Pin Tutorial

What is Instrumentation?

A technique that inserts extra code into a program to collect runtime information

Instrumentation approaches:

- Source instrumentation:
  - Instrument source programs
- **Binary instrumentation**:
  - Instrument executables directly

Why use Dynamic Instrumentation?

- ✓ No need to recompile or relink
- ✓ Discover code at runtime
- ✓ Handle dynamically-generated code
- ✓ Attach to running processes

Advantages of Pin Instrumentation

Easy-to-use Instrumentation:
- Uses dynamic instrumentation
  - Do not need source code, recompilation, post-linking

Programmable Instrumentation:
- Provides rich APIs to write in C/C++ your own instrumentation tools (called Pintools)

Multiplatform:
- Supports x86, x86-64, Itanium, Xscale
- Supports Linux, Windows, MacOS

Robust:
- Instruments real-life applications: Database, web browsers, …
- Instruments multithreaded applications
- Supports signals

Efficient:
- Applies compiler optimizations on instrumentation code

Using Pin

Launch and instrument an application

```
$ pin -t pintool -- application
```

Instrumentation engine (provided in the kit)

Instrumentation tool

(write your own, or use one provided in the kit)

Attach to and instrument an application

```
$ pin -t pintool -pid 1234
```

Pin Instrumentation APIs

Basic APIs are architecture independent:

- Provide common functionalities like determining:
  - Control-flow changes
  - Memory accesses

Architecture-specific APIs

- e.g., Info about segmentation registers on IA32

Call-based APIs:

- Instrumentation routines
- Analysis routines

Instrumentation vs. Analysis

Concepts borrowed from the ATOM tool:

Instrumentation routines define where instrumentation is **inserted**

- e.g., before instruction

☞ **Occurs *first time* an instruction is executed**

Analysis routines define what to do when instrumentation is **activated**

- e.g., increment counter

☞ **Occurs *every time* an instruction is executed**

Pintool 1: Instruction Count

```
sub $0xff, %edx
    counter++;
cmp %esi, %edx
    counter++;
jle <L1>
    counter++;
mov $0x1, %edi
    counter++;
add $0x10, %eax
    counter++;
```

Pintool 1: Instruction Count Output

```
$ /bin/ls
 Makefile imageload.out itrace proccount
 imageload inscount0 atrace itrace.out

$ pin -t inscount0 -- /bin/ls
 Makefile imageload.out itrace proccount
 imageload inscount0 atrace itrace.out

Count 422838
```

ManualExamples/inscount0.cpp

```
#include <iostream>
#include "pin.h"

UINT64 icount = 0;

void docount() { icount++; }
```

analysis routine

```
void Instruction(INS ins, void *v)
{
    I                                                ND);
}

void
{ std::cerr << "Count " << icount << endl; }

int main(int argc, char * argv[])
{
    PIN_Init(argc, argv);
    INS_AddInstrumentFunction(Instruction, 0);
    PIN_AddFiniFunction(Fini, 0);
    PIN_StartProgram();
    return 0;
}
```

instrumentation routine

Same source code works on the 4 architectures

Pin automatically saves/restores application state

Pintool 2: Instruction Trace

```
    Print(ip);
sub $0xff, %edx
    Print(ip);
cmp %esi, %edx
    Print(ip);
jle <L1>
    Print(ip);
mov $0x1, %edi
    Print(ip);
add $0x10, %eax
```

Need to pass ip argument to the analysis routine (printip())

Pintool 2: Instruction Trace Output

```
$ pin -t itrace -- /bin/ls
 Makefile imageload.out itrace proccount
 imageload inscount0 atrace itrace.out


$ head -4 itrace.out
 0x40001e90
 0x40001e91
 0x40001ee4
 0x40001ee5
```

ManualExamples/itrace.cpp

argument to analysis routine

```
#include <stdio.h>
#include "pin.H"
FILE * trace;
void printip(void *ip) { fprintf(trace, "%p\n", ip); }
```

analysis routine

instrumentation routine

```
void Instruction(INS ins, void *v) {
   INS_InsertCall(ins, IPOINT_BEFORE, (AFUNPTR)printip,
                          IARG_INST_PTR, IARG_END);
}
void Fini(INT32 code, void *v) { fclose(trace); }
int main(int argc, char * argv[]) {
    trace = fopen("itrace.out", "w");
    PIN_Init(argc, argv);
    INS_AddInstrumentFunction(Instruction, 0);

    PIN_AddFiniFunction(Fini, 0);
    PIN_StartProgram();
    return 0;
}
```

Examples of Arguments to Analysis Routine

IARG_INST_PTR

- Instruction pointer (program counter) value

IARG_UINT32 <value>

- An integer value

IARG_REG_VALUE <register name>

- Value of the register specified

IARG_BRANCH_TARGET_ADDR

- Target address of the branch instrumented

IARG_MEMORY_READ_EA

- Effective address of a memory read

And many more … (refer to the Pin manual for details)

