int* p = NULL;
```

[46] http://go.yurichev.com/17058
[47] GitHub
[48] http://go.yurichev.com/17060

```
    __try
    {
        printf("hello #1!\n");
        *p = 13;    // causes an access violation exception;
        printf("hello #2!\n");
    }
    __except(GetExceptionCode()==EXCEPTION_ACCESS_VIOLATION ?
            EXCEPTION_EXECUTE_HANDLER : EXCEPTION_CONTINUE_SEARCH)
    {
        printf("access violation, can't recover\n");
    }
}
```

Listing 6.27: MSVC 2003

```
$SG74605 DB    'hello #1!', 0aH, 00H
$SG74606 DB    'hello #2!', 0aH, 00H
$SG74608 DB    'access violation, can''t recover', 0aH, 00H
_DATA    ENDS

; scope table:
CONST     SEGMENT
$T74622   DD    0ffffffffH    ; previous try level
          DD    FLAT:$L74617  ; filter
          DD    FLAT:$L74618  ; handler

CONST    ENDS
_TEXT    SEGMENT
$T74621 = -32 ; size = 4
_p$ = -28     ; size = 4
__$SEHRec$ = -24 ; size = 24
_main    PROC NEAR
    push   ebp
    mov    ebp, esp
    push   -1                              ; previous try level
    push   OFFSET FLAT:$T74622             ; scope table
    push   OFFSET FLAT:__except_handler3   ; handler
    mov    eax, DWORD PTR fs:__except_list
    push   eax                             ; prev
    mov    DWORD PTR fs:__except_list, esp
    add    esp, -16
; 3 registers to be saved:
    push   ebx
    push   esi
    push   edi
    mov    DWORD PTR __$SEHRec$[ebp], esp
    mov    DWORD PTR _p$[ebp], 0
    mov    DWORD PTR __$SEHRec$[ebp+20], 0  ; previous try level
    push   OFFSET FLAT:$SG74605 ; 'hello #1!'
    call   _printf
    add    esp, 4
    mov    eax, DWORD PTR _p$[ebp]
    mov    DWORD PTR [eax], 13
    push   OFFSET FLAT:$SG74606 ; 'hello #2!'
    call   _printf
    add    esp, 4
    mov    DWORD PTR __$SEHRec$[ebp+20], -1  ; previous try level
    jmp    SHORT $L74616

    ; filter code:
$L74617:
$L74627:
    mov    ecx, DWORD PTR __$SEHRec$[ebp+4]
    mov    edx, DWORD PTR [ecx]
    mov    eax, DWORD PTR [edx]
    mov    DWORD PTR $T74621[ebp], eax
    mov    eax, DWORD PTR $T74621[ebp]
    sub    eax, -1073741819; c0000005H
    neg    eax
    sbb    eax, eax
```

```
    inc    eax
$L74619:
$L74626:
    ret    0

    ; handler code:
$L74618:
    mov    esp, DWORD PTR __$SEHRec$[ebp]
    push   OFFSET FLAT:$SG74608 ; 'access violation, can''t recover'
    call   _printf
    add    esp, 4
    mov    DWORD PTR __$SEHRec$[ebp+20], -1 ; setting previous try level back to -1
$L74616:
    xor    eax, eax
    mov    ecx, DWORD PTR __$SEHRec$[ebp+8]
    mov    DWORD PTR fs:__except_list, ecx
    pop    edi
    pop    esi
    pop    ebx
    mov    esp, ebp
    pop    ebp
    ret    0
_main    ENDP
_TEXT    ENDS
END
```

Here we see how the SEH frame is constructed in the stack. The *scope table* is located in the `CONST` segment—indeed, these fields are not to be changed. An interesting thing is how the *previous try level* variable has changed. The initial value is `0xFFFFFFFF` (-1). The moment when the body of the `try` statement is opened is marked with an instruction that writes 0 to the variable. The moment when the body of the `try` statement is closed, -1 is written back to it. We also see the addresses of filter and handler code.

Thus we can easily see the structure of the *try/except* constructs in the function.

Since the SEH setup code in the function prologue may be shared between many functions, sometimes the compiler inserts a call to the `SEH_prolog()` function in the prologue, which does just that.

The SEH cleanup code is in the `SEH_epilog()` function.

Let's try to run this example in tracer:

```
tracer.exe -l:2.exe --dump-seh
```

Listing 6.28: tracer.exe output

```
EXCEPTION_ACCESS_VIOLATION at 2.exe!main+0x44 (0x401054) ExceptionInformation[0]=1
EAX=0x00000000 EBX=0x7efde000 ECX=0x0040cbc8 EDX=0x0008e3c8
ESI=0x00001db1 EDI=0x00000000 EBP=0x0018feac ESP=0x0018fe80
EIP=0x00401054
FLAGS=AF IF RF
* SEH frame at 0x18fe9c prev=0x18ff78 handler=0x401204 (2.exe!_except_handler3)
SEH3 frame. previous trylevel=0
scopetable entry[0]. previous try level=-1, filter=0x401070 (2.exe!main+0x60) handler=0x401088 ⤦
    ↳ (2.exe!main+0x78)
* SEH frame at 0x18ff78 prev=0x18ffc4 handler=0x401204 (2.exe!_except_handler3)
SEH3 frame. previous trylevel=0
scopetable entry[0]. previous try level=-1, filter=0x401531 (2.exe!mainCRTStartup+0x18d) ⤦
    ↳ handler=0x401545 (2.exe!mainCRTStartup+0x1a1)
* SEH frame at 0x18ffc4 prev=0x18ffe4 handler=0x771f71f5 (ntdll.dll!__except_handler4)
SEH4 frame. previous trylevel=0
SEH4 header:    GSCookieOffset=0xfffffffe GSCookieXOROffset=0x0
                EHCookieOffset=0xffffffcc EHCookieXOROffset=0x0
scopetable entry[0]. previous try level=-2, filter=0x771f74d0 (ntdll.dll!⤦
    ↳ ___safe_se_handler_table+0x20) handler=0x771f90eb (ntdll.dll!_TppTerminateProcess@4+0x43)
* SEH frame at 0x18ffe4 prev=0xffffffff handler=0x77247428 (ntdll.dll!_FinalExceptionHandler@16⤦
    ↳ )
```

We see that the SEH chain consists of 4 handlers.

The first two are located in our example. Two? But we made only one? Yes, another one has been set up in the CRT function `_mainCRTStartup()`, and as it seems that it handles at least FPU exceptions. Its source code can be found in the MSVC installation: `crt/src/winxfltr.c`.

The third is the SEH4 one in ntdll.dll, and the fourth handler is not MSVC-related and is located in ntdll.dll, and has a self-describing function name.

As you can see, there are 3 types of handlers in one chain:

one is not related to MSVC at all (the last one) and two MSVC-related: SEH3 and SEH4.

SEH3: two try/except blocks example

```
#include <stdio.h>
#include <windows.h>
#include <excpt.h>

int filter_user_exceptions (unsigned int code, struct _EXCEPTION_POINTERS *ep)
{
    printf("in filter. code=0x%08X\n", code);
    if (code == 0x112233)
    {
        printf("yes, that is our exception\n");
        return EXCEPTION_EXECUTE_HANDLER;
    }
    else
    {
        printf("not our exception\n");
        return EXCEPTION_CONTINUE_SEARCH;
    };
}
int main()
{
    int* p = NULL;
    __try
    {
        __try
        {
            printf ("hello!\n");
            RaiseException (0x112233, 0, 0, NULL);
            printf ("0x112233 raised. now let's crash\n");
            *p = 13;    // causes an access violation exception;
        }
        __except(GetExceptionCode()==EXCEPTION_ACCESS_VIOLATION ?
                EXCEPTION_EXECUTE_HANDLER : EXCEPTION_CONTINUE_SEARCH)
        {
            printf("access violation, can't recover\n");
        }
    }
    __except(filter_user_exceptions(GetExceptionCode(), GetExceptionInformation()))
    {
        // the filter_user_exceptions() function answering to the question
        // "is this exception belongs to this block?"
        // if yes, do the follow:
        printf("user exception caught\n");
    }
}
```

Now there are two `try` blocks. So the *scope table* now has two entries, one for each block. *Previous try level* changes as execution flow enters or exits the `try` block.

Listing 6.29: MSVC 2003

```
$SG74606 DB    'in filter. code=0x%08X', 0aH, 00H
$SG74608 DB    'yes, that is our exception', 0aH, 00H
$SG74610 DB    'not our exception', 0aH, 00H
$SG74617 DB    'hello!', 0aH, 00H
$SG74619 DB    '0x112233 raised. now let''s crash', 0aH, 00H
```

```
$SG74621 DB    'access violation, can''t recover', 0aH, 00H
$SG74623 DB    'user exception caught', 0aH, 00H

_code$ = 8   ; size = 4
_ep$ = 12    ; size = 4
_filter_user_exceptions PROC NEAR
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _code$[ebp]
    push   eax
    push   OFFSET FLAT:$SG74606 ; 'in filter. code=0x%08X'
    call   _printf
    add    esp, 8
    cmp    DWORD PTR _code$[ebp], 1122867; 00112233H
    jne    SHORT $L74607
    push   OFFSET FLAT:$SG74608 ; 'yes, that is our exception'
    call   _printf
    add    esp, 4
    mov    eax, 1
    jmp    SHORT $L74605
$L74607:
    push   OFFSET FLAT:$SG74610 ; 'not our exception'
    call   _printf
    add    esp, 4
    xor    eax, eax
$L74605:
    pop    ebp
    ret    0
_filter_user_exceptions ENDP

; scope table:
CONST    SEGMENT
$T74644   DD    0ffffffffH   ; previous try level for outer block
          DD    FLAT:$L74634 ; outer block filter
          DD    FLAT:$L74635 ; outer block handler
          DD    00H          ; previous try level for inner block
          DD    FLAT:$L74638 ; inner block filter
          DD    FLAT:$L74639 ; inner block handler
CONST    ENDS

$T74643 = -36     ; size = 4
$T74642 = -32     ; size = 4
_p$ = -28         ; size = 4
__$SEHRec$ = -24  ; size = 24
_main    PROC NEAR
    push   ebp
    mov    ebp, esp
    push   -1 ; previous try level
    push   OFFSET FLAT:$T74644
    push   OFFSET FLAT:__except_handler3
    mov    eax, DWORD PTR fs:__except_list
    push   eax
    mov    DWORD PTR fs:__except_list, esp
    add    esp, -20
    push   ebx
    push   esi
    push   edi
    mov    DWORD PTR __$SEHRec$[ebp], esp
    mov    DWORD PTR _p$[ebp], 0
    mov    DWORD PTR __$SEHRec$[ebp+20], 0 ; outer try block entered. set previous try level to↙
    ↳ 0
    mov    DWORD PTR __$SEHRec$[ebp+20], 1 ; inner try block entered. set previous try level to↙
    ↳ 1
    push   OFFSET FLAT:$SG74617 ; 'hello!'
    call   _printf
    add    esp, 4
    push   0
    push   0
    push   0
    push   1122867    ; 00112233H
```

```
    call    DWORD PTR __imp__RaiseException@16
    push    OFFSET FLAT:$SG74619 ; '0x112233 raised. now let''s crash'
    call    _printf
    add     esp, 4
    mov     eax, DWORD PTR _p$[ebp]
    mov     DWORD PTR [eax], 13
    mov     DWORD PTR __$SEHRec$[ebp+20], 0 ; inner try block exited. set previous try level ↙
    ↘ back to 0
    jmp     SHORT $L74615

; inner block filter:
$L74638:
$L74650:
    mov     ecx, DWORD PTR __$SEHRec$[ebp+4]
    mov     edx, DWORD PTR [ecx]
    mov     eax, DWORD PTR [edx]
    mov     DWORD PTR $T74643[ebp], eax
    mov     eax, DWORD PTR $T74643[ebp]
    sub     eax, -1073741819; c0000005H
    neg     eax
    sbb     eax, eax
    inc     eax
$L74640:
$L74648:
    ret     0

; inner block handler:
$L74639:
    mov     esp, DWORD PTR __$SEHRec$[ebp]
    push    OFFSET FLAT:$SG74621 ; 'access violation, can''t recover'
    call    _printf
    add     esp, 4
    mov     DWORD PTR __$SEHRec$[ebp+20], 0 ; inner try block exited. set previous try level ↙
    ↘ back to 0

$L74615:
    mov     DWORD PTR __$SEHRec$[ebp+20], -1 ; outer try block exited, set previous try level ↙
    ↘ back to -1
    jmp     SHORT $L74633

; outer block filter:
$L74634:
$L74651:
    mov     ecx, DWORD PTR __$SEHRec$[ebp+4]
    mov     edx, DWORD PTR [ecx]
    mov     eax, DWORD PTR [edx]
    mov     DWORD PTR $T74642[ebp], eax
    mov     ecx, DWORD PTR __$SEHRec$[ebp+4]
    push    ecx
    mov     edx, DWORD PTR $T74642[ebp]
    push    edx
    call    _filter_user_exceptions
    add     esp, 8
$L74636:
$L74649:
    ret     0

; outer block handler:
$L74635:
    mov     esp, DWORD PTR __$SEHRec$[ebp]
    push    OFFSET FLAT:$SG74623 ; 'user exception caught'
    call    _printf
    add     esp, 4
    mov     DWORD PTR __$SEHRec$[ebp+20], -1 ; both try blocks exited. set previous try level ↙
    ↘ back to -1
$L74633:
    xor     eax, eax
    mov     ecx, DWORD PTR __$SEHRec$[ebp+8]
    mov     DWORD PTR fs:__except_list, ecx
    pop     edi
```

```
    pop    esi
    pop    ebx
    mov    esp, ebp
    pop    ebp
    ret    0
_main    ENDP
```

If we set a breakpoint on the `printf()` function, which is called from the handler, we can also see how yet another SEH handler is added.

Perhaps it's another machinery inside the SEH handling process. Here we also see our *scope table* consisting of 2 entries.

```
tracer.exe -l:3.exe bpx=3.exe!printf --dump-seh
```

Listing 6.30: tracer.exe output

```
(0) 3.exe!printf
EAX=0x0000001b EBX=0x00000000 ECX=0x0040cc58 EDX=0x0008e3c8
ESI=0x00000000 EDI=0x00000000 EBP=0x0018f840 ESP=0x0018f838
EIP=0x004011b6
FLAGS=PF ZF IF
* SEH frame at 0x18f88c prev=0x18fe9c handler=0x771db4ad (ntdll.dll!ExecuteHandler2@20+0x3a)
* SEH frame at 0x18fe9c prev=0x18ff78 handler=0x4012e0 (3.exe!_except_handler3)
SEH3 frame. previous trylevel=1
scopetable entry[0]. previous try level=-1, filter=0x401120 (3.exe!main+0xb0) handler=0x40113b ↙
    ↳ (3.exe!main+0xcb)
scopetable entry[1]. previous try level=0, filter=0x4010e8 (3.exe!main+0x78) handler=0x401100 ↙
    ↳ (3.exe!main+0x90)
* SEH frame at 0x18ff78 prev=0x18ffc4 handler=0x4012e0 (3.exe!_except_handler3)
SEH3 frame. previous trylevel=0
scopetable entry[0]. previous try level=-1, filter=0x40160d (3.exe!mainCRTStartup+0x18d) ↙
    ↳ handler=0x401621 (3.exe!mainCRTStartup+0x1a1)
* SEH frame at 0x18ffc4 prev=0x18ffe4 handler=0x771f71f5 (ntdll.dll!__except_handler4)
SEH4 frame. previous trylevel=0
SEH4 header:    GSCookieOffset=0xfffffffe GSCookieXOROffset=0x0
                EHCookieOffset=0xffffffcc EHCookieXOROffset=0x0
scopetable entry[0]. previous try level=-2, filter=0x771f74d0 (ntdll.dll!↙
    ↳ ___safe_se_handler_table+0x20) handler=0x771f90eb (ntdll.dll!_TppTerminateProcess@4+0x43)
* SEH frame at 0x18ffe4 prev=0xffffffff handler=0x77247428 (ntdll.dll!_FinalExceptionHandler@16↙
    ↳ )
```

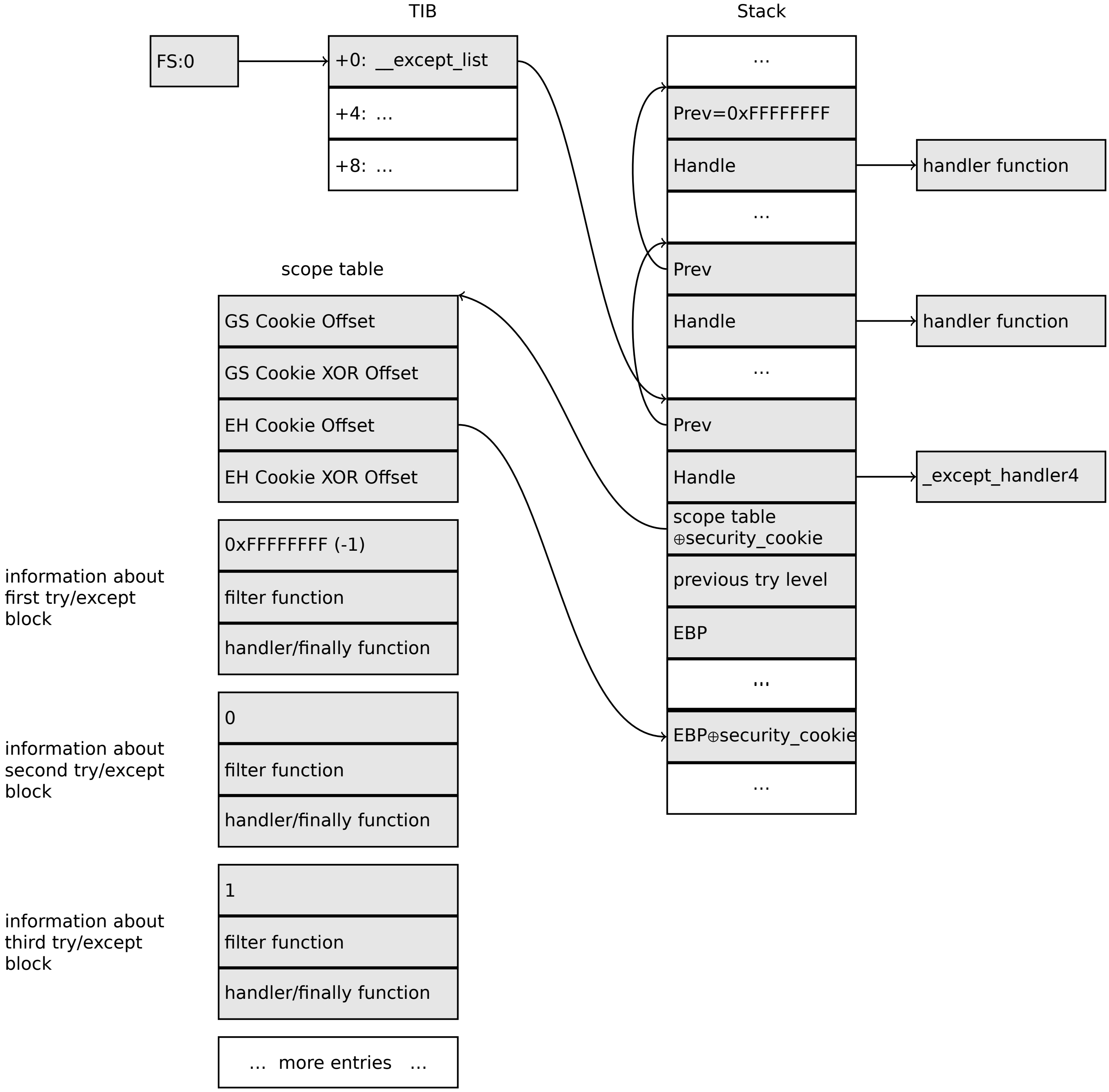
SEH4

During a buffer overflow (1.20.2 on page 275) attack, the address of the *scope table* can be rewritten, so starting from MSVC 2005, SEH3 was upgraded to SEH4 in order to have buffer overflow protection. The pointer to the *scope table* is now xored with a security cookie. The *scope table* was extended to have a header consisting of two pointers to *security cookies*.

Each element has an offset inside the stack of another value: the address of the stack frame (EBP) xored with the `security_cookie` , placed in the stack.

This value will be read during exception handling and checked for correctness. The *security cookie* in the stack is random each time, so hopefully a remote attacker can't predict it.

The initial *previous try level* is -2 in SEH4 instead of -1.



Here are both examples compiled in MSVC 2012 with SEH4:

Listing 6.31: MSVC 2012: one try block example

```
$SG85485 DB    'hello #1!', 0aH, 00H
$SG85486 DB    'hello #2!', 0aH, 00H
$SG85488 DB    'access violation, can''t recover', 0aH, 00H

; scope table:
xdata$x          SEGMENT
__sehtable$_main DD 0fffffffeH   ; GS Cookie Offset
    DD           00H             ; GS Cookie XOR Offset
    DD           0ffffffccH      ; EH Cookie Offset
    DD           00H             ; EH Cookie XOR Offset
    DD           0fffffffeH      ; previous try level
    DD           FLAT:$LN12@main ; filter
    DD           FLAT:$LN8@main  ; handler
xdata$x          ENDS

$T2 = -36        ; size = 4
_p$ = -32        ; size = 4
tv68 = -28       ; size = 4
__$SEHRec$ = -24 ; size = 24
```

```
_main    PROC
    push   ebp
    mov    ebp, esp
    push   -2
    push   OFFSET __sehtable$_main
    push   OFFSET __except_handler4
    mov    eax, DWORD PTR fs:0
    push   eax
    add    esp, -20
    push   ebx
    push   esi
    push   edi
    mov    eax, DWORD PTR ___security_cookie
    xor    DWORD PTR __$SEHRec$[ebp+16], eax ; xored pointer to scope table
    xor    eax, ebp
    push   eax                             ; ebp ^ security_cookie
    lea    eax, DWORD PTR __$SEHRec$[ebp+8] ; pointer to VC_EXCEPTION_REGISTRATION_RECORD
    mov    DWORD PTR fs:0, eax
    mov    DWORD PTR __$SEHRec$[ebp], esp
    mov    DWORD PTR _p$[ebp], 0
    mov    DWORD PTR __$SEHRec$[ebp+20], 0 ; previous try level
    push   OFFSET $SG85485 ; 'hello #1!'
    call   _printf
    add    esp, 4
    mov    eax, DWORD PTR _p$[ebp]
    mov    DWORD PTR [eax], 13
    push   OFFSET $SG85486 ; 'hello #2!'
    call   _printf
    add    esp, 4
    mov    DWORD PTR __$SEHRec$[ebp+20], -2 ; previous try level
    jmp    SHORT $LN6@main

; filter:
$LN7@main:
$LN12@main:
    mov    ecx, DWORD PTR __$SEHRec$[ebp+4]
    mov    edx, DWORD PTR [ecx]
    mov    eax, DWORD PTR [edx]
    mov    DWORD PTR $T2[ebp], eax
    cmp    DWORD PTR $T2[ebp], -1073741819 ; c0000005H
    jne    SHORT $LN4@main
    mov    DWORD PTR tv68[ebp], 1
    jmp    SHORT $LN5@main
$LN4@main:
    mov    DWORD PTR tv68[ebp], 0
$LN5@main:
    mov    eax, DWORD PTR tv68[ebp]
$LN9@main:
$LN11@main:
    ret    0

; handler:
$LN8@main:
    mov    esp, DWORD PTR __$SEHRec$[ebp]
    push   OFFSET $SG85488 ; 'access violation, can''t recover'
    call   _printf
    add    esp, 4
    mov    DWORD PTR __$SEHRec$[ebp+20], -2 ; previous try level
$LN6@main:
    xor    eax, eax
    mov    ecx, DWORD PTR __$SEHRec$[ebp+8]
    mov    DWORD PTR fs:0, ecx
    pop    ecx
    pop    edi
    pop    esi
    pop    ebx
    mov    esp, ebp
    pop    ebp
    ret    0
_main    ENDP
```

Listing 6.32: MSVC 2012: two try blocks example

```
$SG85486 DB    'in filter. code=0x%08X', 0aH, 00H
$SG85488 DB    'yes, that is our exception', 0aH, 00H
$SG85490 DB    'not our exception', 0aH, 00H
$SG85497 DB    'hello!', 0aH, 00H
$SG85499 DB    '0x112233 raised. now let''s crash', 0aH, 00H
$SG85501 DB    'access violation, can''t recover', 0aH, 00H
$SG85503 DB    'user exception caught', 0aH, 00H

xdata$x    SEGMENT
__sehtable$_main DD 0fffffffeH         ; GS Cookie Offset
                 DD    00H             ; GS Cookie XOR Offset
                 DD    0ffffffc8H      ; EH Cookie Offset
                 DD    00H             ; EH Cookie Offset
                 DD    0fffffffeH      ; previous try level for outer block
                 DD    FLAT:$LN19@main ; outer block filter
                 DD    FLAT:$LN9@main  ; outer block handler
                 DD    00H             ; previous try level for inner block
                 DD    FLAT:$LN18@main ; inner block filter
                 DD    FLAT:$LN13@main ; inner block handler
xdata$x    ENDS

$T2 = -40        ; size = 4
$T3 = -36        ; size = 4
_p$ = -32        ; size = 4
tv72 = -28       ; size = 4
__$SEHRec$ = -24 ; size = 24
_main    PROC
    push   ebp
    mov    ebp, esp
    push   -2  ; initial previous try level
    push   OFFSET __sehtable$_main
    push   OFFSET __except_handler4
    mov    eax, DWORD PTR fs:0
    push   eax ; prev
    add    esp, -24
    push   ebx
    push   esi
    push   edi
    mov    eax, DWORD PTR ___security_cookie
    xor    DWORD PTR __$SEHRec$[ebp+16], eax       ; xored pointer to scope table
    xor    eax, ebp                                ; ebp ^ security_cookie
    push   eax
    lea    eax, DWORD PTR __$SEHRec$[ebp+8]        ; pointer to ↙
    ↳ VC_EXCEPTION_REGISTRATION_RECORD
    mov    DWORD PTR fs:0, eax
    mov    DWORD PTR __$SEHRec$[ebp], esp
    mov    DWORD PTR _p$[ebp], 0
    mov    DWORD PTR __$SEHRec$[ebp+20], 0 ; entering outer try block, setting previous try ↙
    ↳ level=0
    mov    DWORD PTR __$SEHRec$[ebp+20], 1 ; entering inner try block, setting previous try ↙
    ↳ level=1
    push   OFFSET $SG85497 ; 'hello!'
    call   _printf
    add    esp, 4
    push   0
    push   0
    push   0
    push   1122867 ; 00112233H
    call   DWORD PTR __imp__RaiseException@16
    push   OFFSET $SG85499 ; '0x112233 raised. now let''s crash'
    call   _printf
    add    esp, 4
    mov    eax, DWORD PTR _p$[ebp]
    mov    DWORD PTR [eax], 13
    mov    DWORD PTR __$SEHRec$[ebp+20], 0 ; exiting inner try block, set previous try level ↙
    ↳ back to 0
    jmp    SHORT $LN2@main

; inner block filter:
```

```
$LN12@main:
$LN18@main:
    mov    ecx, DWORD PTR __$SEHRec$[ebp+4]
    mov    edx, DWORD PTR [ecx]
    mov    eax, DWORD PTR [edx]
    mov    DWORD PTR $T3[ebp], eax
    cmp    DWORD PTR $T3[ebp], -1073741819 ; c0000005H
    jne    SHORT $LN5@main
    mov    DWORD PTR tv72[ebp], 1
    jmp    SHORT $LN6@main
$LN5@main:
    mov    DWORD PTR tv72[ebp], 0
$LN6@main:
    mov    eax, DWORD PTR tv72[ebp]
$LN14@main:
$LN16@main:
    ret    0

; inner block handler:
$LN13@main:
    mov    esp, DWORD PTR __$SEHRec$[ebp]
    push   OFFSET $SG85501 ; 'access violation, can''t recover'
    call   _printf
    add    esp, 4
    mov    DWORD PTR __$SEHRec$[ebp+20], 0 ; exiting inner try block, setting previous try ↙
    ↘ level back to 0
$LN2@main:
    mov    DWORD PTR __$SEHRec$[ebp+20], -2 ; exiting both blocks, setting previous try level ↙
    ↘ back to -2
    jmp    SHORT $LN7@main

; outer block filter:
$LN8@main:
$LN19@main:
    mov    ecx, DWORD PTR __$SEHRec$[ebp+4]
    mov    edx, DWORD PTR [ecx]
    mov    eax, DWORD PTR [edx]
    mov    DWORD PTR $T2[ebp], eax
    mov    ecx, DWORD PTR __$SEHRec$[ebp+4]
    push   ecx
    mov    edx, DWORD PTR $T2[ebp]
    push   edx
    call   _filter_user_exceptions
    add    esp, 8
$LN10@main:
$LN17@main:
    ret    0

; outer block handler:
$LN9@main:
    mov    esp, DWORD PTR __$SEHRec$[ebp]
    push   OFFSET $SG85503 ; 'user exception caught'
    call   _printf
    add    esp, 4
    mov    DWORD PTR __$SEHRec$[ebp+20], -2 ; exiting both blocks, setting previous try level ↙
    ↘ back to -2
$LN7@main:
    xor    eax, eax
    mov    ecx, DWORD PTR __$SEHRec$[ebp+8]
    mov    DWORD PTR fs:0, ecx
    pop    ecx
    pop    edi
    pop    esi
    pop    ebx
    mov    esp, ebp
    pop    ebp
    ret    0
_main    ENDP

_code$ = 8  ; size = 4
```

```
_ep$ = 12   ; size = 4
_filter_user_exceptions PROC
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _code$[ebp]
    push   eax
    push   OFFSET $SG85486 ; 'in filter. code=0x%08X'
    call   _printf
    add    esp, 8
    cmp    DWORD PTR _code$[ebp], 1122867 ; 00112233H
    jne    SHORT $LN2@filter_use
    push   OFFSET $SG85488 ; 'yes, that is our exception'
    call   _printf
    add    esp, 4
    mov    eax, 1
    jmp    SHORT $LN3@filter_use
    jmp    SHORT $LN3@filter_use
$LN2@filter_use:
    push   OFFSET $SG85490 ; 'not our exception'
    call   _printf
    add    esp, 4
    xor    eax, eax
$LN3@filter_use:
    pop    ebp
    ret    0
_filter_user_exceptions ENDP
```

Here is the meaning of the *cookies*: `Cookie Offset` is the difference between the address of the saved EBP value in the stack and the $EBP \oplus security\_cookie$ value in the stack. `Cookie XOR Offset` is an additional difference between the $EBP \oplus security\_cookie$ value and what is stored in the stack.

If this equation is not true, the process is to halt due to stack corruption:

$$security\_cookie \oplus (CookieXOROffset + address\_of\_saved\_EBP) == stack[address\_of\_saved\_EBP + CookieOffset]$$

If `Cookie Offset` is -2, this implies that it is not present.

Cookies checking is also implemented in my tracer, see GitHub for details.

It is still possible to fall back to SEH3 in the compilers after (and including) MSVC 2005 by setting the `/GS-` option, however, the CRT code use SEH4 anyway.

Windows x64

As you might think, it is not very fast to set up the SEH frame at each function prologue. Another performance problem is changing the *previous try level* value many times during the function's execution.

So things are changed completely in x64: now all pointers to `try` blocks, filter and handler functions are stored in another PE segment `.pdata`, and from there the OS's exception handler takes all the information.

Here are the two examples from the previous section compiled for x64:

Listing 6.33: MSVC 2012

```
$SG86276 DB     'hello #1!', 0aH, 00H
$SG86277 DB     'hello #2!', 0aH, 00H
$SG86279 DB     'access violation, can''t recover', 0aH, 00H

pdata   SEGMENT
$pdata$main DD  imagerel $LN9
        DD      imagerel $LN9+61
        DD      imagerel $unwind$main
pdata   ENDS
pdata   SEGMENT
$pdata$main$filt$0 DD imagerel main$filt$0
        DD      imagerel main$filt$0+32
        DD      imagerel $unwind$main$filt$0
pdata   ENDS
xdata   SEGMENT
$unwind$main DD 020609H
```

```
        DD      030023206H
        DD      imagerel __C_specific_handler
        DD      01H
        DD      imagerel $LN9+8
        DD      imagerel $LN9+40
        DD      imagerel main$filt$0
        DD      imagerel $LN9+40
$unwind$main$filt$0 DD 020601H
        DD      050023206H
xdata   ENDS

_TEXT   SEGMENT
main    PROC
$LN9:
        push    rbx
        sub     rsp, 32
        xor     ebx, ebx
        lea     rcx, OFFSET FLAT:$SG86276 ; 'hello #1!'
        call    printf
        mov     DWORD PTR [rbx], 13
        lea     rcx, OFFSET FLAT:$SG86277 ; 'hello #2!'
        call    printf
        jmp     SHORT $LN8@main
$LN6@main:
        lea     rcx, OFFSET FLAT:$SG86279 ; 'access violation, can''t recover'
        call    printf
        npad    1 ; align next label
$LN8@main:
        xor     eax, eax
        add     rsp, 32
        pop     rbx
        ret     0
main    ENDP
_TEXT   ENDS

text$x  SEGMENT
main$filt$0 PROC
        push    rbp
        sub     rsp, 32
        mov     rbp, rdx
$LN5@main$filt$:
        mov     rax, QWORD PTR [rcx]
        xor     ecx, ecx
        cmp     DWORD PTR [rax], -1073741819; c0000005H
        sete    cl
        mov     eax, ecx
$LN7@main$filt$:
        add     rsp, 32
        pop     rbp
        ret     0
        int     3
main$filt$0 ENDP
text$x  ENDS
```

Listing 6.34: MSVC 2012

```
$SG86277 DB     'in filter. code=0x%08X', 0aH, 00H
$SG86279 DB     'yes, that is our exception', 0aH, 00H
$SG86281 DB     'not our exception', 0aH, 00H
$SG86288 DB     'hello!', 0aH, 00H
$SG86290 DB     '0x112233 raised. now let''s crash', 0aH, 00H
$SG86292 DB     'access violation, can''t recover', 0aH, 00H
$SG86294 DB     'user exception caught', 0aH, 00H

pdata   SEGMENT
$pdata$filter_user_exceptions DD imagerel $LN6
        DD      imagerel $LN6+73
        DD      imagerel $unwind$filter_user_exceptions
$pdata$main DD  imagerel $LN14
        DD      imagerel $LN14+95
```

```
        DD      imagerel $unwind$main
pdata   ENDS
pdata   SEGMENT
$pdata$main$filt$0 DD imagerel main$filt$0
        DD      imagerel main$filt$0+32
        DD      imagerel $unwind$main$filt$0
$pdata$main$filt$1 DD imagerel main$filt$1
        DD      imagerel main$filt$1+30
        DD      imagerel $unwind$main$filt$1
pdata   ENDS

xdata   SEGMENT
$unwind$filter_user_exceptions DD 020601H
        DD      030023206H
$unwind$main DD 020609H
        DD      030023206H
        DD      imagerel __C_specific_handler
        DD      02H
        DD      imagerel $LN14+8
        DD      imagerel $LN14+59
        DD      imagerel main$filt$0
        DD      imagerel $LN14+59
        DD      imagerel $LN14+8
        DD      imagerel $LN14+74
        DD      imagerel main$filt$1
        DD      imagerel $LN14+74
$unwind$main$filt$0 DD 020601H
        DD      050023206H
$unwind$main$filt$1 DD 020601H
        DD      050023206H
xdata   ENDS

_TEXT   SEGMENT
main    PROC
$LN14:
        push    rbx
        sub     rsp, 32
        xor     ebx, ebx
        lea     rcx, OFFSET FLAT:$SG86288 ; 'hello!'
        call    printf
        xor     r9d, r9d
        xor     r8d, r8d
        xor     edx, edx
        mov     ecx, 1122867 ; 00112233H
        call    QWORD PTR __imp_RaiseException
        lea     rcx, OFFSET FLAT:$SG86290 ; '0x112233 raised. now let''s crash'
        call    printf
        mov     DWORD PTR [rbx], 13
        jmp     SHORT $LN13@main
$LN11@main:
        lea     rcx, OFFSET FLAT:$SG86292 ; 'access violation, can''t recover'
        call    printf
        npad    1 ; align next label
$LN13@main:
        jmp     SHORT $LN9@main
$LN7@main:
        lea     rcx, OFFSET FLAT:$SG86294 ; 'user exception caught'
        call    printf
        npad    1 ; align next label
$LN9@main:
        xor     eax, eax
        add     rsp, 32
        pop     rbx
        ret     0
main    ENDP

text$x  SEGMENT
main$filt$0 PROC
        push    rbp
        sub     rsp, 32
```

```
        mov     rbp, rdx
$LN10@main$filt$:
        mov     rax, QWORD PTR [rcx]
        xor     ecx, ecx
        cmp     DWORD PTR [rax], -1073741819; c0000005H
        sete    cl
        mov     eax, ecx
$LN12@main$filt$:
        add     rsp, 32
        pop     rbp
        ret     0
        int     3
main$filt$0 ENDP

main$filt$1 PROC
        push    rbp
        sub     rsp, 32
        mov     rbp, rdx
$LN6@main$filt$:
        mov     rax, QWORD PTR [rcx]
        mov     rdx, rcx
        mov     ecx, DWORD PTR [rax]
        call    filter_user_exceptions
        npad    1 ; align next label
$LN8@main$filt$:
        add     rsp, 32
        pop     rbp
        ret     0
        int     3
main$filt$1 ENDP
text$x  ENDS

_TEXT   SEGMENT
code$ = 48
ep$ = 56
filter_user_exceptions PROC
$LN6:
        push    rbx
        sub     rsp, 32
        mov     ebx, ecx
        mov     edx, ecx
        lea     rcx, OFFSET FLAT:$SG86277 ; 'in filter. code=0x%08X'
        call    printf
        cmp     ebx, 1122867; 00112233H
        jne     SHORT $LN2@filter_use
        lea     rcx, OFFSET FLAT:$SG86279 ; 'yes, that is our exception'
        call    printf
        mov     eax, 1
        add     rsp, 32
        pop     rbx
        ret     0
$LN2@filter_use:
        lea     rcx, OFFSET FLAT:$SG86281 ; 'not our exception'
        call    printf
        xor     eax, eax
        add     rsp, 32
        pop     rbx
        ret     0
filter_user_exceptions ENDP
_TEXT   ENDS
```

Read [Igor Skochinsky, *Compiler Internals: Exceptions and RTTI*, (2012)] [49]for more detailed information about this.

Aside from exception information, .pdata is a section that contains the addresses of almost all function starts and ends, hence it may be useful for a tools targeted at automated analysis.

[49]Also available as http://go.yurichev.com/17294

Read more about SEH

[Matt Pietrek, *A Crash Course on the Depths of Win32™ Structured Exception Handling*, (1997)][50], [Igor Skochinsky, *Compiler Internals: Exceptions and RTTI*, (2012)] [51].

6.5.4 Windows NT: Critical section

Critical sections in any OS are very important in multithreaded environment, mostly for giving a guarantee that only one thread can access some data in a single moment of time, while blocking other threads and interrupts.

That is how a CRITICAL_SECTION structure is declared in Windows NT line OS:

Listing 6.35: (Windows Research Kernel v1.2) public/sdk/inc/nturtl.h

```
typedef struct _RTL_CRITICAL_SECTION {
    PRTL_CRITICAL_SECTION_DEBUG DebugInfo;

    //
    //  The following three fields control entering and exiting the critical
    //  section for the resource
    //

    LONG LockCount;
    LONG RecursionCount;
    HANDLE OwningThread;        // from the thread's ClientId->UniqueThread
    HANDLE LockSemaphore;
    ULONG_PTR SpinCount;        // force size on 64-bit systems when packed
} RTL_CRITICAL_SECTION, *PRTL_CRITICAL_SECTION;
```

That's is how EnterCriticalSection() function works:

Listing 6.36: Windows 2008/ntdll.dll/x86 (begin)

```
_RtlEnterCriticalSection@4

var_C           = dword ptr -0Ch
var_8           = dword ptr -8
var_4           = dword ptr -4
arg_0           = dword ptr  8

                mov     edi, edi
                push    ebp
                mov     ebp, esp
                sub     esp, 0Ch
                push    esi
                push    edi
                mov     edi, [ebp+arg_0]
                lea     esi, [edi+4] ; LockCount
                mov     eax, esi
                lock btr dword ptr [eax], 0
                jnb     wait ; jump if CF=0

loc_7DE922DD:
                mov     eax, large fs:18h
                mov     ecx, [eax+24h]
                mov     [edi+0Ch], ecx
                mov     dword ptr [edi+8], 1
                pop     edi
                xor     eax, eax
                pop     esi
                mov     esp, ebp
                pop     ebp
                retn    4

... skipped
```

[50]Also available as http://go.yurichev.com/17293
[51]Also available as http://go.yurichev.com/17294

The most important instruction in this code fragment is BTR (prefixed with LOCK):

the zeroth bit is stored in the CF flag and cleared in memory. This is an atomic operation,

blocking all other CPUs' access to this piece of memory (see the LOCK prefix before the BTR instruction). If the bit at LockCount is 1,

fine, reset it and return from the function: we are in a critical section.

If not—the critical section is already occupied by other thread, so wait.
The wait is performed there using WaitForSingleObject().

And here is how the LeaveCriticalSection() function works:

Listing 6.37: Windows 2008/ntdll.dll/x86 (begin)

```
_RtlLeaveCriticalSection@4 proc near

arg_0           = dword ptr  8

                mov     edi, edi
                push    ebp
                mov     ebp, esp
                push    esi
                mov     esi, [ebp+arg_0]
                add     dword ptr [esi+8], 0FFFFFFFFh ; RecursionCount
                jnz     short loc_7DE922B2
                push    ebx
                push    edi
                lea     edi, [esi+4]    ; LockCount
                mov     dword ptr [esi+0Ch], 0
                mov     ebx, 1
                mov     eax, edi
                lock xadd [eax], ebx
                inc     ebx
                cmp     ebx, 0FFFFFFFFh
                jnz     loc_7DEA8EB7

loc_7DE922B0:
                pop     edi
                pop     ebx

loc_7DE922B2:
                xor     eax, eax
                pop     esi
                pop     ebp
                retn    4

... skipped
```

XADD is “exchange and add”.

In this case, it adds 1 to LockCount, meanwhile saves initial value of LockCount in the EBX register. However, value in EBX is to incremented with a help of subsequent INC EBX, and it also will be equal to the updated value of LockCount.

This operation is atomic since it is prefixed by LOCK as well, meaning that all other CPUs or CPU cores in system are blocked from accessing this point in memory.

The LOCK prefix is very important:

without it two threads, each of which works on separate CPU or CPU core can try to enter a critical section and to modify the value in memory, which will result in non-deterministic behavior.

Chapter 7

Tools

> Now that Dennis Yurichev has made this book free (libre), it is a contribution to the world of free knowledge and free education. However, for our freedom's sake, we need free (libre) reverse engineering tools to replace the proprietary tools described in this book.
>
> Richard M. Stallman

7.1 Binary analysis

Tools you use when you don't run any process.

- (Free, open-source) *ent*[1]: entropy analyzing tool. Read more about entropy: 9.2 on page 948.
- *Hiew*[2]: for small modifications of code in binary files. Has assembler/disassembler.
- (Free, open-source) *GHex*[3]: simple hexadecimal editor for Linux.
- (Free, open-source) *xxd* and *od*: standard UNIX utilities for dumping.
- (Free, open-source) *strings*: *NIX tool for searching for ASCII strings in binary files, including executable ones. Sysinternals has alternative[4] supporting wide char strings (UTF-16, widely used in Windows).
- (Free, open-source) *Binwalk*[5]: analyzing firmware images.
- (Free, open-source) *binary grep*: a small utility for searching any byte sequence in a big pile of files, including non-executable ones: GitHub. There is also rafind2 in rada.re for the same purpose.

7.1.1 Disassemblers

- *IDA*. An older freeware version is available for download [6]. Hot-keys cheatsheet: .6.1 on page 1044
- *Binary Ninja*[7]
- (Free, open-source) *zynamics BinNavi*[8]
- (Free, open-source) *objdump*: simple command-line utility for dumping and disassembling.
- (Free, open-source) *readelf*[9]: dump information about ELF file.

---

1 http://www.fourmilab.ch/random/
2 hiew.ru
3 https://wiki.gnome.org/Apps/Ghex
4 https://technet.microsoft.com/en-us/sysinternals/strings
5 http://binwalk.org/
6 hex-rays.com/products/ida/support/download_freeware.shtml
7 http://binary.ninja/
8 https://www.zynamics.com/binnavi.html
9 https://sourceware.org/binutils/docs/binutils/readelf.html

7.1.2 Decompilers

There is only one known, publicly available, high-quality decompiler to C code: *Hex-Rays*:
hex-rays.com/products/decompiler/

Read more about it: 11.8 on page 1006.

7.1.3 Patch comparison/diffing

You may want to use it when you compare original version of some executable and patched one, in order to find what has been patched and why.

- (Free) *zynamics BinDiff*[10]
- (Free, open-source) *Diaphora*[11]

7.2 Live analysis

Tools you use on a live system or during running of a process.

7.2.1 Debuggers

- (Free) *OllyDbg*. Very popular user-mode win32 debugger[12]. Hot-keys cheatsheet: .6.2 on page 1044
- (Free, open-source) *GDB*. Not quite popular debugger among reverse engineers, because it's intended mostly for programmers. Some commands: .6.5 on page 1045. There is a visual interface for GDB, "GDB dashboard"[13].
- (Free, open-source) *LLDB*[14].
- *WinDbg*[15]: kernel debugger for Windows.
- *IDA* has internal debugger.
- (Free, open-source) *Radare* AKA rada.re AKA r2[16]. A GUI also exists: *ragui*[17].
- (Free, open-source) *tracer*. The author often uses *tracer* [18] instead of a debugger.

  The author of these lines stopped using a debugger eventually, since all he needs from it is to spot function arguments while executing, or registers state at some point. Loading a debugger each time is too much, so a small utility called *tracer* was born. It works from command line, allows intercepting function execution, setting breakpoints at arbitrary places, reading and changing registers state, etc.

  N.B.: the *tracer* isn't evolving, because it was developed as a demonstration tool for this book, not as everyday tool.

7.2.2 Library calls tracing

ltrace[19].

[10] https://www.zynamics.com/software.html
[11] https://github.com/joxeankoret/diaphora
[12] ollydbg.de
[13] https://github.com/cyrus-and/gdb-dashboard
[14] http://lldb.llvm.org/
[15] https://developer.microsoft.com/en-us/windows/hardware/windows-driver-kit
[16] http://rada.re/r/
[17] http://radare.org/ragui/
[18] yurichev.com
[19] http://www.ltrace.org/

7.2.3 System calls tracing

strace / dtruss

It shows which system calls (syscalls(6.3 on page 747)) are called by a process right now.

For example:

```
# strace df -h

...

access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
open("/lib/i386-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\1\1\1\0\0\0\0\0\0\0\0\0\3\0\3\0\1\0\0\0\220\232\1\0004\0\0\0"..., 512) = 512
fstat64(3, {st_mode=S_IFREG|0755, st_size=1770984, ...}) = 0
mmap2(NULL, 1780508, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0xb75b3000
```

Mac OS X has dtruss for doing the same.

Cygwin also has strace, but as far as it's known, it works only for .exe-files compiled for the cygwin environment itself.

7.2.4 Network sniffing

Sniffing is intercepting some information you may be interested in.

(Free, open-source) *Wireshark*[20] for network sniffing. It has also capability for USB sniffing[21].

Wireshark has a younger (or older) brother *tcpdump*[22], simpler command-line tool.

7.2.5 Sysinternals

(Free) Sysinternals (developed by Mark Russinovich) [23]. At least these tools are important and worth studying: Process Explorer, Handle, VMMap, TCPView, Process Monitor.

7.2.6 Valgrind

(Free, open-source) a powerful tool for detecting memory leaks: `http://valgrind.org/`. Due to its powerful JIT mechanism, Valgrind is used as a framework for other tools.

7.2.7 Emulators

- (Free, open-source) *QEMU*[24]: emulator for various CPUs and architectures.
- (Free, open-source) *DosBox*[25]: MS-DOS emulator, mostly used for retrogaming.
- (Free, open-source) *SimH*[26]: emulator of ancient computers, mainframes, etc.

[20] https://www.wireshark.org/
[21] https://wiki.wireshark.org/CaptureSetup/USB
[22] http://www.tcpdump.org/
[23] https://technet.microsoft.com/en-us/sysinternals/bb842062
[24] http://qemu.org
[25] https://www.dosbox.com/
[26] http://simh.trailing-edge.com/

7.3 Other tools

Microsoft Visual Studio Express [27]: Stripped-down free version of Visual Studio, convenient for simple experiments.

Some useful options: .6.3 on page 1044.

There is a website named “Compiler Explorer”, allowing to compile small code snippets and see output in various GCC versions and architectures (at least x86, ARM, MIPS): http://godbolt.org/—I would have used it myself for the book if I would know about it!

7.3.1 Calculators

Good calculator for reverse engineer’s needs should support at least decimal, hexadecimal and binary bases, as well as many important operations like XOR and shifts.

- IDA has built-in calculator (“?”).
- rada.re has *rax2*.
- https://github.com/DennisYurichev/progcalc
- As a last resort, standard calculator in Windows has programmer’s mode.

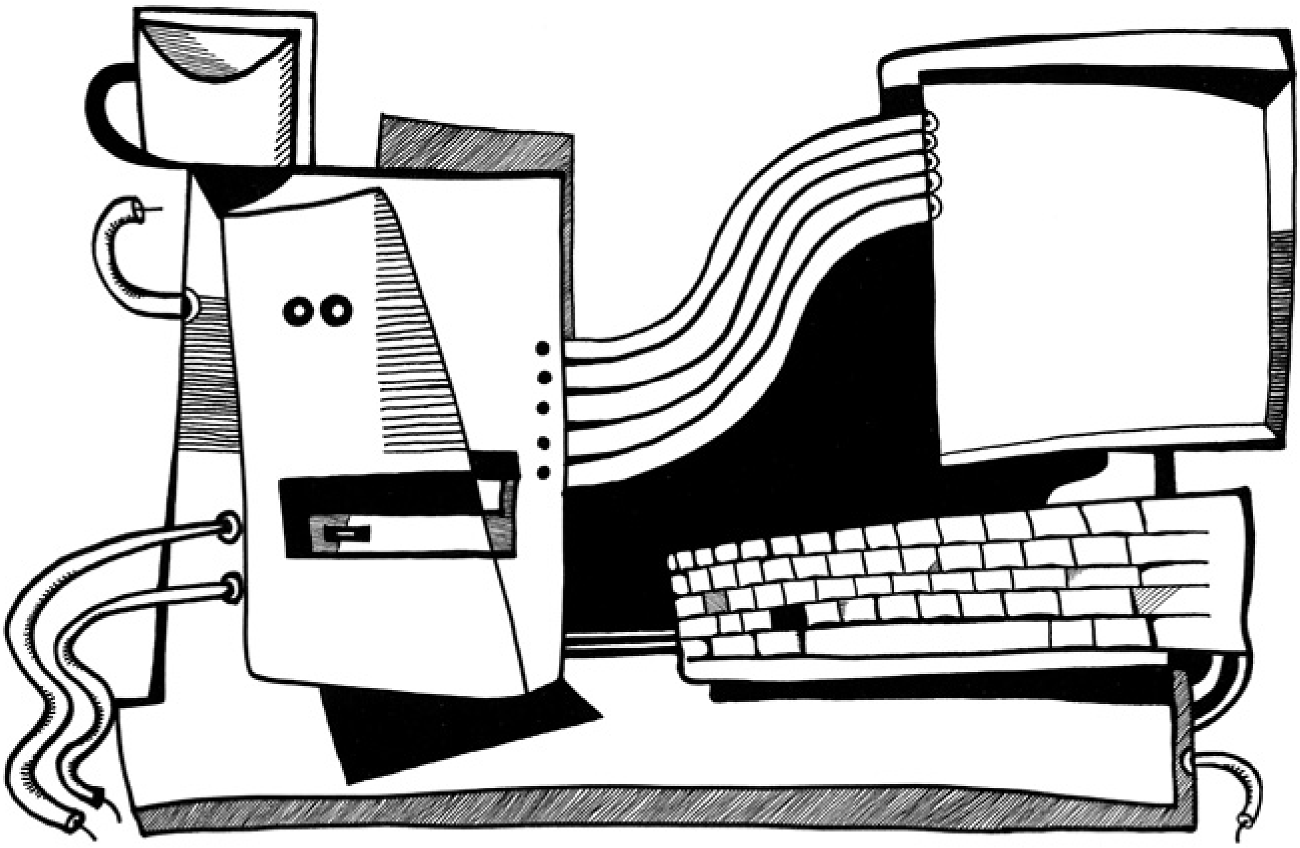
7.4 Do You Think Something Is Missing Here?

If you know a great tool not listed here, please drop a note:
dennis@yurichev.com.

[27] visualstudio.com/en-US/products/visual-studio-express-vs

Chapter 8

Case studies



Instead of epigraph:

> **Seibel:** How do you tackle reading source code? Even reading something in a programming language you already know is a tricky problem.
>
> **Knuth:** But it's really worth it for what it builds in your brain. So how do I do it? There was a machine called the Bunker Ramo 300 and somebody told me that the Fortran compiler for this machine was really amazingly fast, but nobody had any idea why it worked. I got a copy of the source-code listing for it. I didn't have a manual for the machine, so I wasn't even sure what the machine language was.
>
> But I took it as an interesting challenge. I could figure out BEGIN and then I would start to decode. The operation codes had some two-letter mnemonics and so I could start to figure out "This probably was a load instruction, this probably was a branch." And I knew it was a Fortran compiler, so at some point it looked at column seven of a card, and that was where it would tell if it was a comment or not.
>
> After three hours I had figured out a little bit about the machine. Then I found these big, branching tables. So it was a puzzle and I kept just making little charts like I'm working at a security agency trying to decode a secret code. But I knew it worked and I knew it was a Fortran compiler—it wasn't encrypted in the sense that it was intentionally obscure; it was only in code because I hadn't gotten the manual for the machine.
>
> Eventually I was able to figure out why this compiler was so fast. Unfortunately it wasn't because the algorithms were brilliant; it was just because they had used unstructured programming and hand optimized the code to the hilt.
>
> It was just basically the way you solve some kind of an unknown puzzle— make tables and charts and get a little more information here and make a hypothesis. In general when I'm reading a technical paper, it's the same challenge. I'm trying to get into the author's mind, trying to figure out what the concept is. The more you learn to read other people's stuff, the more able you are to invent your own in the future, it seems to me.

(Peter Seibel — Coders at Work: Reflections on the Craft of Programming)

8.1 Task manager practical joke (Windows Vista)

Let's see if it's possible to hack Task Manager slightly so it would detect more CPU cores.

Let us first think, how does the Task Manager know the number of cores?

There is the `GetSystemInfo()` win32 function present in win32 userspace which can tell us this. But it's not imported in `taskmgr.exe`.

There is, however, another one in NTAPI, `NtQuerySystemInformation()`, which is used in `taskmgr.exe` in several places.

To get the number of cores, one has to call this function with the `SystemBasicInformation` constant as a first argument (which is zero [1]).

The second argument has to point to the buffer which is getting all the information.

So we have to find all calls to the `NtQuerySystemInformation(0, ?, ?, ?)` function. Let's open `taskmgr.exe` in IDA.

What is always good about Microsoft executables is that IDA can download the corresponding PDB file for this executable and show all function names.

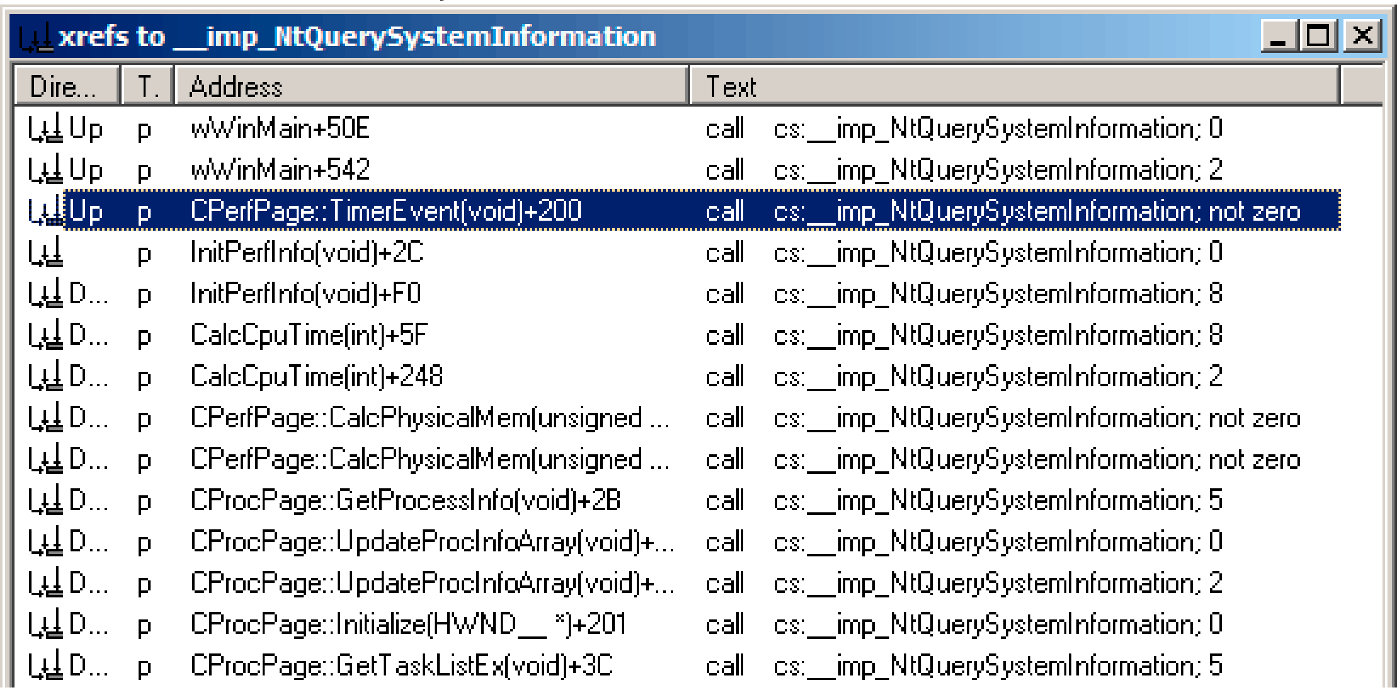
It is visible that Task Manager is written in C++ and some of the function names and classes are really speaking for themselves. There are classes CAdapter, CNetPage, CPerfPage, CProcInfo, CProcPage, CSvcPage, CTaskPage, CUserPage.

Apparently, each class corresponds to each tab in Task Manager.

Let's visit each call and add comment with the value which is passed as the first function argument. We will write "not zero" at some places, because the value there was clearly not zero, but something really different (more about this in the second part of this chapter).

And we are looking for zero passed as argument, after all.

[1] MSDN


xrefs to __imp_NtQuerySystemInformation

Dire...	T.	Address	Text
Up	p	wWinMain+50E	call cs:__imp_NtQuerySystemInformation; 0
Up	p	wWinMain+542	call cs:__imp_NtQuerySystemInformation; 2
Up	p	CPerfPage::TimerEvent(void)+200	call cs:__imp_NtQuerySystemInformation; not zero
	p	InitPerfInfo(void)+2C	call cs:__imp_NtQuerySystemInformation; 0
D...	p	InitPerfInfo(void)+F0	call cs:__imp_NtQuerySystemInformation; 8
D...	p	CalcCpuTime(int)+5F	call cs:__imp_NtQuerySystemInformation; 8
D...	p	CalcCpuTime(int)+248	call cs:__imp_NtQuerySystemInformation; 2
D...	p	CPerfPage::CalcPhysicalMem(unsigned ...	call cs:__imp_NtQuerySystemInformation; not zero
D...	p	CPerfPage::CalcPhysicalMem(unsigned ...	call cs:__imp_NtQuerySystemInformation; not zero
D...	p	CProcPage::GetProcessInfo(void)+2B	call cs:__imp_NtQuerySystemInformation; 5
D...	p	CProcPage::UpdateProcInfoArray(void)+...	call cs:__imp_NtQuerySystemInformation; 0
D...	p	CProcPage::UpdateProcInfoArray(void)+...	call cs:__imp_NtQuerySystemInformation; 2
D...	p	CProcPage::Initialize(HWND__ *)+201	call cs:__imp_NtQuerySystemInformation; 0
D...	p	CProcPage::GetTaskListEx(void)+3C	call cs:__imp_NtQuerySystemInformation; 5

Figure 8.1: IDA: cross references to NtQuerySystemInformation()

Yes, the names are really speaking for themselves.

When we closely investigate each place where `NtQuerySystemInformation(0, ?, ?, ?)` is called, we quickly find what we need in the `InitPerfInfo()` function:

Listing 8.1: taskmgr.exe (Windows Vista)

```
.text:10000B4B3         xor     r9d, r9d
.text:10000B4B6         lea     rdx, [rsp+0C78h+var_C58] ; buffer
.text:10000B4BB         xor     ecx, ecx
.text:10000B4BD         lea     ebp, [r9+40h]
.text:10000B4C1         mov     r8d, ebp
.text:10000B4C4         call    cs:__imp_NtQuerySystemInformation ; 0
.text:10000B4CA         xor     ebx, ebx
.text:10000B4CC         cmp     eax, ebx
.text:10000B4CE         jge     short loc_10000B4D7
.text:10000B4D0
.text:10000B4D0 loc_10000B4D0:                        ; CODE XREF: InitPerfInfo(void)+97
.text:10000B4D0                                       ; InitPerfInfo(void)+AF
.text:10000B4D0         xor     al, al
.text:10000B4D2         jmp     loc_10000B5EA
.text:10000B4D7 ; ---------------------------------------------------------------------------
.text:10000B4D7
.text:10000B4D7 loc_10000B4D7:                        ; CODE XREF: InitPerfInfo(void)+36
.text:10000B4D7         mov     eax, [rsp+0C78h+var_C50]
.text:10000B4DB         mov     esi, ebx
.text:10000B4DD         mov     r12d, 3E80h
.text:10000B4E3         mov     cs:?g_PageSize@@3KA, eax ; ulong g_PageSize
.text:10000B4E9         shr     eax, 0Ah
.text:10000B4EC         lea     r13, __ImageBase
.text:10000B4F3         imul    eax, [rsp+0C78h+var_C4C]
.text:10000B4F8         cmp     [rsp+0C78h+var_C20], bpl
.text:10000B4FD         mov     cs:?g_MEMMax@@3_JA, rax ; __int64 g_MEMMax
.text:10000B504         movzx   eax, [rsp+0C78h+var_C20] ; number of CPUs
.text:10000B509         cmova   eax, ebp
.text:10000B50C         cmp     al, bl
.text:10000B50E         mov     cs:?g_cProcessors@@3EA, al ; uchar g_cProcessors
```

`g_cProcessors` is a global variable, and this name has been assigned by IDA according to the PDB loaded from Microsoft's symbol server.

The byte is taken from `var_C20`. And `var_C58` is passed to `NtQuerySystemInformation()` as a pointer to the receiving buffer. The difference between 0xC20 and 0xC58 is 0x38 (56).

Let's take a look at format of the return structure, which we can find in MSDN:

```
typedef struct _SYSTEM_BASIC_INFORMATION {
    BYTE Reserved1[24];
    PVOID Reserved2[4];
    CCHAR NumberOfProcessors;
} SYSTEM_BASIC_INFORMATION;
```

This is a x64 system, so each PVOID takes 8 bytes.

All *reserved* fields in the structure take $24 + 4 * 8 = 56$ bytes.

Oh yes, this implies that `var_C20` is the local stack is exactly the `NumberOfProcessors` field of the `SYSTEM_BASIC_INFORMATION` structure.

Let's check our guess. Copy `taskmgr.exe` from `C:\Windows\System32` to some other folder (so the *Windows Resource Protection* will not try to restore the patched `taskmgr.exe`).

Let's open it in Hiew and find the place:

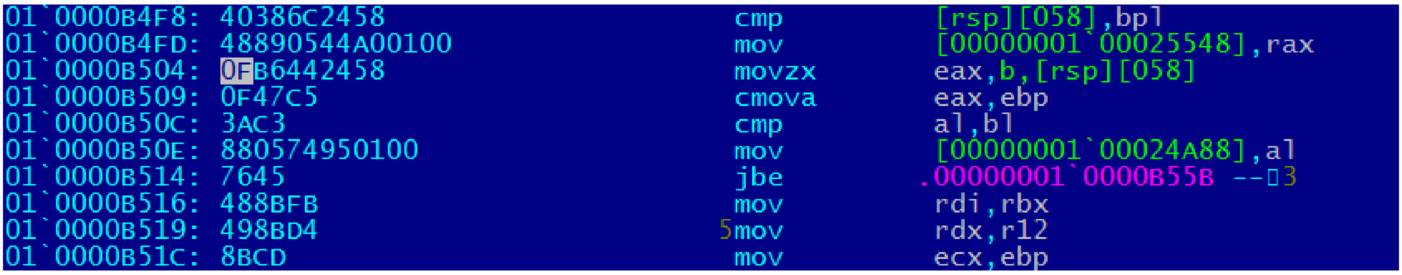


Figure 8.2: Hiew: find the place to be patched

Let's replace the `MOVZX` instruction with ours. Let's pretend we've got 64 CPU cores.

Add one additional NOP (because our instruction is shorter than the original one):

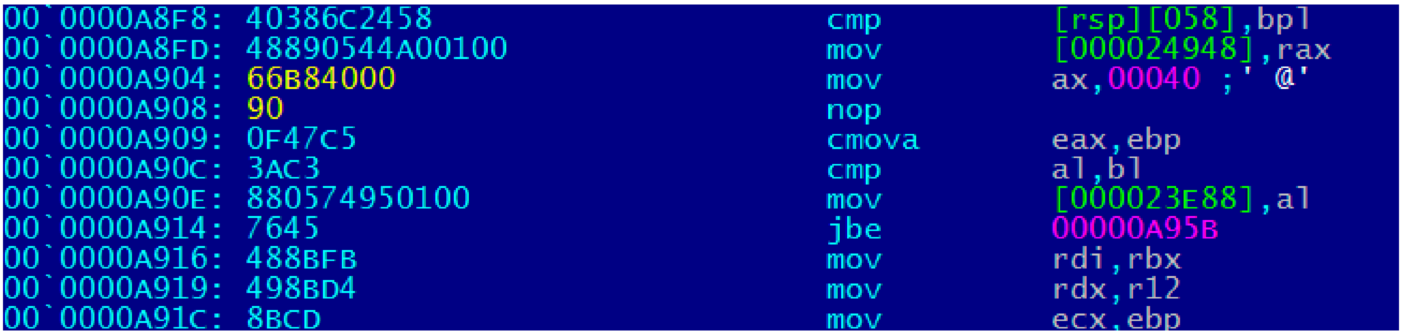


Figure 8.3: Hiew: patch it

And it works! Of course, the data in the graphs is not correct.

At times, Task Manager even shows an overall CPU load of more than 100%.

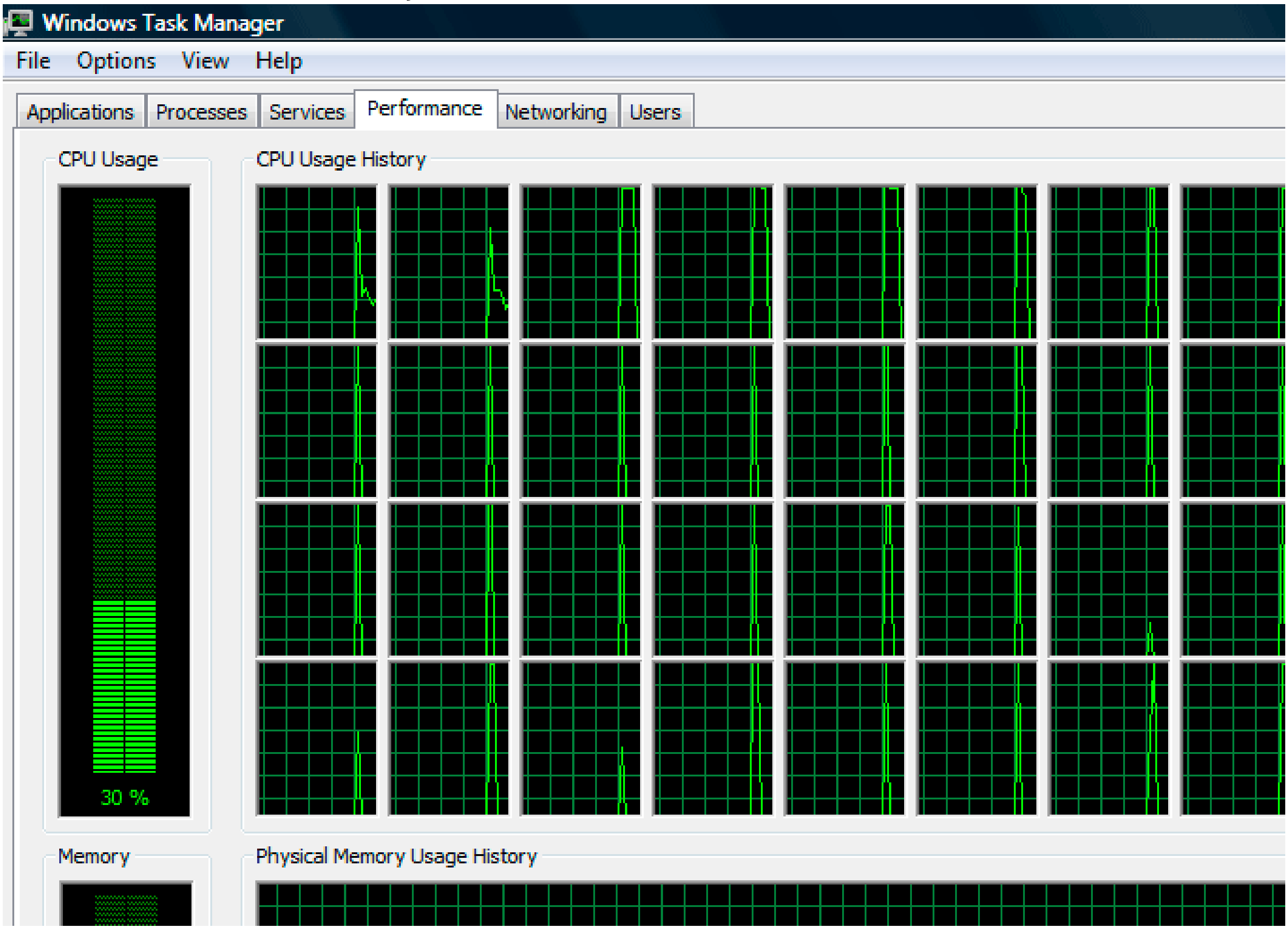


Figure 8.4: Fooled Windows Task Manager

The biggest number Task Manager does not crash with is 64.

Apparently, Task Manager in Windows Vista was not tested on computers with a large number of cores. So there are probably some static data structure(s) inside it limited to 64 cores.

8.1.1 Using LEA to load values

Sometimes, LEA is used in `taskmgr.exe` instead of `MOV` to set the first argument of `NtQuerySystemInformation()`:

Listing 8.2: taskmgr.exe (Windows Vista)

```
                 xor     r9d, r9d
                 div     dword ptr [rsp+4C8h+WndClass.lpfnWndProc]
                 lea     rdx, [rsp+4C8h+VersionInformation]
                 lea     ecx, [r9+2]      ; put 2 to ECX
                 mov     r8d, 138h
                 mov     ebx, eax
; ECX=SystemPerformanceInformation
                 call    cs:__imp_NtQuerySystemInformation ; 2

                 ...

                 mov     r8d, 30h
                 lea     r9, [rsp+298h+var_268]
                 lea     rdx, [rsp+298h+var_258]
                 lea     ecx, [r8-2Dh]    ; put 3 to ECX
; ECX=SystemTimeOfDayInformation
                 call    cs:__imp_NtQuerySystemInformation ; not zero
```

```
                 ...

                 mov     rbp, [rsi+8]
                 mov     r8d, 20h
                 lea     r9, [rsp+98h+arg_0]
                 lea     rdx, [rsp+98h+var_78]
                 lea     ecx, [r8+2Fh]   ; put 0x4F to ECX
                 mov     [rsp+98h+var_60], ebx
                 mov     [rsp+98h+var_68], rbp
; ECX=SystemSuperfetchInformation
                 call    cs:__imp_NtQuerySystemInformation ; not zero
```

Perhaps MSVC did so because machine code of LEA is shorter than `MOV REG, 5` (would be 5 instead of 4).

LEA with offset in $-128..127$ range (offset will occupy 1 byte in opcode) with 32-bit registers is even shorter (for lack of REX prefix)—3 bytes.

Another example of such thing is: 6.1.5 on page 739.

8.2 Color Lines game practical joke

This is a very popular game with several implementations in existence. We can take one of them, called BallTriX, from 1997, available freely at http://go.yurichev.com/17311 [2]. Here is how it looks:

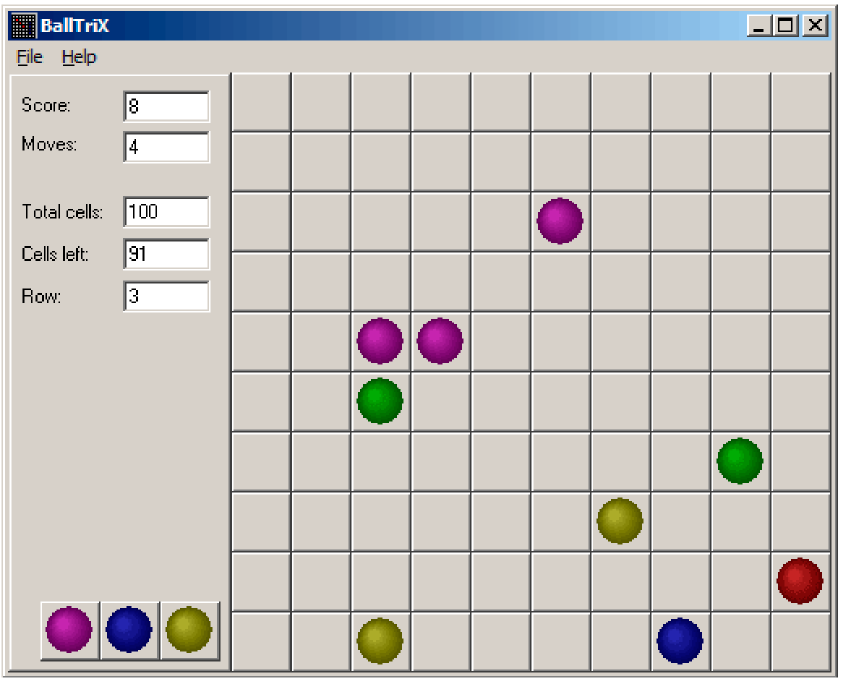


Figure 8.5: This is how the game is usually looks like

[2]Or at http://go.yurichev.com/17365 or http://go.yurichev.com/17366.

So let's see, is it be possible to find the random generator and do some trick with it. IDA quickly recognize the standard _rand function in balltrix.exe at 0x00403DA0. IDA also shows that it is called only from one place:

```
.text:00402C9C sub_402C9C      proc near               ; CODE XREF: sub_402ACA+52
.text:00402C9C                                         ; sub_402ACA+64 ...
.text:00402C9C
.text:00402C9C arg_0           = dword ptr  8
.text:00402C9C
.text:00402C9C                 push    ebp
.text:00402C9D                 mov     ebp, esp
.text:00402C9F                 push    ebx
.text:00402CA0                 push    esi
.text:00402CA1                 push    edi
.text:00402CA2                 mov     eax, dword_40D430
.text:00402CA7                 imul    eax, dword_40D440
.text:00402CAE                 add     eax, dword_40D5C8
.text:00402CB4                 mov     ecx, 32000
.text:00402CB9                 cdq
.text:00402CBA                 idiv    ecx
.text:00402CBC                 mov     dword_40D440, edx
.text:00402CC2                 call    _rand
.text:00402CC7                 cdq
.text:00402CC8                 idiv    [ebp+arg_0]
.text:00402CCB                 mov     dword_40D430, edx
.text:00402CD1                 mov     eax, dword_40D430
.text:00402CD6                 jmp     $+5
.text:00402CDB                 pop     edi
.text:00402CDC                 pop     esi
.text:00402CDD                 pop     ebx
.text:00402CDE                 leave
.text:00402CDF                 retn
.text:00402CDF sub_402C9C      endp
```

We'll call it "random". Let's not to dive into this function's code yet.

This function is referred from 3 places.

Here are the first two:

```
.text:00402B16                 mov     eax, dword_40C03C ; 10 here
.text:00402B1B                 push    eax
.text:00402B1C                 call    random
.text:00402B21                 add     esp, 4
.text:00402B24                 inc     eax
.text:00402B25                 mov     [ebp+var_C], eax
.text:00402B28                 mov     eax, dword_40C040 ; 10 here
.text:00402B2D                 push    eax
.text:00402B2E                 call    random
.text:00402B33                 add     esp, 4
```

Here is the third one:

```
.text:00402BBB                 mov     eax, dword_40C058 ; 5 here
.text:00402BC0                 push    eax
.text:00402BC1                 call    random
.text:00402BC6                 add     esp, 4
.text:00402BC9                 inc     eax
```

So the function has only one argument.

10 is passed in first two cases and 5 in third. We can also notice that the board has a size of 10*10 and there are 5 possible colors. This is it! The standard rand() function returns a number in the 0..0x7FFF range and this is often inconvenient, so many programmers implement their own random functions which returns a random number in a specified range. In our case, the range is $0..n-1$ and n is passed as the sole argument of the function. We can quickly check this in any debugger.

So let's fix the third function call to always return zero. First, we will replace three instructions (PUSH/CALL/ADD) by NOPs. Then we'll add XOR EAX, EAX instruction, to clear the EAX register.

```
.00402BB8: 83C410          add         esp,010
.00402BBB: A158C04000      mov         eax,[00040C058]
.00402BC0: 31C0            xor         eax,eax
.00402BC2: 90              nop
.00402BC3: 90              nop
.00402BC4: 90              nop
.00402BC5: 90              nop
.00402BC6: 90              nop
.00402BC7: 90              nop
.00402BC8: 90              nop
.00402BC9: 40              inc         eax
.00402BCA: 8B4DF8          mov         ecx,[ebp][-8]
.00402BCD: 8D0C49          lea         ecx,[ecx][ecx]*2
.00402BD0: 8B15F4D54000    mov         edx,[00040D5F4]
```

So what we did is we replaced a call to the `random()` function by a code which always returns zero.

Let's run it now:

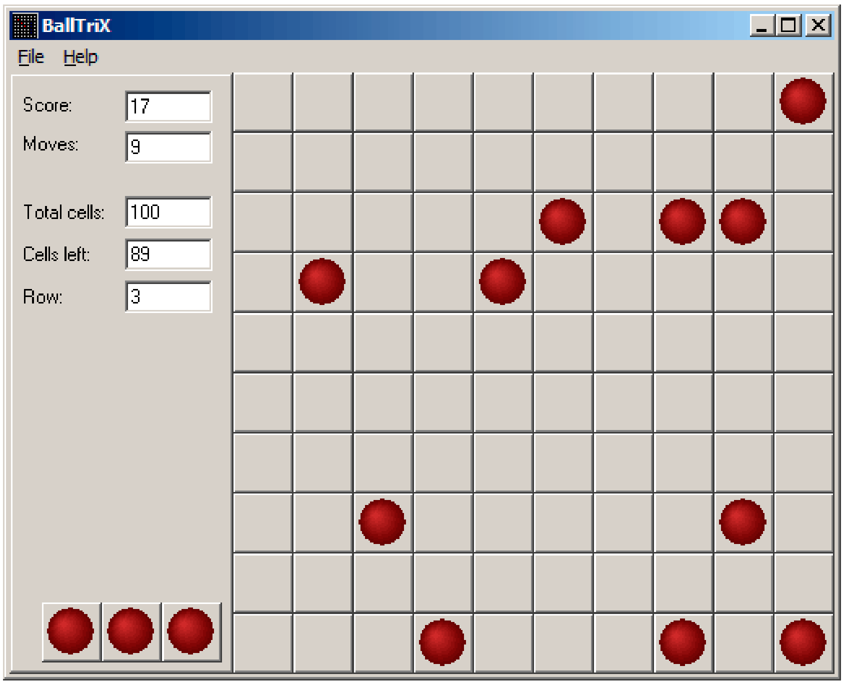


Figure 8.6: Practical joke works

Oh yes, it works[3].

But why are the arguments to the random() functions global variables? That's just because it's possible to change the board size in the game's settings, so these values are not hardcoded. The 10 and 5 values are just defaults.

8.3 Minesweeper (Windows XP)

For those who are not very good at playing Minesweeper, we could try to reveal the hidden mines in the debugger.

As we know, Minesweeper places mines randomly, so there has to be some kind of random number generator or a call to the standard rand() C-function.

What is really cool about reversing Microsoft products is that there are PDB file with symbols (function names, etc). When we load winmine.exe into IDA, it downloads the PDB file exactly for this executable and shows all names.

So here it is, the only call to rand() is this function:

```
.text:01003940 ; __stdcall Rnd(x)
.text:01003940 _Rnd@4          proc near               ; CODE XREF: StartGame()+53
.text:01003940                                         ; StartGame()+61
.text:01003940
.text:01003940 arg_0           = dword ptr  4
.text:01003940
.text:01003940                 call    ds:__imp__rand
.text:01003946                 cdq
.text:01003947                 idiv    [esp+arg_0]
.text:0100394B                 mov     eax, edx
.text:0100394D                 retn    4
.text:0100394D _Rnd@4          endp
```

IDA named it so, and it was the name given to it by Minesweeper's developers.

The function is very simple:

[3]Author of this book once did this as a joke for his coworkers with the hope that they would stop playing. They didn't.

```
int Rnd(int limit)
{
    return rand() % limit;
};
```

(There is no “limit” name in the PDB file; we manually named this argument like this.)

So it returns a random value from 0 to a specified limit.

Rnd() is called only from one place, a function called StartGame(), and as it seems, this is exactly the code which place the mines:

```
.text:010036C7                 push    _xBoxMac
.text:010036CD                 call    _Rnd@4          ; Rnd(x)
.text:010036D2                 push    _yBoxMac
.text:010036D8                 mov     esi, eax
.text:010036DA                 inc     esi
.text:010036DB                 call    _Rnd@4          ; Rnd(x)
.text:010036E0                 inc     eax
.text:010036E1                 mov     ecx, eax
.text:010036E3                 shl     ecx, 5          ; ECX=ECX*32
.text:010036E6                 test    _rgBlk[ecx+esi], 80h
.text:010036EE                 jnz     short loc_10036C7
.text:010036F0                 shl     eax, 5          ; EAX=EAX*32
.text:010036F3                 lea     eax, _rgBlk[eax+esi]
.text:010036FA                 or      byte ptr [eax], 80h
.text:010036FD                 dec     _cBombStart
.text:01003703                 jnz     short loc_10036C7
```

Minesweeper allows you to set the board size, so the X (xBoxMac) and Y (yBoxMac) of the board are global variables. They are passed to Rnd() and random coordinates are generated. A mine is placed by the OR instruction at 0x010036FA. And if it has been placed before (it’s possible if the pair of Rnd() generates a coordinates pair which has been already generated), then TEST and JNZ at 0x010036E6 jumps to the generation routine again.

cBombStart is the global variable containing total number of mines. So this is loop.

The width of the array is 32 (we can conclude this by looking at the SHL instruction, which multiplies one of the coordinates by 32).

The size of the rgBlk global array can be easily determined by the difference between the rgBlk label in the data segment and the next known one. It is 0x360 (864):

```
.data:01005340 _rgBlk          db 360h dup(?)          ; DATA XREF: MainWndProc(x,x,x,x)+574
.data:01005340                                         ; DisplayBlk(x,x)+23
.data:010056A0 _Preferences    dd ?                    ; DATA XREF: FixMenus()+2
...
```

$864/32 = 27$.

So the array size is $27 * 32$? It is close to what we know: when we try to set board size to $100 * 100$ in Minesweeper settings, it fallbacks to a board of size $24 * 30$. So this is the maximal board size here. And the array has a fixed size for any board size.

So let’s see all this in OllyDbg. We will ran Minesweeper, attaching OllyDbg to it and now we can see the memory dump at the address of the rgBlk array (0x01005340) [4].

So we got this memory dump of the array:

```
Address   Hex dump
01005340  10 10 10 10|10 10 10 10|10 10 10 0F|0F 0F 0F 0F|
01005350  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
01005360  10 0F 0F 0F|0F 0F 0F 0F|0F 0F 10 0F|0F 0F 0F 0F|
01005370  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
01005380  10 0F 0F 0F|0F 0F 0F 0F|0F 0F 10 0F|0F 0F 0F 0F|
01005390  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
010053A0  10 0F 0F 0F|0F 0F 0F 0F|8F 0F 10 0F|0F 0F 0F 0F|
010053B0  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
010053C0  10 0F 0F 0F|0F 0F 0F 0F|0F 0F 10 0F|0F 0F 0F 0F|
```

[4] All addresses here are for Minesweeper for Windows XP SP3 English. They may differ for other service packs.

```
010053D0  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
010053E0  10 0F 0F 0F|0F 0F 0F 0F|0F 0F 10 0F|0F 0F 0F 0F|
010053F0  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
01005400  10 0F 0F 8F|0F 0F 8F 0F|0F 0F 10 0F|0F 0F 0F 0F|
01005410  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
01005420  10 8F 0F 0F|8F 0F 0F 0F|0F 0F 10 0F|0F 0F 0F 0F|
01005430  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
01005440  10 8F 0F 0F|0F 0F 8F 0F|0F 8F 10 0F|0F 0F 0F 0F|
01005450  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
01005460  10 0F 0F 0F|0F 8F 0F 0F|0F 8F 10 0F|0F 0F 0F 0F|
01005470  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
01005480  10 10 10 10|10 10 10 10|10 10 10 0F|0F 0F 0F 0F|
01005490  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
010054A0  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
010054B0  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
010054C0  0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|0F 0F 0F 0F|
```

OllyDbg, like any other hexadecimal editor, shows 16 bytes per line. So each 32-byte array row occupies exactly 2 lines here.

This is beginner level (9*9 board).

There is some square structure can be seen visually (0x10 bytes).

We will click “Run” in OllyDbg to unfreeze the Minesweeper process, then we’ll clicked randomly at the Minesweeper window and trapped into mine, but now all mines are visible:

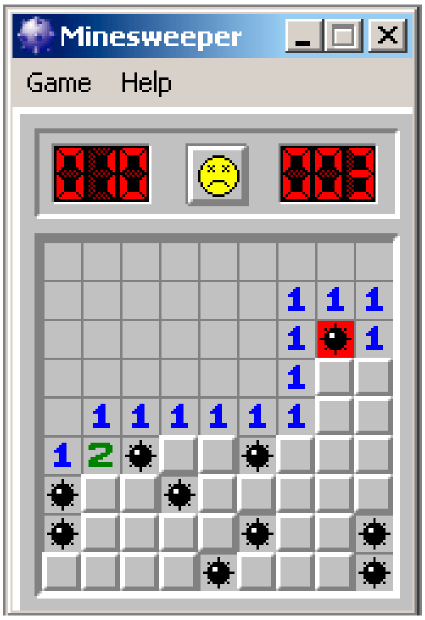


Figure 8.7: Mines

By comparing the mine places and the dump, we can conclude that 0x10 stands for border, 0x0F—empty block, 0x8F—mine. Perhaps, 0x10 is just a *sentinel value*.

Now we’ll add comments and also enclose all 0x8F bytes into square brackets:

```
border:
01005340  10 10 10 10 10 10 10 10 10 10 10 0F 0F 0F 0F 0F
01005350  0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F
line #1:
01005360  10 0F 0F 0F 0F 0F 0F 0F 0F 0F 10 0F 0F 0F 0F 0F
01005370  0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F
line #2:
01005380  10 0F 0F 0F 0F 0F 0F 0F 0F 0F 10 0F 0F 0F 0F 0F
01005390  0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F
line #3:
010053A0  10 0F 0F 0F 0F 0F 0F 0F[8F]0F 10 0F 0F 0F 0F 0F
010053B0  0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F
line #4:
010053C0  10 0F 0F 0F 0F 0F 0F 0F 0F 0F 10 0F 0F 0F 0F 0F
```

```
010053D0  0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F
line #5:
010053E0  10 0F 0F 0F 0F 0F 0F 0F 0F 0F 10 0F 0F 0F 0F 0F
010053F0  0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F
line #6:
01005400  10 0F 0F[8F]0F 0F[8F]0F 0F 0F 10 0F 0F 0F 0F 0F
01005410  0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F
line #7:
01005420  10[8F]0F 0F[8F]0F 0F 0F 0F 0F 10 0F 0F 0F 0F 0F
01005430  0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F
line #8:
01005440  10[8F]0F 0F 0F 0F[8F]0F 0F[8F]10 0F 0F 0F 0F 0F
01005450  0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F
line #9:
01005460  10 0F 0F 0F 0F[8F]0F 0F 0F[8F]10 0F 0F 0F 0F 0F
01005470  0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F
border:
01005480  10 10 10 10 10 10 10 10 10 10 10 0F 0F 0F 0F 0F
01005490  0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F 0F
```

Now we'll remove all *border bytes* (0x10) and what's beyond those:

```
 0F 0F 0F 0F 0F 0F 0F 0F 0F
 0F 0F 0F 0F 0F 0F 0F 0F 0F
 0F 0F 0F 0F 0F 0F 0F[8F]0F
 0F 0F 0F 0F 0F 0F 0F 0F 0F
 0F 0F 0F 0F 0F 0F 0F 0F 0F
 0F 0F[8F]0F 0F[8F]0F 0F 0F
[8F]0F 0F[8F]0F 0F 0F 0F 0F
[8F]0F 0F 0F 0F[8F]0F 0F[8F]
 0F 0F 0F 0F[8F]0F 0F 0F[8F]
```

Yes, these are mines, now it can be clearly seen and compared with the screenshot.

What is interesting is that we can modify the array right in OllyDbg. We can remove all mines by changing all 0x8F bytes by 0x0F, and here is what we'll get in Minesweeper:

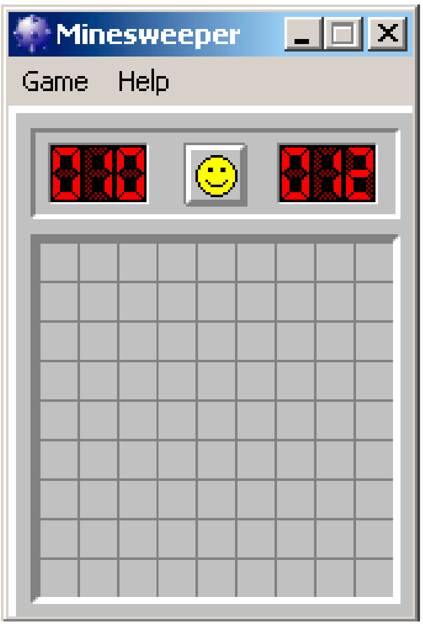


Figure 8.8: All mines are removed in debugger

We can also move all of them to the first line:

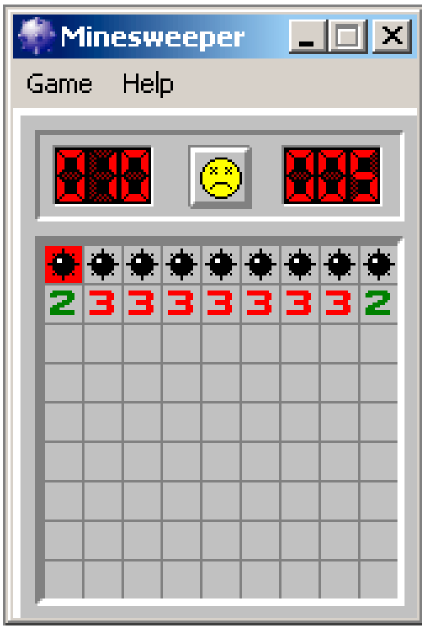


Figure 8.9: Mines set in debugger

Well, the debugger is not very convenient for eavesdropping (which is our goal anyway), so we'll write a small utility to dump the contents of the board:

```
// Windows XP MineSweeper cheater
// written by dennis(a)yurichev.com for http://beginners.re/ book
#include <windows.h>
#include <assert.h>
#include <stdio.h>

int main (int argc, char * argv[])
{
        int i, j;
        HANDLE h;
        DWORD PID, address, rd;
        BYTE board[27][32];
```

```
        if (argc!=3)
        {
                printf ("Usage: %s <PID> <address>\n", argv[0]);
                return 0;
        };

        assert (argv[1]!=NULL);
        assert (argv[2]!=NULL);

        assert (sscanf (argv[1], "%d", &PID)==1);
        assert (sscanf (argv[2], "%x", &address)==1);

        h=OpenProcess (PROCESS_VM_OPERATION | PROCESS_VM_READ | PROCESS_VM_WRITE, FALSE, PID);

        if (h==NULL)
        {
                DWORD e=GetLastError();
                printf ("OpenProcess error: %08X\n", e);
                return 0;
        };

        if (ReadProcessMemory (h, (LPVOID)address, board, sizeof(board), &rd)!=TRUE)
        {
                printf ("ReadProcessMemory() failed\n");
                return 0;
        };

        for (i=1; i<26; i++)
        {
                if (board[i][0]==0x10 && board[i][1]==0x10)
                        break; // end of board
                for (j=1; j<31; j++)
                {
                        if (board[i][j]==0x10)
                                break; // board border
                        if (board[i][j]==0x8F)
                                printf ("*");
                        else
                                printf (" ");

                };
                printf ("\n");
        };

        CloseHandle (h);
};
```

Just set the PID[5] [6] and the address of the array (`0x01005340` for Windows XP SP3 English) and it will dump it [7].

It attaches itself to a win32 process by PID and just reads process memory at the address.

8.3.1 Finding grid automatically

This is kind of nuisance to set address each time when we run our utility. Also, various Minesweeper versions may have the array on different address. Knowing the fact that there is always a border (0x10 bytes), we can just find it in memory:

```
        // find frame to determine the address
        process_mem=(BYTE*)malloc(process_mem_size);
        assert (process_mem!=NULL);

        if (ReadProcessMemory (h, (LPVOID)start_addr, process_mem, process_mem_size, &rd)!=TRUE
    )
```

[5] Program/process ID
[6] PID it can be seen in Task Manager (enable it in "View → Select Columns")
[7] The compiled executable is here: beginners.re

```
        {
                printf ("ReadProcessMemory() failed\n");
                return 0;
        };

        // for 9*9 grid.
        // FIXME: slow!
        for (i=0; i<process_mem_size; i++)
        {
                if (memcmp(process_mem+i, "\x10\x10\x10\x10\x10\x10\x10\x10\x10\x10\x10\x0F\x0F↙
    ↘ \x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x10", 32)↙
    ↘ ==0)
                {
                        // found
                        address=start_addr+i;
                        break;
                };
        };
        if (address==0)
        {
                printf ("Can't determine address of frame (and grid)\n");
                return 0;
        }
        else
        {
                printf ("Found frame and grid at 0x%x\n", address);
        };
```

Full source code: https://github.com/DennisYurichev/RE-for-beginners/blob/master/examples/minesweeper/minesweeper_cheater2.c.

8.3.2 Exercises

- Why do the *border bytes* (or *sentinel values*) (0x10) exist in the array?

  What they are for if they are not visible in Minesweeper's interface? How could it work without them?
- As it turns out, there are more values possible (for open blocks, for flagged by user, etc). Try to find the meaning of each one.
- Modify my utility so it can remove all mines or set them in a fixed pattern that you want in the Minesweeper process currently running.

8.4 Hacking Windows clock

Sometimes I do some kind of first April prank for my coworkers.

Let's find, if we could do something with Windows clock? Can we force to go clock hands backwards?

First of all, when you click on date/time in status bar,
a *C:\WINDOWS\SYSTEM32\TIMEDATE.CPL* module gets executed, which is usual executable PE-file.

Let's see, how it draw hands? When I open the file (from Windows 7) in Resource Hacker, there are clock faces, but with no hands:

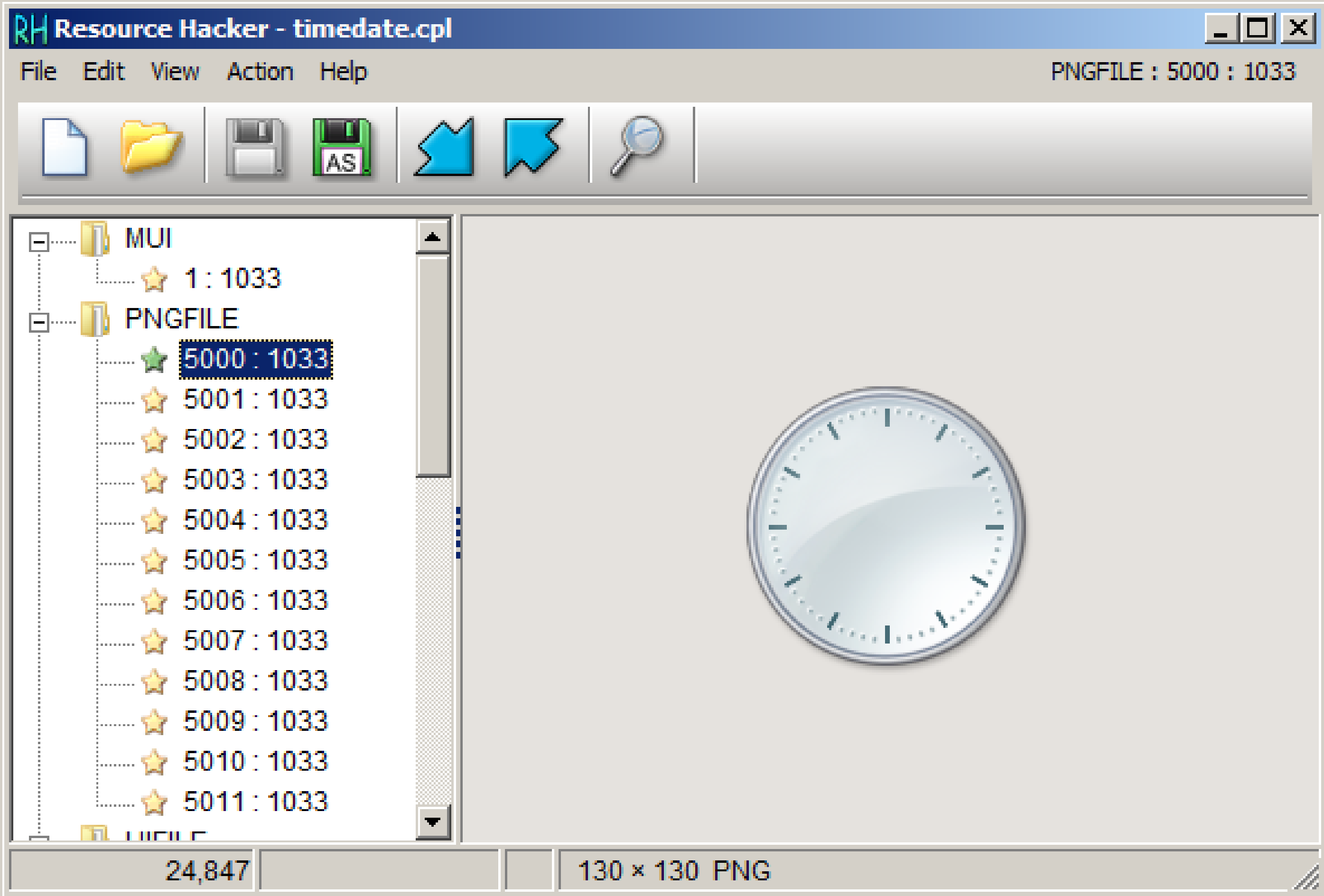


Figure 8.10: Resource Hacker

OK, what we know? How to draw a clock hand? All they are started at the middle of circle, ending with its border. Hence, we must calculate coordinates of a point on circle's border. From school-level mathematics we may recall that we have to use sine/cosine functions to draw circle, or at least square root. There are no such things in *TIMEDATE.CPL*, at least at first glance. But, thanks to Microsoft debugging PDB files, I can find a function named *CAnalogClock::DrawHand()*, which calls *Gdiplus::Graphics::DrawLine()* at least twice.

Here is its code:

```
.text:6EB9DBC7 ; private: enum  Gdiplus::Status __thiscall CAnalogClock::_DrawHand(class ⤦
    ↳ Gdiplus::Graphics *, int, struct ClockHand const &, class Gdiplus::Pen *)
.text:6EB9DBC7 ?_DrawHand@CAnalogClock@@AAE?⤦
    ↳ AW4Status@Gdiplus@@PAVGraphics@3@HABUClockHand@@PAVPen@3@@Z proc near
.text:6EB9DBC7                                         ; CODE XREF: CAnalogClock::_ClockPaint(⤦
    ↳ HDC__ *)+163
.text:6EB9DBC7                                         ; CAnalogClock::_ClockPaint(HDC__ *)+18B
.text:6EB9DBC7
.text:6EB9DBC7 var_10          = dword ptr -10h
.text:6EB9DBC7 var_C           = dword ptr -0Ch
.text:6EB9DBC7 var_8           = dword ptr -8
.text:6EB9DBC7 var_4           = dword ptr -4
.text:6EB9DBC7 arg_0           = dword ptr  8
.text:6EB9DBC7 arg_4           = dword ptr  0Ch
.text:6EB9DBC7 arg_8           = dword ptr  10h
.text:6EB9DBC7 arg_C           = dword ptr  14h
.text:6EB9DBC7
.text:6EB9DBC7                 mov     edi, edi
.text:6EB9DBC9                 push    ebp
.text:6EB9DBCA                 mov     ebp, esp
.text:6EB9DBCC                 sub     esp, 10h
.text:6EB9DBCF                 mov     eax, [ebp+arg_4]
.text:6EB9DBD2                 push    ebx
.text:6EB9DBD3                 push    esi
```

```
.text:6EB9DBD4                 push    edi
.text:6EB9DBD5                 cdq
.text:6EB9DBD6                 push    3Ch
.text:6EB9DBD8                 mov     esi, ecx
.text:6EB9DBDA                 pop     ecx
.text:6EB9DBDB                 idiv    ecx
.text:6EB9DBDD                 push    2
.text:6EB9DBDF                 lea     ebx, table[edx*8]
.text:6EB9DBE6                 lea     eax, [edx+1Eh]
.text:6EB9DBE9                 cdq
.text:6EB9DBEA                 idiv    ecx
.text:6EB9DBEC                 mov     ecx, [ebp+arg_0]
.text:6EB9DBEF                 mov     [ebp+var_4], ebx
.text:6EB9DBF2                 lea     eax, table[edx*8]
.text:6EB9DBF9                 mov     [ebp+arg_4], eax
.text:6EB9DBFC                 call    ?SetInterpolationMode@Graphics@Gdiplus@@QAE?↙
    ↳ AW4Status@2@W4InterpolationMode@2@@Z ; Gdiplus::Graphics::SetInterpolationMode(Gdiplus::↙
    ↳ InterpolationMode)
.text:6EB9DC01                 mov     eax, [esi+70h]
.text:6EB9DC04                 mov     edi, [ebp+arg_8]
.text:6EB9DC07                 mov     [ebp+var_10], eax
.text:6EB9DC0A                 mov     eax, [esi+74h]
.text:6EB9DC0D                 mov     [ebp+var_C], eax
.text:6EB9DC10                 mov     eax, [edi]
.text:6EB9DC12                 sub     eax, [edi+8]
.text:6EB9DC15                 push    8000            ; nDenominator
.text:6EB9DC1A                 push    eax             ; nNumerator
.text:6EB9DC1B                 push    dword ptr [ebx+4] ; nNumber
.text:6EB9DC1E                 mov     ebx, ds:__imp__MulDiv@12 ; MulDiv(x,x,x)
.text:6EB9DC24                 call    ebx ; MulDiv(x,x,x) ; MulDiv(x,x,x)
.text:6EB9DC26                 add     eax, [esi+74h]
.text:6EB9DC29                 push    8000            ; nDenominator
.text:6EB9DC2E                 mov     [ebp+arg_8], eax
.text:6EB9DC31                 mov     eax, [edi]
.text:6EB9DC33                 sub     eax, [edi+8]
.text:6EB9DC36                 push    eax             ; nNumerator
.text:6EB9DC37                 mov     eax, [ebp+var_4]
.text:6EB9DC3A                 push    dword ptr [eax] ; nNumber
.text:6EB9DC3C                 call    ebx ; MulDiv(x,x,x) ; MulDiv(x,x,x)
.text:6EB9DC3E                 add     eax, [esi+70h]
.text:6EB9DC41                 mov     ecx, [ebp+arg_0]
.text:6EB9DC44                 mov     [ebp+var_8], eax
.text:6EB9DC47                 mov     eax, [ebp+arg_8]
.text:6EB9DC4A                 mov     [ebp+var_4], eax
.text:6EB9DC4D                 lea     eax, [ebp+var_8]
.text:6EB9DC50                 push    eax
.text:6EB9DC51                 lea     eax, [ebp+var_10]
.text:6EB9DC54                 push    eax
.text:6EB9DC55                 push    [ebp+arg_C]
.text:6EB9DC58                 call    ?DrawLine@Graphics@Gdiplus@@QAE?↙
    ↳ AW4Status@2@PBVPen@2@ABVPoint@2@1@Z ; Gdiplus::Graphics::DrawLine(Gdiplus::Pen const *,↙
    ↳ Gdiplus::Point const &,Gdiplus::Point const &)
.text:6EB9DC5D                 mov     ecx, [edi+8]
.text:6EB9DC60                 test    ecx, ecx
.text:6EB9DC62                 jbe     short loc_6EB9DCAA
.text:6EB9DC64                 test    eax, eax
.text:6EB9DC66                 jnz     short loc_6EB9DCAA
.text:6EB9DC68                 mov     eax, [ebp+arg_4]
.text:6EB9DC6B                 push    8000            ; nDenominator
.text:6EB9DC70                 push    ecx             ; nNumerator
.text:6EB9DC71                 push    dword ptr [eax+4] ; nNumber
.text:6EB9DC74                 call    ebx ; MulDiv(x,x,x) ; MulDiv(x,x,x)
.text:6EB9DC76                 add     eax, [esi+74h]
.text:6EB9DC79                 push    8000            ; nDenominator
.text:6EB9DC7E                 push    dword ptr [edi+8] ; nNumerator
.text:6EB9DC81                 mov     [ebp+arg_8], eax
.text:6EB9DC84                 mov     eax, [ebp+arg_4]
.text:6EB9DC87                 push    dword ptr [eax] ; nNumber
.text:6EB9DC89                 call    ebx ; MulDiv(x,x,x) ; MulDiv(x,x,x)
.text:6EB9DC8B                 add     eax, [esi+70h]
```

```
.text:6EB9DC8E                 mov     ecx, [ebp+arg_0]
.text:6EB9DC91                 mov     [ebp+var_8], eax
.text:6EB9DC94                 mov     eax, [ebp+arg_8]
.text:6EB9DC97                 mov     [ebp+var_4], eax
.text:6EB9DC9A                 lea     eax, [ebp+var_8]
.text:6EB9DC9D                 push    eax
.text:6EB9DC9E                 lea     eax, [ebp+var_10]
.text:6EB9DCA1                 push    eax
.text:6EB9DCA2                 push    [ebp+arg_C]
.text:6EB9DCA5                 call    ?DrawLine@Graphics@Gdiplus@@QAE?↙
    ↳ AW4Status@2@PBVPen@2@ABVPoint@2@1@Z ; Gdiplus::Graphics::DrawLine(Gdiplus::Pen const *,↙
    ↳ Gdiplus::Point const &,Gdiplus::Point const &)
.text:6EB9DCAA
.text:6EB9DCAA loc_6EB9DCAA:                           ; CODE XREF: CAnalogClock::_DrawHand(↙
    ↳ Gdiplus::Graphics *,int,ClockHand const &,Gdiplus::Pen *)+9B
.text:6EB9DCAA                                         ; CAnalogClock::_DrawHand(Gdiplus::↙
    ↳ Graphics *,int,ClockHand const &,Gdiplus::Pen *)+9F
.text:6EB9DCAA                 pop     edi
.text:6EB9DCAB                 pop     esi
.text:6EB9DCAC                 pop     ebx
.text:6EB9DCAD                 leave
.text:6EB9DCAE                 retn    10h
.text:6EB9DCAE ?_DrawHand@CAnalogClock@@AAE?↙
    ↳ AW4Status@Gdiplus@@PAVGraphics@3@HABUClockHand@@PAVPen@3@@Z endp
.text:6EB9DCAE
```

We can see that *DrawLine()* arguments are dependent on result of *MulDiv()* function and a *table[]* table (name is mine), which has 8-byte elements (look at LEA's second operand).

What is inside of table[]?

