GPU Programming

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July 2017

Debugging

- Debugging parallel programs is difficult.
  - Non-determinism due to thread-scheduling
  - Output can be different
  - Correct intermediate values may be large
- *cuda-gdb*
  - for debugging CUDA programs on real hardware
  - Extension to *gdb*
  - Allows breakpoints, single-step, read/write memory contents.

Sample Error

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

__global__ void K(int *x) {
        *x = 0;
}
int main() {
        int *x;
        K<<<2, 10>>>(x);
        cudaDeviceSynchronize();

        return 0;
}
```

Sample Error

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

__global__ void K(int *x) {
        *x = 0;
        printf("%d\n", *x);       // does not print anything.
}
int main() {
        int *x;
        K<<<2, 10>>>(x);
        cudaDeviceSynchronize();

        return 0;
}
```

Sample Error

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

__global__ void K(int *x) {
        *x = 0;
        printf(“%d\n”, *x);
}
int main() {
        int *x;
        K<<<2, 10>>>(x);
        cudaDeviceSynchronize();
        cudaError_t err = cudaGetLastError();
        printf("error=%d, %s, %s\n", err, cudaGetErrorName(err),
                                          cudaGetErrorString(err));
        return 0;
}
```

error=77, *cudaErrorIllegalAddress*,
an illegal memory access was encountered

CUDA Errors

- cudaSuccess = 0, /// No errors
- cudaErrorMissingConfiguration = 1, /// Missing configuration error
- cudaErrorMemoryAllocation = 2, /// Memory allocation error
- cudaErrorInitializationError = 3, /// Initialization error
- cudaErrorLaunchFailure = 4, /// Launch failure
- cudaErrorPriorLaunchFailure = 5, /// Prior launch failure
- cudaErrorLaunchTimeout = 6, /// Launch timeout error
- cudaErrorLaunchOutOfResources = 7, /// Launch out of resources
- cudaErrorInvalidDeviceFunction = 8, /// Invalid device function
- cudaErrorInvalidConfiguration = 9, /// Invalid configuration
- cudaErrorInvalidDevice = 10, /// Invalid device
- ...

Homework: Write programs to invoke these errors.

cuda-gdb

- Generate debug information
  - nvcc -g -G file.cu
  - Disables optimizations, inserts symbol information.
- Run with cuda-gdb
  - cuda-gdb a.out
  - > run
- May have to stop the windows manager.
- Due to lots of threads, cuda-gdb works with a focus (current thread).

```
__global__ void K(int *x) {
        *x = 0;
        printf("%d\n", *x);
}
```

```
(cuda-gdb) run
Starting program: ..../a.out
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib64/libthread_db.so.1".
[New Thread 0x7ffff7396700 (LWP 10305)]
[New Thread 0x7ffff696d700 (LWP 10306)]

CUDA Exception: Device Illegal Address
The exception was triggered in device 0.

Program received signal CUDA_EXCEPTION_10, Device Illegal Address.
[Switching focus to CUDA kernel 0, grid 1, block (1,0,0), thread (0,0,0), device 0, sm 13, warp 0,
lane 0]
0x0000000000aa9510 in K<<<(2,1,1),(10,1,1)>>> (x=0x0) at gdb2.cu:6
6               printf("%d\n", *x);
(cuda-gdb)
```

cuda-gdb

(cuda-gdb) **info cuda kernels**

```
  Kernel Parent Dev Grid Status    SMs Mask GridDim BlockDim Invocation
*      0      -      0    1    Active 0x00006000  (2,1,1)    (10,1,1)   K(x=0x0)
```

(cuda-gdb) **info threads**

```
  Id   Target Id         Frame
  3    Thread 0x7ffff696d700 (LWP 10497) "a.out" 0x00000038db4df113 in poll ()
   from /lib64/libc.so.6
  2    Thread 0x7ffff7396700 (LWP 10496) "a.out" 0x00000038db4eac6f in
accept4
    () from /lib64/libc.so.6
* 1    Thread 0x7ffff7fca720 (LWP 10487) "a.out" 0x00007ffff77a2118 in
cudbgApiDetach () from /usr/lib64/libcuda.so.1
```

cuda-gdb

(cuda-gdb) **info cuda threads**