Instrumentation Points

Instrument points relative to an instruction:

- *Before (IPOINT_BEFORE)*
- After:
  - Fall-through edge (IPOINT_AFTER)
  - Taken edge (IPOINT_TAKEN_BRANCH)

```
                 cmp   %esi, %edx   count()
count() →
                 jle   <L1>  ──────────→  <L1>:
count() →
                 mov   $0x1, %edi              mov $0x8,%edi
```

Instrumentation Granularity

Instrumentation can be done at three different granularities:

- Instruction
- Basic block
  - A sequence of instructions terminated at a control-flow changing instruction
  - Single entry, single exit
- Trace
  - A sequence of basic blocks terminated at an unconditional control-flow changing instruction
  - Single entry, multiple exits

```
sub   $0xff, %edx
cmp   %esi, %edx
jle   <L1>

mov   $0x1, %edi
add   $0x10, %eax
jmp   <L2>
```

1 Trace, 2 BBs, 6 insts

Recap of Pintool 1: Instruction Count

```
counter++;
sub  $0xff, %edx
counter++;
cmp  %esi, %edx
counter++;
jle  <L1>
counter++;
mov  $0x1, %edi
counter++;
add  $0x10, %eax
```

Straightforward, but the counting can be more efficient

Pintool 3: Faster Instruction Count

counter += 3

```
sub   $0xff, %edx

cmp   %esi, %edx

jle   <L1>
```

counter += 2

```
mov   $0x1, %edi

add   $0x10, %eax
```

basic blocks (bbl)

ManualExamples/inscount1.cpp

```
#include <stdio.h>
#include "pin.H"
UINT64 icount = 0;
void docount(INT32 c) { icount += c; }        analysis routine
void Trace(TRACE trace, void *v) {        instrumentation routine
  for (BBL bbl = TRACE_BblHead(trace);
     BBL_Valid(bbl); bbl = BBL_Next(bbl)) {
     BBL_InsertCall(bbl, IPOINT_BEFORE, (AFUNPTR)docount,
           IARG_UINT32, BBL_NumIns(bbl), IARG_END);
  }
}
void Fini(INT32 code, void *v) {
  fprintf(stderr, "Count %lld\n", icount);
}
int main(int argc, char * argv[]) {
   PIN_Init(argc, argv);
   TRACE_AddInstrumentFunction(Trace, 0);
   PIN_AddFiniFunction(Fini, 0);
   PIN_StartProgram();
   return 0;
}
```

Modifying Program Behavior

Pin allows you not only to observe but also change program behavior

Ways to change program behavior:

- Add/delete instructions
- Change register values
- Change memory values
- Change control flow

Instrumentation Library

```
#include <iostream>
#include "pin.H"

UINT64 icount = 0;

VOID Fini(INT32 code, VOID *v) {
  std::cerr << "Count " << icount <
}
VOID docount() {
  icount++;
}
VOID Instruction(INS ins, VOID *v)
  INS_InsertCall(ins, IPOINT_BEFORE
}
int main(int argc, char * argv[]) {
  PIN_Init(argc, argv);
  INS_AddInstrumentFunction(Instruc
  PIN_AddFiniFunction(Fini, 0);
  PIN_StartProgram();
  return 0;
}
```

Instruction counting Pin Tool

```
#include <iostream>
#include "pin.H"
#include "instlib.H"

INSTLIB::ICOUNT icount;

VOID Fini(INT32 code, VOID *v) {
   cout << "Count" << icount.Count() << endl;
}

int main(int argc, char * argv[]) {
   PIN_Init(argc, argv);
   PIN_AddFiniFunction(Fini, 0);
   icount.Activate();
   PIN_StartProgram();
   return 0;
}
```

Useful InstLib abstractions

- **ICOUNT**
  - # of instructions executed
- **FILTER**
  - Instrument specific routines or libraries only
- **ALARM**
  - Execution count timer for address, routines, etc.
- **FOLLOW_CHILD**
  - Inject Pin into new process created by parent process
- **TIME_WARP**
  - Preserves RDTSC behavior across executions
- **CONTROL**
  - Limit instrumentation address ranges