```
.text:6EB87890 ; int table[]
.text:6EB87890 table           dd 0
.text:6EB87894                 dd 0FFFFE0C1h
.text:6EB87898                 dd 344h
.text:6EB8789C                 dd 0FFFFE0ECh
.text:6EB878A0                 dd 67Fh
.text:6EB878A4                 dd 0FFFFE16Fh
.text:6EB878A8                 dd 9A8h
.text:6EB878AC                 dd 0FFFFE248h
.text:6EB878B0                 dd 0CB5h
.text:6EB878B4                 dd 0FFFFE374h
.text:6EB878B8                 dd 0F9Fh
.text:6EB878BC                 dd 0FFFFE4F0h
.text:6EB878C0                 dd 125Eh
.text:6EB878C4                 dd 0FFFFE6B8h
.text:6EB878C8                 dd 14E9h

...
```

It's referenced only from *DrawHand()* function. It has 120 32-bit words or 60 32-bit pairs... wait, 60? Let's take a closer look at these values. First of all, I'll zap 6 pairs or 12 32-bit words with zeros, and then I'll put patched *TIMEDATE.CPL* into *C:\WINDOWS\SYSTEM32*. (You may need to set owner of the *TIMEDATE.CPL* file to your primary user account (instead of *TrustedInstaller*), and also, boot in safe mode with command prompt so you can copy the file, which is usually locked.)

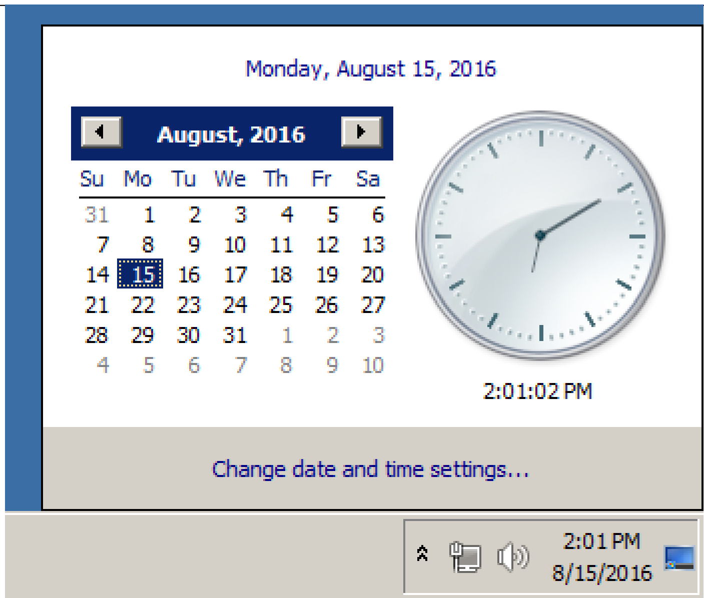


Figure 8.11: Attempt to run

Now when any hand is located at 0..5 seconds/minutes, it's invisible! However, opposite (shorter) part of second hand is visible and moving. When any hand is outside of this area, hand is visible as usual.

Let's take even closer look at the table in Mathematica. I have copypasted table from the *TIMEDATE.CPL* to a *tbl* file (480 bytes). We will take for granted the fact that these are signed values, because half of elements are below zero (0FFFFE0C1h, etc.). If these values would be unsigned, they would be suspiciously huge.

```
In[]:= tbl = BinaryReadList["~/.../tbl", "Integer32"]

Out[]= {0, -7999, 836, -7956, 1663, -7825, 2472, -7608, 3253, -7308, 3999, \
-6928, 4702, -6472, 5353, -5945, 5945, -5353, 6472, -4702, 6928, \
-4000, 7308, -3253, 7608, -2472, 7825, -1663, 7956, -836, 8000, 0, \
7956, 836, 7825, 1663, 7608, 2472, 7308, 3253, 6928, 4000, 6472, \
4702, 5945, 5353, 5353, 5945, 4702, 6472, 3999, 6928, 3253, 7308, \
2472, 7608, 1663, 7825, 836, 7956, 0, 7999, -836, 7956, -1663, 7825, \
-2472, 7608, -3253, 7308, -4000, 6928, -4702, 6472, -5353, 5945, \
-5945, 5353, -6472, 4702, -6928, 3999, -7308, 3253, -7608, 2472, \
-7825, 1663, -7956, 836, -7999, 0, -7956, -836, -7825, -1663, -7608, \
-2472, -7308, -3253, -6928, -4000, -6472, -4702, -5945, -5353, -5353, \
-5945, -4702, -6472, -3999, -6928, -3253, -7308, -2472, -7608, -1663, \
-7825, -836, -7956}

In[]:= Length[tbl]
Out[]= 120
```

Let's treat two consecutive 32-bit values as pair:

```
In[]:= pairs = Partition[tbl, 2]
Out[]= {{0, -7999}, {836, -7956}, {1663, -7825}, {2472, -7608}, \
{3253, -7308}, {3999, -6928}, {4702, -6472}, {5353, -5945}, {5945, \
-5353}, {6472, -4702}, {6928, -4000}, {7308, -3253}, {7608, -2472}, \
{7825, -1663}, {7956, -836}, {8000, 0}, {7956, 836}, {7825,
1663}, {7608, 2472}, {7308, 3253}, {6928, 4000}, {6472,
4702}, {5945, 5353}, {5353, 5945}, {4702, 6472}, {3999,
6928}, {3253, 7308}, {2472, 7608}, {1663, 7825}, {836, 7956}, {0,
7999}, {-836, 7956}, {-1663, 7825}, {-2472, 7608}, {-3253,
7308}, {-4000, 6928}, {-4702, 6472}, {-5353, 5945}, {-5945,
5353}, {-6472, 4702}, {-6928, 3999}, {-7308, 3253}, {-7608,
2472}, {-7825, 1663}, {-7956, 836}, {-7999,
0}, {-7956, -836}, {-7825, -1663}, {-7608, -2472}, {-7308, -3253}, \
{-6928, -4000}, {-6472, -4702}, {-5945, -5353}, {-5353, -5945}, \
{-4702, -6472}, {-3999, -6928}, {-3253, -7308}, {-2472, -7608}, \
{-1663, -7825}, {-836, -7956}}

In[]:= Length[pairs]
```

```
Out[]= 60
```

Let's try to treat each pair as X/Y coordinate and draw all 60 pairs, and also first 15 pairs:

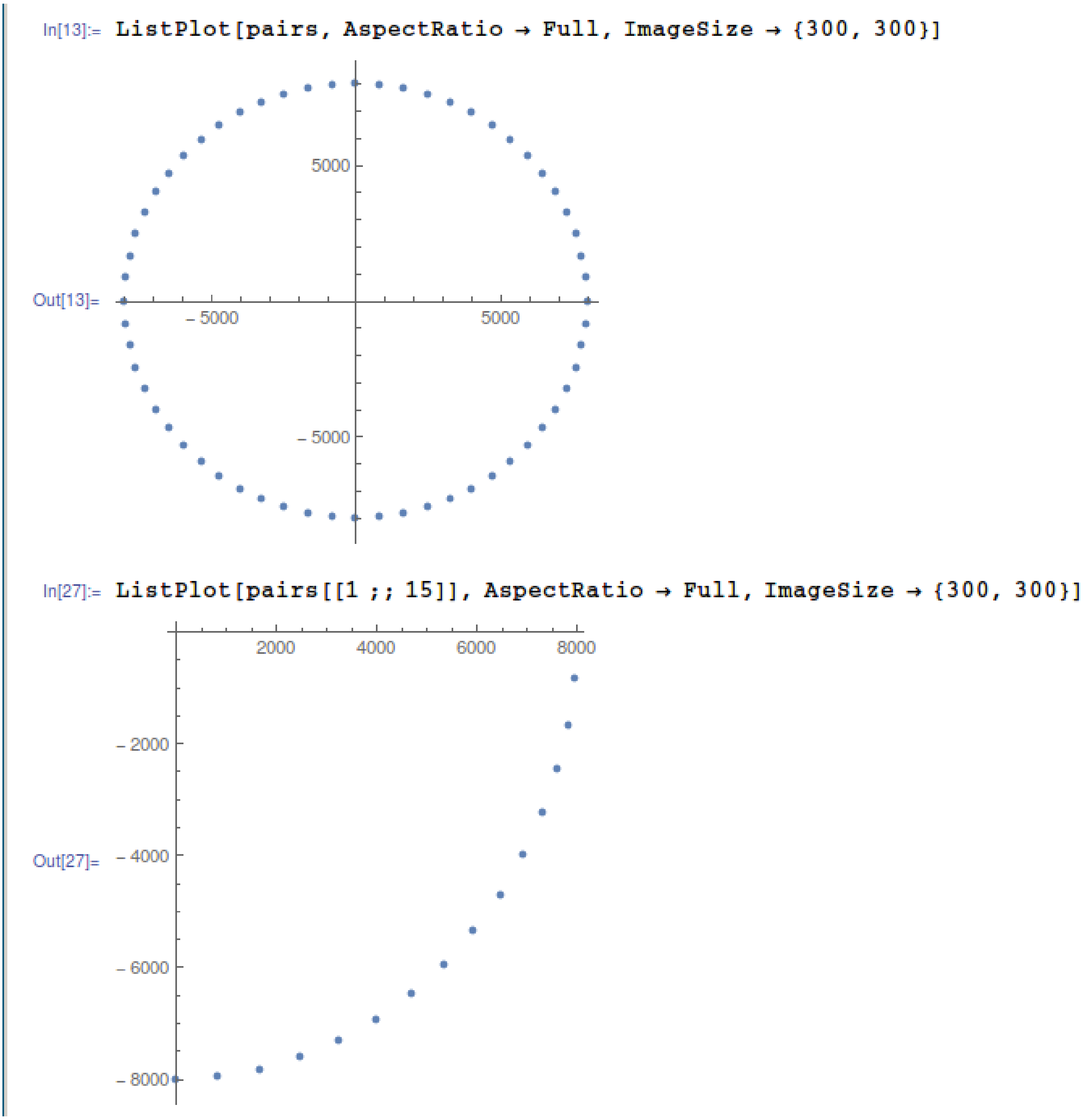


Figure 8.12: Mathematica

Now this is something! Each pair is just coordinate. First 15 pairs are coordinates for $\frac{1}{4}$ of circle.

Perhaps, Microsoft developers precalculated all coordinates and put them into table.

Now I can understand why when I zapped first 6 pairs, hands were invisible at that area: in fact, hands were drawn, they just had zero length, because hand started at 0:0 coordinate and ended there.

The prank (practical joke)

Given all that, how would we force hands to go counterclockwise? In fact, this is simple, we need just to rotate the table, so each hand, instead of drawing at place of zeroth second, would be drawing at place of 59th second.

I made the patcher a long time ago, at the very beginning of 2000s, for Windows 2000. Hard to believe, it still works for Windows 7, perhaps, the table hasn't been changed since then!

Patcher source code: https://github.com/DennisYurichev/random_notes/blob/master/timedate/time_pt.c.

Now I can see all hands goes backwards:

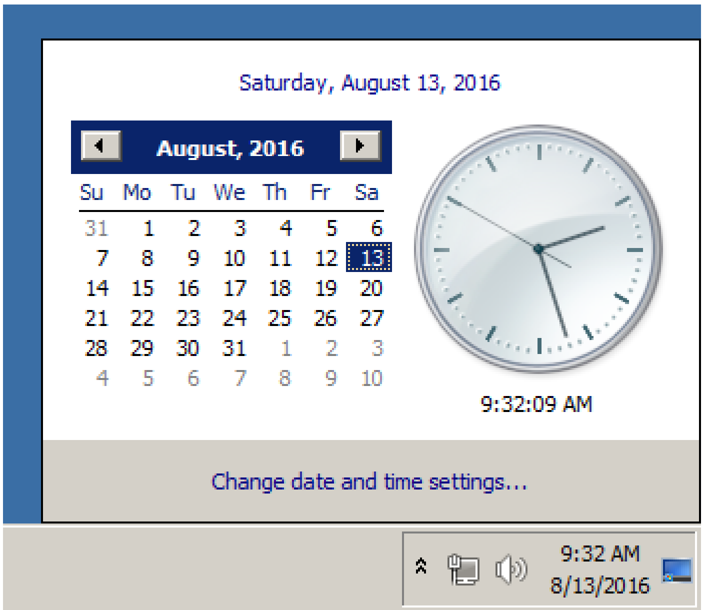


Figure 8.13: Now it works

Well, there is no animation in this book, but if you look closer, you can see, that hands are in fact shows correct time, but the whole clock face is rotated vertically, like we see it from the inside of clock.

Windows 2000 leaked source code

So I did the patcher and then Windows 2000 source code has been leaked (I can't force you to trust me, though). Let's take a look on source code if that function and table.
The file is *win2k/private/shell/cpls/utc/clock.c*:

```
//
//  Array containing the sine and cosine values for hand positions.
//
POINT rCircleTable[] =
{
    { 0,     -7999},
    { 836,   -7956},
    { 1663,  -7825},
    { 2472,  -7608},
    { 3253,  -7308},
...
    { -4702, -6472},
    { -3999, -6928},
    { -3253, -7308},
    { -2472, -7608},
    { -1663, -7825},
    { -836 , -7956},
};

////////////////////////////////////////////////////////////////////////////
//
//  DrawHand
//
//  Draws the hands of the clock.
//
////////////////////////////////////////////////////////////////////////////
```

```
void DrawHand(
    HDC hDC,
    int pos,
    HPEN hPen,
    int scale,
    int patMode,
    PCLOCKSTR np)
{
    LPPOINT lppt;
    int radius;

    MoveTo(hDC, np->clockCenter.x, np->clockCenter.y);
    radius = MulDiv(np->clockRadius, scale, 100);
    lppt = rCircleTable + pos;
    SetROP2(hDC, patMode);
    SelectObject(hDC, hPen);

    LineTo( hDC,
            np->clockCenter.x + MulDiv(lppt->x, radius, 8000),
            np->clockCenter.y + MulDiv(lppt->y, radius, 8000) );
}
```

Now it's clear: coordinates has been precalculated as if clock face has height and width of $2 \cdot 8000$, and then it's rescaled to current clock face radius using *MulDiv()* function.

POINT structure[8] is a structure of two 32-bit values, first is *x*, second is *y*.

8.5 Dongles

The author of these lines, occasionally did software copy-protection dongle replacements, or "dongle emulators" and here are couple examples of how it's happening.

About one of the cases about Rocket and Z3 that is not present here, you can read here: http://yurichev.com/tmp/SAT_SMT_DRAFT.pdf.

8.5.1 Example #1: MacOS Classic and PowerPC

Here is an example of a program for MacOS Classic [9], for PowerPC. The company who developed the software product has disappeared a long time ago, so the (legal) customer was afraid of physical dongle damage.

While running without a dongle connected, a message box with the text "Invalid Security Device" appeared.

Luckily, this text string could easily be found in the executable binary file.

Let's pretend we are not very familiar both with Mac OS Classic and PowerPC, but will try anyway.

IDA opened the executable file smoothly, reported its type as "PEF (Mac OS or Be OS executable)" (indeed, it is a standard Mac OS Classic file format).

By searching for the text string with the error message, we've got into this code fragment:

```
...

seg000:000C87FC 38 60 00 01   li      %r3, 1
seg000:000C8800 48 03 93 41   bl      check1
seg000:000C8804 60 00 00 00   nop
seg000:000C8808 54 60 06 3F   clrlwi. %r0, %r3, 24
seg000:000C880C 40 82 00 40   bne     OK
seg000:000C8810 80 62 9F D8   lwz     %r3, TC_aInvalidSecurityDevice

...
```

[8] https://msdn.microsoft.com/en-us/library/windows/desktop/dd162805(v=vs.85).aspx
[9] pre-UNIX MacOS

Yes, this is PowerPC code.

The CPU is a very typical 32-bit RISC of 1990s era.

Each instruction occupies 4 bytes (just as in MIPS and ARM) and the names somewhat resemble MIPS instruction names.

check1() is a function name we'll give to it later. BL is *Branch Link* instruction, e.g., intended for calling subroutines.

The crucial point is the BNE instruction which jumps if the dongle protection check passes or not if an error occurs: then the address of the text string gets loaded into the r3 register for the subsequent passing into a message box routine.

From the [Steve Zucker, SunSoft and Kari Karhi, IBM, *SYSTEM V APPLICATION BINARY INTERFACE: PowerPC Processor Supplement*, (1995)][10]we will found out that the r3 register is used for return values (and r4, in case of 64-bit values).

Another yet unknown instruction is CLRLWI. From [*PowerPC(tm) Microprocessor Family: The Programming Environments for 32-Bit Microprocessors*, (2000)][11]we'll learn that this instruction does both clearing and loading. In our case, it clears the 24 high bits from the value in r3 and puts them in r0, so it is analogical to MOVZX in x86 (1.17.1 on page 202), but it also sets the flags, so BNE can check them afterwards.

Let's take a look into the check1() function:

```
seg000:00101B40             check1: # CODE XREF: seg000:00063E7Cp
seg000:00101B40                     # sub_64070+160p ...
seg000:00101B40
seg000:00101B40             .set arg_8,  8
seg000:00101B40
seg000:00101B40 7C 08 02 A6         mflr    %r0
seg000:00101B44 90 01 00 08         stw     %r0, arg_8(%sp)
seg000:00101B48 94 21 FF C0         stwu    %sp, -0x40(%sp)
seg000:00101B4C 48 01 6B 39         bl      check2
seg000:00101B50 60 00 00 00         nop
seg000:00101B54 80 01 00 48         lwz     %r0, 0x40+arg_8(%sp)
seg000:00101B58 38 21 00 40         addi    %sp, %sp, 0x40
seg000:00101B5C 7C 08 03 A6         mtlr    %r0
seg000:00101B60 4E 80 00 20         blr
seg000:00101B60             # End of function check1
```

As you can see in IDA, that function is called from many places in the program, but only the r3 register's value is checked after each call.

All this function does is to call the other function, so it is a thunk function: there are function prologue and epilogue, but the r3 register is not touched, so checkl() returns what check2() returns.

BLR[12] looks like the return from the function, but since IDA does the function layout, we probably do not need to care about this.

Since it is a typical RISC, it seems that subroutines are called using a link register, just like in ARM.

The check2() function is more complex:

```
seg000:00118684             check2: # CODE XREF: check1+Cp
seg000:00118684
seg000:00118684             .set var_18, -0x18
seg000:00118684             .set var_C, -0xC
seg000:00118684             .set var_8, -8
seg000:00118684             .set var_4, -4
seg000:00118684             .set arg_8,  8
seg000:00118684
seg000:00118684 93 E1 FF FC   stw     %r31, var_4(%sp)
seg000:00118688 7C 08 02 A6   mflr    %r0
seg000:0011868C 83 E2 95 A8   lwz     %r31, off_1485E8 # dword_24B704
seg000:00118690               .using dword_24B704, %r31
seg000:00118690 93 C1 FF F8   stw     %r30, var_8(%sp)
seg000:00118694 93 A1 FF F4   stw     %r29, var_C(%sp)
seg000:00118698 7C 7D 1B 78   mr      %r29, %r3
seg000:0011869C 90 01 00 08   stw     %r0, arg_8(%sp)
```

[10]Also available as http://yurichev.com/mirrors/PowerPC/elfspec_ppc.pdf
[11]Also available as http://yurichev.com/mirrors/PowerPC/6xx_pem.pdf
[12](PowerPC) Branch to Link Register

```
seg000:001186A0 54 60 06 3E   clrlwi  %r0, %r3, 24
seg000:001186A4 28 00 00 01   cmplwi  %r0, 1
seg000:001186A8 94 21 FF B0   stwu    %sp, -0x50(%sp)
seg000:001186AC 40 82 00 0C   bne     loc_1186B8
seg000:001186B0 38 60 00 01   li      %r3, 1
seg000:001186B4 48 00 00 6C   b       exit
seg000:001186B8
seg000:001186B8              loc_1186B8: # CODE XREF: check2+28j
seg000:001186B8 48 00 03 D5   bl      sub_118A8C
seg000:001186BC 60 00 00 00   nop
seg000:001186C0 3B C0 00 00   li      %r30, 0
seg000:001186C4
seg000:001186C4              skip:       # CODE XREF: check2+94j
seg000:001186C4 57 C0 06 3F   clrlwi. %r0, %r30, 24
seg000:001186C8 41 82 00 18   beq     loc_1186E0
seg000:001186CC 38 61 00 38   addi    %r3, %sp, 0x50+var_18
seg000:001186D0 80 9F 00 00   lwz     %r4, dword_24B704
seg000:001186D4 48 00 C0 55   bl      .RBEFINDNEXT
seg000:001186D8 60 00 00 00   nop
seg000:001186DC 48 00 00 1C   b       loc_1186F8
seg000:001186E0
seg000:001186E0              loc_1186E0: # CODE XREF: check2+44j
seg000:001186E0 80 BF 00 00   lwz     %r5, dword_24B704
seg000:001186E4 38 81 00 38   addi    %r4, %sp, 0x50+var_18
seg000:001186E8 38 60 08 C2   li      %r3, 0x1234
seg000:001186EC 48 00 BF 99   bl      .RBEFINDFIRST
seg000:001186F0 60 00 00 00   nop
seg000:001186F4 3B C0 00 01   li      %r30, 1
seg000:001186F8
seg000:001186F8              loc_1186F8: # CODE XREF: check2+58j
seg000:001186F8 54 60 04 3F   clrlwi. %r0, %r3, 16
seg000:001186FC 41 82 00 0C   beq     must_jump
seg000:00118700 38 60 00 00   li      %r3, 0          # error
seg000:00118704 48 00 00 1C   b       exit
seg000:00118708
seg000:00118708              must_jump:  # CODE XREF: check2+78j
seg000:00118708 7F A3 EB 78   mr      %r3, %r29
seg000:0011870C 48 00 00 31   bl      check3
seg000:00118710 60 00 00 00   nop
seg000:00118714 54 60 06 3F   clrlwi. %r0, %r3, 24
seg000:00118718 41 82 FF AC   beq     skip
seg000:0011871C 38 60 00 01   li      %r3, 1
seg000:00118720
seg000:00118720              exit:       # CODE XREF: check2+30j
seg000:00118720                          # check2+80j
seg000:00118720 80 01 00 58   lwz     %r0, 0x50+arg_8(%sp)
seg000:00118724 38 21 00 50   addi    %sp, %sp, 0x50
seg000:00118728 83 E1 FF FC   lwz     %r31, var_4(%sp)
seg000:0011872C 7C 08 03 A6   mtlr    %r0
seg000:00118730 83 C1 FF F8   lwz     %r30, var_8(%sp)
seg000:00118734 83 A1 FF F4   lwz     %r29, var_C(%sp)
seg000:00118738 4E 80 00 20   blr
seg000:00118738              # End of function check2
```

We are lucky again: some function names are left in the executable (debug symbols section? Hard to say while we are not very familiar with the file format, maybe it is some kind of PE exports? (6.5.2 on page 760)), like `.RBEFINDNEXT()` and `.RBEFINDFIRST()`.

Eventually these functions call other functions with names like `.GetNextDeviceViaUSB()`, `.USBSendPKT()`, so these are clearly dealing with an USB device.

There is even a function named `.GetNextEve3Device()`—sounds familiar, there was a Sentinel Eve3 dongle for ADB port (present on Macs) in 1990s.

Let's first take a look on how the r3 register is set before return, while ignoring everything else.

We know that a "good" r3 value has to be non-zero, zero r3 leads the execution flow to the message box with an error message.

There are two `li %r3, 1` instructions present in the function and one `li %r3, 0` (*Load Immediate*, i.e., loading a value into a register). The first instruction is at 0x001186B0—and frankly speaking, it's hard to say what it means.

What we see next is, however, easier to understand: .RBEFINDFIRST() is called: if it fails, 0 is written into r3 and we jump to *exit*, otherwise another function is called (check3())—if it fails too, .RBEFINDNEXT() is called, probably in order to look for another USB device.

N.B.: `clrlwi. %r0, %r3, 16` it is analogical to what we already saw, but it clears 16 bits, i.e., .RBEFINDFIRST() probably returns a 16-bit value.

B (stands for *branch*) unconditional jump.

BEQ is the inverse instruction of BNE.

Let's see check3():

```
seg000:0011873C             check3: # CODE XREF: check2+88p
seg000:0011873C
seg000:0011873C             .set var_18, -0x18
seg000:0011873C             .set var_C, -0xC
seg000:0011873C             .set var_8, -8
seg000:0011873C             .set var_4, -4
seg000:0011873C             .set arg_8,  8
seg000:0011873C
seg000:0011873C 93 E1 FF FC   stw     %r31, var_4(%sp)
seg000:00118740 7C 08 02 A6   mflr    %r0
seg000:00118744 38 A0 00 00   li      %r5, 0
seg000:00118748 93 C1 FF F8   stw     %r30, var_8(%sp)
seg000:0011874C 83 C2 95 A8   lwz     %r30, off_1485E8 # dword_24B704
seg000:00118750               .using dword_24B704, %r30
seg000:00118750 93 A1 FF F4   stw     %r29, var_C(%sp)
seg000:00118754 3B A3 00 00   addi    %r29, %r3, 0
seg000:00118758 38 60 00 00   li      %r3, 0
seg000:0011875C 90 01 00 08   stw     %r0, arg_8(%sp)
seg000:00118760 94 21 FF B0   stwu    %sp, -0x50(%sp)
seg000:00118764 80 DE 00 00   lwz     %r6, dword_24B704
seg000:00118768 38 81 00 38   addi    %r4, %sp, 0x50+var_18
seg000:0011876C 48 00 C0 5D   bl      .RBEREAD
seg000:00118770 60 00 00 00   nop
seg000:00118774 54 60 04 3F   clrlwi. %r0, %r3, 16
seg000:00118778 41 82 00 0C   beq     loc_118784
seg000:0011877C 38 60 00 00   li      %r3, 0
seg000:00118780 48 00 02 F0   b       exit
seg000:00118784
seg000:00118784             loc_118784: # CODE XREF: check3+3Cj
seg000:00118784 A0 01 00 38   lhz     %r0, 0x50+var_18(%sp)
seg000:00118788 28 00 04 B2   cmplwi  %r0, 0x1100
seg000:0011878C 41 82 00 0C   beq     loc_118798
seg000:00118790 38 60 00 00   li      %r3, 0
seg000:00118794 48 00 02 DC   b       exit
seg000:00118798
seg000:00118798             loc_118798: # CODE XREF: check3+50j
seg000:00118798 80 DE 00 00   lwz     %r6, dword_24B704
seg000:0011879C 38 81 00 38   addi    %r4, %sp, 0x50+var_18
seg000:001187A0 38 60 00 01   li      %r3, 1
seg000:001187A4 38 A0 00 00   li      %r5, 0
seg000:001187A8 48 00 C0 21   bl      .RBEREAD
seg000:001187AC 60 00 00 00   nop
seg000:001187B0 54 60 04 3F   clrlwi. %r0, %r3, 16
seg000:001187B4 41 82 00 0C   beq     loc_1187C0
seg000:001187B8 38 60 00 00   li      %r3, 0
seg000:001187BC 48 00 02 B4   b       exit
seg000:001187C0
seg000:001187C0             loc_1187C0: # CODE XREF: check3+78j
seg000:001187C0 A0 01 00 38   lhz     %r0, 0x50+var_18(%sp)
seg000:001187C4 28 00 06 4B   cmplwi  %r0, 0x09AB
seg000:001187C8 41 82 00 0C   beq     loc_1187D4
seg000:001187CC 38 60 00 00   li      %r3, 0
seg000:001187D0 48 00 02 A0   b       exit
seg000:001187D4
seg000:001187D4             loc_1187D4: # CODE XREF: check3+8Cj
seg000:001187D4 4B F9 F3 D9   bl      sub_B7BAC
```

```
seg000:001187D8 60 00 00 00   nop
seg000:001187DC 54 60 06 3E   clrlwi  %r0, %r3, 24
seg000:001187E0 2C 00 00 05   cmpwi   %r0, 5
seg000:001187E4 41 82 01 00   beq     loc_1188E4
seg000:001187E8 40 80 00 10   bge     loc_1187F8
seg000:001187EC 2C 00 00 04   cmpwi   %r0, 4
seg000:001187F0 40 80 00 58   bge     loc_118848
seg000:001187F4 48 00 01 8C   b       loc_118980
seg000:001187F8
seg000:001187F8              loc_1187F8: # CODE XREF: check3+ACj
seg000:001187F8 2C 00 00 0B   cmpwi   %r0, 0xB
seg000:001187FC 41 82 00 08   beq     loc_118804
seg000:00118800 48 00 01 80   b       loc_118980
seg000:00118804
seg000:00118804              loc_118804: # CODE XREF: check3+C0j
seg000:00118804 80 DE 00 00   lwz     %r6, dword_24B704
seg000:00118808 38 81 00 38   addi    %r4, %sp, 0x50+var_18
seg000:0011880C 38 60 00 08   li      %r3, 8
seg000:00118810 38 A0 00 00   li      %r5, 0
seg000:00118814 48 00 BF B5   bl      .RBEREAD
seg000:00118818 60 00 00 00   nop
seg000:0011881C 54 60 04 3F   clrlwi. %r0, %r3, 16
seg000:00118820 41 82 00 0C   beq     loc_11882C
seg000:00118824 38 60 00 00   li      %r3, 0
seg000:00118828 48 00 02 48   b       exit
seg000:0011882C
seg000:0011882C              loc_11882C: # CODE XREF: check3+E4j
seg000:0011882C A0 01 00 38   lhz     %r0, 0x50+var_18(%sp)
seg000:00118830 28 00 11 30   cmplwi  %r0, 0xFEA0
seg000:00118834 41 82 00 0C   beq     loc_118840
seg000:00118838 38 60 00 00   li      %r3, 0
seg000:0011883C 48 00 02 34   b       exit
seg000:00118840
seg000:00118840              loc_118840: # CODE XREF: check3+F8j
seg000:00118840 38 60 00 01   li      %r3, 1
seg000:00118844 48 00 02 2C   b       exit
seg000:00118848
seg000:00118848              loc_118848: # CODE XREF: check3+B4j
seg000:00118848 80 DE 00 00   lwz     %r6, dword_24B704
seg000:0011884C 38 81 00 38   addi    %r4, %sp, 0x50+var_18
seg000:00118850 38 60 00 0A   li      %r3, 0xA
seg000:00118854 38 A0 00 00   li      %r5, 0
seg000:00118858 48 00 BF 71   bl      .RBEREAD
seg000:0011885C 60 00 00 00   nop
seg000:00118860 54 60 04 3F   clrlwi. %r0, %r3, 16
seg000:00118864 41 82 00 0C   beq     loc_118870
seg000:00118868 38 60 00 00   li      %r3, 0
seg000:0011886C 48 00 02 04   b       exit
seg000:00118870
seg000:00118870              loc_118870: # CODE XREF: check3+128j
seg000:00118870 A0 01 00 38   lhz     %r0, 0x50+var_18(%sp)
seg000:00118874 28 00 03 F3   cmplwi  %r0, 0xA6E1
seg000:00118878 41 82 00 0C   beq     loc_118884
seg000:0011887C 38 60 00 00   li      %r3, 0
seg000:00118880 48 00 01 F0   b       exit
seg000:00118884
seg000:00118884              loc_118884: # CODE XREF: check3+13Cj
seg000:00118884 57 BF 06 3E   clrlwi  %r31, %r29, 24
seg000:00118888 28 1F 00 02   cmplwi  %r31, 2
seg000:0011888C 40 82 00 0C   bne     loc_118898
seg000:00118890 38 60 00 01   li      %r3, 1
seg000:00118894 48 00 01 DC   b       exit
seg000:00118898
seg000:00118898              loc_118898: # CODE XREF: check3+150j
seg000:00118898 80 DE 00 00   lwz     %r6, dword_24B704
seg000:0011889C 38 81 00 38   addi    %r4, %sp, 0x50+var_18
seg000:001188A0 38 60 00 0B   li      %r3, 0xB
seg000:001188A4 38 A0 00 00   li      %r5, 0
seg000:001188A8 48 00 BF 21   bl      .RBEREAD
seg000:001188AC 60 00 00 00   nop
```

```
seg000:001188B0 54 60 04 3F   clrlwi. %r0, %r3, 16
seg000:001188B4 41 82 00 0C   beq     loc_1188C0
seg000:001188B8 38 60 00 00   li      %r3, 0
seg000:001188BC 48 00 01 B4   b       exit
seg000:001188C0
seg000:001188C0              loc_1188C0: # CODE XREF: check3+178j
seg000:001188C0 A0 01 00 38   lhz     %r0, 0x50+var_18(%sp)
seg000:001188C4 28 00 23 1C   cmplwi  %r0, 0x1C20
seg000:001188C8 41 82 00 0C   beq     loc_1188D4
seg000:001188CC 38 60 00 00   li      %r3, 0
seg000:001188D0 48 00 01 A0   b       exit
seg000:001188D4
seg000:001188D4              loc_1188D4: # CODE XREF: check3+18Cj
seg000:001188D4 28 1F 00 03   cmplwi  %r31, 3
seg000:001188D8 40 82 01 94   bne     error
seg000:001188DC 38 60 00 01   li      %r3, 1
seg000:001188E0 48 00 01 90   b       exit
seg000:001188E4
seg000:001188E4              loc_1188E4: # CODE XREF: check3+A8j
seg000:001188E4 80 DE 00 00   lwz     %r6, dword_24B704
seg000:001188E8 38 81 00 38   addi    %r4, %sp, 0x50+var_18
seg000:001188EC 38 60 00 0C   li      %r3, 0xC
seg000:001188F0 38 A0 00 00   li      %r5, 0
seg000:001188F4 48 00 BE D5   bl      .RBEREAD
seg000:001188F8 60 00 00 00   nop
seg000:001188FC 54 60 04 3F   clrlwi. %r0, %r3, 16
seg000:00118900 41 82 00 0C   beq     loc_11890C
seg000:00118904 38 60 00 00   li      %r3, 0
seg000:00118908 48 00 01 68   b       exit
seg000:0011890C
seg000:0011890C              loc_11890C: # CODE XREF: check3+1C4j
seg000:0011890C A0 01 00 38   lhz     %r0, 0x50+var_18(%sp)
seg000:00118910 28 00 1F 40   cmplwi  %r0, 0x40FF
seg000:00118914 41 82 00 0C   beq     loc_118920
seg000:00118918 38 60 00 00   li      %r3, 0
seg000:0011891C 48 00 01 54   b       exit
seg000:00118920
seg000:00118920              loc_118920: # CODE XREF: check3+1D8j
seg000:00118920 57 BF 06 3E   clrlwi  %r31, %r29, 24
seg000:00118924 28 1F 00 02   cmplwi  %r31, 2
seg000:00118928 40 82 00 0C   bne     loc_118934
seg000:0011892C 38 60 00 01   li      %r3, 1
seg000:00118930 48 00 01 40   b       exit
seg000:00118934
seg000:00118934              loc_118934: # CODE XREF: check3+1ECj
seg000:00118934 80 DE 00 00   lwz     %r6, dword_24B704
seg000:00118938 38 81 00 38   addi    %r4, %sp, 0x50+var_18
seg000:0011893C 38 60 00 0D   li      %r3, 0xD
seg000:00118940 38 A0 00 00   li      %r5, 0
seg000:00118944 48 00 BE 85   bl      .RBEREAD
seg000:00118948 60 00 00 00   nop
seg000:0011894C 54 60 04 3F   clrlwi. %r0, %r3, 16
seg000:00118950 41 82 00 0C   beq     loc_11895C
seg000:00118954 38 60 00 00   li      %r3, 0
seg000:00118958 48 00 01 18   b       exit
seg000:0011895C
seg000:0011895C              loc_11895C: # CODE XREF: check3+214j
seg000:0011895C A0 01 00 38   lhz     %r0, 0x50+var_18(%sp)
seg000:00118960 28 00 07 CF   cmplwi  %r0, 0xFC7
seg000:00118964 41 82 00 0C   beq     loc_118970
seg000:00118968 38 60 00 00   li      %r3, 0
seg000:0011896C 48 00 01 04   b       exit
seg000:00118970
seg000:00118970              loc_118970: # CODE XREF: check3+228j
seg000:00118970 28 1F 00 03   cmplwi  %r31, 3
seg000:00118974 40 82 00 F8   bne     error
seg000:00118978 38 60 00 01   li      %r3, 1
seg000:0011897C 48 00 00 F4   b       exit
seg000:00118980
seg000:00118980              loc_118980: # CODE XREF: check3+B8j
```

```
seg000:00118980                         # check3+C4j
seg000:00118980 80 DE 00 00   lwz     %r6, dword_24B704
seg000:00118984 38 81 00 38   addi    %r4, %sp, 0x50+var_18
seg000:00118988 3B E0 00 00   li      %r31, 0
seg000:0011898C 38 60 00 04   li      %r3, 4
seg000:00118990 38 A0 00 00   li      %r5, 0
seg000:00118994 48 00 BE 35   bl      .RBEREAD
seg000:00118998 60 00 00 00   nop
seg000:0011899C 54 60 04 3F   clrlwi. %r0, %r3, 16
seg000:001189A0 41 82 00 0C   beq     loc_1189AC
seg000:001189A4 38 60 00 00   li      %r3, 0
seg000:001189A8 48 00 00 C8   b       exit
seg000:001189AC
seg000:001189AC             loc_1189AC: # CODE XREF: check3+264j
seg000:001189AC A0 01 00 38   lhz     %r0, 0x50+var_18(%sp)
seg000:001189B0 28 00 1D 6A   cmplwi  %r0, 0xAED0
seg000:001189B4 40 82 00 0C   bne     loc_1189C0
seg000:001189B8 3B E0 00 01   li      %r31, 1
seg000:001189BC 48 00 00 14   b       loc_1189D0
seg000:001189C0
seg000:001189C0             loc_1189C0: # CODE XREF: check3+278j
seg000:001189C0 28 00 18 28   cmplwi  %r0, 0x2818
seg000:001189C4 41 82 00 0C   beq     loc_1189D0
seg000:001189C8 38 60 00 00   li      %r3, 0
seg000:001189CC 48 00 00 A4   b       exit
seg000:001189D0
seg000:001189D0             loc_1189D0: # CODE XREF: check3+280j
seg000:001189D0                         # check3+288j
seg000:001189D0 57 A0 06 3E   clrlwi  %r0, %r29, 24
seg000:001189D4 28 00 00 02   cmplwi  %r0, 2
seg000:001189D8 40 82 00 20   bne     loc_1189F8
seg000:001189DC 57 E0 06 3F   clrlwi. %r0, %r31, 24
seg000:001189E0 41 82 00 10   beq     good2
seg000:001189E4 48 00 4C 69   bl      sub_11D64C
seg000:001189E8 60 00 00 00   nop
seg000:001189EC 48 00 00 84   b       exit
seg000:001189F0
seg000:001189F0             good2:      # CODE XREF: check3+2A4j
seg000:001189F0 38 60 00 01   li      %r3, 1
seg000:001189F4 48 00 00 7C   b       exit
seg000:001189F8
seg000:001189F8             loc_1189F8: # CODE XREF: check3+29Cj
seg000:001189F8 80 DE 00 00   lwz     %r6, dword_24B704
seg000:001189FC 38 81 00 38   addi    %r4, %sp, 0x50+var_18
seg000:00118A00 38 60 00 05   li      %r3, 5
seg000:00118A04 38 A0 00 00   li      %r5, 0
seg000:00118A08 48 00 BD C1   bl      .RBEREAD
seg000:00118A0C 60 00 00 00   nop
seg000:00118A10 54 60 04 3F   clrlwi. %r0, %r3, 16
seg000:00118A14 41 82 00 0C   beq     loc_118A20
seg000:00118A18 38 60 00 00   li      %r3, 0
seg000:00118A1C 48 00 00 54   b       exit
seg000:00118A20
seg000:00118A20             loc_118A20: # CODE XREF: check3+2D8j
seg000:00118A20 A0 01 00 38   lhz     %r0, 0x50+var_18(%sp)
seg000:00118A24 28 00 11 D3   cmplwi  %r0, 0xD300
seg000:00118A28 40 82 00 0C   bne     loc_118A34
seg000:00118A2C 3B E0 00 01   li      %r31, 1
seg000:00118A30 48 00 00 14   b       good1
seg000:00118A34
seg000:00118A34             loc_118A34: # CODE XREF: check3+2ECj
seg000:00118A34 28 00 1A EB   cmplwi  %r0, 0xEBA1
seg000:00118A38 41 82 00 0C   beq     good1
seg000:00118A3C 38 60 00 00   li      %r3, 0
seg000:00118A40 48 00 00 30   b       exit
seg000:00118A44
seg000:00118A44             good1:      # CODE XREF: check3+2F4j
seg000:00118A44                         # check3+2FCj
seg000:00118A44 57 A0 06 3E   clrlwi  %r0, %r29, 24
seg000:00118A48 28 00 00 03   cmplwi  %r0, 3
```

```
seg000:00118A4C 40 82 00 20   bne     error
seg000:00118A50 57 E0 06 3F   clrlwi. %r0, %r31, 24
seg000:00118A54 41 82 00 10   beq     good
seg000:00118A58 48 00 4B F5   bl      sub_11D64C
seg000:00118A5C 60 00 00 00   nop
seg000:00118A60 48 00 00 10   b       exit
seg000:00118A64
seg000:00118A64             good:       # CODE XREF: check3+318j
seg000:00118A64 38 60 00 01   li      %r3, 1
seg000:00118A68 48 00 00 08   b       exit
seg000:00118A6C
seg000:00118A6C             error:      # CODE XREF: check3+19Cj
seg000:00118A6C                         # check3+238j ...
seg000:00118A6C 38 60 00 00   li      %r3, 0
seg000:00118A70
seg000:00118A70             exit:       # CODE XREF: check3+44j
seg000:00118A70                         # check3+58j ...
seg000:00118A70 80 01 00 58   lwz     %r0, 0x50+arg_8(%sp)
seg000:00118A74 38 21 00 50   addi    %sp, %sp, 0x50
seg000:00118A78 83 E1 FF FC   lwz     %r31, var_4(%sp)
seg000:00118A7C 7C 08 03 A6   mtlr    %r0
seg000:00118A80 83 C1 FF F8   lwz     %r30, var_8(%sp)
seg000:00118A84 83 A1 FF F4   lwz     %r29, var_C(%sp)
seg000:00118A88 4E 80 00 20   blr
seg000:00118A88             # End of function check3
```

There are a lot of calls to `.RBEREAD()`.

Perhaps, the function returns some values from the dongle, so they are compared here with some hard-coded variables using `CMPLWI`.

We also see that the r3 register is also filled before each call to `.RBEREAD()` with one of these values: 0, 1, 8, 0xA, 0xB, 0xC, 0xD, 4, 5. Probably a memory address or something like that?

Yes, indeed, by googling these function names it is easy to find the Sentinel Eve3 dongle manual!

Perhaps we don't even have to learn any other PowerPC instructions: all this function does is just call `.RBEREAD()`, compare its results with the constants and returns 1 if the comparisons are fine or 0 otherwise.

OK, all we've got is that `check1()` has always to return 1 or any other non-zero value.

But since we are not very confident in our knowledge of PowerPC instructions, we are going to be careful: we will patch the jumps in `check2()` at `0x001186FC` and `0x00118718`.

At `0x001186FC` we'll write bytes 0x48 and 0 thus converting the BEQ instruction in an B (unconditional jump): we can spot its opcode in the code without even referring to [*PowerPC(tm) Microprocessor Family: The Programming Environments for 32-Bit Microprocessors*, (2000)][13].

At `0x00118718` we'll write 0x60 and 3 zero bytes, thus converting it to a NOP instruction: Its opcode we could spot in the code too.

And now it all works without a dongle connected.

In summary, such small modifications can be done with IDA and minimal assembly language knowledge.

8.5.2 Example #2: SCO OpenServer

An ancient software for SCO OpenServer from 1997 developed by a company that disappeared a long time ago.

There is a special dongle driver to be installed in the system, that contains the following text strings: "Copyright 1989, Rainbow Technologies, Inc., Irvine, CA" and "Sentinel Integrated Driver Ver. 3.0 ".

After the installation of the driver in SCO OpenServer, these device files appear in the /dev filesystem:

```
/dev/rbsl8
/dev/rbsl9
/dev/rbsl10
```

[13]Also available as `http://yurichev.com/mirrors/PowerPC/6xx_pem.pdf`

The program reports an error without dongle connected, but the error string cannot be found in the executables.

Thanks to IDA, it is easy to load the COFF executable used in SCO OpenServer.

Let's also try to find "rbsl" string and indeed, found it in this code fragment:

```
.text:00022AB8         public SSQC
.text:00022AB8 SSQC    proc near ; CODE XREF: SSQ+7p
.text:00022AB8
.text:00022AB8 var_44 = byte ptr -44h
.text:00022AB8 var_29 = byte ptr -29h
.text:00022AB8 arg_0  = dword ptr  8
.text:00022AB8
.text:00022AB8         push    ebp
.text:00022AB9         mov     ebp, esp
.text:00022ABB         sub     esp, 44h
.text:00022ABE         push    edi
.text:00022ABF         mov     edi, offset unk_4035D0
.text:00022AC4         push    esi
.text:00022AC5         mov     esi, [ebp+arg_0]
.text:00022AC8         push    ebx
.text:00022AC9         push    esi
.text:00022ACA         call    strlen
.text:00022ACF         add     esp, 4
.text:00022AD2         cmp     eax, 2
.text:00022AD7         jnz     loc_22BA4
.text:00022ADD         inc     esi
.text:00022ADE         mov     al, [esi-1]
.text:00022AE1         movsx   eax, al
.text:00022AE4         cmp     eax, '3'
.text:00022AE9         jz      loc_22B84
.text:00022AEF         cmp     eax, '4'
.text:00022AF4         jz      loc_22B94
.text:00022AFA         cmp     eax, '5'
.text:00022AFF         jnz     short loc_22B6B
.text:00022B01         movsx   ebx, byte ptr [esi]
.text:00022B04         sub     ebx, '0'
.text:00022B07         mov     eax, 7
.text:00022B0C         add     eax, ebx
.text:00022B0E         push    eax
.text:00022B0F         lea     eax, [ebp+var_44]
.text:00022B12         push    offset aDevSlD  ; "/dev/sl%d"
.text:00022B17         push    eax
.text:00022B18         call    nl_sprintf
.text:00022B1D         push    0               ; int
.text:00022B1F         push    offset aDevRbsl8 ; char *
.text:00022B24         call    _access
.text:00022B29         add     esp, 14h
.text:00022B2C         cmp     eax, 0FFFFFFFFh
.text:00022B31         jz      short loc_22B48
.text:00022B33         lea     eax, [ebx+7]
.text:00022B36         push    eax
.text:00022B37         lea     eax, [ebp+var_44]
.text:00022B3A         push    offset aDevRbslD ; "/dev/rbsl%d"
.text:00022B3F         push    eax
.text:00022B40         call    nl_sprintf
.text:00022B45         add     esp, 0Ch
.text:00022B48
.text:00022B48 loc_22B48: ; CODE XREF: SSQC+79j
.text:00022B48         mov     edx, [edi]
.text:00022B4A         test    edx, edx
.text:00022B4C         jle     short loc_22B57
.text:00022B4E         push    edx             ; int
.text:00022B4F         call    _close
.text:00022B54         add     esp, 4
.text:00022B57
.text:00022B57 loc_22B57: ; CODE XREF: SSQC+94j
.text:00022B57         push    2               ; int
.text:00022B59         lea     eax, [ebp+var_44]
.text:00022B5C         push    eax             ; char *
```

```
.text:00022B5D        call    _open
.text:00022B62        add     esp, 8
.text:00022B65        test    eax, eax
.text:00022B67        mov     [edi], eax
.text:00022B69        jge     short loc_22B78
.text:00022B6B
.text:00022B6B loc_22B6B: ; CODE XREF: SSQC+47j
.text:00022B6B        mov     eax, 0FFFFFFFFh
.text:00022B70        pop     ebx
.text:00022B71        pop     esi
.text:00022B72        pop     edi
.text:00022B73        mov     esp, ebp
.text:00022B75        pop     ebp
.text:00022B76        retn
.text:00022B78
.text:00022B78 loc_22B78: ; CODE XREF: SSQC+B1j
.text:00022B78        pop     ebx
.text:00022B79        pop     esi
.text:00022B7A        pop     edi
.text:00022B7B        xor     eax, eax
.text:00022B7D        mov     esp, ebp
.text:00022B7F        pop     ebp
.text:00022B80        retn
.text:00022B84
.text:00022B84 loc_22B84: ; CODE XREF: SSQC+31j
.text:00022B84        mov     al, [esi]
.text:00022B86        pop     ebx
.text:00022B87        pop     esi
.text:00022B88        pop     edi
.text:00022B89        mov     ds:byte_407224, al
.text:00022B8E        mov     esp, ebp
.text:00022B90        xor     eax, eax
.text:00022B92        pop     ebp
.text:00022B93        retn
.text:00022B94
.text:00022B94 loc_22B94: ; CODE XREF: SSQC+3Cj
.text:00022B94        mov     al, [esi]
.text:00022B96        pop     ebx
.text:00022B97        pop     esi
.text:00022B98        pop     edi
.text:00022B99        mov     ds:byte_407225, al
.text:00022B9E        mov     esp, ebp
.text:00022BA0        xor     eax, eax
.text:00022BA2        pop     ebp
.text:00022BA3        retn
.text:00022BA4
.text:00022BA4 loc_22BA4: ; CODE XREF: SSQC+1Fj
.text:00022BA4        movsx   eax, ds:byte_407225
.text:00022BAB        push    esi
.text:00022BAC        push    eax
.text:00022BAD        movsx   eax, ds:byte_407224
.text:00022BB4        push    eax
.text:00022BB5        lea     eax, [ebp+var_44]
.text:00022BB8        push    offset a46CCS   ; "46%c%c%s"
.text:00022BBD        push    eax
.text:00022BBE        call    nl_sprintf
.text:00022BC3        lea     eax, [ebp+var_44]
.text:00022BC6        push    eax
.text:00022BC7        call    strlen
.text:00022BCC        add     esp, 18h
.text:00022BCF        cmp     eax, 1Bh
.text:00022BD4        jle     short loc_22BDA
.text:00022BD6        mov     [ebp+var_29], 0
.text:00022BDA
.text:00022BDA loc_22BDA: ; CODE XREF: SSQC+11Cj
.text:00022BDA        lea     eax, [ebp+var_44]
.text:00022BDD        push    eax
.text:00022BDE        call    strlen
.text:00022BE3        push    eax             ; unsigned int
.text:00022BE4        lea     eax, [ebp+var_44]
```

```
.text:00022BE7          push    eax             ; void *
.text:00022BE8          mov     eax, [edi]
.text:00022BEA          push    eax             ; int
.text:00022BEB          call    _write
.text:00022BF0          add     esp, 10h
.text:00022BF3          pop     ebx
.text:00022BF4          pop     esi
.text:00022BF5          pop     edi
.text:00022BF6          mov     esp, ebp
.text:00022BF8          pop     ebp
.text:00022BF9          retn
.text:00022BFA          db 0Eh dup(90h)
.text:00022BFA SSQC     endp
```

Yes, indeed, the program needs to communicate with the driver somehow.

The only place where the SSQC() function is called is the thunk function:

```
.text:0000DBE8          public SSQ
.text:0000DBE8 SSQ      proc near ; CODE XREF: sys_info+A9p
.text:0000DBE8                    ; sys_info+CBp ...
.text:0000DBE8
.text:0000DBE8 arg_0    = dword ptr  8
.text:0000DBE8
.text:0000DBE8          push    ebp
.text:0000DBE9          mov     ebp, esp
.text:0000DBEB          mov     edx, [ebp+arg_0]
.text:0000DBEE          push    edx
.text:0000DBEF          call    SSQC
.text:0000DBF4          add     esp, 4
.text:0000DBF7          mov     esp, ebp
.text:0000DBF9          pop     ebp
.text:0000DBFA          retn
.text:0000DBFB SSQ      endp
```

SSQ() can be called from at least 2 functions.

One of these is:

```
.data:0040169C _51_52_53       dd offset aPressAnyKeyT_0 ; DATA XREF: init_sys+392r
.data:0040169C                                  ; sys_info+A1r
.data:0040169C                                  ; "PRESS ANY KEY TO CONTINUE: "
.data:004016A0                 dd offset a51          ; "51"
.data:004016A4                 dd offset a52          ; "52"
.data:004016A8                 dd offset a53          ; "53"

...

.data:004016B8 _3C_or_3E       dd offset a3c          ; DATA XREF: sys_info:loc_D67Br
.data:004016B8                                  ; "3C"
.data:004016BC                 dd offset a3e          ; "3E"

; these names we gave to the labels:
.data:004016C0 answers1        dd 6B05h               ; DATA XREF: sys_info+E7r
.data:004016C4                 dd 3D87h
.data:004016C8 answers2        dd 3Ch                 ; DATA XREF: sys_info+F2r
.data:004016CC                 dd 832h
.data:004016D0 _C_and_B        db 0Ch                 ; DATA XREF: sys_info+BAr
.data:004016D0                                  ; sys_info:OKr
.data:004016D1 byte_4016D1     db 0Bh                 ; DATA XREF: sys_info+FDr
.data:004016D2                 db    0

...

.text:0000D652                 xor     eax, eax
.text:0000D654                 mov     al, ds:ctl_port
.text:0000D659                 mov     ecx, _51_52_53[eax*4]
.text:0000D660                 push    ecx
.text:0000D661                 call    SSQ
.text:0000D666                 add     esp, 4
.text:0000D669                 cmp     eax, 0FFFFFFFFh
```

```
.text:0000D66E                 jz      short loc_D6D1
.text:0000D670                 xor     ebx, ebx
.text:0000D672                 mov     al, _C_and_B
.text:0000D677                 test    al, al
.text:0000D679                 jz      short loc_D6C0
.text:0000D67B
.text:0000D67B loc_D67B: ; CODE XREF: sys_info+106j
.text:0000D67B                 mov     eax, _3C_or_3E[ebx*4]
.text:0000D682                 push    eax
.text:0000D683                 call    SSQ
.text:0000D688                 push    offset a4g      ; "4G"
.text:0000D68D                 call    SSQ
.text:0000D692                 push    offset a0123456789 ; "0123456789"
.text:0000D697                 call    SSQ
.text:0000D69C                 add     esp, 0Ch
.text:0000D69F                 mov     edx, answers1[ebx*4]
.text:0000D6A6                 cmp     eax, edx
.text:0000D6A8                 jz      short OK
.text:0000D6AA                 mov     ecx, answers2[ebx*4]
.text:0000D6B1                 cmp     eax, ecx
.text:0000D6B3                 jz      short OK
.text:0000D6B5                 mov     al, byte_4016D1[ebx]
.text:0000D6BB                 inc     ebx
.text:0000D6BC                 test    al, al
.text:0000D6BE                 jnz     short loc_D67B
.text:0000D6C0
.text:0000D6C0 loc_D6C0: ; CODE XREF: sys_info+C1j
.text:0000D6C0                 inc     ds:ctl_port
.text:0000D6C6                 xor     eax, eax
.text:0000D6C8                 mov     al, ds:ctl_port
.text:0000D6CD                 cmp     eax, edi
.text:0000D6CF                 jle     short loc_D652
.text:0000D6D1
.text:0000D6D1 loc_D6D1: ; CODE XREF: sys_info+98j
.text:0000D6D1           ; sys_info+B6j
.text:0000D6D1                 mov     edx, [ebp+var_8]
.text:0000D6D4                 inc     edx
.text:0000D6D5                 mov     [ebp+var_8], edx
.text:0000D6D8                 cmp     edx, 3
.text:0000D6DB                 jle     loc_D641
.text:0000D6E1
.text:0000D6E1 loc_D6E1: ; CODE XREF: sys_info+16j
.text:0000D6E1           ; sys_info+51j ...
.text:0000D6E1                 pop     ebx
.text:0000D6E2                 pop     edi
.text:0000D6E3                 mov     esp, ebp
.text:0000D6E5                 pop     ebp
.text:0000D6E6                 retn
.text:0000D6E8 OK:       ; CODE XREF: sys_info+F0j
.text:0000D6E8           ; sys_info+FBj
.text:0000D6E8                 mov     al, _C_and_B[ebx]
.text:0000D6EE                 pop     ebx
.text:0000D6EF                 pop     edi
.text:0000D6F0                 mov     ds:ctl_model, al
.text:0000D6F5                 mov     esp, ebp
.text:0000D6F7                 pop     ebp
.text:0000D6F8                 retn
.text:0000D6F8 sys_info        endp
```

"3C" and "3E" sound familiar: there was a Sentinel Pro dongle by Rainbow with no memory, providing only one crypto-hashing secret function.

You can read a short description of what hash function is here: 2.11 on page 466.

But let's get back to the program.

So the program can only check the presence or absence of a connected dongle.

No other information can be written to such dongle, as it has no memory. The two-character codes are commands (we can see how the commands are handled in the SSQC() function) and all other strings are hashed inside the dongle, being transformed into a 16-bit number. The algorithm was secret, so it was not possible to write a driver replacement or to remake the dongle hardware that would emulate it perfectly.

However, it is always possible to intercept all accesses to it and to find what constants the hash function results are compared to.

But we need to say that it is possible to build a robust software copy protection scheme based on secret cryptographic hash-function: let it encrypt/decrypt the data files your software uses.

But let's get back to the code.

Codes 51/52/53 are used for LPT printer port selection. 3x/4x are used for "family" selection (that's how Sentinel Pro dongles are differentiated from each other: more than one dongle can be connected to a LPT port).

The only non-2-character string passed to the hashing function is "0123456789".

Then, the result is compared against the set of valid results.

If it is correct, 0xC or 0xB is to be written into the global variable `ctl_model`.

Another text string that gets passed is "PRESS ANY KEY TO CONTINUE: ", but the result is not checked. Hard to say why, probably by mistake [14].

Let's see where the value from the global variable `ctl_mode` is used.

One such place is:

```
.text:0000D708 prep_sys proc near ; CODE XREF: init_sys+46Ap
.text:0000D708
.text:0000D708 var_14   = dword ptr -14h
.text:0000D708 var_10   = byte ptr -10h
.text:0000D708 var_8    = dword ptr -8
.text:0000D708 var_2    = word ptr -2
.text:0000D708
.text:0000D708          push    ebp
.text:0000D709          mov     eax, ds:net_env
.text:0000D70E          mov     ebp, esp
.text:0000D710          sub     esp, 1Ch
.text:0000D713          test    eax, eax
.text:0000D715          jnz     short loc_D734
.text:0000D717          mov     al, ds:ctl_model
.text:0000D71C          test    al, al
.text:0000D71E          jnz     short loc_D77E
.text:0000D720          mov     [ebp+var_8], offset aIeCvulnvvOkgT_ ; "Ie-cvulnvV\\\bOKG]T_"
.text:0000D727          mov     edx, 7
.text:0000D72C          jmp     loc_D7E7

...

.text:0000D7E7 loc_D7E7: ; CODE XREF: prep_sys+24j
.text:0000D7E7           ; prep_sys+33j
.text:0000D7E7          push    edx
.text:0000D7E8          mov     edx, [ebp+var_8]
.text:0000D7EB          push    20h
.text:0000D7ED          push    edx
.text:0000D7EE          push    16h
.text:0000D7F0          call    err_warn
.text:0000D7F5          push    offset station_sem
.text:0000D7FA          call    ClosSem
.text:0000D7FF          call    startup_err
```

If it is 0, an encrypted error message is passed to a decryption routine and printed.

The error string decryption routine seems a simple xoring:

```
.text:0000A43C err_warn        proc near              ; CODE XREF: prep_sys+E8p
.text:0000A43C                                        ; prep_sys2+2Fp ...
.text:0000A43C
.text:0000A43C var_55          = byte ptr -55h
.text:0000A43C var_54          = byte ptr -54h
.text:0000A43C arg_0           = dword ptr  8
```

[14] What a strange feeling: to find bugs in such ancient software.

```
.text:0000A43C arg_4           = dword ptr  0Ch
.text:0000A43C arg_8           = dword ptr  10h
.text:0000A43C arg_C           = dword ptr  14h
.text:0000A43C
.text:0000A43C                 push    ebp
.text:0000A43D                 mov     ebp, esp
.text:0000A43F                 sub     esp, 54h
.text:0000A442                 push    edi
.text:0000A443                 mov     ecx, [ebp+arg_8]
.text:0000A446                 xor     edi, edi
.text:0000A448                 test    ecx, ecx
.text:0000A44A                 push    esi
.text:0000A44B                 jle     short loc_A466
.text:0000A44D                 mov     esi, [ebp+arg_C] ; key
.text:0000A450                 mov     edx, [ebp+arg_4] ; string
.text:0000A453
.text:0000A453 loc_A453:                               ; CODE XREF: err_warn+28j
.text:0000A453                 xor     eax, eax
.text:0000A455                 mov     al, [edx+edi]
.text:0000A458                 xor     eax, esi
.text:0000A45A                 add     esi, 3
.text:0000A45D                 inc     edi
.text:0000A45E                 cmp     edi, ecx
.text:0000A460                 mov     [ebp+edi+var_55], al
.text:0000A464                 jl      short loc_A453
.text:0000A466
.text:0000A466 loc_A466:                               ; CODE XREF: err_warn+Fj
.text:0000A466                 mov     [ebp+edi+var_54], 0
.text:0000A46B                 mov     eax, [ebp+arg_0]
.text:0000A46E                 cmp     eax, 18h
.text:0000A473                 jnz     short loc_A49C
.text:0000A475                 lea     eax, [ebp+var_54]
.text:0000A478                 push    eax
.text:0000A479                 call    status_line
.text:0000A47E                 add     esp, 4
.text:0000A481
.text:0000A481 loc_A481:                               ; CODE XREF: err_warn+72j
.text:0000A481                 push    50h
.text:0000A483                 push    0
.text:0000A485                 lea     eax, [ebp+var_54]
.text:0000A488                 push    eax
.text:0000A489                 call    memset
.text:0000A48E                 call    pcv_refresh
.text:0000A493                 add     esp, 0Ch
.text:0000A496                 pop     esi
.text:0000A497                 pop     edi
.text:0000A498                 mov     esp, ebp
.text:0000A49A                 pop     ebp
.text:0000A49B                 retn
.text:0000A49C
.text:0000A49C loc_A49C:                               ; CODE XREF: err_warn+37j
.text:0000A49C                 push    0
.text:0000A49E                 lea     eax, [ebp+var_54]
.text:0000A4A1                 mov     edx, [ebp+arg_0]
.text:0000A4A4                 push    edx
.text:0000A4A5                 push    eax
.text:0000A4A6                 call    pcv_lputs
.text:0000A4AB                 add     esp, 0Ch
.text:0000A4AE                 jmp     short loc_A481
.text:0000A4AE err_warn        endp
```

That's why we were unable to find the error messages in the executable files, because they are encrypted (which is is popular practice).

Another call to the `SSQ()` hashing function passes the "offln" string to it and compares the result with `0xFE81` and `0x12A9`.

If they don't match, it works with some `timer()` function (maybe waiting for a poorly connected dongle to be reconnected and check again?) and then decrypts another error message to dump.

```
.text:0000DA55 loc_DA55:                               ; CODE XREF: sync_sys+24Cj
.text:0000DA55                 push    offset aOffln   ; "offln"
.text:0000DA5A                 call    SSQ
.text:0000DA5F                 add     esp, 4
.text:0000DA62                 mov     dl, [ebx]
.text:0000DA64                 mov     esi, eax
.text:0000DA66                 cmp     dl, 0Bh
.text:0000DA69                 jnz     short loc_DA83
.text:0000DA6B                 cmp     esi, 0FE81h
.text:0000DA71                 jz      OK
.text:0000DA77                 cmp     esi, 0FFFFF8EFh
.text:0000DA7D                 jz      OK
.text:0000DA83
.text:0000DA83 loc_DA83:                               ; CODE XREF: sync_sys+201j
.text:0000DA83                 mov     cl, [ebx]
.text:0000DA85                 cmp     cl, 0Ch
.text:0000DA88                 jnz     short loc_DA9F
.text:0000DA8A                 cmp     esi, 12A9h
.text:0000DA90                 jz      OK
.text:0000DA96                 cmp     esi, 0FFFFFFF5h
.text:0000DA99                 jz      OK
.text:0000DA9F
.text:0000DA9F loc_DA9F:                               ; CODE XREF: sync_sys+220j
.text:0000DA9F                 mov     eax, [ebp+var_18]
.text:0000DAA2                 test    eax, eax
.text:0000DAA4                 jz      short loc_DAB0
.text:0000DAA6                 push    24h
.text:0000DAA8                 call    timer
.text:0000DAAD                 add     esp, 4
.text:0000DAB0
.text:0000DAB0 loc_DAB0:                               ; CODE XREF: sync_sys+23Cj
.text:0000DAB0                 inc     edi
.text:0000DAB1                 cmp     edi, 3
.text:0000DAB4                 jle     short loc_DA55
.text:0000DAB6                 mov     eax, ds:net_env
.text:0000DABB                 test    eax, eax
.text:0000DABD                 jz      short error

...

.text:0000DAF7 error:                                  ; CODE XREF: sync_sys+255j
.text:0000DAF7                                         ; sync_sys+274j ...
.text:0000DAF7                 mov     [ebp+var_8], offset encrypted_error_message2
.text:0000DAFE                 mov     [ebp+var_C], 17h ; decrypting key
.text:0000DB05                 jmp     decrypt_end_print_message

...

; this name we gave to label:
.text:0000D9B6 decrypt_end_print_message:              ; CODE XREF: sync_sys+29Dj
.text:0000D9B6                                         ; sync_sys+2ABj
.text:0000D9B6                 mov     eax, [ebp+var_18]
.text:0000D9B9                 test    eax, eax
.text:0000D9BB                 jnz     short loc_D9FB
.text:0000D9BD                 mov     edx, [ebp+var_C] ; key
.text:0000D9C0                 mov     ecx, [ebp+var_8] ; string
.text:0000D9C3                 push    edx
.text:0000D9C4                 push    20h
.text:0000D9C6                 push    ecx
.text:0000D9C7                 push    18h
.text:0000D9C9                 call    err_warn
.text:0000D9CE                 push    0Fh
.text:0000D9D0                 push    190h
.text:0000D9D5                 call    sound
.text:0000D9DA                 mov     [ebp+var_18], 1
.text:0000D9E1                 add     esp, 18h
.text:0000D9E4                 call    pcv_kbhit
.text:0000D9E9                 test    eax, eax
.text:0000D9EB                 jz      short loc_D9FB
```

```
...

; this name we gave to label:
.data:00401736 encrypted_error_message2 db 74h, 72h, 78h, 43h, 48h, 6, 5Ah, 49h, 4Ch, 2 dup(47h↙
    ↘ )
.data:00401736                 db 51h, 4Fh, 47h, 61h, 20h, 22h, 3Ch, 24h, 33h, 36h, 76h
.data:00401736                 db 3Ah, 33h, 31h, 0Ch, 0, 0Bh, 1Fh, 7, 1Eh, 1Ah
```

Bypassing the dongle is pretty straightforward: just patch all jumps after the relevant CMP instructions.

Another option is to write our own SCO OpenServer driver, containing a table of questions and answers, all of those which present in the program.

Decrypting error messages

By the way, we can also try to decrypt all error messages. The algorithm that is located in the `err_warn()` function is very simple, indeed:

Listing 8.3: Decryption function

```
.text:0000A44D                 mov     esi, [ebp+arg_C] ; key
.text:0000A450                 mov     edx, [ebp+arg_4] ; string
.text:0000A453 loc_A453:
.text:0000A453                 xor     eax, eax
.text:0000A455                 mov     al, [edx+edi] ; load encrypted byte
.text:0000A458                 xor     eax, esi      ; decrypt it
.text:0000A45A                 add     esi, 3        ; change key for the next byte
.text:0000A45D                 inc     edi
.text:0000A45E                 cmp     edi, ecx
.text:0000A460                 mov     [ebp+edi+var_55], al
.text:0000A464                 jl      short loc_A453
```

As we can see, not just string is supplied to the decryption function, but also the key:

```
.text:0000DAF7 error:                                   ; CODE XREF: sync_sys+255j
.text:0000DAF7                                          ; sync_sys+274j ...
.text:0000DAF7                 mov     [ebp+var_8], offset encrypted_error_message2
.text:0000DAFE                 mov     [ebp+var_C], 17h ; decrypting key
.text:0000DB05                 jmp     decrypt_end_print_message

...

; this name we gave to label manually:
.text:0000D9B6 decrypt_end_print_message:               ; CODE XREF: sync_sys+29Dj
.text:0000D9B6                                          ; sync_sys+2ABj
.text:0000D9B6                 mov     eax, [ebp+var_18]
.text:0000D9B9                 test    eax, eax
.text:0000D9BB                 jnz     short loc_D9FB
.text:0000D9BD                 mov     edx, [ebp+var_C] ; key
.text:0000D9C0                 mov     ecx, [ebp+var_8] ; string
.text:0000D9C3                 push    edx
.text:0000D9C4                 push    20h
.text:0000D9C6                 push    ecx
.text:0000D9C7                 push    18h
.text:0000D9C9                 call    err_warn
```

The algorithm is a simple xoring: each byte is xored with a key, but the key is increased by 3 after the processing of each byte.

We can write a simple Python script to check our hypothesis:

Listing 8.4: Python 3.x

```
#!/usr/bin/python
import sys

msg=[0x74, 0x72, 0x78, 0x43, 0x48, 0x6, 0x5A, 0x49, 0x4C, 0x47, 0x47,
0x51, 0x4F, 0x47, 0x61, 0x20, 0x22, 0x3C, 0x24, 0x33, 0x36, 0x76,
0x3A, 0x33, 0x31, 0x0C, 0x0, 0x0B, 0x1F, 0x7, 0x1E, 0x1A]
```

```
key=0x17
tmp=key
for i in msg:
        sys.stdout.write ("%c" % (i^tmp))
        tmp=tmp+3
sys.stdout.flush()
```

And it prints: “check security device connection”. So yes, this is the decrypted message.

There are also other encrypted messages with their corresponding keys. But needless to say, it is possible to decrypt them without their keys. First, we can see that the key is in fact a byte. It is because the core decryption instruction (XOR) works on byte level. The key is located in the ESI register, but only one byte part of ESI is used. Hence, a key may be greater than 255, but its value is always to be rounded.

As a consequence, we can just try brute-force, trying all possible keys in the 0..255 range. We are also going to skip the messages that has unprintable characters.

Listing 8.5: Python 3.x

```
#!/usr/bin/python
import sys, curses.ascii

msgs=[
[0x74, 0x72, 0x78, 0x43, 0x48, 0x6, 0x5A, 0x49, 0x4C, 0x47, 0x47,
0x51, 0x4F, 0x47, 0x61, 0x20, 0x22, 0x3C, 0x24, 0x33, 0x36, 0x76,
0x3A, 0x33, 0x31, 0x0C, 0x0, 0x0B, 0x1F, 0x7, 0x1E, 0x1A],

[0x49, 0x65, 0x2D, 0x63, 0x76, 0x75, 0x6C, 0x6E, 0x76, 0x56, 0x5C,
8, 0x4F, 0x4B, 0x47, 0x5D, 0x54, 0x5F, 0x1D, 0x26, 0x2C, 0x33,
0x27, 0x28, 0x6F, 0x72, 0x75, 0x78, 0x7B, 0x7E, 0x41, 0x44],

[0x45, 0x61, 0x31, 0x67, 0x72, 0x79, 0x68, 0x52, 0x4A, 0x52, 0x50,
0x0C, 0x4B, 0x57, 0x43, 0x51, 0x58, 0x5B, 0x61, 0x37, 0x33, 0x2B,
0x39, 0x39, 0x3C, 0x38, 0x79, 0x3A, 0x30, 0x17, 0x0B, 0x0C],

[0x40, 0x64, 0x79, 0x75, 0x7F, 0x6F, 0x0, 0x4C, 0x40, 0x9, 0x4D, 0x5A,
0x46, 0x5D, 0x57, 0x49, 0x57, 0x3B, 0x21, 0x23, 0x6A, 0x38, 0x23,
0x36, 0x24, 0x2A, 0x7C, 0x3A, 0x1A, 0x6, 0x0D, 0x0E, 0x0A, 0x14,
0x10],

[0x72, 0x7C, 0x72, 0x79, 0x76, 0x0,
0x50, 0x43, 0x4A, 0x59, 0x5D, 0x5B, 0x41, 0x41, 0x1B, 0x5A,
0x24, 0x32, 0x2E, 0x29, 0x28, 0x70, 0x20, 0x22, 0x38, 0x28, 0x36,
0x0D, 0x0B, 0x48, 0x4B, 0x4E]]


def is_string_printable(s):
    return all(list(map(lambda x: curses.ascii.isprint(x), s)))

cnt=1
for msg in msgs:
        print ("message #%d" % cnt)
        for key in range(0,256):
                result=[]
                tmp=key
                for i in msg:
                        result.append (i^tmp)
                        tmp=tmp+3
                if is_string_printable (result):
                        print ("key=", key, "value=", "".join(list(map(chr, result))))
        cnt=cnt+1
```

And we get:

Listing 8.6: Results

```
message #1
key= 20 value= `eb^h%|``hudw|_af{n~f%ljmSbnwlpk
key= 21 value= ajc]i"}cawtgv{^bgto}g"millcmvkqh
key= 22 value= bkd\j#rbbvsfuz!cduh|d#bhomdlujni
```

```
key= 23 value= check security device connection
key= 24 value= lifbl!pd|tqhsx#ejwjbb!`nQofbshlo
message #2
key= 7 value= No security device found
key= 8 value= An#rbbvsVuz!cduhld#ghtme?!#!'!#!
message #3
key= 7 value= Bk<waoqNUpu$`yreoa\wpmpusj,bkIjh
key= 8 value= Mj?vfnrOjqv%gxqd``_vwlstlk/clHii
key= 9 value= Lm>ugasLkvw&fgpgag^uvcrwml.`mwhj
key= 10 value= Ol!td`tMhwx'efwfbf!tubuvnm!anvok
key= 11 value= No security device station found
key= 12 value= In#rjbvsnuz!{duhdd#r{`whho#gPtme
message #4
key= 14 value= Number of authorized users exceeded
key= 15 value= Ovlmdq!hg#`juknuhydk!vrbsp!Zy`dbefe
message #5
key= 17 value= check security device station
key= 18 value= `ijbh!td`tmhwx'efwfbf!tubuVnm!'!
```

There is some garbage, but we can quickly find the English-language messages!

By the way, since the algorithm is a simple xoring encryption, the very same function can be used to encrypt messages. If needed, we can encrypt our own messages, and patch the program by inserting them.

8.5.3 Example #3: MS-DOS

Another very old software for MS-DOS from 1995 also developed by a company that disappeared a long time ago.

In the pre-DOS extenders era, all the software for MS-DOS mostly relied on 16-bit 8086 or 80286 CPUs, so the code was 16-bit en masse.

The 16-bit code is mostly same as you already saw in this book, but all registers are 16-bit and there are less instructions available.

The MS-DOS environment has no system drivers, and any program can deal with the bare hardware via ports, so here you can see the OUT/IN instructions, which are present in mostly in drivers in our times (it is impossible to access ports directly in user mode on all modern OSes).

Given that, the MS-DOS program which works with a dongle has to access the LPT printer port directly.

So we can just search for such instructions. And yes, here they are:

```
seg030:0034             out_port proc far ; CODE XREF: sent_pro+22p
seg030:0034                               ; sent_pro+2Ap ...
seg030:0034
seg030:0034             arg_0    = byte ptr  6
seg030:0034
seg030:0034 55                   push    bp
seg030:0035 8B EC                mov     bp, sp
seg030:0037 8B 16 7E E7          mov     dx, _out_port ; 0x378
seg030:003B 8A 46 06             mov     al, [bp+arg_0]
seg030:003E EE                   out     dx, al
seg030:003F 5D                   pop     bp
seg030:0040 CB                   retf
seg030:0040             out_port endp
```

(All label names in this example were given by me).

`out_port()` is referenced only in one function:

```
seg030:0041             sent_pro proc far ; CODE XREF: check_dongle+34p
seg030:0041
seg030:0041             var_3    = byte ptr -3
seg030:0041             var_2    = word ptr -2
seg030:0041             arg_0    = dword ptr  6
seg030:0041
seg030:0041 C8 04 00 00          enter   4, 0
seg030:0045 56                   push    si
```

```
seg030:0046 57                  push    di
seg030:0047 8B 16 82 E7         mov     dx, _in_port_1 ; 0x37A
seg030:004B EC                  in      al, dx
seg030:004C 8A D8               mov     bl, al
seg030:004E 80 E3 FE            and     bl, 0FEh
seg030:0051 80 CB 04            or      bl, 4
seg030:0054 8A C3               mov     al, bl
seg030:0056 88 46 FD            mov     [bp+var_3], al
seg030:0059 80 E3 1F            and     bl, 1Fh
seg030:005C 8A C3               mov     al, bl
seg030:005E EE                  out     dx, al
seg030:005F 68 FF 00            push    0FFh
seg030:0062 0E                  push    cs
seg030:0063 E8 CE FF            call    near ptr out_port
seg030:0066 59                  pop     cx
seg030:0067 68 D3 00            push    0D3h
seg030:006A 0E                  push    cs
seg030:006B E8 C6 FF            call    near ptr out_port
seg030:006E 59                  pop     cx
seg030:006F 33 F6               xor     si, si
seg030:0071 EB 01               jmp     short loc_359D4
seg030:0073
seg030:0073             loc_359D3: ; CODE XREF: sent_pro+37j
seg030:0073 46                  inc     si
seg030:0074
seg030:0074             loc_359D4: ; CODE XREF: sent_pro+30j
seg030:0074 81 FE 96 00         cmp     si, 96h
seg030:0078 7C F9               jl      short loc_359D3
seg030:007A 68 C3 00            push    0C3h
seg030:007D 0E                  push    cs
seg030:007E E8 B3 FF            call    near ptr out_port
seg030:0081 59                  pop     cx
seg030:0082 68 C7 00            push    0C7h
seg030:0085 0E                  push    cs
seg030:0086 E8 AB FF            call    near ptr out_port
seg030:0089 59                  pop     cx
seg030:008A 68 D3 00            push    0D3h
seg030:008D 0E                  push    cs
seg030:008E E8 A3 FF            call    near ptr out_port
seg030:0091 59                  pop     cx
seg030:0092 68 C3 00            push    0C3h
seg030:0095 0E                  push    cs
seg030:0096 E8 9B FF            call    near ptr out_port
seg030:0099 59                  pop     cx
seg030:009A 68 C7 00            push    0C7h
seg030:009D 0E                  push    cs
seg030:009E E8 93 FF            call    near ptr out_port
seg030:00A1 59                  pop     cx
seg030:00A2 68 D3 00            push    0D3h
seg030:00A5 0E                  push    cs
seg030:00A6 E8 8B FF            call    near ptr out_port
seg030:00A9 59                  pop     cx
seg030:00AA BF FF FF            mov     di, 0FFFFh
seg030:00AD EB 40               jmp     short loc_35A4F
seg030:00AF
seg030:00AF             loc_35A0F: ; CODE XREF: sent_pro+BDj
seg030:00AF BE 04 00            mov     si, 4
seg030:00B2
seg030:00B2             loc_35A12: ; CODE XREF: sent_pro+ACj
seg030:00B2 D1 E7               shl     di, 1
seg030:00B4 8B 16 80 E7         mov     dx, _in_port_2 ; 0x379
seg030:00B8 EC                  in      al, dx
seg030:00B9 A8 80               test    al, 80h
seg030:00BB 75 03               jnz     short loc_35A20
seg030:00BD 83 CF 01            or      di, 1
seg030:00C0
seg030:00C0             loc_35A20: ; CODE XREF: sent_pro+7Aj
seg030:00C0 F7 46 FE 08+        test    [bp+var_2], 8
seg030:00C5 74 05               jz      short loc_35A2C
seg030:00C7 68 D7 00            push    0D7h ; '+'
```

```
seg030:00CA EB 0B               jmp     short loc_35A37
seg030:00CC
seg030:00CC            loc_35A2C: ; CODE XREF: sent_pro+84j
seg030:00CC 68 C3 00            push    0C3h
seg030:00CF 0E                  push    cs
seg030:00D0 E8 61 FF            call    near ptr out_port
seg030:00D3 59                  pop     cx
seg030:00D4 68 C7 00            push    0C7h
seg030:00D7
seg030:00D7            loc_35A37: ; CODE XREF: sent_pro+89j
seg030:00D7 0E                  push    cs
seg030:00D8 E8 59 FF            call    near ptr out_port
seg030:00DB 59                  pop     cx
seg030:00DC 68 D3 00            push    0D3h
seg030:00DF 0E                  push    cs
seg030:00E0 E8 51 FF            call    near ptr out_port
seg030:00E3 59                  pop     cx
seg030:00E4 8B 46 FE            mov     ax, [bp+var_2]
seg030:00E7 D1 E0               shl     ax, 1
seg030:00E9 89 46 FE            mov     [bp+var_2], ax
seg030:00EC 4E                  dec     si
seg030:00ED 75 C3               jnz     short loc_35A12
seg030:00EF
seg030:00EF            loc_35A4F: ; CODE XREF: sent_pro+6Cj
seg030:00EF C4 5E 06            les     bx, [bp+arg_0]
seg030:00F2 FF 46 06            inc     word ptr [bp+arg_0]
seg030:00F5 26 8A 07            mov     al, es:[bx]
seg030:00F8 98                  cbw
seg030:00F9 89 46 FE            mov     [bp+var_2], ax
seg030:00FC 0B C0               or      ax, ax
seg030:00FE 75 AF               jnz     short loc_35A0F
seg030:0100 68 FF 00            push    0FFh
seg030:0103 0E                  push    cs
seg030:0104 E8 2D FF            call    near ptr out_port
seg030:0107 59                  pop     cx
seg030:0108 8B 16 82 E7         mov     dx, _in_port_1 ; 0x37A
seg030:010C EC                  in      al, dx
seg030:010D 8A C8               mov     cl, al
seg030:010F 80 E1 5F            and     cl, 5Fh
seg030:0112 8A C1               mov     al, cl
seg030:0114 EE                  out     dx, al
seg030:0115 EC                  in      al, dx
seg030:0116 8A C8               mov     cl, al
seg030:0118 F6 C1 20            test    cl, 20h
seg030:011B 74 08               jz      short loc_35A85
seg030:011D 8A 5E FD            mov     bl, [bp+var_3]
seg030:0120 80 E3 DF            and     bl, 0DFh
seg030:0123 EB 03               jmp     short loc_35A88
seg030:0125
seg030:0125            loc_35A85: ; CODE XREF: sent_pro+DAj
seg030:0125 8A 5E FD            mov     bl, [bp+var_3]
seg030:0128
seg030:0128            loc_35A88: ; CODE XREF: sent_pro+E2j
seg030:0128 F6 C1 80            test    cl, 80h
seg030:012B 74 03               jz      short loc_35A90
seg030:012D 80 E3 7F            and     bl, 7Fh
seg030:0130
seg030:0130            loc_35A90: ; CODE XREF: sent_pro+EAj
seg030:0130 8B 16 82 E7         mov     dx, _in_port_1 ; 0x37A
seg030:0134 8A C3               mov     al, bl
seg030:0136 EE                  out     dx, al
seg030:0137 8B C7               mov     ax, di
seg030:0139 5F                  pop     di
seg030:013A 5E                  pop     si
seg030:013B C9                  leave
seg030:013C CB                  retf
seg030:013C            sent_pro endp
```

This is again a Sentinel Pro “hashing” dongle as in the previous example. It is noticeably because text strings are passed here, too, and 16 bit values are returned and compared with others.

So that is how Sentinel Pro is accessed via ports.

The output port address is usually 0x378, i.e., the printer port, where the data to the old printers in pre-USB era was passed to.

The port is uni-directional, because when it was developed, no one imagined that someone will need to transfer information from the printer [15].

The only way to get information from the printer is a status register on port 0x379, which contains such bits as “paper out”, “ack”, “busy”—thus the printer may signal to the host computer if it is ready or not and if paper is present in it.

So the dongle returns information from one of these bits, one bit at each iteration.

_in_port_2 contains the address of the status word (0x379) and _in_port_1 contains the control register address (0x37A).

It seems that the dongle returns information via the “busy” flag at seg030:00B9: each bit is stored in the DI register, which is returned at the end of the function.

What do all these bytes sent to output port mean? Hard to say. Perhaps, commands to the dongle.

But generally speaking, it is not necessary to know: it is easy to solve our task without that knowledge.

Here is the dongle checking routine:

```
00000000 struct_0        struc ; (sizeof=0x1B)
00000000 field_0         db 25 dup(?)            ; string(C)
00000019 _A              dw ?
0000001B struct_0        ends

dseg:3CBC 61 63 72 75+_Q   struct_0 <'hello', 01122h>
dseg:3CBC 6E 00 00 00+       ; DATA XREF: check_dongle+2Eo

... skipped ...

dseg:3E00 63 6F 66 66+     struct_0 <'coffee', 7EB7h>
dseg:3E1B 64 6F 67 00+     struct_0 <'dog', 0FFADh>
dseg:3E36 63 61 74 00+     struct_0 <'cat', 0FF5Fh>
dseg:3E51 70 61 70 65+     struct_0 <'paper', 0FFDFh>
dseg:3E6C 63 6F 6B 65+     struct_0 <'coke', 0F568h>
dseg:3E87 63 6C 6F 63+     struct_0 <'clock', 55EAh>
dseg:3EA2 64 69 72 00+     struct_0 <'dir', 0FFAEh>
dseg:3EBD 63 6F 70 79+     struct_0 <'copy', 0F557h>


seg030:0145             check_dongle proc far ; CODE XREF: sub_3771D+3EP
seg030:0145
seg030:0145             var_6 = dword ptr -6
seg030:0145             var_2 = word ptr -2
seg030:0145
seg030:0145 C8 06 00 00       enter   6, 0
seg030:0149 56                push    si
seg030:014A 66 6A 00          push    large 0         ; newtime
seg030:014D 6A 00             push    0               ; cmd
seg030:014F 9A C1 18 00+      call    _biostime
seg030:0154 52                push    dx
seg030:0155 50                push    ax
seg030:0156 66 58             pop     eax
seg030:0158 83 C4 06          add     sp, 6
seg030:015B 66 89 46 FA       mov     [bp+var_6], eax
seg030:015F 66 3B 06 D8+      cmp     eax, _expiration
seg030:0164 7E 44             jle     short loc_35B0A
seg030:0166 6A 14             push    14h
seg030:0168 90                nop
seg030:0169 0E                push    cs
seg030:016A E8 52 00          call    near ptr get_rand
seg030:016D 59                pop     cx
seg030:016E 8B F0             mov     si, ax
seg030:0170 6B C0 1B          imul    ax, 1Bh
```

[15] If we consider Centronics only. The following IEEE 1284 standard allows the transfer of information from the printer.

