GPU TECHNOLOGY CONFERENCE

NVIDIA

CUDA DEBUGGING WITH COMMAND LINE TOOLS

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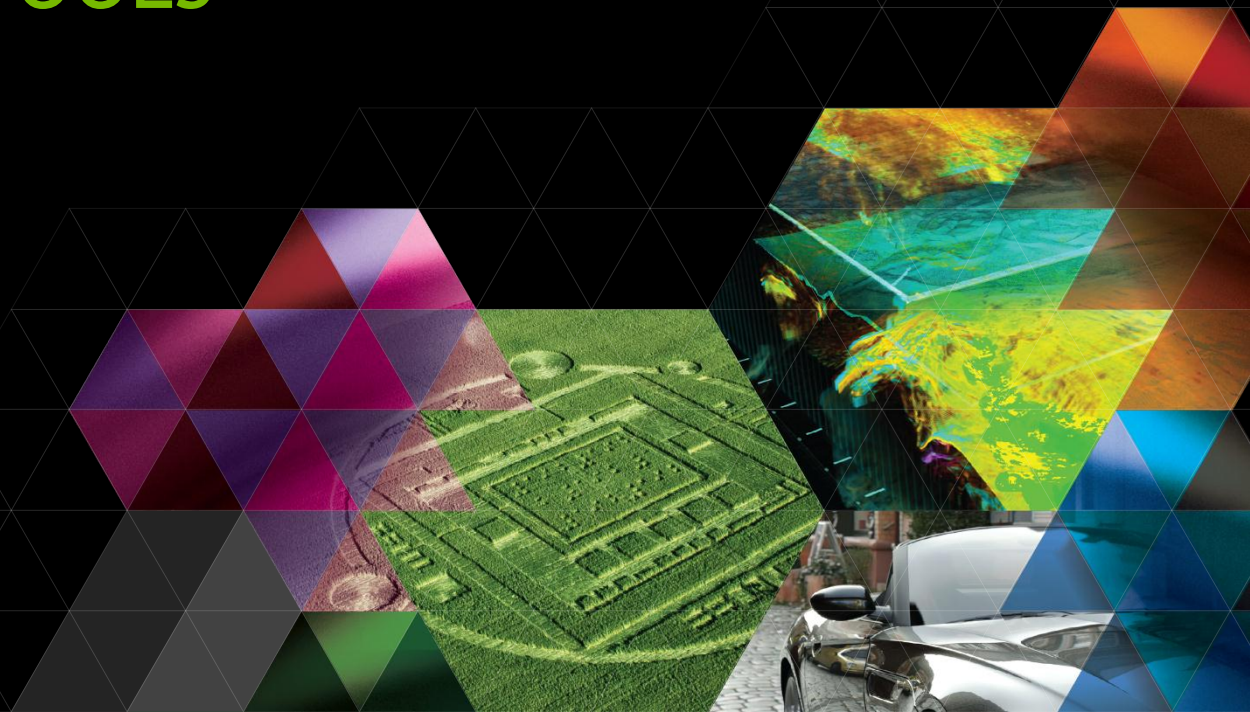


OVERVIEW

- Debugging techniques
  - Return value checks
  - Printf()
  - Assert()
- Tools
  - Cuda-memcheck
  - Cuda-gdb
- Demo

CUDA API CALL

- Asynchronous calls
  - Errors returned by any subsequent call
  - Error state flushed once the device is synchronized
  - Program exit is not a synchronization point
- Check return status of API calls
  - CUDA Runtime API calls return cudaError_t
  - CUDA Driver API calls return CUresult
- CUDA-GDB and CUDA-MEMCHECK will perform these checks

CUDA API Call Checking

- Use macros
- Check all CUDA API calls
- Use cudaGetLastError to see the last error.

```
#define CHECK(x) do {\
 cudaError_t err = (x);\
 if (err != cudaSuccess) {\
   fprintf(stderr, “API error“\
    ”%s:%d Returned:%d\n”, \
    __FILE__, __LINE__, err);\
   exit(1);\
 } while(0)

int main(…)
{
…
CHECK(cudaMalloc(&d_ptr, sz));
}
```

DEVICE SIDE PRINTF()

- SM 2.0 (Fermi) and above only
- C-style format string
  - Must match format string used on host
- Buffered output
  - Flushes only at explicit sync points
- Unordered
  - Think of multi threaded output
- Change the backing global memory storage
  - *cudaDeviceSetLimit(cudaLimitPrintFifoSize, size_t size);*