Useful InstLib ALARM Example

Debugging Pintools

1. **Invoke gdb with your pintool (don't "run")**

```
$ gdb inscount0
(gdb)
```

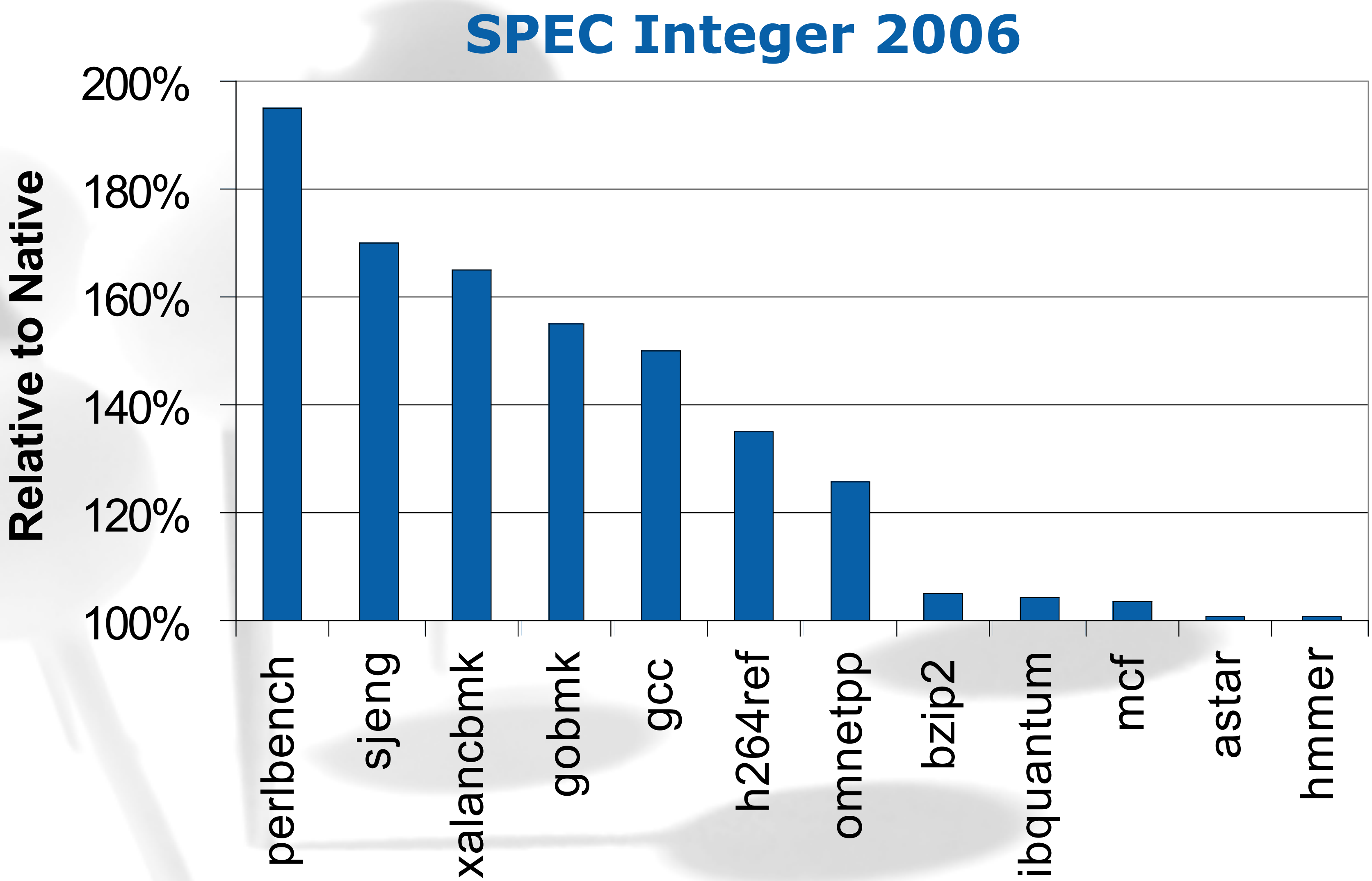
2. **In another window, start your pintool with the "-pause_tool" flag**

```
$ pin –pause_tool 5 –t inscount0 -- /bin/ls
Pausing to attach to pid 32017
```