```
  BlockIdx ThreadIdx To BlockIdx ThreadIdx Count      Virtual PC Filename  Line
Kernel 0
*  (0,0,0)   (0,0,0)     (1,0,0)   (9,0,0)    20 0x0000000000aa9f50  gdb2.cu     6
```

(cuda-gdb) **cuda kernel block thread**

kernel 0, block (0,0,0), thread (0,0,0)

(cuda-gdb) **cuda block 1 thread 0**

[Switching focus to CUDA kernel 0, grid 1, block (1,0,0), thread (0,0,0), device 0, sm 13, warp 0, lane 0]

```
0x0000000000aa9510      6               printf("%d\n", *x);
```

(cuda-gdb) **cuda kernel block thread**

kernel 0, block (1,0,0), thread (0,0,0)

Breakpoints

- `break main` // first instruction in main
- `break file.cu:223` // file:line
- `set cuda break_on_launch application`
  // kernel entry breakpoint
- `break file.cu:23 if threadIdx.x == 1 && i < 5`
  // conditional breakpoint

Step

- Once at a breakpoint, you can single-step
  - `step`, `s` or `<enter>`

```
(cuda-gdb) info cuda sms
  SM  Active Warps Mask
Device 0
    0 0x0000000000000000
    1 0x0000000000000000
    2 0x0000000000000000
    3 0x0000000000000000
    4 0x0000000000000000
    5 0x0000000000000000
    6 0x0000000000000000
    7 0x0000000000000000
    8 0x0000000000000000
    9 0x0000000000000000
   10 0x0000000000000000
   11 0x0000000000000000
   12 0x0000000000000000
   13 0x0000000000000001
* 14 0x0000000000000001
```

(cuda-gdb) **info cuda warps**

```
  Wp Active Lanes Mask Divergent Lanes Mask Active Physical PC Kernel BlockIdx First Active
ThreadIdx
Device 0 SM 14
*  0        0x000003ff          0x00000000 0x0000000000000110      0  (0,0,0)            (0,0,0)
   1        0x00000000          0x00000000                 n/a    n/a      n/a                n/a
   2        0x00000000          0x00000000                 n/a    n/a      n/a                n/a
   3        0x00000000          0x00000000                 n/a    n/a      n/a                n/a
   4        0x00000000          0x00000000                 n/a    n/a      n/a                n/a
   5        0x00000000          0x00000000                 n/a    n/a      n/a                n/a
   6        0x00000000          0x00000000                 n/a    n/a      n/a                n/a
   7        0x00000000          0x00000000                 n/a    n/a      n/a                n/a
   8        0x00000000          0x00000000                 n/a    n/a      n/a                n/a
   9        0x00000000          0x00000000                 n/a    n/a      n/a                n/a
  10        0x00000000          0x00000000                 n/a    n/a      n/a                n/a
---Type <return> to continue, or q <return> to quit---
```

(cuda-gdb) **info cuda lanes**

```
  Ln   State      Physical PC    ThreadIdx       Exception
Device 0 SM 14 Warp 0
*  0   active  0x0000000000000110   (0,0,0) Device Illegal Address
   1   active  0x0000000000000110   (1,0,0) Device Illegal Address
   2   active  0x0000000000000110   (2,0,0) Device Illegal Address
   3   active  0x0000000000000110   (3,0,0) Device Illegal Address
   4   active  0x0000000000000110   (4,0,0) Device Illegal Address
   5   active  0x0000000000000110   (5,0,0) Device Illegal Address
   6   active  0x0000000000000110   (6,0,0) Device Illegal Address
   7   active  0x0000000000000110   (7,0,0) Device Illegal Address
   8   active  0x0000000000000110   (8,0,0) Device Illegal Address
   9   active  0x0000000000000110   (9,0,0) Device Illegal Address
  10  inactive        n/a             n/a          n/a
  11  inactive        n/a             n/a          n/a
  12  inactive        n/a             n/a          n/a
  ...
  29  inactive        n/a             n/a          n/a
  30  inactive        n/a             n/a          n/a
  31  inactive        n/a             n/a          n/a
```

Homework

For the given program, what sequence of cuda-gdb commands would you use to identify the error?