```
seg030:0173 05 BC 3C          add     ax, offset _Q
seg030:0176 1E                push    ds
seg030:0177 50                push    ax
seg030:0178 0E                push    cs
seg030:0179 E8 C5 FE          call    near ptr sent_pro
seg030:017C 83 C4 04          add     sp, 4
seg030:017F 89 46 FE          mov     [bp+var_2], ax
seg030:0182 8B C6             mov     ax, si
seg030:0184 6B C0 12          imul    ax, 18
seg030:0187 66 0F BF C0       movsx   eax, ax
seg030:018B 66 8B 56 FA       mov     edx, [bp+var_6]
seg030:018F 66 03 D0          add     edx, eax
seg030:0192 66 89 16 D8+      mov     _expiration, edx
seg030:0197 8B DE             mov     bx, si
seg030:0199 6B DB 1B          imul    bx, 27
seg030:019C 8B 87 D5 3C       mov     ax, _Q._A[bx]
seg030:01A0 3B 46 FE          cmp     ax, [bp+var_2]
seg030:01A3 74 05             jz      short loc_35B0A
seg030:01A5 B8 01 00          mov     ax, 1
seg030:01A8 EB 02             jmp     short loc_35B0C
seg030:01AA
seg030:01AA             loc_35B0A: ; CODE XREF: check_dongle+1Fj
seg030:01AA                        ; check_dongle+5Ej
seg030:01AA 33 C0             xor     ax, ax
seg030:01AC
seg030:01AC             loc_35B0C: ; CODE XREF: check_dongle+63j
seg030:01AC 5E                pop     si
seg030:01AD C9                leave
seg030:01AE CB                retf
seg030:01AE             check_dongle endp
```

Since the routine can be called very frequently, e.g., before the execution of each important software feature, and accessing the dongle is generally slow (because of the slow printer port and also slow MCU in the dongle), they probably added a way to skip some dongle checks, by checking the current time in the `biostime()` function.

The `get_rand()` function uses the standard C function:

```
seg030:01BF             get_rand proc far ; CODE XREF: check_dongle+25p
seg030:01BF
seg030:01BF             arg_0    = word ptr  6
seg030:01BF
seg030:01BF 55                   push    bp
seg030:01C0 8B EC                mov     bp, sp
seg030:01C2 9A 3D 21 00+         call    _rand
seg030:01C7 66 0F BF C0          movsx   eax, ax
seg030:01CB 66 0F BF 56+         movsx   edx, [bp+arg_0]
seg030:01D0 66 0F AF C2          imul    eax, edx
seg030:01D4 66 BB 00 80+         mov     ebx, 8000h
seg030:01DA 66 99                cdq
seg030:01DC 66 F7 FB             idiv    ebx
seg030:01DF 5D                   pop     bp
seg030:01E0 CB                   retf
seg030:01E0             get_rand endp
```

So the text string is selected randomly, passed into the dongle, and then the result of the hashing is compared with the correct value.

The text strings seem to be constructed randomly as well, during software development.

And this is how the main dongle checking function is called:

```
seg033:087B 9A 45 01 96+   call    check_dongle
seg033:0880 0B C0          or      ax, ax
seg033:0882 74 62          jz      short OK
seg033:0884 83 3E 60 42+   cmp     word_620E0, 0
seg033:0889 75 5B          jnz     short OK
seg033:088B FF 06 60 42    inc     word_620E0
seg033:088F 1E             push    ds
seg033:0890 68 22 44       push    offset aTrupcRequiresA ; "This Software Requires a Software ↙
    ↘ Lock\n"
```

```
seg033:0893 1E            push    ds
seg033:0894 68 60 E9      push    offset byte_6C7E0 ; dest
seg033:0897 9A 79 65 00+  call    _strcpy
seg033:089C 83 C4 08      add     sp, 8
seg033:089F 1E            push    ds
seg033:08A0 68 42 44      push    offset aPleaseContactA ; "Please Contact ..."
seg033:08A3 1E            push    ds
seg033:08A4 68 60 E9      push    offset byte_6C7E0 ; dest
seg033:08A7 9A CD 64 00+  call    _strcat
```

Bypassing the dongle is easy, just force the `check_dongle()` function to always return 0.

For example, by inserting this code at its beginning:

```
mov ax,0
retf
```

The observant reader might recall that the `strcpy()` C function usually requires two pointers in its arguments, but we see that 4 values are passed:

```
seg033:088F 1E                         push    ds
seg033:0890 68 22 44                   push    offset aTrupcRequiresA ; "This Software ⤦
    ↳ Requires a Software Lock\n"
seg033:0893 1E                         push    ds
seg033:0894 68 60 E9                   push    offset byte_6C7E0 ; dest
seg033:0897 9A 79 65 00+               call    _strcpy
seg033:089C 83 C4 08                   add     sp, 8
```

This is related to MS-DOS' memory model. You can read more about it here: 11.6 on page 1003.

So as you may see, `strcpy()` and any other function that take pointer(s) in arguments work with 16-bit pairs.

Let's get back to our example. `DS` is currently set to the data segment located in the executable, that is where the text string is stored.

In the `sent_pro()` function, each byte of the string is loaded at `seg030:00EF`: the LES instruction loads the ES:BX pair simultaneously from the passed argument.

The `MOV` at `seg030:00F5` loads the byte from the memory at which the ES:BX pair points.

8.6 "QR9": Rubik's cube inspired amateur crypto-algorithm

Sometimes amateur cryptosystems appear to be pretty bizarre.

The author of this book was once asked to reverse engineer an amateur cryptoalgorithm of some data encryption utility, the source code for which was lost[16].

Here is the listing exported from IDA for the original encryption utility:

```
.text:00541000 set_bit         proc near  ; CODE XREF: rotate1+42
.text:00541000                            ; rotate2+42 ...
.text:00541000
.text:00541000 arg_0           = dword ptr  4
.text:00541000 arg_4           = dword ptr  8
.text:00541000 arg_8           = dword ptr  0Ch
.text:00541000 arg_C           = byte ptr  10h
.text:00541000
.text:00541000                 mov     al, [esp+arg_C]
.text:00541004                 mov     ecx, [esp+arg_8]
.text:00541008                 push    esi
.text:00541009                 mov     esi, [esp+4+arg_0]
.text:0054100D                 test    al, al
.text:0054100F                 mov     eax, [esp+4+arg_4]
.text:00541013                 mov     dl, 1
.text:00541015                 jz      short loc_54102B
.text:00541017                 shl     dl, cl
```

16He also got permission from the customer to publish the algorithm's details

```
.text:00541019                 mov     cl, cube64[eax+esi*8]
.text:00541020                 or      cl, dl
.text:00541022                 mov     cube64[eax+esi*8], cl
.text:00541029                 pop     esi
.text:0054102A                 retn
.text:0054102B
.text:0054102B loc_54102B:                   ; CODE XREF: set_bit+15
.text:0054102B                 shl     dl, cl
.text:0054102D                 mov     cl, cube64[eax+esi*8]
.text:00541034                 not     dl
.text:00541036                 and     cl, dl
.text:00541038                 mov     cube64[eax+esi*8], cl
.text:0054103F                 pop     esi
.text:00541040                 retn
.text:00541040 set_bit         endp
.text:00541040
.text:00541041                 align 10h
.text:00541050
.text:00541050 ; =============== S U B R O U T I N E =======================================
.text:00541050
.text:00541050
.text:00541050 get_bit         proc near  ; CODE XREF: rotate1+16
.text:00541050                            ; rotate2+16 ...
.text:00541050
.text:00541050 arg_0           = dword ptr  4
.text:00541050 arg_4           = dword ptr  8
.text:00541050 arg_8           = byte ptr  0Ch
.text:00541050
.text:00541050                 mov     eax, [esp+arg_4]
.text:00541054                 mov     ecx, [esp+arg_0]
.text:00541058                 mov     al, cube64[eax+ecx*8]
.text:0054105F                 mov     cl, [esp+arg_8]
.text:00541063                 shr     al, cl
.text:00541065                 and     al, 1
.text:00541067                 retn
.text:00541067 get_bit         endp
.text:00541067
.text:00541068                 align 10h
.text:00541070
.text:00541070 ; =============== S U B R O U T I N E =======================================
.text:00541070
.text:00541070
.text:00541070 rotate1         proc near  ; CODE XREF: rotate_all_with_password+8E
.text:00541070
.text:00541070 internal_array_64= byte ptr -40h
.text:00541070 arg_0           = dword ptr  4
.text:00541070
.text:00541070                 sub     esp, 40h
.text:00541073                 push    ebx
.text:00541074                 push    ebp
.text:00541075                 mov     ebp, [esp+48h+arg_0]
.text:00541079                 push    esi
.text:0054107A                 push    edi
.text:0054107B                 xor     edi, edi   ; EDI is loop1 counter
.text:0054107D                 lea     ebx, [esp+50h+internal_array_64]
.text:00541081
.text:00541081 first_loop1_begin:                 ; CODE XREF: rotate1+2E
.text:00541081                 xor     esi, esi   ; ESI is loop2 counter
.text:00541083
.text:00541083 first_loop2_begin:                 ; CODE XREF: rotate1+25
.text:00541083                 push    ebp        ; arg_0
.text:00541084                 push    esi
.text:00541085                 push    edi
.text:00541086                 call    get_bit
.text:0054108B                 add     esp, 0Ch
.text:0054108E                 mov     [ebx+esi], al ; store to internal array
.text:00541091                 inc     esi
.text:00541092                 cmp     esi, 8
.text:00541095                 jl      short first_loop2_begin
.text:00541097                 inc     edi
```

```
.text:00541098                 add     ebx, 8
.text:0054109B                 cmp     edi, 8
.text:0054109E                 jl      short first_loop1_begin
.text:005410A0                 lea     ebx, [esp+50h+internal_array_64]
.text:005410A4                 mov     edi, 7    ; EDI is loop1 counter, initial state is 7
.text:005410A9
.text:005410A9 second_loop1_begin:               ; CODE XREF: rotate1+57
.text:005410A9                 xor     esi, esi  ; ESI is loop2 counter
.text:005410AB
.text:005410AB second_loop2_begin:               ; CODE XREF: rotate1+4E
.text:005410AB                 mov     al, [ebx+esi] ; value from internal array
.text:005410AE                 push    eax
.text:005410AF                 push    ebp       ; arg_0
.text:005410B0                 push    edi
.text:005410B1                 push    esi
.text:005410B2                 call    set_bit
.text:005410B7                 add     esp, 10h
.text:005410BA                 inc     esi       ; increment loop2 counter
.text:005410BB                 cmp     esi, 8
.text:005410BE                 jl      short second_loop2_begin
.text:005410C0                 dec     edi       ; decrement loop2 counter
.text:005410C1                 add     ebx, 8
.text:005410C4                 cmp     edi, 0FFFFFFFFh
.text:005410C7                 jg      short second_loop1_begin
.text:005410C9                 pop     edi
.text:005410CA                 pop     esi
.text:005410CB                 pop     ebp
.text:005410CC                 pop     ebx
.text:005410CD                 add     esp, 40h
.text:005410D0                 retn
.text:005410D0 rotate1         endp
.text:005410D0
.text:005410D1                 align 10h
.text:005410E0
.text:005410E0 ; =============== S U B R O U T I N E =======================================
.text:005410E0
.text:005410E0
.text:005410E0 rotate2         proc near         ; CODE XREF: rotate_all_with_password+7A
.text:005410E0
.text:005410E0 internal_array_64= byte ptr -40h
.text:005410E0 arg_0           = dword ptr  4
.text:005410E0
.text:005410E0                 sub     esp, 40h
.text:005410E3                 push    ebx
.text:005410E4                 push    ebp
.text:005410E5                 mov     ebp, [esp+48h+arg_0]
.text:005410E9                 push    esi
.text:005410EA                 push    edi
.text:005410EB                 xor     edi, edi  ; loop1 counter
.text:005410ED                 lea     ebx, [esp+50h+internal_array_64]
.text:005410F1
.text:005410F1 loc_5410F1:                       ; CODE XREF: rotate2+2E
.text:005410F1                 xor     esi, esi  ; loop2 counter
.text:005410F3
.text:005410F3 loc_5410F3:                       ; CODE XREF: rotate2+25
.text:005410F3                 push    esi       ; loop2
.text:005410F4                 push    edi       ; loop1
.text:005410F5                 push    ebp       ; arg_0
.text:005410F6                 call    get_bit
.text:005410FB                 add     esp, 0Ch
.text:005410FE                 mov     [ebx+esi], al ; store to internal array
.text:00541101                 inc     esi           ; increment loop1 counter
.text:00541102                 cmp     esi, 8
.text:00541105                 jl      short loc_5410F3
.text:00541107                 inc     edi      ; increment loop2 counter
.text:00541108                 add     ebx, 8
.text:0054110B                 cmp     edi, 8
.text:0054110E                 jl      short loc_5410F1
.text:00541110                 lea     ebx, [esp+50h+internal_array_64]
.text:00541114                 mov     edi, 7   ; loop1 counter is initial state 7
```

```
.text:00541119
.text:00541119 loc_541119:                     ; CODE XREF: rotate2+57
.text:00541119                 xor     esi, esi ; loop2 counter
.text:0054111B
.text:0054111B loc_54111B:                     ; CODE XREF: rotate2+4E
.text:0054111B                 mov     al, [ebx+esi]   ; get byte from internal array
.text:0054111E                 push    eax
.text:0054111F                 push    edi      ; loop1 counter
.text:00541120                 push    esi      ; loop2 counter
.text:00541121                 push    ebp      ; arg_0
.text:00541122                 call    set_bit
.text:00541127                 add     esp, 10h
.text:0054112A                 inc     esi      ; increment loop2 counter
.text:0054112B                 cmp     esi, 8
.text:0054112E                 jl      short loc_54111B
.text:00541130                 dec     edi      ; decrement loop2 counter
.text:00541131                 add     ebx, 8
.text:00541134                 cmp     edi, 0FFFFFFFFh
.text:00541137                 jg      short loc_541119
.text:00541139                 pop     edi
.text:0054113A                 pop     esi
.text:0054113B                 pop     ebp
.text:0054113C                 pop     ebx
.text:0054113D                 add     esp, 40h
.text:00541140                 retn
.text:00541140 rotate2         endp
.text:00541140
.text:00541141                 align 10h
.text:00541150
.text:00541150 ; =============== S U B R O U T I N E =======================================
.text:00541150
.text:00541150
.text:00541150 rotate3         proc near      ; CODE XREF: rotate_all_with_password+66
.text:00541150
.text:00541150 var_40          = byte ptr -40h
.text:00541150 arg_0           = dword ptr  4
.text:00541150
.text:00541150                 sub     esp, 40h
.text:00541153                 push    ebx
.text:00541154                 push    ebp
.text:00541155                 mov     ebp, [esp+48h+arg_0]
.text:00541159                 push    esi
.text:0054115A                 push    edi
.text:0054115B                 xor     edi, edi
.text:0054115D                 lea     ebx, [esp+50h+var_40]
.text:00541161
.text:00541161 loc_541161:                    ; CODE XREF: rotate3+2E
.text:00541161                 xor     esi, esi
.text:00541163
.text:00541163 loc_541163:                    ; CODE XREF: rotate3+25
.text:00541163                 push    esi
.text:00541164                 push    ebp
.text:00541165                 push    edi
.text:00541166                 call    get_bit
.text:0054116B                 add     esp, 0Ch
.text:0054116E                 mov     [ebx+esi], al
.text:00541171                 inc     esi
.text:00541172                 cmp     esi, 8
.text:00541175                 jl      short loc_541163
.text:00541177                 inc     edi
.text:00541178                 add     ebx, 8
.text:0054117B                 cmp     edi, 8
.text:0054117E                 jl      short loc_541161
.text:00541180                 xor     ebx, ebx
.text:00541182                 lea     edi, [esp+50h+var_40]
.text:00541186
.text:00541186 loc_541186:                    ; CODE XREF: rotate3+54
.text:00541186                 mov     esi, 7
.text:0054118B
.text:0054118B loc_54118B:                    ; CODE XREF: rotate3+4E
```

```
.text:0054118B                 mov     al, [edi]
.text:0054118D                 push    eax
.text:0054118E                 push    ebx
.text:0054118F                 push    ebp
.text:00541190                 push    esi
.text:00541191                 call    set_bit
.text:00541196                 add     esp, 10h
.text:00541199                 inc     edi
.text:0054119A                 dec     esi
.text:0054119B                 cmp     esi, 0FFFFFFFFh
.text:0054119E                 jg      short loc_54118B
.text:005411A0                 inc     ebx
.text:005411A1                 cmp     ebx, 8
.text:005411A4                 jl      short loc_541186
.text:005411A6                 pop     edi
.text:005411A7                 pop     esi
.text:005411A8                 pop     ebp
.text:005411A9                 pop     ebx
.text:005411AA                 add     esp, 40h
.text:005411AD                 retn
.text:005411AD rotate3         endp
.text:005411AD
.text:005411AE                 align 10h
.text:005411B0
.text:005411B0 ; =============== S U B R O U T I N E =======================================
.text:005411B0
.text:005411B0
.text:005411B0 rotate_all_with_password proc near  ; CODE XREF: crypt+1F
.text:005411B0                                     ; decrypt+36
.text:005411B0
.text:005411B0 arg_0           = dword ptr  4
.text:005411B0 arg_4           = dword ptr  8
.text:005411B0
.text:005411B0                 mov     eax, [esp+arg_0]
.text:005411B4                 push    ebp
.text:005411B5                 mov     ebp, eax
.text:005411B7                 cmp     byte ptr [eax], 0
.text:005411BA                 jz      exit
.text:005411C0                 push    ebx
.text:005411C1                 mov     ebx, [esp+8+arg_4]
.text:005411C5                 push    esi
.text:005411C6                 push    edi
.text:005411C7
.text:005411C7 loop_begin:             ; CODE XREF: rotate_all_with_password+9F
.text:005411C7                 movsx   eax, byte ptr [ebp+0]
.text:005411CB                 push    eax             ; C
.text:005411CC                 call    _tolower
.text:005411D1                 add     esp, 4
.text:005411D4                 cmp     al, 'a'
.text:005411D6                 jl      short next_character_in_password
.text:005411D8                 cmp     al, 'z'
.text:005411DA                 jg      short next_character_in_password
.text:005411DC                 movsx   ecx, al
.text:005411DF                 sub     ecx, 'a'
.text:005411E2                 cmp     ecx, 24
.text:005411E5                 jle     short skip_subtracting
.text:005411E7                 sub     ecx, 24
.text:005411EA
.text:005411EA skip_subtracting:          ; CODE XREF: rotate_all_with_password+35
.text:005411EA                 mov     eax, 55555556h
.text:005411EF                 imul    ecx
.text:005411F1                 mov     eax, edx
.text:005411F3                 shr     eax, 1Fh
.text:005411F6                 add     edx, eax
.text:005411F8                 mov     eax, ecx
.text:005411FA                 mov     esi, edx
.text:005411FC                 mov     ecx, 3
.text:00541201                 cdq
.text:00541202                 idiv    ecx
.text:00541204                 sub     edx, 0
```

```
.text:00541207                 jz      short call_rotate1
.text:00541209                 dec     edx
.text:0054120A                 jz      short call_rotate2
.text:0054120C                 dec     edx
.text:0054120D                 jnz     short next_character_in_password
.text:0054120F                 test    ebx, ebx
.text:00541211                 jle     short next_character_in_password
.text:00541213                 mov     edi, ebx
.text:00541215
.text:00541215 call_rotate3:               ; CODE XREF: rotate_all_with_password+6F
.text:00541215                 push    esi
.text:00541216                 call    rotate3
.text:0054121B                 add     esp, 4
.text:0054121E                 dec     edi
.text:0054121F                 jnz     short call_rotate3
.text:00541221                 jmp     short next_character_in_password
.text:00541223
.text:00541223 call_rotate2:             ; CODE XREF: rotate_all_with_password+5A
.text:00541223                 test    ebx, ebx
.text:00541225                 jle     short next_character_in_password
.text:00541227                 mov     edi, ebx
.text:00541229
.text:00541229 loc_541229:               ; CODE XREF: rotate_all_with_password+83
.text:00541229                 push    esi
.text:0054122A                 call    rotate2
.text:0054122F                 add     esp, 4
.text:00541232                 dec     edi
.text:00541233                 jnz     short loc_541229
.text:00541235                 jmp     short next_character_in_password
.text:00541237
.text:00541237 call_rotate1:             ; CODE XREF: rotate_all_with_password+57
.text:00541237                 test    ebx, ebx
.text:00541239                 jle     short next_character_in_password
.text:0054123B                 mov     edi, ebx
.text:0054123D
.text:0054123D loc_54123D:               ; CODE XREF: rotate_all_with_password+97
.text:0054123D                 push    esi
.text:0054123E                 call    rotate1
.text:00541243                 add     esp, 4
.text:00541246                 dec     edi
.text:00541247                 jnz     short loc_54123D
.text:00541249
.text:00541249 next_character_in_password:  ; CODE XREF: rotate_all_with_password+26
.text:00541249                              ; rotate_all_with_password+2A ...
.text:00541249                 mov     al, [ebp+1]
.text:0054124C                 inc     ebp
.text:0054124D                 test    al, al
.text:0054124F                 jnz     loop_begin
.text:00541255                 pop     edi
.text:00541256                 pop     esi
.text:00541257                 pop     ebx
.text:00541258
.text:00541258 exit:                        ; CODE XREF: rotate_all_with_password+A
.text:00541258                 pop     ebp
.text:00541259                 retn
.text:00541259 rotate_all_with_password endp
.text:00541259
.text:0054125A                 align 10h
.text:00541260
.text:00541260 ; =============== S U B R O U T I N E =======================================
.text:00541260
.text:00541260
.text:00541260 crypt           proc near    ; CODE XREF: crypt_file+8A
.text:00541260
.text:00541260 arg_0           = dword ptr  4
.text:00541260 arg_4           = dword ptr  8
.text:00541260 arg_8           = dword ptr  0Ch
.text:00541260
.text:00541260                 push    ebx
.text:00541261                 mov     ebx, [esp+4+arg_0]
```

```
.text:00541265                 push    ebp
.text:00541266                 push    esi
.text:00541267                 push    edi
.text:00541268                 xor     ebp, ebp
.text:0054126A
.text:0054126A loc_54126A:                     ; CODE XREF: crypt+41
.text:0054126A                 mov     eax, [esp+10h+arg_8]
.text:0054126E                 mov     ecx, 10h
.text:00541273                 mov     esi, ebx
.text:00541275                 mov     edi, offset cube64
.text:0054127A                 push    1
.text:0054127C                 push    eax
.text:0054127D                 rep movsd
.text:0054127F                 call    rotate_all_with_password
.text:00541284                 mov     eax, [esp+18h+arg_4]
.text:00541288                 mov     edi, ebx
.text:0054128A                 add     ebp, 40h
.text:0054128D                 add     esp, 8
.text:00541290                 mov     ecx, 10h
.text:00541295                 mov     esi, offset cube64
.text:0054129A                 add     ebx, 40h
.text:0054129D                 cmp     ebp, eax
.text:0054129F                 rep movsd
.text:005412A1                 jl      short loc_54126A
.text:005412A3                 pop     edi
.text:005412A4                 pop     esi
.text:005412A5                 pop     ebp
.text:005412A6                 pop     ebx
.text:005412A7                 retn
.text:005412A7 crypt           endp
.text:005412A7
.text:005412A8                 align 10h
.text:005412B0
.text:005412B0 ; =============== S U B R O U T I N E =======================================
.text:005412B0
.text:005412B0
.text:005412B0 ; int __cdecl decrypt(int, int, void *Src)
.text:005412B0 decrypt         proc near       ; CODE XREF: decrypt_file+99
.text:005412B0
.text:005412B0 arg_0           = dword ptr  4
.text:005412B0 arg_4           = dword ptr  8
.text:005412B0 Src             = dword ptr  0Ch
.text:005412B0
.text:005412B0                 mov     eax, [esp+Src]
.text:005412B4                 push    ebx
.text:005412B5                 push    ebp
.text:005412B6                 push    esi
.text:005412B7                 push    edi
.text:005412B8                 push    eax             ; Src
.text:005412B9                 call    __strdup
.text:005412BE                 push    eax             ; Str
.text:005412BF                 mov     [esp+18h+Src], eax
.text:005412C3                 call    __strrev
.text:005412C8                 mov     ebx, [esp+18h+arg_0]
.text:005412CC                 add     esp, 8
.text:005412CF                 xor     ebp, ebp
.text:005412D1
.text:005412D1 loc_5412D1:                     ; CODE XREF: decrypt+58
.text:005412D1                 mov     ecx, 10h
.text:005412D6                 mov     esi, ebx
.text:005412D8                 mov     edi, offset cube64
.text:005412DD                 push    3
.text:005412DF                 rep movsd
.text:005412E1                 mov     ecx, [esp+14h+Src]
.text:005412E5                 push    ecx
.text:005412E6                 call    rotate_all_with_password
.text:005412EB                 mov     eax, [esp+18h+arg_4]
.text:005412EF                 mov     edi, ebx
.text:005412F1                 add     ebp, 40h
.text:005412F4                 add     esp, 8
```

```
.text:005412F7                 mov     ecx, 10h
.text:005412FC                 mov     esi, offset cube64
.text:00541301                 add     ebx, 40h
.text:00541304                 cmp     ebp, eax
.text:00541306                 rep movsd
.text:00541308                 jl      short loc_5412D1
.text:0054130A                 mov     edx, [esp+10h+Src]
.text:0054130E                 push    edx   ; Memory
.text:0054130F                 call    _free
.text:00541314                 add     esp, 4
.text:00541317                 pop     edi
.text:00541318                 pop     esi
.text:00541319                 pop     ebp
.text:0054131A                 pop     ebx
.text:0054131B                 retn
.text:0054131B decrypt         endp
.text:0054131B
.text:0054131C                 align 10h
.text:00541320
.text:00541320 ; =============== S U B R O U T I N E =======================================
.text:00541320
.text:00541320
.text:00541320 ; int __cdecl crypt_file(int Str, char *Filename, int password)
.text:00541320 crypt_file      proc near     ; CODE XREF: _main+42
.text:00541320
.text:00541320 Str             = dword ptr  4
.text:00541320 Filename        = dword ptr  8
.text:00541320 password        = dword ptr  0Ch
.text:00541320
.text:00541320                 mov     eax, [esp+Str]
.text:00541324                 push    ebp
.text:00541325                 push    offset Mode ; "rb"
.text:0054132A                 push    eax         ; Filename
.text:0054132B                 call    _fopen      ; open file
.text:00541330                 mov     ebp, eax
.text:00541332                 add     esp, 8
.text:00541335                 test    ebp, ebp
.text:00541337                 jnz     short loc_541348
.text:00541339                 push    offset Format   ; "Cannot open input file!\n"
.text:0054133E                 call    _printf
.text:00541343                 add     esp, 4
.text:00541346                 pop     ebp
.text:00541347                 retn
.text:00541348
.text:00541348 loc_541348:                             ; CODE XREF: crypt_file+17
.text:00541348                 push    ebx
.text:00541349                 push    esi
.text:0054134A                 push    edi
.text:0054134B                 push    2           ; Origin
.text:0054134D                 push    0           ; Offset
.text:0054134F                 push    ebp         ; File
.text:00541350                 call    _fseek
.text:00541355                 push    ebp         ; File
.text:00541356                 call    _ftell      ; get file size
.text:0054135B                 push    0           ; Origin
.text:0054135D                 push    0           ; Offset
.text:0054135F                 push    ebp         ; File
.text:00541360                 mov     [esp+2Ch+Str], eax
.text:00541364                 call    _fseek      ; rewind to start
.text:00541369                 mov     esi, [esp+2Ch+Str]
.text:0054136D                 and     esi, 0FFFFFFC0h ; reset all lowest 6 bits
.text:00541370                 add     esi, 40h    ; align size to 64-byte border
.text:00541373                 push    esi         ; Size
.text:00541374                 call    _malloc
.text:00541379                 mov     ecx, esi
.text:0054137B                 mov     ebx, eax    ; allocated buffer pointer -> to EBX
.text:0054137D                 mov     edx, ecx
.text:0054137F                 xor     eax, eax
.text:00541381                 mov     edi, ebx
.text:00541383                 push    ebp         ; File
```

```
.text:00541384                 shr     ecx, 2
.text:00541387                 rep stosd
.text:00541389                 mov     ecx, edx
.text:0054138B                 push    1            ; Count
.text:0054138D                 and     ecx, 3
.text:00541390                 rep stosb            ; memset (buffer, 0, aligned_size)
.text:00541392                 mov     eax, [esp+38h+Str]
.text:00541396                 push    eax          ; ElementSize
.text:00541397                 push    ebx          ; DstBuf
.text:00541398                 call    _fread       ; read file
.text:0054139D                 push    ebp          ; File
.text:0054139E                 call    _fclose
.text:005413A3                 mov     ecx, [esp+44h+password]
.text:005413A7                 push    ecx          ; password
.text:005413A8                 push    esi          ; aligned size
.text:005413A9                 push    ebx          ; buffer
.text:005413AA                 call    crypt        ; do crypt
.text:005413AF                 mov     edx, [esp+50h+Filename]
.text:005413B3                 add     esp, 40h
.text:005413B6                 push    offset aWb   ; "wb"
.text:005413BB                 push    edx          ; Filename
.text:005413BC                 call    _fopen
.text:005413C1                 mov     edi, eax
.text:005413C3                 push    edi          ; File
.text:005413C4                 push    1            ; Count
.text:005413C6                 push    3            ; Size
.text:005413C8                 push    offset aQr9  ; "QR9"
.text:005413CD                 call    _fwrite      ; write file signature
.text:005413D2                 push    edi          ; File
.text:005413D3                 push    1            ; Count
.text:005413D5                 lea     eax, [esp+30h+Str]
.text:005413D9                 push    4            ; Size
.text:005413DB                 push    eax          ; Str
.text:005413DC                 call    _fwrite      ; write original file size
.text:005413E1                 push    edi          ; File
.text:005413E2                 push    1            ; Count
.text:005413E4                 push    esi          ; Size
.text:005413E5                 push    ebx          ; Str
.text:005413E6                 call    _fwrite      ; write encrypted file
.text:005413EB                 push    edi          ; File
.text:005413EC                 call    _fclose
.text:005413F1                 push    ebx          ; Memory
.text:005413F2                 call    _free
.text:005413F7                 add     esp, 40h
.text:005413FA                 pop     edi
.text:005413FB                 pop     esi
.text:005413FC                 pop     ebx
.text:005413FD                 pop     ebp
.text:005413FE                 retn
.text:005413FE crypt_file      endp
.text:005413FE
.text:005413FF                 align 10h
.text:00541400
.text:00541400 ; =============== S U B R O U T I N E =======================================
.text:00541400
.text:00541400
.text:00541400 ; int __cdecl decrypt_file(char *Filename, int, void *Src)
.text:00541400 decrypt_file    proc near            ; CODE XREF: _main+6E
.text:00541400
.text:00541400 Filename        = dword ptr  4
.text:00541400 arg_4           = dword ptr  8
.text:00541400 Src             = dword ptr  0Ch
.text:00541400
.text:00541400                 mov     eax, [esp+Filename]
.text:00541404                 push    ebx
.text:00541405                 push    ebp
.text:00541406                 push    esi
.text:00541407                 push    edi
.text:00541408                 push    offset aRb   ; "rb"
.text:0054140D                 push    eax          ; Filename
```

```
.text:0054140E                 call    _fopen
.text:00541413                 mov     esi, eax
.text:00541415                 add     esp, 8
.text:00541418                 test    esi, esi
.text:0054141A                 jnz     short loc_54142E
.text:0054141C                 push    offset aCannotOpenIn_0 ; "Cannot open input file!\n"
.text:00541421                 call    _printf
.text:00541426                 add     esp, 4
.text:00541429                 pop     edi
.text:0054142A                 pop     esi
.text:0054142B                 pop     ebp
.text:0054142C                 pop     ebx
.text:0054142D                 retn
.text:0054142E
.text:0054142E loc_54142E:                             ; CODE XREF: decrypt_file+1A
.text:0054142E                 push    2        ; Origin
.text:00541430                 push    0        ; Offset
.text:00541432                 push    esi      ; File
.text:00541433                 call    _fseek
.text:00541438                 push    esi      ; File
.text:00541439                 call    _ftell
.text:0054143E                 push    0        ; Origin
.text:00541440                 push    0        ; Offset
.text:00541442                 push    esi      ; File
.text:00541443                 mov     ebp, eax
.text:00541445                 call    _fseek
.text:0054144A                 push    ebp      ; Size
.text:0054144B                 call    _malloc
.text:00541450                 push    esi      ; File
.text:00541451                 mov     ebx, eax
.text:00541453                 push    1        ; Count
.text:00541455                 push    ebp      ; ElementSize
.text:00541456                 push    ebx      ; DstBuf
.text:00541457                 call    _fread
.text:0054145C                 push    esi      ; File
.text:0054145D                 call    _fclose
.text:00541462                 add     esp, 34h
.text:00541465                 mov     ecx, 3
.text:0054146A                 mov     edi, offset aQr9_0 ; "QR9"
.text:0054146F                 mov     esi, ebx
.text:00541471                 xor     edx, edx
.text:00541473                 repe cmpsb
.text:00541475                 jz      short loc_541489
.text:00541477                 push    offset aFileIsNotCrypt ; "File is not encrypted!\n"
.text:0054147C                 call    _printf
.text:00541481                 add     esp, 4
.text:00541484                 pop     edi
.text:00541485                 pop     esi
.text:00541486                 pop     ebp
.text:00541487                 pop     ebx
.text:00541488                 retn
.text:00541489
.text:00541489 loc_541489:                             ; CODE XREF: decrypt_file+75
.text:00541489                 mov     eax, [esp+10h+Src]
.text:0054148D                 mov     edi, [ebx+3]
.text:00541490                 add     ebp, 0FFFFFFF9h
.text:00541493                 lea     esi, [ebx+7]
.text:00541496                 push    eax      ; Src
.text:00541497                 push    ebp      ; int
.text:00541498                 push    esi      ; int
.text:00541499                 call    decrypt
.text:0054149E                 mov     ecx, [esp+1Ch+arg_4]
.text:005414A2                 push    offset aWb_0  ; "wb"
.text:005414A7                 push    ecx            ; Filename
.text:005414A8                 call    _fopen
.text:005414AD                 mov     ebp, eax
.text:005414AF                 push    ebp      ; File
.text:005414B0                 push    1        ; Count
.text:005414B2                 push    edi      ; Size
.text:005414B3                 push    esi      ; Str
```

```
.text:005414B4                 call    _fwrite
.text:005414B9                 push    ebp      ; File
.text:005414BA                 call    _fclose
.text:005414BF                 push    ebx      ; Memory
.text:005414C0                 call    _free
.text:005414C5                 add     esp, 2Ch
.text:005414C8                 pop     edi
.text:005414C9                 pop     esi
.text:005414CA                 pop     ebp
.text:005414CB                 pop     ebx
.text:005414CC                 retn
.text:005414CC decrypt_file    endp
```

All function and label names were given by me during the analysis.

Let's start from the top. Here is a function that takes two file names and password.

```
.text:00541320 ; int __cdecl crypt_file(int Str, char *Filename, int password)
.text:00541320 crypt_file      proc near
.text:00541320
.text:00541320 Str             = dword ptr  4
.text:00541320 Filename        = dword ptr  8
.text:00541320 password        = dword ptr  0Ch
.text:00541320
```

Open the file and report if an error occurs:

```
.text:00541320                 mov     eax, [esp+Str]
.text:00541324                 push    ebp
.text:00541325                 push    offset Mode     ; "rb"
.text:0054132A                 push    eax             ; Filename
.text:0054132B                 call    _fopen          ; open file
.text:00541330                 mov     ebp, eax
.text:00541332                 add     esp, 8
.text:00541335                 test    ebp, ebp
.text:00541337                 jnz     short loc_541348
.text:00541339                 push    offset Format   ; "Cannot open input file!\n"
.text:0054133E                 call    _printf
.text:00541343                 add     esp, 4
.text:00541346                 pop     ebp
.text:00541347                 retn
.text:00541348
.text:00541348 loc_541348:
```

Get the file size via `fseek()`/`ftell()`:

```
.text:00541348 push    ebx
.text:00541349 push    esi
.text:0054134A push    edi
.text:0054134B push    2               ; Origin
.text:0054134D push    0               ; Offset
.text:0054134F push    ebp             ; File

; move current file position to the end
.text:00541350 call    _fseek
.text:00541355 push    ebp             ; File
.text:00541356 call    _ftell          ; get current file position
.text:0054135B push    0               ; Origin
.text:0054135D push    0               ; Offset
.text:0054135F push    ebp             ; File
.text:00541360 mov     [esp+2Ch+Str], eax

; move current file position to the start
.text:00541364 call    _fseek
```

This fragment of code calculates the file size aligned on a 64-byte boundary. This is because this cryptographic algorithm works only with 64-byte blocks. The operation is pretty straightforward: divide the file size by 64, forget about the remainder and add 1, then multiply by 64. The following code removes the remainder as if the value has already been divided by 64 and adds 64. It is almost the same.

```
.text:00541369 mov     esi, [esp+2Ch+Str]
; reset all lowest 6 bits
.text:0054136D and     esi, 0FFFFFFC0h
; align size to 64-byte border
.text:00541370 add     esi, 40h
```

Allocate buffer with aligned size:

```
.text:00541373                 push    esi             ; Size
.text:00541374                 call    _malloc
```

Call memset(), e.g., clear the allocated buffer[17].

```
.text:00541379 mov     ecx, esi
.text:0054137B mov     ebx, eax    ; allocated buffer pointer -> to EBX
.text:0054137D mov     edx, ecx
.text:0054137F xor     eax, eax
.text:00541381 mov     edi, ebx
.text:00541383 push    ebp         ; File
.text:00541384 shr     ecx, 2
.text:00541387 rep stosd
.text:00541389 mov     ecx, edx
.text:0054138B push    1           ; Count
.text:0054138D and     ecx, 3
.text:00541390 rep stosb           ; memset (buffer, 0, aligned_size)
```

Read file via the standard C function `fread()`.

```
.text:00541392                 mov     eax, [esp+38h+Str]
.text:00541396                 push    eax             ; ElementSize
.text:00541397                 push    ebx             ; DstBuf
.text:00541398                 call    _fread          ; read file
.text:0054139D                 push    ebp             ; File
.text:0054139E                 call    _fclose
```

Call `crypt()`. This function takes a buffer, buffer size (aligned) and a password string.

```
.text:005413A3                 mov     ecx, [esp+44h+password]
.text:005413A7                 push    ecx             ; password
.text:005413A8                 push    esi             ; aligned size
.text:005413A9                 push    ebx             ; buffer
.text:005413AA                 call    crypt           ; do crypt
```

Create the output file. By the way, the developer forgot to check if it has been created correctly! The file opening result is being checked, though.

```
.text:005413AF                 mov     edx, [esp+50h+Filename]
.text:005413B3                 add     esp, 40h
.text:005413B6                 push    offset aWb      ; "wb"
.text:005413BB                 push    edx             ; Filename
.text:005413BC                 call    _fopen
.text:005413C1                 mov     edi, eax
```

The newly created file handle is in the EDI register now. Write signature "QR9".

```
.text:005413C3                 push    edi             ; File
.text:005413C4                 push    1               ; Count
.text:005413C6                 push    3               ; Size
.text:005413C8                 push    offset aQr9     ; "QR9"
.text:005413CD                 call    _fwrite         ; write file signature
```

Write the actual file size (not aligned):

```
.text:005413D2                 push    edi             ; File
.text:005413D3                 push    1               ; Count
.text:005413D5                 lea     eax, [esp+30h+Str]
.text:005413D9                 push    4               ; Size
```

[17] malloc() + memset() could be replaced by calloc()

```
.text:005413DB                 push    eax             ; Str
.text:005413DC                 call    _fwrite         ; write original file size
```

Write the encrypted buffer:

```
.text:005413E1                 push    edi             ; File
.text:005413E2                 push    1               ; Count
.text:005413E4                 push    esi             ; Size
.text:005413E5                 push    ebx             ; Str
.text:005413E6                 call    _fwrite         ; write encrypted file
```

Close the file and free the allocated buffer:

```
.text:005413EB                 push    edi             ; File
.text:005413EC                 call    _fclose
.text:005413F1                 push    ebx             ; Memory
.text:005413F2                 call    _free
.text:005413F7                 add     esp, 40h
.text:005413FA                 pop     edi
.text:005413FB                 pop     esi
.text:005413FC                 pop     ebx
.text:005413FD                 pop     ebp
.text:005413FE                 retn
.text:005413FE crypt_file      endp
```

Here is the reconstructed C code:

```
void crypt_file(char *fin, char* fout, char *pw)
{
        FILE *f;
        int flen, flen_aligned;
        BYTE *buf;

        f=fopen(fin, "rb");

        if (f==NULL)
        {
                printf ("Cannot open input file!\n");
                return;
        };

        fseek (f, 0, SEEK_END);
        flen=ftell (f);
        fseek (f, 0, SEEK_SET);

        flen_aligned=(flen&0xFFFFFFC0)+0x40;

        buf=(BYTE*)malloc (flen_aligned);
        memset (buf, 0, flen_aligned);

        fread (buf, flen, 1, f);

        fclose (f);

        crypt (buf, flen_aligned, pw);

        f=fopen(fout, "wb");

        fwrite ("QR9", 3, 1, f);
        fwrite (&flen, 4, 1, f);
        fwrite (buf, flen_aligned, 1, f);

        fclose (f);

        free (buf);
};
```

The decryption procedure is almost the same:

```
.text:00541400 ; int __cdecl decrypt_file(char *Filename, int, void *Src)
.text:00541400 decrypt_file    proc near
.text:00541400
.text:00541400 Filename        = dword ptr  4
.text:00541400 arg_4           = dword ptr  8
.text:00541400 Src             = dword ptr  0Ch
.text:00541400
.text:00541400                 mov     eax, [esp+Filename]
.text:00541404                 push    ebx
.text:00541405                 push    ebp
.text:00541406                 push    esi
.text:00541407                 push    edi
.text:00541408                 push    offset aRb      ; "rb"
.text:0054140D                 push    eax             ; Filename
.text:0054140E                 call    _fopen
.text:00541413                 mov     esi, eax
.text:00541415                 add     esp, 8
.text:00541418                 test    esi, esi
.text:0054141A                 jnz     short loc_54142E
.text:0054141C                 push    offset aCannotOpenIn_0 ; "Cannot open input file!\n"
.text:00541421                 call    _printf
.text:00541426                 add     esp, 4
.text:00541429                 pop     edi
.text:0054142A                 pop     esi
.text:0054142B                 pop     ebp
.text:0054142C                 pop     ebx
.text:0054142D                 retn
.text:0054142E
.text:0054142E loc_54142E:
.text:0054142E                 push    2               ; Origin
.text:00541430                 push    0               ; Offset
.text:00541432                 push    esi             ; File
.text:00541433                 call    _fseek
.text:00541438                 push    esi             ; File
.text:00541439                 call    _ftell
.text:0054143E                 push    0               ; Origin
.text:00541440                 push    0               ; Offset
.text:00541442                 push    esi             ; File
.text:00541443                 mov     ebp, eax
.text:00541445                 call    _fseek
.text:0054144A                 push    ebp             ; Size
.text:0054144B                 call    _malloc
.text:00541450                 push    esi             ; File
.text:00541451                 mov     ebx, eax
.text:00541453                 push    1               ; Count
.text:00541455                 push    ebp             ; ElementSize
.text:00541456                 push    ebx             ; DstBuf
.text:00541457                 call    _fread
.text:0054145C                 push    esi             ; File
.text:0054145D                 call    _fclose
```

Check signature (first 3 bytes):

```
.text:00541462                 add     esp, 34h
.text:00541465                 mov     ecx, 3
.text:0054146A                 mov     edi, offset aQr9_0 ; "QR9"
.text:0054146F                 mov     esi, ebx
.text:00541471                 xor     edx, edx
.text:00541473                 repe cmpsb
.text:00541475                 jz      short loc_541489
```

Report an error if the signature is absent:

```
.text:00541477                 push    offset aFileIsNotCrypt ; "File is not encrypted!\n"
.text:0054147C                 call    _printf
.text:00541481                 add     esp, 4
.text:00541484                 pop     edi
.text:00541485                 pop     esi
.text:00541486                 pop     ebp
```

```
.text:00541487                 pop     ebx
.text:00541488                 retn
.text:00541489
.text:00541489 loc_541489:
```

Call decrypt().

```
.text:00541489                 mov     eax, [esp+10h+Src]
.text:0054148D                 mov     edi, [ebx+3]
.text:00541490                 add     ebp, 0FFFFFFF9h
.text:00541493                 lea     esi, [ebx+7]
.text:00541496                 push    eax             ; Src
.text:00541497                 push    ebp             ; int
.text:00541498                 push    esi             ; int
.text:00541499                 call    decrypt
.text:0054149E                 mov     ecx, [esp+1Ch+arg_4]
.text:005414A2                 push    offset aWb_0    ; "wb"
.text:005414A7                 push    ecx             ; Filename
.text:005414A8                 call    _fopen
.text:005414AD                 mov     ebp, eax
.text:005414AF                 push    ebp             ; File
.text:005414B0                 push    1               ; Count
.text:005414B2                 push    edi             ; Size
.text:005414B3                 push    esi             ; Str
.text:005414B4                 call    _fwrite
.text:005414B9                 push    ebp             ; File
.text:005414BA                 call    _fclose
.text:005414BF                 push    ebx             ; Memory
.text:005414C0                 call    _free
.text:005414C5                 add     esp, 2Ch
.text:005414C8                 pop     edi
.text:005414C9                 pop     esi
.text:005414CA                 pop     ebp
.text:005414CB                 pop     ebx
.text:005414CC                 retn
.text:005414CC decrypt_file    endp
```

Here is the reconstructed C code:

```
void decrypt_file(char *fin, char* fout, char *pw)
{
        FILE *f;
        int real_flen, flen;
        BYTE *buf;

        f=fopen(fin, "rb");

        if (f==NULL)
        {
                printf ("Cannot open input file!\n");
                return;
        };

        fseek (f, 0, SEEK_END);
        flen=ftell (f);
        fseek (f, 0, SEEK_SET);

        buf=(BYTE*)malloc (flen);

        fread (buf, flen, 1, f);

        fclose (f);

        if (memcmp (buf, "QR9", 3)!=0)
        {
                printf ("File is not encrypted!\n");
                return;
        };

        memcpy (&real_flen, buf+3, 4);
```

```
        decrypt (buf+(3+4), flen-(3+4), pw);

        f=fopen(fout, "wb");

        fwrite (buf+(3+4), real_flen, 1, f);

        fclose (f);

        free (buf);
};
```

OK, now let's go deeper.

Function `crypt()`:

```
.text:00541260 crypt           proc near
.text:00541260
.text:00541260 arg_0           = dword ptr  4
.text:00541260 arg_4           = dword ptr  8
.text:00541260 arg_8           = dword ptr  0Ch
.text:00541260
.text:00541260                 push    ebx
.text:00541261                 mov     ebx, [esp+4+arg_0]
.text:00541265                 push    ebp
.text:00541266                 push    esi
.text:00541267                 push    edi
.text:00541268                 xor     ebp, ebp
.text:0054126A
.text:0054126A loc_54126A:
```

This fragment of code copies a part of the input buffer to an internal array we later name "cube64". The size is in the ECX register. `MOVSD` stands for *move 32-bit dword*, so, 16 32-bit dwords are exactly 64 bytes.

```
.text:0054126A                 mov     eax, [esp+10h+arg_8]
.text:0054126E                 mov     ecx, 10h
.text:00541273                 mov     esi, ebx   ; EBX is pointer within input buffer
.text:00541275                 mov     edi, offset cube64
.text:0054127A                 push    1
.text:0054127C                 push    eax
.text:0054127D                 rep movsd
```

Call `rotate_all_with_password()`:

```
.text:0054127F                 call    rotate_all_with_password
```

Copy encrypted contents back from "cube64" to buffer:

```
.text:00541284                 mov     eax, [esp+18h+arg_4]
.text:00541288                 mov     edi, ebx
.text:0054128A                 add     ebp, 40h
.text:0054128D                 add     esp, 8
.text:00541290                 mov     ecx, 10h
.text:00541295                 mov     esi, offset cube64
.text:0054129A                 add     ebx, 40h  ; add 64 to input buffer pointer
.text:0054129D                 cmp     ebp, eax  ; EBP = amount of encrypted data.
.text:0054129F                 rep movsd
```

If EBP is not bigger that the size input argument, then continue to the next block.

```
.text:005412A1                 jl      short loc_54126A
.text:005412A3                 pop     edi
.text:005412A4                 pop     esi
.text:005412A5                 pop     ebp
.text:005412A6                 pop     ebx
.text:005412A7                 retn
.text:005412A7 crypt           endp
```

Reconstructed `crypt()` function:

```
void crypt (BYTE *buf, int sz, char *pw)
{
        int i=0;

        do
        {
                memcpy (cube, buf+i, 8*8);
                rotate_all (pw, 1);
                memcpy (buf+i, cube, 8*8);
                i+=64;
        }
        while (i<sz);
};
```

OK, now let's go deeper in function `rotate_all_with_password()`. It takes two arguments: password string and a number.

In `crypt()`, the number 1 is used, and in the `decrypt()` function (where `rotate_all_with_password()` function is called too), the number is 3.

```
.text:005411B0 rotate_all_with_password proc near
.text:005411B0
.text:005411B0 arg_0           = dword ptr  4
.text:005411B0 arg_4           = dword ptr  8
.text:005411B0
.text:005411B0                 mov     eax, [esp+arg_0]
.text:005411B4                 push    ebp
.text:005411B5                 mov     ebp, eax
```

Check the current character in the password. If it is zero, exit:

```
.text:005411B7                 cmp     byte ptr [eax], 0
.text:005411BA                 jz      exit
.text:005411C0                 push    ebx
.text:005411C1                 mov     ebx, [esp+8+arg_4]
.text:005411C5                 push    esi
.text:005411C6                 push    edi
.text:005411C7
.text:005411C7 loop_begin:
```

Call `tolower()`, a standard C function.

```
.text:005411C7                 movsx   eax, byte ptr [ebp+0]
.text:005411CB                 push    eax             ; C
.text:005411CC                 call    _tolower
.text:005411D1                 add     esp, 4
```

Hmm, if the password has non-Latin character, it is skipped! Indeed, when we run the encryption utility and try non-Latin characters in the password, they seem to be ignored.

```
.text:005411D4                 cmp     al, 'a'
.text:005411D6                 jl      short next_character_in_password
.text:005411D8                 cmp     al, 'z'
.text:005411DA                 jg      short next_character_in_password
.text:005411DC                 movsx   ecx, al
```

Subtract the value of "a" (97) from the character.

```
.text:005411DF                 sub     ecx, 'a'  ; 97
```

After subtracting, we'll get 0 for "a" here, 1 for "b", etc. And 25 for "z".

```
.text:005411E2                 cmp     ecx, 24
.text:005411E5                 jle     short skip_subtracting
.text:005411E7                 sub     ecx, 24
```

It seems, "y" and "z" are exceptional characters too. After that fragment of code, "y" becomes 0 and "z" —1. This implies that the 26 Latin alphabet symbols become values in the range of 0..23, (24 in total).

```
.text:005411EA
.text:005411EA skip_subtracting:                         ; CODE XREF: rotate_all_with_password+35
```

This is actually division via multiplication. You can read more about it in the "Division using multiplication" section (3.9 on page 497).

The code actually divides the password character's value by 3.

```
.text:005411EA                 mov     eax, 55555556h
.text:005411EF                 imul    ecx
.text:005411F1                 mov     eax, edx
.text:005411F3                 shr     eax, 1Fh
.text:005411F6                 add     edx, eax
.text:005411F8                 mov     eax, ecx
.text:005411FA                 mov     esi, edx
.text:005411FC                 mov     ecx, 3
.text:00541201                 cdq
.text:00541202                 idiv    ecx
```

EDX is the remainder of the division.

```
.text:00541204 sub     edx, 0
.text:00541207 jz      short call_rotate1 ; if remainder is zero, go to rotate1
.text:00541209 dec     edx
.text:0054120A jz      short call_rotate2 ; .. if it is 1, go to rotate2
.text:0054120C dec     edx
.text:0054120D jnz     short next_character_in_password
.text:0054120F test    ebx, ebx
.text:00541211 jle     short next_character_in_password
.text:00541213 mov     edi, ebx
```

If the remainder is 2, call `rotate3()`. EDI is the second argument of the `rotate_all_with_password()` function. As we already noted, 1 is for the encryption operations and 3 is for the decryption. So, here is a loop. When encrypting, rotate1/2/3 are to be called the same number of times as given in the first argument.

```
.text:00541215 call_rotate3:
.text:00541215                 push    esi
.text:00541216                 call    rotate3
.text:0054121B                 add     esp, 4
.text:0054121E                 dec     edi
.text:0054121F                 jnz     short call_rotate3
.text:00541221                 jmp     short next_character_in_password
.text:00541223
.text:00541223 call_rotate2:
.text:00541223                 test    ebx, ebx
.text:00541225                 jle     short next_character_in_password
.text:00541227                 mov     edi, ebx
.text:00541229
.text:00541229 loc_541229:
.text:00541229                 push    esi
.text:0054122A                 call    rotate2
.text:0054122F                 add     esp, 4
.text:00541232                 dec     edi
.text:00541233                 jnz     short loc_541229
.text:00541235                 jmp     short next_character_in_password
.text:00541237
.text:00541237 call_rotate1:
.text:00541237                 test    ebx, ebx
.text:00541239                 jle     short next_character_in_password
.text:0054123B                 mov     edi, ebx
.text:0054123D
.text:0054123D loc_54123D:
.text:0054123D                 push    esi
.text:0054123E                 call    rotate1
.text:00541243                 add     esp, 4
.text:00541246                 dec     edi
.text:00541247                 jnz     short loc_54123D
.text:00541249
```

Fetch the next character from the password string.

```
.text:00541249 next_character_in_password:
.text:00541249                 mov     al, [ebp+1]
```

Increment the character pointer in the password string:

```
.text:0054124C                 inc     ebp
.text:0054124D                 test    al, al
.text:0054124F                 jnz     loop_begin
.text:00541255                 pop     edi
.text:00541256                 pop     esi
.text:00541257                 pop     ebx
.text:00541258
.text:00541258 exit:
.text:00541258                 pop     ebp
.text:00541259                 retn
.text:00541259 rotate_all_with_password endp
```

Here is the reconstructed C code:

```
void rotate_all (char *pwd, int v)
{
        char *p=pwd;

        while (*p)
        {
                char c=*p;
                int q;

                c=tolower (c);

                if (c>='a' && c<='z')
                {
                        q=c-'a';
                        if (q>24)
                                q-=24;

                        int quotient=q/3;
                        int remainder=q % 3;

                        switch (remainder)
                        {
                        case 0: for (int i=0; i<v; i++) rotate1 (quotient); break;
                        case 1: for (int i=0; i<v; i++) rotate2 (quotient); break;
                        case 2: for (int i=0; i<v; i++) rotate3 (quotient); break;
                        };
                };

                p++;
        };
};
```

Now let’s go deeper and investigate the rotate1/2/3 functions. Each function calls another two functions. We eventually will name them `set_bit()` and `get_bit()`.

Let’s start with `get_bit()`:

```
.text:00541050 get_bit         proc near
.text:00541050
.text:00541050 arg_0           = dword ptr  4
.text:00541050 arg_4           = dword ptr  8
.text:00541050 arg_8           = byte ptr  0Ch
.text:00541050
.text:00541050                 mov     eax, [esp+arg_4]
.text:00541054                 mov     ecx, [esp+arg_0]
.text:00541058                 mov     al, cube64[eax+ecx*8]
.text:0054105F                 mov     cl, [esp+arg_8]
.text:00541063                 shr     al, cl
.text:00541065                 and     al, 1
.text:00541067                 retn
```

```
.text:00541067 get_bit         endp
```

…in other words: calculate an index in the cube64 array: *arg_4 + arg_0 * 8*. Then shift a byte from the array by arg_8 bits right. Isolate the lowest bit and return it.

Let’s see another function, `set_bit()`:

```
.text:00541000 set_bit         proc near
.text:00541000
.text:00541000 arg_0           = dword ptr  4
.text:00541000 arg_4           = dword ptr  8
.text:00541000 arg_8           = dword ptr  0Ch
.text:00541000 arg_C           = byte ptr  10h
.text:00541000
.text:00541000                 mov     al, [esp+arg_C]
.text:00541004                 mov     ecx, [esp+arg_8]
.text:00541008                 push    esi
.text:00541009                 mov     esi, [esp+4+arg_0]
.text:0054100D                 test    al, al
.text:0054100F                 mov     eax, [esp+4+arg_4]
.text:00541013                 mov     dl, 1
.text:00541015                 jz      short loc_54102B
```

The value in the DL is 1 here. It gets shifted left by arg_8. For example, if arg_8 is 4, the value in the DL register is to be 0x10 or 1000b in binary form.

```
.text:00541017                 shl     dl, cl
.text:00541019                 mov     cl, cube64[eax+esi*8]
```

Get a bit from array and explicitly set it.

```
.text:00541020                 or      cl, dl
```

Store it back:

```
.text:00541022                 mov     cube64[eax+esi*8], cl
.text:00541029                 pop     esi
.text:0054102A                 retn
.text:0054102B
.text:0054102B loc_54102B:
.text:0054102B                 shl     dl, cl
```

If arg_C is not zero…

```
.text:0054102D                 mov     cl, cube64[eax+esi*8]
```

…invert DL. For example, if DL’s state after the shift is 0x10 or 0b1000, there is 0xEF to be after the NOT instruction (or 0b11101111b).

```
.text:00541034                 not     dl
```

This instruction clears the bit, in other words, it saves all bits in CL which are also set in DL except those in DL which are cleared. This implies that if DL is 11101111b in binary form, all bits are to be saved except the 5th (counting from lowest bit).

```
.text:00541036                 and     cl, dl
```

Store it back:

```
.text:00541038                 mov     cube64[eax+esi*8], cl
.text:0054103F                 pop     esi
.text:00541040                 retn
.text:00541040 set_bit         endp
```

It is almost the same as `get_bit()`, except, if arg_C is zero, the function clears the specific bit in the array, or sets it otherwise.

We also know that the array’s size is 64. The first two arguments both in the `set_bit()` and `get_bit()` functions could be seen as 2D coordinates. Then the array is to be an 8*8 matrix.

Here is a C representation of what we know up to now:

```
#define IS_SET(flag, bit)       ((flag) & (bit))
#define SET_BIT(var, bit)       ((var) |= (bit))
#define REMOVE_BIT(var, bit)    ((var) &= ~(bit))

static BYTE cube[8][8];

void set_bit (int x, int y, int shift, int bit)
{
        if (bit)
                SET_BIT (cube[x][y], 1<<shift);
        else
                REMOVE_BIT (cube[x][y], 1<<shift);
};

bool get_bit (int x, int y, int shift)
{
        if ((cube[x][y]>>shift)&1==1)
                return 1;
        return 0;
};
```

Now let's get back to the rotate1/2/3 functions.

```
.text:00541070 rotate1         proc near
.text:00541070
```

Internal array allocation in the local stack, with size of 64 bytes:

```
.text:00541070 internal_array_64= byte ptr -40h
.text:00541070 arg_0           = dword ptr  4
.text:00541070
.text:00541070                 sub     esp, 40h
.text:00541073                 push    ebx
.text:00541074                 push    ebp
.text:00541075                 mov     ebp, [esp+48h+arg_0]
.text:00541079                 push    esi
.text:0054107A                 push    edi
.text:0054107B                 xor     edi, edi        ; EDI is loop1 counter
```

EBX is a pointer to the internal array:

```
.text:0054107D                 lea     ebx, [esp+50h+internal_array_64]
.text:00541081
```

Here we have two nested loops:

```
.text:00541081 first_loop1_begin:
.text:00541081    xor     esi, esi      ; ESI is loop 2 counter
.text:00541083
.text:00541083 first_loop2_begin:
.text:00541083    push    ebp           ; arg_0
.text:00541084    push    esi           ; loop 1 counter
.text:00541085    push    edi           ; loop 2 counter
.text:00541086    call    get_bit
.text:0054108B    add     esp, 0Ch
.text:0054108E    mov     [ebx+esi], al ; store to internal array
.text:00541091    inc     esi           ; increment loop 1 counter
.text:00541092    cmp     esi, 8
.text:00541095    jl      short first_loop2_begin
.text:00541097    inc     edi           ; increment loop 2 counter

; increment internal array pointer by 8 at each loop 1 iteration
.text:00541098    add     ebx, 8
.text:0054109B    cmp     edi, 8
.text:0054109E    jl      short first_loop1_begin
```

...we see that both loops' counters are in the range of 0..7. Also they are used as the first and second argument for the `get_bit()` function. The third argument to `get_bit()` is the only argument of `rotate1()`. The return value from `get_bit()` is placed in the internal array.

Prepare a pointer to the internal array again:

```
.text:005410A0    lea     ebx, [esp+50h+internal_array_64]
.text:005410A4    mov     edi, 7     ; EDI is loop 1 counter, initial state is 7
.text:005410A9
.text:005410A9 second_loop1_begin:
.text:005410A9    xor     esi, esi   ; ESI is loop 2 counter
.text:005410AB
.text:005410AB second_loop2_begin:
.text:005410AB    mov     al, [ebx+esi] ; value from internal array
.text:005410AE    push    eax
.text:005410AF    push    ebp        ; arg_0
.text:005410B0    push    edi        ; loop 1 counter
.text:005410B1    push    esi        ; loop 2 counter
.text:005410B2    call    set_bit
.text:005410B7    add     esp, 10h
.text:005410BA    inc     esi        ; increment loop 2 counter
.text:005410BB    cmp     esi, 8
.text:005410BE    jl      short second_loop2_begin
.text:005410C0    dec     edi        ; decrement loop 2 counter
.text:005410C1    add     ebx, 8     ; increment pointer in internal array
.text:005410C4    cmp     edi, 0FFFFFFFFh
.text:005410C7    jg      short second_loop1_begin
.text:005410C9    pop     edi
.text:005410CA    pop     esi
.text:005410CB    pop     ebp
.text:005410CC    pop     ebx
.text:005410CD    add     esp, 40h
.text:005410D0    retn
.text:005410D0 rotate1         endp
```

…this code is placing the contents of the internal array to the cube global array via the `set_bit()` function, *but* in a different order! Now the counter of the first loop is in the range of 7 to 0, decrementing at each iteration!

The C code representation looks like:

```
void rotate1 (int v)
{
        bool tmp[8][8]; // internal array
        int i, j;

        for (i=0; i<8; i++)
                for (j=0; j<8; j++)
                        tmp[i][j]=get_bit (i, j, v);

        for (i=0; i<8; i++)
                for (j=0; j<8; j++)
                        set_bit (j, 7-i, v, tmp[x][y]);
};
```

Not very understandable, but if we take a look at `rotate2()` function:

```
.text:005410E0 rotate2 proc near
.text:005410E0
.text:005410E0 internal_array_64 = byte ptr -40h
.text:005410E0 arg_0 = dword ptr  4
.text:005410E0
.text:005410E0     sub     esp, 40h
.text:005410E3     push    ebx
.text:005410E4     push    ebp
.text:005410E5     mov     ebp, [esp+48h+arg_0]
.text:005410E9     push    esi
.text:005410EA     push    edi
.text:005410EB     xor     edi, edi   ; loop 1 counter
.text:005410ED     lea     ebx, [esp+50h+internal_array_64]
.text:005410F1
.text:005410F1 loc_5410F1:
.text:005410F1     xor     esi, esi   ; loop 2 counter
.text:005410F3
.text:005410F3 loc_5410F3:
```

```
.text:005410F3     push    esi        ; loop 2 counter
.text:005410F4     push    edi        ; loop 1 counter
.text:005410F5     push    ebp        ; arg_0
.text:005410F6     call    get_bit
.text:005410FB     add     esp, 0Ch
.text:005410FE     mov     [ebx+esi], al ; store to internal array
.text:00541101     inc     esi        ; increment loop 1 counter
.text:00541102     cmp     esi, 8
.text:00541105     jl      short loc_5410F3
.text:00541107     inc     edi        ; increment loop 2 counter
.text:00541108     add     ebx, 8
.text:0054110B     cmp     edi, 8
.text:0054110E     jl      short loc_5410F1
.text:00541110     lea     ebx, [esp+50h+internal_array_64]
.text:00541114     mov     edi, 7     ; loop 1 counter is initial state 7
.text:00541119
.text:00541119 loc_541119:
.text:00541119     xor     esi, esi   ; loop 2 counter
.text:0054111B
.text:0054111B loc_54111B:
.text:0054111B     mov     al, [ebx+esi] ; get byte from internal array
.text:0054111E     push    eax
.text:0054111F     push    edi        ; loop 1 counter
.text:00541120     push    esi        ; loop 2 counter
.text:00541121     push    ebp        ; arg_0
.text:00541122     call    set_bit
.text:00541127     add     esp, 10h
.text:0054112A     inc     esi        ; increment loop 2 counter
.text:0054112B     cmp     esi, 8
.text:0054112E     jl      short loc_54111B
.text:00541130     dec     edi        ; decrement loop 2 counter
.text:00541131     add     ebx, 8
.text:00541134     cmp     edi, 0FFFFFFFFh
.text:00541137     jg      short loc_541119
.text:00541139     pop     edi
.text:0054113A     pop     esi
.text:0054113B     pop     ebp
.text:0054113C     pop     ebx
.text:0054113D     add     esp, 40h
.text:00541140     retn
.text:00541140 rotate2 endp
```

It is *almost* the same, except the order of the arguments of the `get_bit()` and `set_bit()` is different. Let's rewrite it in C-like code:

```
void rotate2 (int v)
{
        bool tmp[8][8]; // internal array
        int i, j;

        for (i=0; i<8; i++)
                for (j=0; j<8; j++)
                        tmp[i][j]=get_bit (v, i, j);

        for (i=0; i<8; i++)
                for (j=0; j<8; j++)
                        set_bit (v, j, 7-i, tmp[i][j]);
};
```

Let's also rewrite the `rotate3()` function:

```
void rotate3 (int v)
{
        bool tmp[8][8];
        int i, j;

        for (i=0; i<8; i++)
                for (j=0; j<8; j++)
                        tmp[i][j]=get_bit (i, v, j);
```

```
        for (i=0; i<8; i++)
                for (j=0; j<8; j++)
                        set_bit (7-j, v, i, tmp[i][j]);
};
```

Well, now things are simpler. If we consider cube64 as a 3D cube of size 8*8*8, where each element is a bit, `get_bit()` and `set_bit()` take just the coordinates of a bit as input.

The rotate1/2/3 functions are in fact rotating all bits in a specific plane. These three functions are one for each cube side and the v argument sets the plane in the range of 0..7.

Maybe the algorithm's author was thinking of a 8*8*8 Rubik's cube [18]?!

Yes, indeed.

Let's look closer into the `decrypt()` function, here is its rewritten version:

```
void decrypt (BYTE *buf, int sz, char *pw)
{
        char *p=strdup (pw);
        strrev (p);
        int i=0;

        do
        {
                memcpy (cube, buf+i, 8*8);
                rotate_all (p, 3);
                memcpy (buf+i, cube, 8*8);
                i+=64;
        }
        while (i<sz);

        free (p);
};
```

It is almost the same as for `crypt()`, *but* the password string is reversed by the strrev() [19] standard C function and `rotate_all()` is called with argument 3.

This implies that in case of decryption, each corresponding rotate1/2/3 call is to be performed thrice.

This is almost as in Rubik'c cube! If you want to get back, do the same in reverse order and direction! If you want to undo the effect of rotating one place in clockwise direction, rotate it once in counter-clockwise direction, or thrice in clockwise direction.

`rotate1()` is apparently for rotating the "front" plane. `rotate2()` is apparently for rotating the "top" plane. `rotate3()` is apparently for rotating the "left" plane.

Let's get back to the core of the `rotate_all()` function:

```
q=c-'a';
if (q>24)
        q-=24;

int quotient=q/3; // in range 0..7
int remainder=q % 3;

switch (remainder)
{
    case 0: for (int i=0; i<v; i++) rotate1 (quotient); break; // front
    case 1: for (int i=0; i<v; i++) rotate2 (quotient); break; // top
    case 2: for (int i=0; i<v; i++) rotate3 (quotient); break; // left
};
```

Now it is much simpler to understand: each password character defines a side (one of three) and a plane (one of 8). 3*8 = 24, that is why two the last two characters of the Latin alphabet are remapped to fit an alphabet of exactly 24 elements.

The algorithm is clearly weak: in case of short passwords you can see that in the encrypted file there are the original bytes of the original file in a binary file editor.

[18] wikipedia
[19] MSDN

Here is the whole source code reconstructed:

```
#include <windows.h>

#include <stdio.h>
#include <assert.h>

#define IS_SET(flag, bit)       ((flag) & (bit))
#define SET_BIT(var, bit)       ((var) |= (bit))
#define REMOVE_BIT(var, bit)    ((var) &= ~(bit))

static BYTE cube[8][8];

void set_bit (int x, int y, int z, bool bit)
{
        if (bit)
                SET_BIT (cube[x][y], 1<<z);
        else
                REMOVE_BIT (cube[x][y], 1<<z);
};

bool get_bit (int x, int y, int z)
{
        if ((cube[x][y]>>z)&1==1)
                return true;
        return false;
};

void rotate_f (int row)
{
        bool tmp[8][8];
        int x, y;

        for (x=0; x<8; x++)
                for (y=0; y<8; y++)
                        tmp[x][y]=get_bit (x, y, row);

        for (x=0; x<8; x++)
                for (y=0; y<8; y++)
                        set_bit (y, 7-x, row, tmp[x][y]);
};

void rotate_t (int row)
{
        bool tmp[8][8];
        int y, z;

        for (y=0; y<8; y++)
                for (z=0; z<8; z++)
                        tmp[y][z]=get_bit (row, y, z);

        for (y=0; y<8; y++)
                for (z=0; z<8; z++)
                        set_bit (row, z, 7-y, tmp[y][z]);
};

void rotate_l (int row)
{
        bool tmp[8][8];
        int x, z;

        for (x=0; x<8; x++)
                for (z=0; z<8; z++)
                        tmp[x][z]=get_bit (x, row, z);

        for (x=0; x<8; x++)
                for (z=0; z<8; z++)
                        set_bit (7-z, row, x, tmp[x][z]);
};
```

```
void rotate_all (char *pwd, int v)
{
        char *p=pwd;

        while (*p)
        {
                char c=*p;
                int q;

                c=tolower (c);

                if (c>='a' && c<='z')
                {
                        q=c-'a';
                        if (q>24)
                                q-=24;

                        int quotient=q/3;
                        int remainder=q % 3;

                        switch (remainder)
                        {
                        case 0: for (int i=0; i<v; i++) rotate_f (quotient); break;
                        case 1: for (int i=0; i<v; i++) rotate_t (quotient); break;
                        case 2: for (int i=0; i<v; i++) rotate_l (quotient); break;
                        };
                };

                p++;
        };
};

void crypt (BYTE *buf, int sz, char *pw)
{
        int i=0;

        do
        {
                memcpy (cube, buf+i, 8*8);
                rotate_all (pw, 1);
                memcpy (buf+i, cube, 8*8);
                i+=64;
        }
        while (i<sz);
};

void decrypt (BYTE *buf, int sz, char *pw)
{
        char *p=strdup (pw);
        strrev (p);
        int i=0;

        do
        {
                memcpy (cube, buf+i, 8*8);
                rotate_all (p, 3);
                memcpy (buf+i, cube, 8*8);
                i+=64;
        }
        while (i<sz);

        free (p);
};

void crypt_file(char *fin, char* fout, char *pw)
{
        FILE *f;
        int flen, flen_aligned;
        BYTE *buf;
```

```
        f=fopen(fin, "rb");

        if (f==NULL)
        {
                printf ("Cannot open input file!\n");
                return;
        };

        fseek (f, 0, SEEK_END);
        flen=ftell (f);
        fseek (f, 0, SEEK_SET);

        flen_aligned=(flen&0xFFFFFFC0)+0x40;

        buf=(BYTE*)malloc (flen_aligned);
        memset (buf, 0, flen_aligned);

        fread (buf, flen, 1, f);

        fclose (f);

        crypt (buf, flen_aligned, pw);

        f=fopen(fout, "wb");

        fwrite ("QR9", 3, 1, f);
        fwrite (&flen, 4, 1, f);
        fwrite (buf, flen_aligned, 1, f);

        fclose (f);

        free (buf);

};

void decrypt_file(char *fin, char* fout, char *pw)
{
        FILE *f;
        int real_flen, flen;
        BYTE *buf;

        f=fopen(fin, "rb");

        if (f==NULL)
        {
                printf ("Cannot open input file!\n");
                return;
        };

        fseek (f, 0, SEEK_END);
        flen=ftell (f);
        fseek (f, 0, SEEK_SET);

        buf=(BYTE*)malloc (flen);

        fread (buf, flen, 1, f);

        fclose (f);

        if (memcmp (buf, "QR9", 3)!=0)
        {
                printf ("File is not encrypted!\n");
                return;
        };

        memcpy (&real_flen, buf+3, 4);

        decrypt (buf+(3+4), flen-(3+4), pw);

        f=fopen(fout, "wb");
```

```
        fwrite (buf+(3+4), real_flen, 1, f);

        fclose (f);

        free (buf);
};

// run: input output 0/1 password
// 0 for encrypt, 1 for decrypt

int main(int argc, char *argv[])
{
        if (argc!=5)
        {
                printf ("Incorrect parameters!\n");
                return 1;
        };

        if (strcmp (argv[3], "0")==0)
                crypt_file (argv[1], argv[2], argv[4]);
        else
                if (strcmp (argv[3], "1")==0)
                        decrypt_file (argv[1], argv[2], argv[4]);
                else
                        printf ("Wrong param %s\n", argv[3]);

        return 0;
};
```

8.7 Encrypted database case #1

(This part has been first appeared in my blog at 26-Aug-2015. Some discussion: https://news.ycombinator.com/item?id=10128684.)

8.7.1 Base64 and entropy

I've got the XML file containing some encrypted data. Perhaps, it's related to some orders and/or customers information.


```
<?xml version = "1.0" encoding = "UTF-8"?>
<Orders>
        <Order>
                <OrderID>1</OrderID>
                <Data>yjmxhXUbhB/5MV45chPsXZWAJwIh1S0aD9lFn3XuJMSxJ3/E+UE3hsnH</Data>
        </Order>
        <Order>
                <OrderID>2</OrderID>
                <Data>0KGe/wnypFBjsy+U0C2P9fC5nDZP3XDZLMPCRaiBw9OjIk6Tu5U=</Data>
        </Order>
        <Order>
                <OrderID>3</OrderID>
                <Data>mqkXfdzvQKvEArdzh+zD9oETVGBFvcTBLs2ph1b5bYddExzp</Data>
        </Order>
        <Order>
                <OrderID>4</OrderID>
                <Data>FCx6JhIDqnESyT3HAepyE1BJ3cJd7wCk+APCRUeuNtZdpCvQ2MR/7kLXtfUHuA==</Data>
        </Order>
...
```


The file is available here.

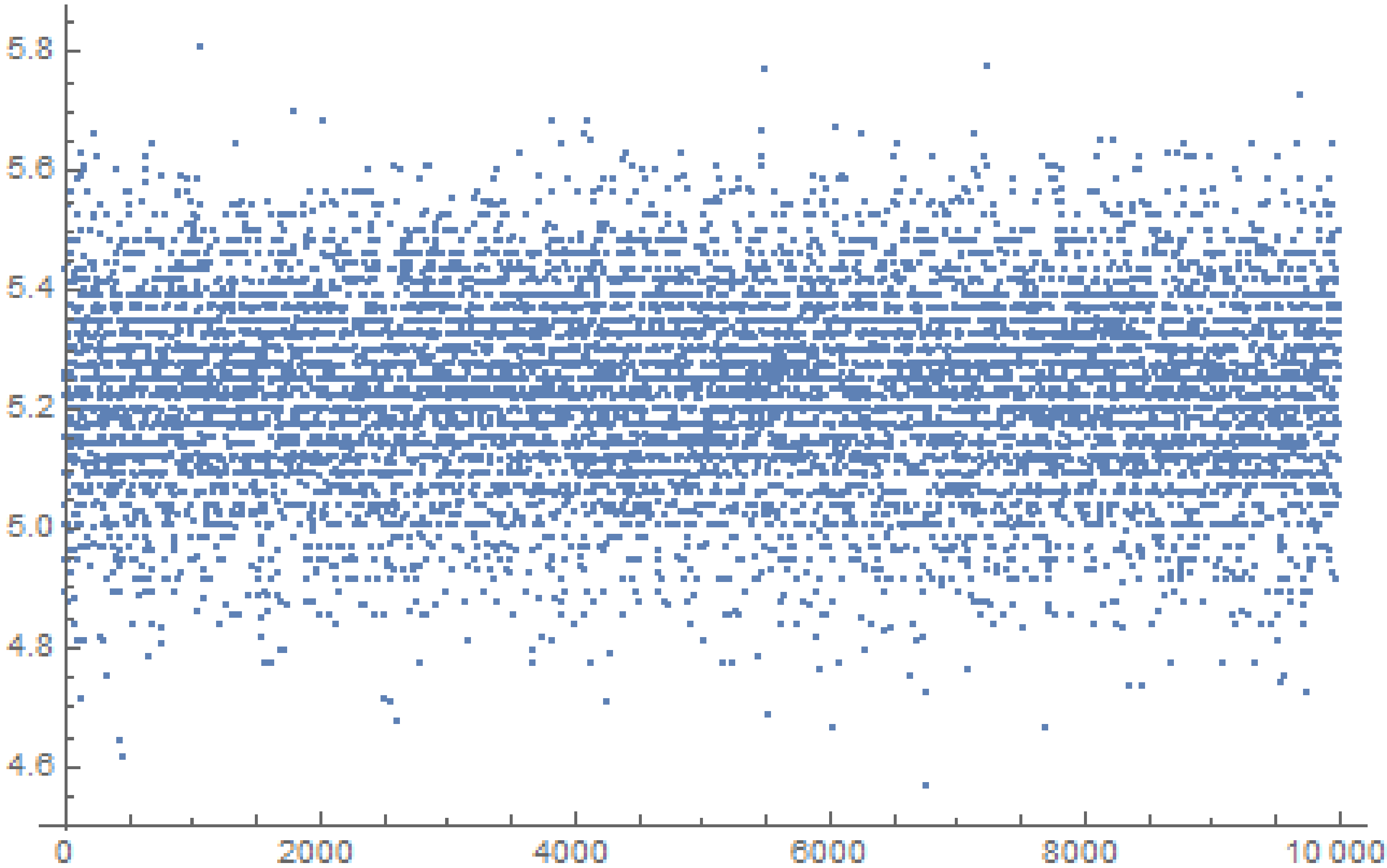
This is clearly base64-encoded data, because all strings consisting of Latin characters, digits, plus (+) and slash (/) symbols. There can be 1 or 2 padding symbols (=), but they are never occurred in the middle of string. Keeping in mind these base64 properties, it's very easy to recognize them.

Let's decode them and calculate entropies (9.2 on page 948) of these blocks in Wolfram Mathematica:

```
In[]:= ListOfBase64Strings =
  Map[First[#[[3]]] &, Cases[Import["encrypted.xml"], XMLElement["Data", _, _], Infinity]];

In[]:= BinaryStrings =
  Map[ImportString[#, {"Base64", "String"}] &, ListOfBase64Strings];

In[]:= Entropies = Map[N[Entropy[2, #]] &, BinaryStrings];

In[]:= Variance[Entropies]
Out[]= 0.0238614
```

Variance is low. This means the entropy values are not very different from each other. This is visible on graph:

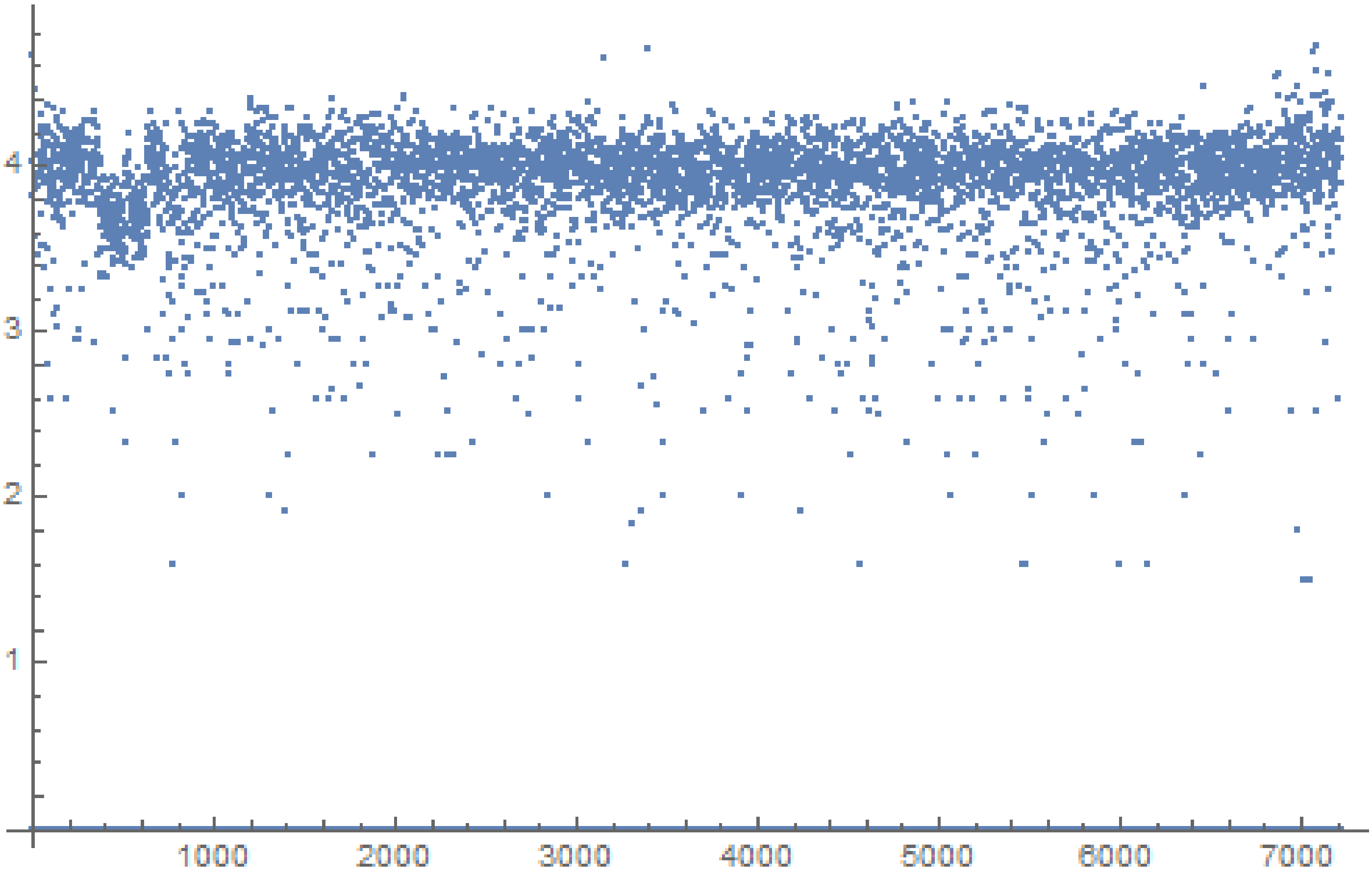
```
In[]:= ListPlot[Entropies]
```



Most values are between 5.0 and 5.4. This is a sign that the data is compressed and/or encrypted.

To understand variance, let's calculate entropies of all lines in Conan Doyle's *The Hound of the Baskervilles* book:

```
In[]:= BaskervillesLines = Import["http://www.gutenberg.org/cache/epub/2852/pg2852.txt", "List↙
    ↘ "];

In[]:= EntropiesT = Map[N[Entropy[2, #]] &, BaskervillesLines];

In[]:= Variance[EntropiesT]
Out[]= 2.73883

In[]:= ListPlot[EntropiesT]
```



Most values are gathered around value of 4, but there are also values which are smaller, and they are influenced final variance value.

Perhaps, shortest strings has smaller entropy, let's take short string from the Conan Doyle's book:

```
In[]:= Entropy[2, "Yes, sir."] // N
Out[]= 2.9477
```

Let's try even shorter:

```
In[]:= Entropy[2, "Yes"] // N
Out[]= 1.58496

In[]:= Entropy[2, "No"] // N
Out[]= 1.
```

8.7.2 Is data compressed?

OK, so our data is compressed and/or encrypted. Is it compressed? Almost all data compressors put some header at the start, signature, or something like that. As we can see, there are no consistent data at the start of each block. It's still possible that this is a handmade data compressor, but they are very rare. On the other hand, handmade cryptoalgorithms are much more popular, because it's very easy to make it work. Even primitive keyless cryptosystems like *memfrob()*[20] and ROT13 works fine without errors. It's a serious challenge to write data compressor from scratch using only fantasy and imagination in a way so it will have no evident bugs. Some programmers implements data compression functions by reading textbooks, but this is also rare. The most popular two ways are: 1) just take open-source library like zlib; 2) copy&paste something from somewhere. Open-source data compressions algorithms usually puts some kind of header, and so do algorithms from sites like http://www.codeproject.com/.

[20] http://linux.die.net/man/3/memfrob

8.7.3 Is data encrypted?

Major data encryption algorithms process data in blocks. DES—8 bytes, AES—16 bytes. If the input buffer is not divided evenly by block size, it's padded by zeroes (or something else), so encrypted data will be aligned by cryptoalgorithm's block size. This is not our case.

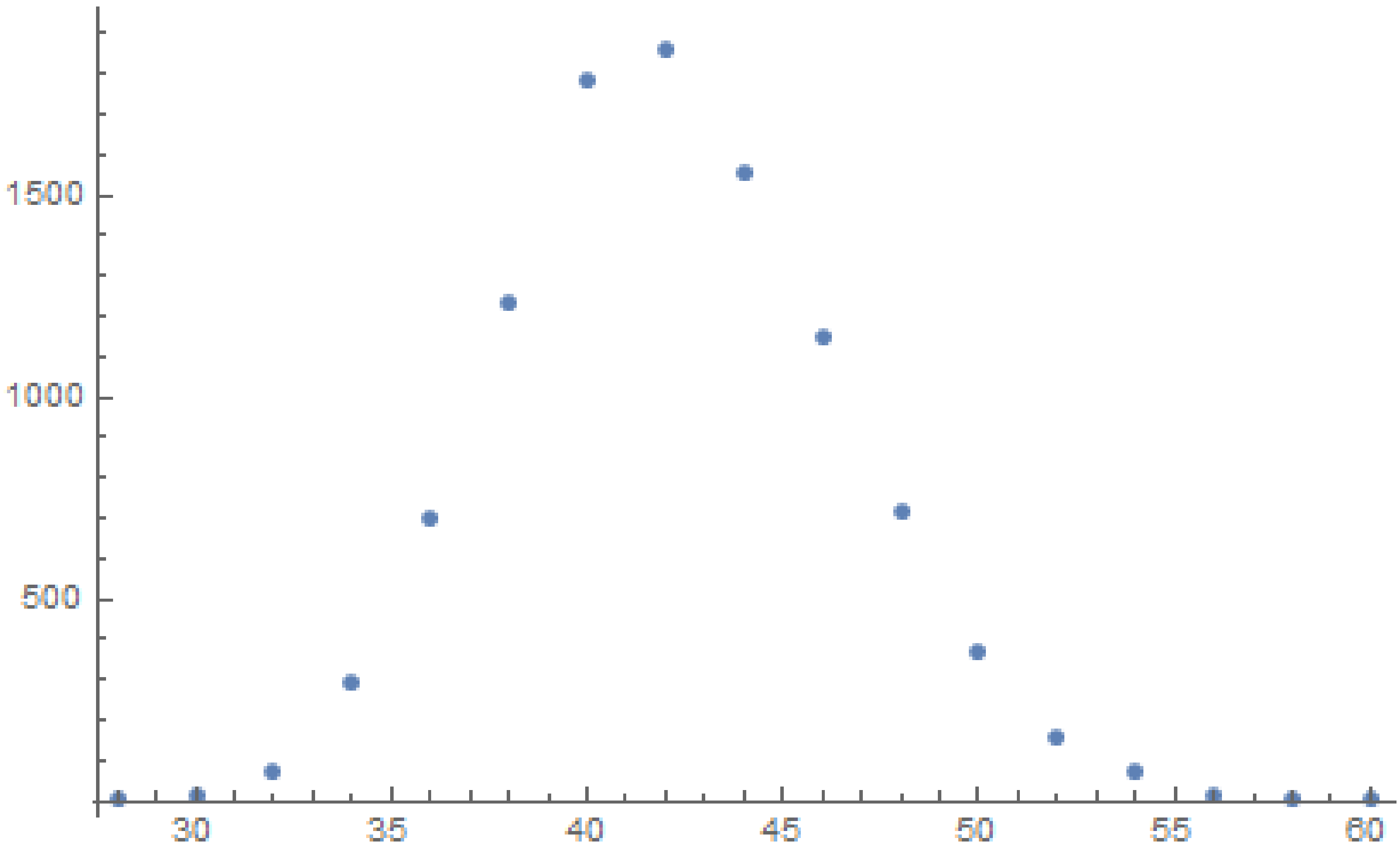
Using Wolfram Mathematica, I analyzed block's lengths:

```
In[]:= Counts[Map[StringLength[#] &, BinaryStrings]]
Out[]= <|42 -> 1858, 38 -> 1235, 36 -> 699, 46 -> 1151, 40 -> 1784,
 44 -> 1558, 50 -> 366, 34 -> 291, 32 -> 74, 56 -> 15, 48 -> 716,
 30 -> 13, 52 -> 156, 54 -> 71, 60 -> 3, 58 -> 6, 28 -> 4|>
```

1858 blocks has size of 42 bytes, 1235 blocks has size of 38 bytes, etc.

I made a graph:

```
ListPlot[Counts[Map[StringLength[#] &, BinaryStrings]]]
```



So, most blocks has size between ~ 36 and ~ 48. There is also another thing to notice: all block sizes are even. No single block with odd size.

There are, however, stream ciphers which can operate on byte level or even on bit level.

8.7.4 CryptoPP

The program which can browse this encrypted database is written C# and the .NET code is heavily obfuscated. Nevertheless, there is DLL with x86 code, which, after brief examination, has parts of the CryptoPP popular open-source library! (I just spotted "CryptoPP" strings inside.) Now it's very easy to find all functions inside of DLL because CryptoPP library is open-source.

CryptoPP library has a lot of crypto-functions, including AES (AKA Rijndael). Newer x86 CPUs has AES helper instructions like AESENC, AESDEC and AESKEYGENASSIST [21]. They are not performing encryption/decryption completely, but they do significant amount of job. And newer CryptoPP versions use them. For example, here: 1, 2. To my surprise, during decryption, AESENC gets executed, while AESDEC is not (I just

[21] https://en.wikipedia.org/wiki/AES_instruction_set

checked with my tracer utility, but any debugger can be used). I checked, if my CPU really supports AES instructions. Some Intel i3 CPUs are not. And if not, CryptoPP library falling back to AES functions implemented in old way [22]. But my CPU supports them. Why AESDEC is still not executed? Why the program use AES encryption in order to decrypt database?

OK, it's not a problem to find a function which encrypts block. It is called *CryptoPP::Rijndael::Enc::ProcessAndXorBl* https://github.com/mmoss/cryptopp/blob/2772f7b57182b31a41659b48d5f35a7b6cedd34d/src/rijndael.cpp#L349, and it can call from another function: *Rijndael::Enc::AdvancedProcessBlocks()* https://github.com/mmoss/cryptopp/blob/2772f7b57182b31a41659b48d5f35a7b6cedd34d/src/rijndael.cpp#L1179, which, in turn, can be call the two functions (AESNI_Enc_Block and AESNI_Enc_4_Blocks) which has AESENC instructions.

So, judging by CryptoPP internals,
CryptoPP::Rijndael::Enc::ProcessAndXorBlock() encrypts one 16-byte block. Let's set breakpoint on it and see, what happens during decryption. I use my simple tracer tool again. The software must decrypt first data block now. Oh, by the way, here is the first data block converted from base64 encoding to hexadecimal data, let's have it at hand:

```
00000000: CA 39 B1 85 75 1B 84 1F  F9 31 5E 39 72 13 EC 5D  .9..u....1^9r..]
00000010: 95 80 27 02 21 D5 2D 1A  0F D9 45 9F 75 EE 24 C4  ..'.!.-...E.u.$.
00000020: B1 27 7F 84 FE 41 37 86  C9 C0                    .'...A7...
```

These are also arguments of the function from CryptoPP source files:

```
size_t Rijndael::Enc::AdvancedProcessBlocks(const byte *inBlocks, const byte *xorBlocks, byte *↙
    ↘ outBlocks, size_t length, word32 flags);
```

So it has 5 arguments. Possible flags are:

```
enum {BT_InBlockIsCounter=1, BT_DontIncrementInOutPointers=2, BT_XorInput=4, ↙
    ↘ BT_ReverseDirection=8, BT_AllowParallel=16} FlagsForAdvancedProcessBlocks;
```

OK, run tracer on *ProcessAndXorBlock()* function:

```
... tracer.exe -l:filename.exe bpf=filename.exe!0x4339a0,args:5,dump_args:0x10

Warning: no tracer.cfg file.
PID=1984|New process software.exe
no module registered with image base 0x77320000
no module registered with image base 0x76e20000
no module registered with image base 0x77320000
no module registered with image base 0x77220000
Warning: unknown (to us) INT3 breakpoint at ntdll.dll!LdrVerifyImageMatchesChecksum+0x96c (0↙
    ↘ x776c103b)
(0) software.exe!0x4339a0(0x38b920, 0x0, 0x38b978, 0x10, 0x0) (called from software.exe!.text+0↙
    ↘ x33c0d (0x13e4c0d))
Argument 1/5
0038B920: 01 00 00 00 FF FF FF FF-79 C1 69 0B 67 C1 04 7D "........y.i.g..}"
Argument 3/5
0038B978: CD CD CD CD CD CD CD CD-CD CD CD CD CD CD CD CD "................"
(0) software.exe!0x4339a0() -> 0x0
Argument 3/5 difference
00000000: C7 39 4E 7B 33 1B D6 1F-B8 31 10 39 39 13 A5 5D ".9N{3....1.99..]"
(0) software.exe!0x4339a0(0x38a828, 0x38a838, 0x38bb40, 0x0, 0x8) (called from software.exe!.↙
    ↘ text+0x3a407 (0x13eb407))
Argument 1/5
0038A828: 95 80 27 02 21 D5 2D 1A-0F D9 45 9F 75 EE 24 C4 "..'.!.-...E.u.$."
Argument 2/5
0038A838: B1 27 7F 84 FE 41 37 86-C9 C0 00 CD CD CD CD CD ".'...A7........"
Argument 3/5
0038BB40: CD CD CD CD CD CD CD CD-CD CD CD CD CD CD CD CD "................"
(0) software.exe!0x4339a0() -> 0x0
(0) software.exe!0x4339a0(0x38b920, 0x38a828, 0x38bb30, 0x10, 0x0) (called from software.exe!.↙
    ↘ text+0x33c0d (0x13e4c0d))
Argument 1/5
0038B920: CA 39 B1 85 75 1B 84 1F-F9 31 5E 39 72 13 EC 5D ".9..u....1^9r..]"
Argument 2/5
0038A828: 95 80 27 02 21 D5 2D 1A-0F D9 45 9F 75 EE 24 C4 "..'.!.-...E.u.$."
```

[22] https://github.com/mmoss/cryptopp/blob/2772f7b57182b31a41659b48d5f35a7b6cedd34d/src/rijndael.cpp#L355

```
Argument 3/5
0038BB30: CD CD CD CD CD CD CD CD-CD CD CD CD CD CD CD CD "................"
(0) software.exe!0x4339a0() -> 0x0
Argument 3/5 difference
00000000: 45 00 20 00 4A 00 4F 00-48 00 4E 00 53 00 00 00 "E. .J.O.H.N.S..."
(0) software.exe!0x4339a0(0x38b920, 0x0, 0x38b978, 0x10, 0x0) (called from software.exe!.text+0⤦
    ↳ x33c0d (0x13e4c0d))
Argument 1/5
0038B920: 95 80 27 02 21 D5 2D 1A-0F D9 45 9F 75 EE 24 C4 "..'.!.-...E.u.$."
Argument 3/5
0038B978: 95 80 27 02 21 D5 2D 1A-0F D9 45 9F 75 EE 24 C4 "..'.!.-...E.u.$."
(0) software.exe!0x4339a0() -> 0x0
Argument 3/5 difference
00000000: B1 27 7F E4 9F 01 E3 81-CF C6 12 FB B9 7C F1 BC ".'...........|.."
PID=1984|Process software.exe exited. ExitCode=0 (0x0)
```

Here we can see inputs to the *ProcessAndXorBlock()* function, and outputs from it.

This is output from the function during first call:

```
00000000: C7 39 4E 7B 33 1B D6 1F-B8 31 10 39 39 13 A5 5D ".9N{3....1.99..]"
```

Then the *ProcessAndXorBlock()* is called with zero-length block, but with 8 flag (*BT_ReverseDirection*).

Second call:

```
00000000: 45 00 20 00 4A 00 4F 00-48 00 4E 00 53 00 00 00 "E. .J.O.H.N.S..."
```

Wow, there is some string familiar to us!

Third call:

```
00000000: B1 27 7F E4 9F 01 E3 81-CF C6 12 FB B9 7C F1 BC ".'...........|.."
```

The first output is very similar to the first 16 bytes of the encrypted buffer.

Output of the first call of *ProcessAndXorBlock()*:

```
00000000: C7 39 4E 7B 33 1B D6 1F-B8 31 10 39 39 13 A5 5D ".9N{3....1.99..]"
```

First 16 bytes of encrypted buffer:

```
00000000: CA 39 B1 85 75 1B 84 1F F9 31 5E 39 72 13 EC 5D  .9..u....1^9r..]
```

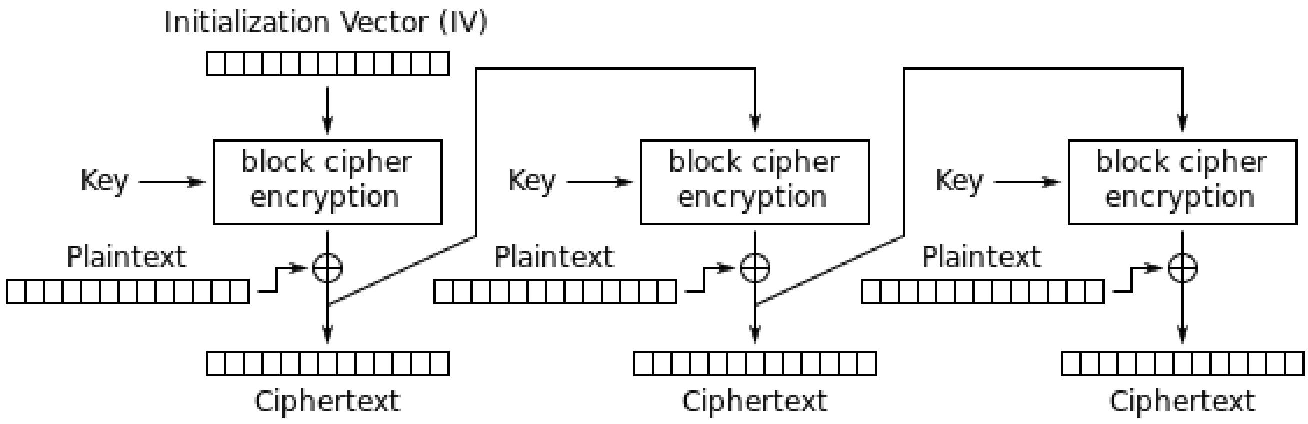
There are too much equal bytes! How come AES encryption result can be very similar to the encrypted buffer while this is not encryption but rather decryption?!

8.7.5 Cipher Feedback mode

The answer is CFB[23]: in this mode, AES algorithm used not as encryption algorithm, but as a device which generates cryptographically secure random data. The actual encryption is happening using simple XOR operation.

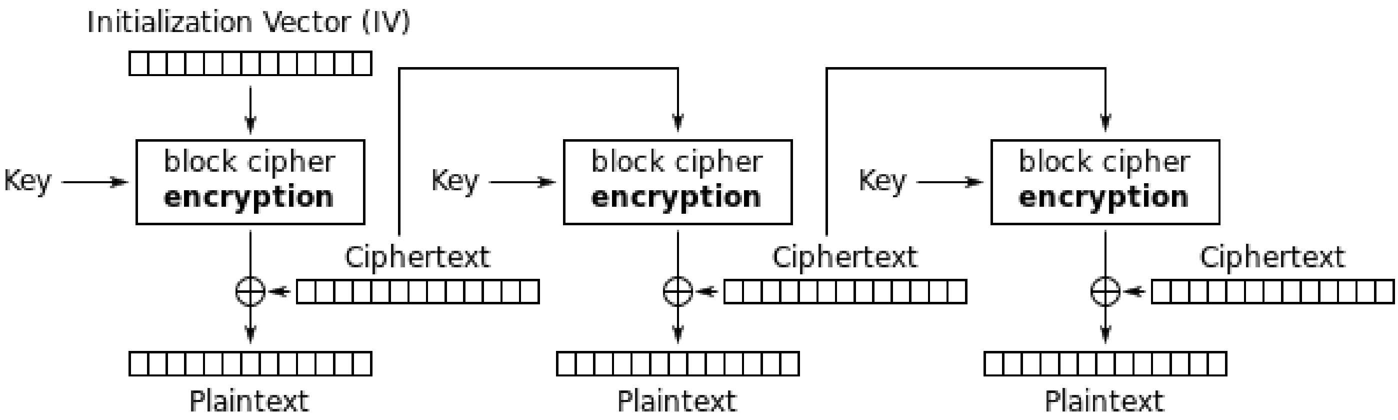
Here is encryption algorithm (images are taken from Wikipedia):

[23] Cipher Feedback



Cipher Feedback (CFB) mode encryption

And decryption:



Cipher Feedback (CFB) mode decryption

Now let's see: AES encryption operation generates 16 bytes (or 128 bits) of *random* data to be used while XOR-ing, who forces us to use all 16 bytes? If at the last iteration we've got 1 byte of data, let's xor 1 byte of data with 1 byte of generated *random* data? This leads to important property of CFB mode: data can be not padded, data of arbitrary size can be encrypted and decrypted.

Oh, that's why all encrypted blocks are not padded. And that's why AESDEC instruction is never called.

Let's try to decrypt first block manually, using Python. CFB mode also use IV, as a *seed* for CSPRNG[24]. In our case, IV is the block which is encrypted at first iteration:

```
0038B920: 01 00 00 00 FF FF FF FF-79 C1 69 0B 67 C1 04 7D "........y.i.g..}"
```

Oh, and we also have to recover encryption key. There is AESKEYGENASSIST is DLL, and it is called, and it is used in the
Rijndael::Base::UncheckedSetKey() function:
https://github.com/mmoss/cryptopp/blob/2772f7b57182b31a41659b48d5f35a7b6cedd34d/src/rijndael.cpp#L198 It's easy to find it in IDA and set breakpoint. Let's see:

```
... tracer.exe -l:filename.exe bpf=filename.exe!0x435c30,args:3,dump_args:0x10

Warning: no tracer.cfg file.
PID=2068|New process software.exe
no module registered with image base 0x77320000
```

[24] Cryptographically Secure Pseudorandom Number Generator

```
no module registered with image base 0x76e20000
no module registered with image base 0x77320000
no module registered with image base 0x77220000
Warning: unknown (to us) INT3 breakpoint at ntdll.dll!LdrVerifyImageMatchesChecksum+0x96c (0↙
    ↳ x776c103b)
(0) software.exe!0x435c30(0x15e8000, 0x10, 0x14f808) (called from software.exe!.text+0x22fa1 (0↙
    ↳ x13d3fa1))
Argument 1/3
015E8000: CD C5 7E AD 28 5F 6D E1-CE 8F CC 29 B1 21 88 8E "..~.(_m....).!.."
Argument 3/3
0014F808: 38 82 58 01 C8 B9 46 00-01 D1 3C 01 00 F8 14 00 "8.X...F...<....."
Argument 3/3 +0x0: software.exe!.rdata+0x5238
Argument 3/3 +0x8: software.exe!.text+0x1c101
(0) software.exe!0x435c30() -> 0x13c2801
PID=2068|Process software.exe exited. ExitCode=0 (0x0)
```

So this is the key: *CD C5 7E AD 28 5F 6D E1-CE 8F CC 29 B1 21 88 8E*.

During manual decryption we've got this:

```
00000000: 0D 00 FF FE 46 00 52 00  41 00 4E 00 4B 00 49 00  ....F.R.A.N.K.I.
00000010: 45 00 20 00 4A 00 4F 00  48 00 4E 00 53 00 66 66  E. .J.O.H.N.S.ff
00000020: 66 66 66 9E 61 40 D4 07  06 01                    fff.a@....
```

Now this is something readable! And now we can see why there were so many equal bytes at the first decryption iteration: because plaintext has so many zero bytes!

Let's decrypt the second block:

```
00000000: 17 98 D0 84 3A E9 72 4F  DB 82 3F AD E9 3E 2A A8  ....:.rO..?..>*.
00000010: 41 00 52 00 52 00 4F 00  4E 00 CD CC CC CC CC CC  A.R.R.O.N.......
00000020: 1B 40 D4 07 06 01                                 .@....
```

Third, fourth and fifth:

```
00000000: 5D 90 59 06 EF F4 96 B4  7C 33 A7 4A BE FF 66 AB  ].Y.....|3.J..f.
00000010: 49 00 47 00 47 00 53 00  00 00 00 00 00 C0 65 40  I.G.G.S.......e@
00000020: D4 07 06 01                                       ....
```

```
00000000: D3 15 34 5D 21 18 7C 6E  AA F8 2D FE 38 F9 D7 4E  ..4]!.|n..-.8..N
00000010: 41 00 20 00 44 00 4F 00  48 00 45 00 52 00 54 00  A. .D.O.H.E.R.T.
00000020: 59 00 48 E1 7A 14 AE FF  68 40 D4 07 06 02        Y.H.z...h@....
```

```
00000000: 1E 8B 90 0A 17 7B C5 52  31 6C 4E 2F DE 1B 27 19  .....{.R1lN...'.
00000010: 41 00 52 00 43 00 55 00  53 00 00 00 00 00 00 60  A.R.C.U.S.......
00000020: 66 40 D4 07 06 03                                 f@....
```

All blocks decrypted seems correctly except of first 16 bytes part.

8.7.6 Initializing Vector

What can affect first 16 bytes?

Let's back to CFB decryption algorithm again: 8.7.5 on the previous page.

We can see that IV can affect to first block decryption operation, but not the second, because during the second iteration, ciphertext from the first iteration is used, and in case of decryption, it's the same, no matter what IV has!

So probably, IV is different each time. Using my tracer, I'll take a look at the first input during decryption of the second block of XML file:

```
0038B920: 02 00 00 00 FE FF FF FF-79 C1 69 0B 67 C1 04 7D "........y.i.g..}"
```

...third:

```
0038B920: 03 00 00 00 FD FF FF FF-79 C1 69 0B 67 C1 04 7D "........y.i.g..}"
```

It seems, first and fifth byte are changed each time. I finally concluded that the first 32-bit integer is just OrderID from the XML file, and the second 32-bit integer is also OrderID, but negated. All other 8 bytes are same for each operation. Now I have decrypted the whole database: https://raw.githubusercontent.com/DennisYurichev/RE-for-beginners/master/examples/encrypted_DB1/decrypted.full.txt.

The Python script used for this is: https://github.com/DennisYurichev/RE-for-beginners/blob/master/examples/encrypted_DB1/decrypt_blocks.py.

Perhaps, the author wanted each block encrypted differently, so he/she used OrderID as part of key. It would be also possible to make different AES key instead of IV.

So now we know that IV only affects first block during decryption in CFB mode, this is feature of it. All other blocks can be decrypted without knowledge IV, but using the key.

OK, so why CFB mode? Apparently, because the very first AES example on CryptoPP wiki uses CFB mode: http://www.cryptopp.com/wiki/Advanced_Encryption_Standard#Encrypting_and_Decrypting_Using_AES. Supposedly, developer choose it for simplicity: the example can encrypt/decrypt text strings with arbitrary lengths, without padding.

It is very likely, program's author(s) just copypasted the example from CryptoPP wiki page. Many programmers do so.

The only difference that IV is chosen randomly in CryptoPP wiki example, while this indeterminism wasn't allowable to programmers of the software we are dissecting now, so they choose to initialize IV using Order ID.

Now we can proceed to analyzing matter of each byte in the decrypted block.

8.7.7 Structure of the buffer

Let's take first four decrypted blocks:

```
00000000: 0D 00 FF FE 46 00 52 00  41 00 4E 00 4B 00 49 00  ....F.R.A.N.K.I.
00000010: 45 00 20 00 4A 00 4F 00  48 00 4E 00 53 00 66 66  E. .J.O.H.N.S.ff
00000020: 66 66 66 9E 61 40 D4 07  06 01                    fff.a@....

00000000: 0B 00 FF FE 4C 00 4F 00  52 00 49 00 20 00 42 00  ....L.O.R.I. .B.
00000010: 41 00 52 00 52 00 4F 00  4E 00 CD CC CC CC CC CC  A.R.R.O.N.......
00000020: 1B 40 D4 07 06 01                                 .@....