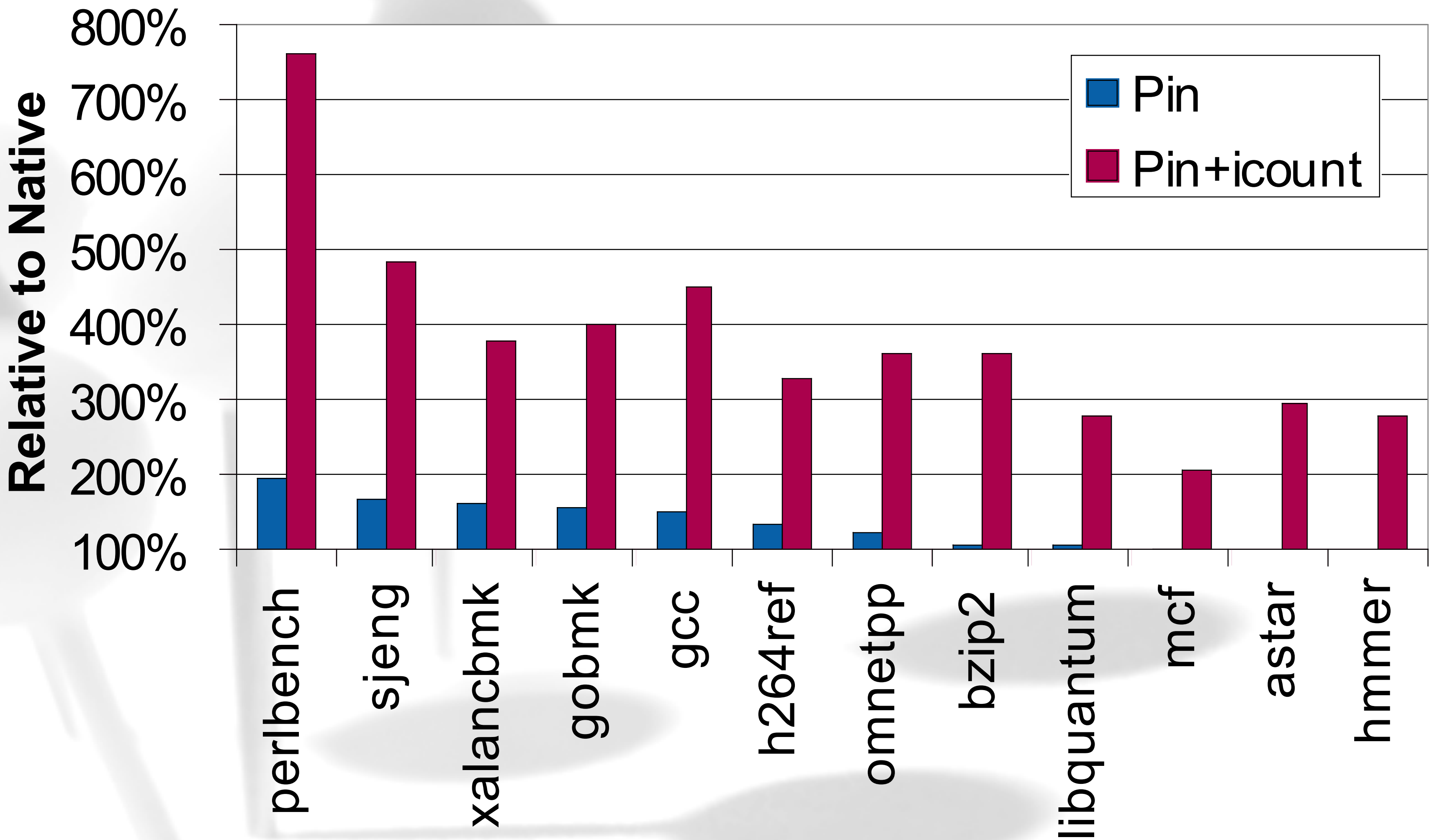
3. **Go back to gdb window:**
   a) Attach to the process
   b) "cont" to continue execution; can set breakpoints as usual

```
(gdb) attach 32017
(gdb) break main
(gdb) cont
```

Pin Overhead



Adding User Instrumentation



Instrumentation Driven Simulation

Fast exploratory studies

- Instrumentation ~= native execution
- Simulation speeds at MIPS

Characterize complex applications

- E.g. Oracle, Java, parallel data-mining apps

Simple to build instrumentation tools

- Tools can feed simulation models in real time
- Tools can gather instruction traces for later use

Performance Models

Branch Predictor Models:

- PC of conditional instructions
- Direction Predictor: Taken/not-taken information
- Target Predictor: PC of target instruction if taken

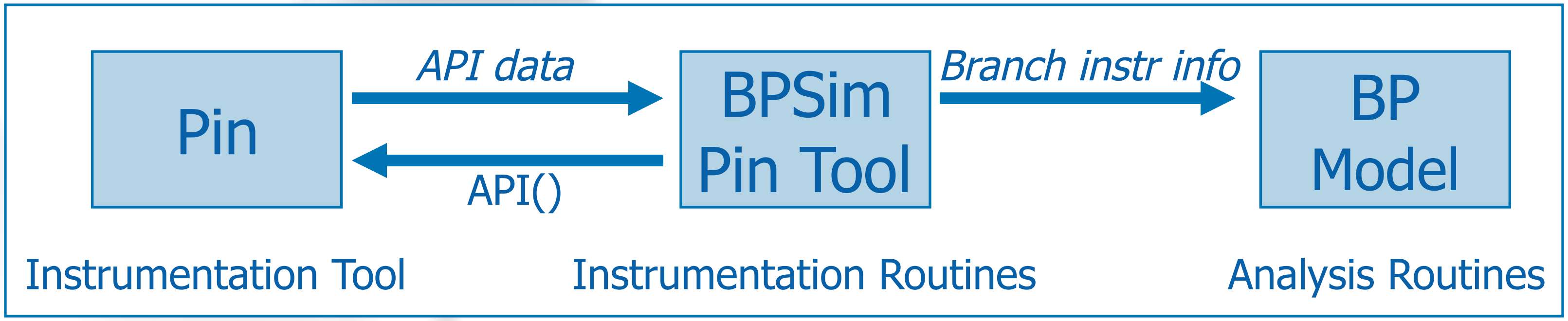
Cache Models:

- Thread ID (if multi-threaded workload)
- Memory address
- Size of memory operation
- Type of memory operation (Read/Write)

Simple Timing Models:

- Latency information

Branch Predictor Model



BPSim Pin Tool

- Instruments all branches
- Uses API to set up call backs to analysis routines

Branch Predictor Model:

- Detailed branch predictor simulator

BP Implementation

```
BranchPredictor myBPU;
```

ANALYSIS

```
VOID ProcessBranch(ADDRINT PC, ADDRINT targetPC, bool BrTaken) {
  BP_Info pred = myBPU.GetPrediction( PC );
  if( pred.Taken != BrTaken ) {
    // Direction Mispredicted
  }
  if( pred.predTarget != targetPC ) {
    // Target Mispredicted
  }
  myBPU.Update( PC, BrTaken, targetPC);
}
```

INSTRUMENT

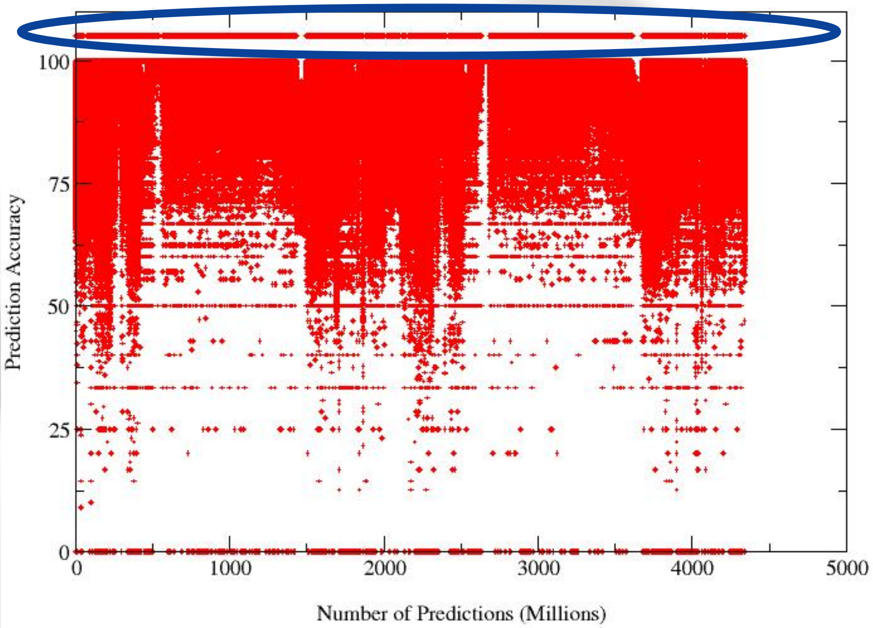
```
VOID Instruction(INS ins, VOID *v)
{
  if( INS_IsDirectBranchOrCall(ins) || INS_HasFallThrough(ins) )
    INS_InsertCall(ins, IPOINT_BEFORE, (AFUNPTR) ProcessBranch,
      ADDRINT, INS_Address(ins),
      IARG_UINT32, INS_DirectBranchOrCallTargetAddress(ins),
      IARG_BRANCH_TAKEN, IARG_END);
}
```

MAIN

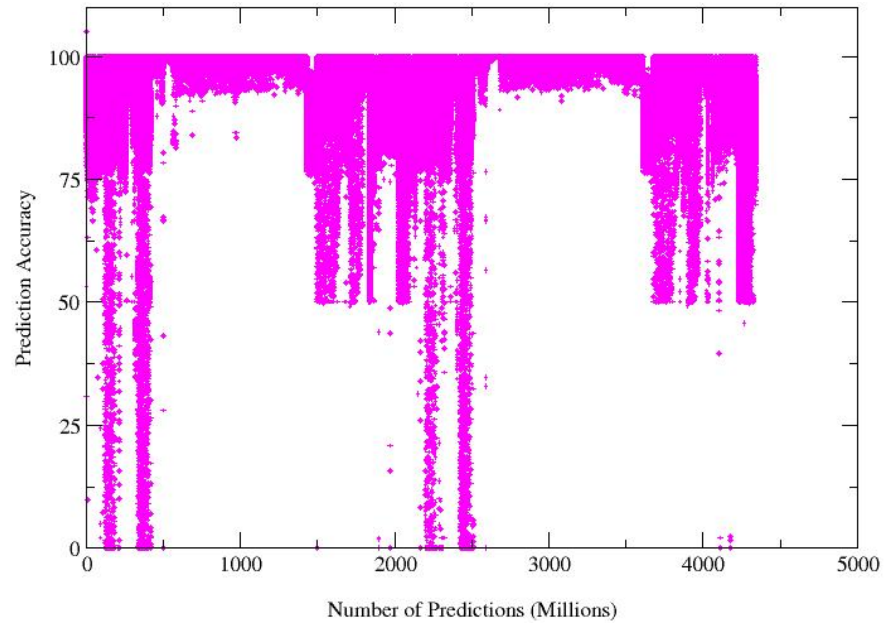
```
int main() {
  PIN_Init();
  INS_AddInstrumentationFunction(Instruction, 0);
  PIN_StartProgram();
}
```