```
__global__ void K(int *p) {
        *p = 0;
        printf("%d\n", *p);
}
int main() {
        int *x, *y;
        cudaMalloc(&x, sizeof(int));
        K<<<2, 10>>>(x);
        cudaDeviceSynchronize();
        y = x;
        cudaFree(y);
        K<<<2, 10>>>(x);
        cudaDeviceSynchronize();
        return 0;
}
```

Profiling

- Measuring “indicators” of performance
  - Time taken by various kernels
  - Memory utilization
  - Number of cache misses
  - Degree of divergence
  - Degree of coalescing
  - ...

CUDA Profiler

- nvprof: command-line
- nvvp, nsight: Visual Profiler

- An **event** is a measurable activity on a device. It corresponds to a hardware counter value.
  - About 140 events
  - tex0_cache_sector_queries
  - gld_inst_8bit
  - inst_executed
  - ...

nvprof

- No changes required to the binary. Uses defaults.
  - `nvprof a.out`
- To profile part of a program, use *cudaProfilerStart()* and *Stop()*.
- Include *cuda_profiler_api.h*
- `nvprof --profile-from-start off a.out`

```
__global__ void K1(int num) {
        num += num;
        ++num;
}
__device__ int sum = 0;
__global__ void K2(int num) {
        atomicAdd(&sum, num);
}
__global__ void K3(int num) {
        __shared__ int sum;
        sum = 0;
        __syncthreads();
        sum += num;
}
int main() {
        for (unsigned ii = 0; ii < 100; ++ii) {
                K1<<<5, 32>>>(ii);          cudaDeviceSynchronize();
        }
        for (unsigned ii = 0; ii < 100; ++ii) {
                K2<<<5, 32>>>(ii);          cudaDeviceSynchronize();
        }
        for (unsigned ii = 0; ii < 100; ++ii) {
                K3<<<5, 32>>>(ii);          cudaDeviceSynchronize();
        }
        return 0;
}
```

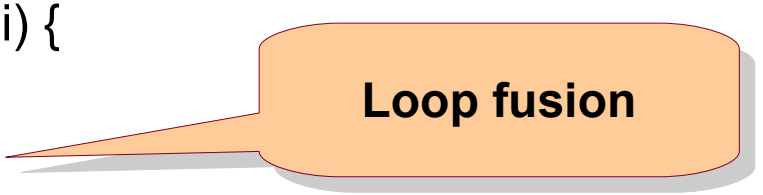
Which kernel should you optimize?
(Which kernel consumes more time?)

```
$ nvprof  a.out

==26519== NVPROF is profiling process 26519, command: a.out
==26519== Profiling application: a.out
==26519== Profiling result:
Time(%)      Time     Calls       Avg       Min       Max  Name
 39.46%  191.46us       100  1.9140us  1.8880us  2.1440us  K2(int)
 33.86%  164.26us       100  1.6420us  1.6000us  1.8880us  K3(int)
 26.68%  129.44us       100  1.2940us  1.2480us  1.5360us  K1(int)


==26519== API calls:
Time(%)      Time     Calls       Avg       Min       Max  Name
 95.75%  369.08ms       300  1.2303ms  10.560us  364.03ms  cudaLaunch
  2.33%  8.9986ms       728  12.360us     186ns  619.78us  cuDeviceGetAttribute
  0.91%  3.5039ms         8  437.98us  396.85us  450.61us  cuDeviceTotalMem
  0.73%  2.8134ms       300  9.3780us  6.4650us  32.547us  cudaDeviceSynchronize
  0.18%  699.99us         8  87.498us  85.431us  90.737us  cuDeviceGetName
  0.05%  194.20us       300     647ns     339ns  10.694us  cudaConfigureCall
  0.04%  156.27us       300     520ns     292ns  2.2700us  cudaSetupArgument
  0.00%  9.4130us        24     392ns     186ns     862ns  cuDeviceGet
  0.00%  5.7760us         3  1.9250us     317ns  4.7490us  cuDeviceGetCount
```

