

Support: Debugging and Profiling

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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 0x7fff7396700 (LWP 10305)]

[New Thread 0x7fff696d700 (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 0x7fff696d700 (LWP 10497)	"a.out" 0x00000038db4df113 in poll () from /lib64/libc.so.6
2	Thread 0x7fff7396700 (LWP 10496)	"a.out" 0x00000038db4eac6f in accept4 () from /lib64/libc.so.6
* 1	Thread 0x7fff7fca720 (LWP 10487)	"a.out" 0x00007fff77a2118 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	0x000000000000aa9f50	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]

0x000000000000aa9510 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 0x00000000000000000000

1 0x00000000000000000000

2 0x00000000000000000000

3 0x00000000000000000000

4 0x00000000000000000000

5 0x00000000000000000000

6 0x00000000000000000000

7 0x00000000000000000000

8 0x00000000000000000000

9 0x00000000000000000000

10 0x00000000000000000000

11 0x00000000000000000000

12 0x00000000000000000000

13 0x00000000000000000000**1**

* 14 0x00000000000000000000**1**

(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	0x0000000000000000110	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	0x00000000000000110	(0,0,0)	Device Illegal Address
1	active	0x00000000000000110	(1,0,0)	Device Illegal Address
2	active	0x00000000000000110	(2,0,0)	Device Illegal Address
3	active	0x00000000000000110	(3,0,0)	Device Illegal Address
4	active	0x00000000000000110	(4,0,0)	Device Illegal Address
5	active	0x00000000000000110	(5,0,0)	Device Illegal Address
6	active	0x00000000000000110	(6,0,0)	Device Illegal Address
7	active	0x00000000000000110	(7,0,0)	Device Illegal Address
8	active	0x00000000000000110	(8,0,0)	Device Illegal Address
9	active	0x00000000000000110	(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
 - ...
- Intrusive versus non-intrusive

CUDA Profiler

- **nvprof**: command-line
- **nvvp**, **nsight**: Visual Profilers
- 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;
}

```

One natural optimization, subject to application semantics, is to merge the loops.

Loop fusion

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;
}

```

What if the launch configuration is changed to <<<100, 5*32>>>?

```

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%	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
- ...