Branch Predictor Performance - GCC

Bimodal not chosen



Bimodal In McFarling Predictor



McFarling Predictor

Branch prediction accuracies range from 0-100%

Branches are hard to predict in some phases

- Can simulate these regions alone by fast forwarding to them in real time

Performance Model Inputs

Branch Predictor Models:

- PC of conditional instructions
- Direction Predictor: Taken/not-taken information
- Target Predictor: PC of target instruction if taken

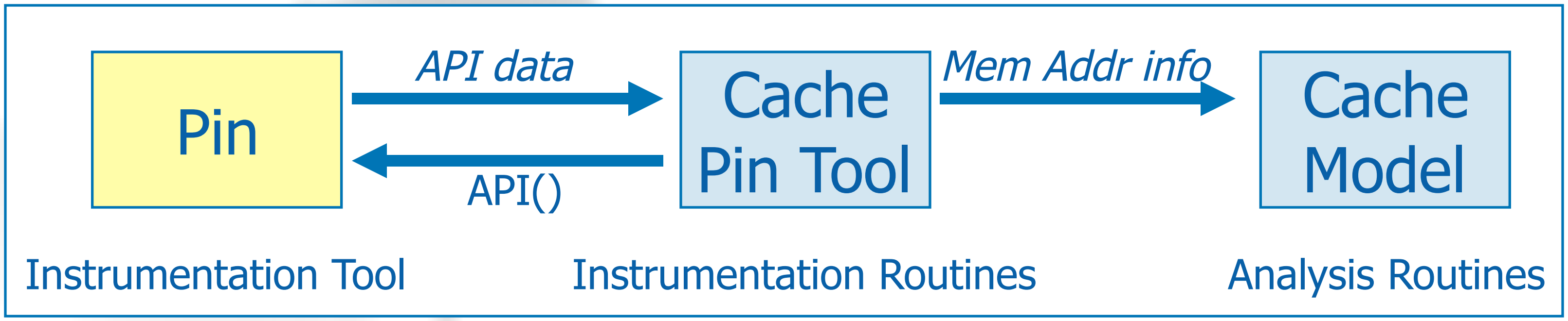
Cache Models:

- Thread ID (if multi-threaded workload)
- Memory address
- Size of memory operation
- Type of memory operation (Read/Write)

Simple Timing Models:

- Latency information

Cache Simulators



Cache Pin Tool

- Instruments all instructions that reference memory
- Use API to set up call backs to analysis routines

Cache Model:

- Detailed cache simulator

Cache Implementation

```
CACHE_t CacheHierarchy[MAX_NUM_THREADS][MAX_NUM_LEVELS];
```

ANALYSIS

```
VOID MemRef(int tid, ADDRINT addrStart, int size, int type) {
  for(addr=addrStart; addr<(addrStart+size); addr+=LINE_SIZE)
    LookupHierarchy( tid, FIRST_LEVEL_CACHE, addr, type);
}
VOID LookupHierarchy(int tid, int level, ADDRINT addr, int accessType){
  result = cacheHier[tid][cacheLevel]->Lookup(addr, accessType );
  if( result == CACHE_MISS ) {
    if( level == LAST_LEVEL_CACHE ) return;
    LookupHierarchy(tid, level+1, addr, accessType);
  }
}
```

INSTRUMENT

```
VOID Instruction(INS ins, VOID *v)
{
  if( INS_IsMemoryRead(ins) )
    INS_InsertCall(ins, IPOINT_BEFORE, (AFUNPTR) MemRef,
      IARG_THREAD_ID, IARG_MEMORYREAD_EA, IARG_MEMORYREAD_SIZE,
      IARG_UINT32, ACCESS_TYPE_LOAD, IARG_END);
  if( INS_IsMemoryWrite(ins) )
    INS_InsertCall(ins, IPOINT_BEFORE, (AFUNPTR) MemRef,
      IARG_THREAD_ID, IARG_MEMORYWRITE_EA, IARG_MEMORYWRITE_SIZE,
      IARG_UINT32, ACCESS_TYPE_STORE, IARG_END);
}
```