DEVICE SIDE PRINTF() USAGE

- Include the *stdio.h* header
- Compile the app for Fermi:

nvcc -arch=compute_20 -o output test.cu

- Run

```
$ ./demo_printf
Var:42
```

```
#include <stdio.h>

__device__ int var = 42;

__global__ void kernel(void)
{
    if (threadIdx.x == 0)
      printf("var:%d\n", var);
}

int main(void)
{
    kernel<<<1,1>>>();
    cudaDeviceSynchronize();

    cudaDeviceReset();
}
```

DEVICE SIDE ASSERT()

- SM 2.0 (Fermi) and above only
- Stops if conditional == 0
- Prints the error message to stderr
- Printf()'s rules for flushing apply
- Stops all subsequent host side calls with cudaErrorAssert

DEVICE SIDE ASSERT() USAGE

- Include the *assert.h* header
- Compile the app for Fermi:

nvcc -arch=compute_20 -o output test.cu

- Run

```
$ ./demo_assert
/tmp/test_assert.cu:7: void
kernel(): block: [0,0,0],
thread: [17,0,0] Assertion
`threadIdx.x <=16` failed.
```

```
#include <assert.h>

__device__ int var;

__global__ void kernel(void)
{
    assert(threadId.x <= 16);
}

int main(void)
{
    kernel<<<1,18>>>();
    cudaDeviceSynchronize();

    cudaDeviceReset();
}
```

NVCC COMPILER OPTIONS

- Device side debug : ***-G***
  - Line number information
  - Full debug information (variables, functions etc)
  - **Disables Optimizations**
- Line number information : ***-lineinfo***
  - Only line number information
  - **No additional debug information (no variables)**
  - **No impact on optimization**
- Host side options
  - Host debug information ***-g***
  - Host symbol information ***-Xcompiler -rdynamic***

WHAT IS CUDA-MEMCHECK ?

- "Why did my kernel fail ?"
- The first tool you should run
- Functional correctness tool suite
- Run time error checker : *memcheck*
  - Precise errors : Memory access
  - Imprecise errors : Hardware reported (SM 2.0+)
- Shared memory hazard checker : *racecheck*
- Cross platform : Linux, Mac, Windows
- Also integrated into cuda-gdb (Linux / Mac Only)

RUNNING CUDA-MEMCHECK

- Standalone

```
$ cuda-memcheck [options] <my_app> <my_app_options>
```

- Default to *memcheck* tool
- Detects misaligned and out of bound access in GPU memory

```
Invalid __global__ read of size 4
     at 0x000000b8 in basic.cu:27:kernel2
     by thread (5,0,0) in block (3,0,0)
     Address 0x05500015 is misaligned
```

— Multiple precise errors using ***--destroy-on-device-error kernel***

RUNNING CUDA-MEMCHECK

- Imprecise errors
  - Can be a few instructions away

```
Out-of-range Shared or Local Address
     at 0x00000798 in kernel.cu:110:test(bool)
     by thread (0,0,0) in block (0,0,0)
```

  - On SM 5.0, the PC of the error is precisely attributed **New in 6.0**

DEVICE MALLOC()/FREE() CHECKING

- Double free() / Invalid free()

```
Malloc/Free error encountered : Double free
      at 0x0002de18
      by thread (1,0,0) in block (0,0,0)
      Address 0x50c8b99a0
```

LEAK CHECKING

- Enable with :

```
$ cuda-memcheck --leak-check full <my_app>
```

- Allocation not freed at cuCtxDestroy/cudaDeviceReset()

```
Leaked 64 bytes at 0x5047c0200
```

  - Host backtrace at cudaMalloc time
- Device heap

```
Leaked 16 bytes at 0x5058bf2e4 on the device heap
```

