GPU TECHNOLOGY CONFERENCE

Debugging Experience with CUDA-GDB and CUDA-MEMCHECK

Geoff Gerfin
Vyas Venkataraman

GPU TECHNOLOGY CONFERENCE

CUDA Debugging Solutions

CUDA-GDB
(Linux & Mac)

CUDA-MEMCHECK
(Linux, Mac, & Windows)

NVIDIA® Parallel Nsight™
Eclipse Edition (NEW!)
Visual Studio Edition

allinea DDT

Allinea
DDT

Rogue Wave
TotalView

CUDA-GDB Overview

- What is it? What does it let you do?
  - Source and Assembly (SASS) Level Debugger
  - 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

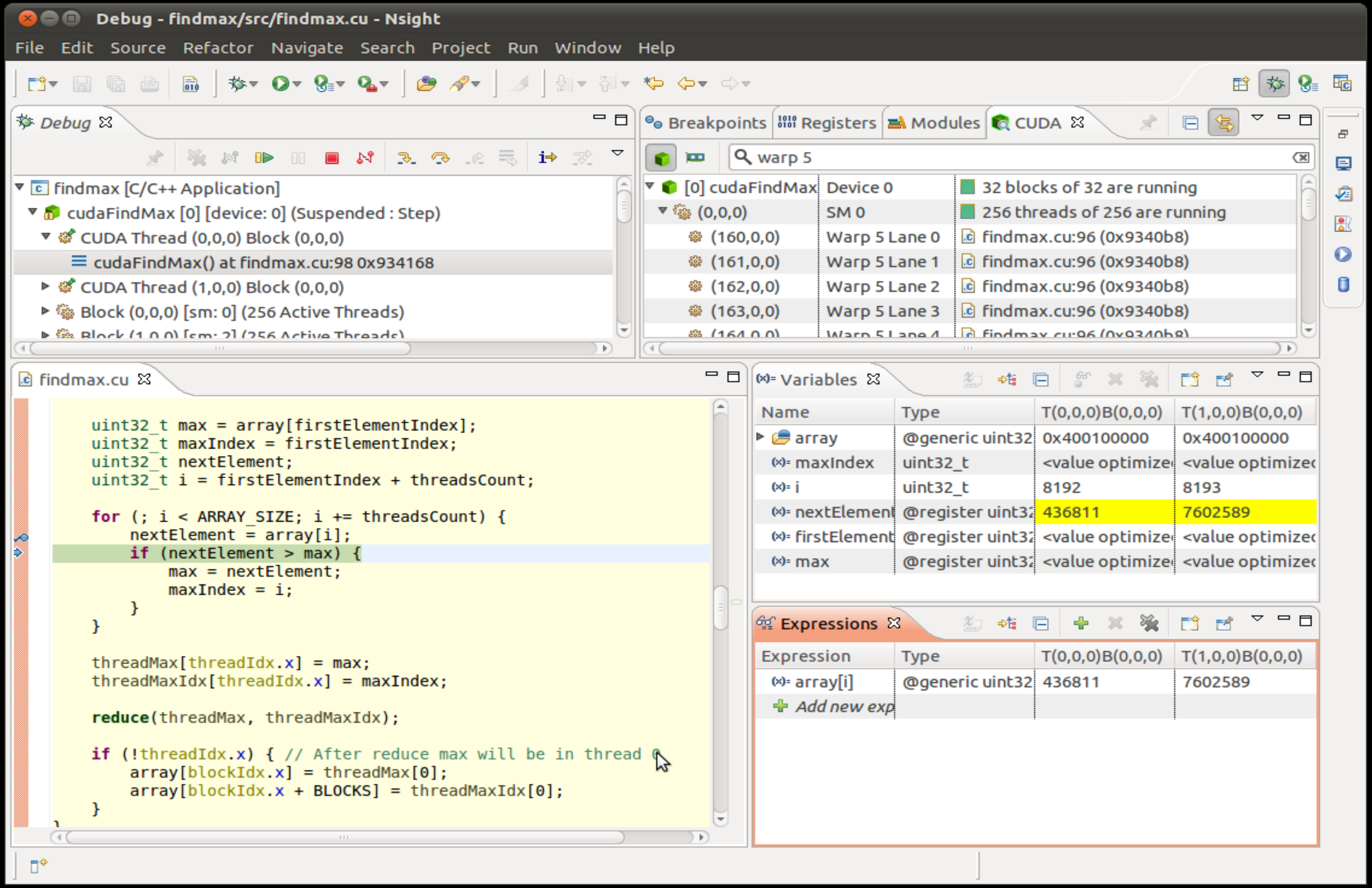
GPU TECHNOLOGY CONFERENCE

NVIDIA® NSIGHT™ ECLIPSE EDITION

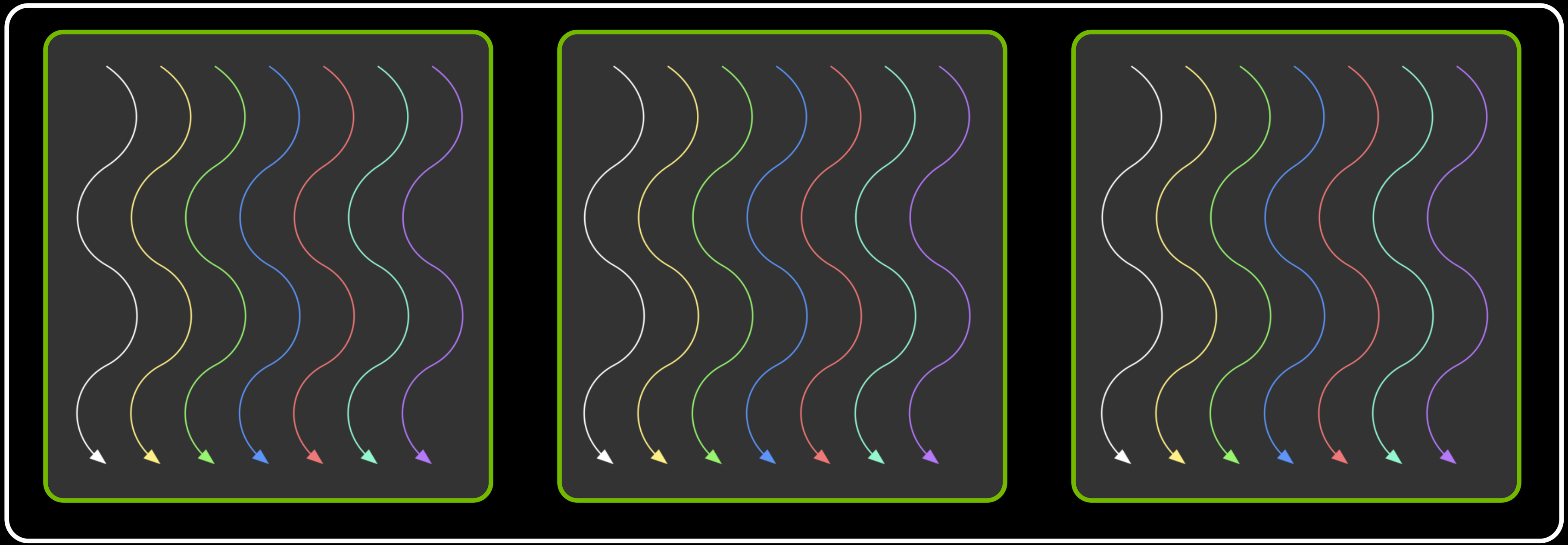
Nsight Eclipse Edition Debug View is powered by cuda-gdb