```
__global__ void K1(int num) {
        num += num;
        ++num;
}
__device__ int sum = 0;
__global__ void K2(int num) {
        atomicAdd(&sum, num);
}
__global__ void K3(int num) {
        __shared__ int sum;
        sum = 0;
        __syncthreads();
        sum += num;
}
int main() {
        for (unsigned ii = 0; ii < 100; ++ii) {
                K1<<<5, 32>>>(ii);
                K2<<<5, 32>>>(ii);
                K3<<<5, 32>>>(ii);
                cudaDeviceSynchronize();
        }
        return 0;
}
```



Doesn't change output much.
We need kernel fusion.

```
__device__ int sumg = 0;
__global__ void K(int num) {
        num += num;
        ++num;
        atomicAdd(&sumg, num);
        __shared__ int sum;
        sum = 0;
        __syncthreads();
        sum += num;
}
int main() {
        for (unsigned ii = 0; ii < 100; ++ii) {
                K<<<5, 32>>>(ii);
                cudaDeviceSynchronize();
        }
        return 0;
}
```

```
                Time(%)      Time     Calls       Avg       Min       Max  Name
                100.00%  194.81us       100  1.9480us  1.9200us  2.3040us  K(int)

                ==26721== API calls:
                Time(%)      Time     Calls       Avg       Min       Max  Name
                 96.26%  375.85ms       100  3.7585ms  18.175us  373.93ms  cudaLaunch
                  2.33%  9.1124ms       728  12.517us     183ns  661.26us  cuDeviceGetAttribute
                  ...
```

```
Time(%)      Time     Calls       Avg       Min       Max  Name
 39.46%  191.46us       100  1.9140us  1.8880us  2.1440us  K2(int)
 33.86%  164.26us       100  1.6420us  1.6000us  1.8880us  K3(int)
 26.68%  129.44us       100  1.2940us  1.2480us  1.5360us  K1(int)


==26519== API calls:
Time(%)      Time     Calls       Avg       Min       Max  Name
 95.75%  369.08ms       300  1.2303ms  10.560us  364.03ms  cudaLaunch
  2.33%  8.9986ms       728  12.360us     186ns  619.78us  cuDeviceGetAttribute
```

```
Time(%)      Time     Calls       Avg       Min       Max  Name
100.00%  194.81us       100  1.9480us  1.9200us  2.3040us  K(int)

==26721== API calls:
Time(%)      Time     Calls       Avg       Min       Max  Name
 96.26%  375.85ms       100  3.7585ms  18.175us  373.93ms  cudaLaunch
  2.33%  9.1124ms       728  12.517us     183ns  661.26us  cuDeviceGetAttribute
  ...
```

```
__device__ int sumg = 0;
__global__ void K(int num) {
        int num = blockIdx.x * blockDim.x + threadIdx.x;
        num += num;
        ++num;
        atomicAdd(&sumg, num);
        __shared__ int sum;
        sum = 0;
        __syncthreads();
        sum += num;
}
int main() {
        K<<<5*100, 32>>>(ii);
        cudaDeviceSynchronize();
        return 0;
}
```

```
Time(%)      Time     Calls       Avg       Min       Max  Name
100.00%  3.7120us         1  3.7120us  3.7120us  3.7120us  K(void)

==26862== API calls:
Time(%)      Time     Calls       Avg       Min       Max  Name
 96.91%  369.68ms         1  369.68ms  369.68ms  369.68ms  cudaLaunch
  2.16%  8.2407ms       728  11.319us     142ns  461.62us  cuDeviceGetAttribute
```

nvprof

- Supports device-specific profiling
- Supports remote profiling
- Output can be dumped to files as a .csv
- ...