00000000: 0A 00 FF FE 47 00 41 00  52 00 59 00 20 00 42 00  ....G.A.R.Y. .B.
00000010: 49 00 47 00 47 00 53 00  00 00 00 00 00 C0 65 40  I.G.G.S.......e@
00000020: D4 07 06 01                                       ....

00000000: 0F 00 FF FE 4D 00 45 00  4C 00 49 00 4E 00 44 00  ....M.E.L.I.N.D.
00000010: 41 00 20 00 44 00 4F 00  48 00 45 00 52 00 54 00  A. .D.O.H.E.R.T.
00000020: 59 00 48 E1 7A 14 AE FF  68 40 D4 07 06 02        Y.H.z...h@....
```

UTF-16 encoded text strings are clearly visible, these are names and surnames. The first byte (or 16-bit word) is seems string length, we can visually check it. *FF FE* is seems Unicode BOM.

There are 12 more bytes after each string.

Using this script (https://github.com/DennisYurichev/RE-for-beginners/blob/master/examples/encrypted_DB1/dump_buffer_rest.py) I've got random selection of the *tails*:

```
dennis@...:$ python decrypt.py encrypted.xml | shuf | head -20
00000000: 48 E1 7A 14 AE 5F 62 40  DD 07 05 08              H.z.._b@....
00000000: 00 00 00 00 00 40 5A 40  DC 07 08 18              .....@Z@....
00000000: 00 00 00 00 00 80 56 40  D7 07 0B 04              ......V@....
00000000: 00 00 00 00 00 60 61 40  D7 07 0C 1C              ......a@....
00000000: 00 00 00 00 00 20 63 40  D9 07 05 18              ..... c@....
00000000: 3D 0A D7 A3 70 FD 34 40  D7 07 07 11              =...p.4@....
00000000: 00 00 00 00 00 A0 63 40  D5 07 05 19              ......c@....
00000000: CD CC CC CC CC 3C 5C 40  D7 07 08 11              .......@....
00000000: 66 66 66 66 66 FE 62 40  D4 07 06 05              fffff.b@....
00000000: 1F 85 EB 51 B8 FE 40 40  D6 07 09 1E              ...Q..@@....
00000000: 00 00 00 00 00 40 5F 40  DC 07 02 18              .....@_@....
00000000: 48 E1 7A 14 AE 9F 67 40  D8 07 05 12              H.z...g@....
00000000: CD CC CC CC CC 3C 5E 40  DC 07 01 07              ......^@....
```

```
00000000: 00 00 00 00 00 00 67 40  D4 07 0B 0E            ......g@....
00000000: 00 00 00 00 00 40 51 40  DC 07 04 0B            .....@Q@....
00000000: 00 00 00 00 00 40 56 40  D7 07 07 0A            .....@V@....
00000000: 8F C2 F5 28 5C 7F 55 40  DB 07 01 16            ...(..U@....
00000000: 00 00 00 00 00 00 32 40  DB 07 06 09            ......2@....
00000000: 66 66 66 66 66 7E 66 40  D9 07 0A 06            fffff~f@....
00000000: 48 E1 7A 14 AE DF 68 40  D5 07 07 16            H.z...h@....
```

We first see the 0x40 and 0x07 bytes present in each *tail*. The very last byte s always in 1..0x1F (1..31) range, I've checked. The penultimate byte is always in 1..0xC (1..12) range. Wow, that looks like a date! Year can be represented as 16-bit value, and maybe last 4 bytes is date (16 bits for year, 8 bits for month and 8 more for day)? 0x7DD is 2013, 0x7D5 is 2005, etc. Seems fine. This is a date. There are 8 more bytes. Judging by the fact this is database named *orders*, maybe some kind of sum is present here? I made attempt to interpret it as double-precision IEEE 754 floating point and dump all values!

Some are:

```
71.0
134.0
51.95
53.0
121.99
96.95
98.95
15.95
85.95
184.99
94.95
29.95
85.0
36.0
130.99
115.95
87.99
127.95
114.0
150.95
```

Looks like real!

Now we can dump names, sums and dates.

```
plain:
00000000: 0D 00 FF FE 46 00 52 00  41 00 4E 00 4B 00 49 00  ....F.R.A.N.K.I.
00000010: 45 00 20 00 4A 00 4F 00  48 00 4E 00 53 00 66 66  E. .J.O.H.N.S.ff
00000020: 66 66 66 9E 61 40 D4 07  06 01                    fff.a@....
OrderID= 1 name= FRANKIE JOHNS sum= 140.95 date= 2004 / 6 / 1

plain:
00000000: 0B 00 FF FE 4C 00 4F 00  52 00 49 00 20 00 42 00  ....L.O.R.I. .B.
00000010: 41 00 52 00 52 00 4F 00  4E 00 CD CC CC CC CC CC  A.R.R.O.N.......
00000020: 1B 40 D4 07 06 01                                 .@....
OrderID= 2 name= LORI BARRON sum= 6.95 date= 2004 / 6 / 1

plain:
00000000: 0A 00 FF FE 47 00 41 00  52 00 59 00 20 00 42 00  ....G.A.R.Y. .B.
00000010: 49 00 47 00 47 00 53 00  00 00 00 00 00 C0 65 40  I.G.G.S.......e@
00000020: D4 07 06 01                                       ....
OrderID= 3 name= GARY BIGGS sum= 174.0 date= 2004 / 6 / 1

plain:
00000000: 0F 00 FF FE 4D 00 45 00  4C 00 49 00 4E 00 44 00  ....M.E.L.I.N.D.
00000010: 41 00 20 00 44 00 4F 00  48 00 45 00 52 00 54 00  A. .D.O.H.E.R.T.
00000020: 59 00 48 E1 7A 14 AE FF  68 40 D4 07 06 02        Y.H.z...h@....
OrderID= 4 name= MELINDA DOHERTY sum= 199.99 date= 2004 / 6 / 2

plain:
00000000: 0B 00 FF FE 4C 00 45 00  4E 00 41 00 20 00 4D 00  ....L.E.N.A. .M.
00000010: 41 00 52 00 43 00 55 00  53 00 00 00 00 00 00 60  A.R.C.U.S.......
00000020: 66 40 D4 07 06 03                                 f@....
```

```
OrderID= 5 name= LENA MARCUS sum= 179.0 date= 2004 / 6 / 3
```

See more: https://raw.githubusercontent.com/DennisYurichev/RE-for-beginners/master/examples/encrypted_DB1/decrypted.full.with_data.txt. Or filtered: https://github.com/DennisYurichev/RE-for-beginners/blob/master/examples/encrypted_DB1/decrypted.short.txt. Seems correct.

This is some kind of OOP serialization, i.e., packing differently typed values into binary buffer for storing and/or transmitting.

8.7.8 Noise at the end

The only question remaining is that sometimes, *tail* is bigger:

```
00000000: 0E 00 FF FE 54 00 48 00  45 00 52 00 45 00 53 00  ....T.H.E.R.E.S.
00000010: 45 00 20 00 54 00 55 00  54 00 54 00 4C 00 45 00  E. .T.U.T.T.L.E.
00000020: 66 66 66 66 66 1E 63 40  D4 07 07 1A 00 07 07 19  fffff.c@........
OrderID= 172 name= THERESE TUTTLE sum= 152.95 date= 2004 / 7 / 26
```

(*00 07 07 19* bytes are not used and is ballast.)

```
00000000: 0C 00 FF FE 4D 00 45 00  4C 00 41 00 4E 00 49 00  ....M.E.L.A.N.I.
00000010: 45 00 20 00 4B 00 49 00  52 00 4B 00 00 00 00 00  E. .K.I.R.K.....
00000020: 00 20 64 40 D4 07 09 02  00 02                    . d@......
OrderID= 286 name= MELANIE KIRK sum= 161.0 date= 2004 / 9 / 2
```

(*00 02* are not used.)

After close examination, we can see, that the noise at the end of *tail* is just left from previous encryption!

Here are two subsequent buffers:

```
00000000: 10 00 FF FE 42 00 4F 00  4E 00 4E 00 49 00 45 00  ....B.O.N.N.I.E.
00000010: 20 00 47 00 4F 00 4C 00  44 00 53 00 54 00 45 00   .G.O.L.D.S.T.E.
00000020: 49 00 4E 00 9A 99 99 99  99 79 46 40 D4 07 07 19  I.N......yF@....
OrderID= 171 name= BONNIE GOLDSTEIN sum= 44.95 date= 2004 / 7 / 25

00000000: 0E 00 FF FE 54 00 48 00  45 00 52 00 45 00 53 00  ....T.H.E.R.E.S.
00000010: 45 00 20 00 54 00 55 00  54 00 54 00 4C 00 45 00  E. .T.U.T.T.L.E.
00000020: 66 66 66 66 66 1E 63 40  D4 07 07 1A 00 07 07 19  fffff.c@........
OrderID= 172 name= THERESE TUTTLE sum= 152.95 date= 2004 / 7 / 26
```

(The last *07 07 19* bytes are copied from the previous plaintext buffer.)

Another two subsequent buffers:

```
00000000: 0D 00 FF FE 4C 00 4F 00  52 00 45 00 4E 00 45 00  ....L.O.R.E.N.E.
00000010: 20 00 4F 00 54 00 4F 00  4F 00 4C 00 45 00 CD CC   .O.T.O.O.L.E...
00000020: CC CC CC 3C 5E 40 D4 07  09 02                    ...<^@....
OrderID= 285 name= LORENE OTOOLE sum= 120.95 date= 2004 / 9 / 2

00000000: 0C 00 FF FE 4D 00 45 00  4C 00 41 00 4E 00 49 00  ....M.E.L.A.N.I.
00000010: 45 00 20 00 4B 00 49 00  52 00 4B 00 00 00 00 00  E. .K.I.R.K.....
00000020: 00 20 64 40 D4 07 09 02  00 02                    . d@......
OrderID= 286 name= MELANIE KIRK sum= 161.0 date= 2004 / 9 / 2
```

The last 02 byte has been copied from the previous plaintext buffer.

It's possible if the buffer used while encrypting is global and/or isn't clearing before each encryption. The final buffer size is also chaotic, nevertheless, the bug left uncaught because it doesn't affect decrypting process, which just ignores noise at the end. This is common mistake. It's been present in OpenSSL (Heartbleed bug).

8.7.9 Conclusion

Summary: every practicing reverse engineer should be familiar with major crypto algorithms and also major cryptographical modes. Some books about it: 12.1.10 on page 1014.

Encrypted database contents has been artificially constructed by me for the sake of demonstration. I've got most popular USA names and surnames from there: http://stackoverflow.com/questions/1803628/raw-list-of-person-names, and combined them randomly. Dates and sums were also generated randomly.

All files used in this part are here: https://github.com/DennisYurichev/RE-for-beginners/tree/master/examples/encrypted_DB1.

Nevertheless, many features like these I've observed in real-world software applications. This example is based on them.

8.7.10 Post Scriptum: brute-forcing IV

The case you have just seen has been artificially constructed, but is based on a real application I've reverse engineered. When I've been working on it, I first noticed that IV has been generating using some 32-bit number, and I wasn't able to find a link between this value and OrderID. So I prepared to use brute-force, which is indeed possible here.

It's not a problem to enumerate all 32-bit values and try each as a base for IV. Then you decrypt the first 16-byte block and check for zero bytes, which are always at fixed places.

8.8 Overclocking Cointerra Bitcoin miner

There was Cointerra Bitcoin miner, looking like that:

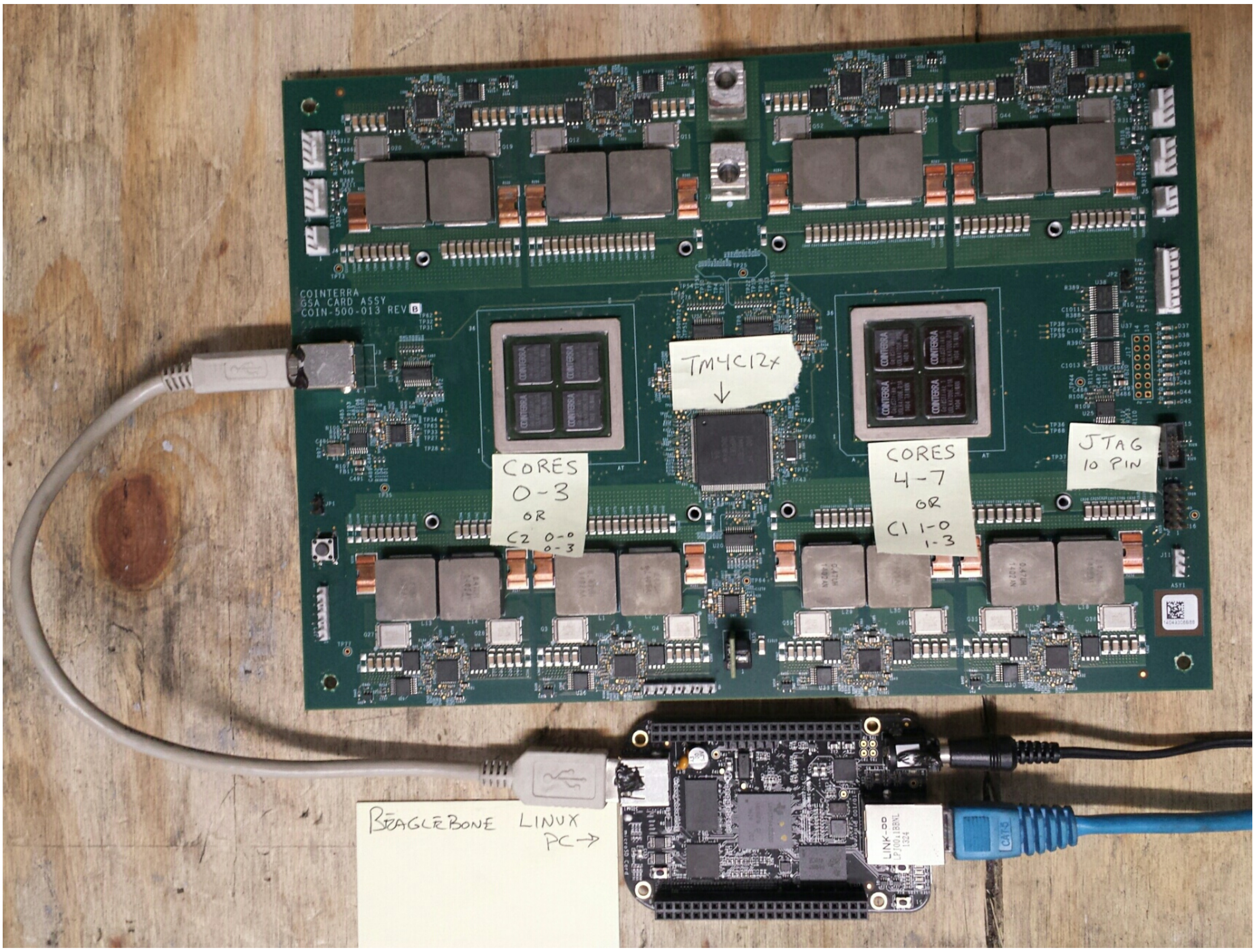


Figure 8.14: Board

And there was also (possibly leaked) utility[25] which can set clock rate for the board. It runs on additional BeagleBone Linux ARM board (small board at bottom of the picture).

And the author was once asked, is it possible to hack this utility to see, which frequency can be set and which are not. And it is possible to tweak it?

The utility must be executed like that: `./cointool-overclock 0 0 900`, where 900 is frequency in MHz. If the frequency is too high, utility will print “Error with arguments” and exit.

This is a fragment of code around reference to “Error with arguments” text string:

```
...

.text:0000ABC4         STR      R3, [R11,#var_28]
.text:0000ABC8         MOV      R3, #optind
.text:0000ABD0         LDR      R3, [R3]
.text:0000ABD4         ADD      R3, R3, #1
.text:0000ABD8         MOV      R3, R3,LSL#2
.text:0000ABDC         LDR      R2, [R11,#argv]
.text:0000ABE0         ADD      R3, R2, R3
.text:0000ABE4         LDR      R3, [R3]
.text:0000ABE8         MOV      R0, R3  ; nptr
.text:0000ABEC         MOV      R1, #0  ; endptr
.text:0000ABF0         MOV      R2, #0  ; base
.text:0000ABF4         BL       strtoll
.text:0000ABF8         MOV      R2, R0
.text:0000ABFC         MOV      R3, R1
.text:0000AC00         MOV      R3, R2
.text:0000AC04         STR      R3, [R11,#var_2C]
.text:0000AC08         MOV      R3, #optind
.text:0000AC10         LDR      R3, [R3]
.text:0000AC14         ADD      R3, R3, #2
.text:0000AC18         MOV      R3, R3,LSL#2
.text:0000AC1C         LDR      R2, [R11,#argv]
.text:0000AC20         ADD      R3, R2, R3
.text:0000AC24         LDR      R3, [R3]
.text:0000AC28         MOV      R0, R3  ; nptr
.text:0000AC2C         MOV      R1, #0  ; endptr
.text:0000AC30         MOV      R2, #0  ; base
.text:0000AC34         BL       strtoll
.text:0000AC38         MOV      R2, R0
.text:0000AC3C         MOV      R3, R1
.text:0000AC40         MOV      R3, R2
.text:0000AC44         STR      R3, [R11,#third_argument]
.text:0000AC48         LDR      R3, [R11,#var_28]
.text:0000AC4C         CMP      R3, #0
.text:0000AC50         BLT      errors_with_arguments
.text:0000AC54         LDR      R3, [R11,#var_28]
.text:0000AC58         CMP      R3, #1
.text:0000AC5C         BGT      errors_with_arguments
.text:0000AC60         LDR      R3, [R11,#var_2C]
.text:0000AC64         CMP      R3, #0
.text:0000AC68         BLT      errors_with_arguments
.text:0000AC6C         LDR      R3, [R11,#var_2C]
.text:0000AC70         CMP      R3, #3
.text:0000AC74         BGT      errors_with_arguments
.text:0000AC78         LDR      R3, [R11,#third_argument]
.text:0000AC7C         CMP      R3, #0x31
.text:0000AC80         BLE      errors_with_arguments
.text:0000AC84         LDR      R2, [R11,#third_argument]
.text:0000AC88         MOV      R3, #950
.text:0000AC8C         CMP      R2, R3
.text:0000AC90         BGT      errors_with_arguments
.text:0000AC94         LDR      R2, [R11,#third_argument]
.text:0000AC98         MOV      R3, #0x51EB851F
.text:0000ACA0         SMULL    R1, R3, R3, R2
.text:0000ACA4         MOV      R1, R3,ASR#4
.text:0000ACA8         MOV      R3, R2,ASR#31
```

[25] Can be downloaded here: https://github.com/DennisYurichev/RE-for-beginners/raw/master/examples/bitcoin_miner/files/cointool-overclock

```
.text:0000ACAC         RSB     R3, R3, R1
.text:0000ACB0         MOV     R1, #50
.text:0000ACB4         MUL     R3, R1, R3
.text:0000ACB8         RSB     R3, R3, R2
.text:0000ACBC         CMP     R3, #0
.text:0000ACC0         BEQ     loc_ACEC
.text:0000ACC4
.text:0000ACC4 errors_with_arguments
.text:0000ACC4
.text:0000ACC4         LDR     R3, [R11,#argv]
.text:0000ACC8         LDR     R3, [R3]
.text:0000ACCC         MOV     R0, R3  ; path
.text:0000ACD0         BL      __xpg_basename
.text:0000ACD4         MOV     R3, R0
.text:0000ACD8         MOV     R0, #aSErrorWithArgu ; format
.text:0000ACE0         MOV     R1, R3
.text:0000ACE4         BL      printf
.text:0000ACE8         B       loc_ADD4
.text:0000ACEC ; ------------------------------------------------------------
.text:0000ACEC
.text:0000ACEC loc_ACEC                ; CODE XREF: main+66C
.text:0000ACEC         LDR     R2, [R11,#third_argument]
.text:0000ACF0         MOV     R3, #499
.text:0000ACF4         CMP     R2, R3
.text:0000ACF8         BGT     loc_AD08
.text:0000ACFC         MOV     R3, #0x64
.text:0000AD00         STR     R3, [R11,#unk_constant]
.text:0000AD04         B       jump_to_write_power
.text:0000AD08 ; ------------------------------------------------------------
.text:0000AD08
.text:0000AD08 loc_AD08                ; CODE XREF: main+6A4
.text:0000AD08         LDR     R2, [R11,#third_argument]
.text:0000AD0C         MOV     R3, #799
.text:0000AD10         CMP     R2, R3
.text:0000AD14         BGT     loc_AD24
.text:0000AD18         MOV     R3, #0x5F
.text:0000AD1C         STR     R3, [R11,#unk_constant]
.text:0000AD20         B       jump_to_write_power
.text:0000AD24 ; ------------------------------------------------------------
.text:0000AD24
.text:0000AD24 loc_AD24                ; CODE XREF: main+6C0
.text:0000AD24         LDR     R2, [R11,#third_argument]
.text:0000AD28         MOV     R3, #899
.text:0000AD2C         CMP     R2, R3
.text:0000AD30         BGT     loc_AD40
.text:0000AD34         MOV     R3, #0x5A
.text:0000AD38         STR     R3, [R11,#unk_constant]
.text:0000AD3C         B       jump_to_write_power
.text:0000AD40 ; ------------------------------------------------------------
.text:0000AD40
.text:0000AD40 loc_AD40                ; CODE XREF: main+6DC
.text:0000AD40         LDR     R2, [R11,#third_argument]
.text:0000AD44         MOV     R3, #999
.text:0000AD48         CMP     R2, R3
.text:0000AD4C         BGT     loc_AD5C
.text:0000AD50         MOV     R3, #0x55
.text:0000AD54         STR     R3, [R11,#unk_constant]
.text:0000AD58         B       jump_to_write_power
.text:0000AD5C ; ------------------------------------------------------------
.text:0000AD5C
.text:0000AD5C loc_AD5C                ; CODE XREF: main+6F8
.text:0000AD5C         LDR     R2, [R11,#third_argument]
.text:0000AD60         MOV     R3, #1099
.text:0000AD64         CMP     R2, R3
.text:0000AD68         BGT     jump_to_write_power
.text:0000AD6C         MOV     R3, #0x50
.text:0000AD70         STR     R3, [R11,#unk_constant]
.text:0000AD74
.text:0000AD74 jump_to_write_power                        ; CODE XREF: main+6B0
.text:0000AD74                                            ; main+6CC ...
```

```
.text:0000AD74          LDR     R3, [R11,#var_28]
.text:0000AD78          UXTB    R1, R3
.text:0000AD7C          LDR     R3, [R11,#var_2C]
.text:0000AD80          UXTB    R2, R3
.text:0000AD84          LDR     R3, [R11,#unk_constant]
.text:0000AD88          UXTB    R3, R3
.text:0000AD8C          LDR     R0, [R11,#third_argument]
.text:0000AD90          UXTH    R0, R0
.text:0000AD94          STR     R0, [SP,#0x44+var_44]
.text:0000AD98          LDR     R0, [R11,#var_24]
.text:0000AD9C          BL      write_power
.text:0000ADA0          LDR     R0, [R11,#var_24]
.text:0000ADA4          MOV     R1, #0x5A
.text:0000ADA8          BL      read_loop
.text:0000ADAC          B       loc_ADD4

...

.rodata:0000B378 aSErrorWithArgu DCB "%s: Error with arguments",0xA,0 ; DATA XREF: main+684

...
```

Function names were present in debugging information of the original binary, like `write_power`, `read_loop`. But labels inside functions were named by me.

`optind` name looks familiar. It is from *getopt* *NIX library intended for command-line parsing—well, this is exactly what happens inside. Then, the 3rd argument (where frequency value is to be passed) is converted from a string to a number using a call to *strtoll()* function.

The value is then checked against various constants. At 0xACEC, it's checked, if it is lesser or equal to 499, and if it is so, 0x64 is to be passed to `write_power()` function (which sends a command through USB using `send_msg()`). If it is greater than 499, jump to 0xAD08 is occurred.

At 0xAD08 it's checked, if it's lesser or equal to 799. 0x5F is then passed to `write_power()` function in case of success.

There are more checks: for 899 at 0xAD24, for 0x999 at 0xAD40 and finally, for 1099 at 0xAD5C. If the input frequency is lesser or equal to 1099, 0x50 will be passed (at 0xAD6C) to `write_power()` function. And there is some kind of bug. If the value is still greater than 1099, the value itself is passed into `write_power()` function. Oh, it's not a bug, because we can't get here: value is checked first against 950 at 0xAC88, and if it is greater, error message will be displayed and the utility will finish.

Now the table between frequency in MHz and value passed to `write_power()` function:

MHz	hexadecimal	decimal
499MHz	0x64	100
799MHz	0x5f	95
899MHz	0x5a	90
999MHz	0x55	85
1099MHz	0x50	80

As it seems, a value passed to the board is gradually decreasing during frequency increasing.

Now we see that value of 950MHz is a hardcoded limit, at least in this utility. Can we trick it?

Let's back to this piece of code:

```
.text:0000AC84      LDR     R2, [R11,#third_argument]
.text:0000AC88      MOV     R3, #950
.text:0000AC8C      CMP     R2, R3
.text:0000AC90      BGT     errors_with_arguments ; I've patched here to 00 00 00 00
```

We must disable BGT branch instruction at 0xAC90 somehow. And this is ARM in ARM mode, because, as we see, all addresses are increasing by 4, i.e., each instruction has size of 4 bytes. NOP (no operation) instruction in ARM mode is just four zero bytes: `00 00 00 00`. So by writing four zeros at 0xAC90 address (or physical offset in file 0x2C90) we can disable the check.

Now it's possible to set frequencies up to 1050MHz. Even more is possible, but due to the bug, if input value is greater than 1099, a value *as is* in MHz will be passed to the board, which is incorrect.

I didn't go further, but if I had to, I would try to decrease a value which is passed to `write_power()` function.

Now the scary piece of code which I skipped at first:

```
.text:0000AC94       LDR      R2, [R11,#third_argument]
.text:0000AC98       MOV      R3, #0x51EB851F
.text:0000ACA0       SMULL    R1, R3, R3, R2 ; R3=3rg_arg/3.125
.text:0000ACA4       MOV      R1, R3,ASR#4 ; R1=R3/16=3rg_arg/50
.text:0000ACA8       MOV      R3, R2,ASR#31 ; R3=MSB(3rg_arg)
.text:0000ACAC       RSB      R3, R3, R1 ; R3=3rd_arg/50
.text:0000ACB0       MOV      R1, #50
.text:0000ACB4       MUL      R3, R1, R3 ; R3=50*(3rd_arg/50)
.text:0000ACB8       RSB      R3, R3, R2
.text:0000ACBC       CMP      R3, #0
.text:0000ACC0       BEQ      loc_ACEC
.text:0000ACC4
.text:0000ACC4 errors_with_arguments
```

Division via multiplication is used here, and constant is 0x51EB851F. I wrote a simple programmer's calculator[26] for myself. And I have there a feature to calculate modulo inverse.

```
modinv32(0x51EB851F)
Warning, result is not integer: 3.125000
(unsigned) dec: 3 hex: 0x3 bin: 11
```

That means that SMULL instruction at 0xACA0 is basically divides 3rd argument by 3.125. In fact, all `modinv32()` function in my calculator does, is this:

$$\frac{1}{\frac{input}{2^{32}}} = \frac{2^{32}}{input}$$

Then there are additional shifts and now we see than 3rg argument is just divided by 50. And then it's multiplied by 50 again. Why? This is simplest check, if the input value is can be divided by 50 evenly. If the value of this expression is non-zero, x can't be divided by 50 evenly:

$$x - ((\frac{x}{50}) \cdot 50)$$

This is in fact simple way to calculate remainder of division.

And then, if the remainder is non-zero, error message is displayed. So this utility takes frequency values in form like 850, 900, 950, 1000, etc., but not 855 or 911.

That's it! If you do something like that, please be warned that you may damage your board, just as in case of overclocking other devices like CPUs, GPU[27]s, etc. If you have a Cointerra board, do this on your own risk!

8.9 Breaking simple executable cryptor

I've got an executable file which is encrypted by relatively simple encryption. Here is it (only executable section is left here).

First, all encryption function does is just adds number of position in buffer to the byte. Here is how this can be encoded in Python:

Listing 8.7: Python script

```
#!/usr/bin/env python
def e(i, k):
    return chr ((ord(i)+k) % 256)
```

[26] https://github.com/DennisYurichev/progcalc
[27] Graphics Processing Unit

```
def encrypt(buf):
    return e(buf[0], 0)+ e(buf[1], 1)+ e(buf[2], 2) + e(buf[3], 3)+ e(buf[4], 4)+ e(buf[5], 5)+↙
    ↳  e(buf[6], 6)+ e(buf[7], 7)+
            e(buf[8], 8)+ e(buf[9], 9)+ e(buf[10], 10)+ e(buf[11], 11)+ e(buf[12], 12)+ e(buf↙
    ↳ [13], 13)+ e(buf[14], 14)+ e(buf[15], 15)
```

Hence, if you encrypt buffer with 16 zeros, you'll get *0, 1, 2, 3 ... 12, 13, 14, 15*.

Propagating Cipher Block Chaining (PCBC) is also used, here is how it works:

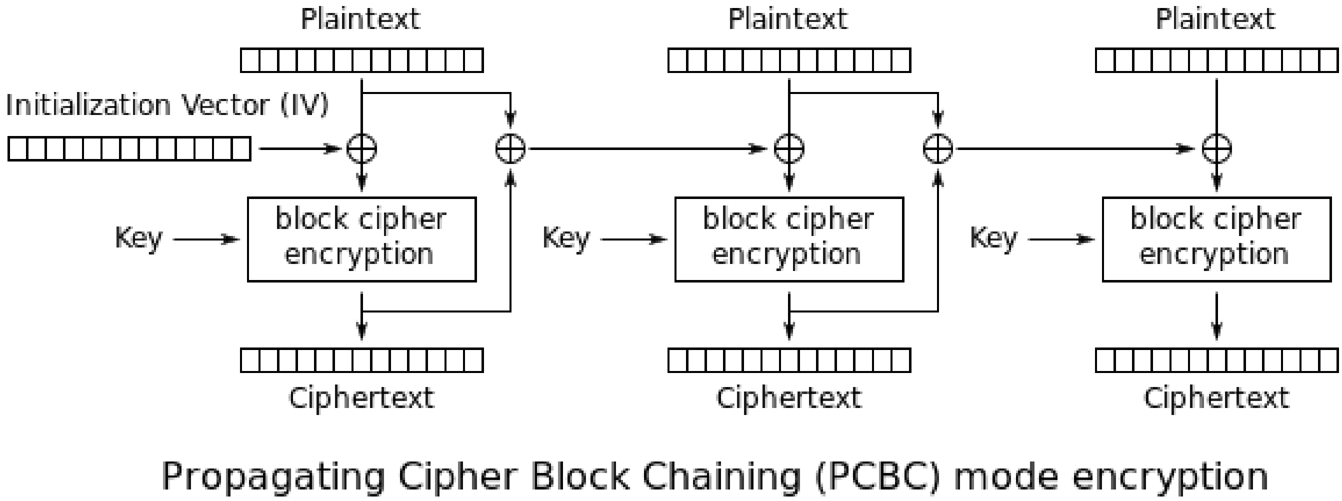


Figure 8.15: Propagating Cipher Block Chaining encryption (image is taken from Wikipedia article)

The problem is that it's too boring to recover IV (Initialization Vector) each time. Brute-force is also not an option, because IV is too long (16 bytes). Let's see, if it's possible to recover IV for arbitrary encrypted executable file?

Let's try simple frequency analysis. This is 32-bit x86 executable code, so let's gather statistics about most frequent bytes and opcodes. I tried huge oracle.exe file from Oracle RDBMS version 11.2 for windows x86 and I've found that the most frequent byte (no surprise) is zero (10%). The next most frequent byte is (again, no surprise) 0xFF (5%). The next is 0x8B (5%).

0x8B is opcode for MOV, this is indeed one of the most busy x86 instructions. Now what about popularity of zero byte? If compiler needs to encode value bigger than 127, it has to use 32-bit displacement instead of 8-bit one, but large values are very rare, so it is padded by zeros. This is at least in LEA, MOV, PUSH, CALL.

For example:

```
8D B0 28 01 00 00                 lea     esi, [eax+128h]
8D BF 40 38 00 00                 lea     edi, [edi+3840h]
```

Displacements bigger than 127 are very popular, but they are rarely exceeds 0x10000 (indeed, such large memory buffers/structures are also rare).

Same story with MOV, large constants are rare, the most heavily used are 0, 1, 10, 100, 2^n, and so on. Compiler has to pad small constants by zeros to represent them as 32-bit values:

```
BF 02 00 00 00                    mov     edi, 2
BF 01 00 00 00                    mov     edi, 1
```

Now about 00 and FF bytes combined: jumps (including conditional) and calls can pass execution flow forward or backwards, but very often, within the limits of the current executable module. If forward, displacement is not very big and also padded with zeros. If backwards, displacement is represented as negative value, so padded with FF bytes. For example, transfer execution flow forward:

```
E8 43 0C 00 00                    call    _function1
E8 5C 00 00 00                    call    _function2
0F 84 F0 0A 00 00                 jz      loc_4F09A0
```

```
0F 84 EB 00 00 00                  jz      loc_4EFBB8
```

Backwards:

```
E8 79 0C FE FF                     call    _function1
E8 F4 16 FF FF                     call    _function2
0F 84 F8 FB FF FF                  jz      loc_8212BC
0F 84 06 FD FF FF                  jz      loc_FF1E7D
```

FF byte is also very often occurred in negative displacements like these:

```
8D 85 1E FF FF FF                  lea     eax, [ebp-0E2h]
8D 95 F8 5C FF FF                  lea     edx, [ebp-0A308h]
```

So far so good. Now we have to try various 16-byte keys, decrypt executable section and measure how often 00, FF ad 8B bytes are occurred. Let's also keep in sight how PCBC decryption works:

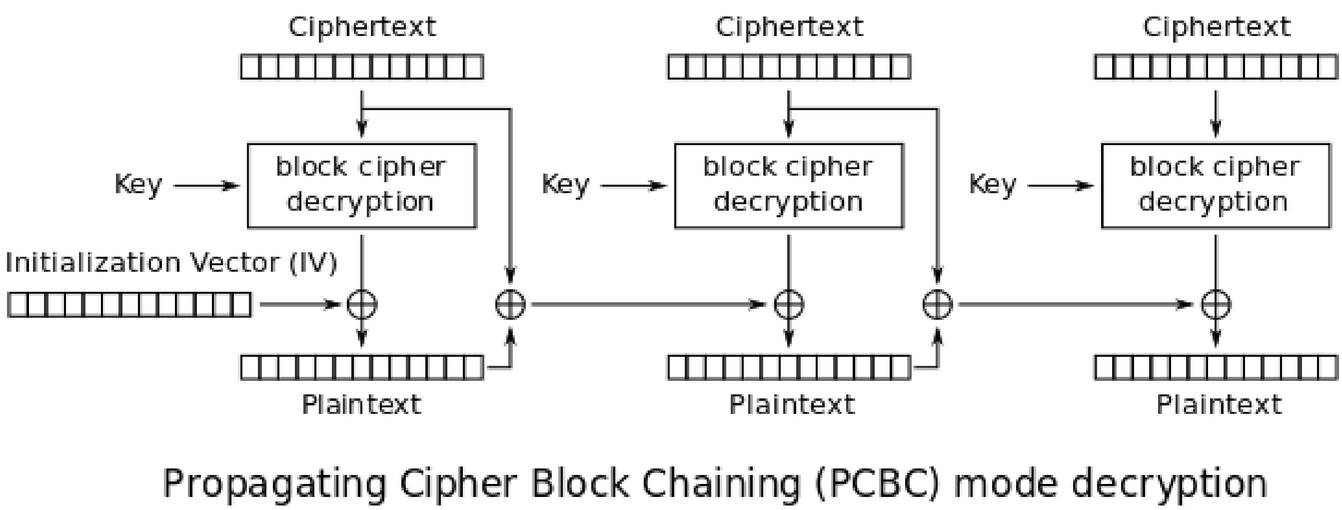


Figure 8.16: Propagating Cipher Block Chaining decryption (image is taken from Wikipedia article)

The good news is that we don't really have to decrypt whole piece of data, but only slice by slice, this is exactly how I did in my previous example: 9.1.5 on page 943.

Now I'm trying all possible bytes (0..255) for each byte in key and just pick the byte producing maximal amount of 00/FF/8B bytes in a decrypted slice:

```
#!/usr/bin/env python
import sys, hexdump, array, string, operator

KEY_LEN=16

def chunks(l, n):
    # split n by l-byte chunks
    # http://stackoverflow.com/questions/312443/how-do-you-split-a-list-into-evenly-sized-↙
    ↳ chunks-in-python
    n = max(1, n)
    return [l[i:i + n] for i in range(0, len(l), n)]

def read_file(fname):
    file=open(fname, mode='rb')
    content=file.read()
    file.close()
    return content

def decrypt_byte (c, key):
    return chr((ord(c)-key) % 256)

def XOR_PCBC_step (IV, buf, k):
```

```
    prev=IV
    rt=""
    for c in buf:
        new_c=decrypt_byte(c, k)
        plain=chr(ord(new_c)^ord(prev))
        prev=chr(ord(c)^ord(plain))
        rt=rt+plain
    return rt

each_Nth_byte=[""]*KEY_LEN

content=read_file(sys.argv[1])
# split input by 16-byte chunks:
all_chunks=chunks(content, KEY_LEN)
for c in all_chunks:
    for i in range(KEY_LEN):
        each_Nth_byte[i]=each_Nth_byte[i] + c[i]

# try each byte of key
for N in range(KEY_LEN):
    print "N=", N
    stat={}
    for i in range(256):
        tmp_key=chr(i)
        tmp=XOR_PCBC_step(tmp_key,each_Nth_byte[N], N)
        # count 0, FFs and 8Bs in decrypted buffer:
        important_bytes=tmp.count('\x00')+tmp.count('\xFF')+tmp.count('\x8B')
        stat[i]=important_bytes
    sorted_stat = sorted(stat.iteritems(), key=operator.itemgetter(1), reverse=True)
    print sorted_stat[0]
```

(Source code can downloaded here.)

I run it and here is a key for which 00/FF/8B bytes presence in decrypted buffer is maximal:

```
N= 0
(147, 1224)
N= 1
(94, 1327)
N= 2
(252, 1223)
N= 3
(218, 1266)
N= 4
(38, 1209)
N= 5
(192, 1378)
N= 6
(199, 1204)
N= 7
(213, 1332)
N= 8
(225, 1251)
N= 9
(112, 1223)
N= 10
(143, 1177)
N= 11
(108, 1286)
N= 12
(10, 1164)
N= 13
(3, 1271)
N= 14
(128, 1253)
N= 15
(232, 1330)
```

Let's write decryption utility with the key we got:

```
#!/usr/bin/env python
import sys, hexdump, array

def xor_strings(s,t):
    # https://en.wikipedia.org/wiki/XOR_cipher#Example_implementation
    """xor two strings together"""
    return "".join(chr(ord(a)^ord(b)) for a,b in zip(s,t))

IV=array.array('B', [147, 94, 252, 218, 38, 192, 199, 213, 225, 112, 143, 108, 10, 3, 128, ↙
    ↳ 232]).tostring()

def chunks(l, n):
    n = max(1, n)
    return [l[i:i + n] for i in range(0, len(l), n)]

def read_file(fname):
    file=open(fname, mode='rb')
    content=file.read()
    file.close()
    return content

def decrypt_byte(i, k):
    return chr ((ord(i)-k) % 256)

def decrypt(buf):
    return "".join(decrypt_byte(buf[i], i) for i in range(16))

fout=open(sys.argv[2], mode='wb')

prev=IV
content=read_file(sys.argv[1])
tmp=chunks(content, 16)
for c in tmp:
    new_c=decrypt(c)
    p=xor_strings (new_c, prev)
    prev=xor_strings(c, p)
    fout.write(p)
fout.close()
```

(Source code can downloaded here.)

Let's check resulting file:

```
$ objdump -b binary -m i386 -D decrypted.bin

...

       5:       8b ff                   mov    %edi,%edi
       7:       55                      push   %ebp
       8:       8b ec                   mov    %esp,%ebp
       a:       51                      push   %ecx
       b:       53                      push   %ebx
       c:       33 db                   xor    %ebx,%ebx
       e:       43                      inc    %ebx
       f:       84 1d a0 e2 05 01       test   %bl,0x105e2a0
      15:       75 09                   jne    0x20
      17:       ff 75 08                pushl  0x8(%ebp)
      1a:       ff 15 b0 13 00 01       call   *0x10013b0
      20:       6a 6c                   push   $0x6c
      22:       ff 35 54 d0 01 01       pushl  0x101d054
      28:       ff 15 b4 13 00 01       call   *0x10013b4
      2e:       89 45 fc                mov    %eax,-0x4(%ebp)
      31:       85 c0                   test   %eax,%eax
      33:       0f 84 d9 00 00 00       je     0x112
      39:       56                      push   %esi
      3a:       57                      push   %edi
      3b:       6a 00                   push   $0x0
      3d:       50                      push   %eax
      3e:       ff 15 b8 13 00 01       call   *0x10013b8
      44:       8b 35 bc 13 00 01       mov    0x10013bc,%esi
```

```
      4a:       8b f8                   mov    %eax,%edi
      4c:       a1 e0 e2 05 01          mov    0x105e2e0,%eax
      51:       3b 05 e4 e2 05 01       cmp    0x105e2e4,%eax
      57:       75 12                   jne    0x6b
      59:       53                      push   %ebx
      5a:       6a 03                   push   $0x3
      5c:       57                      push   %edi
      5d:       ff d6                   call   *%esi

...
```

Yes, this is seems correctly disassembled piece of x86 code. The whole dectyped file can be downloaded here.

In fact, this is text section from regedit.exe from Windows 7. But this example is based on a real case I encountered, so just executable is different (and key), algorithm is the same.

8.9.1 Other ideas to consider

What if I would fail with such simple frequency analysis? There are other ideas on how to measure correctness of decrypted/decompressed x86 code:

- Many modern compilers aligns functions on 0x10 border. So the space left before is filled with NOPs (0x90) or other NOP instructions with known opcodes: .1.7 on page 1038.
- Perhaps, the most frequent pattern in any assembly language is function call: `PUSH chain / CALL / ADD ESP, X`. This sequence can easily detected and found. I've even gathered statistics about average number of function arguments: 11.2 on page 999. (Hence, this is average length of PUSH chain.)

Read more about incorrectly/correctly disassembled code: 5.11 on page 726.

8.10 SAP

8.10.1 About SAP client network traffic compression

(Tracing the connection between the TDW_NOCOMPRESS SAPGUI[28] environment variable and the pesky annoying pop-up window and the actual data compression routine.)

It is known that the network traffic between SAPGUI and SAP is not encrypted by default, but compressed (see here[29] and here[30]).

It is also known that by setting the environment variable *TDW_NOCOMPRESS* to 1, it is possible to turn the network packet compression off.

But you will see an annoying pop-up window that cannot be closed:

[28] SAP GUI client
[29] `http://go.yurichev.com/17221`
[30] blog.yurichev.com

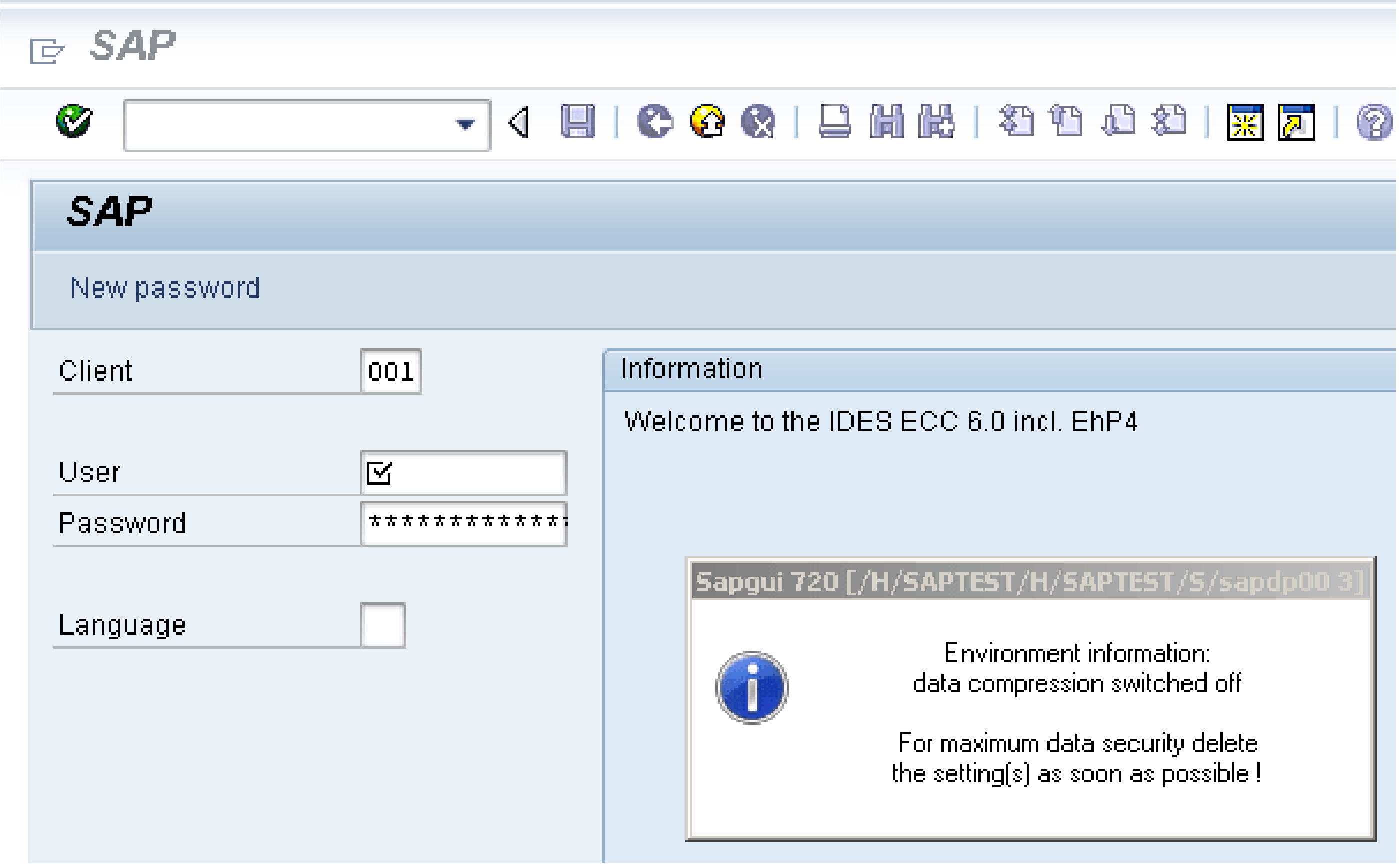


Figure 8.17: Screenshot

Let's see if we can remove the window somehow.

But before this, let's see what we already know.

First: we know that the environment variable *TDW_NOCOMPRESS* is checked somewhere inside the SAPGUI client.

Second: a string like "data compression switched off" must be present somewhere in it.

With the help of the FAR file manager[31] we can found that both of these strings are stored in the SAPguilib.dll file.

So let's open SAPguilib.dll in IDA and search for the *"TDW_NOCOMPRESS "* string. Yes, it is present and there is only one reference to it.

We see the following fragment of code (all file offsets are valid for SAPGUI 720 win32, SAPguilib.dll file version 7200,1,0,9009):

```
.text:6440D51B                 lea     eax, [ebp+2108h+var_211C]
.text:6440D51E                 push    eax             ; int
.text:6440D51F                 push    offset aTdw_nocompress ; "TDW_NOCOMPRESS"
.text:6440D524                 mov     byte ptr [edi+15h], 0
.text:6440D528                 call    chk_env
.text:6440D52D                 pop     ecx
.text:6440D52E                 pop     ecx
.text:6440D52F                 push    offset byte_64443AF8
.text:6440D534                 lea     ecx, [ebp+2108h+var_211C]

; demangled name: int ATL::CStringT::Compare(char const *)const
.text:6440D537                 call    ds:mfc90_1603
.text:6440D53D                 test    eax, eax
.text:6440D53F                 jz      short loc_6440D55A
.text:6440D541                 lea     ecx, [ebp+2108h+var_211C]

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
.text:6440D544                 call    ds:mfc90_910
```

[31] http://go.yurichev.com/17347

```
.text:6440D54A                 push    eax             ; Str
.text:6440D54B                 call    ds:atoi
.text:6440D551                 test    eax, eax
.text:6440D553                 setnz   al
.text:6440D556                 pop     ecx
.text:6440D557                 mov     [edi+15h], al
```

The string returned by chk_env() via its second argument is then handled by the MFC string functions and then atoi()[32] is called. After that, the numerical value is stored in edi+15h.

Also take a look at the chk_env() function (we gave this name to it manually):

```
.text:64413F20 ; int __cdecl chk_env(char *VarName, int)
.text:64413F20 chk_env         proc near
.text:64413F20
.text:64413F20 DstSize         = dword ptr -0Ch
.text:64413F20 var_8           = dword ptr -8
.text:64413F20 DstBuf          = dword ptr -4
.text:64413F20 VarName         = dword ptr  8
.text:64413F20 arg_4           = dword ptr  0Ch
.text:64413F20
.text:64413F20                 push    ebp
.text:64413F21                 mov     ebp, esp
.text:64413F23                 sub     esp, 0Ch
.text:64413F26                 mov     [ebp+DstSize], 0
.text:64413F2D                 mov     [ebp+DstBuf], 0
.text:64413F34                 push    offset unk_6444C88C
.text:64413F39                 mov     ecx, [ebp+arg_4]

; (demangled name) ATL::CStringT::operator=(char const *)
.text:64413F3C                 call    ds:mfc90_820
.text:64413F42                 mov     eax, [ebp+VarName]
.text:64413F45                 push    eax             ; VarName
.text:64413F46                 mov     ecx, [ebp+DstSize]
.text:64413F49                 push    ecx             ; DstSize
.text:64413F4A                 mov     edx, [ebp+DstBuf]
.text:64413F4D                 push    edx             ; DstBuf
.text:64413F4E                 lea     eax, [ebp+DstSize]
.text:64413F51                 push    eax             ; ReturnSize
.text:64413F52                 call    ds:getenv_s
.text:64413F58                 add     esp, 10h
.text:64413F5B                 mov     [ebp+var_8], eax
.text:64413F5E                 cmp     [ebp+var_8], 0
.text:64413F62                 jz      short loc_64413F68
.text:64413F64                 xor     eax, eax
.text:64413F66                 jmp     short loc_64413FBC
.text:64413F68
.text:64413F68 loc_64413F68:
.text:64413F68                 cmp     [ebp+DstSize], 0
.text:64413F6C                 jnz     short loc_64413F72
.text:64413F6E                 xor     eax, eax
.text:64413F70                 jmp     short loc_64413FBC
.text:64413F72
.text:64413F72 loc_64413F72:
.text:64413F72                 mov     ecx, [ebp+DstSize]
.text:64413F75                 push    ecx
.text:64413F76                 mov     ecx, [ebp+arg_4]

; demangled name: ATL::CSimpleStringT<char, 1>::Preallocate(int)
.text:64413F79                 call    ds:mfc90_2691
.text:64413F7F                 mov     [ebp+DstBuf], eax
.text:64413F82                 mov     edx, [ebp+VarName]
.text:64413F85                 push    edx             ; VarName
.text:64413F86                 mov     eax, [ebp+DstSize]
.text:64413F89                 push    eax             ; DstSize
.text:64413F8A                 mov     ecx, [ebp+DstBuf]
.text:64413F8D                 push    ecx             ; DstBuf
.text:64413F8E                 lea     edx, [ebp+DstSize]
.text:64413F91                 push    edx             ; ReturnSize
```

[32] standard C library function that converts the digits in a string to a number

```
.text:64413F92                 call    ds:getenv_s
.text:64413F98                 add     esp, 10h
.text:64413F9B                 mov     [ebp+var_8], eax
.text:64413F9E                 push    0FFFFFFFFh
.text:64413FA0                 mov     ecx, [ebp+arg_4]

; demangled name: ATL::CSimpleStringT::ReleaseBuffer(int)
.text:64413FA3                 call    ds:mfc90_5835
.text:64413FA9                 cmp     [ebp+var_8], 0
.text:64413FAD                 jz      short loc_64413FB3
.text:64413FAF                 xor     eax, eax
.text:64413FB1                 jmp     short loc_64413FBC
.text:64413FB3
.text:64413FB3 loc_64413FB3:
.text:64413FB3                 mov     ecx, [ebp+arg_4]

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
.text:64413FB6                 call    ds:mfc90_910
.text:64413FBC
.text:64413FBC loc_64413FBC:
.text:64413FBC
.text:64413FBC                 mov     esp, ebp
.text:64413FBE                 pop     ebp
.text:64413FBF                 retn
.text:64413FBF chk_env         endp
```

Yes. The `getenv_s()`[33]

function is a Microsoft security-enhanced version of `getenv()`[34].

There are also some MFC string manipulations.

Lots of other environment variables are checked as well. Here is a list of all variables that are being checked and what SAPGUI would write to its trace log when logging is turned on:

DPTRACE	"GUI-OPTION: Trace set to %d"
TDW_HEXDUMP	"GUI-OPTION: Hexdump enabled"
TDW_WORKDIR	"GUI-OPTION: working directory '%s''
TDW_SPLASHSRCEENOFF	"GUI-OPTION: Splash Screen Off"
	"GUI-OPTION: Splash Screen On"
TDW_REPLYTIMEOUT	"GUI-OPTION: reply timeout %d milliseconds"
TDW_PLAYBACKTIMEOUT	"GUI-OPTION: PlaybackTimeout set to %d milliseconds"
TDW_NOCOMPRESS	"GUI-OPTION: no compression read"
TDW_EXPERT	"GUI-OPTION: expert mode"
TDW_PLAYBACKPROGRESS	"GUI-OPTION: PlaybackProgress"
TDW_PLAYBACKNETTRAFFIC	"GUI-OPTION: PlaybackNetTraffic"
TDW_PLAYLOG	"GUI-OPTION: /PlayLog is YES, file %s"
TDW_PLAYTIME	"GUI-OPTION: /PlayTime set to %d milliseconds"
TDW_LOGFILE	"GUI-OPTION: TDW_LOGFILE '%s''
TDW_WAN	"GUI-OPTION: WAN - low speed connection enabled"
TDW_FULLMENU	"GUI-OPTION: FullMenu enabled"
SAP_CP / SAP_CODEPAGE	"GUI-OPTION: SAP_CODEPAGE '%d''
UPDOWNLOAD_CP	"GUI-OPTION: UPDOWNLOAD_CP '%d''
SNC_PARTNERNAME	"GUI-OPTION: SNC name '%s''
SNC_QOP	"GUI-OPTION: SNC_QOP '%s''
SNC_LIB	"GUI-OPTION: SNC is set to: %s"
SAPGUI_INPLACE	"GUI-OPTION: environment variable SAPGUI_INPLACE is on"

The settings for each variable are written in the array via a pointer in the EDI register. EDI is set before the function call:

```
.text:6440EE00                 lea     edi, [ebp+2884h+var_2884] ; options here like +0x15...
.text:6440EE03                 lea     ecx, [esi+24h]
.text:6440EE06                 call    load_command_line
.text:6440EE0B                 mov     edi, eax
.text:6440EE0D                 xor     ebx, ebx
.text:6440EE0F                 cmp     edi, ebx
.text:6440EE11                 jz      short loc_6440EE42
.text:6440EE13                 push    edi
```

[33] MSDN
[34] Standard C library returning environment variable

```
.text:6440EE14                 push    offset aSapguiStoppedA ; "Sapgui stopped after ⤦
    ↳ commandline interp"...
.text:6440EE19                 push    dword_644F93E8
.text:6440EE1F                 call    FEWTraceError
```

Now, can we find the *"data record mode switched on"* string?

Yes, and the only reference is in

`CDwsGui::PrepareInfoWindow()`.

How do we get know the class/method names? There are a lot of special debugging calls that write to the log files, like:

```
.text:64405160                 push    dword ptr [esi+2854h]
.text:64405166                 push    offset aCdwsguiPrepare ; "\nCDwsGui::PrepareInfoWindow: ⤦
    ↳ sapgui env"...
.text:6440516B                 push    dword ptr [esi+2848h]
.text:64405171                 call    dbg
.text:64405176                 add     esp, 0Ch
```

...or:

```
.text:6440237A                 push    eax
.text:6440237B                 push    offset aCclientStart_6 ; "CClient::Start: set shortcut ⤦
    ↳ user to '\%'"...
.text:64402380                 push    dword ptr [edi+4]
.text:64402383                 call    dbg
.text:64402388                 add     esp, 0Ch
```

It is *very* useful.

So let's see the contents of this pesky annoying pop-up window's function:

```
.text:64404F4F CDwsGui__PrepareInfoWindow proc near
.text:64404F4F
.text:64404F4F pvParam         = byte ptr -3Ch
.text:64404F4F var_38          = dword ptr -38h
.text:64404F4F var_34          = dword ptr -34h
.text:64404F4F rc              = tagRECT ptr -2Ch
.text:64404F4F cy              = dword ptr -1Ch
.text:64404F4F h               = dword ptr -18h
.text:64404F4F var_14          = dword ptr -14h
.text:64404F4F var_10          = dword ptr -10h
.text:64404F4F var_4           = dword ptr -4
.text:64404F4F
.text:64404F4F                 push    30h
.text:64404F51                 mov     eax, offset loc_64438E00
.text:64404F56                 call    __EH_prolog3
.text:64404F5B                 mov     esi, ecx        ; ECX is pointer to object
.text:64404F5D                 xor     ebx, ebx
.text:64404F5F                 lea     ecx, [ebp+var_14]
.text:64404F62                 mov     [ebp+var_10], ebx

; demangled name: ATL::CStringT(void)
.text:64404F65                 call    ds:mfc90_316
.text:64404F6B                 mov     [ebp+var_4], ebx
.text:64404F6E                 lea     edi, [esi+2854h]
.text:64404F74                 push    offset aEnvironmentInf ; "Environment information:\n"
.text:64404F79                 mov     ecx, edi

; demangled name: ATL::CStringT::operator=(char const *)
.text:64404F7B                 call    ds:mfc90_820
.text:64404F81                 cmp     [esi+38h], ebx
.text:64404F84                 mov     ebx, ds:mfc90_2539
.text:64404F8A                 jbe     short loc_64404FA9
.text:64404F8C                 push    dword ptr [esi+34h]
.text:64404F8F                 lea     eax, [ebp+var_14]
.text:64404F92                 push    offset aWorkingDirecto ; "working directory: '\%s'\n"
.text:64404F97                 push    eax
```

```
; demangled name: ATL::CStringT::Format(char const *,...)
.text:64404F98                 call    ebx ; mfc90_2539
.text:64404F9A                 add     esp, 0Ch
.text:64404F9D                 lea     eax, [ebp+var_14]
.text:64404FA0                 push    eax
.text:64404FA1                 mov     ecx, edi

; demangled name: ATL::CStringT::operator+=(class ATL::CSimpleStringT<char, 1> const &)
.text:64404FA3                 call    ds:mfc90_941
.text:64404FA9
.text:64404FA9 loc_64404FA9:
.text:64404FA9                 mov     eax, [esi+38h]
.text:64404FAC                 test    eax, eax
.text:64404FAE                 jbe     short loc_64404FD3
.text:64404FB0                 push    eax
.text:64404FB1                 lea     eax, [ebp+var_14]
.text:64404FB4                 push    offset aTraceLevelDAct ; "trace level \%d activated\n"
.text:64404FB9                 push    eax

; demangled name: ATL::CStringT::Format(char const *,...)
.text:64404FBA                 call    ebx ; mfc90_2539
.text:64404FBC                 add     esp, 0Ch
.text:64404FBF                 lea     eax, [ebp+var_14]
.text:64404FC2                 push    eax
.text:64404FC3                 mov     ecx, edi

; demangled name: ATL::CStringT::operator+=(class ATL::CSimpleStringT<char, 1> const &)
.text:64404FC5                 call    ds:mfc90_941
.text:64404FCB                 xor     ebx, ebx
.text:64404FCD                 inc     ebx
.text:64404FCE                 mov     [ebp+var_10], ebx
.text:64404FD1                 jmp     short loc_64404FD6
.text:64404FD3
.text:64404FD3 loc_64404FD3:
.text:64404FD3                 xor     ebx, ebx
.text:64404FD5                 inc     ebx
.text:64404FD6
.text:64404FD6 loc_64404FD6:
.text:64404FD6                 cmp     [esi+38h], ebx
.text:64404FD9                 jbe     short loc_64404FF1
.text:64404FDB                 cmp     dword ptr [esi+2978h], 0
.text:64404FE2                 jz      short loc_64404FF1
.text:64404FE4                 push    offset aHexdumpInTrace ; "hexdump in trace activated\n"
.text:64404FE9                 mov     ecx, edi

; demangled name: ATL::CStringT::operator+=(char const *)
.text:64404FEB                 call    ds:mfc90_945
.text:64404FF1
.text:64404FF1 loc_64404FF1:
.text:64404FF1
.text:64404FF1                 cmp     byte ptr [esi+78h], 0
.text:64404FF5                 jz      short loc_64405007
.text:64404FF7                 push    offset aLoggingActivat ; "logging activated\n"
.text:64404FFC                 mov     ecx, edi

; demangled name: ATL::CStringT::operator+=(char const *)
.text:64404FFE                 call    ds:mfc90_945
.text:64405004                 mov     [ebp+var_10], ebx
.text:64405007
.text:64405007 loc_64405007:
.text:64405007                 cmp     byte ptr [esi+3Dh], 0
.text:6440500B                 jz      short bypass
.text:6440500D                 push    offset aDataCompressio ; "data compression switched off\↙
    ↳ n"
.text:64405012                 mov     ecx, edi

; demangled name: ATL::CStringT::operator+=(char const *)
.text:64405014                 call    ds:mfc90_945
.text:6440501A                 mov     [ebp+var_10], ebx
.text:6440501D
```

```
.text:6440501D bypass:
.text:6440501D                 mov     eax, [esi+20h]
.text:64405020                 test    eax, eax
.text:64405022                 jz      short loc_6440503A
.text:64405024                 cmp     dword ptr [eax+28h], 0
.text:64405028                 jz      short loc_6440503A
.text:6440502A                 push    offset aDataRecordMode ; "data record mode switched on\n↙
    ↘ "
.text:6440502F                 mov     ecx, edi

; demangled name: ATL::CStringT::operator+=(char const *)
.text:64405031                 call    ds:mfc90_945
.text:64405037                 mov     [ebp+var_10], ebx
.text:6440503A
.text:6440503A loc_6440503A:
.text:6440503A
.text:6440503A                 mov     ecx, edi
.text:6440503C                 cmp     [ebp+var_10], ebx
.text:6440503F                 jnz     loc_64405142
.text:64405045                 push    offset aForMaximumData ; "\nFor maximum data security ↙
    ↘ delete\nthe s"...

; demangled name: ATL::CStringT::operator+=(char const *)
.text:6440504A                 call    ds:mfc90_945
.text:64405050                 xor     edi, edi
.text:64405052                 push    edi             ; fWinIni
.text:64405053                 lea     eax, [ebp+pvParam]
.text:64405056                 push    eax             ; pvParam
.text:64405057                 push    edi             ; uiParam
.text:64405058                 push    30h             ; uiAction
.text:6440505A                 call    ds:SystemParametersInfoA
.text:64405060                 mov     eax, [ebp+var_34]
.text:64405063                 cmp     eax, 1600
.text:64405068                 jle     short loc_64405072
.text:6440506A                 cdq
.text:6440506B                 sub     eax, edx
.text:6440506D                 sar     eax, 1
.text:6440506F                 mov     [ebp+var_34], eax
.text:64405072
.text:64405072 loc_64405072:
.text:64405072                 push    edi             ; hWnd
.text:64405073                 mov     [ebp+cy], 0A0h
.text:6440507A                 call    ds:GetDC
.text:64405080                 mov     [ebp+var_10], eax
.text:64405083                 mov     ebx, 12Ch
.text:64405088                 cmp     eax, edi
.text:6440508A                 jz      loc_64405113
.text:64405090                 push    11h             ; i
.text:64405092                 call    ds:GetStockObject
.text:64405098                 mov     edi, ds:SelectObject
.text:6440509E                 push    eax             ; h
.text:6440509F                 push    [ebp+var_10]    ; hdc
.text:644050A2                 call    edi ; SelectObject
.text:644050A4                 and     [ebp+rc.left], 0
.text:644050A8                 and     [ebp+rc.top], 0
.text:644050AC                 mov     [ebp+h], eax
.text:644050AF                 push    401h            ; format
.text:644050B4                 lea     eax, [ebp+rc]
.text:644050B7                 push    eax             ; lprc
.text:644050B8                 lea     ecx, [esi+2854h]
.text:644050BE                 mov     [ebp+rc.right], ebx
.text:644050C1                 mov     [ebp+rc.bottom], 0B4h

; demangled name: ATL::CSimpleStringT::GetLength(void)
.text:644050C8                 call    ds:mfc90_3178
.text:644050CE                 push    eax             ; cchText
.text:644050CF                 lea     ecx, [esi+2854h]

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
.text:644050D5                 call    ds:mfc90_910
```

```
.text:644050DB                 push    eax             ; lpchText
.text:644050DC                 push    [ebp+var_10]    ; hdc
.text:644050DF                 call    ds:DrawTextA
.text:644050E5                 push    4               ; nIndex
.text:644050E7                 call    ds:GetSystemMetrics
.text:644050ED                 mov     ecx, [ebp+rc.bottom]
.text:644050F0                 sub     ecx, [ebp+rc.top]
.text:644050F3                 cmp     [ebp+h], 0
.text:644050F7                 lea     eax, [eax+ecx+28h]
.text:644050FB                 mov     [ebp+cy], eax
.text:644050FE                 jz      short loc_64405108
.text:64405100                 push    [ebp+h]         ; h
.text:64405103                 push    [ebp+var_10]    ; hdc
.text:64405106                 call    edi ; SelectObject
.text:64405108
.text:64405108 loc_64405108:
.text:64405108                 push    [ebp+var_10]    ; hDC
.text:6440510B                 push    0               ; hWnd
.text:6440510D                 call    ds:ReleaseDC
.text:64405113
.text:64405113 loc_64405113:
.text:64405113                 mov     eax, [ebp+var_38]
.text:64405116                 push    80h             ; uFlags
.text:6440511B                 push    [ebp+cy]        ; cy
.text:6440511E                 inc     eax
.text:6440511F                 push    ebx             ; cx
.text:64405120                 push    eax             ; Y
.text:64405121                 mov     eax, [ebp+var_34]
.text:64405124                 add     eax, 0FFFFFED4h
.text:64405129                 cdq
.text:6440512A                 sub     eax, edx
.text:6440512C                 sar     eax, 1
.text:6440512E                 push    eax             ; X
.text:6440512F                 push    0               ; hWndInsertAfter
.text:64405131                 push    dword ptr [esi+285Ch] ; hWnd
.text:64405137                 call    ds:SetWindowPos
.text:6440513D                 xor     ebx, ebx
.text:6440513F                 inc     ebx
.text:64405140                 jmp     short loc_6440514D
.text:64405142
.text:64405142 loc_64405142:
.text:64405142                 push    offset byte_64443AF8

; demangled name: ATL::CStringT::operator=(char const *)
.text:64405147                 call    ds:mfc90_820
.text:6440514D
.text:6440514D loc_6440514D:
.text:6440514D                 cmp     dword_6450B970, ebx
.text:64405153                 jl      short loc_64405188
.text:64405155                 call    sub_6441C910
.text:6440515A                 mov     dword_644F858C, ebx
.text:64405160                 push    dword ptr [esi+2854h]
.text:64405166                 push    offset aCdwsguiPrepare ; "\nCDwsGui::PrepareInfoWindow: ↙
    ↳ sapgui env"...
.text:6440516B                 push    dword ptr [esi+2848h]
.text:64405171                 call    dbg
.text:64405176                 add     esp, 0Ch
.text:64405179                 mov     dword_644F858C, 2
.text:64405183                 call    sub_6441C920
.text:64405188
.text:64405188 loc_64405188:
.text:64405188                 or      [ebp+var_4], 0FFFFFFFFh
.text:6440518C                 lea     ecx, [ebp+var_14]

; demangled name: ATL::CStringT::~CStringT()
.text:6440518F                 call    ds:mfc90_601
.text:64405195                 call    __EH_epilog3
.text:6440519A                 retn
.text:6440519A CDwsGui__PrepareInfoWindow endp
```

At the start of the function ECX has a pointer to the object (since it is a thiscall (3.18.1 on page 542)-type of function). In our case, the object obviously has class type of *CDwsGui*. Depending on the option turned on in the object, a specific message part is to be concatenated with the resulting message.

If the value at address `this+0x3D` is not zero, the compression is off:

```
.text:64405007 loc_64405007:
.text:64405007                 cmp     byte ptr [esi+3Dh], 0
.text:6440500B                 jz      short bypass
.text:6440500D                 push    offset aDataCompressio ; "data compression switched off\
    n"
.text:64405012                 mov     ecx, edi

; demangled name: ATL::CStringT::operator+=(char const *)
.text:64405014                 call    ds:mfc90_945
.text:6440501A                 mov     [ebp+var_10], ebx
.text:6440501D
.text:6440501D bypass:
```

It is interesting that finally the *var_10* variable state defines whether the message is to be shown at all:

```

.text:6440503C                 cmp     [ebp+var_10], ebx
.text:6440503F                 jnz     exit ; bypass drawing

; add strings "For maximum data security delete" / "the setting(s) as soon as possible !":

.text:64405045                 push    offset aForMaximumData ; "\nFor maximum data security 
    delete\nthe s"...
.text:6440504A                 call    ds:mfc90_945 ; ATL::CStringT::operator+=(char const *)
.text:64405050                 xor     edi, edi
.text:64405052                 push    edi             ; fWinIni
.text:64405053                 lea     eax, [ebp+pvParam]
.text:64405056                 push    eax             ; pvParam
.text:64405057                 push    edi             ; uiParam
.text:64405058                 push    30h             ; uiAction
.text:6440505A                 call    ds:SystemParametersInfoA
.text:64405060                 mov     eax, [ebp+var_34]
.text:64405063                 cmp     eax, 1600
.text:64405068                 jle     short loc_64405072
.text:6440506A                 cdq
.text:6440506B                 sub     eax, edx
.text:6440506D                 sar     eax, 1
.text:6440506F                 mov     [ebp+var_34], eax
.text:64405072
.text:64405072 loc_64405072:

start drawing:

.text:64405072                 push    edi             ; hWnd
.text:64405073                 mov     [ebp+cy], 0A0h
.text:6440507A                 call    ds:GetDC
```

Let's check our theory on practice.

JNZ at this line …

```

.text:6440503F                 jnz     exit ; bypass drawing
```

…replace it with just JMP, and we get SAPGUI working without the pesky annoying pop-up window appearing!

Now let's dig deeper and find a connection between the $0x15$ offset in the `load_command_line()` (we gave it this name) function and the `this+0x3D` variable in *CDwsGui::PrepareInfoWindow*. Are we sure the value is the same?

We are starting to search for all occurrences of the `0x15` value in code. For a small programs like SAPGUI, it sometimes works. Here is the first occurrence we've got:

```
.text:64404C19 sub_64404C19    proc near
```

```
.text:64404C19
.text:64404C19 arg_0           = dword ptr  4
.text:64404C19
.text:64404C19                 push    ebx
.text:64404C1A                 push    ebp
.text:64404C1B                 push    esi
.text:64404C1C                 push    edi
.text:64404C1D                 mov     edi, [esp+10h+arg_0]
.text:64404C21                 mov     eax, [edi]
.text:64404C23                 mov     esi, ecx ; ESI/ECX are pointers to some unknown object.
.text:64404C25                 mov     [esi], eax
.text:64404C27                 mov     eax, [edi+4]
.text:64404C2A                 mov     [esi+4], eax
.text:64404C2D                 mov     eax, [edi+8]
.text:64404C30                 mov     [esi+8], eax
.text:64404C33                 lea     eax, [edi+0Ch]
.text:64404C36                 push    eax
.text:64404C37                 lea     ecx, [esi+0Ch]

; demangled name:  ATL::CStringT::operator=(class ATL::CStringT ... &)
.text:64404C3A                 call    ds:mfc90_817
.text:64404C40                 mov     eax, [edi+10h]
.text:64404C43                 mov     [esi+10h], eax
.text:64404C46                 mov     al, [edi+14h]
.text:64404C49                 mov     [esi+14h], al
.text:64404C4C                 mov     al, [edi+15h] ; copy byte from 0x15 offset
.text:64404C4F                 mov     [esi+15h], al ; to 0x15 offset in CDwsGui object
```

The function has been called from the function named *CDwsGui::CopyOptions*! And thanks again for debugging information.

But the real answer is in *CDwsGui::Init()*:

```
.text:6440B0BF loc_6440B0BF:
.text:6440B0BF                 mov     eax, [ebp+arg_0]
.text:6440B0C2                 push    [ebp+arg_4]
.text:6440B0C5                 mov     [esi+2844h], eax
.text:6440B0CB                 lea     eax, [esi+28h] ; ESI is pointer to CDwsGui object
.text:6440B0CE                 push    eax
.text:6440B0CF                 call    CDwsGui__CopyOptions
```

Finally, we understand: the array filled in the `load_command_line()` function is actually placed in the *CDwsGui* class, but at address `this+0x28`. 0x15 + 0x28 is exactly 0x3D. OK, we found the point where the value is copied to.

Let's also find the rest of the places where the 0x3D offset is used. Here is one of them in the *CDwsGui::SapguiRun* function (again, thanks to the debugging calls):

```
.text:64409D58                 cmp     [esi+3Dh], bl   ; ESI is pointer to CDwsGui object
.text:64409D5B                 lea     ecx, [esi+2B8h]
.text:64409D61                 setz    al
.text:64409D64                 push    eax             ; arg_10 of CConnectionContext::↙
    ↳ CreateNetwork
.text:64409D65                 push    dword ptr [esi+64h]

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
.text:64409D68                 call    ds:mfc90_910
.text:64409D68                                         ; no arguments
.text:64409D6E                 push    eax
.text:64409D6F                 lea     ecx, [esi+2BCh]

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
.text:64409D75                 call    ds:mfc90_910
.text:64409D75                                         ; no arguments
.text:64409D7B                 push    eax
.text:64409D7C                 push    esi
.text:64409D7D                 lea     ecx, [esi+8]
.text:64409D80                 call    CConnectionContext__CreateNetwork
```

Let's check our findings.
Replace the `setz al` here with the `xor eax, eax / nop` instructions, clear the TDW_NOCOMPRESS environment variable and run SAPGUI. Wow! There pesky annoying window is no more (just as expected, because the variable is not set) but in Wireshark we can see that the network packets are not compressed anymore! Obviously, this is the point where the compression flag is to be set in the *CConnectionContext* object.

So, the compression flag is passed in the 5th argument of *CConnectionContext::CreateNetwork*. Inside the function, another one is called:

```
...
.text:64403476                 push    [ebp+compression]
.text:64403479                 push    [ebp+arg_C]
.text:6440347C                 push    [ebp+arg_8]
.text:6440347F                 push    [ebp+arg_4]
.text:64403482                 push    [ebp+arg_0]
.text:64403485                 call    CNetwork__CNetwork
```

The compression flag is passed here in the 5th argument to the *CNetwork::CNetwork* constructor.

And here is how the *CNetwork* constructor sets the flag in the *CNetwork* object according to its 5th argument *and* another variable which probably could also affect network packets compression.

```
.text:64411DF1                 cmp     [ebp+compression], esi
.text:64411DF7                 jz      short set_EAX_to_0
.text:64411DF9                 mov     al, [ebx+78h]   ; another value may affect compression?
.text:64411DFC                 cmp     al, '3'
.text:64411DFE                 jz      short set_EAX_to_1
.text:64411E00                 cmp     al, '4'
.text:64411E02                 jnz     short set_EAX_to_0
.text:64411E04
.text:64411E04 set_EAX_to_1:
.text:64411E04                 xor     eax, eax
.text:64411E06                 inc     eax             ; EAX -> 1
.text:64411E07                 jmp     short loc_64411E0B
.text:64411E09
.text:64411E09 set_EAX_to_0:
.text:64411E09
.text:64411E09                 xor     eax, eax        ; EAX -> 0
.text:64411E0B
.text:64411E0B loc_64411E0B:
.text:64411E0B                 mov     [ebx+3A4h], eax ; EBX is pointer to CNetwork object
```

At this point we know the compression flag is stored in the *CNetwork* class at address *this+0x3A4*.

Now let's dig through SAPguilib.dll for the `0x3A4` value. And here is the second occurrence in *CDwsGui::OnClientMessageWrite* (endless thanks for the debugging information):

```
.text:64406F76 loc_64406F76:
.text:64406F76                 mov     ecx, [ebp+7728h+var_7794]
.text:64406F79                 cmp     dword ptr [ecx+3A4h], 1
.text:64406F80                 jnz     compression_flag_is_zero
.text:64406F86                 mov     byte ptr [ebx+7], 1
.text:64406F8A                 mov     eax, [esi+18h]
.text:64406F8D                 mov     ecx, eax
.text:64406F8F                 test    eax, eax
.text:64406F91                 ja      short loc_64406FFF
.text:64406F93                 mov     ecx, [esi+14h]
.text:64406F96                 mov     eax, [esi+20h]
.text:64406F99
.text:64406F99 loc_64406F99:
.text:64406F99                 push    dword ptr [edi+2868h] ; int
.text:64406F9F                 lea     edx, [ebp+7728h+var_77A4]
.text:64406FA2                 push    edx             ; int
.text:64406FA3                 push    30000           ; int
.text:64406FA8                 lea     edx, [ebp+7728h+Dst]
.text:64406FAB                 push    edx             ; Dst
.text:64406FAC                 push    ecx             ; int
.text:64406FAD                 push    eax             ; Src
.text:64406FAE                 push    dword ptr [edi+28C0h] ; int
.text:64406FB4                 call    sub_644055C5       ; actual compression routine
```

```
.text:64406FB9                 add     esp, 1Ch
.text:64406FBC                 cmp     eax, 0FFFFFFF6h
.text:64406FBF                 jz      short loc_64407004
.text:64406FC1                 cmp     eax, 1
.text:64406FC4                 jz      loc_6440708C
.text:64406FCA                 cmp     eax, 2
.text:64406FCD                 jz      short loc_64407004
.text:64406FCF                 push    eax
.text:64406FD0                 push    offset aCompressionErr ; "compression error [rc = \%d]- ↙
    ↳ program wi"...
.text:64406FD5                 push    offset aGui_err_compre ; "GUI_ERR_COMPRESS"
.text:64406FDA                 push    dword ptr [edi+28D0h]
.text:64406FE0                 call    SapPcTxtRead
```

Let's take a look in *sub_644055C5*. In it we can only see the call to memcpy() and another function named (by IDA) *sub_64417440*.

And, let's take a look inside *sub_64417440*. What we see is:

```
.text:6441747C                 push    offset aErrorCsrcompre ; "\nERROR: CsRCompress: invalid ↙
    ↳ handle"
.text:64417481                 call    eax ; dword_644F94C8
.text:64417483                 add     esp, 4
```

Voilà! We've found the function that actually compresses the data. As it was shown in past [35],

this function is used in SAP and also the open-source MaxDB project. So it is available in source form.

Doing the last check here:

```
.text:64406F79                 cmp     dword ptr [ecx+3A4h], 1
.text:64406F80                 jnz     compression_flag_is_zero
```

Replace JNZ here for an unconditional JMP. Remove the environment variable TDW_NOCOMPRESS. Voilà!

In Wireshark we see that the client messages are not compressed. The server responses, however, are compressed.

So we found exact connection between the environment variable and the point where data compression routine can be called or bypassed.

8.10.2 SAP 6.0 password checking functions

One time when the author of this book have returned again to his SAP 6.0 IDES installed in a VMware box, he figured out that he forgot the password for the SAP* account, then he have recalled it, but then he got this error message *«Password logon no longer possible - too many failed attempts»*, since he've made all these attempts in attempt to recall it.

The first extremely good news was that the full *disp+work.pdb* PDB file is supplied with SAP, and it contain almost everything: function names, structures, types, local variable and argument names, etc. What a lavish gift!

There is TYPEINFODUMP[36] utility for converting PDB files into something readable and grepable.

Here is an example of a function information + its arguments + its local variables:

```
FUNCTION ThVmcSysEvent
  Address:         10143190  Size:      675 bytes  Index:    60483  TypeIndex:    60484
  Type: int NEAR_C ThVmcSysEvent (unsigned int, unsigned char, unsigned short*)
Flags: 0
PARAMETER events
  Address: Reg335+288  Size:        4 bytes  Index:    60488  TypeIndex:    60489
  Type: unsigned int
Flags: d0
PARAMETER opcode
  Address: Reg335+296  Size:        1 bytes  Index:    60490  TypeIndex:    60491
  Type: unsigned char
```

[35] http://go.yurichev.com/17312
[36] http://go.yurichev.com/17038

```
Flags: d0
PARAMETER serverName
  Address: Reg335+304  Size:        8 bytes  Index:    60492  TypeIndex:    60493
  Type: unsigned short*
Flags: d0
STATIC_LOCAL_VAR func
  Address:        12274af0  Size:        8 bytes  Index:    60495  TypeIndex:    60496
  Type: wchar_t*
Flags: 80
LOCAL_VAR admhead
  Address: Reg335+304  Size:        8 bytes  Index:    60498  TypeIndex:    60499
  Type: unsigned char*
Flags: 90
LOCAL_VAR record
  Address: Reg335+64  Size:      204 bytes  Index:    60501  TypeIndex:    60502
  Type: AD_RECORD
Flags: 90
LOCAL_VAR adlen
  Address: Reg335+296  Size:        4 bytes  Index:    60508  TypeIndex:    60509
  Type: int
Flags: 90
```

And here is an example of some structure:

```
STRUCT DBSL_STMTID
Size: 120  Variables: 4  Functions: 0  Base classes: 0
MEMBER moduletype
  Type:  DBSL_MODULETYPE
  Offset:        0  Index:        3  TypeIndex:    38653
MEMBER module
  Type:  wchar_t module[40]
  Offset:        4  Index:        3  TypeIndex:      831
MEMBER stmtnum
  Type:  long
  Offset:       84  Index:        3  TypeIndex:      440
MEMBER timestamp
  Type:  wchar_t timestamp[15]
  Offset:       88  Index:        3  TypeIndex:     6612
```

Wow!

Another good news: *debugging* calls (there are plenty of them) are very useful.

Here you can also notice the *ct_level* global variable[37], that reflects the current trace level.

There are a lot of debugging inserts in the *disp+work.exe* file:

```
cmp     cs:ct_level, 1
jl      short loc_1400375DA
call    DpLock
lea     rcx, aDpxxtool4_c ; "dpxxtool4.c"
mov     edx, 4Eh        ; line
call    CTrcSaveLocation
mov     r8, cs:func_48
mov     rcx, cs:hdl     ; hdl
lea     rdx, aSDpreadmemvalu ; "%s: DpReadMemValue (%d)"
mov     r9d, ebx
call    DpTrcErr
call    DpUnlock
```

If the current trace level is bigger or equal to threshold defined in the code here, a debugging message is to be written to the log files like *dev_w0*, *dev_disp*, and other *dev** files.

Let's try grepping in the file that we have got with the help of the TYPEINFODUMP utility:

```
cat "disp+work.pdb.d" | grep FUNCTION | grep -i password
```

We have got:

[37]More about trace level: http://go.yurichev.com/17039

```
FUNCTION rcui::AgiPassword::DiagISelection
FUNCTION ssf_password_encrypt
FUNCTION ssf_password_decrypt
FUNCTION password_logon_disabled
FUNCTION dySignSkipUserPassword
FUNCTION migrate_password_history
FUNCTION password_is_initial
FUNCTION rcui::AgiPassword::IsVisible
FUNCTION password_distance_ok
FUNCTION get_password_downwards_compatibility
FUNCTION dySignUnSkipUserPassword
FUNCTION rcui::AgiPassword::GetTypeName
FUNCTION `rcui::AgiPassword::AgiPassword'::`1'::dtor$2
FUNCTION `rcui::AgiPassword::AgiPassword'::`1'::dtor$0
FUNCTION `rcui::AgiPassword::AgiPassword'::`1'::dtor$1
FUNCTION usm_set_password
FUNCTION rcui::AgiPassword::TraceTo
FUNCTION days_since_last_password_change
FUNCTION rsecgrp_generate_random_password
FUNCTION rcui::AgiPassword::`scalar deleting destructor'
FUNCTION password_attempt_limit_exceeded
FUNCTION handle_incorrect_password
FUNCTION `rcui::AgiPassword::`scalar deleting destructor''::`1'::dtor$1
FUNCTION calculate_new_password_hash
FUNCTION shift_password_to_history
FUNCTION rcui::AgiPassword::GetType
FUNCTION found_password_in_history
FUNCTION `rcui::AgiPassword::`scalar deleting destructor''::`1'::dtor$0
FUNCTION rcui::AgiObj::IsaPassword
FUNCTION password_idle_check
FUNCTION SlicHwPasswordForDay
FUNCTION rcui::AgiPassword::IsaPassword
FUNCTION rcui::AgiPassword::AgiPassword
FUNCTION delete_user_password
FUNCTION usm_set_user_password
FUNCTION Password_API
FUNCTION get_password_change_for_SSO
FUNCTION password_in_USR40
FUNCTION rsec_agrp_abap_generate_random_password
```

Let's also try to search for debug messages which contain the words *«password»* and *«locked»*. One of them is the string *«user was locked by subsequently failed password logon attempts»* , referenced in function *password_attempt_limit_exceeded()*.

Other strings that this function can write to a log file are: *«password logon attempt will be rejected immediately (preventing dictionary attacks)»*, *«failed-logon lock: expired (but not removed due to 'read-only' operation)»*, *«failed-logon lock: expired => removed»*.

After playing for a little with this function, we noticed that the problem is exactly in it. It is called from the *chckpass()* function —one of the password checking functions.

First, we would like to make sure that we are at the correct point:

Run tracer:

```
tracer64.exe -a:disp+work.exe bpf=disp+work.exe!chckpass,args:3,unicode
```

```
PID=2236|TID=2248|(0) disp+work.exe!chckpass (0x202c770, L"Brewered1                    ↙
    ↳     ", 0x41) (called from 0x1402f1060 (disp+work.exe!usrexist+0x3c0))
PID=2236|TID=2248|(0) disp+work.exe!chckpass -> 0x35
```

The call path is: *syssigni() -> DyISigni() -> dychkusr() -> usrexist() -> chckpass()*.

The number 0x35 is an error returned in *chckpass()* at that point:

```
.text:00000001402ED567 loc_1402ED567:                          ; CODE XREF: chckpass+B4
.text:00000001402ED567                 mov     rcx, rbx        ; usr02
.text:00000001402ED56A                 call    password_idle_check
.text:00000001402ED56F                 cmp     eax, 33h
.text:00000001402ED572                 jz      loc_1402EDB4E
```

```
.text:00000001402ED578                 cmp     eax, 36h
.text:00000001402ED57B                 jz      loc_1402EDB3D
.text:00000001402ED581                 xor     edx, edx        ; usr02_readonly
.text:00000001402ED583                 mov     rcx, rbx        ; usr02
.text:00000001402ED586                 call    password_attempt_limit_exceeded
.text:00000001402ED58B                 test    al, al
.text:00000001402ED58D                 jz      short loc_1402ED5A0
.text:00000001402ED58F                 mov     eax, 35h
.text:00000001402ED594                 add     rsp, 60h
.text:00000001402ED598                 pop     r14
.text:00000001402ED59A                 pop     r12
.text:00000001402ED59C                 pop     rdi
.text:00000001402ED59D                 pop     rsi
.text:00000001402ED59E                 pop     rbx
.text:00000001402ED59F                 retn
```

Fine, let's check:

```
tracer64.exe -a:disp+work.exe bpf=disp+work.exe!password_attempt_limit_exceeded,args:4,unicode,↙
    ↘ rt:0
```

```
PID=2744|TID=360|(0) disp+work.exe!password_attempt_limit_exceeded (0x202c770, 0, 0x257758, 0) ↙
    ↘ (called from 0x1402ed58b (disp+work.exe!chckpass+0xeb))
PID=2744|TID=360|(0) disp+work.exe!password_attempt_limit_exceeded -> 1
PID=2744|TID=360|We modify return value (EAX/RAX) of this function to 0
PID=2744|TID=360|(0) disp+work.exe!password_attempt_limit_exceeded (0x202c770, 0, 0, 0) (called↙
    ↘  from 0x1402e9794 (disp+work.exe!chngpass+0xe4))
PID=2744|TID=360|(0) disp+work.exe!password_attempt_limit_exceeded -> 1
PID=2744|TID=360|We modify return value (EAX/RAX) of this function to 0
```

Excellent! We can successfully login now.

By the way, we can pretend we forgot the password, fixing the *chckpass()* function to return a value of 0 is enough to bypass the check:

```
tracer64.exe -a:disp+work.exe bpf=disp+work.exe!chckpass,args:3,unicode,rt:0
```

```
PID=2744|TID=360|(0) disp+work.exe!chckpass (0x202c770, L"bogus                          ↙
    ↘    ", 0x41) (called from 0x1402f1060 (disp+work.exe!usrexist+0x3c0))
PID=2744|TID=360|(0) disp+work.exe!chckpass -> 0x35
PID=2744|TID=360|We modify return value (EAX/RAX) of this function to 0
```

What also can be said while analyzing the *password_attempt_limit_exceeded()* function is that at the very beginning of it, this call can be seen:

```
lea     rcx, aLoginFailed_us ; "login/failed_user_auto_unlock"
call    sapgparam
test    rax, rax
jz      short loc_1402E19DE
movzx   eax, word ptr [rax]
cmp     ax, 'N'
jz      short loc_1402E19D4
cmp     ax, 'n'
jz      short loc_1402E19D4
cmp     ax, '0'
jnz     short loc_1402E19DE
```

Obviously, function *sapgparam()* is used to query the value of some configuration parameter. This function can be called from 1768 different places. It seems that with the help of this information, we can easily find the places in code, the control flow of which can be affected by specific configuration parameters.

It is really sweet. The function names are very clear, much clearer than in the Oracle RDBMS.

It seems that the *disp+work* process is written in C++. Has it been rewritten some time ago?

8.11 Oracle RDBMS

8.11.1 V$VERSION table in the Oracle RDBMS

Oracle RDBMS 11.2 is a huge program, its main module oracle.exe contain approx. 124,000 functions. For comparison, the Windows 7 x86 kernel (ntoskrnl.exe) contains approx. 11,000 functions and the Linux 3.9.8 kernel (with default drivers compiled)—31,000 functions.

Let's start with an easy question. Where does Oracle RDBMS get all this information, when we execute this simple statement in SQL*Plus:

```
SQL> select * from V$VERSION;
```

And we get:

```
BANNER
--------------------------------------------------------

Oracle Database 11g Enterprise Edition Release 11.2.0.1.0 - Production
PL/SQL Release 11.2.0.1.0 - Production
CORE    11.2.0.1.0      Production
TNS for 32-bit Windows: Version 11.2.0.1.0 - Production
NLSRTL Version 11.2.0.1.0 - Production
```

Let's start. Where in the Oracle RDBMS can we find the string V$VERSION?

In the win32-version, oracle.exe file contains the string, it's easy to see. But we can also use the object (.o) files from the Linux version of Oracle RDBMS since, unlike the win32 version oracle.exe, the function names (and global variables as well) are preserved there.

So, the kqf.o file contains the V$VERSION string. The object file is in the main Oracle-library libserver11.a.

A reference to this text string can find in the kqfviw table stored in the same file, kqf.o:

Listing 8.8: kqf.o

```
.rodata:0800C4A0 kqfviw dd 0Bh    ; DATA XREF: kqfchk:loc_8003A6D
.rodata:0800C4A0                  ; kqfgbn+34
.rodata:0800C4A4        dd offset _2__STRING_10102_0 ; "GV$WAITSTAT"
.rodata:0800C4A8        dd 4
.rodata:0800C4AC        dd offset _2__STRING_10103_0 ; "NULL"
.rodata:0800C4B0        dd 3
.rodata:0800C4B4        dd 0
.rodata:0800C4B8        dd 195h
.rodata:0800C4BC        dd 4
.rodata:0800C4C0        dd 0
.rodata:0800C4C4        dd 0FFFFC1CBh
.rodata:0800C4C8        dd 3
.rodata:0800C4CC        dd 0
.rodata:0800C4D0        dd 0Ah
.rodata:0800C4D4        dd offset _2__STRING_10104_0 ; "V$WAITSTAT"
.rodata:0800C4D8        dd 4
.rodata:0800C4DC        dd offset _2__STRING_10103_0 ; "NULL"
.rodata:0800C4E0        dd 3
.rodata:0800C4E4        dd 0
.rodata:0800C4E8        dd 4Eh
.rodata:0800C4EC        dd 3
.rodata:0800C4F0        dd 0
.rodata:0800C4F4        dd 0FFFFC003h
.rodata:0800C4F8        dd 4
.rodata:0800C4FC        dd 0
.rodata:0800C500        dd 5
.rodata:0800C504        dd offset _2__STRING_10105_0 ; "GV$BH"
.rodata:0800C508        dd 4
.rodata:0800C50C        dd offset _2__STRING_10103_0 ; "NULL"
.rodata:0800C510        dd 3
.rodata:0800C514        dd 0
.rodata:0800C518        dd 269h
.rodata:0800C51C        dd 15h
.rodata:0800C520        dd 0
```

```
.rodata:0800C524        dd 0FFFFC1EDh
.rodata:0800C528        dd 8
.rodata:0800C52C        dd 0
.rodata:0800C530        dd 4
.rodata:0800C534        dd offset _2__STRING_10106_0 ; "V$BH"
.rodata:0800C538        dd 4
.rodata:0800C53C        dd offset _2__STRING_10103_0 ; "NULL"
.rodata:0800C540        dd 3
.rodata:0800C544        dd 0
.rodata:0800C548        dd 0F5h
.rodata:0800C54C        dd 14h
.rodata:0800C550        dd 0
.rodata:0800C554        dd 0FFFFC1EEh
.rodata:0800C558        dd 5
.rodata:0800C55C        dd 0
```

By the way, often, while analyzing Oracle RDBMS's internals, you may ask yourself, why are the names of the functions and global variable so weird.

Probably, because Oracle RDBMS is a very old product and was developed in C in the 1980s.

And that was a time when the C standard guaranteed that the function names/variables can support only up to 6 characters inclusive: «6 significant initial characters in an external identifier»[38]

Probably, the table `kqfviw` contains most (maybe even all) views prefixed with V$, these are *fixed views*, present all the time. Superficially, by noticing the cyclic recurrence of data, we can easily see that each `kqfviw` table element has 12 32-bit fields. It is very simple to create a 12-elements structure in IDA and apply it to all table elements. As of Oracle RDBMS version 11.2, there are 1023 table elements, i.e., in it are described 1023 of all possible *fixed views*.

We are going to return to this number later.

As we can see, there is not much information in these numbers in the fields. The first number is always equals to the name of the view (without the terminating zero. This is correct for each element. But this information is not very useful.

We also know that the information about all fixed views can be retrieved from a *fixed view* named `V$FIXED_VIEW_DEFINITION` (by the way, the information for this view is also taken from the `kqfviw` and `kqfvip` tables.) By the way, there are 1023 elements in those too. Coincidence? No.

```
SQL> select * from V$FIXED_VIEW_DEFINITION where view_name='V$VERSION';

VIEW_NAME
------------------------------
VIEW_DEFINITION
------------------------------

V$VERSION
select  BANNER from GV$VERSION where inst_id = USERENV('Instance')
```

So, `V$VERSION` is some kind of a *thunk view* for another view, named `GV$VERSION`, which is, in turn:

```
SQL> select * from V$FIXED_VIEW_DEFINITION where view_name='GV$VERSION';

VIEW_NAME
------------------------------
VIEW_DEFINITION
------------------------------

GV$VERSION
select inst_id, banner from x$version
```

The tables prefixed with X$ in the Oracle RDBMS are service tables too, undocumented, cannot be changed by the user and are refreshed dynamically.

If we search for the text

```
select BANNER from GV\$VERSION where inst\_id =
USERENV('Instance')
```

[38] Draft ANSI C Standard (ANSI X3J11/88-090) (May 13, 1988) (yurichev.com)

... in the `kqf.o` file, we find it in the `kqfvip` table:

Listing 8.9: kqf.o

```
.rodata:080185A0 kqfvip dd offset _2__STRING_11126_0 ; DATA XREF: kqfgvcn+18
.rodata:080185A0                                    ; kqfgvt+F
.rodata:080185A0                                    ; "select inst_id,decode(indx,1,'data bloc"...
.rodata:080185A4        dd offset kqfv459_c_0
.rodata:080185A8        dd 0
.rodata:080185AC        dd 0

...