CUDA API ERROR CHECKING

- Enabled by default

```
$ cuda-memcheck --report-api-errors yes <my_app>
```

- CUDA Driver API

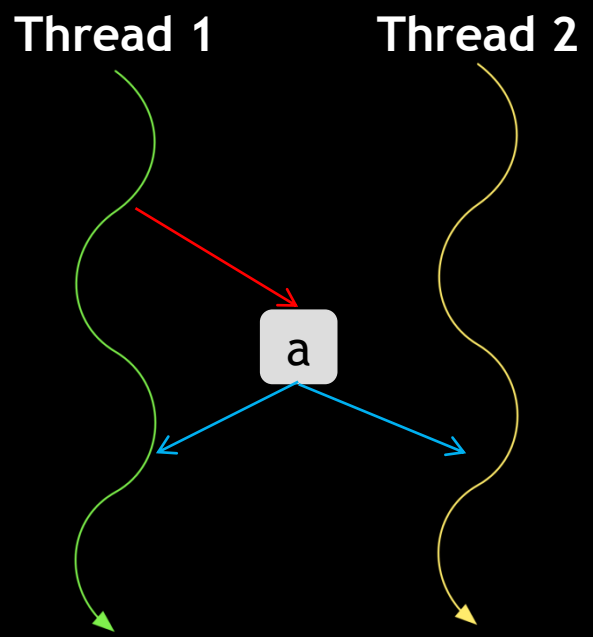
```
Program hit error 1 on CUDA API call to cuMemFree_v2
```

- CUDA Runtime API

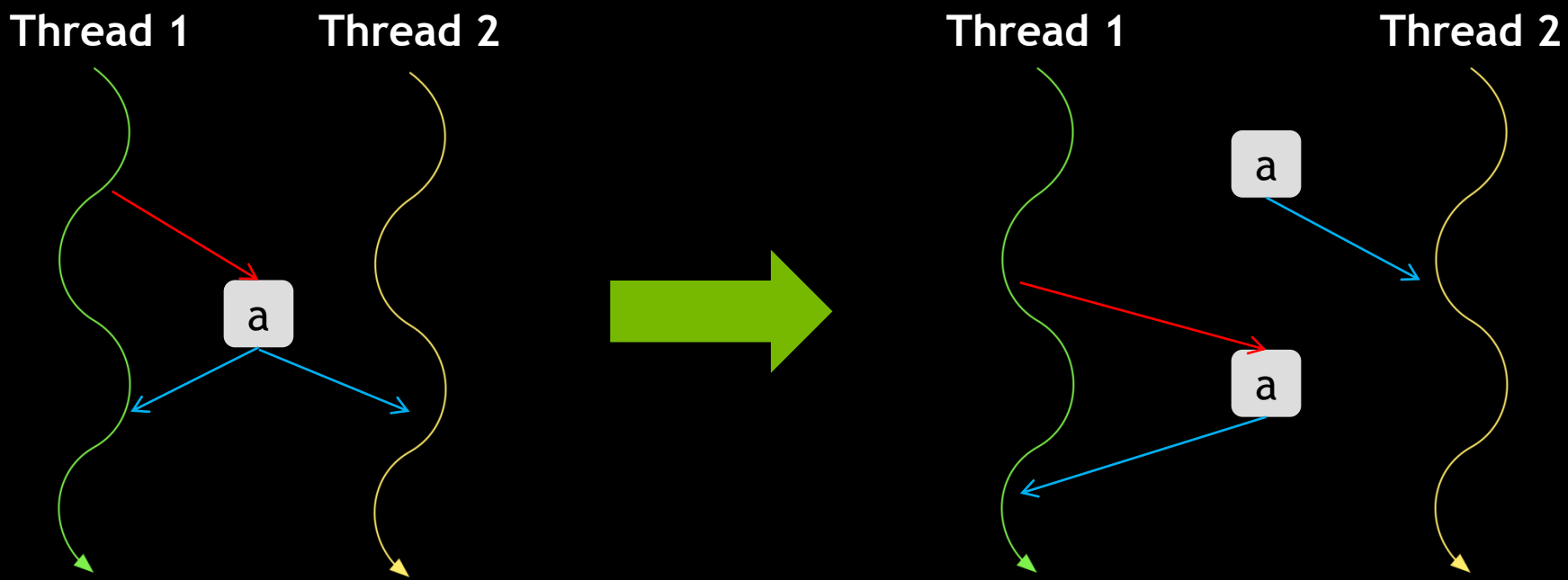
```
Program hit error 17 on CUDA API call to cudaFree
```

BROADCAST IMPLEMENTATION

```
__global__ int bcast(void) {
    int x;
    __shared__ int a;
    if (threadIdx.x == WRITER)
        a = threadIdx.x;
    x = a;
    // do some work
}
```



Sharing data between threads



- Data access hazard
- Data being read in thread 2 can be stale
- Need ordering

CUDA-MEMCHECK TOOL : RACECHECK

- Built into cuda-memcheck
  - Use option ***--tool racecheck***

```
$ cuda-memcheck --tool racecheck <my_app> <my_app_options>
```