- *Visualize* device state
- Edit/Build/Debug/Profile
- Supported on Linux/Mac

Live demo Wed. @ 9am!
S0420 – Room A5



CUDA 101: Threads, Blocks, Grids



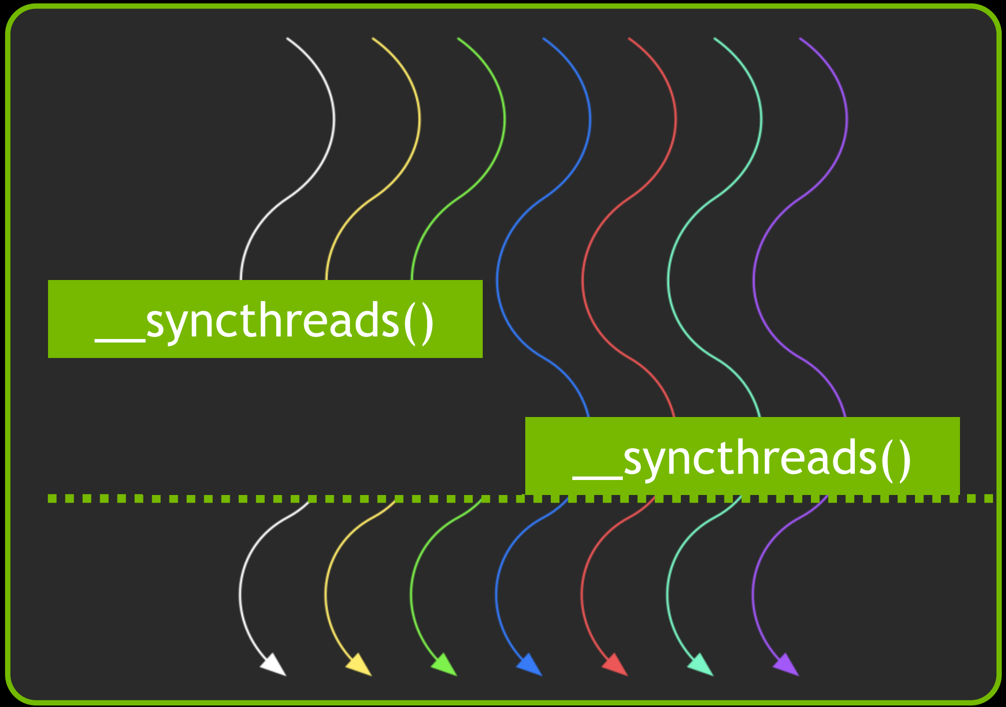
- Threads are grouped into blocks
- Blocks are grouped into a grid
- A kernel is executed as a grid of blocks of threads

CUDA 101: Synchronization

1. First set of threads arrive

2. Second set of threads arrive

3. All threads resume



- __syncthreads() enforces synchronization within a block
  - Threads wait until all other threads in the same block have arrived

GPU TECHNOLOGY CONFERENCE

Execution Control

- Execution Control is 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

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 *$pc
```

- 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, ...)

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)
```

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)
```

GPU TECHNOLOGY CONFERENCE

Devices

- To obtain the list of devices in the system:

```
(cuda-gdb) info cuda devices

 Dev    Desc    Type   SMs Wps/SM Lns/Wp Regs/Ln Active SMs Mask
*  0   gf100   sm_20    14     48     32      64            0xfff
   1   gt200   sm_13    30     32     32     128              0x0
```

- The * indicates the device of the kernel currently in focus

Kernels

- To obtain the list of running kernels:

```
(cuda-gdb) info cuda kernels

  Kernel Dev Grid   SMs Mask   GridDim   BlockDim Name Args
*      1   0    2     0x3fff (240,1,1) (128,1,1) acos parms=...
       2   0    3     0x4000 (240,1,1) (128,1,1) asin parms=...
```

- The * indicates the kernel currently in focus

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
```

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

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

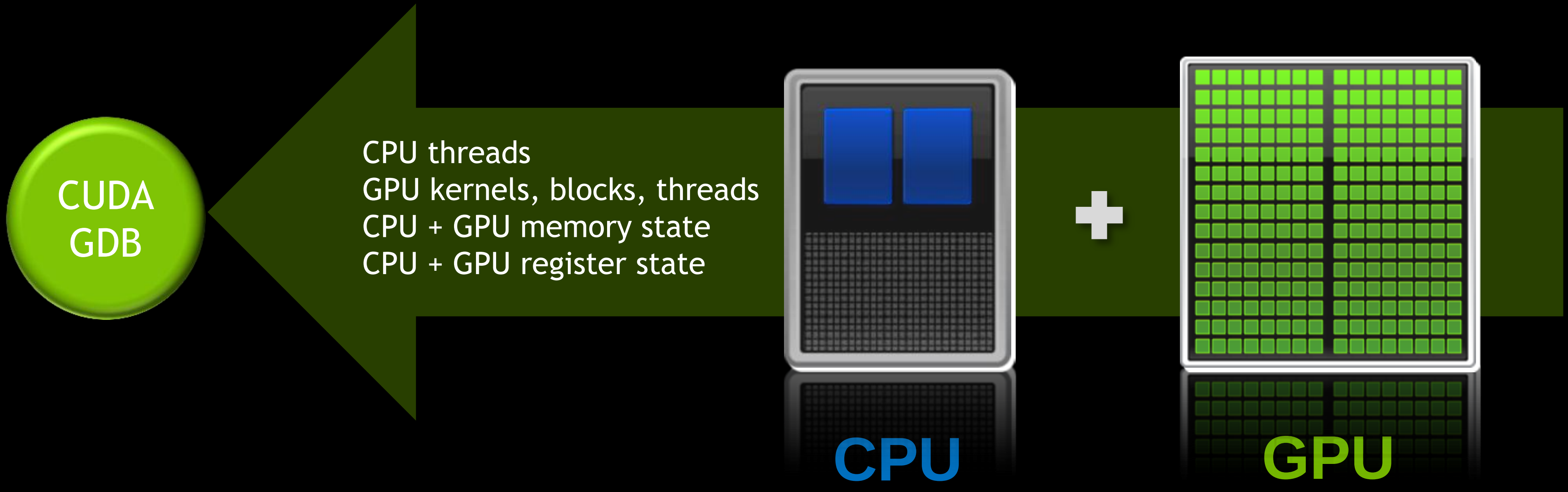
```
(cuda-gdb) x/10i $pc
0x123830a8 <_Z9my_kernel10params+8>:   MOV R0, c [0x0] [0x8]
0x123830b0 <_Z9my_kernel10params+16>:  MOV R2, c [0x0] [0x14]
0x123830b8 <_Z9my_kernel10params+24>:  IMUL.U32.U32 R0, R0, R2
0x123830c0 <_Z9my_kernel10params+32>:  MOV R2, R0
0x123830c8 <_Z9my_kernel10params+40>:  S2R R0, SR_CTAid_X
0x123830d0 <_Z9my_kernel10params+48>:  MOV R0, R0
0x123830d8 <_Z9my_kernel10params+56>:  MOV R3, c [0x0] [0x8]
0x123830e0 <_Z9my_kernel10params+64>:  IMUL.U32.U32 R0, R0, R3
0x123830e8 <_Z9my_kernel10params+72>:  MOV R0, R0
0x123830f0 <_Z9my_kernel10params+80>:  MOV R0, R0
```