.rodata:08019570        dd offset _2__STRING_11378_0 ; "select  BANNER from GV$VERSION where in↙
    ↪ "...
.rodata:08019574        dd offset kqfv133_c_0
.rodata:08019578        dd 0
.rodata:0801957C        dd 0
.rodata:08019580        dd offset _2__STRING_11379_0 ; "select inst_id,decode(bitand(cfflg,1)↙
    ↪ ,0"...
.rodata:08019584        dd offset kqfv403_c_0
.rodata:08019588        dd 0
.rodata:0801958C        dd 0
.rodata:08019590        dd offset _2__STRING_11380_0 ; "select  STATUS , NAME, IS_RECOVERY_DEST↙
    ↪ "...
.rodata:08019594        dd offset kqfv199_c_0
```

The table appear to have 4 fields in each element. By the way, there are 1023 elements in it, again, the number we already know.

The second field points to another table that contains the table fields for this *fixed view*. As for `V$VERSION`, this table has only two elements, the first is 6 and the second is the BANNER string (the number 6 is this string's length) and after, a *terminating* element that contains 0 and a *null* C string:

Listing 8.10: kqf.o

```
.rodata:080BBAC4 kqfv133_c_0 dd 6     ; DATA XREF: .rodata:08019574
.rodata:080BBAC8             dd offset _2__STRING_5017_0 ; "BANNER"
.rodata:080BBACC             dd 0
.rodata:080BBAD0             dd offset _2__STRING_0_0
```

By joining data from both `kqfviw` and `kqfvip` tables, we can get the SQL statements which are executed when the user wants to query information from a specific *fixed view*.

So we can write an oracle tables[39] program, to gather all this information from Oracle RDBMS for Linux's object files. For `V$VERSION`, we find this:

Listing 8.11: Result of oracle tables

```
kqfviw_element.viewname: [V$VERSION] ?: 0x3 0x43 0x1 0xffffc085 0x4
kqfvip_element.statement: [select  BANNER from GV$VERSION where inst_id = USERENV('Instance')]
kqfvip_element.params:
[BANNER]
```

And:

Listing 8.12: Result of oracle tables

```
kqfviw_element.viewname: [GV$VERSION] ?: 0x3 0x26 0x2 0xffffc192 0x1
kqfvip_element.statement: [select inst_id, banner from x$version]
kqfvip_element.params:
[INST_ID] [BANNER]
```

The `GV$VERSION` *fixed view* is different from `V$VERSION` only in that it has one more field with the identifier *instance*.

Anyway, we are going to stick with the `X$VERSION` table. Just like any other X$-table, it is undocumented, however, we can query it:

[39] yurichev.com

```
SQL> select * from x$version;

ADDR           INDX    INST_ID
-------- ---------- ----------
BANNER
------------------------------

0DBAF574          0          1
Oracle Database 11g Enterprise Edition Release 11.2.0.1.0 - Production

...
```

This table has some additional fields, like ADDR and INDX.

While scrolling kqf.o in IDA we can spot another table that contains a pointer to the X$VERSION string, this is kqftab:

Listing 8.13: kqf.o

```
.rodata:0803CAC0      dd 9                    ; element number 0x1f6
.rodata:0803CAC4      dd offset _2__STRING_13113_0 ; "X$VERSION"
.rodata:0803CAC8      dd 4
.rodata:0803CACC      dd offset _2__STRING_13114_0 ; "kqvt"
.rodata:0803CAD0      dd 4
.rodata:0803CAD4      dd 4
.rodata:0803CAD8      dd 0
.rodata:0803CADC      dd 4
.rodata:0803CAE0      dd 0Ch
.rodata:0803CAE4      dd 0FFFFC075h
.rodata:0803CAE8      dd 3
.rodata:0803CAEC      dd 0
.rodata:0803CAF0      dd 7
.rodata:0803CAF4      dd offset _2__STRING_13115_0 ; "X$KQFSZ"
.rodata:0803CAF8      dd 5
.rodata:0803CAFC      dd offset _2__STRING_13116_0 ; "kqfsz"
.rodata:0803CB00      dd 1
.rodata:0803CB04      dd 38h
.rodata:0803CB08      dd 0
.rodata:0803CB0C      dd 7
.rodata:0803CB10      dd 0
.rodata:0803CB14      dd 0FFFFC09Dh
.rodata:0803CB18      dd 2
.rodata:0803CB1C      dd 0
```

There are a lot of references to the X$-table names, apparently, to all Oracle RDBMS 11.2 X$-tables. But again, we don't have enough information.

It's not clear what does the kqvt string stands for.

The kq prefix may mean *kernel* or *query*.

v apparently stands for *version* and t—*type*? Hard to say.

A table with a similar name can be found in kqf.o:

Listing 8.14: kqf.o

```
.rodata:0808C360 kqvt_c_0 kqftap_param <4, offset _2__STRING_19_0, 917h, 0, 0, 0, 4, 0, 0>
.rodata:0808C360                                   ; DATA XREF: .rodata:08042680
.rodata:0808C360                                   ; "ADDR"
.rodata:0808C384          kqftap_param <4, offset _2__STRING_20_0, 0B02h, 0, 0, 0, 4, 0, 0> ; "↙
    ↘ INDX"
.rodata:0808C3A8          kqftap_param <7, offset _2__STRING_21_0, 0B02h, 0, 0, 0, 4, 0, 0> ; "↙
    ↘ INST_ID"
.rodata:0808C3CC          kqftap_param <6, offset _2__STRING_5017_0, 601h, 0, 0, 0, 50h, 0, 0> ↙
    ↘ ; "BANNER"
.rodata:0808C3F0          kqftap_param <0, offset _2__STRING_0_0, 0, 0, 0, 0, 0, 0, 0>
```

It contains information about all fields in the X$VERSION table. The only reference to this table is in the kqftap table:

Listing 8.15: kqf.o

```
.rodata:08042680                 kqftap_element <0, offset kqvt_c_0, offset kqvrow, 0> ; ↙
    ↳ element 0x1f6
```

It is interesting that this element here is `0x1f6th` (502nd), just like the pointer to the `X$VERSION` string in the `kqftab` table.

Probably, the `kqftap` and `kqftab` tables complement each other, just like `kqfvip` and `kqfviw`.

We also see a pointer to the `kqvrow()` function. Finally, we got something useful!

So we will add these tables to our oracle tables[40] utility too. For `X$VERSION` we get:

Listing 8.16: Result of oracle tables

```
kqftab_element.name: [X$VERSION] ?: [kqvt] 0x4 0x4 0x4 0xc 0xffffc075 0x3
kqftap_param.name=[ADDR] ?: 0x917 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INDX] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INST_ID] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[BANNER] ?: 0x601 0x0 0x0 0x0 0x50 0x0 0x0
kqftap_element.fn1=kqvrow
kqftap_element.fn2=NULL
```

With the help of tracer, it is easy to check that this function is called 6 times in row (from the `qerfxFetch()` function) while querying the `X$VERSION` table.

Let's run tracer in cc mode (it comments each executed instruction):

```
tracer -a:oracle.exe bpf=oracle.exe!_kqvrow,trace:cc
```

```
_kqvrow_  proc near

var_7C    = byte ptr -7Ch
var_18    = dword ptr -18h
var_14    = dword ptr -14h
Dest      = dword ptr -10h
var_C     = dword ptr -0Ch
var_8     = dword ptr -8
var_4     = dword ptr -4
arg_8     = dword ptr  10h
arg_C     = dword ptr  14h
arg_14    = dword ptr  1Ch
arg_18    = dword ptr  20h

; FUNCTION CHUNK AT .text1:056C11A0 SIZE 00000049 BYTES

          push    ebp
          mov     ebp, esp
          sub     esp, 7Ch
          mov     eax, [ebp+arg_14] ; [EBP+1Ch]=1
          mov     ecx, TlsIndex   ; [69AEB08h]=0
          mov     edx, large fs:2Ch
          mov     edx, [edx+ecx*4] ; [EDX+ECX*4]=0xc98c938
          cmp     eax, 2          ; EAX=1
          mov     eax, [ebp+arg_8] ; [EBP+10h]=0xcdfe554
          jz      loc_2CE1288
          mov     ecx, [eax]      ; [EAX]=0..5
          mov     [ebp+var_4], edi ; EDI=0xc98c938

loc_2CE10F6: ; CODE XREF: _kqvrow_+10A
             ; _kqvrow_+1A9
          cmp     ecx, 5          ; ECX=0..5
          ja      loc_56C11C7
          mov     edi, [ebp+arg_18] ; [EBP+20h]=0
          mov     [ebp+var_14], edx ; EDX=0xc98c938
          mov     [ebp+var_8], ebx ; EBX=0
          mov     ebx, eax        ; EAX=0xcdfe554
          mov     [ebp+var_C], esi ; ESI=0xcdfe248
```

[40] yurichev.com

```
loc_2CE110D: ; CODE XREF: _kqvrow_+29E00E6
          mov     edx, ds:off_628B09C[ecx*4] ; [ECX*4+628B09Ch]=0x2ce1116, 0x2ce11ac, 0x2ce11db↙
    ↳ , 0x2ce11f6, 0x2ce1236, 0x2ce127a
          jmp     edx             ; EDX=0x2ce1116, 0x2ce11ac, 0x2ce11db, 0x2ce11f6, 0x2ce1236, ↙
    ↳ 0x2ce127a

loc_2CE1116: ; DATA XREF: .rdata:off_628B09C
          push    offset aXKqvvsnBuffer ; "x$kqvvsn buffer"
          mov     ecx, [ebp+arg_C] ; [EBP+14h]=0x8a172b4
          xor     edx, edx
          mov     esi, [ebp+var_14] ; [EBP-14h]=0xc98c938
          push    edx             ; EDX=0
          push    edx             ; EDX=0
          push    50h
          push    ecx             ; ECX=0x8a172b4
          push    dword ptr [esi+10494h] ; [ESI+10494h]=0xc98cd58
          call    _kghalf         ; tracing nested maximum level (1) reached, skipping this ↙
    ↳ CALL
          mov     esi, ds:__imp__vsnnum ; [59771A8h]=0x61bc49e0
          mov     [ebp+Dest], eax ; EAX=0xce2ffb0
          mov     [ebx+8], eax    ; EAX=0xce2ffb0
          mov     [ebx+4], eax    ; EAX=0xce2ffb0
          mov     edi, [esi]      ; [ESI]=0xb200100
          mov     esi, ds:__imp__vsnstr ; [597D6D4h]=0x65852148, "- Production"
          push    esi             ; ESI=0x65852148, "- Production"
          mov     ebx, edi        ; EDI=0xb200100
          shr     ebx, 18h        ; EBX=0xb200100
          mov     ecx, edi        ; EDI=0xb200100
          shr     ecx, 14h        ; ECX=0xb200100
          and     ecx, 0Fh        ; ECX=0xb2
          mov     edx, edi        ; EDI=0xb200100
          shr     edx, 0Ch        ; EDX=0xb200100
          movzx   edx, dl         ; DL=0
          mov     eax, edi        ; EDI=0xb200100
          shr     eax, 8          ; EAX=0xb200100
          and     eax, 0Fh        ; EAX=0xb2001
          and     edi, 0FFh       ; EDI=0xb200100
          push    edi             ; EDI=0
          mov     edi, [ebp+arg_18] ; [EBP+20h]=0
          push    eax             ; EAX=1
          mov     eax, ds:__imp__vsnban ; [597D6D8h]=0x65852100, "Oracle Database 11g ↙
    ↳ Enterprise Edition Release %d.%d.%d.%d.%d %s"
          push    edx             ; EDX=0
          push    ecx             ; ECX=2
          push    ebx             ; EBX=0xb
          mov     ebx, [ebp+arg_8] ; [EBP+10h]=0xcdfe554
          push    eax             ; EAX=0x65852100, "Oracle Database 11g Enterprise Edition ↙
    ↳ Release %d.%d.%d.%d.%d %s"
          mov     eax, [ebp+Dest] ; [EBP-10h]=0xce2ffb0
          push    eax             ; EAX=0xce2ffb0
          call    ds:__imp__sprintf ; op1=MSVCR80.dll!sprintf tracing nested maximum level (1) ↙
    ↳ reached, skipping this CALL
          add     esp, 38h
          mov     dword ptr [ebx], 1

loc_2CE1192: ; CODE XREF: _kqvrow_+FB
             ; _kqvrow_+128 ...
          test    edi, edi        ; EDI=0
          jnz     __VInfreq__kqvrow
          mov     esi, [ebp+var_C] ; [EBP-0Ch]=0xcdfe248
          mov     edi, [ebp+var_4] ; [EBP-4]=0xc98c938
          mov     eax, ebx        ; EBX=0xcdfe554
          mov     ebx, [ebp+var_8] ; [EBP-8]=0
          lea     eax, [eax+4]    ; [EAX+4]=0xce2ffb0, "NLSRTL Version 11.2.0.1.0 - Production↙
    ↳ ", "Oracle Database 11g Enterprise Edition Release 11.2.0.1.0 - Production", "PL/SQL ↙
    ↳ Release 11.2.0.1.0 - Production", "TNS for 32-bit Windows: Version 11.2.0.1.0 - ↙
    ↳ Production"

loc_2CE11A8: ; CODE XREF: _kqvrow_+29E00F6
          mov     esp, ebp
```

```
        pop     ebp
        retn                    ; EAX=0xcdfe558

loc_2CE11AC: ; DATA XREF: .rdata:0628B0A0
        mov     edx, [ebx+8]    ; [EBX+8]=0xce2ffb0, "Oracle Database 11g Enterprise Edition ↙
    ↳ Release 11.2.0.1.0 - Production"
        mov     dword ptr [ebx], 2
        mov     [ebx+4], edx    ; EDX=0xce2ffb0, "Oracle Database 11g Enterprise Edition ↙
    ↳ Release 11.2.0.1.0 - Production"
        push    edx             ; EDX=0xce2ffb0, "Oracle Database 11g Enterprise Edition ↙
    ↳ Release 11.2.0.1.0 - Production"
        call    _kkxvsn         ; tracing nested maximum level (1) reached, skipping this ↙
    ↳ CALL
        pop     ecx
        mov     edx, [ebx+4]    ; [EBX+4]=0xce2ffb0, "PL/SQL Release 11.2.0.1.0 - Production"
        movzx   ecx, byte ptr [edx] ; [EDX]=0x50
        test    ecx, ecx        ; ECX=0x50
        jnz     short loc_2CE1192
        mov     edx, [ebp+var_14]
        mov     esi, [ebp+var_C]
        mov     eax, ebx
        mov     ebx, [ebp+var_8]
        mov     ecx, [eax]
        jmp     loc_2CE10F6

loc_2CE11DB: ; DATA XREF: .rdata:0628B0A4
        push    0
        push    50h
        mov     edx, [ebx+8]    ; [EBX+8]=0xce2ffb0, "PL/SQL Release 11.2.0.1.0 - Production"
        mov     [ebx+4], edx    ; EDX=0xce2ffb0, "PL/SQL Release 11.2.0.1.0 - Production"
        push    edx             ; EDX=0xce2ffb0, "PL/SQL Release 11.2.0.1.0 - Production"
        call    _lmxver         ; tracing nested maximum level (1) reached, skipping this ↙
    ↳ CALL
        add     esp, 0Ch
        mov     dword ptr [ebx], 3
        jmp     short loc_2CE1192

loc_2CE11F6: ; DATA XREF: .rdata:0628B0A8
        mov     edx, [ebx+8]    ; [EBX+8]=0xce2ffb0
        mov     [ebp+var_18], 50h
        mov     [ebx+4], edx    ; EDX=0xce2ffb0
        push    0
        call    _npinli         ; tracing nested maximum level (1) reached, skipping this ↙
    ↳ CALL
        pop     ecx
        test    eax, eax        ; EAX=0
        jnz     loc_56C11DA
        mov     ecx, [ebp+var_14] ; [EBP-14h]=0xc98c938
        lea     edx, [ebp+var_18] ; [EBP-18h]=0x50
        push    edx             ; EDX=0xd76c93c
        push    dword ptr [ebx+8] ; [EBX+8]=0xce2ffb0
        push    dword ptr [ecx+13278h] ; [ECX+13278h]=0xacce190
        call    _nrtnsvrs       ; tracing nested maximum level (1) reached, skipping this ↙
    ↳ CALL
        add     esp, 0Ch

loc_2CE122B: ; CODE XREF: _kqvrow_+29E0118
        mov     dword ptr [ebx], 4
        jmp     loc_2CE1192

loc_2CE1236: ; DATA XREF: .rdata:0628B0AC
        lea     edx, [ebp+var_7C] ; [EBP-7Ch]=1
        push    edx             ; EDX=0xd76c8d8
        push    0
        mov     esi, [ebx+8]    ; [EBX+8]=0xce2ffb0, "TNS for 32-bit Windows: Version ↙
    ↳ 11.2.0.1.0 - Production"
        mov     [ebx+4], esi    ; ESI=0xce2ffb0, "TNS for 32-bit Windows: Version 11.2.0.1.0 ↙
    ↳ - Production"
        mov     ecx, 50h
        mov     [ebp+var_18], ecx ; ECX=0x50
```

```
        push    ecx             ; ECX=0x50
        push    esi             ; ESI=0xce2ffb0, "TNS for 32-bit Windows: Version 11.2.0.1.0 ↙
    ↘ - Production"
        call    _lxvers         ; tracing nested maximum level (1) reached, skipping this ↙
    ↘ CALL
        add     esp, 10h
        mov     edx, [ebp+var_18] ; [EBP-18h]=0x50
        mov     dword ptr [ebx], 5
        test    edx, edx        ; EDX=0x50
        jnz     loc_2CE1192
        mov     edx, [ebp+var_14]
        mov     esi, [ebp+var_C]
        mov     eax, ebx
        mov     ebx, [ebp+var_8]
        mov     ecx, 5
        jmp     loc_2CE10F6

loc_2CE127A: ; DATA XREF: .rdata:0628B0B0
        mov     edx, [ebp+var_14] ; [EBP-14h]=0xc98c938
        mov     esi, [ebp+var_C] ; [EBP-0Ch]=0xcdfe248
        mov     edi, [ebp+var_4] ; [EBP-4]=0xc98c938
        mov     eax, ebx        ; EBX=0xcdfe554
        mov     ebx, [ebp+var_8] ; [EBP-8]=0

loc_2CE1288: ; CODE XREF: _kqvrow_+1F
        mov     eax, [eax+8]    ; [EAX+8]=0xce2ffb0, "NLSRTL Version 11.2.0.1.0 - Production"
        test    eax, eax        ; EAX=0xce2ffb0, "NLSRTL Version 11.2.0.1.0 - Production"
        jz      short loc_2CE12A7
        push    offset aXKqvvsnBuffer ; "x$kqvvsn buffer"
        push    eax             ; EAX=0xce2ffb0, "NLSRTL Version 11.2.0.1.0 - Production"
        mov     eax, [ebp+arg_C] ; [EBP+14h]=0x8a172b4
        push    eax             ; EAX=0x8a172b4
        push    dword ptr [edx+10494h] ; [EDX+10494h]=0xc98cd58
        call    _kghfrf         ; tracing nested maximum level (1) reached, skipping this ↙
    ↘ CALL
        add     esp, 10h

loc_2CE12A7: ; CODE XREF: _kqvrow_+1C1
        xor     eax, eax
        mov     esp, ebp
        pop     ebp
        retn                    ; EAX=0
_kqvrow_  endp
```

Now it is easy to see that the row number is passed from outside. The function returns the string, constructing it as follows:

String 1	Using vsnstr, vsnnum, vsnban global variables. Calls sprintf().
String 2	Calls kkxvsn().
String 3	Calls lmxver().
String 4	Calls npinli(), nrtnsvrs().
String 5	Calls lxvers().

That's how the corresponding functions are called for determining each module's version.

8.11.2 X$KSMLRU table in Oracle RDBMS

There is a mention of a special table in the *Diagnosing and Resolving Error ORA-04031 on the Shared Pool or Other Memory Pools [Video] [ID 146599.1]* note:

> There is a fixed table called X$KSMLRU that tracks allocations in the shared pool that cause other objects in the shared pool to be aged out. This fixed table can be used to identify what is causing the large allocation.
>
> If many objects are being periodically flushed from the shared pool then this will cause response time problems and will likely cause library cache latch contention problems when

> the objects are reloaded into the shared pool.
> One unusual thing about the X$KSMLRU fixed table is that the contents of the fixed table are erased whenever someone selects from the fixed table. This is done since the fixed table stores only the largest allocations that have occurred. The values are reset after being selected so that subsequent large allocations can be noted even if they were not quite as large as others that occurred previously. Because of this resetting, the output of selecting from this table should be carefully kept since it cannot be retrieved back after the query is issued.

However, as it can be easily checked, the contents of this table are cleared each time it's queried. Are we able to find why? Let's get back to tables we already know: `kqftab` and `kqftap` which were generated with oracle tables[41]'s help, that has all information about the X$-tables. We can see here that the `ksmlrs()` function is called to prepare this table's elements:

Listing 8.17: Result of oracle tables

```
kqftab_element.name: [X$KSMLRU] ?: [ksmlr] 0x4 0x64 0x11 0xc 0xffffc0bb 0x5
kqftap_param.name=[ADDR] ?: 0x917 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INDX] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INST_ID] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[KSMLRIDX] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[KSMLRDUR] ?: 0xb02 0x0 0x0 0x0 0x4 0x4 0x0
kqftap_param.name=[KSMLRSHRPOOL] ?: 0xb02 0x0 0x0 0x0 0x4 0x8 0x0
kqftap_param.name=[KSMLRCOM] ?: 0x501 0x0 0x0 0x0 0x14 0xc 0x0
kqftap_param.name=[KSMLRSIZ] ?: 0x2 0x0 0x0 0x0 0x4 0x20 0x0
kqftap_param.name=[KSMLRNUM] ?: 0x2 0x0 0x0 0x0 0x4 0x24 0x0
kqftap_param.name=[KSMLRHON] ?: 0x501 0x0 0x0 0x0 0x20 0x28 0x0
kqftap_param.name=[KSMLROHV] ?: 0xb02 0x0 0x0 0x0 0x4 0x48 0x0
kqftap_param.name=[KSMLRSES] ?: 0x17 0x0 0x0 0x0 0x4 0x4c 0x0
kqftap_param.name=[KSMLRADU] ?: 0x2 0x0 0x0 0x0 0x4 0x50 0x0
kqftap_param.name=[KSMLRNID] ?: 0x2 0x0 0x0 0x0 0x4 0x54 0x0
kqftap_param.name=[KSMLRNSD] ?: 0x2 0x0 0x0 0x0 0x4 0x58 0x0
kqftap_param.name=[KSMLRNCD] ?: 0x2 0x0 0x0 0x0 0x4 0x5c 0x0
kqftap_param.name=[KSMLRNED] ?: 0x2 0x0 0x0 0x0 0x4 0x60 0x0
kqftap_element.fn1=ksmlrs
kqftap_element.fn2=NULL
```

Indeed, with tracer's help it is easy to see that this function is called each time we query the X$KSMLRU table.

Here we see a references to the `ksmsplu_sp()` and `ksmsplu_jp()` functions, each of them calls the `ksmsplu()` at the end. At the end of the `ksmsplu()` function we see a call to `memset()`:

Listing 8.18: ksm.o

```
...

.text:00434C50 loc_434C50:    ; DATA XREF: .rdata:off_5E50EA8
.text:00434C50         mov     edx, [ebp-4]
.text:00434C53         mov     [eax], esi
.text:00434C55         mov     esi, [edi]
.text:00434C57         mov     [eax+4], esi
.text:00434C5A         mov     [edi], eax
.text:00434C5C         add     edx, 1
.text:00434C5F         mov     [ebp-4], edx
.text:00434C62         jnz     loc_434B7D
.text:00434C68         mov     ecx, [ebp+14h]
.text:00434C6B         mov     ebx, [ebp-10h]
.text:00434C6E         mov     esi, [ebp-0Ch]
.text:00434C71         mov     edi, [ebp-8]
.text:00434C74         lea     eax, [ecx+8Ch]
.text:00434C7A         push    370h            ; Size
.text:00434C7F         push    0               ; Val
.text:00434C81         push    eax             ; Dst
.text:00434C82         call    __intel_fast_memset
.text:00434C87         add     esp, 0Ch
.text:00434C8A         mov     esp, ebp
```

[41] yurichev.com

```
.text:00434C8C         pop     ebp
.text:00434C8D         retn
.text:00434C8D _ksmsplu  endp
```

Constructions like `memset (block, 0, size)` are often used just to zero memory block. What if we take a risk, block the `memset()` call and see what happens?

Let's run tracer with the following options: set breakpoint at `0x434C7A` (the point where the arguments to `memset()` are to be passed), so that tracer will set program counter EIP to the point where the arguments passed to `memset()` are to be cleared (at `0x434C8A`) It can be said that we just simulate an unconditional jump from address `0x434C7A` to `0x434C8A`.

```
tracer -a:oracle.exe bpx=oracle.exe!0x00434C7A,set(eip,0x00434C8A)
```

(Important: all these addresses are valid only for the win32 version of Oracle RDBMS 11.2)

Indeed, now we can query the X$KSMLRU table as many times as we want and it is not being cleared anymore!

~~Do not try this at home ("MythBusters")~~ Do not try this on your production servers.

It is probably not a very useful or desired system behavior, but as an experiment for locating a piece of code that we need, it perfectly suits our needs!

8.11.3 V$TIMER table in Oracle RDBMS

V$TIMER is another *fixed view* that reflects a rapidly changing value:

> V$TIMER displays the elapsed time in hundredths of a second. Time is measured since the beginning of the epoch, which is operating system specific, and wraps around to 0 again whenever the value overflows four bytes (roughly 497 days).

(From Oracle RDBMS documentation [42])

It is interesting that the periods are different for Oracle for win32 and for Linux. Will we be able to find the function that generates this value?

As we can see, this information is finally taken from the X$KSUTM table.

```
SQL> select * from V$FIXED_VIEW_DEFINITION where view_name='V$TIMER';

VIEW_NAME
------------------------------
VIEW_DEFINITION
------------------------------

V$TIMER
select  HSECS from GV$TIMER where inst_id = USERENV('Instance')

SQL> select * from V$FIXED_VIEW_DEFINITION where view_name='GV$TIMER';

VIEW_NAME
------------------------------
VIEW_DEFINITION
------------------------------

GV$TIMER
select inst_id,ksutmtim from x$ksutm
```

Now we are stuck in a small problem, there are no references to value generating function(s) in the tables `kqftab`/`kqftap`:

Listing 8.19: Result of oracle tables

```
kqftab_element.name: [X$KSUTM] ?: [ksutm] 0x1 0x4 0x4 0x0 0xffffc09b 0x3
kqftap_param.name=[ADDR] ?: 0x10917 0x0 0x0 0x0 0x4 0x0 0x0
```

[42] http://go.yurichev.com/17088

```
kqftap_param.name=[INDX] ?: 0x20b02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INST_ID] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[KSUTMTIM] ?: 0x1302 0x0 0x0 0x0 0x4 0x0 0x1e
kqftap_element.fn1=NULL
kqftap_element.fn2=NULL
```

When we try to find the string KSUTMTIM, we see it in this function:

```
kqfd_DRN_ksutm_c proc near    ; DATA XREF: .rodata:0805B4E8

arg_0   = dword ptr  8
arg_8   = dword ptr  10h
arg_C   = dword ptr  14h

        push    ebp
        mov     ebp, esp
        push    [ebp+arg_C]
        push    offset ksugtm
        push    offset _2__STRING_1263_0 ; "KSUTMTIM"
        push    [ebp+arg_8]
        push    [ebp+arg_0]
        call    kqfd_cfui_drain
        add     esp, 14h
        mov     esp, ebp
        pop     ebp
        retn
kqfd_DRN_ksutm_c endp
```

The `kqfd_DRN_ksutm_c()` function is mentioned in the `kqfd_tab_registry_0` table:

```
dd offset _2__STRING_62_0 ; "X$KSUTM"
dd offset kqfd_OPN_ksutm_c
dd offset kqfd_tabl_fetch
dd 0
dd 0
dd offset kqfd_DRN_ksutm_c
```

There is a function `ksugtm()` referenced here. Let's see what's in it (Linux x86):

Listing 8.20: ksu.o

```
ksugtm  proc near

var_1C  = byte ptr -1Ch
arg_4   = dword ptr  0Ch

        push    ebp
        mov     ebp, esp
        sub     esp, 1Ch
        lea     eax, [ebp+var_1C]
        push    eax
        call    slgcs
        pop     ecx
        mov     edx, [ebp+arg_4]
        mov     [edx], eax
        mov     eax, 4
        mov     esp, ebp
        pop     ebp
        retn
ksugtm  endp
```

The code in the win32 version is almost the same.

Is this the function we are looking for? Let's see:

```
tracer -a:oracle.exe bpf=oracle.exe!_ksugtm,args:2,dump_args:0x4
```

Let's try again:

```
SQL> select * from V$TIMER;

     HSECS
----------
  27294929

SQL> select * from V$TIMER;

     HSECS
----------
  27295006

SQL> select * from V$TIMER;

     HSECS
----------
  27295167
```

Listing 8.21: tracer output

```
TID=2428|(0) oracle.exe!_ksugtm (0x0, 0xd76c5f0) (called from oracle.exe!__VInfreq__qerfxFetch↙
    ↳ +0xfad (0x56bb6d5))
Argument 2/2
0D76C5F0: 38 C9                                           "8.              "
TID=2428|(0) oracle.exe!_ksugtm () -> 0x4 (0x4)
Argument 2/2 difference
00000000: D1 7C A0 01                                     ".|..            "
TID=2428|(0) oracle.exe!_ksugtm (0x0, 0xd76c5f0) (called from oracle.exe!__VInfreq__qerfxFetch↙
    ↳ +0xfad (0x56bb6d5))
Argument 2/2
0D76C5F0: 38 C9                                           "8.              "
TID=2428|(0) oracle.exe!_ksugtm () -> 0x4 (0x4)
Argument 2/2 difference
00000000: 1E 7D A0 01                                     ".}..            "
TID=2428|(0) oracle.exe!_ksugtm (0x0, 0xd76c5f0) (called from oracle.exe!__VInfreq__qerfxFetch↙
    ↳ +0xfad (0x56bb6d5))
Argument 2/2
0D76C5F0: 38 C9                                           "8.              "
TID=2428|(0) oracle.exe!_ksugtm () -> 0x4 (0x4)
Argument 2/2 difference
00000000: BF 7D A0 01                                     ".}..            "
```

Indeed—the value is the same we see in SQL*Plus and it is returned via the second argument.

Let's see what is in slgcs() (Linux x86):

```
slgcs   proc near

var_4   = dword ptr -4
arg_0   = dword ptr  8

        push    ebp
        mov     ebp, esp
        push    esi
        mov     [ebp+var_4], ebx
        mov     eax, [ebp+arg_0]
        call    $+5
        pop     ebx
        nop                     ; PIC mode
        mov     ebx, offset _GLOBAL_OFFSET_TABLE_
        mov     dword ptr [eax], 0
        call    sltrgatime64    ; PIC mode
        push    0
        push    0Ah
        push    edx
        push    eax
        call    __udivdi3       ; PIC mode
        mov     ebx, [ebp+var_4]
        add     esp, 10h
        mov     esp, ebp
```

```
        pop     ebp
        retn
slgcs   endp
```

(it is just a call to `sltrgatime64()`

and division of its result by 10 (3.9 on page 497))

And win32-version:

```
_slgcs  proc near     ; CODE XREF: _dbgefgHtElResetCount+15
                      ; _dbgerRunActions+1528
        db      66h
        nop
        push    ebp
        mov     ebp, esp
        mov     eax, [ebp+8]
        mov     dword ptr [eax], 0
        call    ds:__imp__GetTickCount@0 ; GetTickCount()
        mov     edx, eax
        mov     eax, 0CCCCCCCDh
        mul     edx
        shr     edx, 3
        mov     eax, edx
        mov     esp, ebp
        pop     ebp
        retn
_slgcs  endp
```

It is just the result of `GetTickCount()` [43] divided by 10 (3.9 on page 497).

Voilà! That's why the win32 version and the Linux x86 version show different results, because they are generated by different OS functions.

Drain apparently implies *connecting* a specific table column to a specific function.

We will add support of the table `kqfd_tab_registry_0` to oracle tables[44], now we can see how the table column's variables are *connected* to a specific functions:

```
[X$KSUTM] [kqfd_OPN_ksutm_c] [kqfd_tabl_fetch] [NULL] [NULL] [kqfd_DRN_ksutm_c]
[X$KSUSGIF] [kqfd_OPN_ksusg_c] [kqfd_tabl_fetch] [NULL] [NULL] [kqfd_DRN_ksusg_c]
```

OPN, apparently stands for, *open*, and *DRN*, apparently, for *drain*.

8.12 Handwritten assembly code

8.12.1 EICAR test file

This .COM-file is intended for testing antivirus software, it is possible to run in in MS-DOS and it prints this string: "EICAR-STANDARD-ANTIVIRUS-TEST-FILE!" [45].

Its important property is that it's consists entirely of printable ASCII-symbols, which, in turn, makes it possible to create it in any text editor:

```
X5O!P%@AP[4\PZX54(P^)7CC)7}$EICAR-STANDARD-ANTIVIRUS-TEST-FILE!$H+H*
```

Let's decompile it:

```
; initial conditions: SP=0FFFEh, SS:[SP]=0
0100 58           pop     ax
; AX=0, SP=0
0101 35 4F 21     xor     ax, 214Fh
; AX = 214Fh and SP = 0
0104 50           push    ax
```

[43] MSDN
[44] yurichev.com
[45] wikipedia

```
; AX = 214Fh, SP = FFFEh and SS:[FFFE] = 214Fh
0105 25 40 41      and     ax, 4140h
; AX = 140h, SP = FFFEh and SS:[FFFE] = 214Fh
0108 50            push    ax
; AX = 140h, SP = FFFCh, SS:[FFFC] = 140h and SS:[FFFE] = 214Fh
0109 5B            pop     bx
; AX = 140h, BX = 140h, SP = FFFEh and SS:[FFFE] = 214Fh
010A 34 5C         xor     al, 5Ch
; AX = 11Ch, BX = 140h, SP = FFFEh and SS:[FFFE] = 214Fh
010C 50            push    ax
010D 5A            pop     dx
; AX = 11Ch, BX = 140h, DX = 11Ch, SP = FFFEh and SS:[FFFE] = 214Fh
010E 58            pop     ax
; AX = 214Fh, BX = 140h, DX = 11Ch and SP = 0
010F 35 34 28      xor     ax, 2834h
; AX = 97Bh, BX = 140h, DX = 11Ch and SP = 0
0112 50            push    ax
0113 5E            pop     si
; AX = 97Bh, BX = 140h, DX = 11Ch, SI = 97Bh and SP = 0
0114 29 37         sub     [bx], si
0116 43            inc     bx
0117 43            inc     bx
0118 29 37         sub     [bx], si
011A 7D 24         jge     short near ptr word_10140
011C 45 49 43 ...  db 'EICAR-STANDARD-ANTIVIRUS-TEST-FILE!$'
0140 48 2B   word_10140  dw 2B48h  ; CD 21 (INT 21) will be here
0142 48 2A               dw 2A48h  ; CD 20 (INT 20) will be here
0144 0D                  db  0Dh
0145 0A                  db  0Ah
```

We will add comments about the registers and stack after each instruction.

Essentially, all these instructions are here only to execute this code:

```
B4 09     MOV AH, 9
BA 1C 01  MOV DX, 11Ch
CD 21     INT 21h
CD 20     INT 20h
```

INT 21h with 9th function (passed in AH) just prints a string, the address of which is passed in DS:DX. By the way, the string has to be terminated with the '$' sign. Apparently, it's inherited from CP/M and this function was left in DOS for compatibility. INT 20h exits to DOS.

But as we can see, these instruction's opcodes are not strictly printable. So the main part of EICAR file is:

- preparing the register (AH and DX) values that we need;
- preparing INT 21 and INT 20 opcodes in memory;
- executing INT 21 and INT 20.

By the way, this technique is widely used in shellcode construction, when one have to pass x86 code in string form.

Here is also a list of all x86 instructions which have printable opcodes: .1.6 on page 1037.

8.13 Demos

Demos (or demomaking) were an excellent exercise in mathematics, computer graphics programming and very tight x86 hand coding.

8.13.1 10 PRINT CHR$(205.5+RND(1)); : GOTO 10

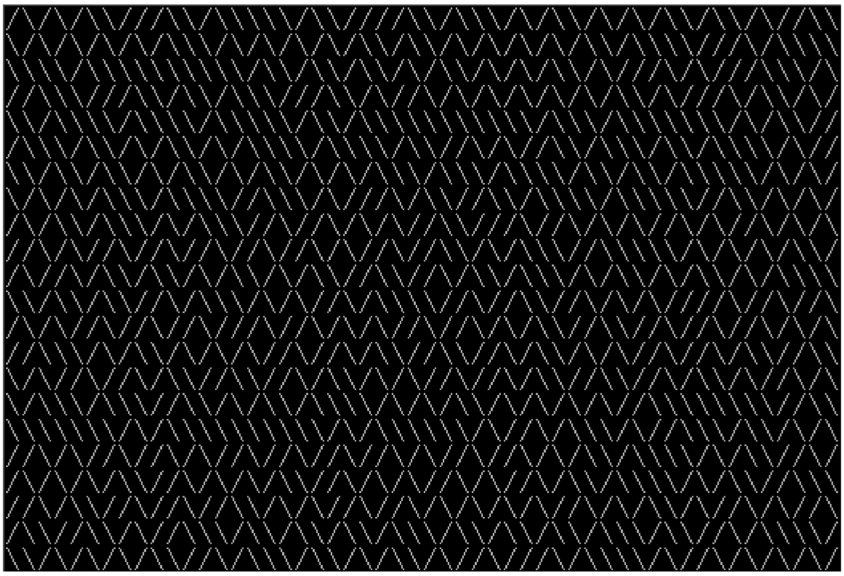
All examples here are MS-DOS .COM files.

In [Nick Montfort et al, *10 PRINT CHR$(205.5+RND(1)); : GOTO 10*, (The MIT Press:2012)] [46]

[46] Also available as http://go.yurichev.com/17286

we can read about one of the most simple possible random maze generators.

It just prints a slash or backslash characters randomly and endlessly, resulting in something like this:



There are a few known implementations for 16-bit x86.

Trixter's 42 byte version

The listing was taken from his website[47], but the comments are mine.

```
00000000: B001          mov         al,1        ; set 40x25 video mode
00000002: CD10          int         010
00000004: 30FF          xor         bh,bh       ; set video page for int 10h call
00000006: B9D007        mov         cx,007D0    ; 2000 characters to output
00000009: 31C0          xor         ax,ax
0000000B: 9C            pushf                   ; push flags
; get random value from timer chip
0000000C: FA            cli                     ; disable interrupts
0000000D: E643          out         043,al      ; write 0 to port 43h
; read 16-bit value from port 40h
0000000F: E440          in          al,040
00000011: 88C4          mov         ah,al
00000013: E440          in          al,040
00000015: 9D            popf                    ; enable interrupts by restoring IF flag
00000016: 86C4          xchg        ah,al
; here we have 16-bit pseudorandom value
00000018: D1E8          shr         ax,1
0000001A: D1E8          shr         ax,1
; CF currently have second bit from the value
0000001C: B05C          mov         al,05C ;'\'
; if CF=1, skip the next instruction
0000001E: 7202          jc          000000022
; if CF=0, reload AL register with another character
00000020: B02F          mov         al,02F ;'/'
; output character
00000022: B40E          mov         ah,00E
00000024: CD10          int         010
00000026: E2E1          loop        000000009 ; loop 2000 times
00000028: CD20          int         020       ; exit to DOS
```

The pseudo-random value here is in fact the time that has passed from the system's boot, taken from the 8253 time chip, the value increases by one 18.2 times per second.

By writing zero to port 43h, we send the command "select counter 0", "counter latch", "binary counter" (not a BCD value).

[47] http://go.yurichev.com/17305

The interrupts are enabled back with the POPF instruction, which restores the IF flag as well.

It is not possible to use the IN instruction with registers other than AL, hence the shuffling.

My attempt to reduce Trixter's version: 27 bytes

We can say that since we use the timer not to get a precise time value, but a pseudo-random one, we do not need to spend time (and code) to disable the interrupts.

Another thing we can say is that we need only one bit from the low 8-bit part, so let's read only it.

We can reduced the code slightly and we've got 27 bytes:

```
00000000: B9D007   mov    cx,007D0 ; limit output to 2000 characters
00000003: 31C0     xor    ax,ax    ; command to timer chip
00000005: E643     out    043,al
00000007: E440     in     al,040   ; read 8-bit of timer
00000009: D1E8     shr    ax,1     ; get second bit to CF flag
0000000B: D1E8     shr    ax,1
0000000D: B05C     mov    al,05C   ; prepare '\'
0000000F: 7202     jc     000000013
00000011: B02F     mov    al,02F   ; prepare '/'
; output character to screen
00000013: B40E     mov    ah,00E
00000015: CD10     int    010
00000017: E2EA     loop   000000003
; exit to DOS
00000019: CD20     int    020
```

Taking random memory garbage as a source of randomness

Since it is MS-DOS, there is no memory protection at all, we can read from whatever address we want. Even more than that: a simple LODSB instruction reads a byte from the DS:SI address, but it's not a problem if the registers' values are not set up, let it read 1) random bytes; 2) from a random place in memory!

It is suggested in Trixter's webpage[48]to use LODSB without any setup.

It is also suggested that the SCASB

instruction can be used instead, because it sets a flag according to the byte it reads.

Another idea to minimize the code is to use the INT 29h DOS syscall, which just prints the character stored in the AL register.

That is what Peter Ferrie and Andrey "herm1t" Baranovich did (11 and 10 bytes) [49]:

Listing 8.22: Andrey "herm1t" Baranovich: 11 bytes

```
00000000: B05C       mov        al,05C    ;'\'
; read AL byte from random place of memory
00000002: AE         scasb
; PF = parity (AL - random_memory_byte) = parity (5Ch - random_memory_byte)
00000003: 7A02       jp         000000007
00000005: B02F       mov        al,02F    ;'/'
00000007: CD29       int        029       ; output AL to screen
00000009: EBF5       jmp        000000000 ; loop endlessly
```

SCASB also uses the value in the AL register, it subtract a random memory byte's value from the 5Ch value in AL. JP is a rare instruction, here it used for checking the parity flag (PF), which is generated by the formulae in the listing. As a consequence, the output character is determined not by some bit in a random memory byte, but by a sum of bits, this (hopefully) makes the result more distributed.

It is possible to make this even shorter by using the undocumented x86 instruction SALC (AKA SETALC) ("Set AL CF"). It was introduced in the NEC V20 CPU and sets AL to 0xFF if CF is 1 or to 0 if otherwise.

[48] http://go.yurichev.com/17305
[49] http://go.yurichev.com/17087

Listing 8.23: Peter Ferrie: 10 bytes

```
; AL is random at this point
00000000: AE         scasb
; CF is set according subtracting random memory byte from AL.
; so it is somewhat random at this point
00000001: D6         setalc
; AL is set to 0xFF if CF=1 or to 0 if otherwise
00000002: 242D       and         al,02D ;'-'
; AL here is 0x2D or 0
00000004: 042F       add         al,02F ;'/'
; AL here is 0x5C or 0x2F
00000006: CD29       int         029       ; output AL to screen
00000008: EBF6       jmps        000000000 ; loop endlessly
```

So it is possible to get rid of conditional jumps at all. The ASCII code of backslash ("\") is 0x5C and 0x2F for slash ("/"). So we have to convert one (pseudo-random) bit in the CF flag to a value of 0x5C or 0x2F.

This is done easily: by AND-ing all bits in AL (where all 8 bits are set or cleared) with 0x2D we have just 0 or 0x2D.

By adding 0x2F to this value, we get 0x5C or 0x2F.

Then we just output it to the screen.

Conclusion

It is also worth mentioning that the result may be different in DOSBox, Windows NT and even MS-DOS,

due to different conditions: the timer chip can be emulated differently and the initial register contents may be different as well.

8.13.2 Mandelbrot set

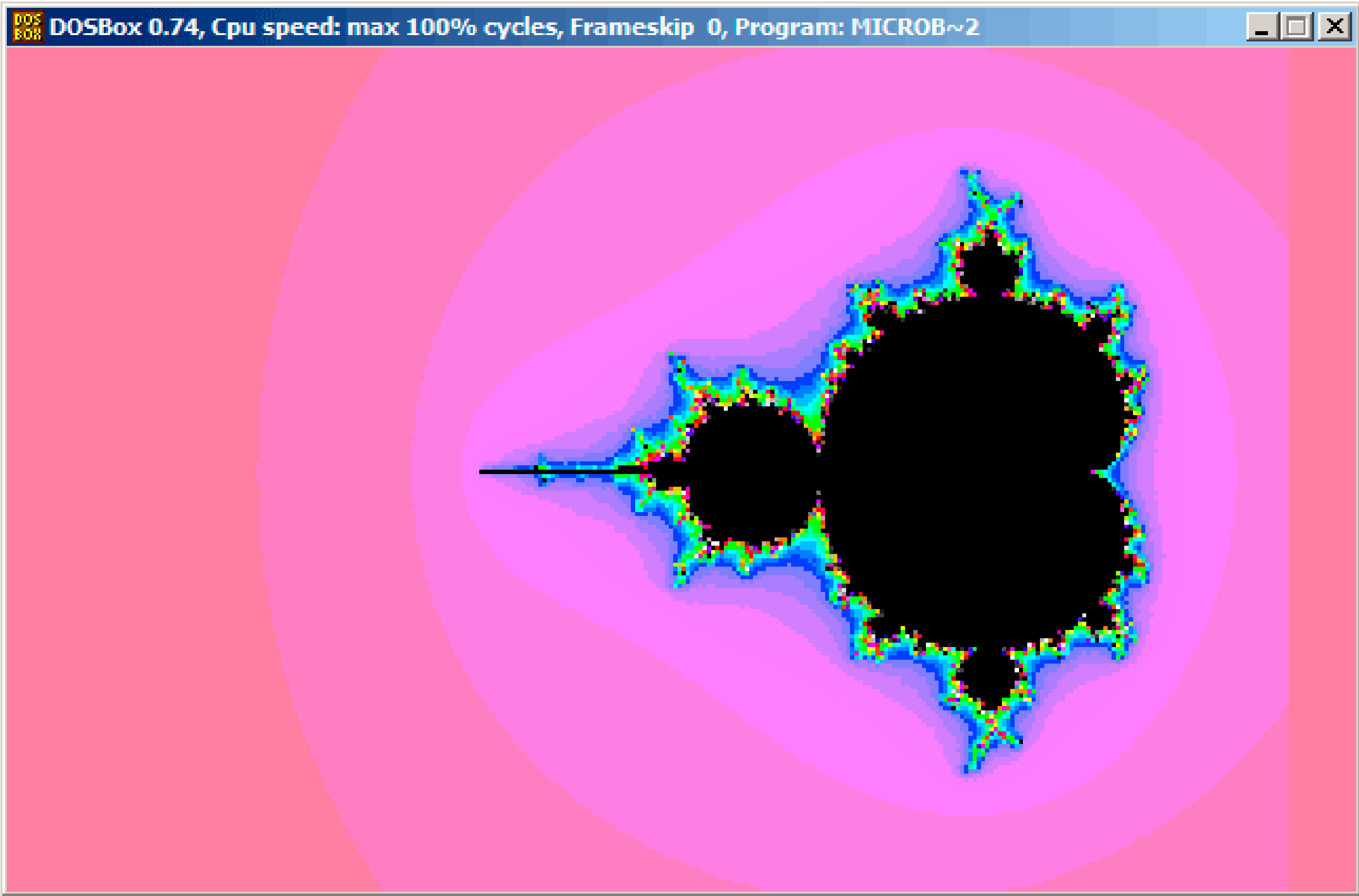
> You know, if you magnify the coastline, it still looks like a coastline, and a lot of other things have this property. Nature has recursive algorithms that it uses to generate clouds and Swiss cheese and things like that.
>
> Donald Knuth, interview (1993)

Mandelbrot set is a fractal, which exhibits self-similarity.

When you increase scale, you see that this characteristic pattern repeating infinitely.

Here is a demo[50] written by "Sir_Lagsalot" in 2009, that draws the Mandelbrot set, which is just a x86 program with executable file size of only 64 bytes. There are only 30 16-bit x86 instructions.

Here it is what it draws:



Let's try to understand how it works.

Theory

A word about complex numbers

A complex number is a number that consists of two parts—real (Re) and imaginary (Im).

The complex plane is a two-dimensional plane where any complex number can be placed: the real part is one coordinate and the imaginary part is the other.

Some basic rules we have to keep in mind:

- Addition: $(a + bi) + (c + di) = (a + c) + (b + d)i$

  In other words:

[50] Download it here,

Re(sum) = Re(a) + Re(b)

Im(sum) = Im(a) + Im(b)

- Multiplication: $(a+bi)(c+di) = (ac-bd) + (bc+ad)i$

  In other words:

  Re$(product)$ = Re$(a)\cdot$ Re(c) − Re$(b)\cdot$ Re(d)

  Im$(product)$ = Im$(b)\cdot$ Im(c) + Im$(a)\cdot$ Im(d)

- Square: $(a+bi)^2 = (a+bi)(a+bi) = (a^2-b^2) + (2ab)i$

  In other words:

  Re$(square)$ = Re$(a)^2$ − Im$(a)^2$

  Im$(square) = 2\cdot$ Re$(a)\cdot$ Im(a)

How to draw the Mandelbrot set

The Mandelbrot set is a set of points for which the $z_{n+1} = {z_n}^2 + c$ recursive sequence (where z and c are complex numbers and c is the starting value) does not approach infinity.

In plain English language:

- Enumerate all points on screen.
- Check if the specific point is in the Mandelbrot set.
- Here is how to check it:
  - Represent the point as a complex number.
  - Calculate the square of it.
  - Add the starting value of the point to it.
  - Does it go off limits? If yes, break.
  - Move the point to the new place at the coordinates we just calculated.
  - Repeat all this for some reasonable number of iterations.
- The point is still in limits? Then draw the point.
- The point has eventually gone off limits?
  - (For a black-white image) do not draw anything.
  - (For a colored image) transform the number of iterations to some color. So the color shows the speed with which point has gone off limits.

Here is Pythonesque algorithm for both complex and integer number representations:

Listing 8.24: For complex numbers

```
def check_if_is_in_set(P):
    P_start=P
    iterations=0

    while True:
        if (P>bounds):
            break
        P=P^2+P_start
        if iterations > max_iterations:
            break
        iterations++

    return iterations

# black-white
for each point on screen P:
    if check_if_is_in_set (P) < max_iterations:
        draw point
```

```
# colored
for each point on screen P:
    iterations = if check_if_is_in_set (P)
    map iterations to color
    draw color point
```

The integer version is where the operations on complex numbers are replaced with integer operations according to the rules which were explained above.

Listing 8.25: For integer numbers

```
def check_if_is_in_set(X, Y):
    X_start=X
    Y_start=Y
    iterations=0

    while True:
        if (X^2 + Y^2 > bounds):
            break
        new_X=X^2 - Y^2 + X_start
        new_Y=2*X*Y + Y_start
        if iterations > max_iterations:
            break
        iterations++

    return iterations

# black-white
for X = min_X to max_X:
    for Y = min_Y to max_Y:
        if check_if_is_in_set (X,Y) < max_iterations:
            draw point at X, Y

# colored
for X = min_X to max_X:
    for Y = min_Y to max_Y:
        iterations = if check_if_is_in_set (X,Y)
        map iterations to color
        draw color point at X,Y
```

Here is also a C# source which is present in the Wikipedia article[51], but we'll modify it so it will print the iteration numbers instead of some symbol [52]:

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;

namespace Mnoj
{
    class Program
    {
        static void Main(string[] args)
        {
            double realCoord, imagCoord;
            double realTemp, imagTemp, realTemp2, arg;
            int iterations;
            for (imagCoord = 1.2; imagCoord >= -1.2; imagCoord -= 0.05)
            {
                for (realCoord = -0.6; realCoord <= 1.77; realCoord += 0.03)
                {
                    iterations = 0;
                    realTemp = realCoord;
                    imagTemp = imagCoord;
                    arg = (realCoord * realCoord) + (imagCoord * imagCoord);
                    while ((arg < 2*2) && (iterations < 40))
                    {
```

[51] wikipedia
[52] Here is also the executable file: beginners.re

```
                        realTemp2 = (realTemp * realTemp) - (imagTemp * imagTemp) - realCoord;
                        imagTemp = (2 * realTemp * imagTemp) - imagCoord;
                        realTemp = realTemp2;
                        arg = (realTemp * realTemp) + (imagTemp * imagTemp);
                        iterations += 1;
                    }
                    Console.Write("{0,2:D} ", iterations);
                }
                Console.Write("\n");
            }
            Console.ReadKey();
        }
    }
}
```

Here is the resulting file, which is too wide to be included here:
beginners.re.

The maximal number of iterations is 40, so when you see 40 in this dump, it means that this point has been wandering for 40 iterations but never got off limits.

A number n less than 40 means that point remained inside the bounds only for n iterations, then it went outside them.

There is a cool demo available at http://go.yurichev.com/17309, which shows visually how the point moves on the plane at each iteration for some specific point. Here are two screenshots.

First, we've clicked inside the yellow area and saw that the trajectory (green line) eventually swirls at some point inside:

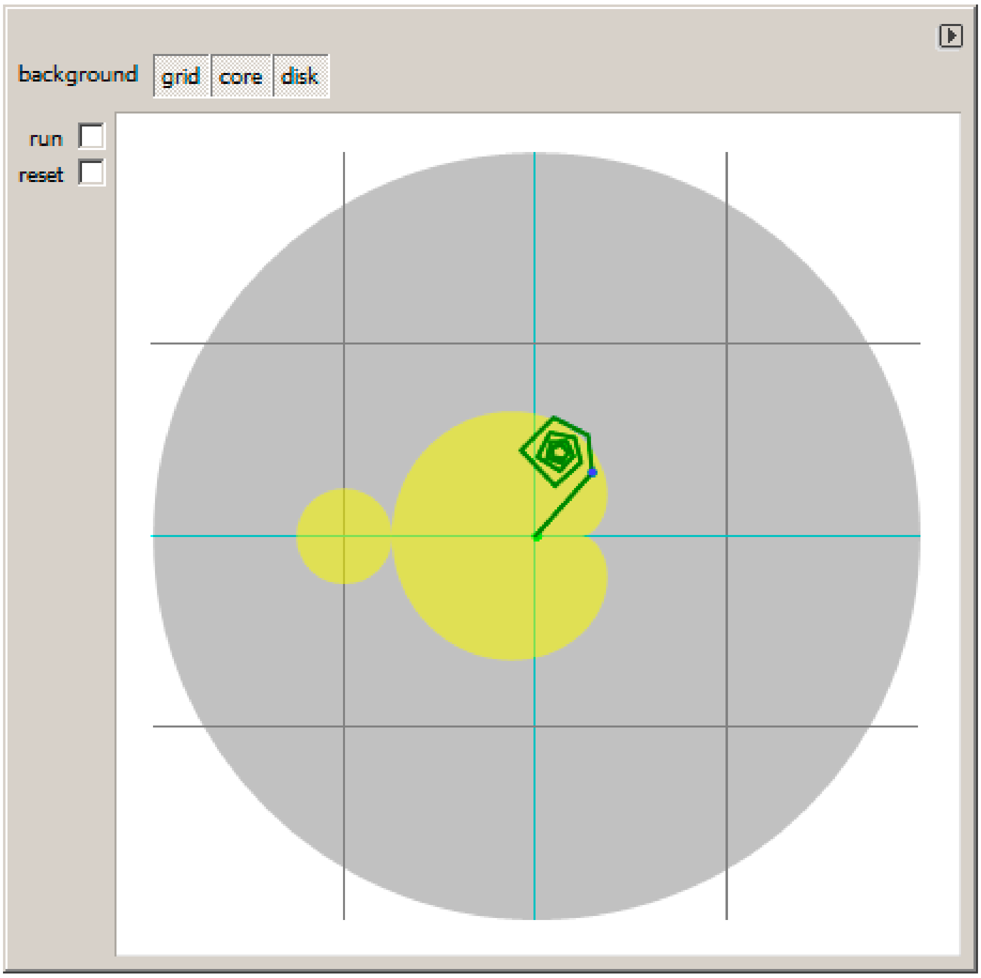


Figure 8.18: Click inside yellow area

This implies that the point we've clicked belongs to the Mandelbrot set.

Then we've clicked outside the yellow area and saw a much more chaotic point movement, which quickly went off bounds:

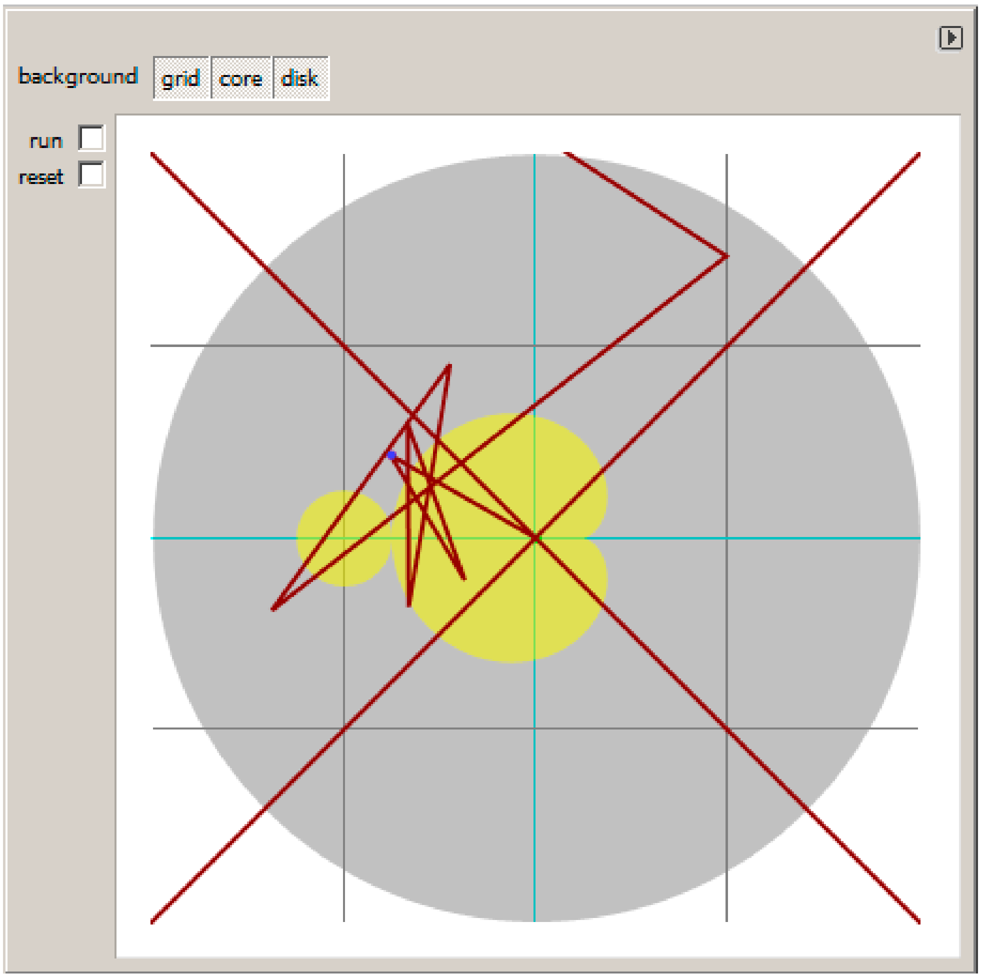


Figure 8.19: Click outside yellow area

This means the point doesn't belong to Mandelbrot set.

Another good demo is available here: http://go.yurichev.com/17310.

Let's get back to the demo

The demo, although very tiny (just 64 bytes or 30 instructions), implements the common algorithm described here, but using some coding tricks.

The source code is easily downloadable, so here is it, but let's also add comments:

Listing 8.26: Commented source code

```
; X is column on screen
; Y is row on screen


; X=0, Y=0              X=319, Y=0
; +------------------------------->
; |
; |
; |
; |
; |
; |
; v
; X=0, Y=199            X=319, Y=199


; switch to VGA 320*200*256 graphics mode
mov al,13h
int 10h
; initial BX is 0
; initial DI is 0xFFFE
; DS:BX (or DS:0) is pointing to Program Segment Prefix at this moment
; ... first 4 bytes of which are CD 20 FF 9F
les ax,[bx]
; ES:AX=9FFF:20CD

FillLoop:
; set DX to 0. CWD works as: DX:AX = sign_extend(AX).
; AX here 0x20CD (at startup) or less then 320 (when getting back after loop),
; so DX will always be 0.
cwd
mov ax,di
; AX is current pointer within VGA buffer
; divide current pointer by 320
mov cx,320
div cx
; DX (start_X) - remainder (column: 0..319); AX - result (row: 0..199)
sub ax,100
; AX=AX-100, so AX (start_Y) now is in range -100..99
; DX is in range 0..319 or 0x0000..0x013F
dec dh
; DX now is in range 0xFF00..0x003F (-256..63)

xor bx,bx
xor si,si
; BX (temp_X)=0; SI (temp_Y)=0

; get maximal number of iterations
; CX is still 320 here, so this is also maximal number of iteration
MandelLoop:
mov bp,si      ; BP = temp_Y
imul si,bx     ; SI = temp_X*temp_Y
add si,si      ; SI = SI*2 = (temp_X*temp_Y)*2
imul bx,bx     ; BX = BX^2 = temp_X^2
jo MandelBreak ; overflow?
imul bp,bp     ; BP = BP^2 = temp_Y^2
jo MandelBreak ; overflow?
add bx,bp      ; BX = BX+BP = temp_X^2 + temp_Y^2
jo MandelBreak ; overflow?
sub bx,bp      ; BX = BX-BP = temp_X^2 + temp_Y^2 - temp_Y^2 = temp_X^2
sub bx,bp      ; BX = BX-BP = temp_X^2 - temp_Y^2

```

```
63 ; correct scale:
64 sar bx,6       ; BX=BX/64
65 add bx,dx      ; BX=BX+start_X
66 ; now temp_X = temp_X^2 - temp_Y^2 + start_X
67 sar si,6       ; SI=SI/64
68 add si,ax      ; SI=SI+start_Y
69 ; now temp_Y = (temp_X*temp_Y)*2 + start_Y
70
71 loop MandelLoop
72
73 MandelBreak:
74 ; CX=iterations
75 xchg ax,cx
76 ; AX=iterations. store AL to VGA buffer at ES:[DI]
77 stosb
78 ; stosb also increments DI, so DI now points to the next point in VGA buffer
79 ; jump always, so this is eternal loop here
80 jmp FillLoop
```

Algorithm:

- Switch to 320*200 VGA video mode, 256 colors. $320 * 200 = 64000$ (0xFA00).

  Each pixel is encoded by one byte, so the buffer size is 0xFA00 bytes. It is addressed using the ES:DI registers pair.

  ES must be 0xA000 here, because this is the segment address of the VGA video buffer, but storing 0xA000 to ES requires at least 4 bytes (`PUSH 0A000h / POP ES`). You can read more about the 16-bit MS-DOS memory model here: 11.6 on page 1003.

  Assuming that BX is zero here, and the Program Segment Prefix is at the zeroth address, the 2-byte `LES AX,[BX]` instruction stores 0x20CD to AX and 0x9FFF to ES.

  So the program starts to draw 16 pixels (or bytes) before the actual video buffer. But this is MS-DOS,

  there is no memory protection, so a write happens into the very end of conventional memory, and usually, there is nothing important. That's why you see a red strip 16 pixels wide at the right side. The whole picture is shifted left by 16 pixels. This is the price of saving 2 bytes.

- An infinite loop processes each pixel.

  Probably, the most common way to enumerate all pixels on the screen is with two loops: one for the X coordinate, another for the Y coordinate. But then you'll need to multiply the coordinates to address a byte in the VGA video buffer.

  The author of this demo decided to do it otherwise: enumerate all bytes in the video buffer by using one single loop instead of two, and get the coordinates of the current point using division. The resulting coordinates are: X in the range of $-256..63$ and Y in the range of $-100..99$. You can see on the screenshot that the picture is somewhat shifted to the right part of screen.

  That's because the biggest heart-shaped black hole usually appears on coordinates 0,0 and these are shifted here to right. Could the author just subtract 160 from the value to get X in the range of $-160..159$? Yes, but the instruction `SUB DX, 160` takes 4 bytes, while `DEC DH`—2 bytes (which subtracts 0x100 (256) from DX). So the whole picture is shifted for the cost of another 2 bytes of saved space.

  - Check, if the current point is inside the Mandelbrot set. The algorithm is the one that has been described here.
  - The loop is organized using the `LOOP` instruction, which uses the CX register as counter.

    The author could set the number of iterations to some specific number, but he didn't: 320 is already present in CX (has been set at line 35), and this is good maximal iteration number anyway. We save here some space by not the reloading CX register with another value.
  - `IMUL` is used here instead of `MUL`, because we work with signed values: keep in mind that the 0,0 coordinates has to be somewhere near the center of the screen.

    It's the same with `SAR` (arithmetic shift for signed values): it's used instead of `SHR`.
  - Another idea is to simplify the bounds check. We must check a coordinate pair, i.e., two variables. What the author does is to checks thrice for overflow: two squaring operations and one addition.

Indeed, we use 16-bit registers, which hold signed values in the range of -32768..32767, so if any of the coordinates is greater than 32767 during the signed multiplication, this point is definitely out of bounds: we jump to the `MandelBreak` label.

- There is also a division by 64 (SAR instruction). 64 sets scale.

  Try to increase the value and you can get a closer look, or to decrease if for a more distant look.

- We are at the `MandelBreak` label, there are two ways of getting here: the loop ended with CX=0 (the point is inside the Mandelbrot set); or because an overflow has happened (CX still holds some value). Now we write the low 8-bit part of CX (CL) to the video buffer.

  The default palette is rough, nevertheless, 0 is black: hence we see black holes in the places where the points are in the Mandelbrot set. The palette can be initialized at the program's start, but keep in mind, this is only a 64 bytes program!

- The program runs in an infinite loop, because an additional check where to stop, or any user interface will result in additional instructions.

Some other optimization tricks:

- The 1-byte CWD is used here for clearing DX instead of the 2-byte `XOR DX, DX` or even the 3-byte `MOV DX, 0`.

- The 1-byte `XCHG AX, CX` is used instead of the 2-byte `MOV AX,CX`. The current value of AX is not needed here anyway.

- DI (position in video buffer) is not initialized, and it is 0xFFFE at the start [53].

  That's OK, because the program works for all DI in the range of 0..0xFFFF eternally, and the user can't notice that it is started off the screen (the last pixel of a 320*200 video buffer is at address 0xF9FF). So some work is actually done off the limits of the screen.

  Otherwise, you'll need an additional instructions to set DI to 0 and check for the video buffer's end.

My "fixed" version

Listing 8.27: My "fixed" version

```
org 100h
mov al,13h
int 10h

; set palette
mov dx, 3c8h
mov al, 0
out dx, al
mov cx, 100h
inc dx
l00:
mov al, cl
shl ax, 2
out dx, al ; red
out dx, al ; green
out dx, al ; blue
loop l00

push 0a000h
pop es

xor di, di

FillLoop:
cwd
mov ax,di
mov cx,320
div cx
sub ax,100
sub dx,160

```

[53] More information about initial register values: http://go.yurichev.com/17004

```
32 xor bx,bx
33 xor si,si
34
35 MandelLoop:
36 mov bp,si
37 imul si,bx
38 add si,si
39 imul bx,bx
40 jo MandelBreak
41 imul bp,bp
42 jo MandelBreak
43 add bx,bp
44 jo MandelBreak
45 sub bx,bp
46 sub bx,bp
47
48 sar bx,6
49 add bx,dx
50 sar si,6
51 add si,ax
52
53 loop MandelLoop
54
55 MandelBreak:
56 xchg ax,cx
57 stosb
58 cmp di, 0FA00h
59 jb FillLoop
60
61 ; wait for keypress
62 xor ax,ax
63 int 16h
64 ; set text video mode
65 mov ax, 3
66 int 10h
67 ; exit
68 int 20h
```

The author of these lines made an attempt to fix all these oddities: now the palette is smooth grayscale, the video buffer is at the correct place (lines 19..20), the picture is drawn on center of the screen (line 30), the program eventually ends and waits for the user's keypress (lines 58..68).

But now it's much bigger: 105 bytes (or 54 instructions) [54].

[54] You can experiment by yourself: get DosBox and NASM and compile it as: `nasm fiole.asm -fbin -o file.com`

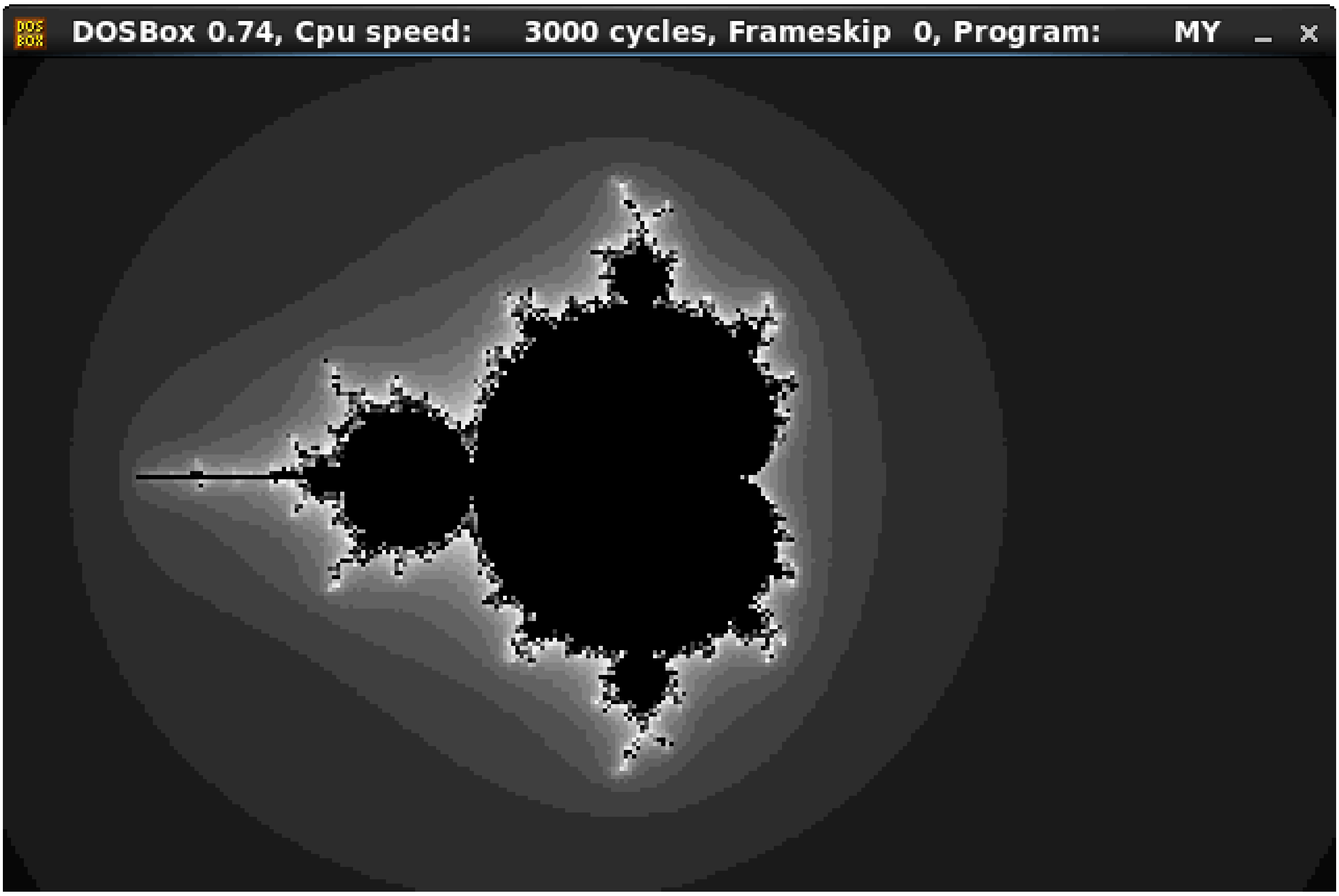


Figure 8.20: My “fixed” version

8.14 Other examples

An example about Z3 and manual decompilation was here. It is (temporarily) moved there: http://yurichev.com/tmp/SAT_SMT_DRAFT.pdf.

Chapter 9

Examples of reversing proprietary file formats

9.1 Primitive XOR-encryption

9.1.1 Simplest ever XOR encryption

I once saw a software where all debugging messages has been encrypted using XOR by value of 3. In other words, two lowest bits of all characters has been flipped.

“Hello, world” would become “Kfool/#tlqog”:

```
#!/usr/bin/python

msg="Hello, world!"

print "".join(map(lambda x: chr(ord(x)^3), msg))
```

This is quite interesting encryption (or rather obfuscation), because it has two important properties: 1) single function for encryption/decryption, just apply it again; 2) resulting characters are also printable, so the whole string can be used in source code without escaping characters.

The second property exploits the fact that all printable characters organized in rows: 0x2x-0x7x, and when you flip two lowest bits, character *moving* 1 or 3 characters left or right, but never *moved* to another (maybe non-printable) row:

```
Characters in the coded character set ascii.
---------------------------------------------------------------------
       0   1   2   3   4   5   6   7   8   9   A   B   C   D   E   F
    0x C-@ C-a C-b C-c C-d C-e C-f C-g C-h TAB C-j C-k C-l RET C-n C-o
    1x C-p C-q C-r C-s C-t C-u C-v C-w C-x C-y C-z ESC C-\ C-] C-^ C-_
    2x     !   "   #   $   %   &   '   (   )   *   +   ,   -   .   /
    3x 0   1   2   3   4   5   6   7   8   9   :   ;   <   =   >   ?
    4x @   A   B   C   D   E   F   G   H   I   J   K   L   M   N   O
    5x P   Q   R   S   T   U   V   W   X   Y   Z   [   \   ]   ^   _
    6x `   a   b   c   d   e   f   g   h   i   j   k   l   m   n   o
    7x p   q   r   s   t   u   v   w   x   y   z   {   |   }   ~   DEL
```

Figure 9.1: 7-bit ASCII table in Emacs

…with a single exception of 0x7F character.

For example, let’s *encrypt* characters in A-Z range:

```
#!/usr/bin/python

msg="@ABCDEFGHIJKLMNO"

print "".join(map(lambda x: chr(ord(x)^3), msg))
```

Result:

```
CBA@GFEDKJIHONML
```

It's like "@" and "C" characters has been swapped, and so are "B" and "a".

Yet again, this is interesting example of exploiting XOR properties, rather than encryption: the very same effect of *preserving printableness* can be achieved while flipping any of lowest 4 bits, in any combination.

9.1.2 Norton Guide: simplest possible 1-byte XOR encryption

Norton Guide[1] was popular in the epoch of MS-DOS, it was a resident program that worked as a hypertext reference manual.

Norton Guide's databases are files with the extension .ng, the contents of which look encrypted:

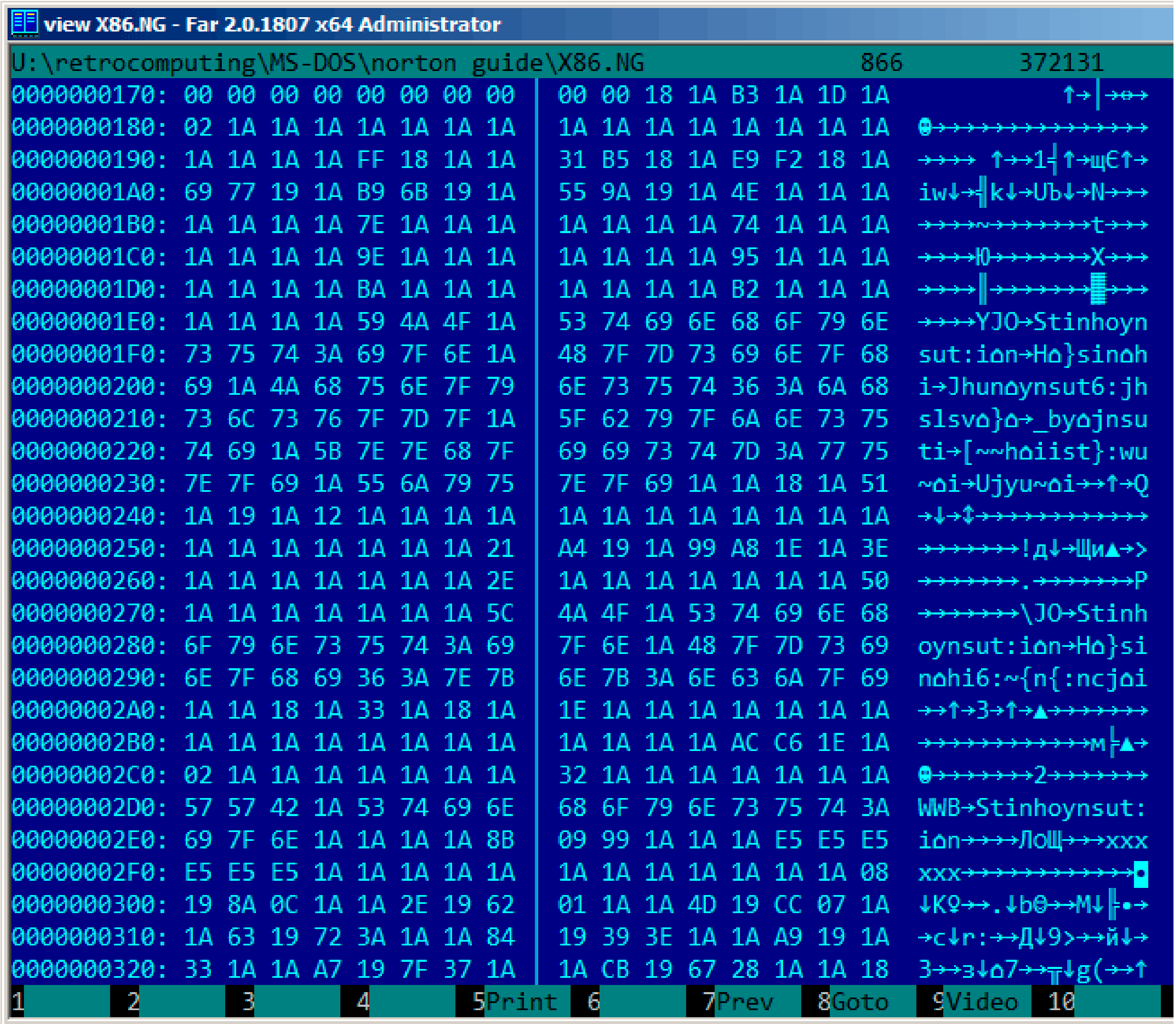


Figure 9.2: Very typical look

Why did we think that it's encrypted but not compressed?

We see that the 0x1A byte (looking like "→") occurs often, it would not be possible in a compressed file.

We also see long parts that consist only of Latin letters, and they look like strings in an unknown language.

[1] wikipedia

Since the 0x1A byte occurs so often, we can try to decrypt the file, assuming that it's encrypted by the simplest XOR-encryption.

If we apply XOR with the 0x1A constant to each byte in Hiew, we can see familiar English text strings:

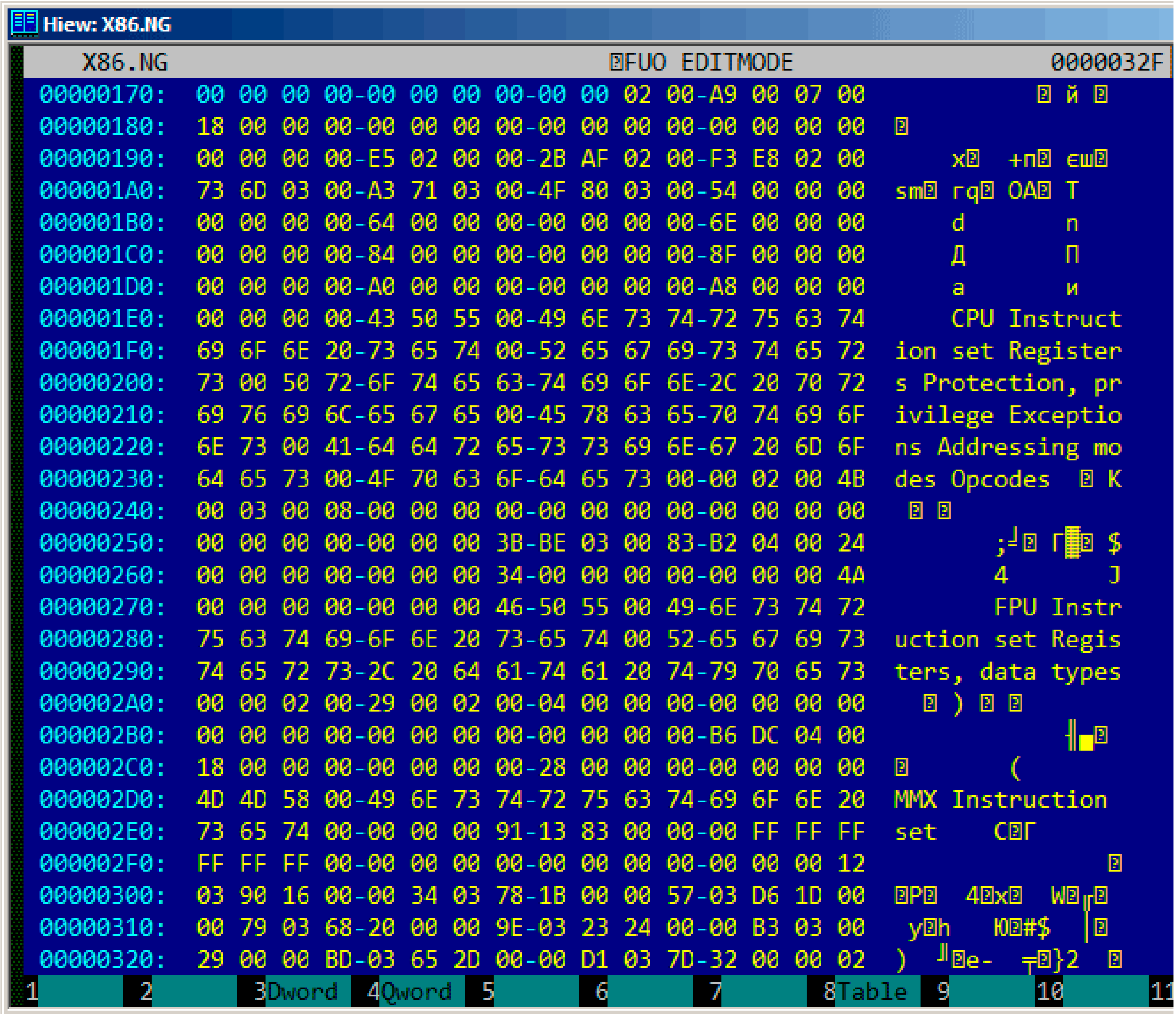


Figure 9.3: Hiew XORing with 0x1A

XOR encryption with one single constant byte is the simplest possible encryption method, which is, nevertheless, encountered sometimes.

Now we understand why the 0x1A byte is occurring so often: because there are so many zero bytes and they were replaced by 0x1A in encrypted form.

But the constant might be different. In this case, we could try every constant in the 0..255 range and look for something familiar in the decrypted file. 256 is not so much.

More about Norton Guide's file format: http://go.yurichev.com/17317.

Entropy

A very important property of such primitive encryption systems is that the information entropy of the encrypted/decrypted block is the same.

Here is my analysis in Wolfram Mathematica 10.

Listing 9.1: Wolfram Mathematica 10

```
In[1]:= input = BinaryReadList["X86.NG"];

In[2]:= Entropy[2, input] // N
Out[2]= 5.62724

In[3]:= decrypted = Map[BitXor[#, 16^^1A] &, input];

In[4]:= Export["X86_decrypted.NG", decrypted, "Binary"];

In[5]:= Entropy[2, decrypted] // N
Out[5]= 5.62724

In[6]:= Entropy[2, ExampleData[{"Text", "ShakespearesSonnets"}]] // N
Out[6]= 4.42366
```

What we do here is load the file, get its entropy, decrypt it, save it and get the entropy again (the same!).

Mathematica also offers some well-known English language texts for analysis.

So we also get the entropy of Shakespeare's sonnets, and it is close to the entropy of the file we just analyzed.

The file we analyzed consists of English language sentences, which are close to the language of Shakespeare.

And the XOR-ed bitwise English language text has the same entropy.

However, this is not true when the file is XOR-ed with a pattern larger than one byte.

The file we analyzed can be downloaded here: http://go.yurichev.com/17350.

One more word about base of entropy

Wolfram Mathematica calculates entropy with base of e (base of the natural logarithm), and the UNIX *ent* utility[2]uses base 2.

So we set base 2 explicitly in `Entropy` command, so Mathematica will give us the same results as the *ent* utility.

[2] http://www.fourmilab.ch/random/

9.1.3 Simplest possible 4-byte XOR encryption

If a longer pattern was used for XOR-encryption, for example a 4 byte pattern, it's easy to spot as well.

For example, here is the beginning of the kernel32.dll file (32-bit version from Windows Server 2008):

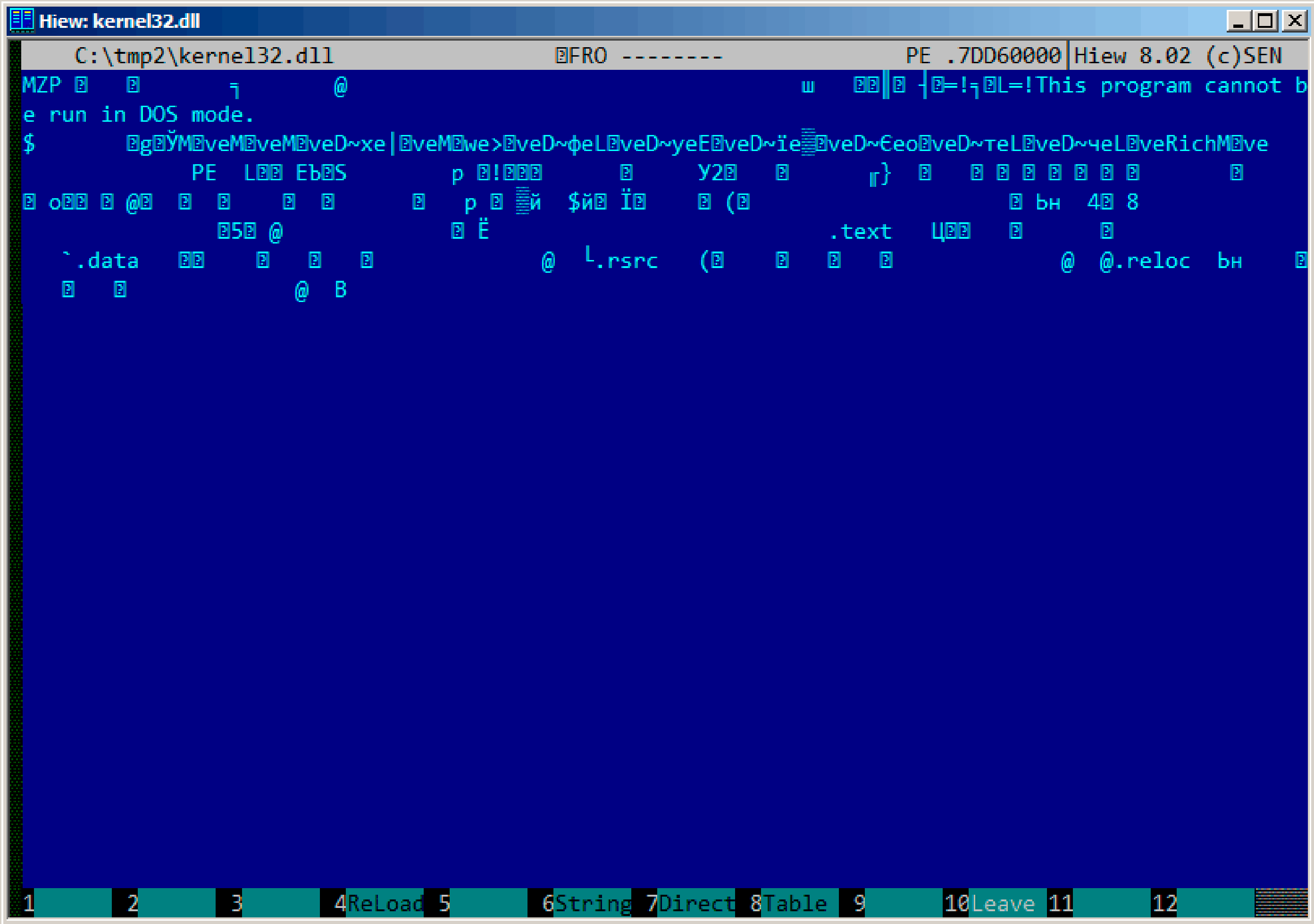


Figure 9.4: Original file

Here it is “encrypted” with a 4-byte key:

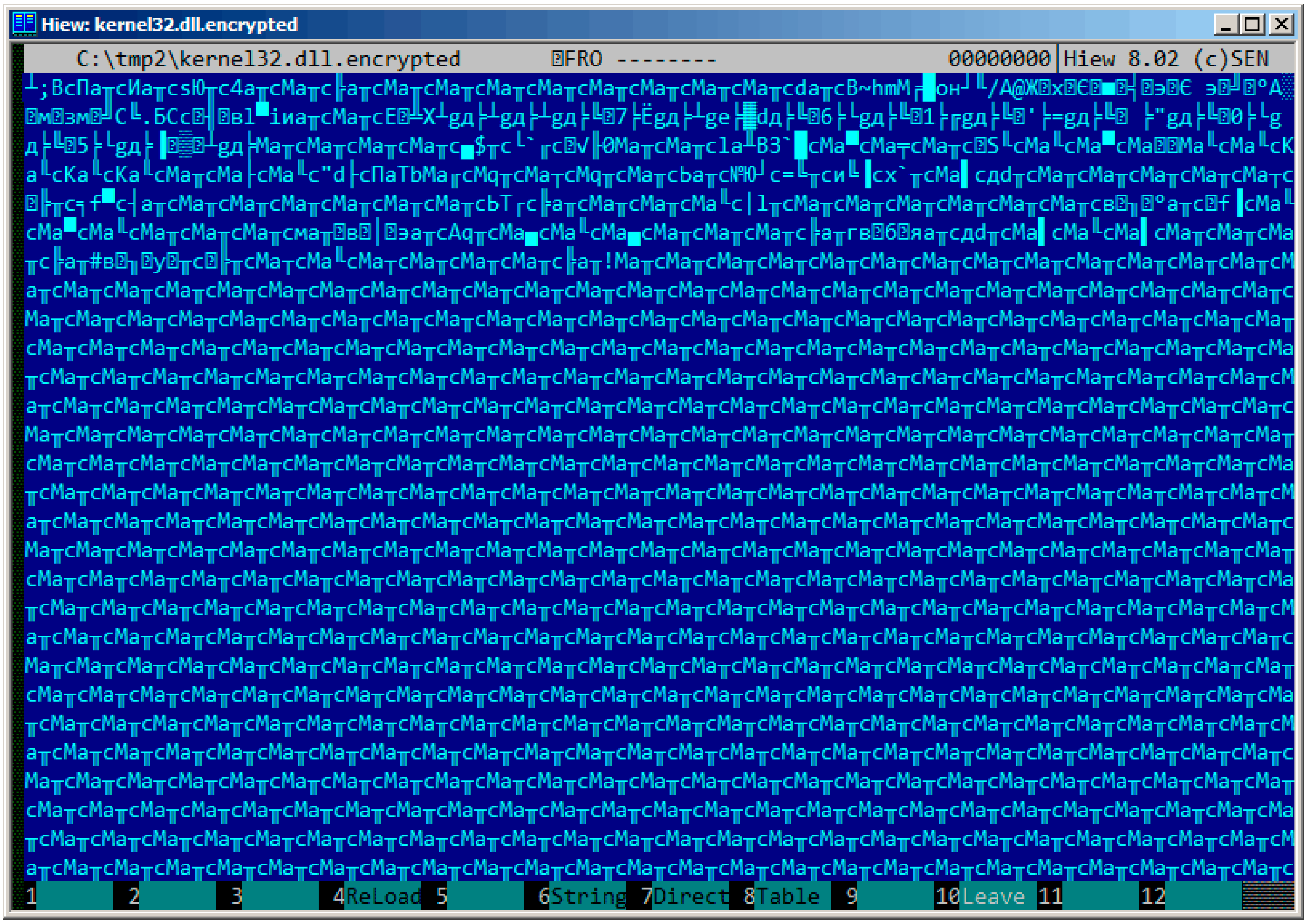


Figure 9.5: “Encrypted” file

It’s very easy to spot the recurring 4 symbols.

Indeed, the header of a PE-file has a lot of long zero areas, which are the reason for the key to become visible.

Here is the beginning of a PE-header in hexadecimal form:

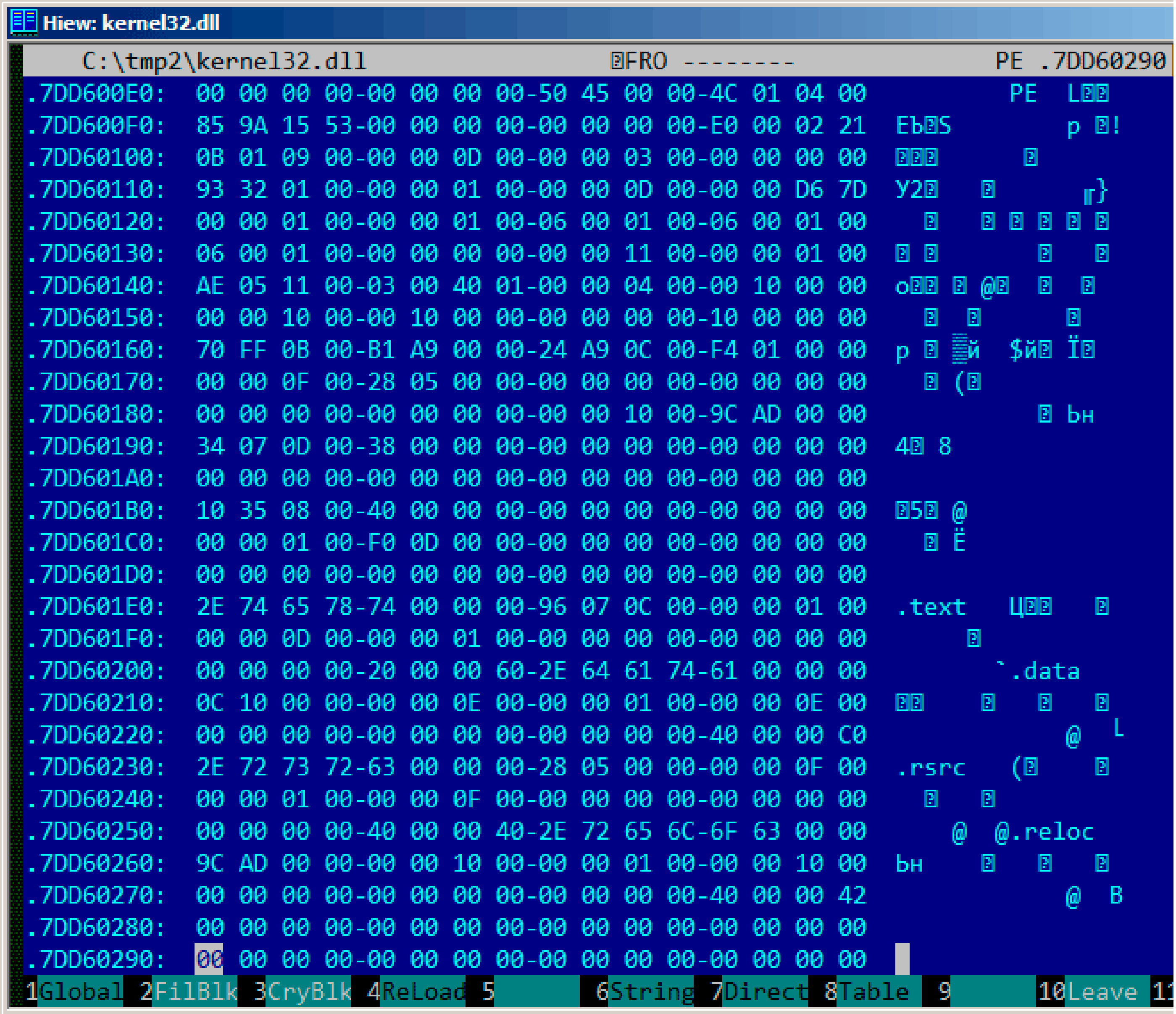


Figure 9.6: PE-header

Here it is “encrypted”:

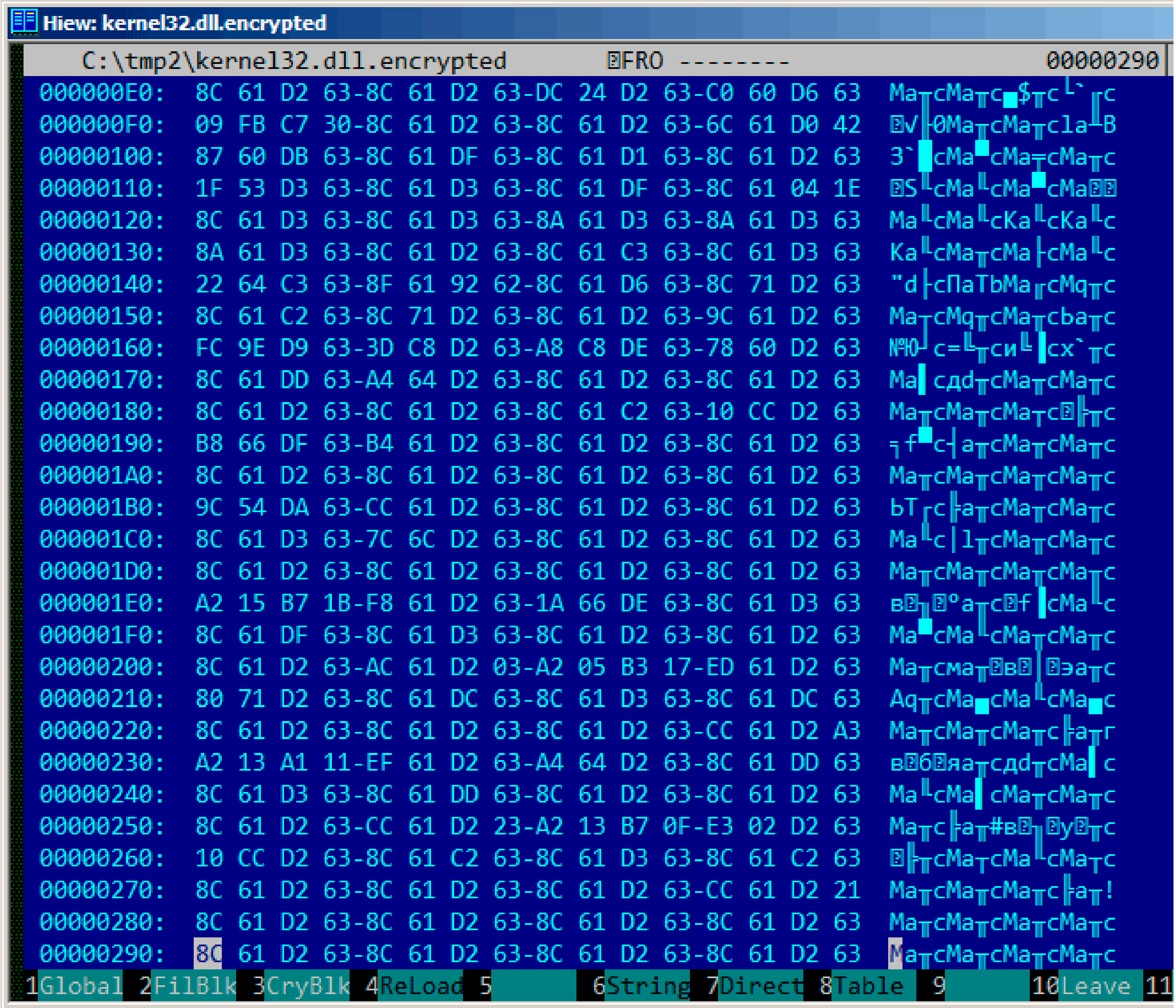


Figure 9.7: “Encrypted” PE-header

It’s easy to spot that the key is the following 4 bytes: `8C 61 D2 63`.

With this information, it’s easy to decrypt the whole file.

So it is important to keep in mind these properties of PE-files: 1) PE-header has many zero-filled areas; 2) all PE-sections are padded with zeros at a page boundary (4096 bytes), so long zero areas are usually present after each section.

Some other file formats may contain long zero areas.

It’s typical for files used by scientific and engineering software.

For those who want to inspect these files on their own, they are downloadable here: http://go.yurichev.com/17352.

Exercise

- http://challenges.re/50

9.1.4 Simple encryption using XOR mask

I've found an old interactive fiction game while diving deep into *if-archive*[3]:

```
The New Castle v3.5 - Text/Adventure Game
in the style of the original Infocom (tm)
type games, Zork, Collosal Cave (Adventure),
etc.  Can you solve the mystery of the
abandoned castle?
Shareware from Software Customization.
Software Customization [ASP] Version 3.5 Feb. 2000
```

It's downloadable here: https://github.com/DennisYurichev/RE-for-beginners/blob/master/ff/XOR/mask_1/files/newcastle.tgz.

There is a file inside (named *castle.dbf*) which is clearly encrypted, but not by a real crypto algorithm, nor it's compressed, this is something rather simpler. I wouldn't even measure entropy level (9.2 on page 948) of the file, because I'm sure it's low. Here is how it looks like in Midnight Commander:

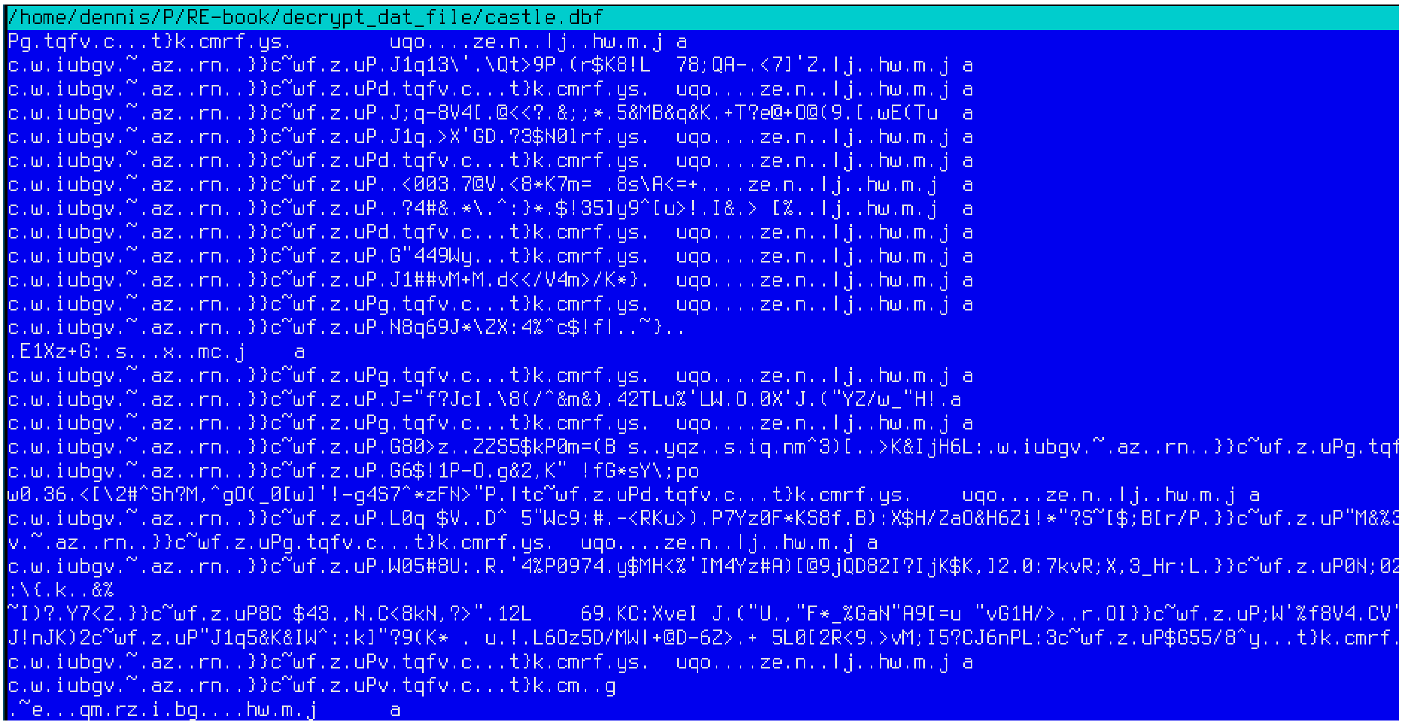


Figure 9.8: Encrypted file in Midnight Commander

The encrypted file can be downloaded here: https://github.com/DennisYurichev/RE-for-beginners/blob/master/ff/XOR/mask_1/files/castle.dbf.bz2.

Will it be possible to decrypt it without accessing to the program, using just this file?

There is a clearly visible pattern of repeating string. If a simple encryption by XOR mask was applied, such repeating strings is a prominent signature, because, probably, there were a long lacunas[4] of zero bytes, which, in turn, are present in many executable files as well as in binary data files.