- Default : Byte accurate hazard reports
- Can provide source file and line
- Other useful options :
  - ***--save*** to save output to a disk
  - ***--print-level*** to control output

RACECHECK ANALYSIS MODE

- Invoke with

```
$ cuda-memcheck --tool racecheck --racecheck-report analysis
<my_app> <my_app_options>
```

- Analyzes thousands of hazard reports to produce simple user guidance

```
Race reported between Write access at 0x00000018 in
raceGroupBasic.cu:13:Basic(void)

    and Write access at 0x00000018 in
raceGroupBasic.cu:13:Basic(void)
```

CUDA-MEMCHECK FEATURES

- Misaligned and out of bounds memory access
- Hardware error reporting
- Shared memory hazard detection
- Device side malloc()/free() error checking
- Device heap allocation leak checking
- Device + Host stack back traces
- CUDA API error checking
- Name demangling (with parameters) for kernels

CUDA-GDB OVERVIEW

- What is it? What does it let you do?
  - Command line source and assembly (SASS) level debugger
  - Feature set parity with Nsight Eclipse Edition
  - Simultaneous CPU and GPU debugging
    - Set Breakpoints and Conditional Breakpoints
    - Dump stack frames for thousands of CUDA threads
    - Inspect memory, registers, local/shared/global variables
  - Runtime Error Detection (stack overflow,...)
    - Can't figure out why your kernel launch is failing? Run cuda-gdb!
    - Integrated cuda-memcheck support for increased precision
  - Supports multiple GPUs, multiple contexts, multiple kernels

CUDA-GDB OVERVIEW

- Which hardware does it support?
  - All CUDA-capable GPUs SM1.1 and beyond
  - Compatible with NVIDIA Optimus laptops

- Which platforms does it support?
  - All CUDA-supported Linux distributions
  - Mac OS X
  - 32-bit and 64-bit platforms

EXECUTION CONTROL

- Identical to host debugging:
- Launch the application

```
(cuda-gdb) run
```

- Resume the application (all host threads and device threads)

```
(cuda-gdb) continue
```

- Kill the application

```
(cuda-gdb) kill
```

- Interrupt the application: CTRL-C

EXECUTION CONTROL

- Single-Stepping
  - Applies to 32 threads at a time (a warp)

Single-Stepping	At the source level	At the assembly level
Over function calls	next	nexti
Into function calls	step	stepi

- Behavior varies when stepping `__syncthreads()`

PC at a *barrier?*	Single-stepping applies to	Notes
Yes	All threads in the current **block**.	Required to step over the barrier.
No	**Active threads** in the current warp.	

BREAKPOINTS

- By name

```
(cuda-gdb) break my_kernel
(cuda-gdb) break _Z6kernelIfiEvPT_PT0
```

- By file name and line number

```
(cuda-gdb) break acos.cu:380
```

- By address

```
(cuda-gdb) break *0x3e840a8
(cuda-gdb) break *target_var
```

- At every kernel launch

```
(cuda-gdb) set cuda break_on_launch application
```

CONDITIONAL BREAKPOINTS

- Only reports hit breakpoint if condition is met
  - All breakpoints are still hit
  - Condition is evaluated every time for all the threads

- Condition
  - C/C++ syntax
  - supports built-in variables (blockIdx, threadIdx, ...)

```
(cuda-gdb) break acos.cu:380 if (...)
```

THREAD FOCUS

- Some commands apply only to the thread in focus
  - Print local or shared variables
  - Print registers
  - Print stack contents

- Components
  - Kernel : unique, assigned at kernel launch time
  - Block : the application `blockIdx`
  - Thread : the application `threadIdx`

THREAD FOCUS

- To switch focus to any currently running thread

```
(cuda-gdb) cuda kernel 2 block 1,0,0 thread 3,0,0
[Switching focus to CUDA kernel 2 block (1,0,0), thread (3,0,0)

(cuda-gdb) cuda kernel 2 block 2 thread 4
[Switching focus to CUDA kernel 2 block (2,0,0), thread (4,0,0)

(cuda-gdb) cuda thread 5
[Switching focus to CUDA kernel 2 block (2,0,0), thread (5,0,0)
```

- Can also switch by HW coordinates : device/SM/warp/lane

THREAD FOCUS

- To obtain the current focus:

```
(cuda-gdb) cuda kernel block thread
kernel 2 block (2,0,0), thread (5,0,0)

(cuda-gdb) cuda thread
thread (5,0,0)
```