GPU TECHNOLOGY CONFERENCE

CUDA-GDB 5.0 Features

- Attach to a running CUDA process (SM 2.0 and beyond)
- Attach upon GPU exceptions (SM 2.0 and beyond)
- Separate Compilation Support (SM 2.0 and beyond)
- Inlined Subroutine Debugging (SM 2.0 and beyond)
- CUDA API error reporting
- Enhanced interoperation with cuda-memcheck

CUDA-GDB 5.0 Features - Attach



Attach at any point in time!

CUDA-GDB 5.0 Features - Attach

- Run your program at full speed, then attach with cuda-gdb
- 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
```

GPU TECHNOLOGY CONFERENCE

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-GDB 5.0 Features - Error Reporting

- 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
  – Display faulting address and memory segment

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

CUDA-MEMCHECK

What is CUDA-MEMCHECK ?

- “Why did my kernel fail ?”
- Lightweight tool
- Run time error checker
  - Precise errors : Memory access
  - Imprecise errors : Hardware reported (SM 2.0+)
- Cross platform : Linux, Mac, Windows
- Integrated into cuda-gdb (Linux / Mac Only)

Running CUDA-MEMCHECK

- Standalone

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

- Misaligned and Out of bound access in global 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
```

Running CUDA-MEMCHECK

- Imprecise errors

```
Out-of-range Shared or Local Address
     at 0x00000798 in kernel1
     by thread (0,0,0) in block (0,0,0)
```

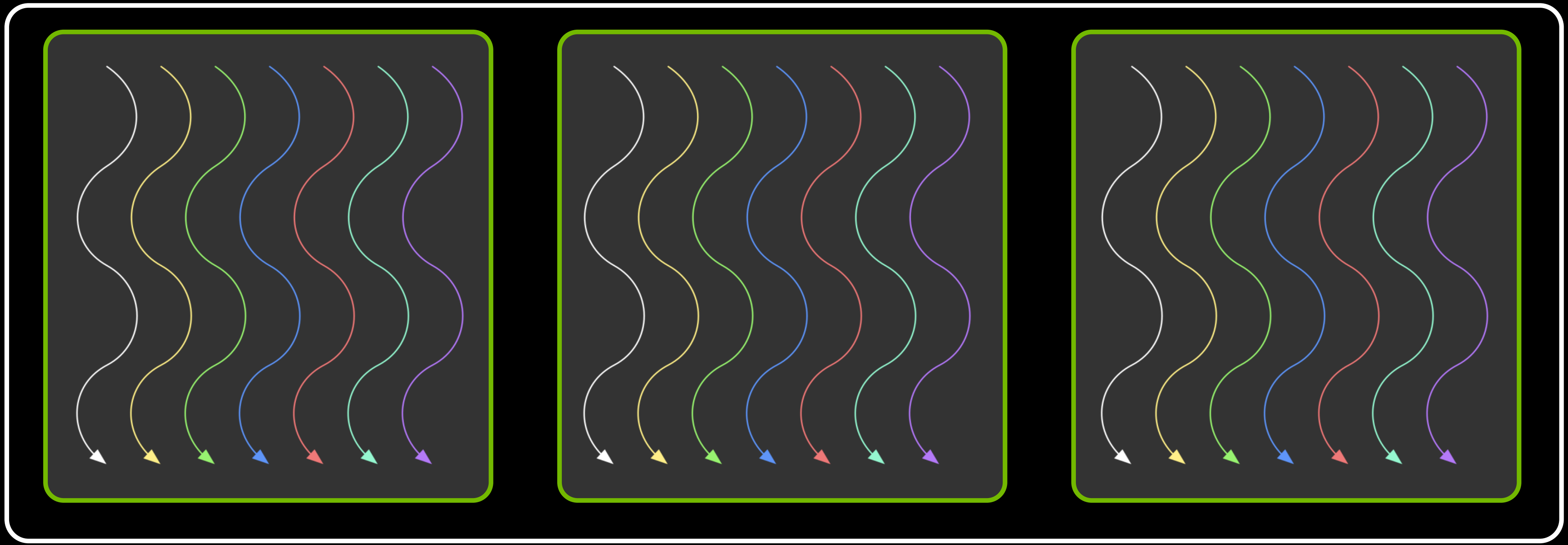
- Multiple precise errors using continue mode
- Leak checking of cudaMalloc() allocations
  – Allocation that has not been cudaFree()'d at context destroy
- Integrated mode in CUDA-GDB

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

New features in 5.0

- Shared memory hazard detection (racecheck)
- Improved precise detection in address spaces
- Device side malloc()/free() error checking
- Device heap allocation leak checking
- Stack back traces
- CUDA API error checking
- Better reporting inside cuda-gdb
- Improved precision for device heap checks
- Name demangling (with parameters) for kernels