MAIN

```
int main() {
  PIN_Init();
  INS_AddInstrumentationFunction(Instruction, 0);
  PIN_StartProgram();
}
```

Performance Models

Branch Predictor Models:

- PC of conditional instructions
- Direction Predictor: Taken/not-taken information
- Target Predictor: PC of target instruction if taken

Cache Models:

- Thread ID (if multi-threaded workload)
- Memory address
- Size of memory operation
- Type of memory operation (Read/Write)

Simple Timing Models:

- Latency information

Simple Timing Model

Assume 1-stage pipeline

- T_i cycles for instruction execution

Assume branch misprediction penalty

- T_b cycles penalty for branch misprediction

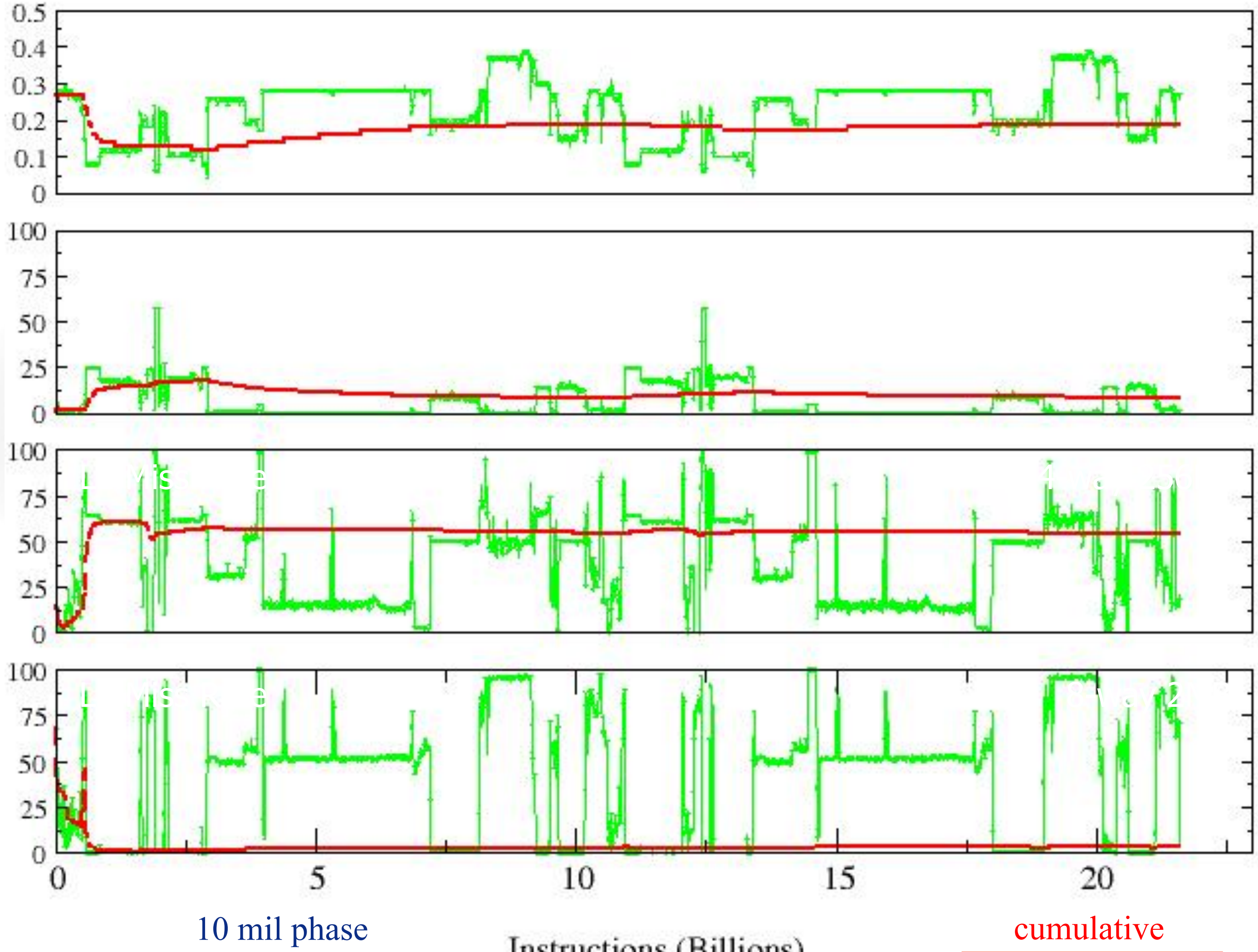
Assume cache access & miss penalty

- T_l cycles for demand reference to cache level l
- T_m cycles for demand reference to memory

Total cycles $= \alpha T_i + \beta T_b + \sum_{l=1}^{LLC} A_l T_l + \eta T_m$

α = instruction count; β = # branch mispredicts ;
A_l = # accesses to cache level l ; η = # last level cache (LLC) misses