THREADS

- To obtain the list of running threads for kernel 2:

```
(cuda-gdb) info cuda threads kernel 2

    Block  Thread To  Block  Thread Cnt        PC Filename Line
* (0,0,0) (0,0,0)   (3,0,0) (7,0,0)  32 0x7fae70  acos.cu  380
  (4,0,0) (0,0,0)   (7,0,0) (7,0,0)  32 0x7fae60  acos.cu  377
```

- Threads are displayed in (block,thread) ranges
- Divergent threads are in separate ranges
- The * indicates the range where the thread in focus resides

STACK TRACE

- Applies to the thread in focus

```
(cuda-gdb) info stack
#0  fibo_aux (n=6) at fibo.cu:88
#1  0x7bbda0 in fibo_aux (n=7) at fibo.cu:90
#2  0x7bbda0 in fibo_aux (n=8) at fibo.cu:90
#3  0x7bbda0 in fibo_aux (n=9) at fibo.cu:90
#4  0x7bbda0 in fibo_aux (n=10) at fibo.cu:90
#5  0x7cfdb8 in fibo_main<<<(1,1,1),(1,1,1)>>> (...) at fibo.cu:95
```

ACCESSING VARIABLES AND MEMORY

- Read a source variable

```
(cuda-gdb) print my_variable
$1 = 3
(cuda-gdb) print &my_variable
$2 = (@global int *) 0x200200020
```

- Write a source variable

```
(cuda-gdb) print my_variable = 5
$3 = 5
(cuda-gdb) set my_variable = 6
$4 = 6
```

- Access any GPU memory segment using storage specifiers
  - @global, @shared, @local, @generic, @texture, @parameter, @managed

HARDWARE REGISTERS

- CUDA Registers
  - virtual PC: $pc (read-only)
  - SASS registers: $R0, $R1,...
- Show a list of registers (blank for all)

```
(cuda-gdb) info registers R0 R1 R4
R0             0x6      6
R1             0xfffc68 16776296
R4             0x6      6
```

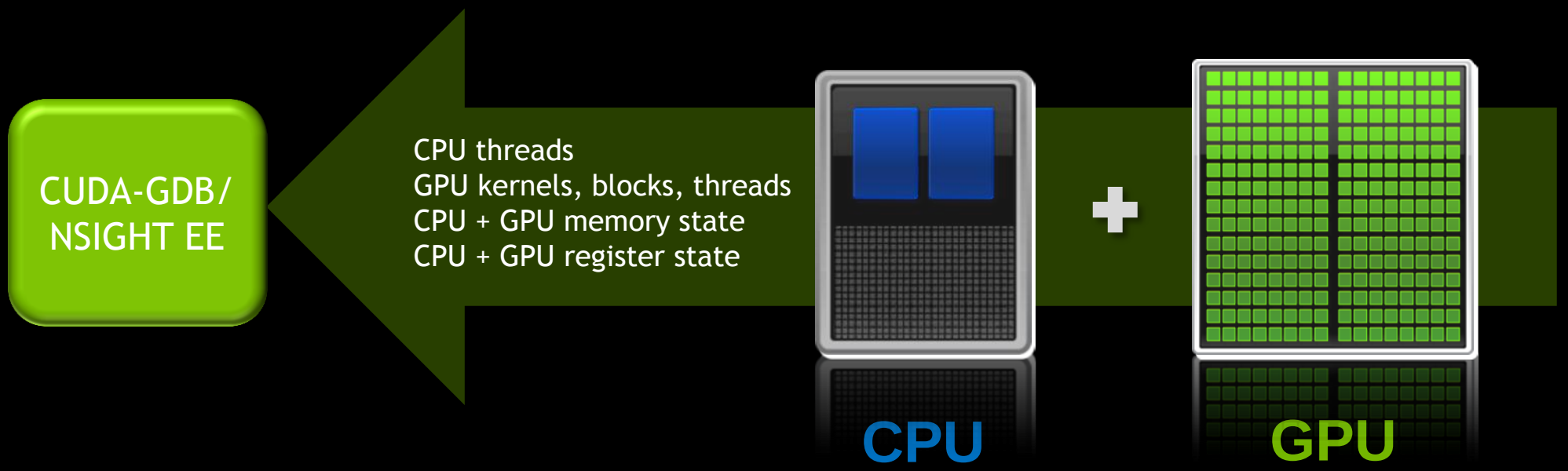
- Modify one register

```
(cuda-gdb) print $R3 = 3
```