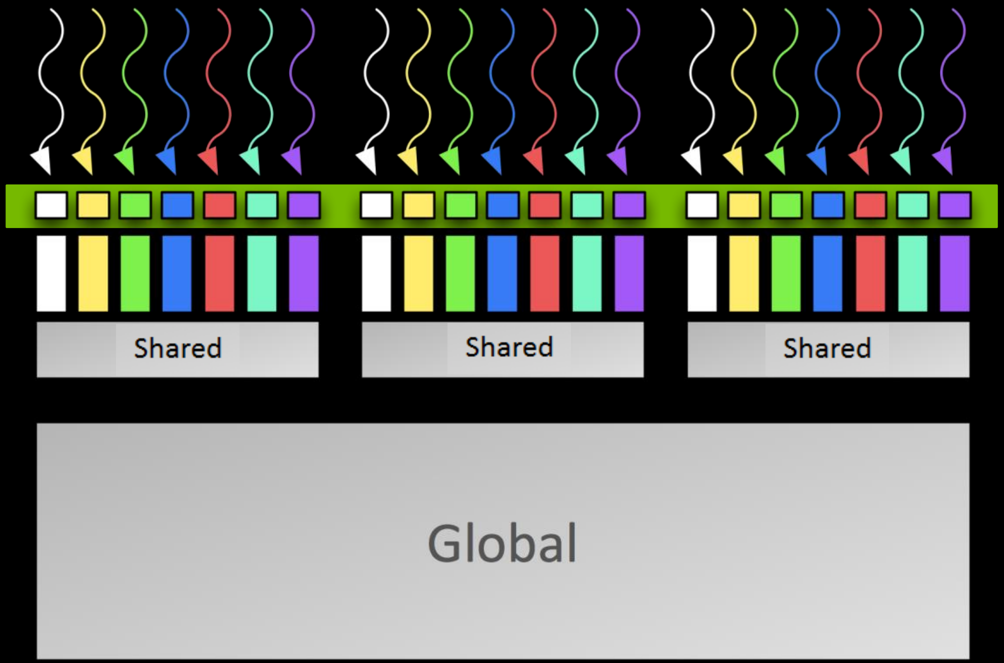
Threads revisited



- Threads are grouped into blocks
- Blocks are grouped into a grid
- A kernel is executed as a grid of blocks of threads

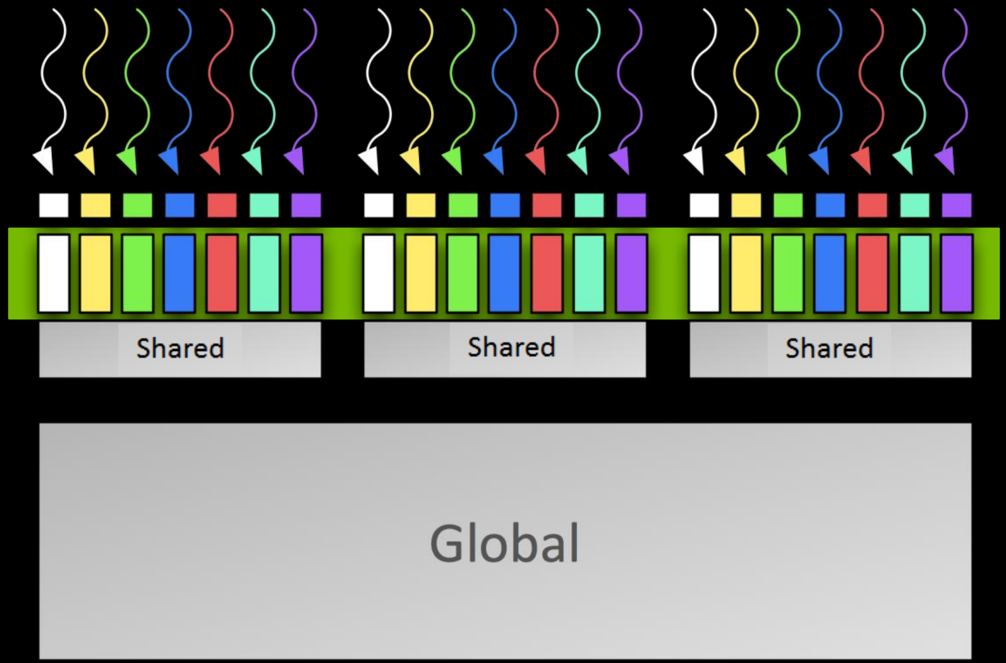
Memory hierarchy

- Thread:
  - Registers
  - Local memory
- Block of threads:
  - Shared memory
- All blocks:
  - Global memory



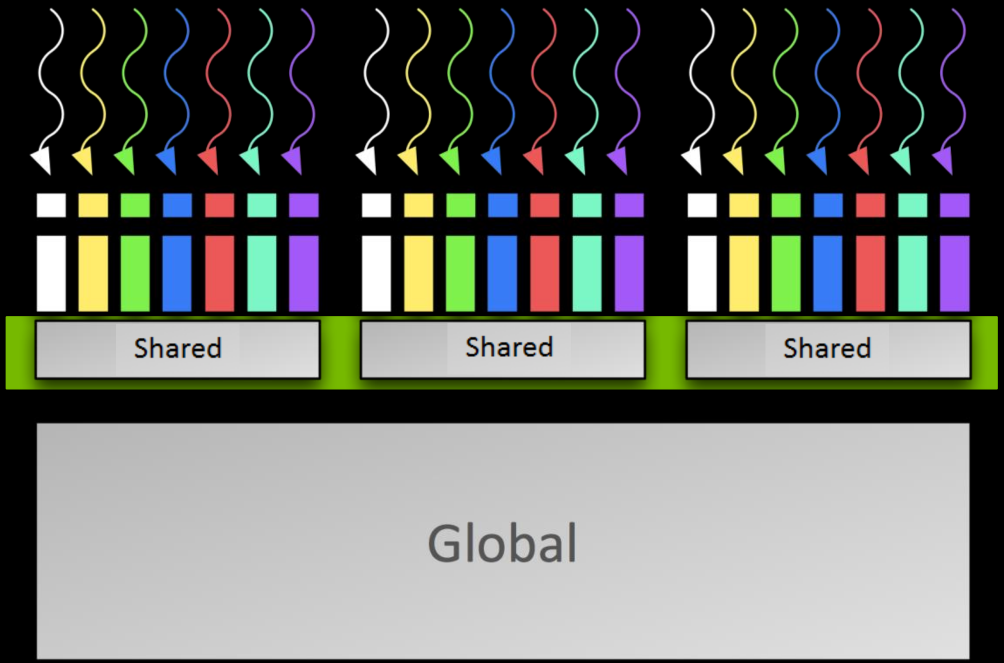
Memory hierarchy

- Thread:
  - Registers
  - Local memory
- Block of threads:
  - Shared memory
- All blocks:
  - Global memory