Here I'll dump the file's beginning using *xxd* UNIX utility:

```
...

0000030: 09 61 0d 63 0f 77 14 69 75 62 67 76 01 7e 1d 61  .a.c.w.iubgv.~.a
0000040: 7a 11 0f 72 6e 03 05 7d 7d 63 7e 77 66 1e 7a 02  z..rn..}}c~wf.z.
0000050: 75 50 02 4a 31 71 31 33 5c 27 08 5c 51 74 3e 39  uP.J1q13\'.\Qt>9
0000060: 50 2e 28 72 24 4b 38 21 4c 09 37 38 3b 51 41 2d  P.(r$K8!L.78;QA-
0000070: 1c 3c 37 5d 27 5a 1c 7c 6a 10 14 68 77 08 6d 1a  .<7]'Z.|j..hw.m.
```

[3] http://www.ifarchive.org/

[4] As in https://en.wikipedia.org/wiki/Lacuna_(manuscripts)

```
0000080: 6a 09 61 0d 63 0f 77 14 69 75 62 67 76 01 7e 1d  j.a.c.w.iubgv.~.
0000090: 61 7a 11 0f 72 6e 03 05 7d 7d 63 7e 77 66 1e 7a  az..rn..}}c~wf.z
00000a0: 02 75 50 64 02 74 71 66 76 19 63 08 13 17 74 7d  .uPd.tqfv.c...t}
00000b0: 6b 19 63 6d 72 66 0e 79 73 1f 09 75 71 6f 05 04  k.cmrf.ys..uqo..
00000c0: 7f 1c 7a 65 08 6e 0e 12 7c 6a 10 14 68 77 08 6d  ..ze.n..|j..hw.m

00000d0: 1a 6a 09 61 0d 63 0f 77 14 69 75 62 67 76 01 7e  .j.a.c.w.iubgv.~
00000e0: 1d 61 7a 11 0f 72 6e 03 05 7d 7d 63 7e 77 66 1e  .az..rn..}}c~wf.
00000f0: 7a 02 75 50 01 4a 3b 71 2d 38 56 34 5b 13 40 3c  z.uP.J;q-8V4[.@<
0000100: 3c 3f 19 26 3b 3b 2a 0e 35 26 4d 42 26 71 26 4b  <?.&;;*.5&MB&q&K
0000110: 04 2b 54 3f 65 40 2b 4f 40 28 39 10 5b 2e 77 45  .+T?e@+O@(9.[.wE

0000120: 28 54 75 09 61 0d 63 0f 77 14 69 75 62 67 76 01  (Tu.a.c.w.iubgv.
0000130: 7e 1d 61 7a 11 0f 72 6e 03 05 7d 7d 63 7e 77 66  ~.az..rn..}}c~wf
0000140: 1e 7a 02 75 50 02 4a 31 71 15 3e 58 27 47 44 17  .z.uP.J1q.>X'GD.
0000150: 3f 33 24 4e 30 6c 72 66 0e 79 73 1f 09 75 71 6f  ?3$N0lrf.ys..uqo
0000160: 05 04 7f 1c 7a 65 08 6e 0e 12 7c 6a 10 14 68 77  ....ze.n..|j..hw

...
```

Let's stick at visible repeating iubgv string. By looking at this dump, we can clearly see that the period of the string occurrence is 0x51 or 81. Probably, 81 is size of block? The size of the file is 1658961, and it can be divided evenly by 81 (and there are 20481 blocks then).

Now I'll use Mathematica to analyze, are there repeating 81-byte blocks in the file? I'll split input file by 81-byte blocks and then I'll use *Tally[]*[5] function which just counts, how many times some item has been occurred in the input list. Tally's output is not sorted, so I also add *Sort[]* function to sort it by number of occurrences in descending order.

```
input = BinaryReadList["/home/dennis/.../castle.dbf"];

blocks = Partition[input, 81];

stat = Sort[Tally[blocks], #1[[2]] > #2[[2]] &]
```

And here is output:

```
{{{80, 103, 2, 116, 113, 102, 118, 25, 99, 8, 19, 23, 116, 125, 107,
   25, 99, 109, 114, 102, 14, 121, 115, 31, 9, 117, 113, 111, 5, 4,
   127, 28, 122, 101, 8, 110, 14, 18, 124, 106, 16, 20, 104, 119, 8,
   109, 26, 106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118,
   1, 126, 29, 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126,
   119, 102, 30, 122, 2, 117}, 1739},
{{80, 100, 2, 116, 113, 102, 118, 25, 99, 8, 19, 23, 116,
   125, 107, 25, 99, 109, 114, 102, 14, 121, 115, 31, 9, 117, 113,
   111, 5, 4, 127, 28, 122, 101, 8, 110, 14, 18, 124, 106, 16, 20,
   104, 119, 8, 109, 26, 106, 9, 97, 13, 99, 15, 119, 20, 105, 117,
   98, 103, 118, 1, 126, 29, 97, 122, 17, 15, 114, 110, 3, 5, 125,
   125, 99, 126, 119, 102, 30, 122, 2, 117}, 1422},
{{80, 101, 2, 116, 113, 102, 118, 25, 99, 8, 19, 23, 116,
   125, 107, 25, 99, 109, 114, 102, 14, 121, 115, 31, 9, 117, 113,
   111, 5, 4, 127, 28, 122, 101, 8, 110, 14, 18, 124, 106, 16, 20,
   104, 119, 8, 109, 26, 106, 9, 97, 13, 99, 15, 119, 20, 105, 117,
   98, 103, 118, 1, 126, 29, 97, 122, 17, 15, 114, 110, 3, 5, 125,
   125, 99, 126, 119, 102, 30, 122, 2, 117}, 1012},
{{80, 120, 2, 116, 113, 102, 118, 25, 99, 8, 19, 23, 116,
   125, 107, 25, 99, 109, 114, 102, 14, 121, 115, 31, 9, 117, 113,
   111, 5, 4, 127, 28, 122, 101, 8, 110, 14, 18, 124, 106, 16, 20,
   104, 119, 8, 109, 26, 106, 9, 97, 13, 99, 15, 119, 20, 105, 117,
   98, 103, 118, 1, 126, 29, 97, 122, 17, 15, 114, 110, 3, 5, 125,
   125, 99, 126, 119, 102, 30, 122, 2, 117}, 377},

...

{{80, 2, 74, 49, 113, 21, 62, 88, 39, 71, 68, 23, 63, 51, 36, 78, 48,
   108, 114, 102, 14, 121, 115, 31, 9, 117, 113, 111, 5, 4, 127, 28,
   122, 101, 8, 110, 14, 18, 124, 106, 16, 20, 104, 119, 8, 109, 26,
   106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118, 1, 126,
```

[5] https://reference.wolfram.com/language/ref/Tally.html

```
   29, 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, 102,
   30, 122, 2, 117}, 1},
{{80, 1, 74, 59, 113, 45, 56, 86, 52, 91, 19, 64, 60, 60, 63,
   25, 38, 59, 59, 42, 14, 53, 38, 77, 66, 38, 113, 38, 75, 4, 43, 84,
    63, 101, 64, 43, 79, 64, 40, 57, 16, 91, 46, 119, 69, 40, 84, 117,
    9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118, 1, 126, 29,
   97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, 102, 30,
   122, 2, 117}, 1},
{{80, 2, 74, 49, 113, 49, 51, 92, 39, 8, 92, 81, 116, 62, 57,
   80, 46, 40, 114, 36, 75, 56, 33, 76, 9, 55, 56, 59, 81, 65, 45, 28,
    60, 55, 93, 39, 90, 28, 124, 106, 16, 20, 104, 119, 8, 109, 26,
   106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118, 1, 126,
   29, 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, 102,
   30, 122, 2, 117}, 1}}
```

Tally's output is a list of pairs, each pair has 81-byte block and number of times it has been occurred in the file. We see that the most frequent block is the first, it has been occurred 1739 times. The second one has been occurred 1422 times. There are others: 1012 times, 377 times, etc. 81-byte blocks which has been occurred just once are at the end of output.

Let's try to compare these blocks. The first and the second. Is there a function in Mathematica which compares lists/arrays? Certainly is, but for educational purposes, I'll use XOR operation for comparison. Indeed: if bytes in two input arrays are identical, XOR result is 0. If they are non-equal, result will be non-zero.

Let's compare first block (occurred 1739 times) and the second (occurred 1422 times):

```
In[]:= BitXor[stat[[1]][[1]], stat[[2]][[1]]]
Out[]= {0, 3, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}
```

They are differ only in the second byte.

Let's compare the second block (occurred 1422 times) and the third (occurred 1012 times):

```
In[]:= BitXor[stat[[2]][[1]], stat[[3]][[1]]]
Out[]= {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}
```

They are also differ only in the second byte.

Anyway, let's try to use the most occurred block as a XOR key and try to decrypt four first 81-byte blocks in the file:

```
In[]:= key = stat[[1]][[1]]
Out[]= {80, 103, 2, 116, 113, 102, 118, 25, 99, 8, 19, 23, 116, \
125, 107, 25, 99, 109, 114, 102, 14, 121, 115, 31, 9, 117, 113, 111, \
5, 4, 127, 28, 122, 101, 8, 110, 14, 18, 124, 106, 16, 20, 104, 119, \
8, 109, 26, 106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118, \
1, 126, 29, 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, \
102, 30, 122, 2, 117}

In[]:= ToASCII[val_] := If[val == 0, " ", FromCharacterCode[val, "PrintableASCII"]]

In[]:= DecryptBlockASCII[blk_] := Map[ToASCII[#] &, BitXor[key, blk]]

In[]:= DecryptBlockASCII[blocks[[1]]]
Out[]= {" ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " \
", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " \
", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " \
", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " \
", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " \
", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " "}

In[]:= DecryptBlockASCII[blocks[[2]]]
Out[]= {" ", "e", "H", "E", " ", "W", "E", "E", "D", " ", "O", \
"F", " ", "C", "R", "I", "M", "E", " ", "B", "E", "A", "R", "S", " ", \
```

```
"B", "I", "T", "T", "E", "R", " ", "F", "R", "U", "I", "T", "?", \
" ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", \
" ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", \
" ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", \
" "}

In[]:= DecryptBlockASCII[blocks[[3]]]
Out[]= {" ", "?", " ", " ", " ", " ", " ", " ", " ", " ", " \
", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " \
", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " \
", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " \
", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " \
", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " \
"}

In[]:= DecryptBlockASCII[blocks[[4]]]
Out[]= {" ", "f", "H", "O", " ", "K", "N", "O", "W", "S", " ", \
"W", "H", "A", "T", " ", "E", "V", "I", "L", " ", "L", "U", "R", "K", \
"S", " ", "I", "N", " ", "T", "H", "E", " ", "H", "E", "A", "R", "T", \
"S", " ", "O", "F", " ", "M", "E", "N", "?", " ", " ", " ", " ", \
" ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", \
" ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", " ", \
" "}
```

(I've replaced unprintable characters by "?".)

So we see that the first and the third blocks are empty (or almost empty), but the second and the fourth has clearly visible English language words/phrases. It seems that our assumption about key is correct (at least partially). This means that the most occurred 81-byte block in the file can be found at places of lacunas of zero bytes or something like that.

Let's try to decrypt the whole file:

```
DecryptBlock[blk_] := BitXor[key, blk]

decrypted = Map[DecryptBlock[#] &, blocks];

BinaryWrite["/home/dennis/.../tmp", Flatten[decrypted]]

Close["/home/dennis/.../tmp"]
```

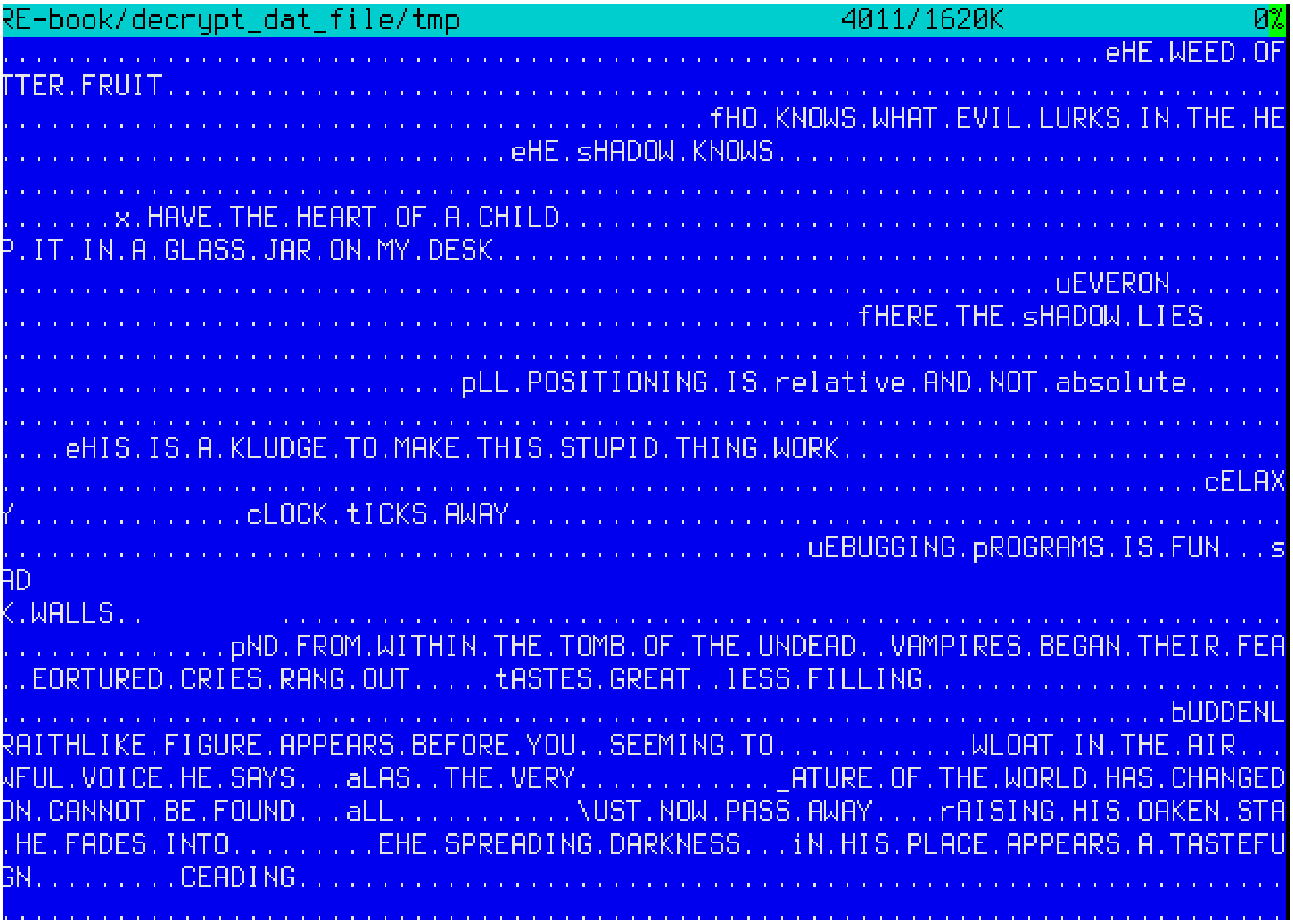


Figure 9.9: Decrypted file in Midnight Commander, 1st attempt

Looks like some kind of English phrases from some game, but something wrong. First of all, cases are inverted: phrases and some words are started with lowercase characters, while other characters are in upper case. Also, some phrases started with wrong letters. Take a look at the very first phrase: "eHE WEED OF CRIME BEARS BITTER FRUIT". What is "eHE"? Isn't "tHE" have to be here? Is it possible that our decryption key has wrong byte at this place?

Let's look again at the second block in the file, at key and at decryption result:

```
In[]:= blocks[[2]]
Out[]= {80, 2, 74, 49, 113, 49, 51, 92, 39, 8, 92, 81, 116, 62, \
57, 80, 46, 40, 114, 36, 75, 56, 33, 76, 9, 55, 56, 59, 81, 65, 45, \
28, 60, 55, 93, 39, 90, 28, 124, 106, 16, 20, 104, 119, 8, 109, 26, \
106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118, 1, 126, 29, \
97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, 102, 30, \
122, 2, 117}

In[]:= key
Out[]= {80, 103, 2, 116, 113, 102, 118, 25, 99, 8, 19, 23, 116, \
125, 107, 25, 99, 109, 114, 102, 14, 121, 115, 31, 9, 117, 113, 111, \
5, 4, 127, 28, 122, 101, 8, 110, 14, 18, 124, 106, 16, 20, 104, 119, \
8, 109, 26, 106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118, \
1, 126, 29, 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, \
102, 30, 122, 2, 117}

In[]:= BitXor[key, blocks[[2]]]
Out[]= {0, 101, 72, 69, 0, 87, 69, 69, 68, 0, 79, 70, 0, 67, 82, \
73, 77, 69, 0, 66, 69, 65, 82, 83, 0, 66, 73, 84, 84, 69, 82, 0, 70, \
82, 85, 73, 84, 14, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0}
```

Encrypted byte is 2, the byte from the key is 103, $2 \oplus 103 = 101$ and 101 is ASCII code for "e" character. What byte of a key must be equal to, so the resulting ASCII code will be 116 (for "t" character)? $2 \oplus 116 = 118$, let's put 118 in key at the second byte ...

```
key = {80, 118, 2, 116, 113, 102, 118, 25, 99, 8, 19, 23, 116, 125,
  107, 25, 99, 109, 114, 102, 14, 121, 115, 31, 9, 117, 113, 111, 5,
  4, 127, 28, 122, 101, 8, 110, 14, 18, 124, 106, 16, 20, 104, 119, 8,
   109, 26, 106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118,
  1, 126, 29, 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119,
   102, 30, 122, 2, 117}
```

...and decrypt the whole file again.

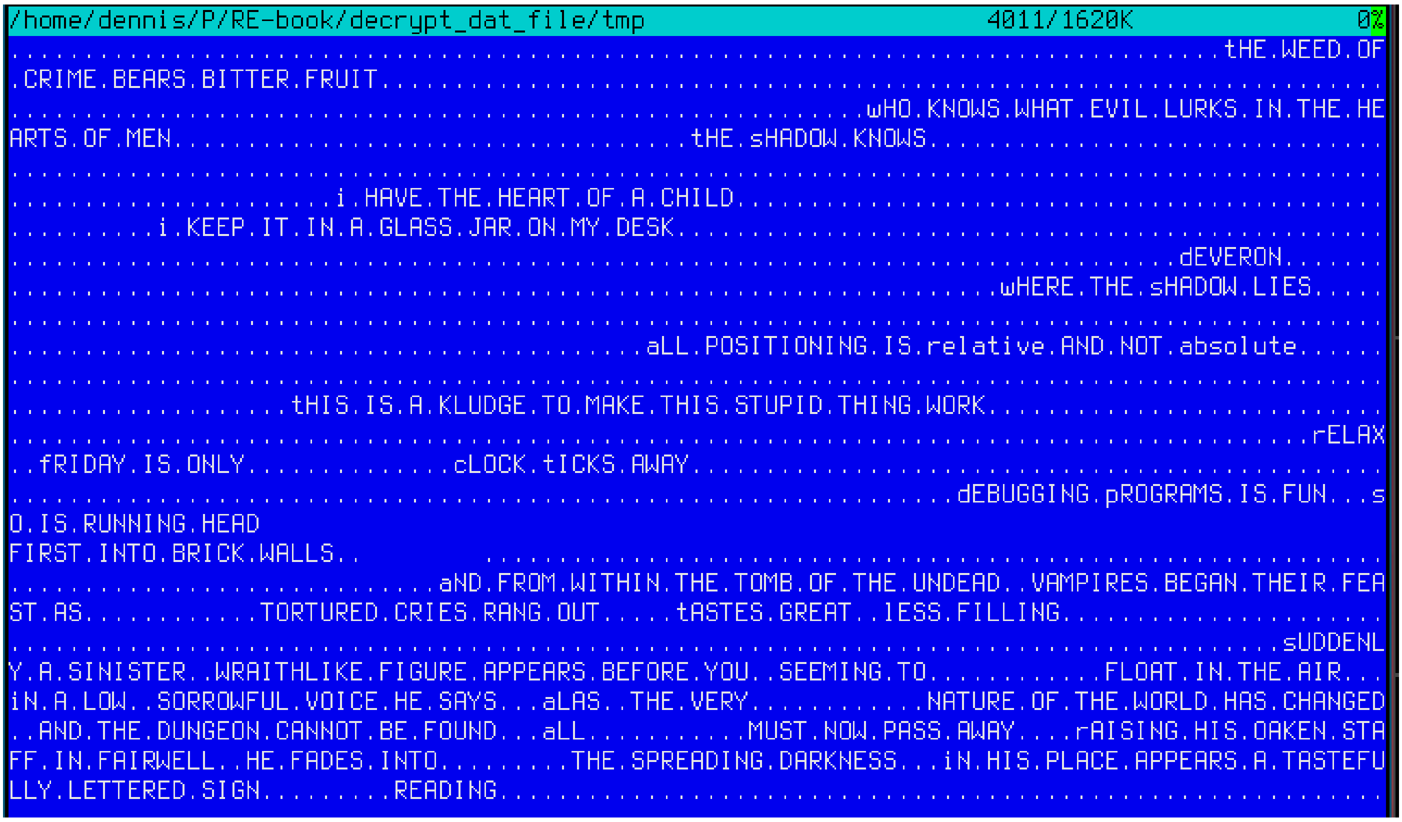
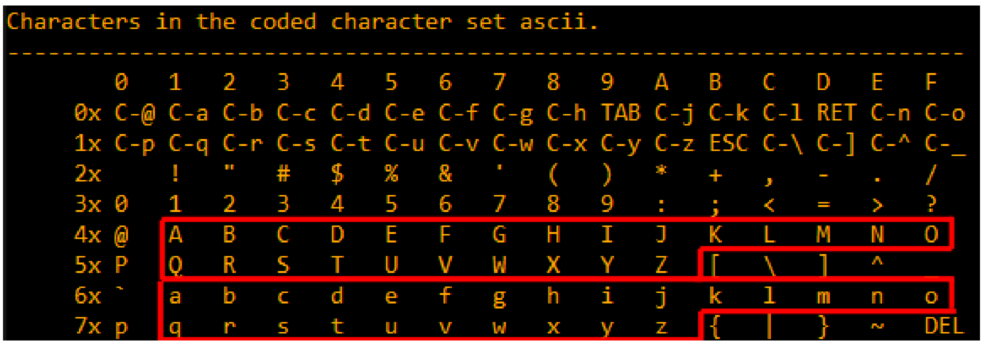


Figure 9.10: Decrypted file in Midnight Commander, 2nd attempt

Wow, now the grammar is correct, all phrases started with correct letters. But still, case inversion is suspicious. Why would game's developer write them in such a manner? Maybe our key is still incorrect?

While observing ASCII table we can notice that uppercase and lowercase letter's ASCII codes are differ in just one bit (6th bit starting at 1st, 0b100000):


Characters in the coded character set ascii.

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0x	C-@	C-a	C-b	C-c	C-d	C-e	C-f	C-g	C-h	TAB	C-j	C-k	C-l	RET	C-n	C-o
1x	C-p	C-q	C-r	C-s	C-t	C-u	C-v	C-w	C-x	C-y	C-z	ESC	C-\	C-]	C-^	C-_
2x		!	"	#	$	%	&	'	(	)	*	+	,	-	.	/
3x	0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?
4x	@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
5x	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	^	_
6x	`	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
7x	p	q	r	s	t	u	v	w	x	y	z	{	|	}	~	DEL

Figure 9.11: 7-bit ASCII table in Emacs

6th bit set in a zero byte has decimal form of 32. But 32 is ASCII code for space!

Indeed, one can switch case just by XOR-ing ASCII character code with 32 (more about it: 3.16.3 on page 537).

It is possible that the empty lacunas in the file are not zero bytes, but rather spaces? Let's modify XOR key one more time (I'll XOR each byte of key by 32):

```
(* "32" is scalar and "key" is vector, but that's OK *)

In[]:= key3 = BitXor[32, key]
Out[]= {112, 86, 34, 84, 81, 70, 86, 57, 67, 40, 51, 55, 84, 93, 75, \
57, 67, 77, 82, 70, 46, 89, 83, 63, 41, 85, 81, 79, 37, 36, 95, 60, \
90, 69, 40, 78, 46, 50, 92, 74, 48, 52, 72, 87, 40, 77, 58, 74, 41, \
65, 45, 67, 47, 87, 52, 73, 85, 66, 71, 86, 33, 94, 61, 65, 90, 49, \
47, 82, 78, 35, 37, 93, 93, 67, 94, 87, 70, 62, 90, 34, 85}

In[]:= DecryptBlock[blk_] := BitXor[key3, blk]
```

Let's decrypt the input file again:

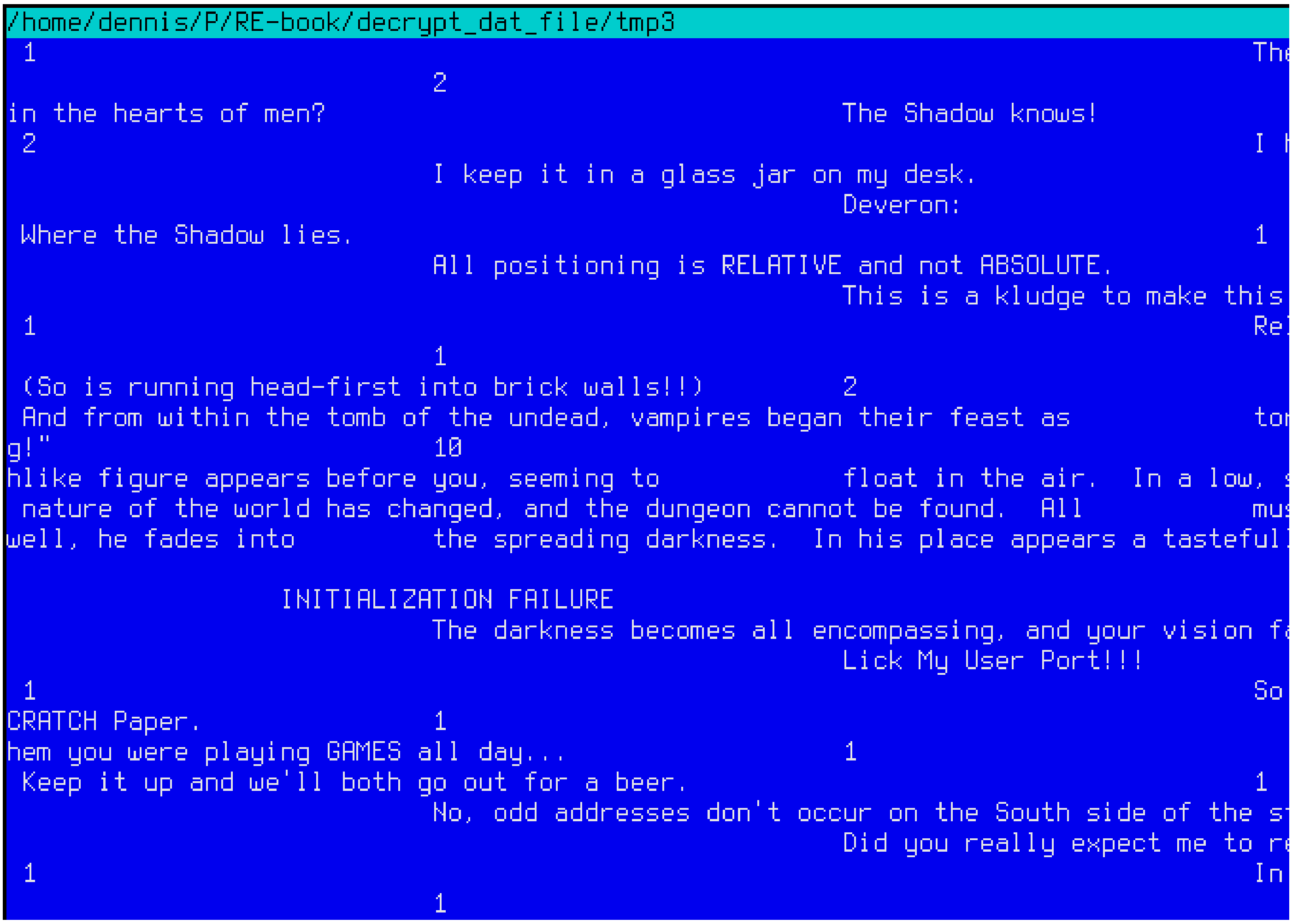


Figure 9.12: Decrypted file in Midnight Commander, final attempt

(Decrypted file is available here: `https://github.com/DennisYurichev/RE-for-beginners/blob/master/ff/XOR/mask_1/files/decrypted.dat.bz2`.)

This is undoubtedly a correct source file. Oh, and we see numbers at the start of each block. It has to be a source of our erroneous XOR key. As it seems, the most occurred 81-byte block in the file is a block filled with spaces and containing "1" character at the place of second byte. Indeed, somehow, many blocks here are interleaved with this one. Maybe it's some kind of padding for short phrases/messages? Other frequently occurred 81-byte blocks are also space-filled blocks, but with different digit, hence, they are differ only at the second byte.

That's all! Now we can write an utility to encrypt the file back, and maybe modify it before.

Mathematica notebook file is downloadable here: https://github.com/DennisYurichev/RE-for-beginners/blob/master/ff/XOR/mask_1/files/XOR_mask_1.nb.

Summary: XOR encryption like that is not robust at all. It has been intended by game's developer(s), probably, just to prevent gamer(s) to peek into internals of game, nothing else more serious. Still, encryption like that is extremely popular due to its simplicity and many reverse engineers are usually familiar with it.

9.1.5 Simple encryption using XOR mask, case II

I've got another encrypted file, which is clearly encrypted by something simple, like XOR-ing:

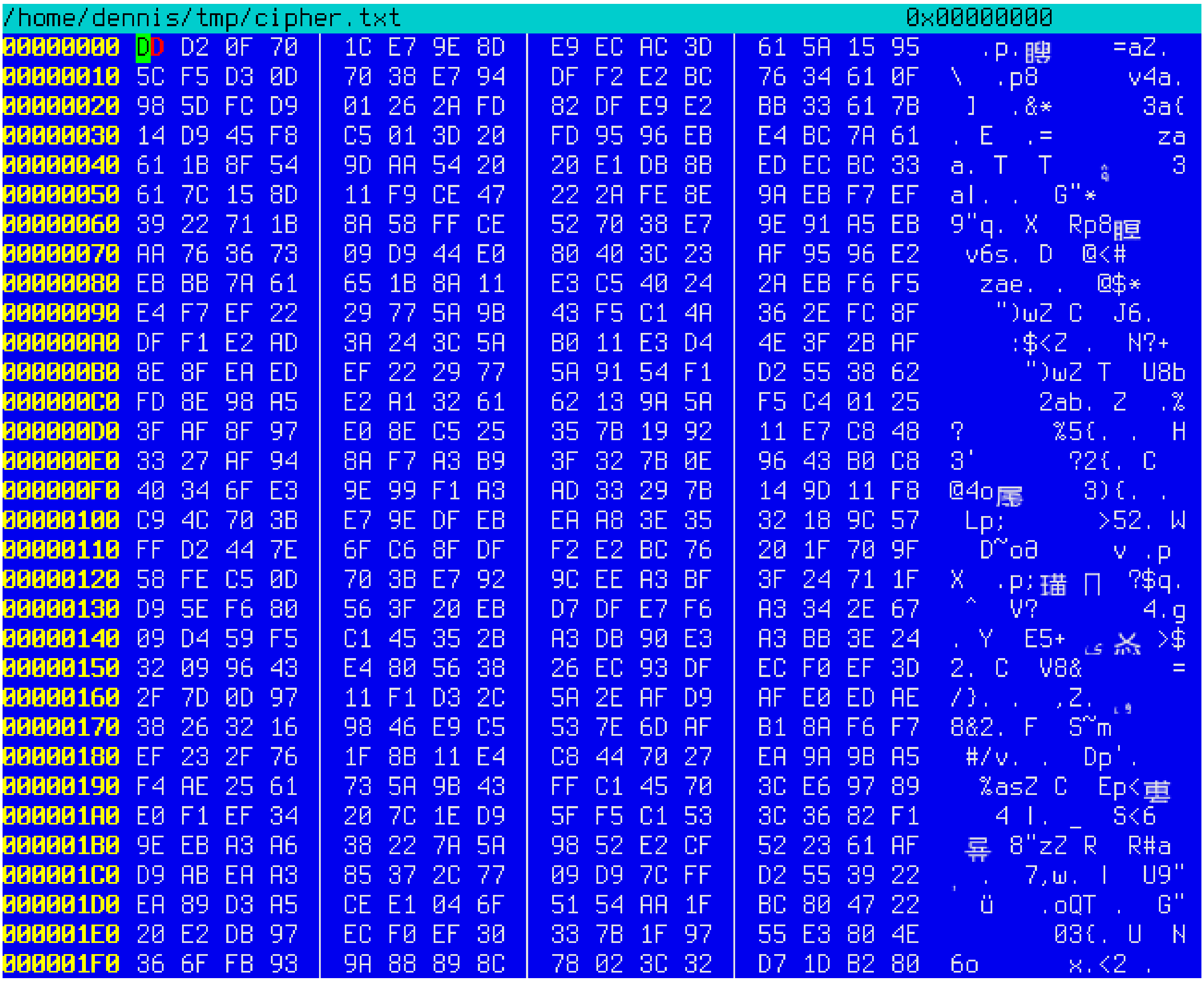


Figure 9.13: Encrypted file in Midnight Commander

The encrypted file can be downloaded here.

ent Linux utility reports about ~7.5 bits per byte, and this is high level of entropy (9.2 on page 948), close to compressed or properly encrypted file. But still, we clearly see some pattern, there are some blocks with size of 17 bytes, and you can see some kind of ladder, shifting by 1 byte at each 16-byte line.

It's also known that the plain text is just English language text.

Now let's assume that this piece of text is encrypted by simple XOR-ing with 17-byte key.

I tried to find some repeating 17-byte blocks using Mathematica, like I did before in my previous example (9.1.4 on page 936):

Listing 9.2: Mathematica

```
In[]:=input = BinaryReadList["/home/dennis/tmp/cipher.txt"];

In[]:=blocks = Partition[input, 17];

In[]:=Sort[Tally[blocks], #1[[2]] > #2[[2]] &]

Out[]:={{{248,128,88,63,58,175,159,154,232,226,161,50,97,127,3,217,80},1},
{{226,207,67,60,42,226,219,150,246,163,166,56,97,101,18,144,82},1},
{{228,128,79,49,59,250,137,154,165,236,169,118,53,122,31,217,65},1},
{{252,217,1,39,39,238,143,223,241,235,170,91,75,119,2,152,82},1},
{{244,204,88,112,59,234,151,147,165,238,170,118,49,126,27,144,95},1},
{{241,196,78,112,54,224,142,223,242,236,186,58,37,50,17,144,95},1},
{{176,201,71,112,56,230,143,151,234,246,187,118,44,125,8,156,17},1},
...
{{255,206,82,112,56,231,158,145,165,235,170,118,54,115,9,217,68},1},
{{249,206,71,34,42,254,142,154,235,247,239,57,34,113,27,138,88},1},
{{157,170,84,32,32,225,219,139,237,236,188,51,97,124,21,141,17},1},
{{248,197,1,61,32,253,149,150,235,228,188,122,97,97,27,143,84},1},
{{252,217,1,38,42,253,130,223,233,226,187,51,97,123,20,217,69},1},
{{245,211,13,112,56,231,148,223,242,226,188,118,52,97,15,152,93},1},
{{221,210,15,112,28,231,158,141,233,236,172,61,97,90,21,149,92},1}}
```

No luck, each 17-byte block is unique within the file and occurred only once. Perhaps, there are no 17-byte zero lacunas, or lacunas containing only spaces. It is possible indeed: such long space indentation and padding may be absent in tightly typeset text.

The first idea is to try all possible 17-byte keys and find those, which will result in readable text after decryption. Bruteforce is not an option, because there are 256^{17} possible keys ($\sim 10^{40}$), that's too much. But there are good news: who said we have to test 17-byte key as a whole, why can't we test each byte of key separately? It is possible indeed.

Now the algorithm is:

- try all 256 bytes for 1st byte of key;
- decrypt 1st byte of each 17-byte blocks in the file;
- are all decrypted bytes we got are printable? keep tabs on it;
- do so for all 17 bytes of key.

I've written the following Python script to check this idea:

Listing 9.3: Python script

```
each_Nth_byte=[""]*KEY_LEN

content=read_file(sys.argv[1])
# split input by 17-byte chunks:
all_chunks=chunks(content, KEY_LEN)
for c in all_chunks:
    for i in range(KEY_LEN):
        each_Nth_byte[i]=each_Nth_byte[i] + c[i]

# try each byte of key
for N in range(KEY_LEN):
    print "N=", N
    possible_keys=[]
    for i in range(256):
        tmp_key=chr(i)*len(each_Nth_byte[N])
        tmp=xor_strings(tmp_key,each_Nth_byte[N])
        # are all characters in tmp[] are printable?
        if is_string_printable(tmp)==False:
            continue
        possible_keys.append(i)
    print possible_keys, "len=", len(possible_keys)
```

(Full version of the source code is here.)

Here is its output:

```
N= 0
[144, 145, 151] len= 3
```

```
N= 1
[160, 161] len= 2
N= 2
[32, 33, 38] len= 3
N= 3
[80, 81, 87] len= 3
N= 4
[78, 79] len= 2
N= 5
[142, 143] len= 2
N= 6
[250, 251] len= 2
N= 7
[254, 255] len= 2
N= 8
[130, 132, 133] len= 3
N= 9
[130, 131] len= 2
N= 10
[206, 207] len= 2
N= 11
[81, 86, 87] len= 3
N= 12
[64, 65] len= 2
N= 13
[18, 19] len= 2
N= 14
[122, 123] len= 2
N= 15
[248, 249] len= 2
N= 16
[48, 49] len= 2
```

So there are 2 or 3 possible bytes for each byte of 17-byte key. This is much better than 256 possible bytes for each byte, but still too much. There are up to 1 million of possible keys:

Listing 9.4: Mathematica

```
In[]:= 3*2*3*3*2*2*2*2*3*2*2*3*2*2*2*2*2
Out[]= 995328
```

It's possible to check all of them, but then we must check visually, if the decrypted text is looks like English language text.

Let's also take into consideration the fact that we deal with 1) natural language; 2) English language. Natural languages has some prominent statistical features. First of all, punctuation and word lengths. What is average word length in English language? Let's just count spaces in some well-known English language texts using Mathematica.

Here is "The Complete Works of William Shakespeare" text file from Gutenberg Library:

Listing 9.5: Mathematica

```
In[]:= input = BinaryReadList["/home/dennis/tmp/pg100.txt"];

In[]:= Tally[input]
Out[]= {{239, 1}, {187, 1}, {191, 1}, {84, 39878}, {104,
  218875}, {101, 406157}, {32, 1285884}, {80, 12038}, {114,
  209907}, {111, 282560}, {106, 2788}, {99, 67194}, {116,
  291243}, {71, 11261}, {117, 115225}, {110, 216805}, {98,
  46768}, {103, 57328}, {69, 42703}, {66, 15450}, {107, 29345}, {102,
  69103}, {67, 21526}, {109, 95890}, {112, 46849}, {108, 146532}, {87,
   16508}, {115, 215605}, {105, 199130}, {97, 245509}, {83,
  34082}, {44, 83315}, {121, 85549}, {13, 124787}, {10, 124787}, {119,
   73155}, {100, 134216}, {118, 34077}, {46, 78216}, {89, 9128}, {45,
  8150}, {76, 23919}, {42, 73}, {79, 33268}, {82, 29040}, {73,
  55893}, {72, 18486}, {68, 15726}, {58, 1843}, {65, 44560}, {49,
  982}, {50, 373}, {48, 325}, {91, 2076}, {35, 3}, {93, 2068}, {74,
  2071}, {57, 966}, {52, 107}, {70, 11770}, {85, 14169}, {78,
  27393}, {75, 6206}, {77, 15887}, {120, 4681}, {33, 8840}, {60,
  468}, {86, 3587}, {51, 343}, {88, 608}, {40, 643}, {41, 644}, {62,
```

```
  440}, {39, 31077}, {34, 488}, {59, 17199}, {126, 1}, {95, 71}, {113,
   2414}, {81, 1179}, {63, 10476}, {47, 48}, {55, 45}, {54, 73}, {64,
  3}, {53, 94}, {56, 47}, {122, 1098}, {90, 532}, {124, 33}, {38,
  21}, {96, 1}, {125, 2}, {37, 1}, {36, 2}}

In[]:= Length[input]/1285884 // N
Out[]= 4.34712
```

There are 1285884 spaces in the whole file, and the frequency of space occurrence is 1 space per ~ 4.3 characters.

Now here is Alice's Adventures in Wonderland, by Lewis Carroll from the same library:

Listing 9.6: Mathematica

```
In[]:= input = BinaryReadList["/home/dennis/tmp/pg11.txt"];

In[]:= Tally[input]
Out[]= {{239, 1}, {187, 1}, {191, 1}, {80, 172}, {114, 6398}, {111,
  9243}, {106, 222}, {101, 15082}, {99, 2815}, {116, 11629}, {32,
  27964}, {71, 193}, {117, 3867}, {110, 7869}, {98, 1621}, {103,
  2750}, {39, 2885}, {115, 6980}, {65, 721}, {108, 5053}, {105,
  7802}, {100, 5227}, {118, 911}, {87, 256}, {97, 9081}, {44,
  2566}, {121, 2442}, {76, 158}, {119, 2696}, {67, 185}, {13,
  3735}, {10, 3735}, {84, 571}, {104, 7580}, {66, 125}, {107,
  1202}, {102, 2248}, {109, 2245}, {46, 1206}, {89, 142}, {112,
  1796}, {45, 744}, {58, 255}, {68, 242}, {74, 13}, {50, 12}, {53,
  13}, {48, 22}, {56, 10}, {91, 4}, {69, 313}, {35, 1}, {49, 68}, {93,
   4}, {82, 212}, {77, 222}, {57, 11}, {52, 10}, {42, 88}, {83,
  288}, {79, 234}, {70, 134}, {72, 309}, {73, 831}, {85, 111}, {78,
  182}, {75, 88}, {86, 52}, {51, 13}, {63, 202}, {40, 76}, {41,
  76}, {59, 194}, {33, 451}, {113, 135}, {120, 170}, {90, 1}, {122,
  79}, {34, 135}, {95, 4}, {81, 85}, {88, 6}, {47, 24}, {55, 6}, {54,
  7}, {37, 1}, {64, 2}, {36, 2}}

In[]:= Length[input]/27964 // N
Out[]= 5.99049
```

The result is different probably because of different formatting of these texts (maybe indentation and/or padding).

OK, so let's assume the average frequency of space in English language is 1 space per 4..7 characters.

Now the good news again: we can measure frequency of spaces while decrypting our file gradually. Now I count spaces in each *slice* and throw away 1-byte keys which produce results with too small number of spaces (or too large, but this is almost impossible given so short key):

Listing 9.7: Python script

```
each_Nth_byte=[""]*KEY_LEN

content=read_file(sys.argv[1])
# split input by 17-byte chunks:
all_chunks=chunks(content, KEY_LEN)
for c in all_chunks:
    for i in range(KEY_LEN):
        each_Nth_byte[i]=each_Nth_byte[i] + c[i]

# try each byte of key
for N in range(KEY_LEN):
    print "N=", N
    possible_keys=[]
    for i in range(256):
        tmp_key=chr(i)*len(each_Nth_byte[N])
        tmp=xor_strings(tmp_key,each_Nth_byte[N])
        # are all characters in tmp[] are printable?
        if is_string_printable(tmp)==False:
            continue
        # count spaces in decrypted buffer:
        spaces=tmp.count(' ')
        if spaces==0:
```

```
            continue
        spaces_ratio=len(tmp)/spaces
        if spaces_ratio<4:
            continue
        if spaces_ratio>7:
            continue
        possible_keys.append(i)
    print possible_keys, "len=", len(possible_keys)
```

(Full version of the source code is here.)

This reports just one single possible byte for each byte of key:

```
N= 0
[144] len= 1
N= 1
[160] len= 1
N= 2
[33] len= 1
N= 3
[80] len= 1
N= 4
[79] len= 1
N= 5
[143] len= 1
N= 6
[251] len= 1
N= 7
[255] len= 1
N= 8
[133] len= 1
N= 9
[131] len= 1
N= 10
[207] len= 1
N= 11
[86] len= 1
N= 12
[65] len= 1
N= 13
[18] len= 1
N= 14
[122] len= 1
N= 15
[249] len= 1
N= 16
[49] len= 1
```

Let's check this key in Mathematica:

Listing 9.8: Mathematica

```
In[]:= input = BinaryReadList["/home/dennis/tmp/cipher.txt"];

In[]:= blocks = Partition[input, 17];

In[]:= key = {144, 160, 33, 80, 79, 143, 251, 255, 133, 131, 207, 86, 65, 18, 122, 249, 49};

In[]:= EncryptBlock[blk_] := BitXor[key, blk]

In[]:= encrypted = Map[EncryptBlock[#] &, blocks];

In[]:= BinaryWrite["/home/dennis/tmp/plain2.txt", Flatten[encrypted]]

In[]:= Close["/home/dennis/tmp/plain2.txt"]
```

And the plain text is:

```
Mr. Sherlock Holmes, who was usually very late in the mornings, save
upon those not infrequent occasions when he was up all night, was seated
at the breakfast table. I stood upon the hearth-rug and picked up the
```

```
stick which our visitor had left behind him the night before. It was a
fine, thick piece of wood, bulbous-headed, of the sort which is known as
a "Penang lawyer." Just under the head was a broad silver band nearly
an inch across. "To James Mortimer, M.R.C.S., from his friends of the
C.C.H.," was engraved upon it, with the date "1884." It was just such a
stick as the old-fashioned family practitioner used to carry--dignified,
solid, and reassuring.

"Well, Watson, what do you make of it?"

Holmes was sitting with his back to me, and I had given him no sign of
my occupation.

...
```

(Full version of the text is here.)

The text looks correct. Yes, I made up this example and choose well-known text of Conan Doyle, but it's very close to what I had in my practice some time ago.

Other ideas to consider

If we would fail with space counting, there are other ideas to try:

- Take into consideration the fact that lowercase letters are much more frequent than uppercase ones.
- Frequency analysis.
- There is also a good technique to detect language of a text: trigrams. Each language has some very frequent letter triplets, these may be "the" and "tha" for English. Read more about it: N-Gram-Based Text Categorization, `http://code.activestate.com/recipes/326576/`. Interestingly enough, trigrams detection can be used when you decrypt a ciphertext gradually, like in this example (you just have to test 3 adjacent decrypted characters).

  For non-Latin writing systems encoded in UTF-8, things may be easier. For example, Russian text encoded in UTF-8 has each byte interleaved with 0xD0/0xD1 byte. It is because Cyrillic characters are placed in 4th block of Unicode table. Other writing systems has their own blocks.

9.2 Information entropy

For the sake of simplification, I would say, information entropy is a measure, how tightly some piece of data can be compressed. For example, it is usually not possible to compress already compressed archive file, so it has high entropy. On the other hand, 1MiB of zero bytes can be compressed to a tiny output file. Indeed, in plain English language, one million of zeros can be described just as "resulting file is one million zero bytes". Compressed files are usually a list of instructions to decompressor, like this: "put 1000 zeros, then 0x23 byte, then 0x45 byte, then put a block of size 10 bytes which we've seen 500 bytes back, etc."

Texts written in natural languages are also can be compressed tightly, because natural languages has a lot of redundancy (otherwise, a tiny typo will always lead to misunderstanding, like any toggled bit in compressed archive make decompression nearly impossible), some words are used very often, etc. In everyday speech, it's possible to drop up to half of words and it still be recognizable.

Code for CPUs is also can be compressed, because some ISA instructions are used much more often than others. In x86, most used instructions are `MOV`/`PUSH`/`CALL` (5.11.2 on page 731).

Data compressors and ciphers tend to produce very high entropy results. Good PRNG also produce data which cannot be compressed (it is possible to measure their quality by this sign).

So, in other words, entropy is a measure which can help to probe contents of unknown data block.

9.2.1 Analyzing entropy in Mathematica

(This part has been first appeared in my blog at 13-May-2015. Some discussion: `https://news.ycombinator.com/item?id=9545276`.)

It is possible to slice a file by blocks, calculate entropy of each and draw a graph. I did this in Wolfram Mathematica for demonstration and here is a source code (Mathematica 10):

```
(* loading the file *)
input=BinaryReadList["file.bin"];

(* setting block sizes *)
BlockSize=4096;BlockSizeToShow=256;

(* slice blocks by 4k *)
blocks=Partition[input,BlockSize];

(* how many blocks we've got? *)
Length[blocks]

(* calculate entropy for each block. 2 in Entropy[] (base) is set with the intention so Entropy↙
    ↳ []
function will produce the same results as Linux ent utility does *)
entropies=Map[N[Entropy[2,#]]&,blocks];

(* helper functions *)
fBlockToShow[input_,offset_]:=Take[input,{1+offset,1+offset+BlockSizeToShow}]
fToASCII[val_]:=FromCharacterCode[val,"PrintableASCII"]
fToHex[val_]:=IntegerString[val,16]
fPutASCIIWindow[data_]:=Framed[Grid[Partition[Map[fToASCII,data],16]]]
fPutHexWindow[data_]:=Framed[Grid[Partition[Map[fToHex,data],16],Alignment->Right]]

(* that will be the main knob here *)
{Slider[Dynamic[offset],{0,Length[input]-BlockSize,BlockSize}],Dynamic[BaseForm[offset,16]]}

(* main UI part *)
Dynamic[{ListLinePlot[entropies,GridLines->{{-1,offset/BlockSize,1}},Filling->Axis,AxesLabel↙
    ↳ ->{"offset","entropy"}],
CurrentBlock=fBlockToShow[input,offset];
fPutHexWindow[CurrentBlock],
fPutASCIIWindow[CurrentBlock]}]
```

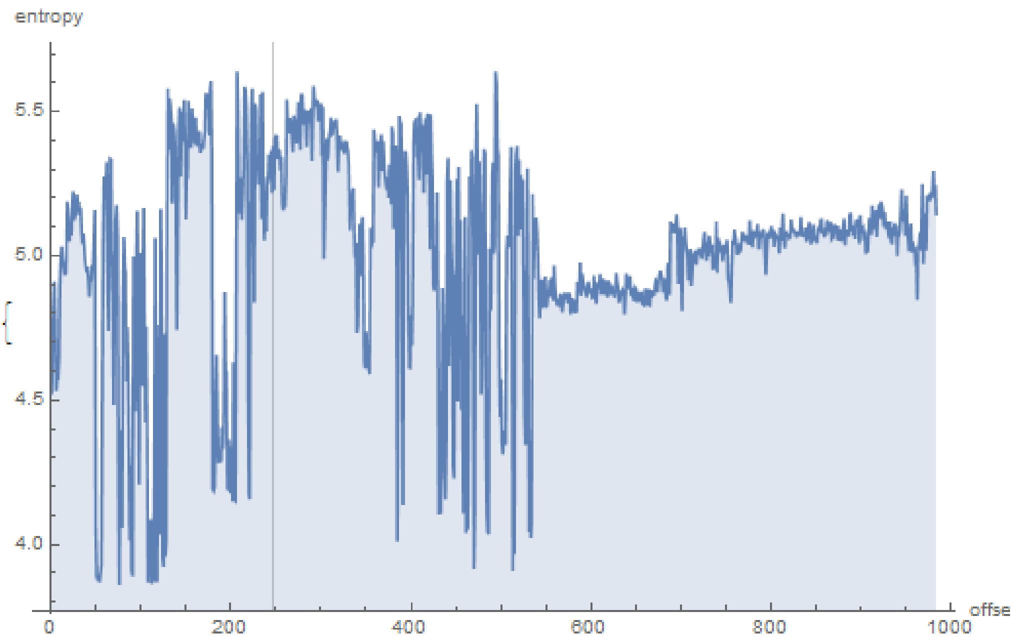
GeoIP ISP database

Let's start with the GeoIP file (which assigns ISP to the block of IP addresses). This binary file *GeoIPISP.dat* has some tables (which are IP address ranges perhaps) plus some text blob at the end of the file (containing ISP names).

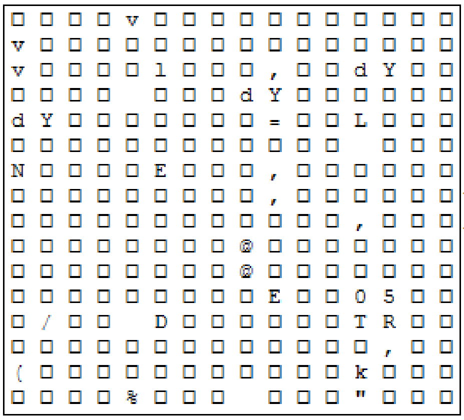
When I load it to Mathematica, I see this:

```
In[68]:= (* that will be the main knob here *)
         {Slider[Dynamic[offset], {0, Length[input] - BlockSize, BlockSize}]

Out[68]= {[slider], f7000₁₆}
```

```
In[59]:= (* main UI part *)
         Dynamic[{ListLinePlot[entropies, GridLines → {{-1, offset / BlockSiz
           CurrentBlock = fBlockToShow[input, offset];
           fPutHexWindow[CurrentBlock], fPutASCIIWindow[CurrentBlock]}]

Out[59]=
```




```
 1 ee  1 0 76 eb 5 0 17 c0  5 0 f3 de  5 0
76 eb  5 0  3 ee 1 0  4 ee  1 0  5 ee  1 0
76 eb  5 0 aa 6c 6 0 fd 2c  4 0 64 59 14 0
 7 ee  1 0  a ee 1 0 64 59 14 0  8 ee  1 0
64 59 14 0  9 ee 1 0 f0 3d  6 0 4c d3  6 0
 b ee  1 0  e ee 1 0  c ee  1 0  d ee  1 0
4e bc  6 0 17 45 6 0 fd 2c  4 0 b6 ed  4 0
 f ee  1 0 10 ee 1 0 fd 2c  4 0 f3 a3  5 0
8d df  5 0  2 dc 6 0 12 ee  1 0 2c ee  1 0
13 ee  1 0 1d ee 1 0 40 14  6 0 14 ee  1 0
15 ee  1 0 19 ee 1 0 40 14  6 0 16 ee  1 0
17 ee  1 0 18 ee 1 0  6 45  6 0 30 35  6 0
 c 2f  6 0  d 44 6 0 1a ee  1 0 54 52 14 0
1b ee  1 0 1c ee 1 0 e2 f8  6 0 fd 2c  4 0
28 c4  6 0 ee e0 5 0 1e ee  1 0 6b dc  e 0
1f ee  1 0 25 ee 1 0 20 ee  1 0 22 ee  1 0
```

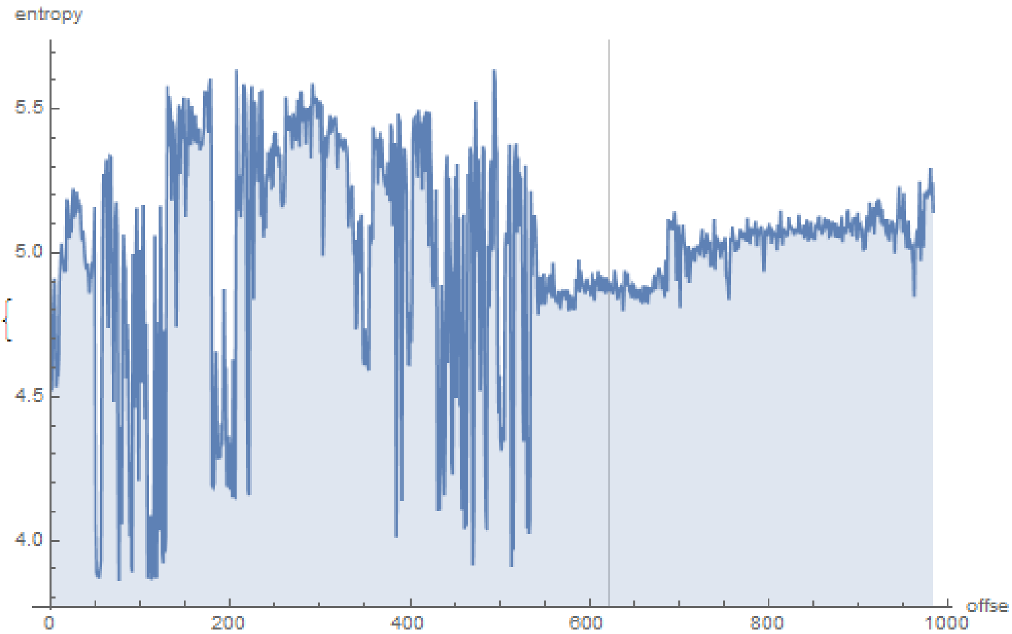


There are two parts in graph: first is somewhat chaotic, second is more steady.

0 in horizontal axis in graph means lowest entropy (the data which can be compressed very tightly, *ordered* in other words) and 8 is highest (cannot be compressed at all, *chaotic* or *random* in other words). Why 0 and 8? 0 means 0 bits per byte (byte as a container is not filled at all) and 8 means 8 bits per byte, i.e., the whole byte container is filled with the information tightly.

So I put slider to point in the middle of the first block, and I clearly see some array of 32-bit integers. Now I put slider in the middle of the second block and I see English text:

```
In[68]:= (* that will be the main knob here *)
         {Slider[Dynamic[offset], {0, Length[input] - BlockSize, BlockSize}]}

Out[68]= {[slider], 26d000₁₆}

In[59]:= (* main UI part *)
         Dynamic[{ListLinePlot[entropies, GridLines → {{-1, offset / BlockSiz
           CurrentBlock = fBlockToShow[input, offset];
           fPutHexWindow[CurrentBlock], fPutASCIIWindow[CurrentBlock]}]

Out[59]=
```




```
6c 69 73 68 69 6e 67 20 43 6f 6d 70 61 6e 79  0
43 61 6e 76 61 73 20 54 65 63 68 6e 6f 6c 6f 67
79  0 43 6f 6c 75 6d 62 75 73 20 4d 69 64 64 6c
65 20 53 63 68 6f 6f 6c  0 43 6f 61 73 74 61 6c
20 57 69 72 65 20 26 20 43 61 62 6c 65  0 43 75
72 72 65 6e 65 78  0 41 75 67 75 73 74 20 53 6f
66 74 77 61 72 65 20 43 6f 72 70 6f 72 61 74 69
6f 6e  0 41 6d 65 72 69 63 61 6e 20 41 75 74 6f
6d 6f 62 69 6c 65 20 41 73 73 6f 63 69 61 74 69
6f 6e 20 4e 61 74 6f 69 6e 61 6c 20 4f 66 66 69
63 65  0 41 63 75 72 65 78 20 45 6e 76 69 72 6f
6e 6d 65 6e 74 61 6c 20 43 6f 72 70 2e  0 50 72
69 6e 63 65 20 43 6f 72 70 6f 72 61 74 69 6f 6e
 0 47 6f 32 74 65 6c 2e 63 6f 6d  0 45 6d 70 6c
6f 79 6d 65 6e 74 20 53 65 63 75 72 69 74 79 20
43 6f 6d 6d 69 73 73 69 6f 6e  0 47 6c 6f 62 61
```

```
l i s h i n g   C o m p a n y □
C a n v a s   T e c h n o l o g
y □ C o l u m b u s   M i d d l
e   S c h o o l □ C o a s t a l
  W i r e   &   C a b l e □ C u
r r e n e x □ A u g u s t   S o
f t w a r e   C o r p o r a t i
o n □ A m e r i c a n   A u t o
m o b i l e   A s s o c i a t i
o n   N a t o i n a l   O f f i
c e □ A c u r e x   E n v i r o
n m e n t a l   C o r p . □ P r
i n c e   C o r p o r a t i o n
□ G o 2 t e l . c o m □ E m p l
o y m e n t   S e c u r i t y
C o m m i s s i o n □ G l o b a
```

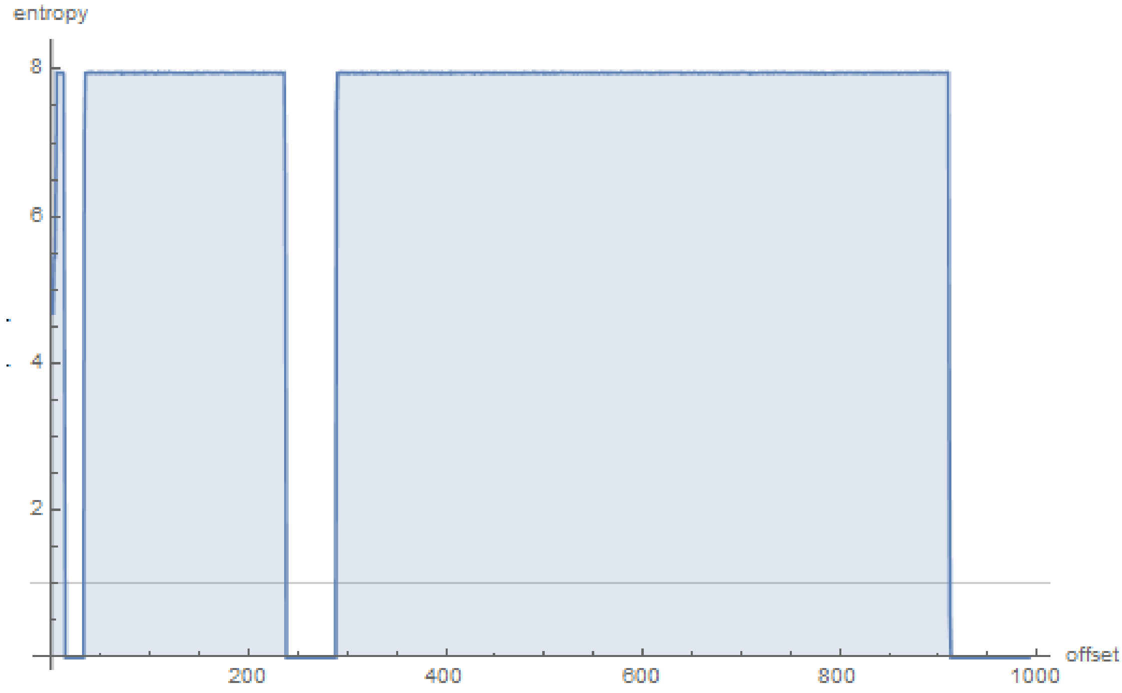
Indeed, this are names of ISPs. So, entropy of English text is 4.5-5.5 bits per byte? Yes, something like this. Wolfram Mathematica has some well-known English literature corpus embedded, and we can see entropy of Shakespeare's sonnets:

```
In[]:= Entropy[2,ExampleData[{"Text","ShakespearesSonnets"}]]//N
Out[]= 4.42366
```

4.4 is close to what we've got (4.7-5.3). Of course, classic English literature texts are somewhat different from ISP names and other English texts we can find in binary files (debugging/logging/error messages), but this value is close.

TP-Link WR941 firmware

Next example. I've got firmware for TP-Link WR941 router:



We see here 3 blocks with empty lacunas. Then the first block with high entropy (started at address 0) is small, second (address somewhere at 0x22000) is bigger and third (address 0x123000) is biggest. I can't be sure about exact entropy of the first block, but 2nd and 3rd has very high entropy, meaning that these blocks are either compressed and/or encrypted.

I tried binwalk for this firmware file:

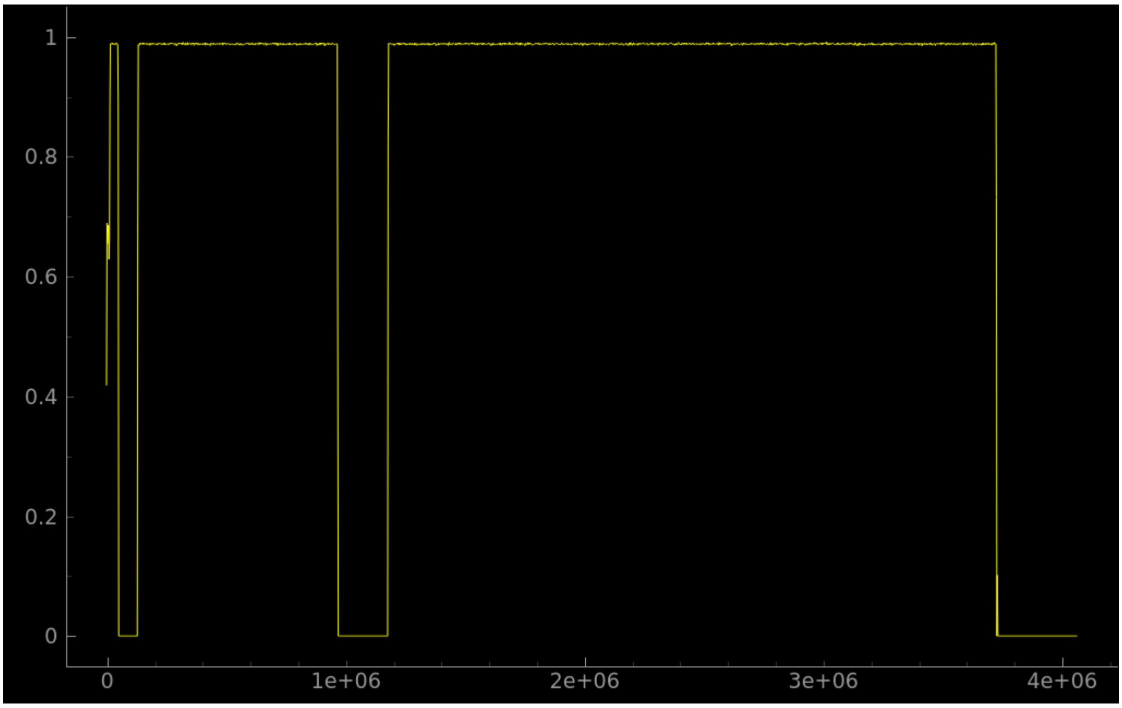
```
DECIMAL       HEXADECIMAL     DESCRIPTION
--------------------------------------------------------------------------------
0             0x0             TP-Link firmware header, firmware version: 0.-15221.3, image ↙
    ↳ version: "", product ID: 0x0, product version: 155254789, kernel load address: 0x0, ↙
    ↳ kernel entry point: 0x-7FFFE000, kernel offset: 4063744, kernel length: 512, rootfs ↙
    ↳ offset: 837431, rootfs length: 1048576, bootloader offset: 2883584, bootloader length: 0
14832         0x39F0          U-Boot version string, "U-Boot 1.1.4 (Jun 27 2014 - 14:56:49)"
14880         0x3A20          CRC32 polynomial table, big endian
16176         0x3F30          uImage header, header size: 64 bytes, header CRC: 0x3AC66E95, ↙
    ↳ created: 2014-06-27 06:56:50, image size: 34587 bytes, Data Address: 0x80010000, Entry ↙
    ↳ Point: 0x80010000, data CRC: 0xDF2DBA0B, OS: Linux, CPU: MIPS, image type: Firmware Image↙
    ↳ , compression type: lzma, image name: "u-boot image"
16240         0x3F70          LZMA compressed data, properties: 0x5D, dictionary size: 33554432↙
    ↳  bytes, uncompressed size: 90000 bytes
131584        0x20200         TP-Link firmware header, firmware version: 0.0.3, image version: ↙
    ↳ "", product ID: 0x0, product version: 155254789, kernel load address: 0x0, kernel entry ↙
    ↳ point: 0x-7FFFE000, kernel offset: 3932160, kernel length: 512, rootfs offset: 837431, ↙
    ↳ rootfs length: 1048576, bootloader offset: 2883584, bootloader length: 0
132096        0x20400         LZMA compressed data, properties: 0x5D, dictionary size: 33554432↙
    ↳  bytes, uncompressed size: 2388212 bytes
1180160       0x120200        Squashfs filesystem, little endian, version 4.0, compression:lzma↙
    ↳ , size: 2548511 bytes, 536 inodes, blocksize: 131072 bytes, created: 2014-06-27 07:06:52
```

Indeed: there are some stuff at the beginning, but two large LZMA compressed blocks are started at 0x20400 and 0x120200. These are roughly addresses we have seen in Mathematica. Oh, and by the way, binwalk can show entropy information as well (-E option):

```
DECIMAL       HEXADECIMAL     ENTROPY
--------------------------------------------------------------------------------
0             0x0             Falling entropy edge (0.419187)
16384         0x4000          Rising entropy edge (0.988639)
51200         0xC800          Falling entropy edge (0.000000)
133120        0x20800         Rising entropy edge (0.987596)
968704        0xEC800         Falling entropy edge (0.508720)
1181696       0x120800        Rising entropy edge (0.989615)
3727360       0x38E000        Falling entropy edge (0.732390)
```

Rising edges are corresponding to rising edges of block on our graph. Falling edges are the points where empty lacunas are started.

Binwalk can also generate PNG graphs (`-E -J`):

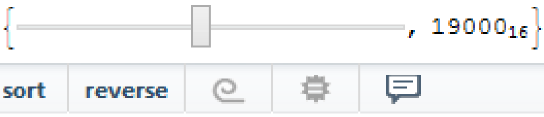


What can we say about lacunas? By looking in hex editor, we see that these are just filled with 0xFF bytes. Why developers put them? Perhaps, because they weren't able to calculate precise compressed blocks sizes, so they allocated space for them with some reserve.

Notepad

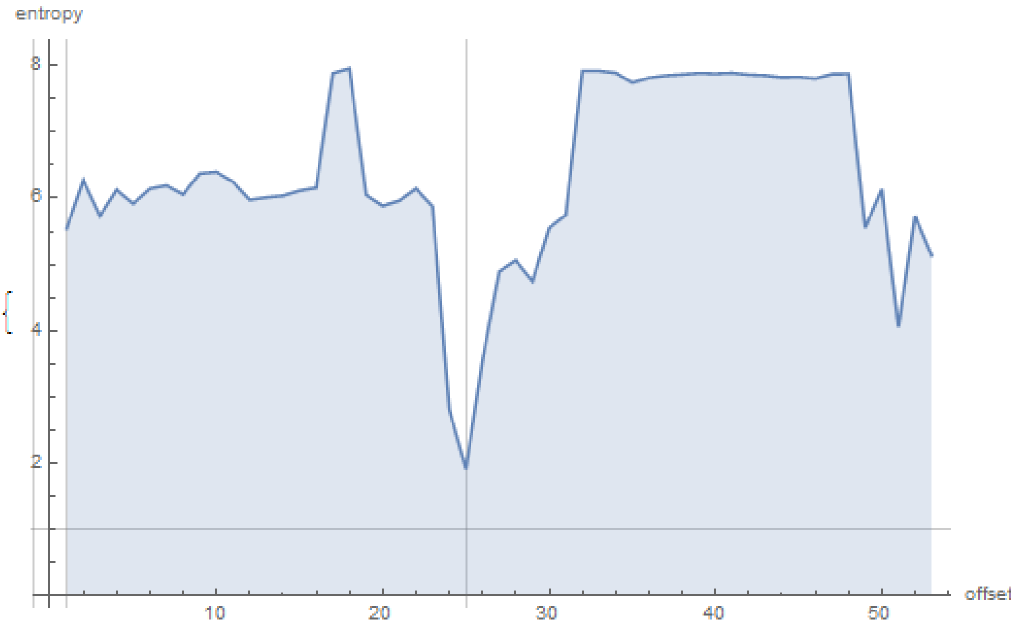
Another example is notepad.exe I've picked in Windows 8.1:

```
In[72]:= (* that will be the main knob here *)
         {Slider[Dynamic[offset], {0, Length[input] - BlockSize, BlockSize}],
```

Out[72]= 


```
In[59]:= (* main UI part *)
         Dynamic[{ListLinePlot[entropies, GridLines → {{-1, offset / BlockSiz
           CurrentBlock = fBlockToShow[input, offset];
           fPutHexWindow[CurrentBlock], fPutASCIIWindow[CurrentBlock]}]
```

Out[59]=



60	7f	1	0	d0	69	0	0	24	6a	0	0	8c	7f	1	0
24	6a	0	0	e0	6a	0	0	94	7f	1	0	e0	6a	0	0
a5	6b	0	0	14	7d	1	0	c0	6b	0	0	c	6c	0	0
c	7d	1	0	c	6c	0	0	5b	6c	0	0	9c	7f	1	0
5b	6c	0	0	a4	6c	0	0	15	c1	1	0	a4	6c	0	0
5f	6d	0	0	bc	7f	1	0	5f	6d	0	0	c0	6d	0	0
9d	c0	1	0	c0	6d	0	0	14	6e	0	0	28	7f	1	0
80	78	0	0	9e	78	0	0	bd	c1	1	0	9e	78	0	0
c4	78	0	0	f1	c0	1	0	c4	78	0	0	19	79	0	0
ed	c1	1	0	19	79	0	0	d7	81	0	0	31	c0	1	0
d7	81	0	0	d1	83	0	0	3d	c0	1	0	d1	83	0	0
b2	86	0	0	d	c0	1	0	b2	86	0	0	1f	87	0	0
69	c1	1	0	1f	87	0	0	3d	87	0	0	9	c1	1	0
3d	87	0	0	5a	87	0	0	15	c1	1	0	5a	87	0	0
83	87	0	0	85	c0	1	0	83	87	0	0	25	8a	0	0
61	c0	1	0	25	8a	0	0	36	8a	0	0	d5	c1	1	0

`	□	□	□	□	i	□	□	$	j	□	□	□	□	□	□
$	j	□	□	□	j	□	□	□	□	□	□	□	j	□	□
□	k	□	□	□	}	□	□	□	k	□	□	□	l	□	□
□	}	□	□	□	l	□	□	[	l	□	□	□	□	□	□
[	l	□	□	□	l	□	□	□	□	□	□	□	l	□	□
_	m	□	□	□	□	□	□	_	m	□	□	□	m	□	□
□	□	□	□	□	m	□	□	□	n	□	□	(	□	□	□
□	x	□	□	□	x	□	□	□	□	□	□	□	x	□	□
□	x	□	□	□	□	□	□	□	x	□	□	□	y	□	□
□	□	□	□	□	y	□	□	□	□	□	□	1	□	□	□
□	□	□	□	□	□	□	□	=	□	□	□	□	□	□	□
□	□	□	□		□	□	□	□	□	□	□	□	□	□	□
i	□	□	□	□	□	□	□	=	□	□	□	□	□	□	□
=	□	□	□	Z	□	□	□	□	□	□	□	Z	□	□	□
□	□	□	□	□	□	□	□	□	□	□	□	%	□	□	□
a	□	□	□	%	□	□	□	6	□	□	□	□	□	□	□

There is cavity at $\approx 0x19000$ (absolute file offset). I've opened the executable file in hex editor and found imports table there (which has lower entropy than x86-64 code in the first half of graph).

There are also high entropy block started at $\approx 0x20000$:

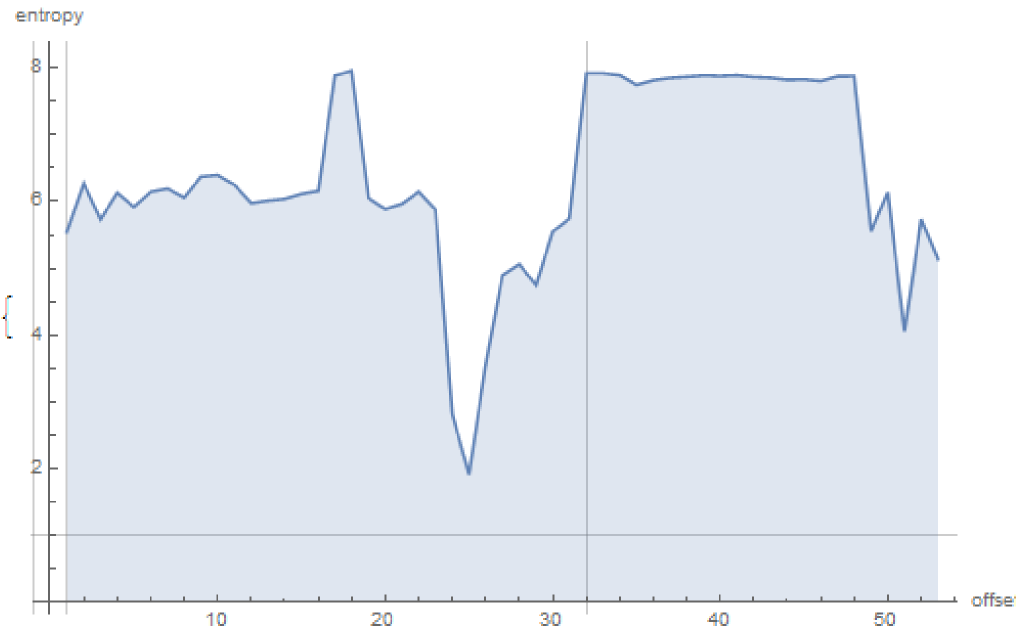
```
In[72]:= (* that will be the main knob here *)
         {Slider[Dynamic[offset], {0, Length[input] - BlockSize, BlockSize}],
```

Out[72]= {, 20000$_{16}$}

sort reverse

```
In[59]:= (* main UI part *)
         Dynamic[{ListLinePlot[entropies, GridLines → {{-1, offset / BlockSiz
           CurrentBlock = fBlockToShow[input, offset];
           fPutHexWindow[CurrentBlock], fPutASCIIWindow[CurrentBlock]}]
```

Out[59]= {




```
f5 d3  2  2 4f 6e  6 31 3a b9 86 33 4f 77 7e 3e
f4 b5  f fa df 4d b9 7d cd 8d 37 ad ff f3 25 97
9e ee f5 da eb  7 52 f2  b d7 1a ef cf de 83  5
19 d1 a3 1f 6b dd ba f0 ba 9b 6f 55 24 f1 c6 e8
e1 d3 f0 7e b6 da 4d 52 a8 6e ec 84 b7 df 4b 8f
7f cf a3 4f 1c 1e fe c1 98 41  8 25 9e cc af 5c
b8 6d 2b de 3f ff 91 24 90 50 6d 64 75 a3 d7 9b
6f 55 62 70 2a f0 ad 89 13 e2 31 3f b1  e 5e ff
73 53 da e4 ef c0 61 2c f4 3c 34 32 7c e0 9c  5
13 93 fd 87 8e 3a 30 76 da  7 1f b2 aa 82 f2 e6
17 f6 d4 26 88 e2 93 77 a7 cd 39 c1 d0 84 a3 dd
61 e9 f3 bb 38 79  5 86  c 2d 24 f0 6d c1 f4 43
7c 1e c0 3f a8 5b c6 c2 cc af bf f9 e6 ab 2f a1
 0 48  0 34 34  3 c8 e7 b8  6 c6 26 49 41 c5 22
99 36 37 40 c6 4f 7a 1f b1 ff 66 59 b5 73 9f ec
38 76 4a ca 96 ac 90 51 33 e6  9 fe d8 64 c4 f8
```

```
□ □ □ □ O n □ 1 : □ □ 3 O w ~ >
□ □ □ □ □ M □ } □ □ 7 □ □ □ % □
□ □ □ □ □ □ R □ □ □ □ □ □ □ □ □
□ □ □ □ k □ □ □ □ □ o U $ □ □ □
□ □ □ ~ □ □ M R □ n □ □ □ □ K □
□ □ □ O □ □ □ □ □ A □ % □ □ □ \
□ m + □ ? □ □ $ □ P m d u □ □ □
o U b p * □ □ □ □ □ 1 ? □ □ ^ □
s S □ □ □ □ a , □ < 4 2 | □ □ □
□ □ □ □ □ : 0 v □ □ □ □ □ □ □ □
□ □ □ & □ □ □ w □ □ 9 □ □ □ □ □
a □ □ □ 8 y □ □ □ - $ □ m □ □ C
| □ □ ? □ [ □ □ □ □ □ □ □ □ / □
□ H □ 4 4 □ □ □ □ □ □ & I A □ "
□ 6 7 @ □ O z □ □ □ f Y □ s □ □
8 v J □ □ □ □ Q 3 □ □ □ □ d □ □
```

}

In hex editor I can see PNG file here, embedded in the PE file resource section (it is a large image of notepad icon). PNG files are compressed, indeed.

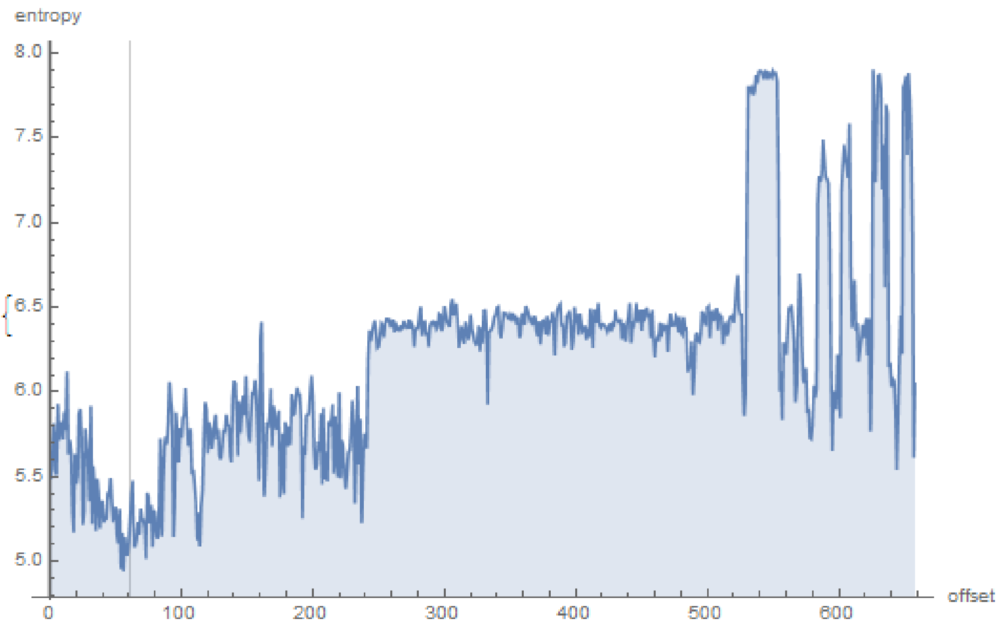
Unnamed dashcam

Now the most advanced example in this part is the firmware of some unnamed dashcam I've received from friend:

```
In[63]:= (* that will be the main knob here *)
         {Slider[Dynamic[offset], {0, Length[input] - BlockSize, BlockSize}],
```


```
In[59]:= (* main UI part *)
         Dynamic[{ListLinePlot[entropies, GridLines → {{-1, offset / BlockSiz
           CurrentBlock = fBlockToShow[input, offset];
           fPutHexWindow[CurrentBlock], fPutASCIIWindow[CurrentBlock]}]
```

Out[59]=




```
44 5f 53 50 49 5f 46 57 32  0  0  0 53 45 4d 49
44 5f 53 50 49 5f 46 57 33  0  0  0 53 45 4d 49
44 5f 53 50 49 5f 50 53  0  0  0  0 53 45 4d 49
44 5f 53 50 49 5f 50 53 32  0  0  0 53 45 4d 49
44 5f 53 50 49 5f 50 53 33  0  0  0 53 45 4d 49
44 5f 53 50 49 5f 46 41 54  0  0  0 53 45 4d 49
44 5f 53 50 49 5f 46 41 54 32  0  0 53 45 4d 49
44 5f 53 50 49 5f 46 41 54 33  0  0 5e 52 25 73
3a 3a 25 73 28 29 3a 25 64 2d 45 52 52 3a 20 25
73 3a 20 53 65 6e 4d 6f 64 65 28 25 64 29 20 6f
75 74 20 6f 66 20 72 61 6e 67 65 21 21 21  d  a
 0  0  0  0 41 52 30 33 33 30  0  0 5e 52 25 73
3a 3a 25 73 28 29 3a 25 64 2d 45 52 52 3a 20 45
72 72 6f 72 20 74 72 61 6e 73 6d 69 74 20 64 61
74 61 20 28 77 72 69 74 65 20 61 64 64 72 29 21
21  d  a  0 5e 52 25 73 3a 3a 25 73 28 29 3a 25
```

```
D _ S P I _ F W 2 □ □ □ S E M I
D _ S P I _ F W 3 □ □ □ S E M I
D _ S P I _ P S □ □ □ □ S E M I
D _ S P I _ P S 2 □ □ □ S E M I
D _ S P I _ P S 3 □ □ □ S E M I
D _ S P I _ F A T □ □ □ S E M I
D _ S P I _ F A T 2 □ □ S E M I
D _ S P I _ F A T 3 □ □ ^ R % s
: : % s ( ) : % d - E R R :   %
s :   S e n M o d e ( % d )   o
u t   o f   r a n g e ! ! !
□ □ □ □ A R 0 3 3 0 □ □ ^ R % s
: : % s ( ) : % d - E R R :   E
r r o r   t r a n s m i t   d a
t a   ( w r i t e   a d d r ) !
!       □ ^ R % s : : % s ( ) : %
```

The cavity at the very beginning is an English text: debugging messages. I checked various ISAs and I found that the first third of the whole file (with the text segment inside) is in fact MIPS (little-endian) code.

For instance, this is very distinctive MIPS function epilogue:

```
ROM:000013B0                 move    $sp, $fp
ROM:000013B4                 lw      $ra, 0x1C($sp)
ROM:000013B8                 lw      $fp, 0x18($sp)
ROM:000013BC                 lw      $s1, 0x14($sp)
ROM:000013C0                 lw      $s0, 0x10($sp)
ROM:000013C4                 jr      $ra
ROM:000013C8                 addiu   $sp, 0x20
```

From our graph we can see that MIPS code has entropy of 5-6 bits per byte. Indeed, I once measured various ISAs entropy and I've got these values:

- x86: .text section of ntoskrnl.exe file from Windows 2003: 6.6

- x64: .text section of ntoskrnl.exe file from Windows 7 x64: 6.5
- ARM (thumb mode), Angry Birds Classic: 7.05
- ARM (ARM mode) Linux Kernel 3.8.0: 6.03
- MIPS (little endian), .text section of user32.dll from Windows NT 4: 6.09

So the entropy of executable code is higher than of English text, but still can be compressed.

Now the second third is started at 0xF5000. I don't know what this is. I tried different ISAs but without success. The entropy of the block is looks even steadier than for executable one. Maybe some kind of data?

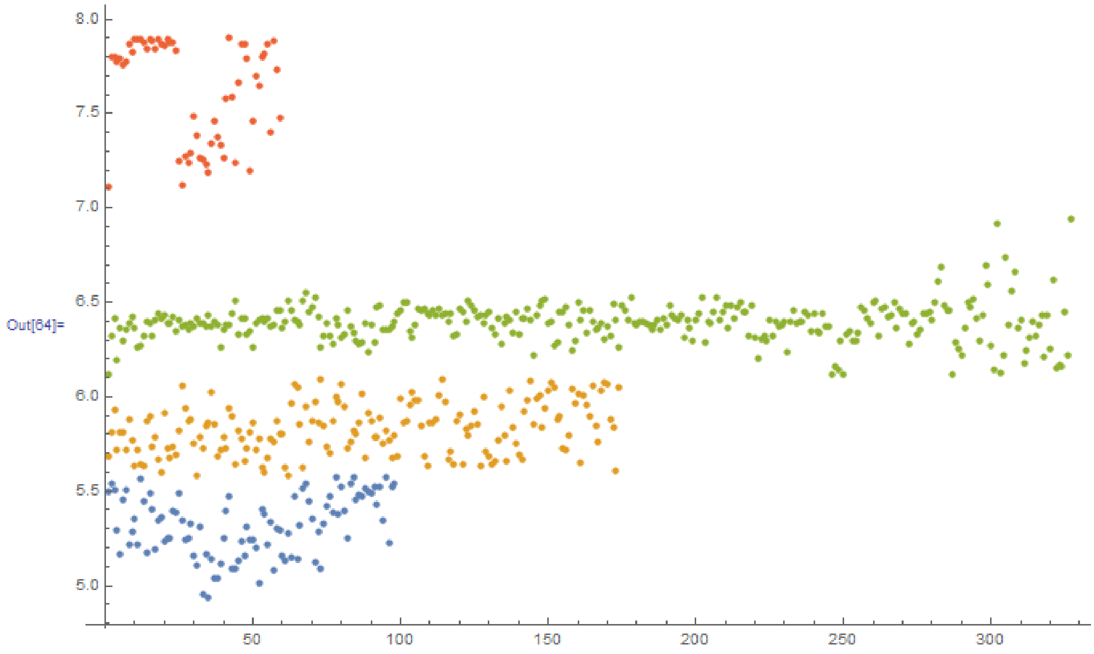
There is also a spike at $\approx 0x213000$. I checked it in hex editor and I found JPEG file there (which, of course, compressed)! I also don't know what is at the end. Let's try Binwalk for this file:

```
% binwalk FW96650A.bin

DECIMAL       HEXADECIMAL     DESCRIPTION
--------------------------------------------------------------------------------
167698        0x28F12         Unix path: /15/20/24/25/30/60/120/240fps can be served..
280286        0x446DE         Copyright string: "Copyright (c) 2012 Novatek Microelectronic ↙
    ↳ Corp."
2169199       0x21196F        JPEG image data, JFIF standard 1.01
2300847       0x231BAF        MySQL MISAM compressed data file Version 3

% binwalk -E FW96650A.bin

DECIMAL       HEXADECIMAL     ENTROPY
--------------------------------------------------------------------------------
0             0x0             Falling entropy edge (0.579792)
2170880       0x212000        Rising entropy edge (0.967373)
2267136       0x229800        Falling entropy edge (0.802974)
2426880       0x250800        Falling entropy edge (0.846639)
2490368       0x260000        Falling entropy edge (0.849804)
2560000       0x271000        Rising entropy edge (0.974340)
2574336       0x274800        Rising entropy edge (0.970958)
2588672       0x278000        Falling entropy edge (0.763507)
2592768       0x279000        Rising entropy edge (0.951883)
2596864       0x27A000        Falling entropy edge (0.712814)
2600960       0x27B000        Rising entropy edge (0.968167)
2607104       0x27C800        Rising entropy edge (0.958582)
2609152       0x27D000        Falling entropy edge (0.760989)
2654208       0x288000        Rising entropy edge (0.954127)
2670592       0x28C000        Rising entropy edge (0.967883)
2676736       0x28D800        Rising entropy edge (0.975779)
2684928       0x28F800        Falling entropy edge (0.744369)
```

Yes, it found JPEG file and even MySQL data! But I'm not sure if it's true—I didn't check it yet.

It's also interesting to try clusterization in Mathematica:

```
In[64]:= (* let also take a look on clustering attempt of Mathematica *)
         ListPlot[FindClusters[entropies]]
```



Here is an example of how Mathematica grouped various entropy values into distinctive groups. Indeed, there is something credible. Blue dots in range of 5.0-5.5 are supposedly related to English text. Yellow dots in 5.5-6 are MIPS code. A lot of green dots in 6.0-6.5 is the unknown second third. Orange dots close to 8.0 are related to compressed JPEG file. Other orange dots are supposedly related to the end of the firmware (unknown to us data).

Links

Binary files used in this part: https://github.com/DennisYurichev/RE-for-beginners/tree/master/ff/entropy/files. Wolfram Mathematica notebook file: https://github.com/DennisYurichev/RE-for-begi blob/master/ff/entropy/files/binary_file_entropy.nb (all cells must be evaluated to start things working).

9.2.2 Conclusion

Information entropy can be used as a quick-n-dirty method for inspecting unknown binary files. In particular, it is a very quick way to find compressed/encrypted pieces of data. Someone say it's possible to find RSA[6] (and other asymmetric cryptographic algorithms) public/private keys in executable code (keys has high entropy as well), but I didn't try this myself.

9.2.3 Tools

Handy Linux *ent* utility to measure entropy of a file[7].

There is a great online entropy visualizer made by Aldo Cortesi, which I tried to mimic using Mathematica: http://binvis.io. His articles about entropy visualization are worth reading: http://corte.si/posts/visualisation/entropy/index.html, http://corte.si/posts/visualisation/malware/index.html, http://corte.si/posts/visualisation/binvis/index.html.

radare2 framework has *#entropy* command for this.

A tool for IDA: IDAtropy[8].

[6] Rivest Shamir Adleman
[7] http://www.fourmilab.ch/random/
[8] https://github.com/danigargu/IDAtropy

9.2.4 A word about primitive encryption like XORing

It's interesting that simple XOR encryption doesn't affect entropy of data. I've shown this in *Norton Guide* example in the book (9.1.2 on page 929).

Generalizing: encryption by substitution cipher also doesn't affect entropy of data (and XOR can be viewed as substitution cipher). The reason of that is because entropy calculation algorithm view data on byte-level. On the other hand, the data encrypted by 2 or 4-byte XOR pattern will result in another level of entropy.

Nevertheless, low entropy is usually a good sign of weak amateur cryptography (which is also used in license keys/files, etc.).

9.2.5 More about entropy of executable code

It is quickly noticeable that probably a biggest source of high-entropy in executable code are relative offsets encoded in opcodes. For example, these two consequent instructions will have different relative offsets in their opcodes, while they are in fact pointing to the same function:

```
function proc
...
function endp

...

CALL function
...
CALL function
```

Ideal executable code compressor would encode information like this: *there is a CALL to a "function" at address X and the same CALL at address Y* without necessity to encode address of the *function* twice.

To deal with this, executable compressors are sometimes able to reduce entropy here. One example is UPX: `http://sourceforge.net/p/upx/code/ci/default/tree/doc/filter.txt`.

9.2.6 PRNG

When I run GnuPG to generate new private (secret) key, it asking for some entropy …

```
We need to generate a lot of random bytes. It is a good idea to perform
some other action (type on the keyboard, move the mouse, utilize the
disks) during the prime generation; this gives the random number
generator a better chance to gain enough entropy.

Not enough random bytes available.  Please do some other work to give
the OS a chance to collect more entropy! (Need 169 more bytes)
```

This means that good a PRNG produces long high-entropy results, and this is what the secret asymmetrical cryptographical key needs. But CPRNG[9] is tricky (because computer is highly deterministic device itself), so the GnuPG asking for some additional randomness from the user.

9.2.7 More examples

Here is a case where I try to calculate entropy of some blocks with unknown contents: 8.7 on page 864.

9.2.8 Entropy of various files

Entropy of random data is close to 8:

```
% dd bs=1M count=1 if=/dev/urandom | ent
Entropy = 7.999803 bits per byte.
```

[9]Cryptographically secure PseudoRandom Number Generator

This means, almost all available space inside of byte is filled with information.

256 bytes in range of 0..255 gives exact value of 8:

```
#!/usr/bin/env python
import sys

for i in range(256):
    sys.stdout.write(chr(i))
```

```
% python 1.py | ent
Entropy = 8.000000 bits per byte.
```

Order of bytes doesn't matter. This means, all available space inside of byte is filled.

Entropy of any block filled with zero bytes is 0:

```
% dd bs=1M count=1 if=/dev/zero | ent
Entropy = 0.000000 bits per byte.
```

Entropy of a string constisting of a single (any) byte is 0:

```
% echo -n "aaaaaaaaaaaaaaaaaaa" | ent
Entropy = 0.000000 bits per byte.
```

Entropy of base64 string is the same as entropy of source data, but multiplied by $\frac{3}{4}$. This is because base64 encoding uses 64 symbols instead of 256.

```
% dd bs=1M count=1 if=/dev/urandom | base64 | ent
Entropy = 6.022068 bits per byte.
```

Perhaps, 6.02 not that close to 6 because padding symbols (=) spoils our statistics for a little.

Uuencode also uses 64 symbols:

```
% dd bs=1M count=1 if=/dev/urandom | uuencode - | ent
Entropy = 6.013162 bits per byte.
```

This means, any base64 and Uuencode strings can be transmitted using 6-bit bytes or characters.

Any random information in hexadecimal form has entropy of 4 bits per byte:

```
% openssl rand -hex $\$$(( 2**16 )) | ent
Entropy = 4.000013 bits per byte.
```

Entropy of randomly picked English language text from Gutenberg library has entropy ≈ 4.5. The reason of this is because English texts uses mostly 26 symbols, and $log_2(26) = \approx 4.7$, i.e., you would need 5-bit bytes to transmit uncompressed English texts, that would be enough (it was indeed so in teletype era).

Randomly chosen Russian language text from http://lib.ru library is F.M.Dostoevsky "Idiot"[10], internally encoded in CP1251 encoding.

And this file has entropy of ≈ 4.98. Russian language has 33 characters, and $log_2(33) = \approx 5.04$. But it has unpopular and rare "ë" character. And $log_2(32) = 5$ (Russian alphabet without this rare character)—now this close to what we've got.

However, the text we studying uses "ë" letter, but, probably, it's still rarely used there.

The very same file transcoded from CP1251 to UTF-8 gave entropy of ≈ 4.23. Each Cyrillic character encoded in UTF-8 is usually encoded as a pair, and the first byte is always one of: 0xD0 or 0xD1. Perhaps, this caused bias.

Let's generate random bits and output them as "T" and "F" characters:

```
#!/usr/bin/env python
import random, sys

rt=""
for i in range(102400):
    if random.randint(0,1)==1:
```

[10] http://az.lib.ru/d/dostoewskij_f_m/text_0070.shtml

```
        rt=rt+"T"
    else:
        rt=rt+"F"
print rt
```

Sample: ...TTTFTFTTTFFFTTTFTTTTTTFTTFFTTTFTFTTFTTFFFFFF....

Entropy is very close to 1 (i.e., 1 bit per byte).

Let's generate random decimal digits:

```
#!/usr/bin/env python
import random, sys

rt=""
for i in range(102400):
    rt=rt+"%d" % random.randint(0,9)
print rt
```

Sample: ...52203466119390328807552582367031963888032....

Entropy will be close to 3.32, indeed, this is $log_2(10)$.

9.2.9 Making lower level of entropy

The author of these lines once saw a software which stored each byte of encrypted data in 3 bytes: each has $\approx \frac{byte}{3}$ value, so reconstructing encrypted byte back involving summing up 3 consecutive bytes. Looks absurdly.

But some people say this was done in order to conceal the very fact the data has something encrypted inside: measuring entropy of such block will show much lower level of it.

9.3 Millenium game save file

The "Millenium Return to Earth" is an ancient DOS game (1991), that allows you to mine resources, build ships, equip them and send them on other planets, and so on[11].

Like many other games, it allows you to save all game state into a file.

Let's see if we can find something in it.

[11] It can be downloaded for free here

So there is a mine in the game. Mines at some planets work faster, or slower on others. The set of resources is also different.

Here we can see what resources are mined at the time:

Figure 9.14: Mine: state 1

Let’s save a game state. This is a file of size 9538 bytes.

Let’s wait some “days” here in the game, and now we’ve got more resources from the mine:

Figure 9.15: Mine: state 2

Let's save game state again.

Now let's try to just do binary comparison of the save files using the simple DOS/Windows FC utility:

```
...> FC /b 2200save.i.v1 2200SAVE.I.V2

Comparing files 2200save.i.v1 and 2200SAVE.I.V2
00000016: 0D 04
00000017: 03 04
0000001C: 1F 1E
00000146: 27 3B
00000BDA: 0E 16
00000BDC: 66 9B
00000BDE: 0E 16
00000BE0: 0E 16
00000BE6: DB 4C
00000BE7: 00 01
00000BE8: 99 E8
00000BEC: A1 F3
00000BEE: 83 C7
00000BFB: A8 28
00000BFD: 98 18
00000BFF: A8 28
00000C01: A8 28
00000C07: D8 58
00000C09: E4 A4
00000C0D: 38 B8
00000C0F: E8 68
...
```

The output is incomplete here, there are more differences, but we will cut result to show the most interesting.

In the first state, we have 14 "units" of hydrogen and 102 "units" of oxygen.

We have 22 and 155 "units" respectively in the second state. If these values are saved into the save file, we would see this in the difference. And indeed we do. There is 0x0E (14) at position 0xBDA and this value is 0x16 (22) in the new version of the file. This is probably hydrogen. There is 0x66 (102) at position 0xBDC in the old version and 0x9B (155) in the new version of the file. This seems to be the oxygen.

Both files are available on the website for those who wants to inspect them (or experiment) more: beginners.re.

Here is the new version of file opened in Hiew, we marked the values related to the resources mined in the game:

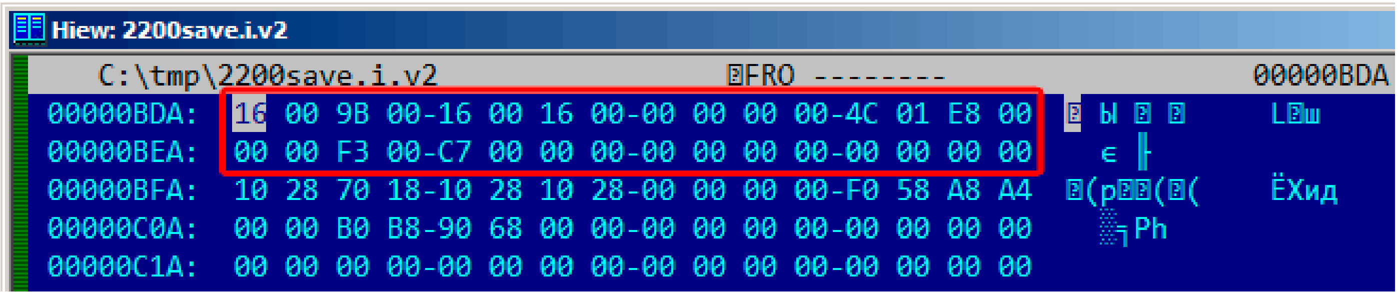


Figure 9.16: Hiew: state 1

Let’s check each of them.

These are clearly 16-bit values: not a strange thing for 16-bit DOS software where the *int* type has 16-bit width.

Let's check our assumptions. We will write the 1234 (0x4D2) value at the first position (this must be hydrogen):

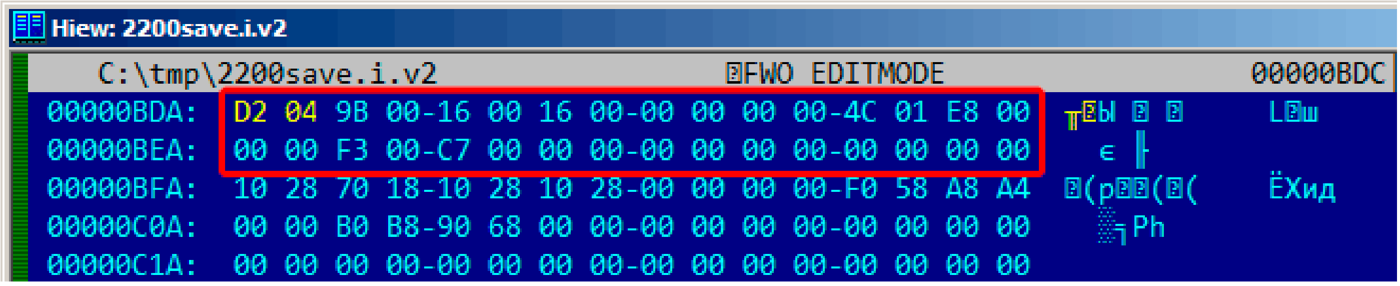


Figure 9.17: Hiew: let's write 1234 (0x4D2) there

Then we will load the changed file in the game and took a look at mine statistics:

Figure 9.18: Let's check for hydrogen value

So yes, this is it.