CODE DISASSEMBLY

```
(cuda-gdb) x/10i $pc
0x123830a8 <_Z9my_kernel+8>:   MOV R0, c [0x0] [0x8]
0x123830b0 <_Z9my_kernel+16>:  MOV R2, c [0x0] [0x14]
0x123830b8 <_Z9my_kernel+24>:  IMUL.U32.U32 R0, R0, R2
0x123830c0 <_Z9my_kernel+32>:  MOV R2, R0
0x123830c8 <_Z9my_kernel+40>:  S2R R0, SR_CTAid_X
0x123830d0 <_Z9my_kernel+48>:  MOV R0, R0
0x123830d8 <_Z9my_kernel+56>:  MOV R3, c [0x0] [0x8]
0x123830e0 <_Z9my_kernel+64>:  IMUL.U32.U32 R0, R0, R3
0x123830e8 <_Z9my_kernel+72>:  MOV R0, R0
0x123830f0 <_Z9my_kernel+80>:  MOV R0, R0
```

GPU ATTACH



Attach at any point in time!

GPU ATTACH

- Run your program at full speed, then attach with cuda-gdb/Nsight EE
- No environment variables required!
- Inspect CPU and GPU state at any point in time
  - List all resident CUDA kernels
  - Utilize all existing CUDA-GDB commands
- Attach to CUDA programs forked by your application
- Detach and resume CPU and GPU execution

ATTACHING TO A RUNNING CUDA PROCESS

1. Run your program, as usual

```
$ myCudaApplication
```

2. Attach with cuda-gdb, and see what's going on

```
$ cuda-gdb myCudaApplication PID

Program received signal SIGTRAP, Trace/breakpoint trap.
[Switching focus to CUDA kernel 0, grid 2, block (0,0,0), thread (0,0,0),
device 0, sm 11, warp 1, lane 0]

0xae6688 in acos_main<<<(240,1,1),(128,1,1)>>> (parms=...) at acos.cu:383
383         while (!flag);
(cuda-gdb) p flag
$1 = 0
```

ATTACHING ON GPU EXCEPTIONS

1. Run your program, asking the GPU to wait on exceptions

```
$ CUDA_DEVICE_WAITS_ON_EXCEPTION=1 myCudaApplication
```

2. Upon hitting a fault, the following message is printed

```
The application encountered a device error and CUDA_DEVICE_WAITS_ON_EXCEPTION is
set.  You can now attach a debugger to the application for inspection.
```

3. Attach with cuda-gdb, and see which kernel faulted

```
$ cuda-gdb myCudaApplication PID

Program received signal CUDA_EXCEPTION_10, Device Illegal Address.

(cuda-gdb) info cuda kernels
  Kernel Dev Grid   SMs Mask   GridDim BlockDim             Name Args
•  0   0    1 0x00000800  (1,1,1)   (1,1,1) exception_kernel data=...
```

CUDA ERROR REPORTING IN CUDA-GDB

- CUDA API error reporting (three modes)
  1. Trace all CUDA APIs that return an error code (default)

```
warning:  CUDA API error detected:  cudaMalloc returned (0xb)
```

  2. Stop in the debugger when any CUDA API fails
  3. Hide all CUDA API errors (do not print them)

```
(cuda-gdb) set cuda api failures [ignore | stop | hide]
```