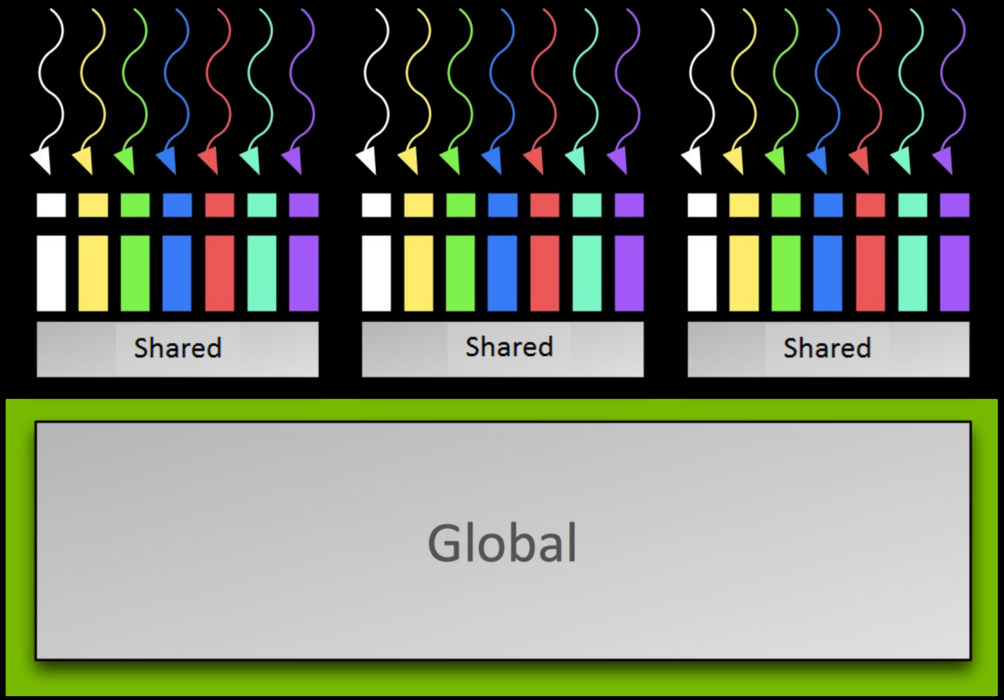
Memory hierarchy

- Thread:
  - Registers
  - Local memory
- Block of threads:
  - Shared memory
- All blocks:
  - Global memory



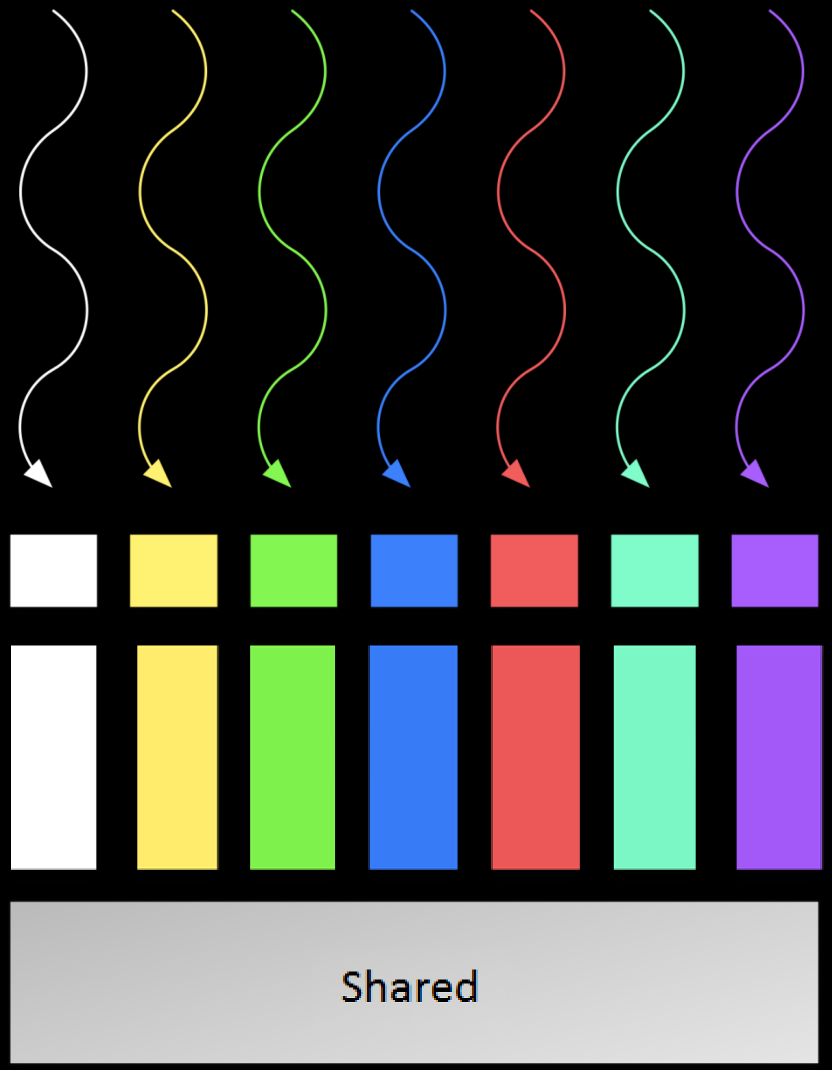
Memory hierarchy

- Thread:
  - Registers
  - Local memory
- Block of threads:
  - Shared memory
- All blocks:
  - Global memory



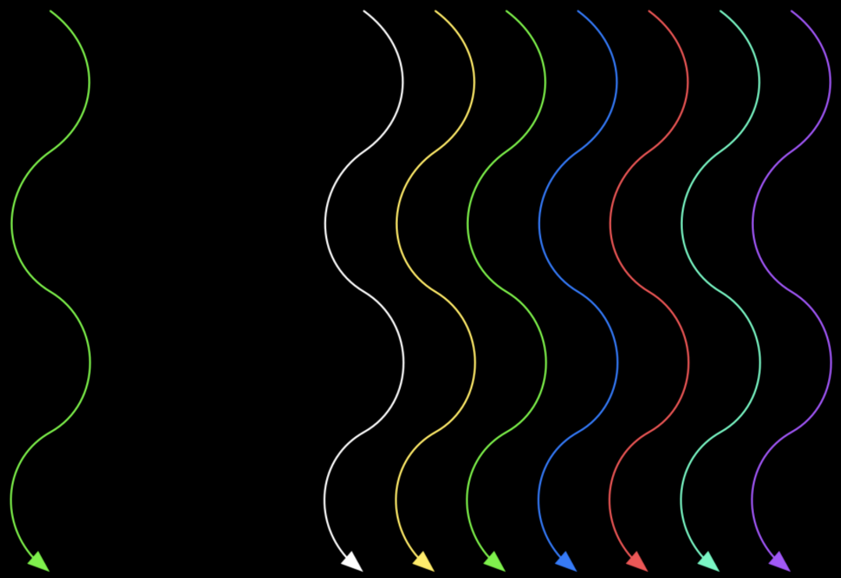
Shared memory

- Allocated per thread block
- Same lifetime as the block
- Accessible by any thread in the block
- Low latency
- High aggregate bandwidth
- Several uses:
  - Sharing data among threads in a block
  - User-managed cache (reducing global memory accesses)