Now let's try to finish the game as soon as possible, set the maximal values everywhere:

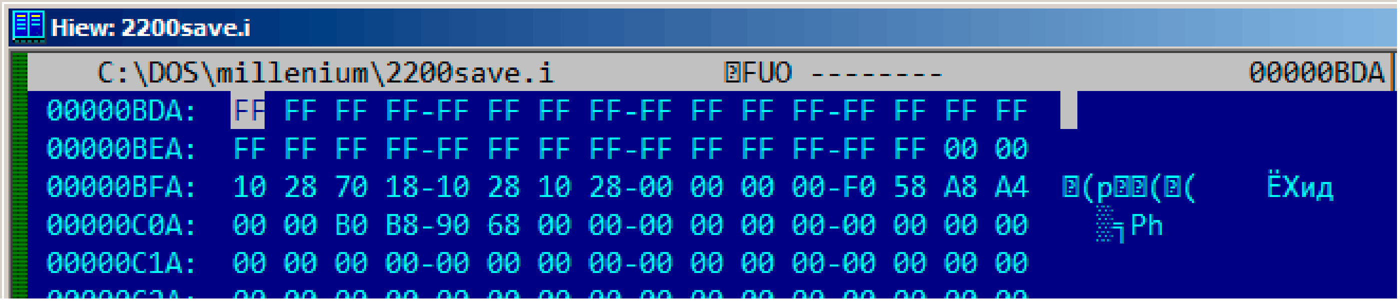


Figure 9.19: Hiew: let's set maximal values

0xFFFF is 65535, so yes, we now have a lot of resources:

Figure 9.20: All resources are 65535 (0xFFFF) indeed

Let's skip some "days" in the game and oops! We have a lower amount of some resources:

Figure 9.21: Resource variables overflow

That's just overflow.

The game's developer supposedly didn't think about such high amounts of resources, so there are probably no overflow checks, but the mine is "working" in the game, resources are added, hence the overflows. Apparently, it is a bad idea to be that greedy.

There are probably a lot of more values saved in this file.

So this is very simple method of cheating in games. High score files often can be easily patched like that.

More about files and memory snapshots comparing: 5.10.2 on page 725.

9.4 *fortune* program indexing file

(This part was first appeared in my blog at 25-Apr-2015.)

fortune is well-known UNIX program which shows random phrase from a collection. Some geeks are often set up their system in such way, so *fortune* can be called after logging on. *fortune* takes phrases from the text files laying in */usr/share/games/fortunes* (as of Ubuntu Linux). Here is example ("fortunes" text file):

```
A day for firm decisions!!!!!  Or is it?
%
A few hours grace before the madness begins again.
%
A gift of a flower will soon be made to you.
%
A long-forgotten loved one will appear soon.

Buy the negatives at any price.
%
```

```
A tall, dark stranger will have more fun than you.
%
...
```

So it is just phrases, sometimes multiline ones, divided by percent sign. The task of *fortune* program is to find random phrase and to print it. In order to achieve this, it must scan the whole text file, count phrases, choose random and print it. But the text file can get bigger, and even on modern computers, this naive algorithm is a bit uneconomical to computer resources. The straightforward way is to keep binary index file containing offset of each phrase in text file. With index file, *fortune* program can work much faster: just to choose random index element, take offset from there, set offset in text file and read phrase from it. This is actually done in *fortune* program. Let's inspect what is in its index file inside (these are .dat files in the same directory) in hexadecimal editor. This program is open-source of course, but intentionally, I will not peek into its source code.

```
% od -t x1 --address-radix=x fortunes.dat
000000 00 00 00 02 00 00 01 af 00 00 00 bb 00 00 00 0f
000010 00 00 00 00 25 00 00 00 00 00 00 00 00 00 00 2b
000020 00 00 00 60 00 00 00 8f 00 00 00 df 00 00 01 14
000030 00 00 01 48 00 00 01 7c 00 00 01 ab 00 00 01 e6
000040 00 00 02 20 00 00 02 3b 00 00 02 7a 00 00 02 c5
000050 00 00 03 04 00 00 03 3d 00 00 03 68 00 00 03 a7
000060 00 00 03 e1 00 00 04 19 00 00 04 2d 00 00 04 7f
000070 00 00 04 ad 00 00 04 d5 00 00 05 05 00 00 05 3b
000080 00 00 05 64 00 00 05 82 00 00 05 ad 00 00 05 ce
000090 00 00 05 f7 00 00 06 1c 00 00 06 61 00 00 06 7a
0000a0 00 00 06 d1 00 00 07 0a 00 00 07 53 00 00 07 9a
0000b0 00 00 07 f8 00 00 08 27 00 00 08 59 00 00 08 8b
0000c0 00 00 08 a0 00 00 08 c4 00 00 08 e1 00 00 08 f9
0000d0 00 00 09 27 00 00 09 43 00 00 09 79 00 00 09 a3
0000e0 00 00 09 e3 00 00 0a 15 00 00 0a 4d 00 00 0a 5e
0000f0 00 00 0a 8a 00 00 0a a6 00 00 0a bf 00 00 0a ef
000100 00 00 0b 18 00 00 0b 43 00 00 0b 61 00 00 0b 8e
000110 00 00 0b cf 00 00 0b fa 00 00 0c 3b 00 00 0c 66
000120 00 00 0c 85 00 00 0c b9 00 00 0c d2 00 00 0d 02
000130 00 00 0d 3b 00 00 0d 67 00 00 0d ac 00 00 0d e0
000140 00 00 0e 1e 00 00 0e 67 00 00 0e a5 00 00 0e da
000150 00 00 0e ff 00 00 0f 43 00 00 0f 8a 00 00 0f bc
000160 00 00 0f e5 00 00 10 1e 00 00 10 63 00 00 10 9d
000170 00 00 10 e3 00 00 11 10 00 00 11 46 00 00 11 6c
000180 00 00 11 99 00 00 11 cb 00 00 11 f5 00 00 12 32
000190 00 00 12 61 00 00 12 8c 00 00 12 ca 00 00 13 87
0001a0 00 00 13 c4 00 00 13 fc 00 00 14 1a 00 00 14 6f
0001b0 00 00 14 ae 00 00 14 de 00 00 15 1b 00 00 15 55
0001c0 00 00 15 a6 00 00 15 d8 00 00 16 0f 00 00 16 4e
...
```

Without any special aid we could see that there are four 4-byte elements on each 16-byte line. Perhaps, it's our index array. I'm trying to load the whole file in Wolfram Mathematica as 32-bit integer array:

```
In[]:= BinaryReadList["c:/tmp1/fortunes.dat", "UnsignedInteger32"]

Out[]= {33554432, 2936078336, 3137339392, 251658240, 0, 37, 0, \
721420288, 1610612736, 2399141888, 3741319168, 335609856, 1208025088, \
2080440320, 2868969472, 3858825216, 537001984, 989986816, 2046951424, \
3305242624, 67305472, 1023606784, 1745027072, 2801991680, 3775070208, \
419692544, 755236864, 2130968576, 2902720512, 3573809152, 84213760, \
990183424, 1678049280, 2181365760, 2902786048, 3456434176, \
4144300032, 470155264, 1627783168, 2047213568, 3506831360, 168230912, \
1392967680, 2584150016, 4161208320, 654835712, 1493696512, \
2332557312, 2684878848, 3288858624, 3775397888, 4178051072, \
...
```

Nope, something wrong. Numbers are suspiciously big. But let's back to *od* output: each 4-byte element has two zero bytes and two non-zero bytes, so the offsets (at least at the beginning of the file) are 16-bit at maximum. Probably different endianness is used in the file? Default endiannes in Mathematica is little-endian, as used in Intel CPUs. Now I'm changing it to big-endian:

```
In[]:= BinaryReadList["c:/tmp1/fortunes.dat", "UnsignedInteger32",
 ByteOrdering -> 1]
```

```
Out[]= {2, 431, 187, 15, 0, 620756992, 0, 43, 96, 143, 223, 276, \
328, 380, 427, 486, 544, 571, 634, 709, 772, 829, 872, 935, 993, \
1049, 1069, 1151, 1197, 1237, 1285, 1339, 1380, 1410, 1453, 1486, \
1527, 1564, 1633, 1658, 1745, 1802, 1875, 1946, 2040, 2087, 2137, \
2187, 2208, 2244, 2273, 2297, 2343, 2371, 2425, 2467, 2531, 2581, \
2637, 2654, 2698, 2726, 2751, 2799, 2840, 2883, 2913, 2958, 3023, \
3066, 3131, 3174, 3205, 3257, 3282, 3330, 3387, 3431, 3500, 3552, \
...
```

Yes, this is something readable. I choose random element (3066) which is 0xBFA in hexadecimal form. I'm opening 'fortunes' text file in hex editor, I'm setting 0xBFA as offset and I see this phrase:

```
% od -t x1 -c --skip-bytes=0xbfa --address-radix=x fortunes
000bfa  44  6f  20  77  68  61  74  20  63  6f  6d  65  73  20  6e  61
         D   o       w   h   a   t       c   o   m   e   s       n   a
000c0a  74  75  72  61  6c  6c  79  2e  20  20  53  65  65  74  68  65
         t   u   r   a   l   l   y   .           S   e   e   t   h   e
000c1a  20  61  6e  64  20  66  75  6d  65  20  61  6e  64  20  74  68
             a   n   d       f   u   m   e       a   n   d       t   h
....
```

Or:

```
Do what comes naturally.  Seethe and fume and throw a tantrum.
%
```

Other offset are also can be checked, yes, they are valid offsets.

I can also check in Mathematica that each subsequent element is bigger than previous. I.e., elements of array are ascending. In mathematics lingo, this is called *strictly increasing monotonic function*.

```
In[]:= Differences[input]

Out[]= {429, -244, -172, -15, 620756992, -620756992, 43, 53, 47, \
80, 53, 52, 52, 47, 59, 58, 27, 63, 75, 63, 57, 43, 63, 58, 56, 20, \
82, 46, 40, 48, 54, 41, 30, 43, 33, 41, 37, 69, 25, 87, 57, 73, 71, \
94, 47, 50, 50, 21, 36, 29, 24, 46, 28, 54, 42, 64, 50, 56, 17, 44, \
28, 25, 48, 41, 43, 30, 45, 65, 43, 65, 43, 31, 52, 25, 48, 57, 44, \
69, 52, 62, 73, 62, 53, 37, 68, 71, 50, 41, 57, 69, 58, 70, 45, 54, \
38, 45, 50, 42, 61, 47, 43, 62, 189, 61, 56, 30, 85, 63, 48, 61, 58, \
81, 50, 55, 63, 83, 80, 49, 42, 94, 54, 67, 81, 52, 57, 68, 43, 28, \
120, 64, 53, 81, 33, 82, 88, 29, 61, 32, 75, 63, 70, 47, 101, 60, 79, \
33, 48, 65, 35, 59, 47, 55, 22, 43, 35, 102, 53, 80, 65, 45, 31, 29, \
69, 32, 25, 38, 34, 35, 49, 59, 39, 41, 18, 43, 41, 83, 37, 31, 34, \
59, 72, 72, 81, 77, 53, 53, 50, 51, 45, 53, 39, 70, 54, 103, 33, 70, \
51, 95, 67, 54, 55, 65, 61, 54, 54, 53, 45, 100, 63, 48, 65, 71, 23, \
28, 43, 51, 61, 101, 65, 39, 78, 66, 43, 36, 56, 40, 67, 92, 65, 61, \
31, 45, 52, 94, 82, 82, 91, 46, 76, 55, 19, 58, 68, 41, 75, 30, 67, \
92, 54, 52, 108, 60, 56, 76, 41, 79, 54, 65, 74, 112, 76, 47, 53, 61, \
66, 53, 28, 41, 81, 75, 69, 89, 63, 60, 18, 18, 50, 79, 92, 37, 63, \
88, 52, 81, 60, 80, 26, 46, 80, 64, 78, 70, 75, 46, 91, 22, 63, 46, \
34, 81, 75, 59, 62, 66, 74, 76, 111, 55, 73, 40, 61, 55, 38, 56, 47, \
78, 81, 62, 37, 41, 60, 68, 40, 33, 54, 34, 41, 36, 49, 44, 68, 51, \
50, 52, 36, 53, 66, 46, 41, 45, 51, 44, 44, 33, 72, 40, 71, 57, 55, \
39, 66, 40, 56, 68, 43, 88, 78, 30, 54, 64, 36, 55, 35, 88, 45, 56, \
76, 61, 66, 29, 76, 53, 96, 36, 46, 54, 28, 51, 82, 53, 60, 77, 21, \
84, 53, 43, 104, 85, 50, 47, 39, 66, 78, 81, 94, 70, 49, 67, 61, 37, \
51, 91, 99, 58, 51, 49, 46, 68, 72, 40, 56, 63, 65, 41, 62, 47, 41, \
43, 30, 43, 67, 78, 80, 101, 61, 73, 70, 41, 82, 69, 45, 65, 38, 41, \
57, 82, 66}
```

As we can see, except of the very first 6 values (which is probably belongs to index file header), all numbers are in fact length of all text phrases (offset of the next phrase minus offset of the current phrase is in fact length of the current phrase).

It's very important to keep in mind that bit-endiannes can be confused with incorrect array start. Indeed, from *od* output we see that each element started with two zeros. But when shifted by two bytes in either side, we can interpret this array as little-endian:

```
% od -t x1 --address-radix=x --skip-bytes=0x32 fortunes.dat
000032 01 48 00 00 01 7c 00 00 01 ab 00 00 01 e6 00 00
000042 02 20 00 00 02 3b 00 00 02 7a 00 00 02 c5 00 00
000052 03 04 00 00 03 3d 00 00 03 68 00 00 03 a7 00 00
000062 03 e1 00 00 04 19 00 00 04 2d 00 00 04 7f 00 00
000072 04 ad 00 00 04 d5 00 00 05 05 00 00 05 3b 00 00
000082 05 64 00 00 05 82 00 00 05 ad 00 00 05 ce 00 00
000092 05 f7 00 00 06 1c 00 00 06 61 00 00 06 7a 00 00
0000a2 06 d1 00 00 07 0a 00 00 07 53 00 00 07 9a 00 00
0000b2 07 f8 00 00 08 27 00 00 08 59 00 00 08 8b 00 00
0000c2 08 a0 00 00 08 c4 00 00 08 e1 00 00 08 f9 00 00
0000d2 09 27 00 00 09 43 00 00 09 79 00 00 09 a3 00 00
0000e2 09 e3 00 00 0a 15 00 00 0a 4d 00 00 0a 5e 00 00
...
```

If we would interpret this array as little-endian, the first element is 0x4801, second is 0x7C01, etc. High 8-bit part of each of these 16-bit values are seems random to us, and the lowest 8-bit part is seems ascending.

But I'm sure that this is big-endian array, because the very last 32-bit element of the file is big-endian (*00 00 5f c4* here):

```
% od -t x1 --address-radix=x fortunes.dat
...
000660 00 00 59 0d 00 00 59 55 00 00 59 7d 00 00 59 b5
000670 00 00 59 f4 00 00 5a 35 00 00 5a 5e 00 00 5a 9c
000680 00 00 5a cb 00 00 5a f4 00 00 5b 1f 00 00 5b 3d
000690 00 00 5b 68 00 00 5b ab 00 00 5b f9 00 00 5c 49
0006a0 00 00 5c ae 00 00 5c eb 00 00 5d 34 00 00 5d 7a
0006b0 00 00 5d a3 00 00 5d f5 00 00 5e 3a 00 00 5e 67
0006c0 00 00 5e a8 00 00 5e ce 00 00 5e f7 00 00 5f 30
0006d0 00 00 5f 82 00 00 5f c4
0006d8
```

Perhaps, *fortune* program developer had big-endian computer or maybe it was ported from something like it.

OK, so the array is big-endian, and, judging by common sense, the very first phrase in the text file must be started at zeroth offset. So zero value should be present in the array somewhere at the very beginning. We've got couple of zero elements at the beginning. But the second is most appealing: 43 is going right after it and 43 is valid offset to valid English phrase in the text file.

The last array element is 0x5FC4, and there are no such byte at this offset in the text file. So the last array element is pointing behind the end of file. It's supposedly done because phrase length is calculated as difference between offset to the current phrase and offset to the next phrase. This can be faster than traversing phrase string for percent character. But this wouldn't work for the last element. So the *dummy* element is also added at the end of array.

So the first 6 32-bit integer values are supposedly some kind of header.

Oh, I forgot to count phrases in text file:

```
% cat fortunes | grep % | wc -l
432
```

The number of phrases can be present in index, but may be not. In case of very simple index files, number of elements can be easily deduced from index file size. Anyway, there are 432 phrases in the text file. And we see something very familiar at the second element (value 431). I've checked other files (literature.dat and riddles.dat in Ubuntu Linux) and yes, the second 32-bit element is indeed number of phrases minus 1. Why *minus 1*? Perhaps, this is not number of phrases, but rather the number of the last phrase (starting at zero)?

And there are some other elements in the header. In Mathematica, I'm loading each of three available files and I'm taking a look on the header:

```
In[14]:= input = BinaryReadList["c:/tmp1/fortunes.dat", "UnsignedInteger32",
           ByteOrdering → 1];

In[18]:= BaseForm[Take[input, {1, 6}], 16]

Out[18]//BaseForm=
         {2_16, 1af_16, bb_16, f_16, 0_16, 25000000_16}

In[19]:= input = BinaryReadList["c:/tmp1/literature.dat", "UnsignedInteger32",
           ByteOrdering → 1];

In[20]:= BaseForm[Take[input, {1, 6}], 16]

Out[20]//BaseForm=
         {2_16, 106_16, 983_16, 1a_16, 0_16, 25000000_16}

In[21]:= input = BinaryReadList["c:/tmp1/riddles.dat", "UnsignedInteger32", ByteOrdering → 1];

In[22]:= BaseForm[Take[input, {1, 6}], 16]

Out[22]//BaseForm=
         {2_16, 80_16, 7f2_16, 24_16, 0_16, 25000000_16}
```

I have no idea what other values mean, except the size of index file. Some fields are the same for all files, some are not. From my own experience, there could be:

- file signature;
- file version;
- checksum;
- some flags;
- maybe even text language identifier;
- text file timestamp, so the *fortune* program will regenerate index file if a user modified text file.

For example, Oracle .SYM files (9.5 on the following page) which contain symbols table for DLL files, also contain timestamp of corresponding DLL file, so to be sure it is still valid.

On the other hand, text file and index file timestamps can gone out of sync after archiving/unarchiving/installing/deploying/etc.

But there are no timestamp, in my opinion. The most compact way of representing date and time is UNIX time value, which is big 32-bit number. We don't see any of such here. Other ways of representation are even less compact.

So here is algorithm, how *fortune* supposedly works:

- take number of last phrase from the second element;
- generate random number in range of 0..number_of_last_phrase;
- find corresponding element in array of offsets, take also following offset;
- output to *stdout* all characters from the text file starting at the offset until the next offset minus 2 (so to ignore terminating percent sign and character of the following phrase).

9.4.1 Hacking

Let's try to check some of our assumptions. I will create this text file under the path and name */usr/share/games/fortunes/fortunes*:

```
Phrase one.
%
Phrase two.
%
```

Then this fortunes.dat file. I take header from the original fortunes.dat, I changed second field (count of all phrases) to zero and I left two elements in the array: 0 and 0x1c, because the whole length of the text *fortunes* file is 28 (0x1c) bytes:

```
% od -t x1 --address-radix=x fortunes.dat
000000 00 00 00 02 00 00 00 00 00 00 00 bb 00 00 00 0f
000010 00 00 00 00 25 00 00 00 00 00 00 00 00 00 00 1c
```

Now I run it:

```
% /usr/games/fortune
fortune: no fortune found
```

Something wrong. Let's change the second field to 1:

```
% od -t x1 --address-radix=x fortunes.dat
000000 00 00 00 02 00 00 00 01 00 00 00 bb 00 00 00 0f
000010 00 00 00 00 25 00 00 00 00 00 00 00 00 00 00 1c
```

Now it works. It's always shows only the first phrase:

```
% /usr/games/fortune
Phrase one.
```

Hmmm. Let's leave only one element in array (0) without terminating one:

```
% od -t x1 --address-radix=x fortunes.dat
000000 00 00 00 02 00 00 00 01 00 00 00 bb 00 00 00 0f
000010 00 00 00 00 25 00 00 00 00 00 00 00
00001c
```

Fortune program always shows only first phrase.

From this experiment we got to know that percent sign in text file is parsed and the size is not calculated as I deduced before, perhaps, even terminal array element is not used. However, it still can be used. And probably it was used in past?

9.4.2 The files

For the sake of demonstration, I still didn't take a look in *fortune* source code. If you want to try to understand meaning of other values in index file header, you may try to achieve it without looking into source code as well. Files I took from Ubuntu Linux 14.04 are here: http://beginners.re/examples/fortune/, hacked files are also here.

Oh, and I took the files from x64 version of Ubuntu, but array elements are still has size of 32 bit. It is because *fortune* text files are probably never exceeds 4GiB[12] size. But if it will, all elements must have size of 64 bit so to be able to store offset to the text file larger than 4GiB.

For impatient readers, the source code of *fortune* is here: https://launchpad.net/ubuntu/+source/fortune-mod/1:1.99.1-3.1ubuntu4.

9.5 Oracle RDBMS: .SYM-files

When an Oracle RDBMS process experiences some kind of crash, it writes a lot of information into log files, including stack trace, like this:

```
----- Call Stack Trace -----
calling              call     entry                argument values in hex
location             type     point                (? means dubious value)
-------------------- -------- -------------------- ----------------------------
_kqvrow()                     00000000
_opifch2()+2729      CALLptr  00000000             23D4B914 E47F264 1F19AE2
                                                   EB1C8A8 1
_kpoal8()+2832       CALLrel  _opifch2()           89 5 EB1CC74
```

[12] Gibibyte

```
_opiodr()+1248       CALLreg  00000000           5E 1C EB1F0A0
_ttcpip()+1051       CALLreg  00000000           5E 1C EB1F0A0 0
_opitsk()+1404       CALL???  00000000           C96C040 5E EB1F0A0 0 EB1ED30
                                                 EB1F1CC 53E52E 0 EB1F1F8
_opiino()+980        CALLrel  _opitsk()          0 0
_opiodr()+1248       CALLreg  00000000           3C 4 EB1FBF4
_opidrv()+1201       CALLrel  _opiodr()          3C 4 EB1FBF4 0
_sou2o()+55          CALLrel  _opidrv()          3C 4 EB1FBF4
_opimai_real()+124   CALLrel  _sou2o()           EB1FC04 3C 4 EB1FBF4
_opimai()+125        CALLrel  _opimai_real()     2 EB1FC2C
_OracleThreadStart@  CALLrel  _opimai()          2 EB1FF6C 7C88A7F4 EB1FC34 0
4()+830                                          EB1FD04
77E6481C             CALLreg  00000000           E41FF9C 0 0 E41FF9C 0 EB1FFC4
00000000             CALL???  00000000
```

But of course, Oracle RDBMS's executables must have some kind of debug information or map files with symbol information included or something like that.

Windows NT Oracle RDBMS has symbol information in files with .SYM extension, but the format is proprietary. (Plain text files are good, but needs additional parsing, hence offer slower access.)

Let's see if we can understand its format.

We will pick the shortest `orawtc8.sym` file that comes with the `orawtc8.dll` file in Oracle 8.1.7 [13].

[13] We can chose an ancient Oracle RDBMS version intentionally due to the smaller size of its modules

Here is the file opened in Hiew:

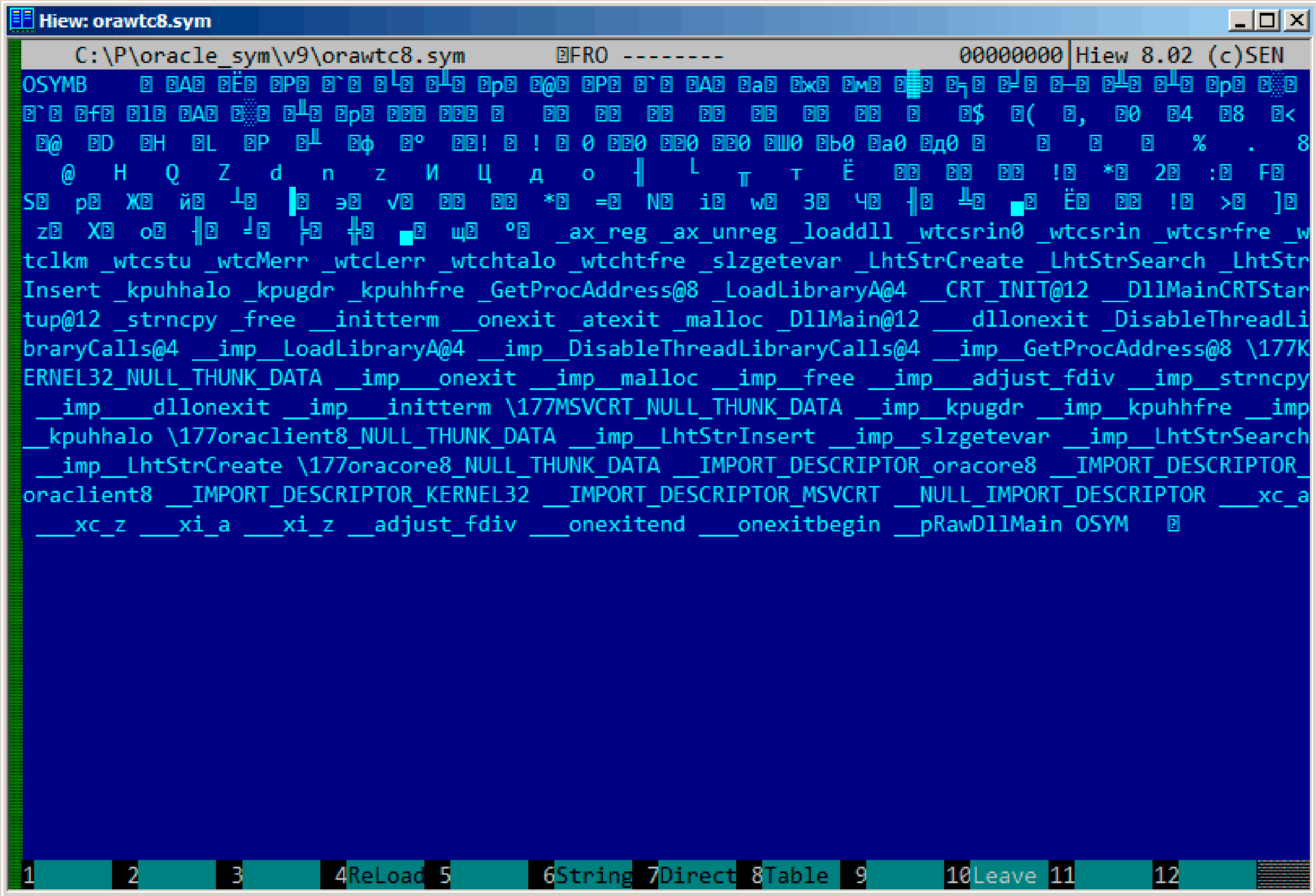


Figure 9.22: The whole file in Hiew

By comparing the file with other .SYM files, we can quickly see that OSYM is always header (and footer), so this is maybe the file's signature.

We also see that basically, the file format is: OSYM + some binary data + zero delimited text strings + OSYM. The strings are, obviously, function and global variable names.

We will mark the OSYM signatures and strings here:

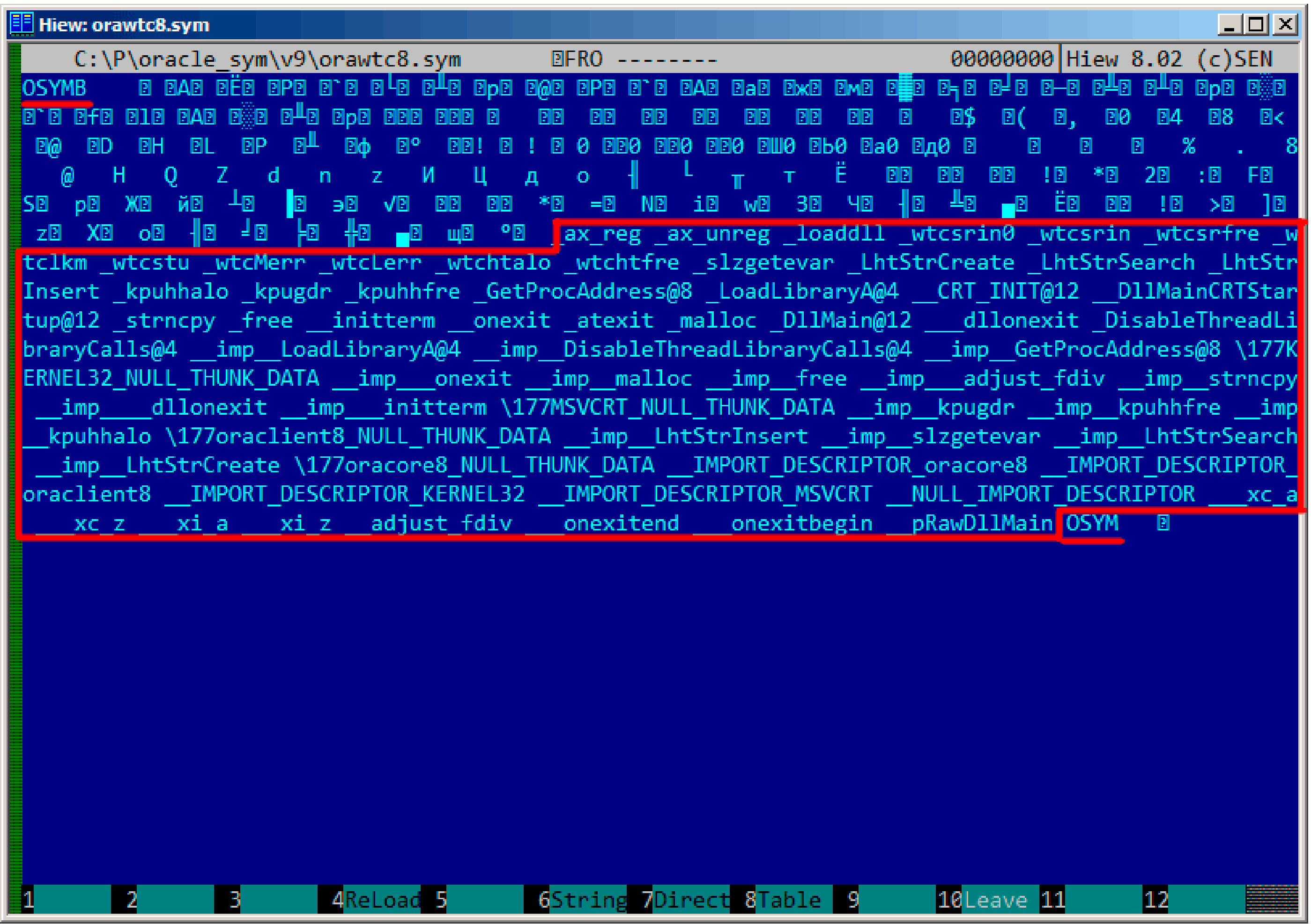


Figure 9.23: OSYM signature and text strings

Well, let's see. In Hiew, we will mark the whole strings block (except the trailing OSYM signatures) and put it into a separate file. Then we run UNIX *strings* and *wc* utilities to count the text strings:

```
strings strings_block | wc -l
66
```

So there are 66 text strings. Please note that number.

We can say, in general, as a rule, the number of *anything* is often stored separately in binary files.

It's indeed so, we can find the 66 value (0x42) at the file's start, right after the OSYM signature:

```
$ hexdump -C orawtc8.sym
00000000  4f 53 59 4d 42 00 00 00  00 10 00 10 80 10 00 10  |OSYMB...........|
00000010  f0 10 00 10 50 11 00 10  60 11 00 10 c0 11 00 10  |....P...`.......|
00000020  d0 11 00 10 70 13 00 10  40 15 00 10 50 15 00 10  |....p...@...P...|
00000030  60 15 00 10 80 15 00 10  a0 15 00 10 a6 15 00 10  |`...............|
....
```

Of course, 0x42 here is not a byte, but most likely a 32-bit value packed as little-endian, hence we see 0x42 and then at least 3 zero bytes.

Why do we believe it's 32-bit? Because, Oracle RDBMS's symbol files may be pretty big.

The oracle.sym file for the main oracle.exe (version 10.2.0.4) executable contains `0x3A38E` (238478) symbols. A 16-bit value isn't enough here.

We can check other .SYM files like this and it proves our guess: the value after the 32-bit OSYM signature always reflects the number of text strings in the file.

It's a general feature of almost all binary files: a header with a signature plus some other information about the file.

Now let's investigate closer what this binary block is.

Using Hiew again, we put the block starting at address 8 (i.e., after the 32-bit *count* value) ending at the strings block, into a separate binary file.

Let's see the binary block in Hiew:

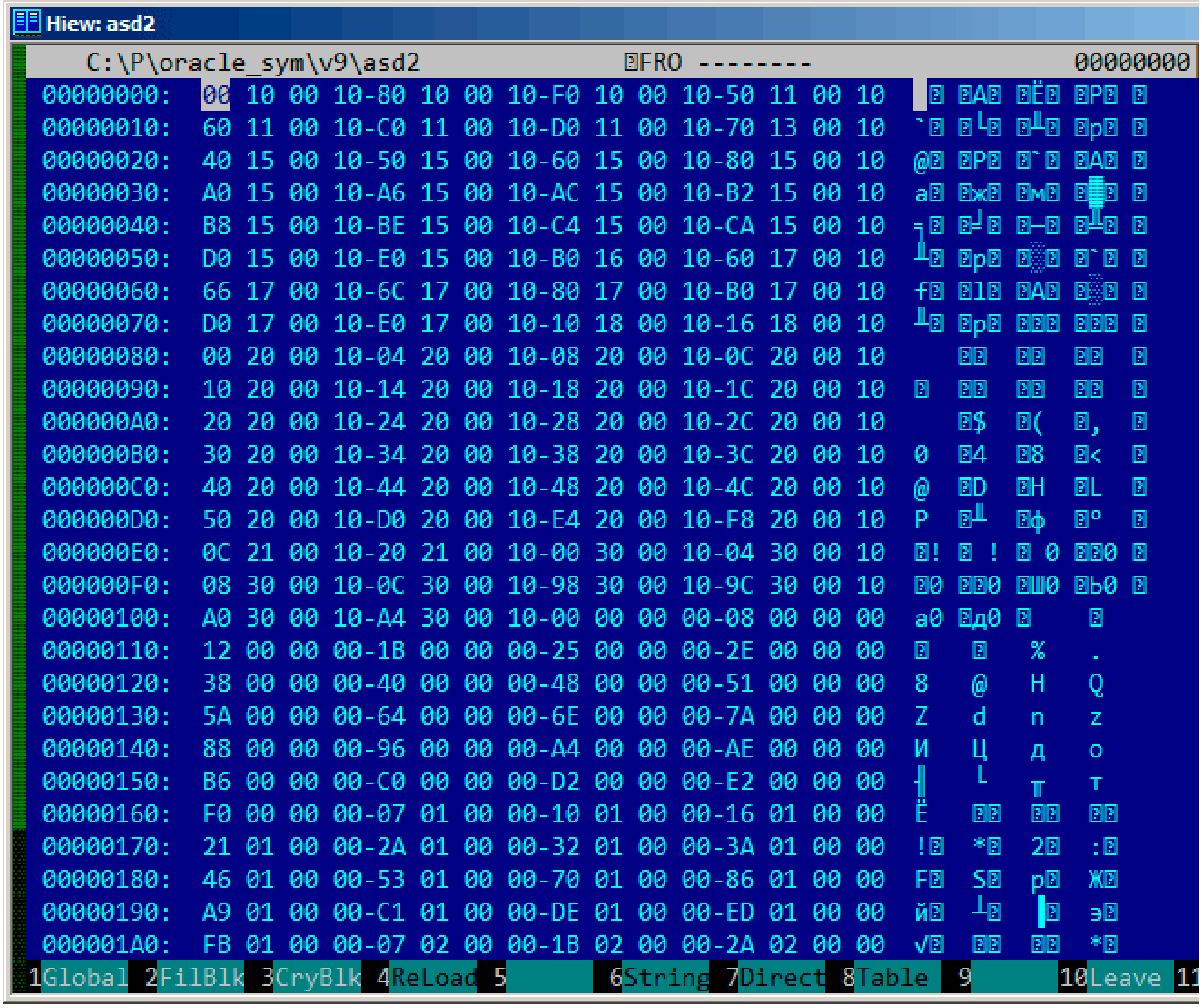


Figure 9.24: Binary block

There is a clear pattern in it.

We will add red lines to divide the block:

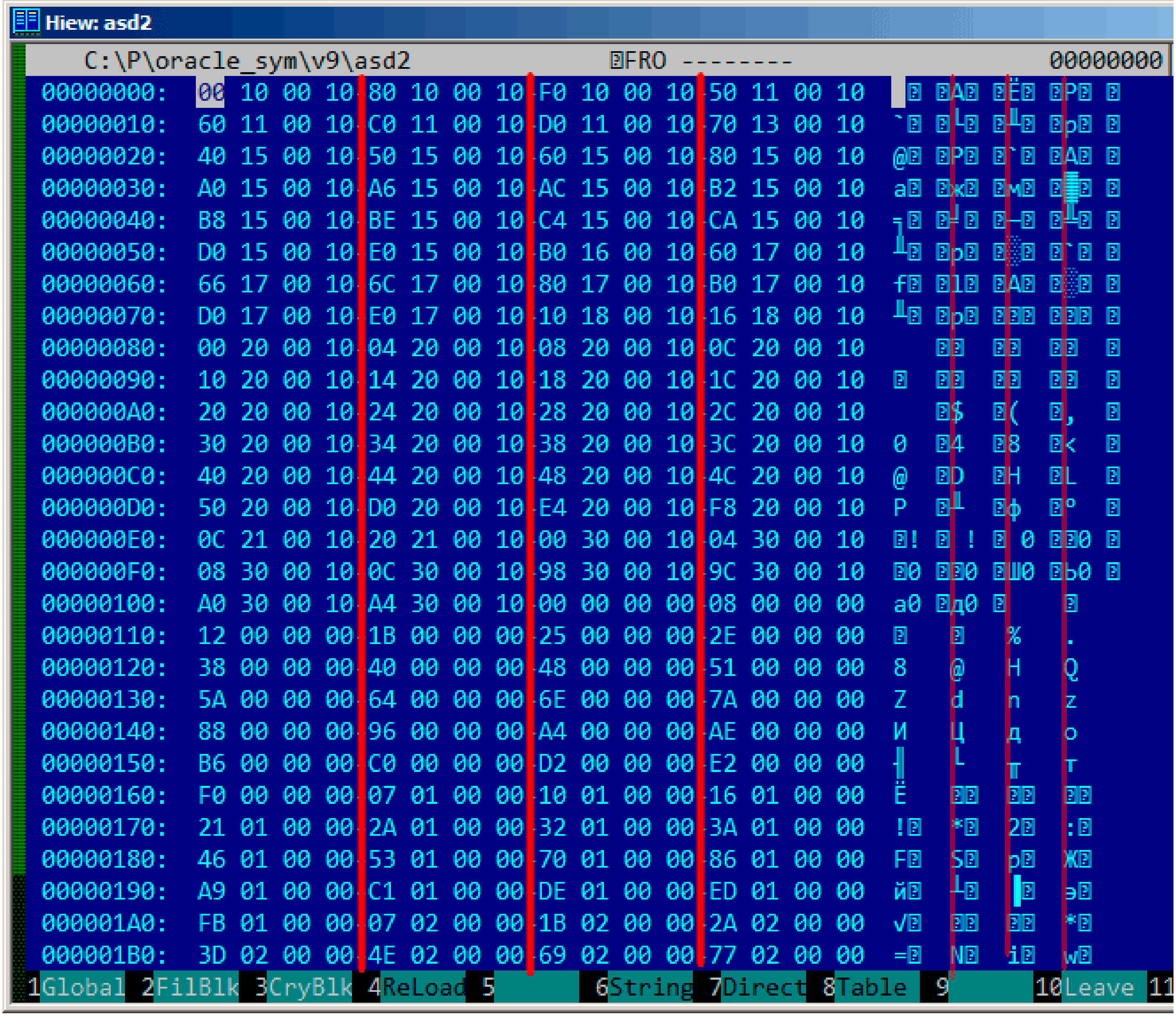


Figure 9.25: Binary block patterns

Hiew, like almost any other hexadecimal editor, shows 16 bytes per line. So the pattern is clearly visible: there are 4 32-bit values per line.

The pattern is visually visible because some values here (till address 0x104) are always in 0x1000xxxx form, started with 0x10 and zero bytes.

Other values (starting at 0x108) are in 0x0000xxxx form, so always started with two zero bytes.

Let's dump the block as an array of 32-bit values:

Listing 9.9: first column is address

```
$ od -v -t x4 binary_block
0000000 10001000 10001080 100010f0 10001150
0000020 10001160 100011c0 100011d0 10001370
0000040 10001540 10001550 10001560 10001580
0000060 100015a0 100015a6 100015ac 100015b2
0000100 100015b8 100015be 100015c4 100015ca
0000120 100015d0 100015e0 100016b0 10001760
0000140 10001766 1000176c 10001780 100017b0
0000160 100017d0 100017e0 10001810 10001816
0000200 10002000 10002004 10002008 1000200c
0000220 10002010 10002014 10002018 1000201c
```

```
0000240 10002020 10002024 10002028 1000202c
0000260 10002030 10002034 10002038 1000203c
0000300 10002040 10002044 10002048 1000204c
0000320 10002050 100020d0 100020e4 100020f8
0000340 1000210c 10002120 10003000 10003004
0000360 10003008 1000300c 10003098 1000309c
0000400 100030a0 100030a4 00000000 00000008
0000420 00000012 0000001b 00000025 0000002e
0000440 00000038 00000040 00000048 00000051
0000460 0000005a 00000064 0000006e 0000007a
0000500 00000088 00000096 000000a4 000000ae
0000520 000000b6 000000c0 000000d2 000000e2
0000540 000000f0 00000107 00000110 00000116
0000560 00000121 0000012a 00000132 0000013a
0000600 00000146 00000153 00000170 00000186
0000620 000001a9 000001c1 000001de 000001ed
0000640 000001fb 00000207 0000021b 0000022a
0000660 0000023d 0000024e 00000269 00000277
0000700 00000287 00000297 000002b6 000002ca
0000720 000002dc 000002f0 00000304 00000321
0000740 0000033e 0000035d 0000037a 00000395
0000760 000003ae 000003b6 000003be 000003c6
0001000 000003ce 000003dc 000003e9 000003f8
0001020
```

There are 132 values, that's 66*2. Probably, there are two 32-bit values for each symbol, but maybe there are two arrays? Let's see.

Values starting with `0x1000` may be addresses.

This is a .SYM file for a DLL after all, and the default base address of win32 DLLs is `0x10000000`, and the code usually starts at `0x10001000`.

When we open the orawtc8.dll file in IDA, the base address is different, but nevertheless, the first function is:

```
.text:60351000 sub_60351000    proc near
.text:60351000
.text:60351000 arg_0    = dword ptr  8
.text:60351000 arg_4    = dword ptr  0Ch
.text:60351000 arg_8    = dword ptr  10h
.text:60351000
.text:60351000          push    ebp
.text:60351001          mov     ebp, esp
.text:60351003          mov     eax, dword_60353014
.text:60351008          cmp     eax, 0FFFFFFFFh
.text:6035100B          jnz     short loc_6035104F
.text:6035100D          mov     ecx, hModule
.text:60351013          xor     eax, eax
.text:60351015          cmp     ecx, 0FFFFFFFFh
.text:60351018          mov     dword_60353014, eax
.text:6035101D          jnz     short loc_60351031
.text:6035101F          call    sub_603510F0
.text:60351024          mov     ecx, eax
.text:60351026          mov     eax, dword_60353014
.text:6035102B          mov     hModule, ecx
.text:60351031
.text:60351031 loc_60351031:    ; CODE XREF: sub_60351000+1D
.text:60351031          test    ecx, ecx
.text:60351033          jbe     short loc_6035104F
.text:60351035          push    offset ProcName ; "ax_reg"
.text:6035103A          push    ecx             ; hModule
.text:6035103B          call    ds:GetProcAddress
...
```

Wow, "ax_reg" string sounds familiar.

It's indeed the first string in the strings block! So the name of this function seems to be "ax_reg".

The second function is:

```
.text:60351080 sub_60351080    proc near
.text:60351080
.text:60351080 arg_0    = dword ptr  8
.text:60351080 arg_4    = dword ptr  0Ch
.text:60351080
.text:60351080          push    ebp
.text:60351081          mov     ebp, esp
.text:60351083          mov     eax, dword_60353018
.text:60351088          cmp     eax, 0FFFFFFFFh
.text:6035108B          jnz     short loc_603510CF
.text:6035108D          mov     ecx, hModule
.text:60351093          xor     eax, eax
.text:60351095          cmp     ecx, 0FFFFFFFFh
.text:60351098          mov     dword_60353018, eax
.text:6035109D          jnz     short loc_603510B1
.text:6035109F          call    sub_603510F0
.text:603510A4          mov     ecx, eax
.text:603510A6          mov     eax, dword_60353018
.text:603510AB          mov     hModule, ecx
.text:603510B1
.text:603510B1 loc_603510B1:    ; CODE XREF: sub_60351080+1D
.text:603510B1          test    ecx, ecx
.text:603510B3          jbe     short loc_603510CF
.text:603510B5          push    offset aAx_unreg ; "ax_unreg"
.text:603510BA          push    ecx             ; hModule
.text:603510BB          call    ds:GetProcAddress
...
```

The “ax_unreg” string is also the second string in the strings block!

The starting address of the second function is `0x60351080`, and the second value in the binary block is `10001080`. So this is the address, but for a DLL with the default base address.

We can quickly check and be sure that the first 66 values in the array (i.e., the first half of the array) are just function addresses in the DLL, including some labels, etc. Well, what’s the other part of array then? The other 66 values that start with `0x0000`? These seem to be in range `[0...0x3F8]`. And they do not look like bitfields: the series of numbers is increasing.

The last hexadecimal digit seems to be random, so, it’s unlikely the address of something (it would be divisible by 4 or maybe 8 or 0x10 otherwise).

Let’s ask ourselves: what else Oracle RDBMS’s developers would save here, in this file?

Quick wild guess: it could be the address of the text string (function name).

It can be quickly checked, and yes, each number is just the position of the first character in the strings block.

This is it! All done.

We will write an utility to convert these .SYM files into IDA script, so we can load the .idc script and it sets the function names:

```
#include <stdio.h>
#include <stdint.h>
#include <io.h>
#include <assert.h>
#include <malloc.h>
#include <fcntl.h>
#include <string.h>

int main (int argc, char *argv[])
{
        uint32_t sig, cnt, offset;
        uint32_t *d1, *d2;
        int     h, i, remain, file_len;
        char    *d3;
        uint32_t array_size_in_bytes;

        assert (argv[1]); // file name
        assert (argv[2]); // additional offset (if needed)
```

```
        // additional offset
        assert (sscanf (argv[2], "%X", &offset)==1);

        // get file length
        assert ((h=open (argv[1], _O_RDONLY | _O_BINARY, 0))!=-1);
        assert ((file_len=lseek (h, 0, SEEK_END))!=-1);
        assert (lseek (h, 0, SEEK_SET)!=-1);

        // read signature
        assert (read (h, &sig, 4)==4);
        // read count
        assert (read (h, &cnt, 4)==4);

        assert (sig==0x4D59534F); // OSYM

        // skip timedatestamp (for 11g)
        //_lseek (h, 4, 1);

        array_size_in_bytes=cnt*sizeof(uint32_t);

        // load symbol addresses array
        d1=(uint32_t*)malloc (array_size_in_bytes);
        assert (d1);
        assert (read (h, d1, array_size_in_bytes)==array_size_in_bytes);

        // load string offsets array
        d2=(uint32_t*)malloc (array_size_in_bytes);
        assert (d2);
        assert (read (h, d2, array_size_in_bytes)==array_size_in_bytes);

        // calculate strings block size
        remain=file_len-(8+4)-(cnt*8);

        // load strings block
        assert (d3=(char*)malloc (remain));
        assert (read (h, d3, remain)==remain);

        printf ("#include <idc.idc>\n\n");
        printf ("static main() {\n");

        for (i=0; i<cnt; i++)
                printf ("\tMakeName(0x%08X, \"%s\");\n", offset + d1[i], &d3[d2[i]]);

        printf ("}\n");

        close (h);
        free (d1); free (d2); free (d3);
};
```

Here is an example of its work:

```
#include <idc.idc>

static main() {
        MakeName(0x60351000, "_ax_reg");
        MakeName(0x60351080, "_ax_unreg");
        MakeName(0x603510F0, "_loaddll");
        MakeName(0x60351150, "_wtcsrin0");
        MakeName(0x60351160, "_wtcsrin");
        MakeName(0x603511C0, "_wtcsrfre");
        MakeName(0x603511D0, "_wtclkm");
        MakeName(0x60351370, "_wtcstu");
...
}
```

The example files were used in this example are here: beginners.re.

Oh, let's also try Oracle RDBMS for win64. There has to be 64-bit addresses instead, right?

The 8-byte pattern is visible even easier here:

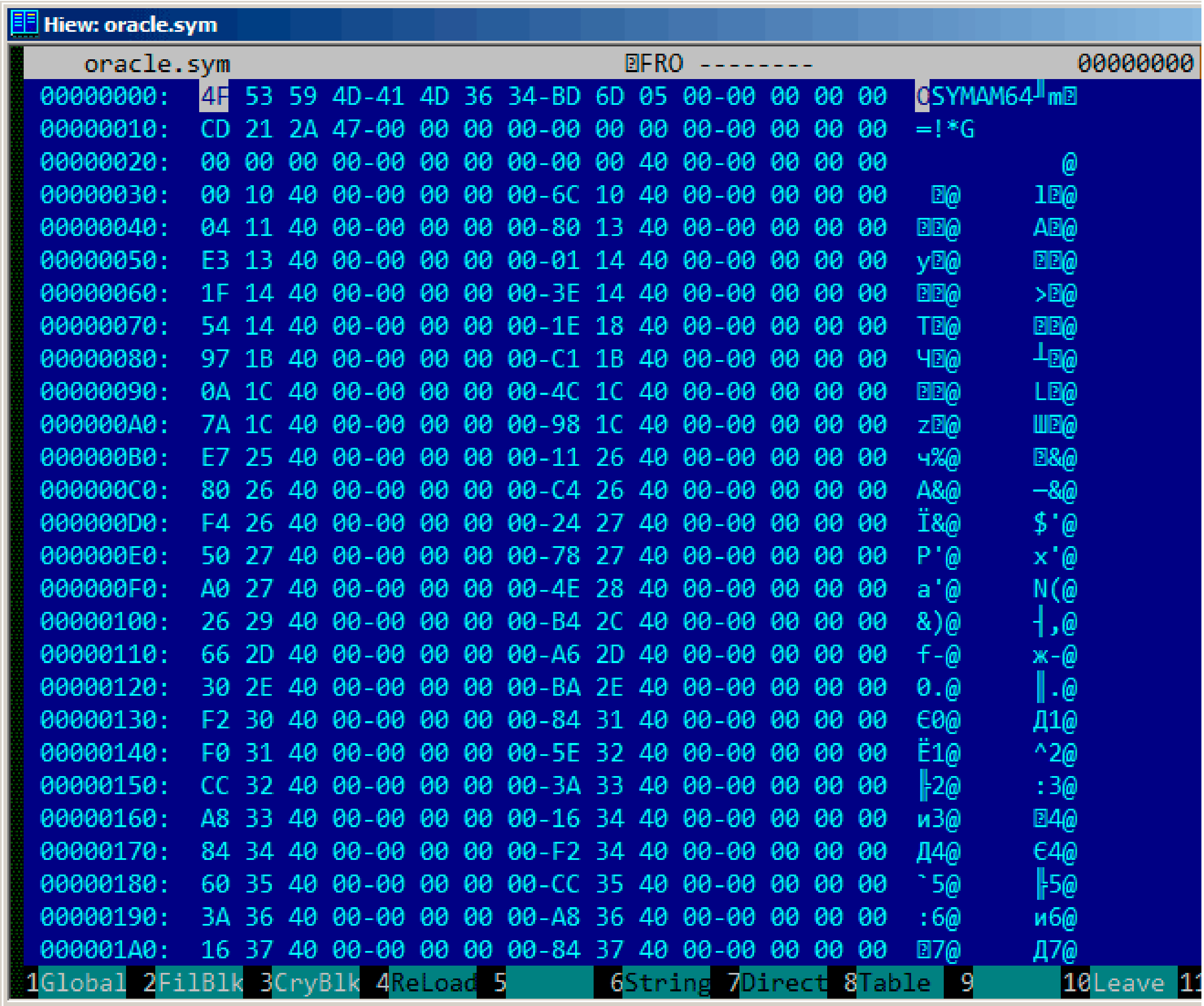


Figure 9.26: .SYM-file example from Oracle RDBMS for win64

So yes, all tables now have 64-bit elements, even string offsets!

The signature is now `OSYMAM64`, to distinguish the target platform, apparently.

This is it!

Here is also library which has functions to access Oracle RDBMS.SYM-files: GitHub.

9.6 Oracle RDBMS: .MSB-files

> When working toward the solution of a problem, it always helps if you know the answer.
>
> Murphy's Laws, Rule of Accuracy

This is a binary file that contains error messages with their corresponding numbers. Let's try to understand its format and find a way to unpack it.

There are Oracle RDBMS error message files in text form, so we can compare the text and packed binary files [14].

This is the beginning of the ORAUS.MSG text file with some irrelevant comments stripped:

Listing 9.10: Beginning of ORAUS.MSG file without comments

```
00000, 00000, "normal, successful completion"
00001, 00000, "unique constraint (%s.%s) violated"
00017, 00000, "session requested to set trace event"
00018, 00000, "maximum number of sessions exceeded"
00019, 00000, "maximum number of session licenses exceeded"
00020, 00000, "maximum number of processes (%s) exceeded"
00021, 00000, "session attached to some other process; cannot switch session"
00022, 00000, "invalid session ID; access denied"
00023, 00000, "session references process private memory; cannot detach session"
00024, 00000, "logins from more than one process not allowed in single-process mode"
00025, 00000, "failed to allocate %s"
00026, 00000, "missing or invalid session ID"
00027, 00000, "cannot kill current session"
00028, 00000, "your session has been killed"
00029, 00000, "session is not a user session"
00030, 00000, "User session ID does not exist."
00031, 00000, "session marked for kill"
...
```

The first number is the error code. The second is perhaps maybe some additional flags.

[14] Open-source text files don't exist in Oracle RDBMS for every .MSB file, so that's why we will work on their file format

Now let's open the ORAUS.MSB binary file and find these text strings. And there are:

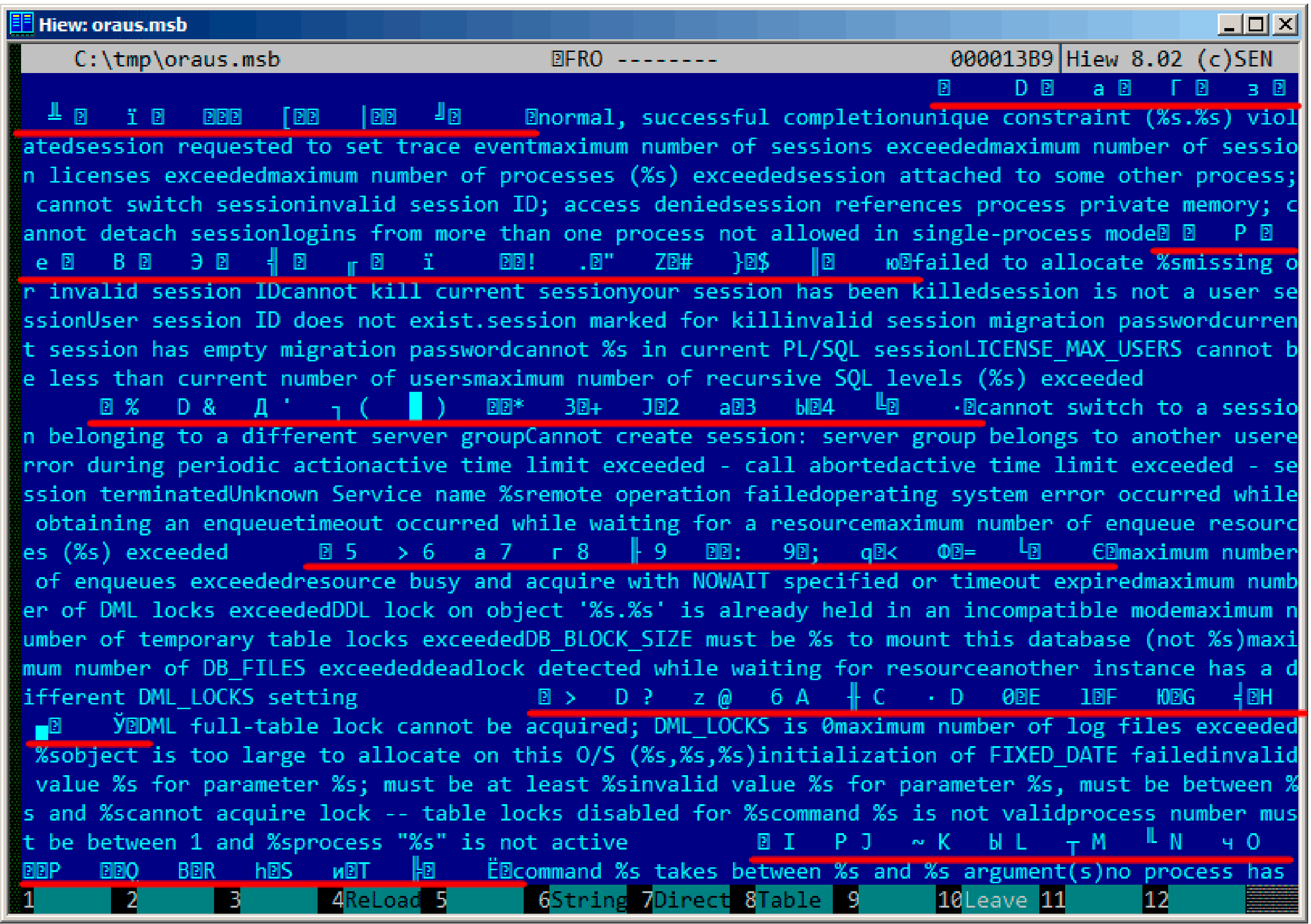


Figure 9.27: Hiew: first block

We see the text strings (including those from the beginning of the ORAUS.MSG file) interleaved with some binary values. By quick investigation, we can see that main part of the binary file is divided by blocks of size 0x200 (512) bytes.

Let's see the contents of the first block:

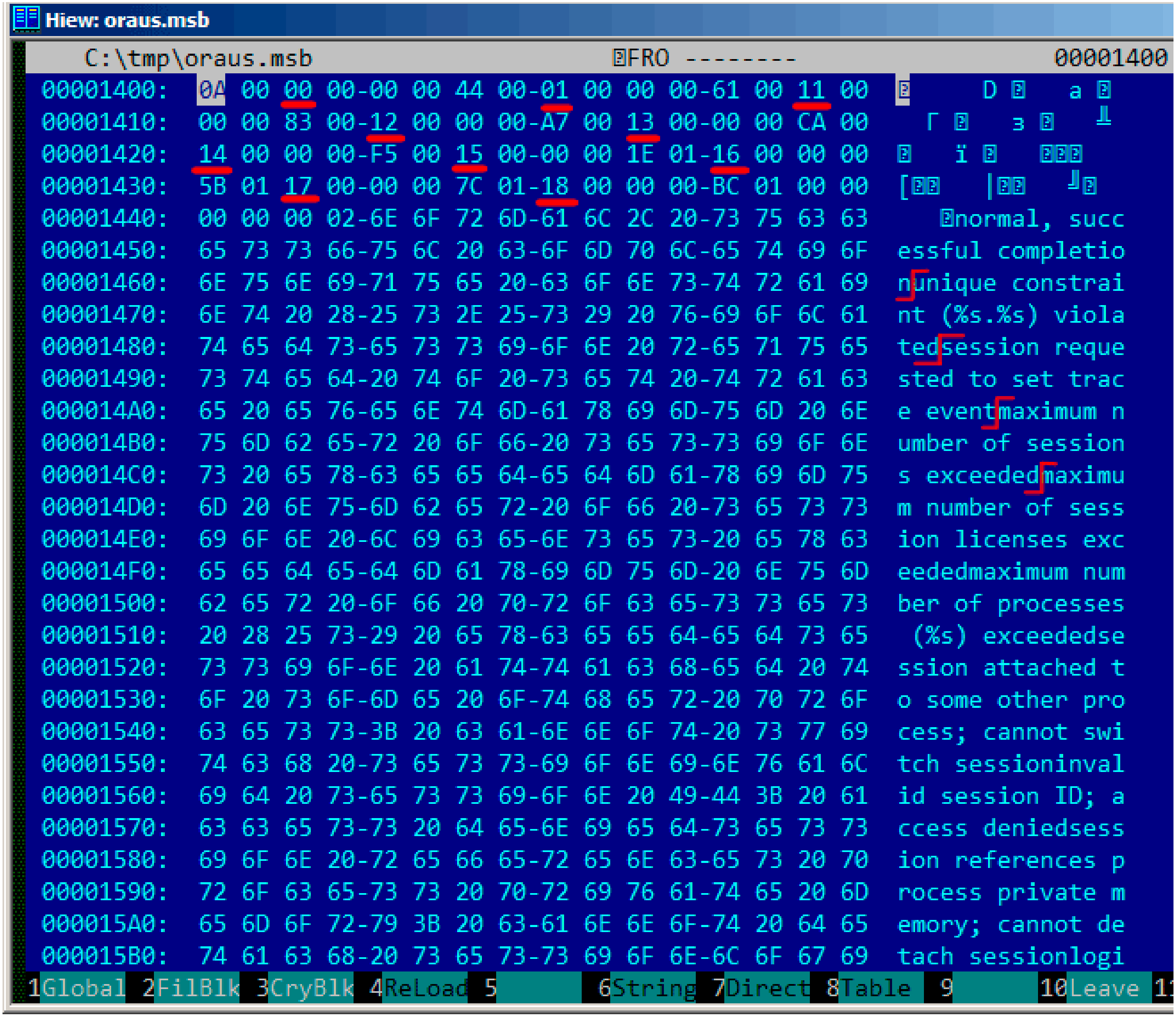


Figure 9.28: Hiew: first block

Here we see the texts of the first messages errors. What we also see is that there are no zero bytes between the error messages. This implies that these are not null-terminated C strings. As a consequence, the length of each error message must be encoded somehow. Let's also try to find the error numbers. The ORAUS.MSG files starts with these: 0, 1, 17 (0x11), 18 (0x12), 19 (0x13), 20 (0x14), 21 (0x15), 22 (0x16), 23 (0x17), 24 (0x18)... We will find these numbers at the beginning of the block and mark them with red lines. The period between error codes is 6 bytes.

This implies that there are probably 6 bytes of information allocated for each error message.

The first 16-bit value (0xA here or 10) means the number of messages in each block: this can be checked by investigating other blocks. Indeed: the error messages have arbitrary size. Some are longer, some are shorter. But block size is always fixed, hence, you never know how many text messages can be packed in each block.

As we already noted, since these are not null-terminated C strings, their size must be encoded somewhere. The size of the first string "normal, successful completion" is 29 (0x1D) bytes. The size of the second string "unique constraint (%s.%s) violated" is 34 (0x22) bytes. We can't find these values (0x1D or/and 0x22) in the block.

There is also another thing. Oracle RDBMS has to determine the position of the string it needs to load in the block, right? The first string "normal, successful completion" starts at position 0x1444 (if we count starting at the beginning of the file) or at 0x44 (from the block's start). The second string "unique constraint

(%s.%s) violated" starts at position 0x1461 (from the file's start) or at 0x61 (from the at the block's start). These numbers (0x44 and 0x61) are familiar somehow! We can clearly see them at the start of the block.

So, each 6-byte block is:

- 16-bit error number;
- 16-bit zero (maybe additional flags);
- 16-bit starting position of the text string within the current block.

We can quickly check the other values and be sure our guess is correct. And there is also the last "dummy" 6-byte block with an error number of zero and starting position beyond the last error message's last character. Probably that's how text message length is determined? We just enumerate 6-byte blocks to find the error number we need, then we get the text string's position, then we get the position of the text string by looking at the next 6-byte block! This way we determine the string's boundaries! This method allows to save some space by not saving the text string's size in the file!

It's not possible to say it saves a lot of space, but it's a clever trick.

Let's back to the header of .MSB-file:

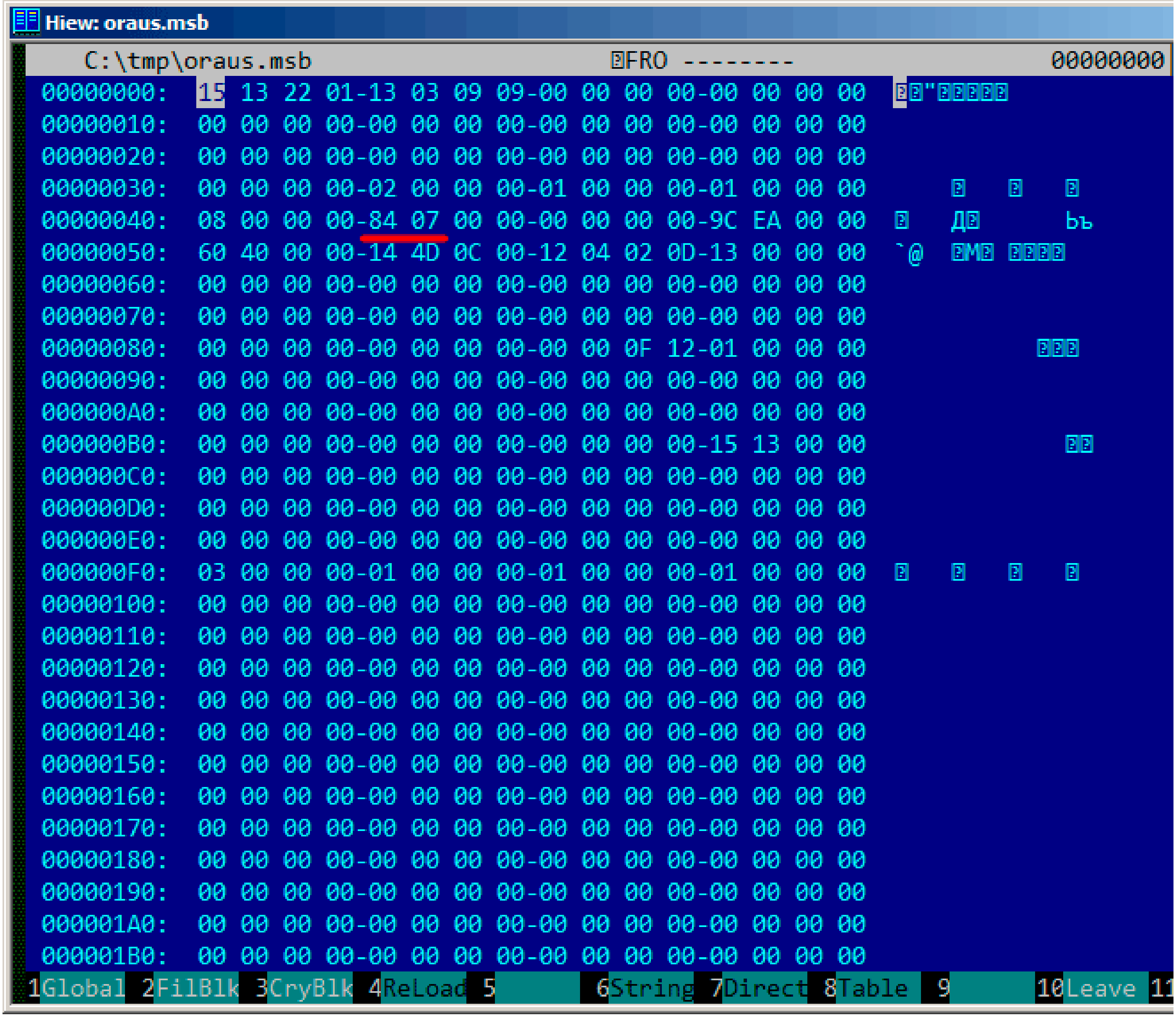


Figure 9.29: Hiew: file header

Now we can quickly find the number of blocks in the file (marked by red). We can checked other .MSB-files and we see that it's true for all of them.

There are a lot of other values, but we will not investigate them, since our job (an unpacking utility) is done.

If we have to write a .MSB file packer, we would probably have to understand the meaning of the other values.

There is also a table that came after the header which probably contains 16-bit values:

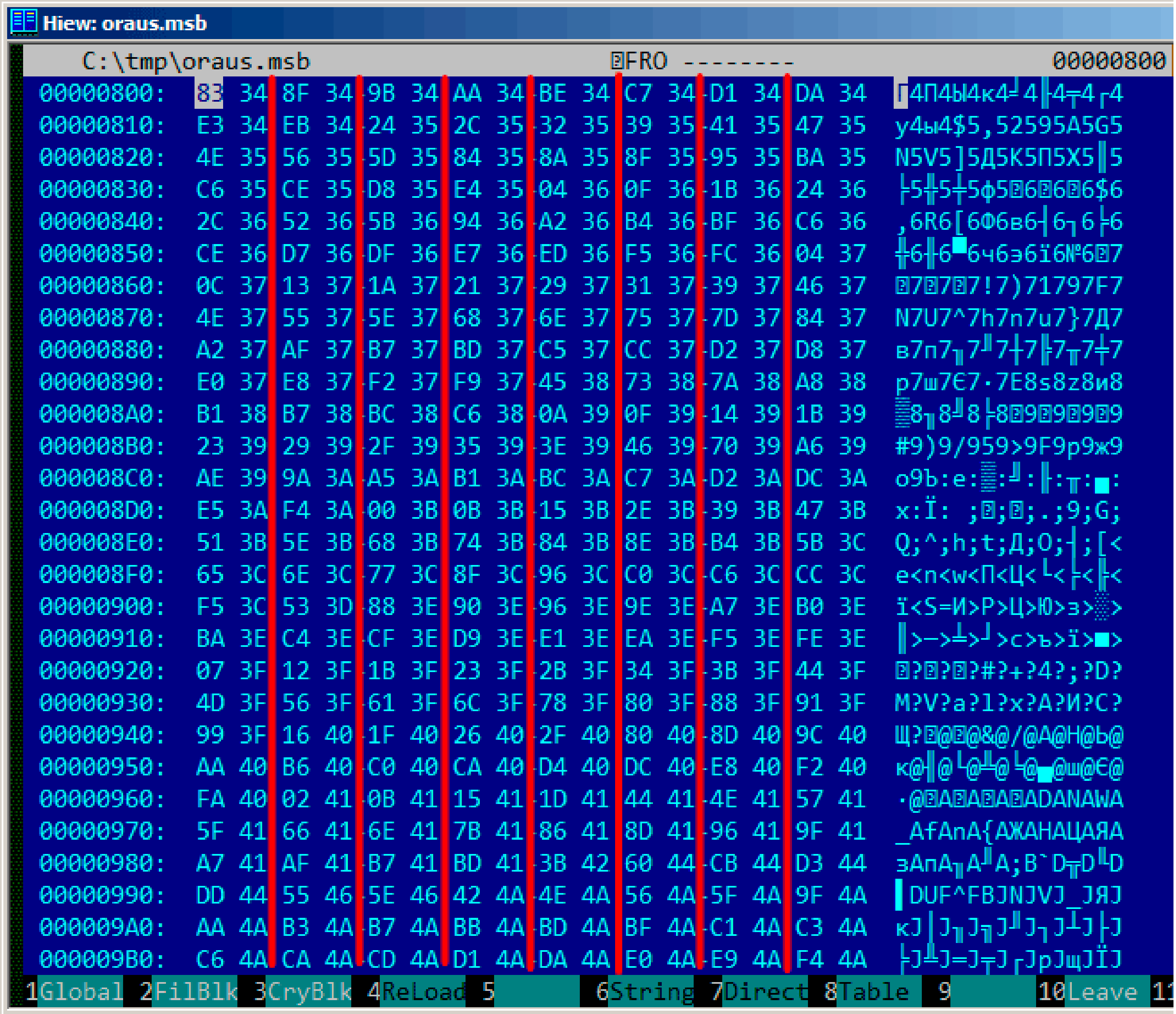


Figure 9.30: Hiew: last_errnos table

Their size can be determined visually (red lines are drawn here).

While dumping these values, we have found that each 16-bit number is the last error code for each block.

So that's how Oracle RDBMS quickly finds the error message:

- load a table we will call last_errnos (that contains the last error number for each block);
- find a block that contains the error code we need, assuming all error codes increase across each block and across the file as well;
- load the specific block;
- enumerate the 6-byte structures until the specific error number is found;
- get the position of the first character from the current 6-byte block;
- get the position of the last character from the next 6-byte block;
- load all characters of the message in this range.

This is C program that we wrote which unpacks .MSB-files: beginners.re.

There are also the two files which were used in the example (Oracle RDBMS 11.1.0.6): beginners.re, beginners.re.

9.6.1 Summary

The method is probably too old-school for modern computers. Supposedly, this file format was developed in the mid-80's by someone who also coded for *big iron* with memory/disk space economy in mind. Nevertheless, it has been an interesting and yet easy task to understand a proprietary file format without looking into Oracle RDBMS's code.

9.7 Exercises

Try to reverse engineer of any binary files of your favorite game, including high-score files, resources, etc.

There are also binary files with known structure: utmp/wtmp files, try to understand its structure without documentation.

The EXIF header in JPEG file is documented, but you can try to understand its structure without help, just shoot photos at various date/time, places, and try to find date/time and GPS location in EXIF. Try to patch GPS location, upload JPEG file to Facebook and see, how it will put your picture on the map.

Try to patch any information in MP3 file and see how your favorite MP3-player will react.

9.8 Further reading

Pierre Capillon – Black-box cryptanalysis of home-made encryption algorithms: a practical case study.

Chapter 10

Dynamic binary instrumentation

DBI tools can be viewed as highly advanced and fast debuggers.

10.1 Using PIN DBI for XOR interception

PIN from Intel is a DBI tool. That means, it takes compiled binary and inserts your instructions in it, where you want.

Let's try to intercept all XOR instructions. These are heavily used in cryptography, and we can try to run WinRAR archiver in encryption mode with a hope that some XOR instruction is indeed is used while encryption.

Here is the source code of my PIN tool: https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/XOR/files/XOR_ins.cpp.

The code is almost self-explanatory: it scans input executable file for all XOR/PXOR instructions and inserts a call to our function before each. log_info() function first checks, if operands are different (since XOR is often used just to clear register, like XOR EAX, EAX), and if they are different, it increments a counter at this EIP/RIP, so the statistics will be gathered.

I have prepared two files for test: test1.bin (30720 bytes) and test2.bin (5547752 bytes), I'll compress them by RAR with password and see difference in statistics.

You'll also need to turn off ASLR[1], so the PIN tool will report the same RIPs as in RAR executable.

Now let's run it:

```
c:\pin-3.2-81205-msvc-windows\pin.exe -t XOR_ins.dll -- rar a -pLongPassword tmp.rar test1.bin
c:\pin-3.2-81205-msvc-windows\pin.exe -t XOR_ins.dll -- rar a -pLongPassword tmp.rar test2.bin
```

Now here is statistics for the test1.bin:
https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/XOR/files/XOR_ins.out.test1. ... and for test2.bin:
https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/XOR/files/XOR_ins.out.test2. So far, you can ignore all addresses other than ip=0x1400xxxxx, which are in other DLLs.

Now let's see a difference: https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/XOR/files/XOR_ins.diff.

Some XOR instructions executed more often for test2.bin (which is bigger) than for test1.bin (which is smaller). So these are clearly related to file size!

The first block of differences is:

```
< ip=0x140017b21 count=0xd84
< ip=0x140017b48 count=0x81f
< ip=0x140017b59 count=0x858
< ip=0x140017b6a count=0xc13
< ip=0x140017b7b count=0xefc
< ip=0x140017b8a count=0xefd
< ip=0x140017b92 count=0xb86
```

[1] https://stackoverflow.com/questions/9560993/how-do-you-disable-aslr-address-space-layout-randomization-on-windows

```
< ip=0x140017ba1 count=0xf01
---
> ip=0x140017b21 count=0x9eab5
> ip=0x140017b48 count=0x79863
> ip=0x140017b59 count=0x862e8
> ip=0x140017b6a count=0x99495
> ip=0x140017b7b count=0xa891c
> ip=0x140017b8a count=0xa89f4
> ip=0x140017b92 count=0x8ed72
> ip=0x140017ba1 count=0xa8a8a
```

This is indeed some kind of loop inside of RAR.EXE:

```
.text:0000000140017B21 loc_140017B21:
.text:0000000140017B21                 xor     r11d, [rbx]
.text:0000000140017B24                 mov     r9d, [rbx+4]
.text:0000000140017B28                 add     rbx, 8
.text:0000000140017B2C                 mov     eax, r9d
.text:0000000140017B2F                 shr     eax, 18h
.text:0000000140017B32                 movzx   edx, al
.text:0000000140017B35                 mov     eax, r9d
.text:0000000140017B38                 shr     eax, 10h
.text:0000000140017B3B                 movzx   ecx, al
.text:0000000140017B3E                 mov     eax, r9d
.text:0000000140017B41                 shr     eax, 8
.text:0000000140017B44                 mov     r8d, [rsi+rdx*4]
.text:0000000140017B48                 xor     r8d, [rsi+rcx*4+400h]
.text:0000000140017B50                 movzx   ecx, al
.text:0000000140017B53                 mov     eax, r11d
.text:0000000140017B56                 shr     eax, 18h
.text:0000000140017B59                 xor     r8d, [rsi+rcx*4+800h]
.text:0000000140017B61                 movzx   ecx, al
.text:0000000140017B64                 mov     eax, r11d
.text:0000000140017B67                 shr     eax, 10h
.text:0000000140017B6A                 xor     r8d, [rsi+rcx*4+1000h]
.text:0000000140017B72                 movzx   ecx, al
.text:0000000140017B75                 mov     eax, r11d
.text:0000000140017B78                 shr     eax, 8
.text:0000000140017B7B                 xor     r8d, [rsi+rcx*4+1400h]
.text:0000000140017B83                 movzx   ecx, al
.text:0000000140017B86                 movzx   eax, r9b
.text:0000000140017B8A                 xor     r8d, [rsi+rcx*4+1800h]
.text:0000000140017B92                 xor     r8d, [rsi+rax*4+0C00h]
.text:0000000140017B9A                 movzx   eax, r11b
.text:0000000140017B9E                 mov     r11d, r8d
.text:0000000140017BA1                 xor     r11d, [rsi+rax*4+1C00h]
.text:0000000140017BA9                 sub     rdi, 1
.text:0000000140017BAD                 jnz     loc_140017B21
```

What does it do? No idea yet.

The next:

```
< ip=0x14002c4f1 count=0x4fce
---
> ip=0x14002c4f1 count=0x4463be
```

0x4fce is 20430, which is close to size of test1.bin (30720 bytes). 0x4463be is 4481982 which is close to size of test2.bin (5547752 bytes). Not equal, but close.

This is a piece of code with that XOR instruction:

```
.text:000000014002C4EA loc_14002C4EA:
.text:000000014002C4EA                 movzx   eax, byte ptr [r8]
.text:000000014002C4EE                 shl     ecx, 5
.text:000000014002C4F1                 xor     ecx, eax
.text:000000014002C4F3                 and     ecx, 7FFFh
.text:000000014002C4F9                 cmp     [r11+rcx*4], esi
.text:000000014002C4FD                 jb      short loc_14002C507
.text:000000014002C4FF                 cmp     [r11+rcx*4], r10d
```

```
.text:000000014002C503                 ja      short loc_14002C507
.text:000000014002C505                 inc     ebx
```

Loop body can be written as:

```
state = input_byte ^ (state<<5) & 0x7FFF}.
```

state is then used as index in some table. Is this some kind of CRC[2]? I don't know, but this could be a checksumming routine. Or maybe optimized CRC routine? Any ideas?

The next block:

```
< ip=0x14004104a count=0x367
< ip=0x140041057 count=0x367
---
> ip=0x14004104a count=0x24193
> ip=0x140041057 count=0x24193
```

```
.text:0000000140041039 loc_140041039:
.text:0000000140041039                 mov     rax, r10
.text:000000014004103C                 add     r10, 10h
.text:0000000140041040                 cmp     byte ptr [rcx+1], 0
.text:0000000140041044                 movdqu  xmm0, xmmword ptr [rax]
.text:0000000140041048                 jz      short loc_14004104E
.text:000000014004104A                 pxor    xmm0, xmm1
.text:000000014004104E
.text:000000014004104E loc_14004104E:
.text:000000014004104E                 movdqu  xmm1, xmmword ptr [rcx+18h]
.text:0000000140041053                 movsxd  r8, dword ptr [rcx+4]
.text:0000000140041057                 pxor    xmm1, xmm0
.text:000000014004105B                 cmp     r8d, 1
.text:000000014004105F                 jle     short loc_14004107C
.text:0000000140041061                 lea     rdx, [rcx+28h]
.text:0000000140041065                 lea     r9d, [r8-1]
.text:0000000140041069
.text:0000000140041069 loc_140041069:
.text:0000000140041069                 movdqu  xmm0, xmmword ptr [rdx]
.text:000000014004106D                 lea     rdx, [rdx+10h]
.text:0000000140041071                 aesenc  xmm1, xmm0
.text:0000000140041076                 sub     r9, 1
.text:000000014004107A                 jnz     short loc_140041069
.text:000000014004107C
```

This piece has both PXOR and AESENC instructions (the last is AES[3] encryption instruction). So yes, we found encryption function, RAR uses AES.

There is also another big block of almost contiguous XOR instructions:

```
< ip=0x140043e10 count=0x23006
---
> ip=0x140043e10 count=0x23004
499c510
< ip=0x140043e56 count=0x22ffd
---
> ip=0x140043e56 count=0x23002
```

But, its count is not very different during compressing/encrypting test1.bin/test2.bin. What is on these addresses?

```
.text:0000000140043E07                 xor     ecx, r9d
.text:0000000140043E0A                 mov     r11d, eax
.text:0000000140043E0D                 and     ecx, r10d
.text:0000000140043E10                 xor     ecx, r8d
.text:0000000140043E13                 rol     eax, 8
.text:0000000140043E16                 and     eax, esi
.text:0000000140043E18                 ror     r11d, 8
.text:0000000140043E1C                 add     edx, 5A827999h
```

[2]Cyclic redundancy check
[3]Advanced Encryption Standard

```
.text:0000000140043E22                 ror     r10d, 2
.text:0000000140043E26                 add     r8d, 5A827999h
.text:0000000140043E2D                 and     r11d, r12d
.text:0000000140043E30                 or      r11d, eax
.text:0000000140043E33                 mov     eax, ebx
```

Let's google 5A827999h constant... this looks like SHA-1! But why would RAR use SHA-1 during encryption?

Here is the answer:

```
In comparison, WinRAR uses its own key derivation scheme that requires (password length * 2 + ↙
    ↘ 11)*4096 SHA-1 transformations. 'Thats why it takes longer to brute-force attack ↙
    ↘ encrypted WinRAR archives.
```

(http://www.tomshardware.com/reviews/password-recovery-gpu,2945-8.html)

This is key scheduling: input password hashed many times and the hash is then used as AES key. This is why we see the count of XOR instruction is almost unchanged during we switched to bigger test file.

This is it, it took couple of hours for me to write this tool and to get at least 3 points: 1) probably checksumming; 2) AES encryption; 3) SHA-1 calculation. The first function is still unknown for me.

Still, this is impressive, because I didn't dig into RAR code (which is proprietary, of course). I didn't even peek into UnRAR source code (which is available).

The files, including test files and RAR executable I've used (win64, 5.40):
https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/XOR/files.

10.2 Cracking Minesweeper with PIN

In this book, I wrote about cracking Minesweeper for Windows XP: 8.3 on page 802.

The Minesweeper in Windows Vista and 7 is different: probably it was (re)written to C++, and a cell information is now stored not in global array, but rather in malloc'ed heap blocks.

This is a case when we can try PIN DBI tool.

10.2.1 Intercepting all rand() calls

First, since Minesweeper places mines randomly, it has to call rand() or similar function. Let's intercept all rand() calls: https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/minesweeper/minesweeper1.cpp.

Now we can run it:

```
c:\pin-3.2-81205-msvc-windows\pin.exe -t minesweeper1.dll -- C:\PATH\TO\MineSweeper.exe
```

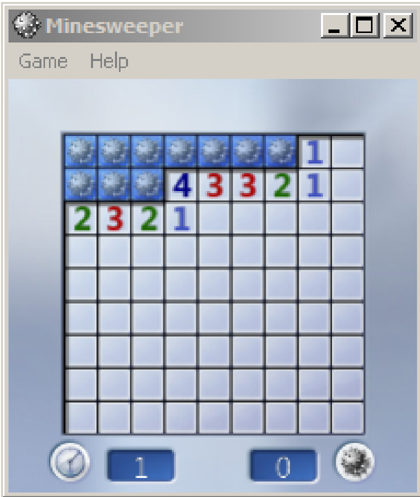
During startup, PIN searches for all calls to rand() function and adds a hook right after each call. The hook is the RandAfter() function we defined: it is logging about return value and also about return address. Here is a log I got during run of standard 9*9 configuration (10 mines): https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/minesweeper/minesweeper1.out.10mines. The rand() function was called many times from several places, but was called from 0x10002770d just 10 times. I switched Minesweeper to 16*16 configuration (40 mines) and rand() was called from 0x10002770d 40 times. So yes, this is our point. When I load minesweeper.exe (from Windows 7) into IDA and PDB from Microsoft website is fetched, the function which calls rand() at 0x10002770d called Board::placeMines().

10.2.2 Replacing rand() calls with our function

Let's now try to replace rand() function with our version, let it always return zero: https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/minesweeper/minesweeper2.cpp. During startup, PIN replaces all calls to rand() to calls to our function, which writes to log and returns zero. OK, I run it, and clicked on leftmost/topmost cell:

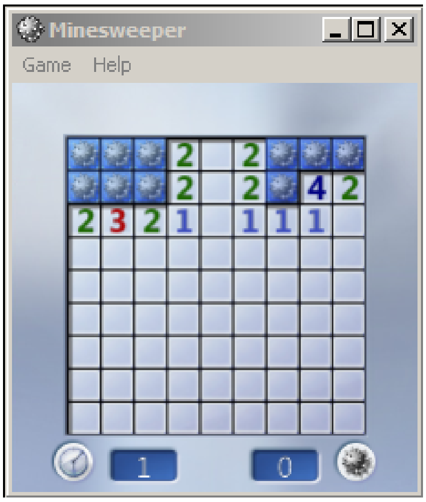
Yes, unlike Minesweeper from Windows XP, mines are places randomly *after* user's click on cell, so to guarantee there is no mine at the cell user first clicked. So Minesweeper placed cells on cells other than leftmost/topmost (where I clicked).

Now I clicked on rightmost/topmost cell:



This can be some kind of practical joke? I don't know.

I clicked on 5th cell (right at the middle) at the 1st row:



This is nice, because Minesweeper can do some correct placement even with such a broken PRNG!

10.2.3 Peeking into placement of mines

How can we get information about where mines are placed? rand()'s result is seems to be useless: it returned zero all the time, but Minesweeper somehow managed to place mines in different cells, though, lined up.

This Minesweeper also written in C++ tradition, so it has no global arrays.

Let us put ourselves in the position of programmer. It has to be loop like:

```
for (int i; i<mines_total; i++)
{
        // get coordinates using rand()
        // put a cell: in other words, modify a block allocated in heap
};
```

How can we get information about heap block which gets modified at the 2nd step? What we need to do: 1) track all heap allocations by intercepting malloc()/realloc()/free(). 2) track all memory writes (slow). 3) intercept calls to rand().

Now the algorithm: 1) mark all heap blocks gets modified between 1st and 2nd call to rand() from 0x10002770d; 2) whenever heap block gets freed, dump its contents.

Tracking all memory writes is slow, but after 2nd call to rand(), we don't need to track it (since we've got already a list of blocks of interest at this point), so we turn it off.

Now the code: https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/minesweeper/minesweeper3.cpp.

As it turns out, only 4 heap blocks gets modified between first two rand() calls, this is how they looks like:

```
free(0x20aa6360)
free(): we have this block in our records, size=0x28
0x20AA6360: 36 00 00 00 4E 00 00 00-2D 00 00 00 29 00 00 00 "6...N...-...)..."
0x20AA6370: 06 00 00 00 37 00 00 00-35 00 00 00 19 00 00 00 "....7...5......."
0x20AA6380: 46 00 00 00 0B 00 00 00-                        "F.......        "

...

free(0x20af9d10)
free(): we have this block in our records, size=0x18
0x20AF9D10: 0A 00 00 00 0A 00 00 00-0A 00 00 00 00 00 00 00 "................"
0x20AF9D20: 60 63 AA 20 00 00 00 00-                        "`c. ....        "

...

free(0x20b28b20)
free(): we have this block in our records, size=0x140
0x20B28B20: 02 00 00 00 03 00 00 00-04 00 00 00 05 00 00 00 "................"
0x20B28B30: 07 00 00 00 08 00 00 00-0C 00 00 00 0D 00 00 00 "................"
0x20B28B40: 0E 00 00 00 0F 00 00 00-10 00 00 00 11 00 00 00 "................"
0x20B28B50: 12 00 00 00 13 00 00 00-14 00 00 00 15 00 00 00 "................"
0x20B28B60: 16 00 00 00 17 00 00 00-18 00 00 00 1A 00 00 00 "................"
0x20B28B70: 1B 00 00 00 1C 00 00 00-1D 00 00 00 1E 00 00 00 "................"
0x20B28B80: 1F 00 00 00 20 00 00 00-21 00 00 00 22 00 00 00 ".... ...!..."..."
0x20B28B90: 23 00 00 00 24 00 00 00-25 00 00 00 26 00 00 00 "#...$...%...&..."
0x20B28BA0: 27 00 00 00 28 00 00 00-2A 00 00 00 2B 00 00 00 "'...(...*...+..."
0x20B28BB0: 2C 00 00 00 2E 00 00 00-2F 00 00 00 30 00 00 00 ",......./...0..."
0x20B28BC0: 31 00 00 00 32 00 00 00-33 00 00 00 34 00 00 00 "1...2...3...4..."
0x20B28BD0: 38 00 00 00 39 00 00 00-3A 00 00 00 3B 00 00 00 "8...9...:...;..."
0x20B28BE0: 3C 00 00 00 3D 00 00 00-3E 00 00 00 3F 00 00 00 "<...=...>...?..."
0x20B28BF0: 40 00 00 00 41 00 00 00-42 00 00 00 43 00 00 00 "@...A...B...C..."
0x20B28C00: 44 00 00 00 45 00 00 00-47 00 00 00 48 00 00 00 "D...E...G...H..."
0x20B28C10: 49 00 00 00 4A 00 00 00-4B 00 00 00 4C 00 00 00 "I...J...K...L..."
0x20B28C20: 4D 00 00 00 4F 00 00 00-50 00 00 00 50 00 00 00 "M...O...P...P..."
0x20B28C30: 50 00 00 00 50 00 00 00-50 00 00 00 50 00 00 00 "P...P...P...P..."
0x20B28C40: 50 00 00 00 50 00 00 00-50 00 00 00 50 00 00 00 "P...P...P...P..."
0x20B28C50: 50 00 00 00 00 00 00 00-00 00 00 00 00 00 00 00 "P..............."

...
```

```
free(0x20af9cf0)
free(): we have this block in our records, size=0x18
0x20AF9CF0: 43 00 00 00 50 00 00 00-10 00 00 00 20 00 74 00 "C...P....... .t."
0x20AF9D00: 20 8B B2 20 00 00 00 00-                         " .. ....        "
```

We can easily see that the biggest blocks (with size 0x28 and 0x140) are just arrays of values up to ≈ 0x50. Wait... 0x50 is 80 in decimal representation. And 9*9=81 (standard minesweeper configuration).

After quick investigation, I've found that each 32-bit element is indeed cell coordinate. A cell is represented using a single number, it's a number inside of 2D-array. Row and column of each mine is decoded like that: *row=n / WIDTH; col=n % HEIGHT;*

So when I tried to decode these two biggest blocks, I've got these cell maps:

```
try_to_dump_cells(). unique elements=0xa
......*..
..*......
.......*.
.........
.....*...
*.......*
**.......
.......*.
......*..

...

try_to_dump_cells(). unique elements=0x44
*.****.**
...******
*******.*
*********
*****.***
.*******.
..*******
*******.*
******.**
```

It seems that the first block is just a list of mines placed, while the second block is a list of free cells, but, the second is somewhat out of sync with the first one, and it's negative version of the first one coincides only partially. Nevertheless, the first map is correct - we can peek into it in log file when Minesweeper is still loaded and almost all cells are hidden, and click safely on cells marked as dots here.

So it seems, when user first clicked somewhere, Minesweeper places 10 mines, than destroys the block with a list of it (perhaps, it copies all the data to another block before?), so we can see it during free() call.

Another fact: the method Array<NodeType>::Add(NodeType) modifies blocks we observed, and is called from various places, including Board::placeMines(). But what is cool: I never got into its details, everything has been resolved using just PIN.

The files: https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/minesweeper.

10.2.4 Exercise

Try to understand how rand()'s result being converted into coordinate(s). As a practical joke, make rand() to output such results, so mines will be placed in shape of some symbol or figure.

10.3 Why "instrumentation"?

Perhaps, this is term of code profiling. There are at least two methods: 1) "sampling": you break into running code as many times as possible (hundreds per second), and see, where it is executed at the moment; 2) "instrumentation": compiled code is interleaved with other code, which can increment counters, etc.

Perhaps, DBI tools inherited the term?

Chapter 11

Other things

11.1 Executable files patching

11.1.1 Text strings

The C strings are the thing that is the easiest to patch (unless they are encrypted) in any hex editor. This technique is available even for those who are not aware of machine code and executable file formats. The new string has not to be bigger than the old one, because there's a risk of overwriting another value or code there.

Using this method, a lot of software was *localized* in the MS-DOS era, at least in the ex-USSR countries in 80's and 90's. It was the reason why some weird abbreviations were present in the *localized* software: there was no room for longer strings.

As for Delphi strings, the string's size must also be corrected, if needed.

11.1.2 x86 code

Frequent patching tasks are:

- One of the most frequent jobs is to disable some instruction. It is often done by filling it using byte `0x90` (NOP).
- Conditional jumps, which have an opcode like `74 xx` (`JZ`), can be filled with two NOPs.

  It is also possible to disable a conditional jump by writing 0 at the second byte (*jump offset*).
- Another frequent job is to make a conditional jump to always trigger: this can be done by writing `0xEB` instead of the opcode, which stands for `JMP`.
- A function's execution can be disabled by writing `RETN` (0xC3) at its beginning. This is true for all functions excluding `stdcall` (6.1.2 on page 734). While patching `stdcall` functions, one has to determine the number of arguments (for example, by finding `RETN` in this function), and use `RETN` with a 16-bit argument (0xC2).
- Sometimes, a disabled functions has to return 0 or 1. This can be done by `MOV EAX, 0` or `MOV EAX, 1`, but it's slightly verbose.
  A better way is `XOR EAX, EAX` (2 bytes `0x31 0xC0`) or `XOR EAX, EAX / INC EAX` (3 bytes `0x31 0xC0 0x40`).

A software may be protected against modifications.

This protection is often done by reading the executable code and calculating a checksum. Therefore, the code must be read before protection is triggered.

This can be determined by setting a breakpoint on reading memory.

tracer has the BPM option for this.

PE executable file relocs (6.5.2 on page 759) must not to be touched while patching, because the Windows loader may overwrite your new code. (They are grayed in Hiew, for example: fig.1.21).

As a last resort, it is possible to write jumps that circumvent the relocs, or you will have to edit the relocs table.

11.2 Function arguments number statistics

I've always been interesting in what is average number of function arguments.

I've analyzed many Windows 7 32-bit DLLs
(crypt32.dll, mfc71.dll, msvcr100.dll, shell32.dll, user32.dll, d3d11.dll, mshtml.dll, msxml6.dll, sqlncli11.dll, wininet.dll, mfc120.dll, msvbvm60.dll, ole32.dll, themeui.dll, wmp.dll) (because they use *stdcall* convention, and so it is easy to *grep* disassembly output just by `RETN X`).

- no arguments: $\approx 29\%$
- 1 argument: $\approx 23\%$
- 2 arguments: $\approx 20\%$
- 3 arguments: $\approx 11\%$
- 4 arguments: $\approx 7\%$
- 5 arguments: $\approx 3\%$
- 6 arguments: $\approx 2\%$
- 7 arguments: $\approx 1\%$

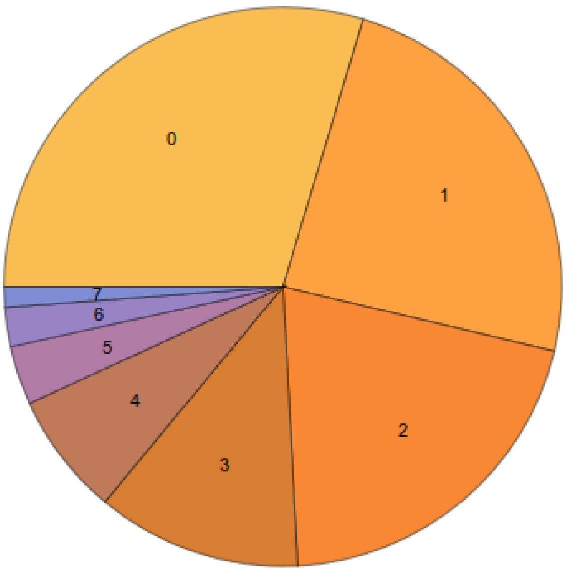


Figure 11.1: Function arguments number statistics

This is heavily dependent on programming style and may be very different for other software products.

11.3 Compiler intrinsic

A function specific to a compiler which is not an usual library function. The compiler generates a specific machine code instead of a call to it. It is often a pseudofunction for specific CPU instruction.

For example, there are no cyclic shift operations in C/C++ languages, but they are present in most CPUs.

For programmer's convenience, at least MSVC has pseudofunctions *_rotl()* and *_rotr()*[1] which are translated by the compiler directly to the ROL/ROR x86 instructions.

Another example are functions to generate SSE-instructions right in the code.

Full list of MSVC intrinsics: MSDN.

11.4 Compiler's anomalies

11.4.1 Oracle RDBMS 11.2 and Intel C++ 10.1

Intel C++ 10.1, which was used for Oracle RDBMS 11.2 Linux86 compilation, may emit two JZ in row, and there are no references to the second JZ. The second JZ is thus meaningless.

Listing 11.1: kdli.o from libserver11.a

```
.text:08114CF1                   loc_8114CF1: ; CODE XREF: __PGOSF539_kdlimemSer+89A
.text:08114CF1                                ; __PGOSF539_kdlimemSer+3994
.text:08114CF1 8B 45 08              mov     eax, [ebp+arg_0]
.text:08114CF4 0F B6 50 14           movzx   edx, byte ptr [eax+14h]
.text:08114CF8 F6 C2 01              test    dl, 1
.text:08114CFB 0F 85 17 08 00 00     jnz     loc_8115518
.text:08114D01 85 C9                 test    ecx, ecx
.text:08114D03 0F 84 8A 00 00 00     jz      loc_8114D93
.text:08114D09 0F 84 09 08 00 00     jz      loc_8115518
.text:08114D0F 8B 53 08              mov     edx, [ebx+8]
.text:08114D12 89 55 FC              mov     [ebp+var_4], edx
.text:08114D15 31 C0                 xor     eax, eax
.text:08114D17 89 45 F4              mov     [ebp+var_C], eax
.text:08114D1A 50                    push    eax
.text:08114D1B 52                    push    edx
.text:08114D1C E8 03 54 00 00        call    len2nbytes
.text:08114D21 83 C4 08              add     esp, 8
```

Listing 11.2: from the same code

```
.text:0811A2A5                   loc_811A2A5: ; CODE XREF: kdliSerLengths+11C
.text:0811A2A5                                ; kdliSerLengths+1C1
.text:0811A2A5 8B 7D 08              mov     edi, [ebp+arg_0]
.text:0811A2A8 8B 7F 10              mov     edi, [edi+10h]
.text:0811A2AB 0F B6 57 14           movzx   edx, byte ptr [edi+14h]
.text:0811A2AF F6 C2 01              test    dl, 1
.text:0811A2B2 75 3E                 jnz     short loc_811A2F2
.text:0811A2B4 83 E0 01              and     eax, 1
.text:0811A2B7 74 1F                 jz      short loc_811A2D8
.text:0811A2B9 74 37                 jz      short loc_811A2F2
.text:0811A2BB 6A 00                 push    0
.text:0811A2BD FF 71 08              push    dword ptr [ecx+8]
.text:0811A2C0 E8 5F FE FF FF        call    len2nbytes
```

It is supposedly a code generator bug that was not found by tests, because resulting code works correctly anyway.