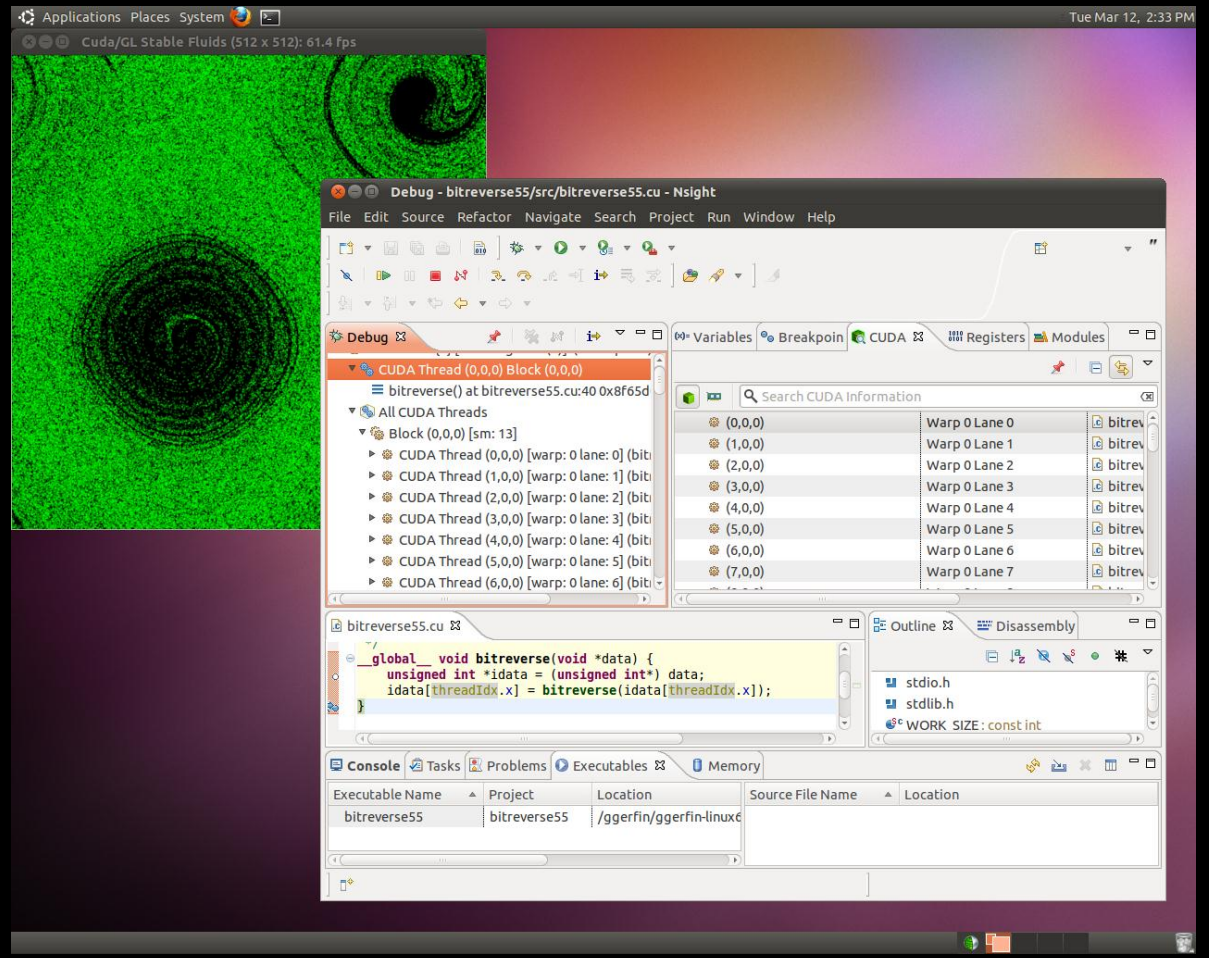
- Enhanced interoperation with cuda-memcheck

```
(cuda-gdb) set cuda memcheck on
```

```
Memcheck detected an illegal access to address (@global)0x500200028
```

SINGLE GPU DEBUGGING

- BETA feature in CUDA-GDB and in Nsight EE
- SM 3.5+ Only
- CDP debugging supported



CUDA DYNAMIC PARALLELISM LAUNCH TRACE

- Examine ancestors of Cuda Dynamic Parallelism GPU launched kernels

```
(cuda-gdb) info cuda launch trace
  Lvl Kernel Dev Grid   Status GridDim BlockDim Invocation

* #0   5   0   -7   Active (1,1,1)   (1,1,1) cdp_launchtrace(int)(depth = 3)
  #1   3   0   -6 Sleeping (1,1,1)   (1,1,1) cdp_launchtrace(int)(depth = 2)
  #2   2   0   -5 Sleeping (1,1,1)   (1,1,1) cdp_launchtrace(int)(depth = 1)
  #3   1   0    2 Sleeping (1,1,1)   (1,1,1) cdp_launchtrace(int)(depth = 0)
```

UNIFIED MEMORY

- New in CUDA 6.0
- Transparent host and device access
- Removes the need for cudaMemcpy
- Global/file-scope static variables ***__managed__***
- Dynamic allocation : ***cudaMallocManaged***
- **More sessions:**
  - **S4830 - Cuda 6 and Beyond, Tuesday, 3pm @ 220C**
  - **S4081 - Hands on lab : Wednesday, 9am @230B**