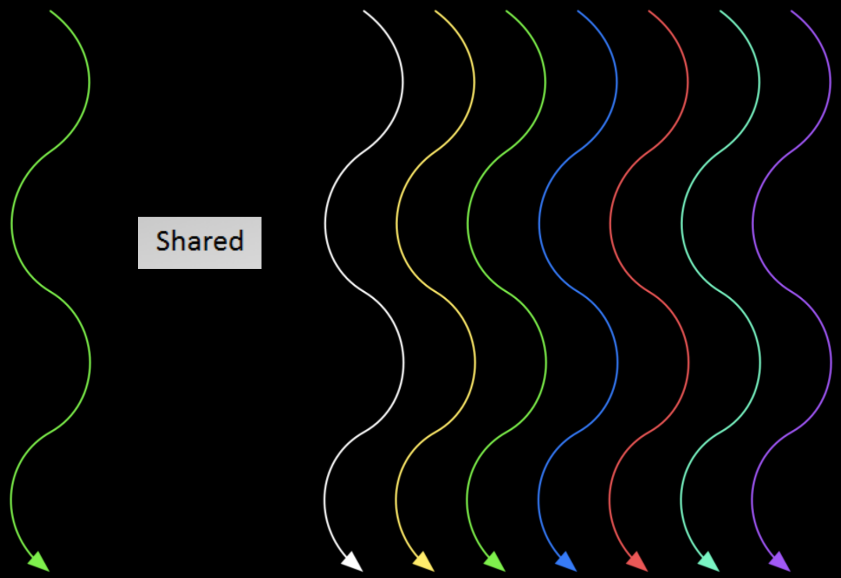
Sharing data between threads

- Broadcast a value
- One writer thread
- Multiple reader threads
- Value is scoped to the grid



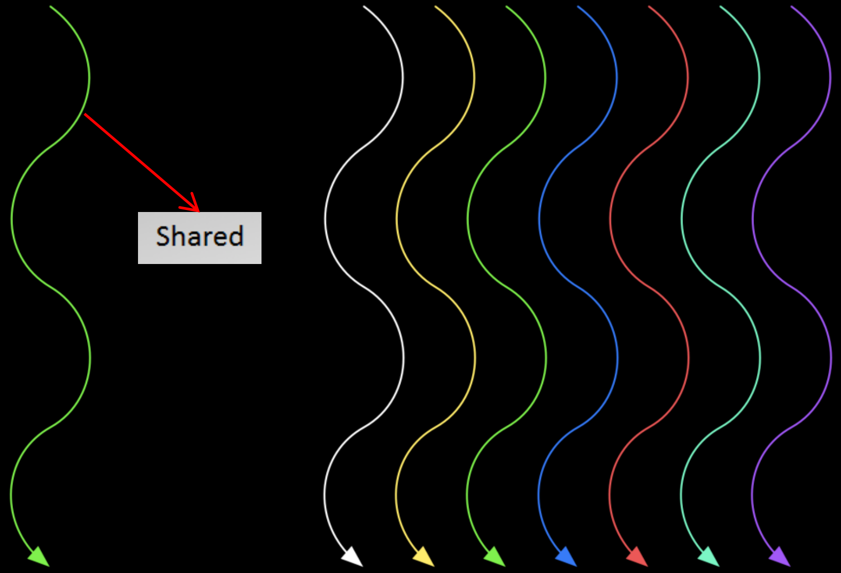
Sharing data between threads

- Broadcast a value
- One writer thread
- Multiple reader threads
- Value is scoped to the grid



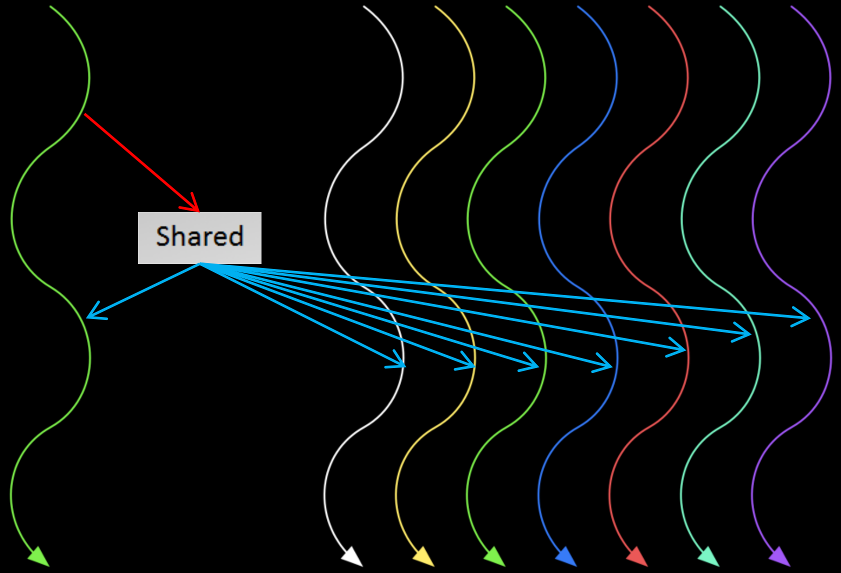
Sharing data between threads

- Broadcast a value
- One writer thread
- Multiple reader threads
- Value is scoped to the grid



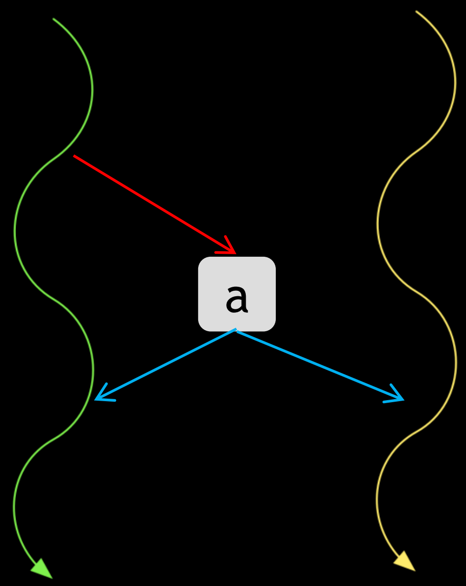
Sharing data between threads

- Broadcast a value
- One writer thread
- Multiple reader threads
- Value is scoped to the grid