11.4.2 MSVC 6.0

Just found in some old code:

```
                fabs
                fild    [esp+50h+var_34]
                fabs
                fxch    st(1) ; first instruction
                fxch    st(1) ; second instruction
                faddp   st(1), st
```

[1] MSDN

```
                 fcomp   [esp+50h+var_3C]
                 fnstsw  ax
                 test    ah, 41h
                 jz      short loc_100040B7
```

The first FXCH instruction swaps ST(0) and ST(1), the second do the same, so both do nothing. This is a program uses MFC42.dll, so it could be MSVC 6.0, 5.0 or maybe even MSVC 4.2 from 1990s.

This pair do nothing, so it probably wasn't caught by MSVC compiler tests. Or maybe I wrong?

11.4.3 Summary

Other compiler anomalies here in this book: 1.22.2 on page 315, 3.7.3 on page 493, 3.15.7 on page 532, 1.20.7 on page 302, 1.14.4 on page 147, 1.22.5 on page 332.

Such cases are demonstrated here in this book, to show that such compilers errors are possible and sometimes one should not to rack one's brain while thinking why did the compiler generate such strange code.

11.5 Itanium

Although almost failed, Intel Itanium (IA64) is a very interesting architecture.

While OOE CPUs decides how to rearrange their instructions and execute them in parallel, EPIC[2] was an attempt to shift these decisions to the compiler: to let it group the instructions at the compile stage.

This resulted in notoriously complex compilers.

Here is one sample of IA64 code: simple cryptographic algorithm from the Linux kernel:

Listing 11.3: Linux kernel 3.2.0.4

```
#define TEA_ROUNDS              32
#define TEA_DELTA               0x9e3779b9

static void tea_encrypt(struct crypto_tfm *tfm, u8 *dst, const u8 *src)
{
        u32 y, z, n, sum = 0;
        u32 k0, k1, k2, k3;
        struct tea_ctx *ctx = crypto_tfm_ctx(tfm);
        const __le32 *in = (const __le32 *)src;
        __le32 *out = (__le32 *)dst;

        y = le32_to_cpu(in[0]);
        z = le32_to_cpu(in[1]);

        k0 = ctx->KEY[0];
        k1 = ctx->KEY[1];
        k2 = ctx->KEY[2];
        k3 = ctx->KEY[3];

        n = TEA_ROUNDS;

        while (n-- > 0) {
                sum += TEA_DELTA;
                y += ((z << 4) + k0) ^ (z + sum) ^ ((z >> 5) + k1);
                z += ((y << 4) + k2) ^ (y + sum) ^ ((y >> 5) + k3);
        }

        out[0] = cpu_to_le32(y);
        out[1] = cpu_to_le32(z);
}
```

Here is how it was compiled:

[2] Explicitly Parallel Instruction Computing

Listing 11.4: Linux Kernel 3.2.0.4 for Itanium 2 (McKinley)

```
0090|                   tea_encrypt:
0090|08 80 80 41 00 21     adds r16 = 96, r32             // ptr to ctx->KEY[2]
0096|80 C0 82 00 42 00     adds r8 = 88, r32              // ptr to ctx->KEY[0]
009C|00 00 04 00           nop.i 0
00A0|09 18 70 41 00 21     adds r3 = 92, r32              // ptr to ctx->KEY[1]
00A6|F0 20 88 20 28 00     ld4 r15 = [r34], 4             // load z
00AC|44 06 01 84           adds r32 = 100, r32;;          // ptr to ctx->KEY[3]
00B0|08 98 00 20 10 10     ld4 r19 = [r16]                // r19=k2
00B6|00 01 00 00 42 40     mov r16 = r0                   // r0 always contain zero
00BC|00 08 CA 00           mov.i r2 = ar.lc               // save lc register
00C0|05 70 00 44 10 10
     9E FF FF FF 7F 20     ld4 r14 = [r34]                // load y
00CC|92 F3 CE 6B           movl r17 = 0xFFFFFFFF9E3779B9;; // TEA_DELTA
00D0|08 00 00 00 01 00     nop.m 0
00D6|50 01 20 20 20 00     ld4 r21 = [r8]                 // r21=k0
00DC|F0 09 2A 00           mov.i ar.lc = 31               // TEA_ROUNDS is 32
00E0|0A A0 00 06 10 10     ld4 r20 = [r3];;               // r20=k1
00E6|20 01 80 20 20 00     ld4 r18 = [r32]                // r18=k3
00EC|00 00 04 00           nop.i 0
00F0|
00F0|                               loc_F0:
00F0|09 80 40 22 00 20     add r16 = r16, r17             // r16=sum, r17=TEA_DELTA
00F6|D0 71 54 26 40 80     shladd r29 = r14, 4, r21       // r14=y, r21=k0
00FC|A3 70 68 52           extr.u r28 = r14, 5, 27;;
0100|03 F0 40 1C 00 20     add r30 = r16, r14
0106|B0 E1 50 00 40 40     add r27 = r28, r20;;           // r20=k1
010C|D3 F1 3C 80           xor r26 = r29, r30;;
0110|0B C8 6C 34 0F 20     xor r25 = r27, r26;;
0116|F0 78 64 00 40 00     add r15 = r15, r25             // r15=z
011C|00 00 04 00           nop.i 0;;
0120|00 00 00 00 01 00     nop.m 0
0126|80 51 3C 34 29 60     extr.u r24 = r15, 5, 27
012C|F1 98 4C 80           shladd r11 = r15, 4, r19       // r19=k2
0130|0B B8 3C 20 00 20     add r23 = r15, r16;;
0136|A0 C0 48 00 40 00     add r10 = r24, r18             // r18=k3
013C|00 00 04 00           nop.i 0;;
0140|0B 48 28 16 0F 20     xor r9 = r10, r11;;
0146|60 B9 24 1E 40 00     xor r22 = r23, r9
014C|00 00 04 00           nop.i 0;;
0150|11 00 00 00 01 00     nop.m 0
0156|E0 70 58 00 40 A0     add r14 = r14, r22
015C|A0 FF FF 48           br.cloop.sptk.few loc_F0;;
0160|09 20 3C 42 90 15     st4 [r33] = r15, 4             // store z
0166|00 00 00 02 00 00     nop.m 0
016C|20 08 AA 00           mov.i ar.lc = r2;;             // restore lc register
0170|11 00 38 42 90 11     st4 [r33] = r14                // store y
0176|00 00 00 02 00 80     nop.i 0
017C|08 00 84 00           br.ret.sptk.many b0;;
```

First of all, all IA64 instructions are grouped into 3-instruction bundles.

Each bundle has a size of 16 bytes (128 bits) and consists of template code (5 bits) + 3 instructions (41 bits for each).

IDA shows the bundles as 6+6+4 bytes —you can easily spot the pattern.

All 3 instructions from each bundle usually executes simultaneously, unless one of instructions has a “stop bit”.

Supposedly, Intel and HP engineers gathered statistics on most frequent instruction patterns and decided to bring bundle types (AKA “templates”): a bundle code defines the instruction types in the bundle. There are 12 of them.

For example, the zeroth bundle type is `MII`, which implies the first instruction is Memory (load or store), the second and third ones are I (integer instructions).

Another example is the bundle of type `0x1d`: `MFB`: the first instruction is Memory (load or store), the second one is Float (FPU instruction), and the third is Branch (branch instruction).

If the compiler cannot pick a suitable instruction for the relevant bundle slot, it may insert a NOP: you can see here the `nop.i` instructions (NOP at the place where the integer instruction might be) or `nop.m` (a memory instruction might be at this slot).

NOPs are inserted automatically when one uses assembly language manually.

And that is not all. Bundles are also grouped.

Each bundle may have a “stop bit”, so all the consecutive bundles with a terminating bundle which has the “stop bit” can be executed simultaneously.

In practice, Itanium 2 can execute 2 bundles at once, resulting in the execution of 6 instructions at once.

So all instructions inside a bundle and a bundle group cannot interfere with each other (i.e., must not have data hazards).

If they do, the results are to be undefined.

Each stop bit is marked in assembly language as two semicolons (`;;`) after the instruction.

So, the instructions at [90-ac] may be executed simultaneously: they do not interfere. The next group is [b0-cc].

We also see a stop bit at 10c. The next instruction at 110 has a stop bit too.

This implies that these instructions must be executed isolated from all others (as in CISC).

Indeed: the next instruction at 110 uses the result from the previous one (the value in register r26), so they cannot be executed at the same time.

Apparently, the compiler was not able to find a better way to parallelize the instructions, in other words, to load CPU as much as possible, hence too much stop bits and NOPs.

Manual assembly programming is a tedious job as well: the programmer has to group the instructions manually.

The programmer is still able to add stop bits to each instructions, but this will degrade the performance that Itanium was made for.

An interesting examples of manual IA64 assembly code can be found in the Linux kernel’s sources:

`http://go.yurichev.com/17322`.

Another introductory paper on Itanium assembly: [Mike Burrell, *Writing Efficient Itanium 2 Assembly Code* (2010)][3], [papasutra of haquebright, *WRITING SHELLCODE FOR IA-64* (2001)][4].

Another very interesting Itanium feature is the *speculative execution* and the NaT (“not a thing”) bit, somewhat resembling NaN numbers:
MSDN.

11.6 8086 memory model

When dealing with 16-bit programs for MS-DOS or Win16 (8.5.3 on page 832 or 3.29.5 on page 654), we can see that the pointers consist of two 16-bit values. What do they mean? Oh yes, that is another weird MS-DOS and 8086 artifact.

8086/8088 was a 16-bit CPU, but was able to address 20-bit address in RAM (thus being able to access 1MB of external memory).

The external memory address space was divided between RAM (640KB max), ROM, windows for video memory, EMS cards, etc.

Let’s also recall that 8086/8088 was in fact an inheritor of the 8-bit 8080 CPU.

The 8080 has a 16-bit memory space, i.e., it was able to address only 64KB.

And probably because of reason of old software porting[5], 8086 can support many 64KB windows simultaneously, placed within the 1MB address space.

This is some kind of a toy-level virtualization.

[3] Also available as `http://yurichev.com/mirrors/RE/itanium.pdf`
[4] Also available as `http://phrack.org/issues/57/5.html`
[5] The author is not 100% sure here

All 8086 registers are 16-bit, so to address more, special segment registers (CS, DS, ES, SS) were introduced.

Each 20-bit pointer is calculated using the values from a segment register and an address register pair (e.g. DS:BX) as follows:

$$real\_address = (segment\_register \ll 4) + address\_register$$

For example, the graphics (EGA[6], VGA[7]) video RAM window on old IBM PC-compatibles has a size of 64KB.

To access it, a value of 0xA000 has to be stored in one of the segment registers, e.g. into DS.

Then DS:0 will address the first byte of video RAM and DS:0xFFFF — the last byte of RAM.

The real address on the 20-bit address bus, however, will range from 0xA0000 to 0xAFFFF.

The program may contain hard-coded addresses like 0x1234, but the OS may need to load the program at arbitrary addresses, so it recalculates the segment register values in a way that the program does not have to care where it's placed in the RAM.

So, any pointer in the old MS-DOS environment in fact consisted of the segment address and the address inside segment, i.e., two 16-bit values. 20-bit was enough for that, though, but we needed to recalculate the addresses very often: passing more information on the stack seemed a better space/convenience balance.

By the way, because of all this it was not possible to allocate a memory block larger than 64KB.

The segment registers were reused at 80286 as selectors, serving a different function.

When the 80386 CPU and computers with bigger RAM were introduced, MS-DOS was still popular, so the DOS extenders emerged: these were in fact a step toward a "serious" OS, switching the CPU in protected mode and providing much better memory APIs for the programs which still needed to run under MS-DOS.

Widely popular examples include DOS/4GW (the DOOM video game was compiled for it), Phar Lap, PMODE.

By the way, the same way of addressing memory was used in the 16-bit line of Windows 3.x, before Win32.

11.7 Basic blocks reordering

11.7.1 Profile-guided optimization

This optimization method can move some basic blocks to another section of the executable binary file.

Obviously, there are parts of a function which are executed more frequently (e.g., loop bodies) and less often (e.g., error reporting code, exception handlers).

The compiler adds instrumentation code into the executable, then the developer runs it with a lot of tests to collect statistics.

Then the compiler, with the help of the statistics gathered, prepares final the executable file with all infrequently executed code moved into another section.

As a result, all frequently executed function code is compacted, and that is very important for execution speed and cache usage.

An example from Oracle RDBMS code, which was compiled with Intel C++:

Listing 11.5: orageneric11.dll (win32)

```
                public _skgfsync
_skgfsync       proc near

; address 0x6030D86A

                db      66h
                nop
                push    ebp
                mov     ebp, esp
                mov     edx, [ebp+0Ch]
                test    edx, edx
```

[6] Enhanced Graphics Adapter
[7] Video Graphics Array

```
                jz      short loc_6030D884
                mov     eax, [edx+30h]
                test    eax, 400h
                jnz     __VInfreq__skgfsync  ; write to log
continue:
                mov     eax, [ebp+8]
                mov     edx, [ebp+10h]
                mov     dword ptr [eax], 0
                lea     eax, [edx+0Fh]
                and     eax, 0FFFFFFFCh
                mov     ecx, [eax]
                cmp     ecx, 45726963h
                jnz     error                ; exit with error
                mov     esp, ebp
                pop     ebp
                retn
_skgfsync       endp

...

; address 0x60B953F0

__VInfreq__skgfsync:
                mov     eax, [edx]
                test    eax, eax
                jz      continue
                mov     ecx, [ebp+10h]
                push    ecx
                mov     ecx, [ebp+8]
                push    edx
                push    ecx
                push    offset ... ; "skgfsync(se=0x%x, ctx=0x%x, iov=0x%x)\n"
                push    dword ptr [edx+4]
                call    dword ptr [eax] ; write to log
                add     esp, 14h
                jmp     continue

error:
                mov     edx, [ebp+8]
                mov     dword ptr [edx], 69AAh ; 27050 "function called with invalid FIB/IOV ↙
    ↘ structure"
                mov     eax, [eax]
                mov     [edx+4], eax
                mov     dword ptr [edx+8], 0FA4h ; 4004
                mov     esp, ebp
                pop     ebp
                retn
; END OF FUNCTION CHUNK FOR _skgfsync
```

The distance of addresses between these two code fragments is almost 9 MB.

All infrequently executed code was placed at the end of the code section of the DLL file, among all function parts.

This part of the function was marked by the Intel C++ compiler with the `VInfreq` prefix.

Here we see that a part of the function that writes to a log file (presumably in case of error or warning or something like that) which was probably not executed very often when Oracle's developers gathered statistics (if it was executed at all).

The writing to log basic block eventually returns the control flow to the "hot" part of the function.

Another "infrequent" part is the basic block returning error code 27050.

In Linux ELF files, all infrequently executed code is moved by Intel C++ into the separate `text.unlikely` section, leaving all "hot" code in the `text.hot` section.

From a reverse engineer's perspective, this information may help to split the function into its core and error handling parts.

11.8 My experience with Hex-Rays 2.2.0

11.8.1 Bugs

There are couple of bugs.

First of all, Hex-Rays is getting lost when FPU instructions are interleaved (by compiler codegenerator) with others.

For example, this:

```
f               proc    near

                lea     eax, [esp+4]
                fild    dword ptr [eax]
                lea     eax, [esp+8]
                fild    dword ptr [eax]
                fabs
                fcompp
                fnstsw  ax
                test    ah, 1
                jz      l01

                mov     eax, 1
                retn
l01:
                mov     eax, 2
                retn

f               endp
```

...will be correcly decompiled to:

```
signed int __cdecl f(signed int a1, signed int a2)
{
  signed int result; // eax@2

  if ( fabs((double)a2) >= (double)a1 )
    result = 2;
  else
    result = 1;
  return result;
}
```

But let's comment one of the instructions at the end:

```
...
l01:
                ;mov    eax, 2
                retn
...
```

...we getting an obvious bug:

```
void __cdecl f(char a1, char a2)
{
  fabs((double)a2);
}
```

This is another bug:

```
extrn f1:dword
extrn f2:dword

f               proc    near

                fld     dword ptr [esp+4]
                fadd    dword ptr [esp+8]
                fst     dword ptr [esp+12]
```

```
                fcomp   ds:const_100
                fld     dword ptr [esp+16]      ; comment this instruction and it will be OK
                fnstsw  ax
                test    ah, 1

                jnz     short l01

                call    f1
                retn
l01:
                call    f2
                retn

f               endp

...

const_100       dd 42C80000h            ; 100.0
```

Result:

```
int __cdecl f(float a1, float a2, float a3, float a4)
{
  double v5; // st7@1
  char v6; // c0@1
  int result; // eax@2

  v5 = a4;
  if ( v6 )
    result = f2(v5);
  else
    result = f1(v5);
  return result;
}
```

v6 variable has *char* type and if you'll try to compile this code, compiler will warn you about variable usage before assignment.

Another bug: FPATAN instruction is correctly decompiled into *atan2()*, but arguments are swapped.

11.8.2 Odd peculiarities

Hex-Rays too often promotes 32-bit *int* to 64-bit one. Here is example:

```
f               proc    near

                mov     eax, [esp+4]
                cdq
                xor     eax, edx
                sub     eax, edx
                ; EAX=abs(a1)

                sub     eax, [esp+8]
                ; EAX=EAX-a2

                ; EAX at this point somehow gets promoted to 64-bit (RAX)

                cdq
                xor     eax, edx
                sub     eax, edx
                ; EAX=abs(abs(a1)-a2)

                retn

f               endp
```

Result:

```
int __cdecl f(int a1, int a2)
{
  __int64 v2; // rax@1

  v2 = abs(a1) - a2;
  return (HIDWORD(v2) ^ v2) - HIDWORD(v2);
}
```

Perhaps, this is result of CDQ instruction? I'm not sure. Anyway, whenever you see *__int64* type in 32-bit code, pay attention.

This is also weird:

```
f               proc    near

                mov     esi, [esp+4]

                lea     ebx, [esi+10h]
                cmp     esi, ebx
                jge     short l00

                cmp     esi, 1000
                jg      short l00

                mov     eax, 2
                retn

l00:
                mov     eax, 1
                retn

f               endp
```

Result:

```
signed int __cdecl f(signed int a1)
{
  signed int result; // eax@3

  if ( __OFSUB__(a1, a1 + 16) ^ 1 && a1 <= 1000 )
    result = 2;
  else
    result = 1;
  return result;
}
```

The code is correct, but needs manual intervention.

Sometimes, Hex-Rays doesn't fold (or reduce) division by multiplication code:

```
f               proc    near

                mov     eax, [esp+4]
                mov     edx, 2AAAAAABh
                imul    edx
                mov     eax, edx

                retn

f               endp
```

Result:

```
int __cdecl f(int a1)
{
  return (unsigned __int64)(715827883i64 * a1) >> 32;
}
```

This can be folded (rewritten) manually.

Many of these peculiarities can be solved by manual reordering of instructions, recompiling assembly code, and then feeding it to Hex-Rays again.

11.8.3 Silence

```
extrn some_func:dword

f               proc    near

                mov     ecx, [esp+4]
                mov     eax, [esp+8]
                push    eax
                call    some_func
                add     esp, 4

                ; use ECX
                mov     eax, ecx

                retn

f               endp
```

Result:

```
int __cdecl f(int a1, int a2)
{
  int v2; // ecx@1

  some_func(a2);
  return v2;
}
```

v2 variable (from ECX) is lost …Yes, this code is incorrect (ECX value doesn't saved during call to another function), but it would be good for Hex-Rays to give a warning.

Another one:

```
extrn some_func:dword

f               proc    near

                call    some_func
                jnz     l01

                mov     eax, 1
                retn
l01:
                mov     eax, 2
                retn

f               endp
```

Result:

```
signed int f()
{
  char v0; // zf@1
  signed int result; // eax@2

  some_func();
  if ( v0 )
    result = 1;
  else
    result = 2;
  return result;
}
```

Again, warning would be great.

Anyway, whenever you see variable of *char* type, or variable which is used without initialization, this is clear sign that something went wrong and needs manual intervention.

11.8.4 Comma

Comma in C/C++ has a bad fame, because it can lead to a confusing code.

Quick quiz, what does this C/C++ function returns?

```
int f()
{
        return 1, 2;
};
```

It's 2: when compiler encounters comma-expression, it generates code which executes all sub-expressions, and *returns* value of the last sub-expression.

I've seen something like that in production code:

```
if (cond)
        return global_var=123, 456; // 456 is returned
else
        return global_var=789, 321; // 321 is returned
```

Apparently, programmer wanted to make code slightly shorter without additional curly brackets. In other words, comma allows to pack couple of expressions into one, without forming statement/code block inside of curly brackets.

Comma in C/C++ is close to begin in Scheme/Racket: https://docs.racket-lang.org/guide/begin.html.

Perhaps, the only widely accepted usage of comma is in *for()* statements:

```
char *s="hello, world";
for(int i=0; *s; s++, i++);
; i = string lenght
```

Both *s++* and *i++* are executed at each loop iteration.

Read more: http://stackoverflow.com/questions/52550/what-does-the-comma-operator-do-in-c.

I'm writing all this because Hex-Rays produces (at least in my case) code which is rich with both commas and short-circuit expressions. For example, this is real output from Hex-Rays:

```
 if ( a >= b || (c = a, (d[a] - e) >> 2 > f) )
    {
        ...
```

This is correct, it compiles and works, and let god help you to understand it. Here is it rewritten:

```
if (cond1 || (comma_expr, cond2))
{
        ...
```

Short-circuit is effective here: first *cond1* is checked, if it's *true*, *if()* body is executed, the rest of *if()* expression is ignored completely. If *cond1* is *false*, *comma_expr* is executed (in the previous example, *a* gets copied to *c*), then *cond2* is checked. If *cond2* is *true*, *if()* body gets executed, or not. In other words, *if()* body gets executed if *cond1* is *true* or *cond2* is *true*, but if the latter is *true*, *comma_expr* is also executed.

Now you can see why comma is so notorious.

A word about short-circuit. A common beginner's misconception is that sub-conditions are checked in some unspecified order, which is not true. In a | b | c expression, a, b and c gets evaluated in unspecified order, so that is why || has also been added to C/C++, to apply short-circuit explicitly.

11.8.5 Data types

Data types is a problem for decompilers.

Hex-Rays can be blind to arrays in local stack, if they weren't set correctly before decompilation. Same story about global arrays.

Another problem is too big functions, where a single slot in local stack can be used by several variables across function's execution. It's not a rare case when a slot is used for *int*-variable, then for pointer, then for *float*-variable. Hex-Rays correctly decompiles it: it creates a variable with some type, then cast it to another type in various parts of functions. This problem has been solved by me by manual splitting big function into several smaller. Just make local variables as global ones, etc, etc. And don't forget about tests.

11.8.6 Long and messed expressions

Sometimes, during rewriting, you can end up with long and hard to understand expressions in *if()* constructs, like:

```
if ((! (v38 && v30 <= 5 && v27 != -1)) && ((! (v38 && v30 <= 5) && v27 != -1) || (v24 >= 5 || ↙
    ↘ v26)) && v25)
{
...
}
```

Wolfram Mathematica can minimize some of them, using `BooleanMinimize[]` function:

```
In[1]:= BooleanMinimize[(! (v38 && v30 <= 5 && v27 != -1)) && v38 && v30 <= 5 && v25 == 0]

Out[1]:= v38 && v25 == 0 && v27 == -1 && v30 <= 5
```

There is even better way, to find common subexpressions:

```
In[2]:= Experimental`OptimizeExpression[(! (v38 && v30 <= 5 &&
      v27 != -1)) && ((! (v38 && v30 <= 5) &&
      v27 != -1) || (v24 >= 5 || v26)) && v25]

Out[2]= Experimental`OptimizedExpression[
 Block[{Compile`$1, Compile`$2}, Compile`$1 = v30 <= 5;
  Compile`$2 =
   v27 != -1; ! (v38 && Compile`$1 &&
      Compile`$2) && ((! (v38 && Compile`$1) && Compile`$2) ||
     v24 >= 5 || v26) && v25]]
```

Mathematica adds two new variables: `Compile`$1` and `Compile`$2`, values of which will be used several times in expression. So we can add two additional variables.

11.8.7 My plan

- Split big functions (and don't forget about tests). Sometimes it's very helpful to form new functions out of big loop bodies.
- Check/set data type of variables, arrays, etc.
- If you see odd result, *dangling* variable (which used before initialization), try to swap instructions manually, recompile it and feed to Hex-Rays again.

11.8.8 Summary

Nevertheless, quality of Hex-Rays 2.2.0 is very, very good. It makes life way easier.

Chapter 12

Books/blogs worth reading

12.1 Books and other materials

12.1.1 Reverse Engineering

- Eldad Eilam, *Reversing: Secrets of Reverse Engineering*, (2005)
- Bruce Dang, Alexandre Gazet, Elias Bachaalany, Sebastien Josse, *Practical Reverse Engineering: x86, x64, ARM, Windows Kernel, Reversing Tools, and Obfuscation*, (2014)
- Michael Sikorski, Andrew Honig, *Practical Malware Analysis: The Hands-On Guide to Dissecting Malicious Software*, (2012)
- Chris Eagle, *IDA Pro Book*, (2011)

Also, Kris Kaspersky's books.

12.1.2 Windows

- Mark Russinovich, *Microsoft Windows Internals*

Blogs:

- Microsoft: Raymond Chen
- nynaeve.net

12.1.3 C/C++

- Brian W. Kernighan, Dennis M. Ritchie, *The C Programming Language*, 2ed, (1988)
- *ISO/IEC 9899:TC3 (C C99 standard)*, (2007)[1]
- Bjarne Stroustrup, *The C++ Programming Language, 4th Edition*, (2013)
- C++11 standard[2]
- Agner Fog, *Optimizing software in C++* (2015)[3]
- Marshall Cline, *C++ FAQ*[4]
- Dennis Yurichev, *C/C++ programming language notes*[5]
- JPL Institutional Coding Standard for the C Programming Language[6]

[1] Also available as http://go.yurichev.com/17274
[2] Also available as http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2013/n3690.pdf.
[3] Also available as http://agner.org/optimize/optimizing_cpp.pdf.
[4] Also available as http://go.yurichev.com/17291
[5] Also available as http://yurichev.com/C-book.html
[6] Also available as https://yurichev.com/mirrors/C/JPL_Coding_Standard_C.pdf

12.1.4 x86 / x86-64

- Intel manuals[7]
- AMD manuals[8]
- Agner Fog, *The microarchitecture of Intel, AMD and VIA CPUs*, (2016)[9]
- Agner Fog, *Calling conventions* (2015)[10]
- [*Intel® 64 and IA-32 Architectures Optimization Reference Manual*, (2014)]
- [*Software Optimization Guide for AMD Family 16h Processors*, (2013)]

Somewhat outdated, but still interesting to read:

Michael Abrash, *Graphics Programming Black Book*, 1997[11] (he is known for his work on low-level optimization for such projects as Windows NT 3.1 and id Quake).

12.1.5 ARM

- ARM manuals[12]
- *ARM(R) Architecture Reference Manual, ARMv7-A and ARMv7-R edition*, (2012)
- [*ARM Architecture Reference Manual, ARMv8, for ARMv8-A architecture profile*, (2013)][13]
- Advanced RISC Machines Ltd, *The ARM Cookbook*, (1994)[14]

12.1.6 Assembly language

Richard Blum — Professional Assembly Language.

12.1.7 Java

[Tim Lindholm, Frank Yellin, Gilad Bracha, Alex Buckley, *The Java(R) Virtual Machine Specification / Java SE 7 Edition*] [15].

12.1.8 UNIX

Eric S. Raymond, *The Art of UNIX Programming*, (2003)

12.1.9 Programming in general

- Brian W. Kernighan, Rob Pike, *Practice of Programming*, (1999)
- Henry S. Warren, *Hacker's Delight*, (2002). Some people say tricks and hacks from the book are not relevant today because they were good only for RISC CPUs, where branching instructions are expensive. Nevertheless, these can help immensely to understand boolean algebra and what all the mathematics near it.

[7] Also available as http://www.intel.com/content/www/us/en/processors/architectures-software-developer-manuals.html

[8] Also available as http://developer.amd.com/resources/developer-guides-manuals/

[9] Also available as http://agner.org/optimize/microarchitecture.pdf

[10] Also available as http://www.agner.org/optimize/calling_conventions.pdf

[11] Also available as https://github.com/jagregory/abrash-black-book

[12] Also available as http://infocenter.arm.com/help/index.jsp?topic=/com.arm.doc.subset.architecture.reference/index.html

[13] Also available as http://yurichev.com/mirrors/ARMv8-A_Architecture_Reference_Manual_(Issue_A.a).pdf

[14] Also available as http://go.yurichev.com/17273

[15] Also available as https://docs.oracle.com/javase/specs/jvms/se7/jvms7.pdf; http://docs.oracle.com/javase/specs/jvms/se7/html/

- (For hard-core geeks with computer science and mathematical background) Donald E. Knuth, *The Art of Computer Programming*. Some people arguing, if it worth for mediocre programmer to try hard to read these quite hard fundamental books. I would say, it's worth just to skim them, to learn what **CS!**[16] consists of.

12.1.10 Cryptography

- Bruce Schneier, *Applied Cryptography*, (John Wiley & Sons, 1994)
- (Free) lvh, *Crypto 101*[17]
- (Free) Dan Boneh, Victor Shoup, *A Graduate Course in Applied Cryptography*[18].

12.1.11 Dedication

As the first page of this book says, "This book is dedicated to Robert Jourdain, John Socha, Ralf Brown and Peter Abel". These are authors of well-known assembly language related books and references from 1980's and 1990's:

- Robert Jourdain – Programmer's problem solver for the IBM PC, XT, & AT (1986)
- Peter Norton and John Socha – The Peter Norton Programmer's Guide to the IBM PC (1985), Peter Norton's Assembly Language Book for the IBM PC (1989). In fact, John Socha is a real author of these books, it can be said, he was ghostwriter. He is also the author of Norton Commander.
- Ralph Brown was known for "Ralf Brown's Interrupt List"[19].
- Peter Abel – IBM PC assembly language and programming (1991)

These are outdated books, of course. But maybe someone will recall "those times".

[16] **CS!**
[17] Also available as https://www.crypto101.io/
[18] Also available as https://crypto.stanford.edu/~dabo/cryptobook/
[19] http://www.ctyme.com/rbrown.htm

Chapter 13

Communities

There are two excellent RE[1]-related subreddits on reddit.com: reddit.com/r/ReverseEngineering/ and reddit.com/r/remath (on the topics for the intersection of RE and mathematics).

There is also a RE part of the Stack Exchange website: reverseengineering.stackexchange.com.

On IRC there's a ##re channel on FreeNode[2].

[1] Reverse Engineering
[2] freenode.net

Afterword

13.1 Questions?

Do not hesitate to mail any questions to the author:
<dennis@yurichev.com>. Do you have any suggestion on new content for to the book? Please do not hesitate to send any corrections (including grammar (you see how horrible my English is?)), etc.

The author is working on the book a lot, so the page and listing numbers, etc., are changing very rapidly. Please do not refer to page and listing numbers in your emails to me. There is a much simpler method: make a screenshot of the page, in a graphics editor underline the place where you see the error, and send it to the author. He'll fix it much faster. And if you familiar with git and LaTeX you can fix the error right in the source code:

GitHub.

Do not worry to bother me while writing me about any petty mistakes you found, even if you are not very confident. I'm writing for beginners, after all, so beginners' opinions and comments are crucial for my job.

Appendix

.1 x86

.1.1 Terminology

Common for 16-bit (8086/80286), 32-bit (80386, etc.), 64-bit.

byte 8-bit. The DB assembly directive is used for defining variables and arrays of bytes. Bytes are passed in the 8-bit part of registers: `AL/BL/CL/DL/AH/BH/CH/DH/SIL/DIL/R*L`.

word 16-bit. DW assembly directive —"—. Words are passed in the 16-bit part of the registers: `AX/BX/CX/DX/SI/DI/R*W`.

double word ("dword") 32-bit. DD assembly directive —"—. Double words are passed in registers (x86) or in the 32-bit part of registers (x64). In 16-bit code, double words are passed in 16-bit register pairs.

quad word ("qword") 64-bit. DQ assembly directive —"—. In 32-bit environment, quad words are passed in 32-bit register pairs.

tbyte (10 bytes) 80-bit or 10 bytes (used for IEEE 754 FPU registers).

paragraph (16 bytes)—term was popular in MS-DOS environment.

Data types of the same width (BYTE, WORD, DWORD) are also the same in Windows API.

.1.2 General purpose registers

It is possible to access many registers by byte or 16-bit word parts. .

It is all inheritance from older Intel CPUs (up to the 8-bit 8080) still supported for backward compatibility. Older 8-bit CPUs (8080) had 16-bit registers divided by two.

Programs written for 8080 could access the low byte part of 16-bit registers, high byte part or the whole 16-bit register.

Perhaps, this feature was left in 8086 as a helper for easier porting.

This feature is usually not present in RISC CPUs.

Registers prefixed with `R-` appeared in x86-64, and those prefixed with `E-`—in 80386.

Thus, R-registers are 64-bit, and E-registers—32-bit.

8 more GPR's were added in x86-86: R8-R15. .

N.B.: In the Intel manuals the byte parts of these registers are prefixed by *L*, e.g.: *R8L*, but IDA names these registers by adding the *B* suffix, e.g.: *R8B*.

RAX/EAX/AX/AL

<table>
<tr><td colspan="8">Byte number:</td></tr>
<tr><td>7th</td><td>6th</td><td>5th</td><td>4th</td><td>3rd</td><td>2nd</td><td>1st</td><td>0th</td></tr>
<tr><td colspan="8">RAX^{x64}</td></tr>
<tr><td colspan="4"></td><td colspan="4">EAX</td></tr>
<tr><td colspan="6"></td><td colspan="2">AX</td></tr>
<tr><td colspan="6"></td><td>AH</td><td>AL</td></tr>
</table>

AKA accumulator. The result of a function is usually returned via this register.

RBX/EBX/BX/BL

<table>
<tr><td colspan="8">Byte number:</td></tr>
<tr><td>7th</td><td>6th</td><td>5th</td><td>4th</td><td>3rd</td><td>2nd</td><td>1st</td><td>0th</td></tr>
<tr><td colspan="8">RBX^{x64}</td></tr>
<tr><td colspan="4"></td><td colspan="4">EBX</td></tr>
<tr><td colspan="6"></td><td colspan="2">BX</td></tr>
<tr><td colspan="6"></td><td>BH</td><td>BL</td></tr>
</table>

RCX/ECX/CX/CL

<table>
<tr><td colspan="8">Byte number:</td></tr>
<tr><td>7th</td><td>6th</td><td>5th</td><td>4th</td><td>3rd</td><td>2nd</td><td>1st</td><td>0th</td></tr>
<tr><td colspan="8">RCX^{x64}</td></tr>
<tr><td colspan="4"></td><td colspan="4">ECX</td></tr>
<tr><td colspan="6"></td><td colspan="2">CX</td></tr>
<tr><td colspan="6"></td><td>CH</td><td>CL</td></tr>
</table>

AKA counter: in this role it is used in REP prefixed instructions and also in shift instructions (SHL/SHR/RxL/RxR).

RDX/EDX/DX/DL

<table>
<tr><td colspan="8">Byte number:</td></tr>
<tr><td>7th</td><td>6th</td><td>5th</td><td>4th</td><td>3rd</td><td>2nd</td><td>1st</td><td>0th</td></tr>
<tr><td colspan="8">RDX^{x64}</td></tr>
<tr><td colspan="4"></td><td colspan="4">EDX</td></tr>
<tr><td colspan="6"></td><td colspan="2">DX</td></tr>
<tr><td colspan="6"></td><td>DH</td><td>DL</td></tr>
</table>

RSI/ESI/SI/SIL

<table>
<tr><td colspan="8">Byte number:</td></tr>
<tr><td>7th</td><td>6th</td><td>5th</td><td>4th</td><td>3rd</td><td>2nd</td><td>1st</td><td>0th</td></tr>
<tr><td colspan="8">RSI^{x64}</td></tr>
<tr><td colspan="4"></td><td colspan="4">ESI</td></tr>
<tr><td colspan="6"></td><td colspan="2">SI</td></tr>
<tr><td colspan="7"></td><td>SIL^{x64}</td></tr>
</table>

AKA “source index”. Used as source in the instructions REP MOVSx, REP CMPSx.

RDI/EDI/DI/DIL

<table>
<tr><td colspan="8">Byte number:</td></tr>
<tr><td>7th</td><td>6th</td><td>5th</td><td>4th</td><td>3rd</td><td>2nd</td><td>1st</td><td>0th</td></tr>
<tr><td colspan="8">RDI^{x64}</td></tr>
<tr><td colspan="4"></td><td colspan="4">EDI</td></tr>
<tr><td colspan="6"></td><td colspan="2">DI</td></tr>
<tr><td colspan="7"></td><td>DIL^{x64}</td></tr>
</table>

AKA “destination index”. Used as a pointer to the destination in the instructions REP MOVSx, REP STOSx.

R8/R8D/R8W/R8L

<table>
<tr><td colspan="8">Byte number:</td></tr>
<tr><td>7th</td><td>6th</td><td>5th</td><td>4th</td><td>3rd</td><td>2nd</td><td>1st</td><td>0th</td></tr>
<tr><td colspan="8">R8</td></tr>
<tr><td colspan="4"></td><td colspan="4">R8D</td></tr>
<tr><td colspan="6"></td><td colspan="2">R8W</td></tr>
<tr><td colspan="7"></td><td>R8L</td></tr>
</table>

R9/R9D/R9W/R9L

<table>
<tr><td colspan="8">Byte number:</td></tr>
<tr><td>7th</td><td>6th</td><td>5th</td><td>4th</td><td>3rd</td><td>2nd</td><td>1st</td><td>0th</td></tr>
<tr><td colspan="8">R9</td></tr>
<tr><td colspan="4"></td><td colspan="4">R9D</td></tr>
<tr><td colspan="6"></td><td colspan="2">R9W</td></tr>
<tr><td colspan="7"></td><td>R9L</td></tr>
</table>

R10/R10D/R10W/R10L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R10							
				R10D			
						R10W	
							R10L

R11/R11D/R11W/R11L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R11							
				R11D			
						R11W	
							R11L

R12/R12D/R12W/R12L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R12							
				R12D			
						R12W	
							R12L

R13/R13D/R13W/R13L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R13							
				R13D			
						R13W	
							R13L

R14/R14D/R14W/R14L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R14							
				R14D			
						R14W	
							R14L

R15/R15D/R15W/R15L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R15							
				R15D			
						R15W	
							R15L

RSP/ESP/SP/SPL

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RSP							
				ESP			
						SP	
							SPL

AKA stack pointer. Usually points to the current stack except in those cases when it is not yet initialized.

RBP/EBP/BP/BPL

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RBP							
				EBP			
						BP	
							BPL

AKA frame pointer. Usually used for local variables and accessing the arguments of the function. More about it: (1.9.1 on page 67).

RIP/EIP/IP

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RIP^{x64}							
				EIP			
						IP	

AKA "instruction pointer" [3]. Usually always points to the instruction to be executed right now. Cannot be modified, however, it is possible to do this (which is equivalent):

```
MOV EAX, ...
JMP EAX
```

Or:

```
PUSH value
RET
```

CS/DS/ES/SS/FS/GS

16-bit registers containing code selector (CS), data selector (DS), stack selector (SS).

FS in win32 points to TLS, GS took this role in Linux. It is made so for faster access to the TLS and other structures like the TIB.
In the past, these registers were used as segment registers (11.6 on page 1003).

Flags register

AKA EFLAGS.

[3] Sometimes also called "program counter"

Bit (mask)	Abbreviation (meaning)	Description
0 (1)	CF (Carry)	The CLC/STC/CMC instructions are used for setting/resetting/toggling this flag
2 (4)	PF (Parity)	(1.19.7 on page 234).
4 (0x10)	AF (Adjust)	Exist solely for work with BCD-numbers
6 (0x40)	ZF (Zero)	Setting to 0 if the last operation's result is equal to 0.
7 (0x80)	SF (Sign)	
8 (0x100)	TF (Trap)	Used for debugging. If turned on, an exception is to be generated after each instruction's execution.
9 (0x200)	IF (Interrupt enable)	Are interrupts enabled. The CLI/STI instructions are used for setting/resetting the flag
10 (0x400)	DF (Direction)	A directions is set for the REP MOVSx/CMPSx/LODSx/SCASx instructions. The CLD/STD instructions are used for setting/resetting the flag See also: 3.24 on page 636.
11 (0x800)	OF (Overflow)	
12, 13 (0x3000)	IOPL (I/O privilege level)[i286]	
14 (0x4000)	NT (Nested task)[i286]	
16 (0x10000)	RF (Resume)[i386]	Used for debugging. The CPU ignores the hardware breakpoint in DRx if the flag is set.
17 (0x20000)	VM (Virtual 8086 mode)[i386]	
18 (0x40000)	AC (Alignment check)[i486]	
19 (0x80000)	VIF (Virtual interrupt)[i586]	
20 (0x100000)	VIP (Virtual interrupt pending)[i586]	
21 (0x200000)	ID (Identification)[i586]	

All the rest flags are reserved.

.1.3 FPU registers

8 80-bit registers working as a stack: ST(0)-ST(7). N.B.: IDA calls ST(0) as just ST. Numbers are stored in the IEEE 754 format.

long double value format:

79	78 … 64	63	62 … 0
S	exponent	I	mantissa or fraction

(S—sign, I—integer part)

Control Word

Register controlling the behavior of the FPU.

Bit	Abbreviation (meaning)	Description
0	IM (Invalid operation Mask)	
1	DM (Denormalized operand Mask)	
2	ZM (Zero divide Mask)	
3	OM (Overflow Mask)	
4	UM (Underflow Mask)	
5	PM (Precision Mask)	
7	IEM (Interrupt Enable Mask)	Exceptions enabling, 1 by default (disabled)
8, 9	PC (Precision Control)	00 — 24 bits (REAL4) 10 — 53 bits (REAL8) 11 — 64 bits (REAL10)
10, 11	RC (Rounding Control)	00 — (by default) round to nearest 01 — round toward $-\infty$ 10 — round toward $+\infty$ 11 — round toward 0
12	IC (Infinity Control)	0 — (by default) treat $+\infty$ and $-\infty$ as unsigned 1 — respect both $+\infty$ and $-\infty$

The PM, UM, OM, ZM, DM, IM flags define if to generate exception in the case of a corresponding error.

Status Word

Read-only register.

Bit	Abbreviation (meaning)	Description
15	B (Busy)	Is FPU do something (1) or results are ready (0)
14	C3	
13, 12, 11	TOP	points to the currently zeroth register
10	C2	
9	C1	
8	C0	
7	IR (Interrupt Request)	
6	SF (Stack Fault)	
5	P (Precision)	
4	U (Underflow)	
3	O (Overflow)	
2	Z (Zero)	
1	D (Denormalized)	
0	I (Invalid operation)	

The SF, P, U, O, Z, D, I bits signal about exceptions.

About the C3, C2, C1, C0 you can read more here: (1.19.7 on page 234).

N.B.: When ST(x) is used, the FPU adds x to TOP (by modulo 8) and that is how it gets the internal register's number.

Tag Word

The register has current information about the usage of numbers registers.

Bit	Abbreviation (meaning)
15, 14	Tag(7)
13, 12	Tag(6)
11, 10	Tag(5)
9, 8	Tag(4)
7, 6	Tag(3)
5, 4	Tag(2)
3, 2	Tag(1)
1, 0	Tag(0)

Each tag contains information about a physical FPU register (R(x)), not logical (ST(x)).

For each tag:

- 00 — The register contains a non-zero value

- 01 — The register contains 0
- 10 — The register contains a special value (NAN[4], ∞, or denormal)
- 11 — The register is empty

.1.4 SIMD registers

MMX registers

8 64-bit registers: MM0..MM7.

SSE and AVX registers

SSE: 8 128-bit registers: XMM0..XMM7. In the x86-64 8 more registers were added: XMM8..XMM15.

AVX is the extension of all these registers to 256 bits ist eine Erweiterung all Register auf 256 Bit.

.1.5 Debugging registers

Used for hardware breakpoints control.

- DR0 — address of breakpoint #1
- DR1 — address of breakpoint #2
- DR2 — address of breakpoint #3
- DR3 — address of breakpoint #4
- DR6 — a cause of break is reflected here
- DR7 — breakpoint types are set here

DR6

Bit (mask)	Description
0 (1)	B0 — breakpoint #1 has been triggered
1 (2)	B1 — breakpoint #2 has been triggered
2 (4)	B2 — breakpoint #3 has been triggered
3 (8)	B3 — breakpoint #4 has been triggered
13 (0x2000)	BD — modification attempt of one of the DRx registers. may be raised if GD is enabled
14 (0x4000)	BS — single step breakpoint (TF flag has been set in EFLAGS). Highest priority. Other bits may also be set.
15 (0x8000)	BT (task switch flag)

N.B. A single step breakpoint is a breakpoint which occurs after each instruction. It can be enabled by setting TF in EFLAGS (.1.2 on page 1022).

DR7

Breakpoint types are set here.

[4] Not a Number

Bit (mask)	Description
0 (1)	L0 — enable breakpoint #1 for the current task
1 (2)	G0 — enable breakpoint #1 for all tasks
2 (4)	L1 — enable breakpoint #2 for the current task
3 (8)	G1 — enable breakpoint #2 for all tasks
4 (0x10)	L2 — enable breakpoint #3 for the current task
5 (0x20)	G2 — enable breakpoint #3 for all tasks
6 (0x40)	L3 — enable breakpoint #4 for the current task
7 (0x80)	G3 — enable breakpoint #4 for all tasks
8 (0x100)	LE — not supported since P6
9 (0x200)	GE — not supported since P6
13 (0x2000)	GD — exception is to be raised if any MOV instruction tries to modify one of the DRx registers
16,17 (0x30000)	breakpoint #1: R/W — type
18,19 (0xC0000)	breakpoint #1: LEN — length
20,21 (0x300000)	breakpoint #2: R/W — type
22,23 (0xC00000)	breakpoint #2: LEN — length
24,25 (0x3000000)	breakpoint #3: R/W — type
26,27 (0xC000000)	breakpoint #3: LEN — length
28,29 (0x30000000)	breakpoint #4: R/W — type
30,31 (0xC0000000)	breakpoint #4: LEN — length

The breakpoint type is to be set as follows (R/W):

- 00 — instruction execution
- 01 — data writes
- 10 — I/O reads or writes (not available in user-mode)
- 11 — on data reads or writes

N.B.: breakpoint type for data reads is absent, indeed.

Breakpoint length is to be set as follows (LEN):

- 00 — one-byte
- 01 — two-byte
- 10 — undefined for 32-bit mode, eight-byte in 64-bit mode
- 11 — four-byte

.1.6 Instructions

Instructions marked as (M) are not usually generated by the compiler: if you see one of them, it is probably a hand-written piece of assembly code, or a compiler intrinsic (11.3 on page 999).

Only the most frequently used instructions are listed here. You can read 12.1.4 on page 1013 for a full documentation.

Do you have to know all instruction's opcodes by heart? No, only those which are used for code patching (11.1.2 on page 998). All the rest of the opcodes don't need to be memorized.

Prefixes

LOCK forces CPU to make exclusive access to the RAM in multiprocessor environment. For the sake of simplification, it can be said that when an instruction with this prefix is executed, all other CPUs in a multiprocessor system are stopped. Most often it is used for critical sections, semaphores, mutexes. Commonly used with ADD, AND, BTR, BTS, CMPXCHG, OR, XADD, XOR. You can read more about critical sections here (6.5.4 on page 787).

REP is used with the MOVSx and STOSx instructions: execute the instruction in a loop, the counter is located in the CX/ECX/RCX register. For a detailed description, read more about the MOVSx (.1.6 on page 1029) and STOSx (.1.6 on page 1030) instructions.

The instructions prefixed by REP are sensitive to the DF flag, which is used to set the direction.

REPE/REPNE (AKA REPZ/REPNZ) used with CMPSx and SCASx instructions: execute the last instruction in a loop, the count is set in the CX/ECX/RCX register. It terminates prematurely if ZF is 0 (REPE) or if ZF is 1 (REPNE).

For a detailed description, you can read more about the CMPSx (.1.6 on page 1032) and SCASx (.1.6 on page 1030) instructions.

Instructions prefixed by REPE/REPNE are sensitive to the DF flag, which is used to set the direction.

Most frequently used instructions

These can be memorized in the first place.

ADC (*add with carry*) add values, increment the result if the CF flag is set. ADC is often used for the addition of large values, for example, to add two 64-bit values in a 32-bit environment using two ADD and ADC instructions. For example:

```
; work with 64-bit values: add val1 to val2.
; .lo means lowest 32 bits, .hi means highest.
ADD val1.lo, val2.lo
ADC val1.hi, val2.hi ; use CF set or cleared at the previous instruction
```

One more example: 1.28 on page 396.

ADD add two values

AND logical “and”

CALL call another function:
`PUSH address_after_CALL_instruction; JMP label`

CMP compare values and set flags, the same as SUB but without writing the result

DEC decrement.Unlike other arithmetic instructions, DEC doesn’t modify CF flag.

IMUL signed multiply IMUL often used instead of MUL, read more about it: 2.2.1.

INC increment.Unlike other arithmetic instructions, INC doesn’t modify CF flag.

JCXZ, JECXZ, JRCXZ (M) jump if CX/ECX/RCX=0

JMP jump to another address. The opcode has a jump offset.

Jcc (where cc—condition code)

A lot of these instructions have synonyms (denoted with AKA), this was done for convenience. Synonymous instructions are translated into the same opcode. The opcode has a jump offset.

JAE AKA JNC: jump if above or equal (unsigned): CF=0

JA AKA JNBE: jump if greater (unsigned): CF=0 and ZF=0

JBE jump if lesser or equal (unsigned): CF=1 or ZF=1

JB AKA JC: jump if below (unsigned): CF=1

JC AKA JB: jump if CF=1

JE AKA JZ: jump if equal or zero: ZF=1

JGE jump if greater or equal (signed): SF=OF

JG jump if greater (signed): ZF=0 and SF=OF

JLE jump if lesser or equal (signed): ZF=1 or SF≠OF

JL jump if lesser (signed): SF≠OF

JNAE AKA JC: jump if not above or equal (unsigned) CF=1

JNA jump if not above (unsigned) CF=1 and ZF=1

JNBE jump if not below or equal (unsigned): CF=0 and ZF=0

JNB AKA JNC: jump if not below (unsigned): CF=0

JNC AKA JAE: jump CF=0 synonymous to JNB.

JNE AKA JNZ: jump if not equal or not zero: ZF=0

JNGE jump if not greater or equal (signed): SF≠OF

JNG jump if not greater (signed): ZF=1 or SF≠OF

JNLE jump if not lesser (signed): ZF=0 and SF=OF

JNL jump if not lesser (signed): SF=OF

JNO jump if not overflow: OF=0

JNS jump if SF flag is cleared

JNZ AKA JNE: jump if not equal or not zero: ZF=0

JO jump if overflow: OF=1

JPO jump if PF flag is cleared (Jump Parity Odd)

JP AKA JPE: jump if PF flag is set

JS jump if SF flag is set

JZ AKA JE: jump if equal or zero: ZF=1

LAHF copy some flag bits to AH:

7	6		4		2		0
SF	ZF		AF		PF		CF

This instruction is often used in FPU-related code.

LEAVE equivalent of the `MOV ESP, EBP` and `POP EBP` instruction pair—in other words, this instruction sets the stack pointer (ESP) back and restores the EBP register to its initial state.

LEA (*Load Effective Address*) form an address

This instruction was intended not for summing values and multiplication but for forming an address, e.g., for calculating the address of an array element by adding the array address, element index, with multiplication of element size[5].

So, the difference between `MOV` and LEA is that `MOV` forms a memory address and loads a value from memory or stores it there, but LEA just forms an address.

But nevertheless, it is can be used for any other calculations.

LEA is convenient because the computations performed by it does not alter CPU flags. This may be very important for OOE processors (to create less data dependencies).

Aside from this, starting at least at Pentium, LEA instruction is executed in 1 cycle.

```
int f(int a, int b)
{
        return a*8+b;
};
```

Listing 1: Optimizing MSVC 2010

```
_a$ = 8         ; size = 4
_b$ = 12        ; size = 4
_f      PROC
        mov     eax, DWORD PTR _b$[esp-4]
        mov     ecx, DWORD PTR _a$[esp-4]
        lea     eax, DWORD PTR [eax+ecx*8]
        ret     0
_f      ENDP
```

Intel C++ uses LEA even more:

```
int f1(int a)
{
        return a*13;
};
```

[5]See also: wikipedia

Listing 2: Intel C++ 2011

```
_f1     PROC NEAR
        mov       ecx, DWORD PTR [4+esp]      ; ecx = a
        lea       edx, DWORD PTR [ecx+ecx*8]  ; edx = a*9
        lea       eax, DWORD PTR [edx+ecx*4]  ; eax = a*9 + a*4 = a*13
        ret
```

These two instructions performs faster than one IMUL.

MOVSB/MOVSW/MOVSD/MOVSQ copy byte/ 16-bit word/ 32-bit word/ 64-bit word from the address which is in SI/ESI/RSI into the address which is in DI/EDI/RDI.

Together with the REP prefix, it is to be repeated in a loop, the count is to be stored in the CX/ECX/RCX register: it works like memcpy() in C. If the block size is known to the compiler in the compile stage, memcpy() is often inlined into a short code fragment using REP MOVSx, sometimes even as several instructions.

The memcpy(EDI, ESI, 15) equivalent is:

```
; copy 15 bytes from ESI to EDI
CLD         ; set direction to forward
MOV ECX, 3
REP MOVSD   ; copy 12 bytes
MOVSW       ; copy 2 more bytes
MOVSB       ; copy remaining byte
```

(Supposedly, it works faster than copying 15 bytes using just one REP MOVSB).

MOVSX load with sign extension see also: (1.17.1 on page 201)

MOVZX load and clear all other bits see also: (1.17.1 on page 202)

MOV load value. this instruction name is misnomer, resulting in some confusion (data is not moved but copied), in other architectures the same instructions is usually named “LOAD” and/or “STORE” or something like that.

One important thing: if you set the low 16-bit part of a 32-bit register in 32-bit mode, the high 16 bits remains as they were. But if you modify the low 32-bit part of the register in 64-bit mode, the high 32 bits of the register will be cleared.

Supposedly, it was done to simplify porting code to x86-64.

MUL unsigned multiply. `IMUL` often used instead of `MUL`, read more about it: 2.2.1.

NEG negation: $op = -op$ Same as `NOT op / ADD op, 1`.

NOP NOP. Its opcode is 0x90, it is in fact the `XCHG EAX,EAX` idle instruction. This implies that x86 does not have a dedicated NOP instruction (as in many RISC). This book has at least one listing where GDB shows NOP as 16-bit XCHG instruction: 1.8.1 on page 48.

More examples of such operations: (.1.7 on page 1038).

NOP may be generated by the compiler for aligning labels on a 16-byte boundary. Another very popular usage of NOP is to replace manually (patch) some instruction like a conditional jump to NOP in order to disable its execution.

NOT op1: $op1 = \neg op1$. logical inversion Important feature—the instruction doesn’t change flags.

OR logical “or”

POP get a value from the stack: `value=SS:[ESP]; ESP=ESP+4 (or 8)`

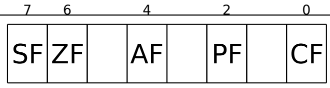
PUSH push a value into the stack: `ESP=ESP-4 (or 8); SS:[ESP]=value`

RET return from subroutine: `POP tmp; JMP tmp`.

In fact, RET is an assembly language macro, in Windows and *NIX environment it is translated into RETN (“return near”) or, in MS-DOS times, where the memory was addressed differently (11.6 on page 1003), into RETF (“return far”).

RET can have an operand. Then it works like this:
`POP tmp; ADD ESP op1; JMP tmp`. RET with an operand usually ends functions in the *stdcall* calling convention, see also: 6.1.2 on page 734.

SAHF copy bits from AH to CPU flags:



This instruction is often used in FPU-related code.

SBB (*subtraction with borrow*) subtract values, decrement the result if the CF flag is set. SBB is often used for subtraction of large values, for example, to subtract two 64-bit values in 32-bit environment using two SUB and SBB instructions. For example:

```
; work with 64-bit values: subtract val2 from val1.
; .lo means lowest 32 bits, .hi means highest.
SUB val1.lo, val2.lo
SBB val1.hi, val2.hi ; use CF set or cleared at the previous instruction
```

One more example: 1.28 on page 396.

SCASB/SCASW/SCASD/SCASQ (M) compare byte/ 16-bit word/ 32-bit word/ 64-bit word that's stored in AX/EAX/RAX with a variable whose address is in DI/EDI/RDI. Set flags as CMP does.

This instruction is often used with the REPNE prefix: continue to scan the buffer until a special value stored in AX/EAX/RAX is found. Hence "NE" in REPNE: continue to scan while the compared values are not equal and stop when equal.

It is often used like the strlen() C standard function, to determine an ASCIIZ string's length:

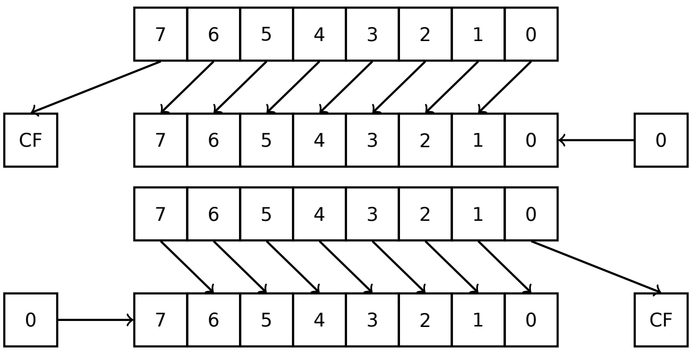
Example:

```
lea     edi, string
mov     ecx, 0FFFFFFFFh ; scan 2^32 - 1 bytes, i.e., almost infinitely
xor     eax, eax        ; 0 is the terminator
repne scasb
add     edi, 0FFFFFFFFh ; correct it

; now EDI points to the last character of the ASCIIZ string.

; lets determine string length
; current ECX = -1-strlen

not     ecx
dec     ecx

; now ECX contain string length
```

If we use a different AX/EAX/RAX value, the function acts like the memchr() standard C function, i.e., it finds a specific byte.

SHL shift value left

SHR shift value right:



These instructions are frequently used for multiplication and division by 2^n. Another very frequent application is processing bit fields: 1.22 on page 304.

SHRD op1, op2, op3: shift value in op2 right by op3 bits, taking bits from op1.

Example: 1.28 on page 396.

STOSB/STOSW/STOSD/STOSQ store byte/ 16-bit word/ 32-bit word/ 64-bit word from AX/EAX/RAX into the address which is in DI/EDI/RDI.

Together with the REP prefix, it is to be repeated in a loop, the counter is in the CX/ECX/RCX register: it works like memset() in C. If the block size is known to the compiler on compile stage, memset() is often inlined into a short code fragment using REP MOVSx, sometimes even as several instructions.

memset(EDI, 0xAA, 15) equivalent is:

```
; store 15 0xAA bytes to EDI
CLD                     ; set direction to forward
MOV EAX, 0AAAAAAAAh
MOV ECX, 3
REP STOSD               ; write 12 bytes
STOSW                   ; write 2 more bytes
STOSB                   ; write remaining byte
```

(Supposedly, it works faster than storing 15 bytes using just one REP STOSB).

SUB subtract values. A frequently occurring pattern is `SUB reg,reg`, which implies zeroing of *reg*.

TEST same as AND but without saving the result, see also: 1.22 on page 304

XOR op1, op2: XOR[6] values. $op1 = op1 \oplus op2$. A frequently occurring pattern is `XOR reg,reg`, which implies zeroing of *reg*. See also: 2.6 on page 461.

Less frequently used instructions

BSF *bit scan forward*, see also: 1.29.2 on page 419

BSR *bit scan reverse*

BSWAP *(byte swap)*, change value endianness.

BTC bit test and complement

BTR bit test and reset

BTS bit test and set

BT bit test

CBW/CWD/CWDE/CDQ/CDQE Sign-extend value:

- **CBW** convert byte in AL to word in AX
- **CWD** convert word in AX to doubleword in DX:AX
- **CWDE** convert word in AX to doubleword in EAX
- **CDQ** convert doubleword in EAX to quadword in EDX:EAX
- **CDQE** (x64) convert doubleword in EAX to quadword in RAX

These instructions consider the value's sign, extending it to high part of the newly constructed value. See also: 1.28.5 on page 405.

Interestingly to know these instructions was initially named as SEX (*Sign EXtend*), as Stephen P. Morse (one of Intel 8086 CPU designers) wrote in [Stephen P. Morse, *The 8086 Primer*, (1980)][7]:

> The process of stretching numbers by extending the sign bit is called sign extension. The 8086 provides instructions (Fig. 3.29) to facilitate the task of sign extension. These instructions were initially named SEX (sign extend) but were later renamed to the more conservative CBW (convert byte to word) and CWD (convert word to double word).

CLD clear DF flag.

CLI (M) clear IF flag

CMC (M) toggle CF flag

CMOVcc conditional MOV: load if the condition is true. The condition codes are the same as in the Jcc instructions (.1.6 on page 1027).

[6] eXclusive OR
[7] Also available as `https://archive.org/details/The8086Primer`

CMPSB/CMPSW/CMPSD/CMPSQ (M) compare byte/ 16-bit word/ 32-bit word/ 64-bit word from the address which is in SI/ESI/RSI with the variable at the address stored in DI/EDI/RDI. Set flags as CMP does.

Together with the REP prefix, it is to be repeated in a loop, the counter is stored in the CX/ECX/RCX register, the process will run until the ZF flag is zero (e.g., until the compared values are equal to each other, hence "E" in REPE).

It works like memcmp() in C.

Example from the Windows NT kernel (WRK v1.2):

Listing 3: base\ntos\rtl\i386\movemem.asm

```
; ULONG
; RtlCompareMemory (
;    IN PVOID Source1,
;    IN PVOID Source2,
;    IN ULONG Length
;    )
;
; Routine Description:
;
;    This function compares two blocks of memory and returns the number
;    of bytes that compared equal.
;
; Arguments:
;
;    Source1 (esp+4) - Supplies a pointer to the first block of memory to
;       compare.
;
;    Source2 (esp+8) - Supplies a pointer to the second block of memory to
;       compare.
;
;    Length (esp+12) - Supplies the Length, in bytes, of the memory to be
;       compared.
;
; Return Value:
;
;    The number of bytes that compared equal is returned as the function
;    value. If all bytes compared equal, then the length of the original
;    block of memory is returned.
;
;--

RcmSource1      equ     [esp+12]
RcmSource2      equ     [esp+16]
RcmLength       equ     [esp+20]

CODE_ALIGNMENT
cPublicProc _RtlCompareMemory,3
cPublicFpo 3,0

        push    esi                     ; save registers
        push    edi                     ;
        cld                             ; clear direction
        mov     esi,RcmSource1          ; (esi) -> first block to compare
        mov     edi,RcmSource2          ; (edi) -> second block to compare

;
;   Compare dwords, if any.
;

rcm10:  mov     ecx,RcmLength           ; (ecx) = length in bytes
        shr     ecx,2                   ; (ecx) = length in dwords
        jz      rcm20                   ; no dwords, try bytes
        repe    cmpsd                   ; compare dwords
        jnz     rcm40                   ; mismatch, go find byte

;
;   Compare residual bytes, if any.
;
```

```
rcm20:  mov     ecx,RcmLength           ; (ecx) = length in bytes
        and     ecx,3                   ; (ecx) = length mod 4
        jz      rcm30                   ; 0 odd bytes, go do dwords
        repe    cmpsb                   ; compare odd bytes
        jnz     rcm50                   ; mismatch, go report how far we got

;
;   All bytes in the block match.
;

rcm30:  mov     eax,RcmLength           ; set number of matching bytes
        pop     edi                     ; restore registers
        pop     esi                     ;
        stdRET  _RtlCompareMemory

;
;   When we come to rcm40, esi (and edi) points to the dword after the
;   one which caused the mismatch.  Back up 1 dword and find the byte.
;   Since we know the dword didn't match, we can assume one byte won't.
;

rcm40:  sub     esi,4                   ; back up
        sub     edi,4                   ; back up
        mov     ecx,5                   ; ensure that ecx doesn't count out
        repe    cmpsb                   ; find mismatch byte

;
;   When we come to rcm50, esi points to the byte after the one that
;   did not match, which is TWO after the last byte that did match.
;

rcm50:  dec     esi                     ; back up
        sub     esi,RcmSource1          ; compute bytes that matched
        mov     eax,esi                 ;
        pop     edi                     ; restore registers
        pop     esi                     ;
        stdRET  _RtlCompareMemory

stdENDP _RtlCompareMemory
```

N.B.: this function uses a 32-bit word comparison (CMPSD) if the block size is a multiple of 4, or per-byte comparison (CMPSB) otherwise.

CPUID get information about the CPU's features. see also: (1.24.6 on page 369).

DIV unsigned division

IDIV signed division

INT (M): `INT x` is analogous to `PUSHF; CALL dword ptr [x*4]` in 16-bit environment. It was widely used in MS-DOS, functioning as a syscall vector. The registers AX/BX/CX/DX/SI/DI were filled with the arguments and then the flow jumped to the address in the Interrupt Vector Table (located at the beginning of the address space). It was popular because INT has a short opcode (2 bytes) and the program which needs some MS-DOS services is not bother to determine the address of the service's entry point. The interrupt handler returns the control flow to caller using the IRET instruction.

The most busy MS-DOS interrupt number was 0x21, serving a huge part of its API. See also: [Ralf Brown *Ralf Brown's Interrupt List*], for the most comprehensive interrupt lists and other MS-DOS information.

In the post-MS-DOS era, this instruction was still used as syscall both in Linux and Windows (6.3 on page 747), but was later replaced by the SYSENTER or SYSCALL instructions.

INT 3 (M): this instruction is somewhat close to `INT`, it has its own 1-byte opcode (`0xCC`), and is actively used while debugging. Often, the debuggers just write the `0xCC` byte at the address of the breakpoint to be set, and when an exception is raised, the original byte is restored and the original instruction at this address is re-executed.
As of Windows NT, an `EXCEPTION_BREAKPOINT` exception is to be raised when the CPU executes this instruction. This debugging event may be intercepted and handled by a host debugger, if one is

loaded. If it is not loaded, Windows offers to run one of the registered system debuggers. If MSVS[8] is installed, its debugger may be loaded and connected to the process. In order to protect from reverse engineering, a lot of anti-debugging methods check integrity of the loaded code.

MSVC has compiler intrinsic for the instruction: `__debugbreak()`[9].

There is also a win32 function in kernel32.dll named `DebugBreak()`[10], which also executes `INT 3`.

IN (M) input data from port. The instruction usually can be seen in OS drivers or in old MS-DOS code, for example (8.5.3 on page 832).

IRET : was used in the MS-DOS environment for returning from an interrupt handler after it was called by the INT instruction. Equivalent to `POP tmp; POPF; JMP tmp`.

LOOP (M) decrement CX/ECX/RCX, jump if it is still not zero.

LOOP instruction was often used in DOS-code which works with external devices. To add small delay, this was done:

```
        MOV     CX, nnnn
LABEL:  LOOP    LABEL
```

Drawback is obvious: length of delay depends on CPU speed.

OUT (M) output data to port. The instruction usually can be seen in OS drivers or in old MS-DOS code, for example (8.5.3 on page 832).

POPA (M) restores values of (R|E)DI, (R|E)SI, (R|E)BP, (R|E)BX, (R|E)DX, (R|E)CX, (R|E)AX registers from the stack.

POPCNT population count. Counts the number of 1 bits in the value.

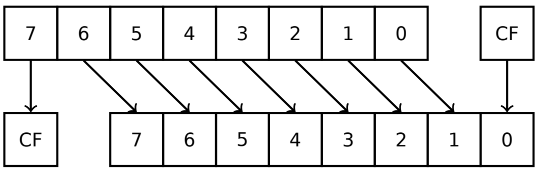
See: 2.7 on page 463.

POPF restore flags from the stack (AKA EFLAGS register)

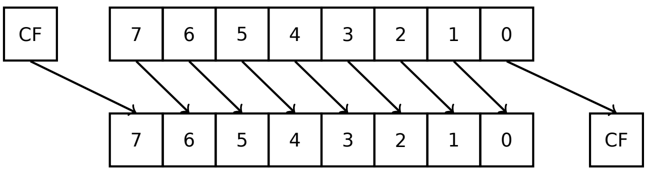
PUSHA (M) pushes the values of the (R|E)AX, (R|E)CX, (R|E)DX, (R|E)BX, (R|E)BP, (R|E)SI, (R|E)DI registers to the stack.

PUSHF push flags (AKA EFLAGS register)

RCL (M) rotate left via CF flag:

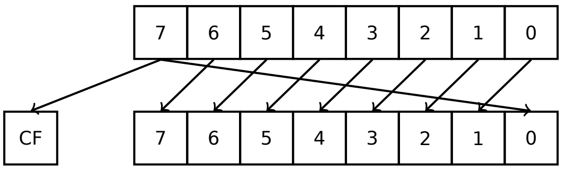


RCR (M) rotate right via CF flag:



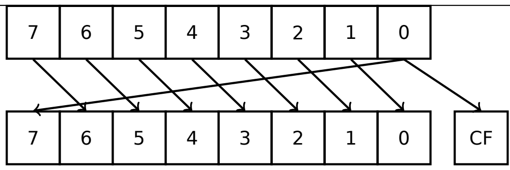
ROL/ROR (M) cyclic shift

ROL: rotate left:



ROR: rotate right:

[8] Microsoft Visual Studio
[9] MSDN
[10] MSDN

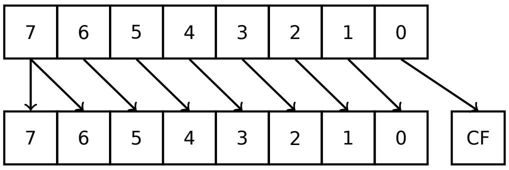


Despite the fact that almost all CPUs have these instructions, there are no corresponding operations in C/C++, so the compilers of these PLs usually do not generate these instructions.

For the programmer's convenience, at least MSVC has the pseudofunctions (compiler intrinsics) *_rotl()* and *_rotr()*[11], which are translated by the compiler directly to these instructions.

SAL Arithmetic shift left, synonymous to SHL

SAR Arithmetic shift right



Hence, the sign bit always stays at the place of the MSB.

SETcc op: load 1 to operand (byte only) if the condition is true or zero otherwise. The condition codes are the same as in the Jcc instructions (.1.6 on page 1027).

STC (M) set CF flag

STD (M) set DF flag. This instruction is not generated by compilers and generally rare. For example, it can be found in the `ntoskrnl.exe` Windows kernel file, in the hand-written memory copy routines.

STI (M) set IF flag

SYSCALL (AMD) call syscall (6.3 on page 747)

SYSENTER (Intel) call syscall (6.3 on page 747)

UD2 (M) undefined instruction, raises exception. Used for testing.

XCHG (M) exchange the values in the operands

This instruction is rare: compilers don't generate it, because starting at Pentium, XCHG with address in memory in operand executes as if it has LOCK prefix ([Michael Abrash, *Graphics Programming Black Book*, 1997chapter 19]). Perhaps, Intel engineers did so for compatibility with synchronizing primitives. Hence, XCHG starting at Pentium can be slow. On the other hand, XCHG was very popular in assembly language programmers. So if you see XCHG in code, it can be a sign that this piece of code is written manually. However, at least Borland Delphi compiler generates this instruction.

FPU instructions

-R suffix in the mnemonic usually implies that the operands are reversed, -P suffix implies that one element is popped from the stack after the instruction's execution, -PP suffix implies that two elements are popped.

-P instructions are often useful when we do not need the value in the FPU stack to be present anymore after the operation.

FABS replace value in ST(0) by absolute value in ST(0)

FADD op: ST(0)=op+ST(0)

FADD ST(0), ST(i): ST(0)=ST(0)+ST(i)

FADDP ST(1)=ST(0)+ST(1); pop one element from the stack, i.e., the values in the stack are replaced by their sum

FCHS ST(0)=-ST(0)

FCOM compare ST(0) with ST(1)

FCOM op: compare ST(0) with op

FCOMP compare ST(0) with ST(1); pop one element from the stack

[11] MSDN

FCOMPP compare ST(0) with ST(1); pop two elements from the stack

FDIVR op: ST(0)=op/ST(0)

FDIVR ST(i), ST(j): ST(i)=ST(j)/ST(i)

FDIVRP op: ST(0)=op/ST(0); pop one element from the stack

FDIVRP ST(i), ST(j): ST(i)=ST(j)/ST(i); pop one element from the stack

FDIV op: ST(0)=ST(0)/op

FDIV ST(i), ST(j): ST(i)=ST(i)/ST(j)

FDIVP ST(1)=ST(0)/ST(1); pop one element from the stack, i.e., the dividend and divisor values in the stack are replaced by quotient

FILD op: convert integer and push it to the stack.

FIST op: convert ST(0) to integer op

FISTP op: convert ST(0) to integer op; pop one element from the stack

FLD1 push 1 to stack

FLDCW op: load FPU control word (.1.3 on page 1023) from 16-bit op.

FLDZ push zero to stack

FLD op: push op to the stack.

FMUL op: ST(0)=ST(0)*op

FMUL ST(i), ST(j): ST(i)=ST(i)*ST(j)

FMULP op: ST(0)=ST(0)*op; pop one element from the stack

FMULP ST(i), ST(j): ST(i)=ST(i)*ST(j); pop one element from the stack

FSINCOS : tmp=ST(0); ST(1)=sin(tmp); ST(0)=cos(tmp)

FSQRT : $ST(0) = \sqrt{ST(0)}$

FSTCW op: store FPU control word (.1.3 on page 1023) into 16-bit op after checking for pending exceptions.

FNSTCW op: store FPU control word (.1.3 on page 1023) into 16-bit op.

FSTSW op: store FPU status word (.1.3 on page 1024) into 16-bit op after checking for pending exceptions.

FNSTSW op: store FPU status word (.1.3 on page 1024) into 16-bit op.

FST op: copy ST(0) to op

FSTP op: copy ST(0) to op; pop one element from the stack

FSUBR op: ST(0)=op-ST(0)

FSUBR ST(0), ST(i): ST(0)=ST(i)-ST(0)

FSUBRP ST(1)=ST(0)-ST(1); pop one element from the stack, i.e., the value in the stack is replaced by the difference

FSUB op: ST(0)=ST(0)-op

FSUB ST(0), ST(i): ST(0)=ST(0)-ST(i)

FSUBP ST(1)=ST(1)-ST(0); pop one element from the stack, i.e., the value in the stack is replaced by the difference

FUCOM ST(i): compare ST(0) and ST(i)

FUCOM compare ST(0) and ST(1)

FUCOMP compare ST(0) and ST(1); pop one element from stack.

FUCOMPP compare ST(0) and ST(1); pop two elements from stack.

The instructions perform just like FCOM, but an exception is raised only if one of the operands is SNaN, while QNaN numbers are processed smoothly.

FXCH ST(i) exchange values in ST(0) and ST(i)

FXCH exchange values in ST(0) and ST(1)

Instructions having printable ASCII opcode

(In 32-bit mode).

These can be suitable for shellcode construction. See also: 8.12.1 on page 911.

ASCII character	hexadecimal code	x86 instruction
0	30	XOR
1	31	XOR
2	32	XOR
3	33	XOR
4	34	XOR
5	35	XOR
7	37	AAA
8	38	CMP
9	39	CMP
:	3a	CMP
;	3b	CMP
<	3c	CMP
=	3d	CMP
?	3f	AAS
@	40	INC
A	41	INC
B	42	INC
C	43	INC
D	44	INC
E	45	INC
F	46	INC
G	47	INC
H	48	DEC
I	49	DEC
J	4a	DEC
K	4b	DEC
L	4c	DEC
M	4d	DEC
N	4e	DEC
O	4f	DEC
P	50	PUSH
Q	51	PUSH
R	52	PUSH
S	53	PUSH
T	54	PUSH
U	55	PUSH
V	56	PUSH
W	57	PUSH
X	58	POP
Y	59	POP
Z	5a	POP
[	5b	POP
\	5c	POP
]	5d	POP
^	5e	POP
_	5f	POP
`	60	PUSHA
a	61	POPA
f	66	(in 32-bit mode) switch to 16-bit operand size
g	67	in 32-bit mode) switch to 16-bit address size
h	68	PUSH
i	69	IMUL
j	6a	PUSH

k	6b	IMUL
p	70	JO
q	71	JNO
r	72	JB
s	73	JAE
t	74	JE
u	75	JNE
v	76	JBE
w	77	JA
x	78	JS
y	79	JNS
z	7a	JP

In summary: AAA, AAS, CMP, DEC, IMUL, INC, JA, JAE, JB, JBE, JE, JNE, JNO, JNS, JO, JP, JS, POP, POPA, PUSH, PUSHA, XOR.

.1.7 npad

It is an assembly language macro for aligning labels on a specific boundary.

That's often needed for the busy labels to where the control flow is often passed, e.g., loop body starts. So the CPU can load the data or code from the memory effectively, through the memory bus, cache lines, etc.

Taken from `listing.inc` (MSVC):

By the way, it is a curious example of the different NOP variations. All these instructions have no effects whatsoever, but have a different size.

Having a single idle instruction instead of couple of NOP-s, is accepted to be better for CPU performance.

```
;; LISTING.INC
;;
;; This file contains assembler macros and is included by the files created
;; with the -FA compiler switch to be assembled by MASM (Microsoft Macro
;; Assembler).
;;
;; Copyright (c) 1993-2003, Microsoft Corporation. All rights reserved.

;; non destructive nops
npad macro size
if size eq 1
  nop
else
 if size eq 2
   mov edi, edi
 else
  if size eq 3
    ; lea ecx, [ecx+00]
    DB 8DH, 49H, 00H
  else
   if size eq 4
     ; lea esp, [esp+00]
     DB 8DH, 64H, 24H, 00H
   else
    if size eq 5
      add eax, DWORD PTR 0
    else
     if size eq 6
       ; lea ebx, [ebx+00000000]
       DB 8DH, 9BH, 00H, 00H, 00H, 00H
     else
      if size eq 7
        ; lea esp, [esp+00000000]
        DB 8DH, 0A4H, 24H, 00H, 00H, 00H, 00H
      else
```

```
       if size eq 8
        ; jmp .+8; .npad 6
        DB 0EBH, 06H, 8DH, 9BH, 00H, 00H, 00H, 00H
       else
        if size eq 9
         ; jmp .+9; .npad 7
         DB 0EBH, 07H, 8DH, 0A4H, 24H, 00H, 00H, 00H, 00H
        else
         if size eq 10
          ; jmp .+A; .npad 7; .npad 1
          DB 0EBH, 08H, 8DH, 0A4H, 24H, 00H, 00H, 00H, 00H, 90H
         else
          if size eq 11
           ; jmp .+B; .npad 7; .npad 2
           DB 0EBH, 09H, 8DH, 0A4H, 24H, 00H, 00H, 00H, 00H, 8BH, 0FFH
          else
           if size eq 12
            ; jmp .+C; .npad 7; .npad 3
            DB 0EBH, 0AH, 8DH, 0A4H, 24H, 00H, 00H, 00H, 00H, 8DH, 49H, 00H
           else
            if size eq 13
             ; jmp .+D; .npad 7; .npad 4
             DB 0EBH, 0BH, 8DH, 0A4H, 24H, 00H, 00H, 00H, 00H, 8DH, 64H, 24H, 00H
            else
             if size eq 14
              ; jmp .+E; .npad 7; .npad 5
              DB 0EBH, 0CH, 8DH, 0A4H, 24H, 00H, 00H, 00H, 00H, 05H, 00H, 00H, 00H, 00H
             else
              if size eq 15
               ; jmp .+F; .npad 7; .npad 6
               DB 0EBH, 0DH, 8DH, 0A4H, 24H, 00H, 00H, 00H, 00H, 8DH, 9BH, 00H, 00H, 00H, 00H
              else
               %out error: unsupported npad size
               .err
              endif
             endif
            endif
           endif
          endif
         endif
        endif
       endif
      endif
     endif
    endif
   endif
  endif
 endif
endif
endm
```

.2 ARM

.2.1 Terminology

ARM was initially developed as 32-bit CPU, so that's why a *word* here, unlike x86, is 32-bit.

byte 8-bit. The DB assembly directive is used for defining variables and arrays of bytes.

halfword 16-bit. DCW assembly directive —”—.

word 32-bit. DCD assembly directive —”—.

doubleword 64-bit.

quadword 128-bit.

.2.2 Versions

- ARMv4: Thumb mode introduced.
- ARMv6: used in iPhone 1st gen., iPhone 3G (Samsung 32-bit RISC ARM 1176JZ(F)-S that supports Thumb-2)
- ARMv7: Thumb-2 was added (2003). was used in iPhone 3GS, iPhone 4, iPad 1st gen. (ARM Cortex-A8), iPad 2 (Cortex-A9), iPad 3rd gen.
- ARMv7s: New instructions added. Was used in iPhone 5, iPhone 5c, iPad 4th gen. (Apple A6).
- ARMv8: 64-bit CPU, AKA ARM64 AKA AArch64. Was used in iPhone 5S, iPad Air (Apple A7). There is no Thumb mode in 64-bit mode, only ARM (4-byte instructions).

.2.3 32-bit ARM (AArch32)

General purpose registers

- R0— function result is usually returned using R0
- R1...R12—GPRs
- R13—AKA SP (stack pointer)
- R14—AKA LR (link register)
- R15—AKA PC (program counter)

`R0-R3` are also called “scratch registers”: the function’s arguments are usually passed in them, and the values in them are not required to be restored upon the function’s exit.

Current Program Status Register (CPSR)

Bit	Description
0..4	M—processor mode
5	T—Thumb state
6	F—FIQ disable
7	I—IRQ disable
8	A—imprecise data abort disable
9	E—data endianness
10..15, 25, 26	IT—if-then state
16..19	GE—greater-than-or-equal-to
20..23	DNM—do not modify
24	J—Java state
27	Q—sticky overflow
28	V—overflow
29	C—carry/borrow/extend
30	Z—zero bit
31	N—negative/less than

VFP (floating point) and NEON registers

<table>
<tr><td>0..31^{bits}</td><td>32..64</td><td>65..96</td><td>97..127</td></tr>
<tr><td colspan="4">Q0 (128 bits)</td></tr>
<tr><td colspan="2">D0 (64 bits)</td><td colspan="2">D1</td></tr>
<tr><td>S0 (32 bits)</td><td>S1</td><td>S2</td><td>S3</td></tr>
</table>

S-registers are 32-bit, used for the storage of single precision numbers.

D-registers are 64-bit ones, used for the storage of double precision numbers.

D- and S-registers share the same physical space in the CPU—it is possible to access a D-register via the S-registers (it is senseless though).

Likewise, the NEON Q-registers are 128-bit ones and share the same physical space in the CPU with the other floating point registers.

In VFP 32 S-registers are present: S0..S31.

In VFPv2 there 16 D-registers are added, which in fact occupy the same space as S0..S31.

In VFPv3 (NEON or "Advanced SIMD") there are 16 more D-registers, D0..D31, but the D16..D31 registers are not sharing space with any other S-registers.

In NEON or "Advanced SIMD" another 16 128-bit Q-registers were added, which share the same space as D0..D31.

.2.4 64-bit ARM (AArch64)

General purpose registers

The number of registers was doubled since AArch32.

- X0— function result is usually returned using X0
- X0...X7—Function arguments are passed here.
- X8
- X9...X15—are temporary registers, the callee function can use and not restore them.
- X16
- X17
- X18
- X19...X29—callee function can use them, but must restore them upon exit.
- X29—used as FP (at least GCC)
- X30—"Procedure Link Register" AKA LR (link register).
- X31—register always contains zero AKA XZR or "Zero Register". It's 32-bit part is called WZR.
- SP, not a general purpose register anymore.

See also: [*Procedure Call Standard for the ARM 64-bit Architecture (AArch64)*, (2013)][12].

The 32-bit part of each X-register is also accessible via W-registers (W0, W1, etc.).

High 32-bit part	low 32-bit part
X0	
	W0

.2.5 Instructions

There is a *-S* suffix for some instructions in ARM, indicating that the instruction sets the flags according to the result. Instructions which lacks this suffix are not modify flags. For example `ADD` unlike `ADDS` will add two numbers, but the flags will not be touched. Such instructions are convenient to use between `CMP` where the flags are set and, e.g. conditional jumps, where the flags are used. They are also better in terms of data dependency analysis (because less number of registers are modified during execution).

[12]Also available as `http://go.yurichev.com/17287`

Conditional codes table

Code	Description	Flags
EQ	Equal	Z == 1
NE	Not equal	Z == 0
CS AKA HS (Higher or Same)	Carry set / Unsigned, Greater than, equal	C == 1
CC AKA LO (LOwer)	Carry clear / Unsigned, Less than	C == 0
MI	Minus, negative / Less than	N == 1
PL	Plus, positive or zero / Greater than, equal	N == 0
VS	Overflow	V == 1
VC	No overflow	V == 0
HI	Unsigned higher / Greater than	C == 1 and Z == 0
LS	Unsigned lower or same / Less than or equal	C == 0 or Z == 1
GE	Signed greater than or equal / Greater than or equal	N == V
LT	Signed less than / Less than	N != V
GT	Signed greater than / Greater than	Z == 0 and N == V
LE	Signed less than or equal / Less than, equal	Z == 1 or N != V
None / AL	Always	Any

.3 MIPS

.3.1 Registers

(O32 calling convention)

General purpose registers GPR

Number	Pseudoname	Description
$0	$ZERO	Always zero. Writing to this register is like NOP.
$1	$AT	Used as a temporary register for assembly macros and pseudo instructions.
$2 ...$3	$V0 ...$V1	Function result is returned here.
$4 ...$7	$A0 ...$A3	Function arguments.
$8 ...$15	$T0 ...$T7	Used for temporary data.
$16 ...$23	$S0 ...$S7	Used for temporary data*.
$24 ...$25	$T8 ...$T9	Used for temporary data.
$26 ...$27	$K0 ...$K1	Reserved for OS kernel.
$28	$GP	Global Pointer**.
$29	$SP	SP*.
$30	$FP	FP*.
$31	$RA	RA.
n/a	PC	PC.
n/a	HI	high 32 bit of multiplication or division remainder***.
n/a	LO	low 32 bit of multiplication and division remainder***.

Floating-point registers

Name	Description
$F0..$F1	Function result returned here.
$F2..$F3	Not used.
$F4..$F11	Used for temporary data.
$F12..$F15	First two function arguments.
$F16..$F19	Used for temporary data.
$F20..$F31	Used for temporary data*.

*—Callee must preserve the value.
**—Callee must preserve the value (except in PIC code).

***—accessible using the MFHI and MFLO instructions.

.3.2 Instructions

There are 3 kinds of instructions:

- R-type: those which have 3 registers. R-instruction usually have the following form:

```
instruction destination, source1, source2
```

  One important thing to keep in mind is that when the first and second register are the same, IDA may show the instruction in its shorter form:

```
instruction destination/source1, source2
```

  That somewhat reminds us of the Intel syntax for x86 assembly language.

- I-type: those which have 2 registers and a 16-bit immediate value.
- J-type: jump/branch instructions, have 26 bits for encoding the offset.

Jump instructions

What is the difference between B- instructions (BEQ, B, etc.) and J- ones (JAL, JALR, etc.)?

The B-instructions have an I-type, hence, the B-instructions' offset is encoded as a 16-bit immediate. JR and JALR are R-type and jump to an absolute address specified in a register. J and JAL are J-type, hence the offset is encoded as a 26-bit immediate.

In short, B-instructions can encode a condition (B is in fact pseudo instruction for `BEQ $ZERO, $ZERO, LABEL`), while J-instructions can't.

.4 Some GCC library functions

name	meaning
__divdi3	signed division
__moddi3	getting remainder (modulo) of signed division
__udivdi3	unsigned division
__umoddi3	getting remainder (modulo) of unsigned division

.5 Some MSVC library functions

`ll` in function name stands for "long long", e.g., a 64-bit data type.

name	meaning
__alldiv	signed division
__allmul	multiplication
__allrem	remainder of signed division
__allshl	shift left
__allshr	signed shift right
__aulldiv	unsigned division
__aullrem	remainder of unsigned division
__aullshr	unsigned shift right

Multiplication and shift left procedures are the same for both signed and unsigned numbers, hence there is only one function for each operation here. .

The source code of these function can be found in the installed MSVS, in `VC/crt/src/intel/*.asm` `VC/crt/src/intel/*.asm`.

.6 Cheatsheets

.6.1 IDA

Hot-keys cheatsheet:

key	meaning
Space	switch listing and graph view
C	convert to code
D	convert to data
A	convert to string
*	convert to array
U	undefine
O	make offset of operand
H	make decimal number
R	make char
B	make binary number
Q	make hexadecimal number
N	rename identifier
?	calculator
G	jump to address
:	add comment
Ctrl-X	show references to the current function, label, variable (incl. in local stack)
X	show references to the function, label, variable, etc.
Alt-I	search for constant
Ctrl-I	search for the next occurrence of constant
Alt-B	search for byte sequence
Ctrl-B	search for the next occurrence of byte sequence
Alt-T	search for text (including instructions, etc.)Text suchen (inkl. Anweisungen, usw.)
Ctrl-T	search for the next occurrence of text
Alt-P	edit current function
Enter	jump to function, variable, etc.
Esc	get back
Num -	fold function or selected area
Num +	unhide function or area

Function/area folding may be useful for hiding function parts when you realize what they do. . this is used in my script[13] for hiding some often used patterns of inline code. .

.6.2 OllyDbg

Hot-keys cheatsheet:

hot-key	meaning
F7	trace into
F8	step over
F9	run
Ctrl-F2	restart

.6.3 MSVC

Some useful options which were used through this book. .

[13] GitHub

option	meaning
/O1	minimize space
/Ob0	no inline expansion
/Ox	maximum optimizations
/GS-	disable security checks (buffer overflows)
/Fa(file)	generate assembly listing
/Zi	enable debugging information
/Zp(n)	pack structs on n-byte boundary
/MD	produced executable will use `MSVCR*.DLL` `MSVCR*.DLL`

Some information about MSVC versions: 5.1.1 on page 699.

.6.4 GCC

Some useful options which were used through this book.

option	meaning
-Os	code size optimization
-O3	maximum optimization
-regparm=	how many arguments are to be passed in registers
-o file	set name of output file
-g	produce debugging information in resulting executable
-S	generate assembly listing file
-masm=intel	produce listing in Intel syntax
-fno-inline	do not inline functions

.6.5 GDB

Some of commands we used in this book:

option	meaning
break filename.c:number	set a breakpoint on line number in source code
break function	set a breakpoint on function
break *address	set a breakpoint on address
b	—”—
p variable	print value of variable
run	run
r	—”—
cont	continue execution
c	—”—
bt	print stack
set disassembly-flavor intel	set Intel syntax
disas	disassemble current function
disas function	disassemble function
disas function,+50	disassemble portion
disas $eip,+0x10	—”—
disas/r	disassemble with opcodes
info registers	print all registers
info float	print FPU-registers
info locals	dump local variables (if known)
x/w ...	dump memory as 32-bit word
x/w $rdi	dump memory as 32-bit word at address in RDI
x/10w ...	dump 10 memory words
x/s ...	dump memory as string
x/i ...	dump memory as code
x/10c ...	dump 10 characters
x/b ...	dump bytes
x/h ...	dump 16-bit halfwords
x/g ...	dump giant (64-bit) words
finish	execute till the end of function
next	next instruction (don’t dive into functions)
step	next instruction (dive into functions)
set step-mode on	do not use line number information while stepping
frame n	switch stack frame
info break	list of breakpoints
del n	delete breakpoint
set args ...	set command-line arguments

Acronyms used

OS Operating System xvi

OOP Object-Oriented Programming 542

PL Programming Language xiv

PRNG Pseudorandom Number Generator ix

ROM Read-Only Memory 81

ALU Arithmetic Logic Unit 26

PID Program/process ID 807

LF Line Feed (10 or '\n' in C/C++) 525

CR Carriage Return (13 or '\r' in C/C++) 525

LIFO Last In First Out 30

MSB Most Significant Bit 317

LSB Least Significant Bit

NSA National Security Agency 464

CFB Cipher Feedback 869

CSPRNG Cryptographically Secure Pseudorandom Number Generator 870

SICP Structure and Interpretation of Computer Programs xvii

ABI Application Binary Interface 15

RA Return Address 22

PE Portable Executable 5

SP stack pointer. SP/ESP/RSP in x86/x64. SP in ARM. 19

DLL Dynamic-Link Library 756

PC Program Counter. IP/EIP/RIP in x86/64. PC in ARM. 20

LR Link Register 6

IDA Interactive Disassembler and Debugger developed by Hex-Rays 6

IAT Import Address Table 757

INT Import Name Table 757

RVA Relative Virtual Address 757

VA Virtual Address 757

OEP Original Entry Point 746

MSVC Microsoft Visual C++

MSVS Microsoft Visual Studio 1034

ASLR Address Space Layout Randomization 622

MFC Microsoft Foundation Classes 760

TLS Thread Local Storage 284

AKA Also Known As 30

CRT C Runtime library 10

CPU Central Processing Unit xvi

GPU Graphics Processing Unit 879

FPU Floating-Point Unit v

CISC Complex Instruction Set Computing 20

RISC Reduced Instruction Set Computing 2

GUI Graphical User Interface 753

RTTI Run-Time Type Information 557

BSS Block Started by Symbol 25

SIMD Single Instruction, Multiple Data 195

BSOD Blue Screen of Death 747

DBMS Database Management Systems xiv

ISA Instruction Set Architecture x

HPC High-Performance Computing 517

SEH Structured Exception Handling 37

ELF Executable File format widely used in *NIX systems including Linux 79

TIB Thread Information Block 284

PIC Position Independent Code 539

NAN Not a Number 1025

NOP No Operation 6

BEQ (PowerPC, ARM) Branch if Equal 95

BNE (PowerPC, ARM) Branch if Not Equal 209

BLR (PowerPC) Branch to Link Register 816

XOR eXclusive OR 1031

MCU Microcontroller Unit 495

RAM Random-Access Memory 3

GCC GNU Compiler Collection 4

EGA Enhanced Graphics Adapter 1004

VGA Video Graphics Array 1004

API Application Programming Interface 631

ASCII American Standard Code for Information Interchange 294

ASCIIZ ASCII Zero (null-terminated ASCII string) 92

IA64 Intel Architecture 64 (Itanium) 465

EPIC Explicitly Parallel Instruction Computing 1001

OOE Out-of-Order Execution 466

MSDN Microsoft Developer Network 624

STL (C++) Standard Template Library 564

PODT (C++) Plain Old Data Type 575

HDD Hard Disk Drive 587

VM Virtual Memory

WRK Windows Research Kernel 716

GPR General Purpose Registers 2

SSDT System Service Dispatch Table 747

RE Reverse Engineering 1015

RAID Redundant Array of Independent Disks vii

BCD Binary-Coded Decimal 447

BOM Byte Order Mark 706

GDB GNU Debugger 48

FP Frame Pointer 24

MBR Master Boot Record 712

JPE Jump Parity Even (x86 instruction) 239

CIDR Classless Inter-Domain Routing 485

STMFD Store Multiple Full Descending (ARM instruction)

LDMFD Load Multiple Full Descending (ARM instruction)

STMED Store Multiple Empty Descending (ARM instruction) 30

LDMED Load Multiple Empty Descending (ARM instruction) 30

STMFA Store Multiple Full Ascending (ARM instruction) 30

LDMFA Load Multiple Full Ascending (ARM instruction) 30

STMEA Store Multiple Empty Ascending (ARM instruction) 30

LDMEA Load Multiple Empty Ascending (ARM instruction) 30

APSR (ARM) Application Program Status Register 262

FPSCR (ARM) Floating-Point Status and Control Register 262

RFC Request for Comments 710

TOS Top of Stack 662

LVA (Java) Local Variable Array 668

JVM Java Virtual Machine ix

JIT Just-In-Time compilation 661

CDFS Compact Disc File System 723

CD Compact Disc

ADC Analog-to-Digital Converter 719

EOF End of File 85

DIY Do It Yourself 627

MMU Memory Management Unit 621

DES Data Encryption Standard 448

MIME Multipurpose Internet Mail Extensions 448

DBI Dynamic Binary Instrumentation 524

XML Extensible Markup Language 635

JSON JavaScript Object Notation 635

URL Uniform Resource Locator 4

IV Initialization Vector xi

RSA Rivest Shamir Adleman 958

CPRNG Cryptographically secure PseudoRandom Number Generator 959

GiB Gibibyte 973

CRC Cyclic redundancy check 993

AES Advanced Encryption Standard 993

Glossary

heap usually, a big chunk of memory provided by the OS so that applications can divide it by themselves as they wish. malloc()/free() work with the heap . 30, 348, 560, 562, 563, 575, 577, 592, 593, 636, 755, 757

real number numbers which may contain a dot. this is *float* and *double* in C/C++ . 218

decrement Decrease by 1 . 19, 184, 203, 440, 726, 858, 1027, 1030, 1034

increment Increase by 1 . 16, 20, 184, 188, 203, 209, 326, 329, 440, 855, 1027

integral data type usual numbers, but not a real ones. may be used for passing variables of boolean data type and enumerations . 232

product Multiplication result . 97, 224, 227, 407, 431, 454

arithmetic mean a sum of all values divided by their count . 519

stack pointer A register pointing to a place in the stack. 10, 11, 20, 30, 35, 42, 54, 55, 73, 99, 544, 651, 734–737, 1022, 1028, 1040, 1048

tail call It is when the compiler (or interpreter) transforms the recursion (with which it is possible: *tail recursion*) into an iteration for efficiency : wikipedia . 481

quotient Division result . 218, 220, 222, 223, 227, 430, 497, 520

anti-pattern Generally considered as bad practice . 32, 76, 465

atomic operation "$\alpha\tau o\mu o\varsigma$" stands for "indivisible" in Greek, so an atomic operation is guaranteed not to be interrupted by other threads . 646, 788

basic block a group of instructions that do not have jump/branch instructions, and also don't have jumps inside the block from the outside. In IDA it looks just like as a list of instructions without empty lines . 691, 1004, 1005

callee A function being called by another . 32, 33, 46, 66, 86, 97, 99, 101, 420, 465, 544, 651, 734–737, 739, 740, 1042

caller A function calling another . 6, 8, 10, 30, 46, 86, 97, 98, 100, 108, 154, 420, 469, 544, 734, 736, 737, 740

compiler intrinsic A function specific to a compiler which is not an usual library function. The compiler generates a specific machine code instead of a call to it. Often, it's a pseudofunction for a specific CPU instruction. Read more: (11.3 on page 999) . 1034

CP/M Control Program for Microcomputers: a very basic disk OS used before MS-DOS. 912

dongle Dongle is a small piece of hardware connected to LPT printer port (in past) or to USB . Its function was similar to a security token, it has some memory and, sometimes, a secret (crypto-)hashing algorithmi . 815

endianness Byte order: 2.8 on page 464. 22, 78, 346, 1031

GiB Gibibyte: 2^{30} or 1024 mebibytes or 1073741824 bytes . 15

jump offset a part of the JMP or Jcc instruction's opcode, to be added to the address of the next instruction, and this is how the new PC is calculated. May be negative as well . 93, 133, 1027

kernel mode A restrictions-free CPU mode in which the OS kernel and drivers execute. cf. user mode. 1054

leaf function A function which does not call any other function . 28, 32

link register (RISC) A register where the return address is usually stored. This makes it possible to call leaf functions without using the stack, i.e., faster . 32, 816, 1040, 1041

loop unwinding It is when a compiler, instead of generating loop code for n iterations, generates just n copies of the loop body, in order to get rid of the instructions for loop maintenance . 186

name mangling used at least in C++, where the compiler needs to encode the name of class, method and argument types in one string, which will become the internal name of the function. You can read more about it here : 3.18.1 on page 542. 542, 700, 701

NaN not a number: a special cases for floating point numbers, usually signaling about errors . 235, 257, 1003

NEON AKA "Advanced SIMD"—SIMD from ARM . 1041

NOP "no operation", idle instruction . 726

NTAPI API available only in the Windows NT line. Largely not documented by Microsoft . 794

padding *Padding* in English language means to stuff a pillow with something to give it a desired (bigger) form. In computer science, padding means to add more bytes to a block so it will have desired size, like 2^n bytes. . 708

PDB (Win32) Debugging information file, usually just function names, but sometimes also function arguments and local variables names . 699, 758, 794, 795, 802, 803, 895

POKE BASIC language instruction for writing a byte at a specific address . 726

register allocator The part of the compiler that assigns CPU registers to local variables . 202, 307, 420

reverse engineering act of understanding how the thing works, sometimes in order to clone it . iv, 1034

security cookie A random value, different at each execution. You can read more about it here : 1.20.3 on page 283. 778

stack frame A part of the stack that contains information specific to the current function: local variables, function arguments, RA, etc. . 67, 68, 97, 98, 477, 778

stdout standard output. 22, 35, 154

thunk function Tiny function with a single role: call another function . 23, 393, 816, 825

tracer My own simple debugging tool. You can read more about it here : 7.2.1 on page 790. 189–191, 703, 714, 717, 774, 783, 897, 903, 907, 908, 910, 998

user mode A restricted CPU mode in which it all application software code is executed. cf. kernel mode. 832, 1054

Windows NT Windows NT, 2000, XP, Vista, 7, 8, 10. 293, 418, 649, 707, 747, 757, 787, 915, 1033

word data type fitting in GPR. In the computers older than PCs, the memory size was often measured in words rather than bytes . 447–450, 455, 566, 637

xoring often used in the English language, which implying applying the XOR operation . 778, 827, 830

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