UNIFIED MEMORY

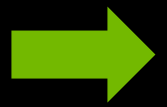
```
void sortfile(FILE *fp, int N) {
    char *gpu_data, *host_data;
    cudaMalloc(&gpu_data, N);

    char *host_data = (char *)malloc(N);
    fread(host_data, 1, N, fp);
    cudaMemcpy(gpu_data, host_data, N, ...);

    sort<<< ... >>>(gpu_data, N);
    cudaDeviceSynchronize();

    cudaMemcpy(host_data, gpu_data, N, ...);
    use_data(host_data);

    free(host_data);
    cudaFree(gpu_data);
}
```



```
void sortfile(FILE *fp, int N) {
    char *data;
    cudaMallocManaged(&data, N);

    fread(data, 1, N, fp);

    sort<<< ... >>>(data, N);
    cudaDeviceSynchronize();

    use_data(data);

    cudaFree(data);
}
```

UNIFIED MEMORY IN CUDA-GDB

- Print variables

```
(cuda-gdb) print managed_ptr
$1 = (@managed int *) 0x204600000
(cuda-gdb) print managed_var
$2 = 3
(cuda-gdb) print &managed_var
$3 = (@managed int **) 0x204500000
```

- Info cuda managed

```
(cuda-gdb) info cuda managed
Static managed variables on host are:
managed_var = 3
```

UNIFIED MEMORY

- Access rules
  - CPU cannot access memory while GPU is accessing it
  - CPU signal delivered

```
__managed__ int x;
__global__ int kern(void) {
    x = 2;
}
int main(void) {
    x = 1; // Legal
    kern<<<1,1>>>();
    x = 3; // Illegal
}
```

UNIFIED MEMORY

- Access rules
  - CPU cannot access memory while GPU is accessing it
  - CPU signal delivered

```
__managed__ int x;
__global__ int kern(void) {
    x = 2;
}
int main(void) {
    x = 1; // Legal
    kern<<<1,1>>>();
    cudaDeviceSynchronize();
    x = 3; // Legal
}
```

UNIFIED MEMORY

- CUDA-GDB will detect signals from bad CPU accesses
- Special signal information printed

```
$ cuda-gdb myApplication

Program received signal CUDA_EXCEPTION_15, Invalid Managed Memory Access.
0x0000000000402800 in main () at uvm.cu:10
10          x = 3;

(cuda-gdb) p &x
$1 = (@managed int **) 0x204500000
```

UNIFIED MEMORY

- Assign memory visibility
  - Host only
  - All streams on Device
  - Per stream
- Default can be set at creation time
  - 3rd parameter to cudaMallocManaged
  - Default only allows Host only or all streams
- Can be changed dynamically
  - cudaStreamAttachMemAsync
- Controls access from GPU
  - No enforced correctness : Use cuda-memcheck !

CUDA-MEMCHECK + MANAGED MEMORY

- Check GPU accesses to managed memory
  - Out of Bounds access
  - Attachment based invalid access
  - Misaligned access
  - Leak checking

SIMPLE KERNEL

```
__global__ int kern(int *x) {
    *x = 2;
}
int main(void) {
    int *x;
    cudaMallocManaged((void**)&x, sizeof(*x), cudaMemAttachHost);
    *x = 1;
    kern<<<1,1>>>(x);
    cudaDeviceSynchronize();
}
```

PRECISE ERROR DETECTION

```
Invalid __global__ read of size 4
     at 0x00000028 in uvm.cu:2:kern(int*)
     by thread (0,0,0) in block (0,0,0)
     Address 0x204500000 is out of bounds
```

SUPPORT FOR MPS (NEW IN 6.0)

- CUDA Multi Process Service (MPS)
  - Allows multiple software CUDA contexts to share a single device
- Memcheck can run on any MPS client
- Precise errors do not affect other MPS clients

CUDA-GDB NEW FEATURES IN 6.0

- Support for SM 5.0
  - Supports precise attribution of hardware exceptions

```
The exception was triggered at PC 0xa8d080 (test.cu:94)
```

- Single stepping optimizations

```
(cuda-gdb) set cuda single_stepping_optimizations off
```

- No launch notifications

```
(cuda-gdb) set cuda kernel_events on
```

DEMO

THANK YOU

- CUDA 6.0 : http://www.nvidia.com/getcuda
- Second session @GTC (S4580 – Wednesday 10:00 Room LL21D)
- Recordings from GTCs (http://gputechconf.com)
- Demo booth @GTC
- Experts Table @GTC
- Online documentation (http://docs.nvidia.com/cuda/)
- Forums (http://devtalk.nvidia.com/)
- Email : cudatools@nvidia.com