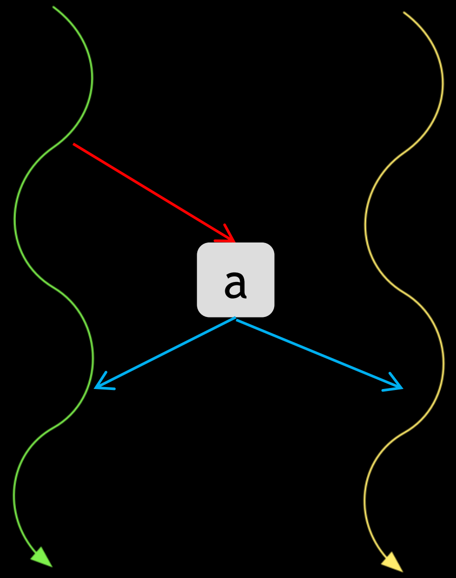


Broadcast Implementation

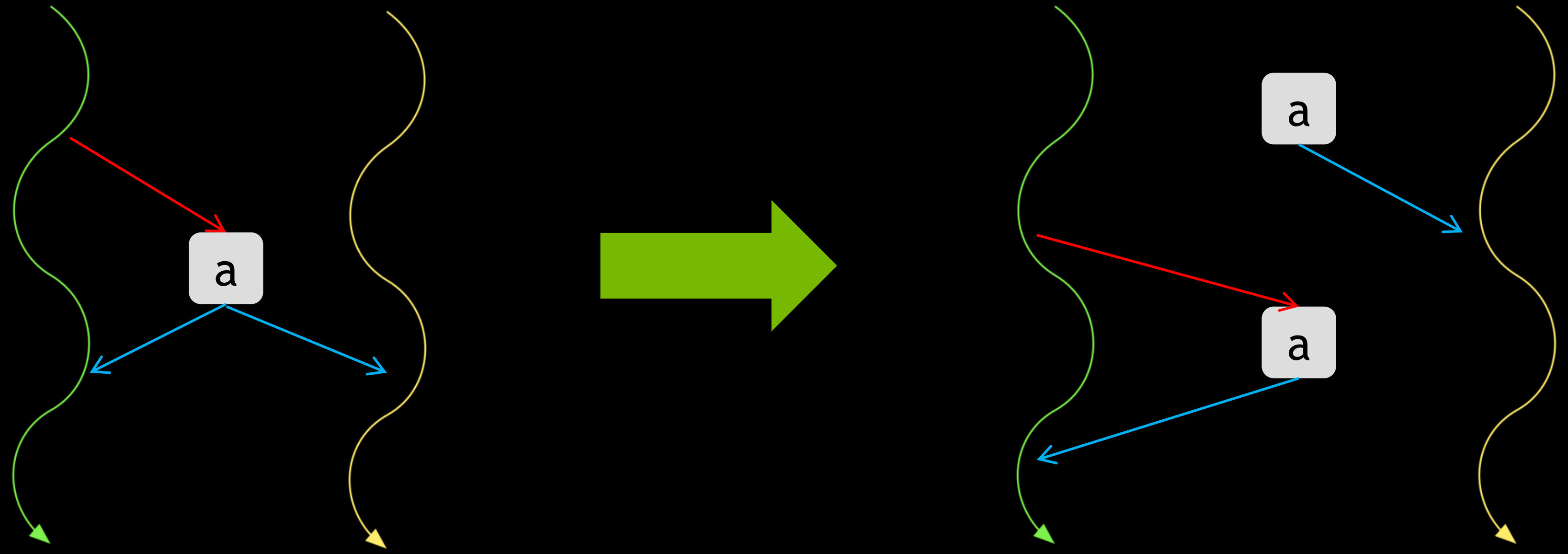
```
__global__ int bcast(void) {
   int x;
   __shared__ int a;
   if (threadIdx.x == WRITER)
       a = threadIdx.x;
   x = a;
   // do some work
}
```



Sharing data between threads



Sharing data between threads



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

Racecheck : Overview

- Mutations
  - Inconsistent data
- Detect three types of hazards
  - Write after Write (WAW)
  - Read after Write (RAW)
  - Write after Read (WAR)
- Internal heuristics
  - Reduce false positives
  - Prioritize hazards

Racecheck : Usage

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

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

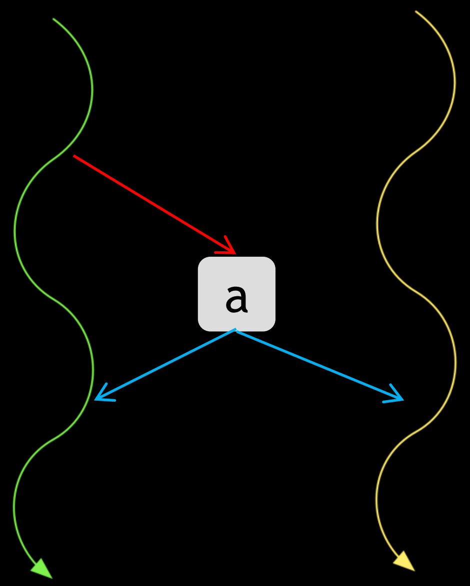
- Byte accurate
- Can provide source file and line
- Other useful options :
  - save to save output to a disk
  - print-level to control output

Racecheck : Internal Heuristic Filters

- Each report is assigned a priority
  - Error
    - Highest priority
  - Warning
    - Usually hit only by advanced users
  - Information
    - Same data for a Write After Write conflict (WAW)
- Hazard visibility can be controlled using --print-level option

Racecheck : Broadcast

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



- Launch of 64 threads
- Ran app with Racecheck

Racecheck : Broadcast

- On a 16 SM GF100
- 4 errors found (1 report per byte)
- RAW (Read after Write) hazards
  - Based on executed interleaving
- Identified bad accesses to shared memory

```
ERROR: Potential RAW hazard detected at __shared__ 0x3 in block
(0, 0, 0) :
  Write Thread (0, 0, 0) at 0x000000d8 in race.cu:25:bcast(void)
  Read Thread (35, 0, 0) at 0x000000e8 in race.cu:27:bcast(void)
  Current Value : 0
```

Racecheck : Anatomy of a report

```
ERROR: Potential RAW hazard detected at __shared__ 0x3 in block
(0, 0, 0) :
  Write Thread (0, 0, 0) at 0x000000d8 in race.cu:25:bcast(void)
  Read Thread (35, 0, 0) at 0x000000e8 in race.cu:27:bcast(void)
  Current Value : 0
```

Racecheck : Anatomy of a report

```
ERROR: Potential RAW hazard detected at __shared__ 0x3 in block
(0, 0, 0) :
  Write Thread (0, 0, 0) at 0x000000d8 in race.cu:25:bcast(void)
  Read Thread (35, 0, 0) at 0x000000e8 in race.cu:27:bcast(void)
  Current Value : 0
```

- Priority level of report

Racecheck : Anatomy of a report

```
ERROR: Potential RAW hazard detected at __shared__ 0x3 in block
(0, 0, 0) :
  Write Thread (0, 0, 0) at 0x000000d8 in race.cu:25:bcast(void)
  Read Thread (35, 0, 0) at 0x000000e8 in race.cu:27:bcast(void)
  Current Value : 0
```

- Priority level of report
- Type of hazard

Racecheck : Anatomy of a report

```
ERROR: Potential RAW hazard detected at __shared__ 0x3 in block
(0, 0, 0) :
  Write Thread (0, 0, 0) at 0x000000d8 in race.cu:25:bcast(void)
  Read Thread (35, 0, 0) at 0x000000e8 in race.cu:27:bcast(void)
  Current Value : 0
```

- Priority level of report
- Type of hazard
- Location of hazard

Racecheck : Anatomy of a report

```
ERROR: Potential RAW hazard detected at __shared__ 0x3 in block
(0, 0, 0) :
  Write Thread (0, 0, 0) at 0x000000d8 in race.cu:25:bcast(void)
  Read Thread (35, 0, 0) at 0x000000e8 in race.cu:27:bcast(void)
  Current Value : 0
```

- Priority level of report
- Type of hazard
- Location of hazard
- Block index (x, y, z)

Racecheck : Anatomy of a report

```
ERROR: Potential RAW hazard detected at __shared__ 0x3 in block
(0, 0, 0) :
  Write Thread (0, 0, 0) at 0x000000d8 in race.cu:25:bcast(void)
  Read Thread (35, 0, 0) at 0x000000e8 in race.cu:27:bcast(void)
  Current Value : 0
```