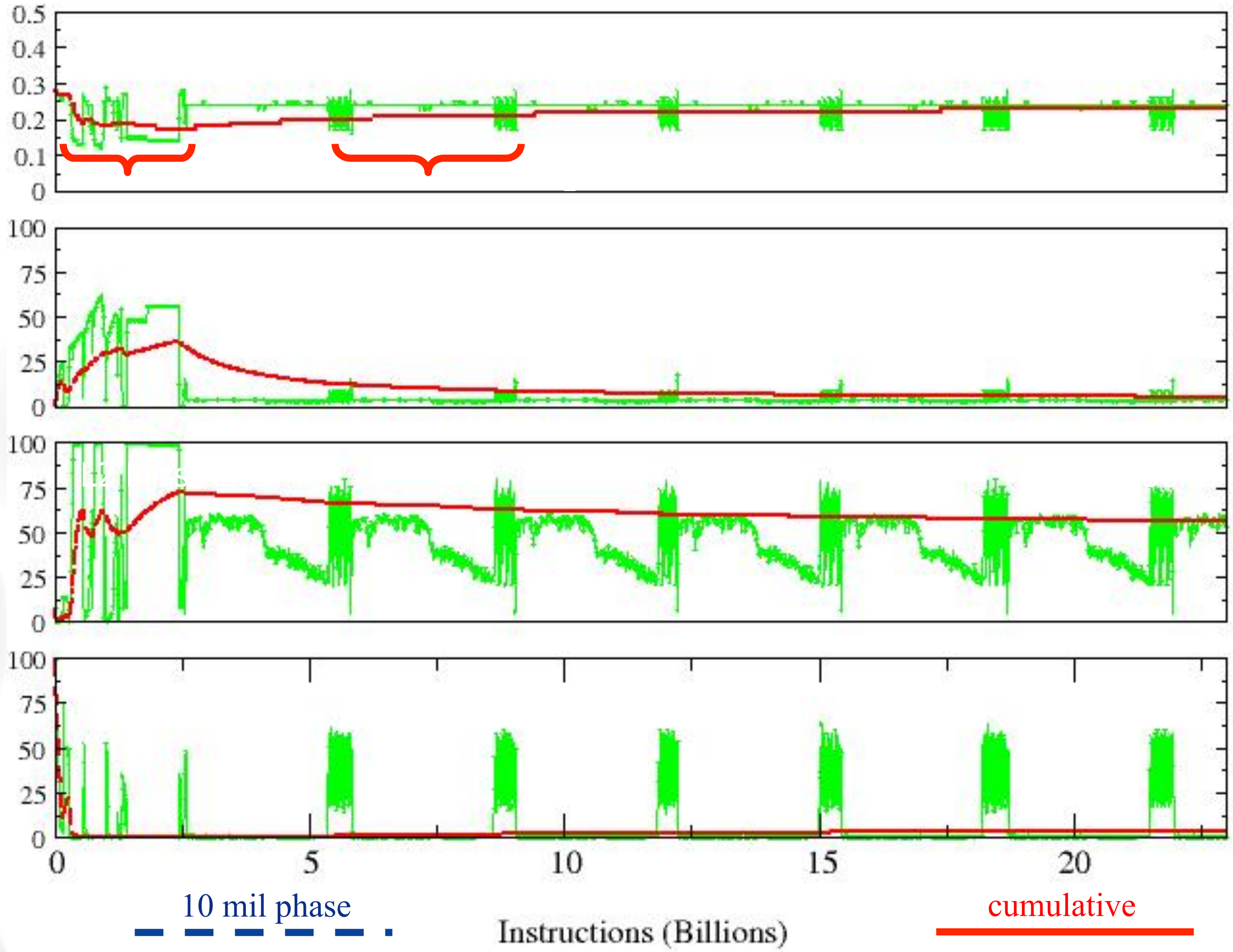
Performance - GCC



Several phases of execution

- Important to pick the correct phase of execution

Performance – AMMP



One loop (3 billion instructions) is representative

- High miss rate at beginning; exploits locality at end

Knobs- Getting command arguments to your PIN tool

Example declarations:

KNOB<string> KnobOutputFile(KNOB_MODE_WRITEONCE, "pintool", "o", "dcache.out", "specify dcache file name");

KNOB<BOOL> KnobTrackLoads(KNOB_MODE_WRITEONCE, "pintool", "l", "0", "track individual loads -- increases profiling time");

KNOB<UINT32> KnobThresholdMiss (KNOB_MODE_WRITEONCE, "pintool", "m","100", "only report memops with miss count above threshold");

-m # is the command flag to the pin tool

100 is the default value

“only report…” usage of that parm

Knobs- Getting command arguments to your PIN tool

Example knob use:

```
TrackLoads= KnobTrackLoads.Value();

 if( TrackLoads )
     {

    }
```