- Priority level of report
- Type of hazard
- Location of hazard
- Block index (x, y, z)
- Per thread
  - Access type

Racecheck : Anatomy of a report

```
ERROR: Potential RAW hazard detected at __shared__ 0x3 in block
(0, 0, 0) :
  Write Thread (0, 0, 0) at 0x000000d8 in race.cu:25:bcast(void)
  Read Thread (35, 0, 0) at 0x000000e8 in race.cu:27:bcast(void)
  Current Value : 0
```

- Priority level of report
- Type of hazard
- Location of hazard
- Block index (x, y, z)
- Per thread
  - Access type
  - Thread index (x, y, z)

Racecheck : Anatomy of a report

```
ERROR: Potential RAW hazard detected at __shared__ 0x3 in block
(0, 0, 0) :
  Write Thread (0, 0, 0) at 0x000000d8 in race.cu:25:bcast(void)
  Read Thread (35, 0, 0) at 0x000000e8 in race.cu:27:bcast(void)
  Current Value : 0
```

- Priority level of report
- Type of hazard
- Location of hazard
- Block index (x, y, z)
- Per thread
  - Access type
  - Thread index (x, y, z)
  - Instruction offset in kernel

Racecheck : Anatomy of a report

```
ERROR: Potential RAW hazard detected at __shared__ 0x3 in block
(0, 0, 0) :
  Write Thread (0, 0, 0) at 0x000000d8 in race.cu:25:bcast(void)
  Read Thread (35, 0, 0) at 0x000000e8 in race.cu:27:bcast(void)
  Current Value : 0
```

- Priority level of report
- Type of hazard
- Location of hazard
- Block index (x, y, z)
- Per thread
  - Access type
  - Thread index (x, y, z)
  - Instruction offset in kernel
  - File name and line number (if available)

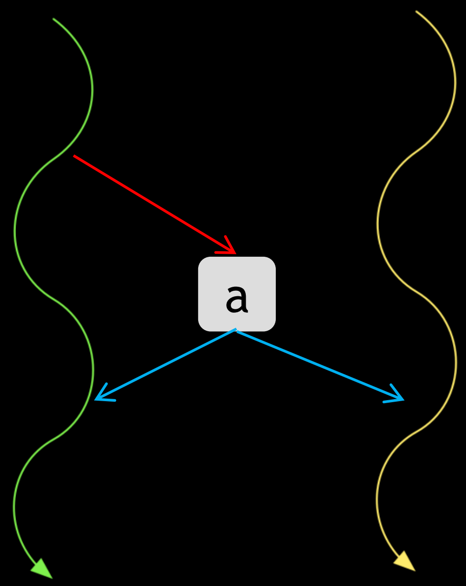
Racecheck : Anatomy of a report

```
ERROR: Potential RAW hazard detected at __shared__ 0x3 in block
(0, 0, 0) :
  Write Thread (0, 0, 0) at 0x000000d8 in race.cu:25:bcast(void)
  Read Thread (35, 0, 0) at 0x000000e8 in race.cu:27:bcast(void)
  Current Value : 0
```

- Priority level of report
- Type of hazard
- Location of hazard
- Block index (x, y, z)
- Per thread
  - Access type
  - Thread index (x, y, z)
  - Instruction offset in kernel
  - File name and line number (if available)
  - Kernel name

Broadcast Implementation Revisited

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

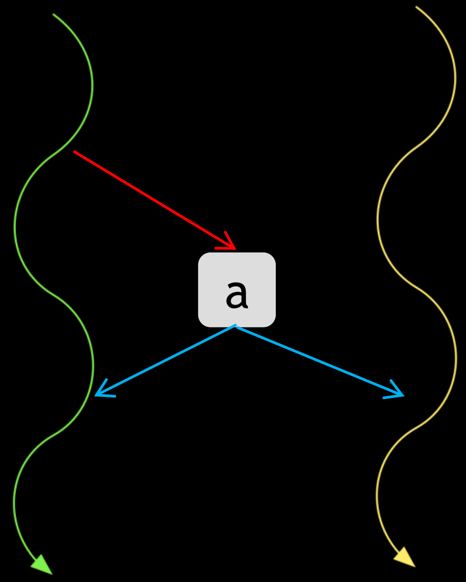


- Unsafe read, write skipped for some threads
- Fix by forcing an order

GPU TECHNOLOGY CONFERENCE

Fixed Broadcast Implementation

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



Stack Back Traces

- Saved host back trace at call site
  - Precise errors : Kernel launch site
  - Global Leaks : cudaMalloc site
  - CUDA API errors : CUDA API call site
- Device function call back trace at error
- Supported host OS : Linux, Mac, Windows
- Supported devices : Fermi+
  - Only in non blocking launch mode
- Enabled by default

Sample Back Trace

```
Invalid __local__ write of size 4
    at 0x000000e8 in localRecursive.cu:24:recursive(int*)
    by thread (6,0,0) in block (0,0,0)
    Address 0x00fffbfc is out of bounds
    Device Frame:recursive(int*) (fibonacci(int, int) : 0xe0)
    Device Frame:recursive(int*) (fibonacci(int, int) : 0xe0)
    Device Frame:recursive(int*) (fibonacci(int, int) : 0xe0)
    Device Frame:recursive(int*) (recursive(int*) : 0x28)
    Saved host backtrace up to driver entry point at kernel launch time
    Host Frame:libcuda.so (cuLaunchKernel + 0x3ae) [0xcb8ae]
    Host Frame:libcudart.so.5.0 [0x11dd4]
    Host Frame:libcudart.so.5.0 (cudaLaunch + 0x182) [0x3ad82]
    Host Frame:localRecursive (_Z28__device_stub__Z9recursivePiPi + 0x33) [0xfa3]
    Host Frame:localRecursive (main + 0x2cd) [0x12ad]
    Host Frame:/lib64/libc.so.6 (__libc_start_main + 0xfd) [0x1eb1d]
    Host Frame:localRecursive [0xdc9]
```

CUDA API Error Checking

- Checks all CUDA API calls
- Message when call will return an error
- Application will not terminate
- Standalone only
- Enable using --report-api-errors yes

Improved Precise Checking

- Improved precise error reporting
  - Shared loads and stores
  - Local loads and stores
  - Global atomics and reductions
- Error messages now have an address space qualifier
- Enabled in both integrated and standalone modes
- Enabled on all supported architectures

Summary

- CUDA-GDB
  - Usage
  - Attach
  - API error checking
- CUDA-MEMCHECK
  - Usage
  - Shared memory data access hazard detection (race check)
  - Stack back traces
  - API error checking

Thank You

- Availability:
  – CUDA toolkit : http://www.nvdia.com/getcuda
- CUDA experts table
- For more questions, come to our booth on the demo floor
- Repeat session on Wednesday @ 2 pm