CUDA SDK — Basic Concepts

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→ https://tinyurl.com/cudafordummies/ii/l3/notes-l3.pdf

Outline

- Nowadays on github (curated, re-structured, toolkit-dependent)

→ https://github.com/nvidia/cuda-samples

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- Constantly growing collection of basic CUDA programming exercises (educational resource, not HPC-focussed)

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- Excellent place for beginners to start looking around

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- Showcases all GPU features and explains fundamental CUDA concepts
- Open source and easily expandable with own projects
- Excellent place for beginners to start looking around
- Thematically organized into 7 major subject areas

→ https://github.com/nvidia/cuda-samples

Basic Conventions

CUDA SDK cont.

```
cuda-zen sh@n3073-009:~$ git clone https://github.com/NVIDIA/cuda-samples
cuda-zen sh@n3073-009:~$ cd cuda-samples/Samples
cuda-zen sh@n3073-009:Samples$ ls

0_Introduction  2_Concepts_and_Techniques  4_CUDA_Libraries   6_Performance
1_Utilities     3_CUDA_Features            5_Domain_Specific

cuda-zen sh@n3073-009:Samples$ cd 0_Introduction
cuda-zen sh@n3073-009:0_Introduction$ ls

asyncAPI              README.md                    simpleLayeredTexture       simpleTexture3D
c++11_cuda            simpleAssert                 simpleMPI                  simpleTextureDrv
clock                 simpleAssert_nvrtc           simpleMultiCopy            simpleVoteIntrinsics
clock_nvrtc           simpleAtomicIntrinsics       simpleMultiGPU             simpleVoteIntrinsics_nvrtc
concurrentKernels     simpleAtomicIntrinsics_nvrtc simpleOccupancy            simpleZeroCopy
cppIntegration        simpleAttributes             simpleP2P                  systemWideAtomics
cppOverload           simpleAWBarrier              simplePitchLinearTexture   template
cudaOpenMP            simpleCallback               simplePrintf               UnifiedMemoryStreams
fp16ScalarProduct     simpleCooperativeGroups      simpleSeparateCompilation  vectorAdd
matrixMul             simpleCubemapTexture         simpleStreams              vectorAddDrv
matrixMulDrv          simpleCUDA2GL                simpleSurfaceWrite         vectorAddMMAP
matrixMulDynlinkJIT   simpleDrvRuntime             simpleTemplates            vectorAdd_nvrtc
matrixMul_nvrtc       simpleHyperQ                 simpleTemplates_nvrtc
mergeSort             simpleIPC                    simpleTexture
```

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Basic Conventions

CUDA SDK cont.

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0_Introduction  2_Concepts_and_Techniques  4_CUDA_Libraries  6_Performance
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asyncAPI              README.md                    simpleLayeredTexture       simpleTexture3D
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clock                 simpleAssert_nvrtc           simpleMultiCopy            simpleVoteIntrinsics
clock_nvrtc           simpleAtomicIntrinsics       simpleMultiGPU             simpleVoteIntrinsics_nvrtc
concurrentKernels     simpleAtomicIntrinsics_nvrtc simpleOccupancy            simpleZeroCopy
cppIntegration        simpleAttributes             simpleP2P                  systemWideAtomics
cppOverload           simpleAWBarrier              simplePitchLinearTexture   template
cudaOpenMP            simpleCallback               simplePrintf               UnifiedMemoryStreams
fp16ScalarProduct     simpleCooperativeGroups      simpleSeparateCompilation  vectorAdd
matrixMul             simpleCubemapTexture         simpleStreams              vectorAddDrv
matrixMulDrv          simpleCUDA2GL                simpleSurfaceWrite         vectorAddMMAP
matrixMulDynlinkJIT   simpleDrvRuntime             simpleTemplates            vectorAdd_nvrtc
matrixMul_nvrtc       simpleHyperQ                 simpleTemplates_nvrtc
mergeSort             simpleIPC                    simpleTexture
```

→ https://github.com/nvidia/cuda-samples

Basic Conventions

CUDA SDK cont.

0_Introduction	CUDA samples for beginners that illustrate key concepts with using CUDA and CUDA runtime APIs
1_Utilities	Utility samples that demonstrate how to query device capabilities and measure GPU/CPU bandwidth
2_Concepts_and_Techniques	CUDA related concepts and common problem solving techniques
3_CUDA_Features	Samples that demonstrate CUDA Features (cooperative groups, dynamic parallelism, graphs etc)
4_CUDA_Libraries	Samples that illustrate how to use CUDA platform libraries, NPP, NVJPEG, NVGRAPH cuBLAS, cuFFT, cuSPARSE, cuSOLVER and cuRAND
5_Domain_Specific	Samples from specific domains (graphics, finance, image processing)
6_Performance	Samples that illustrate performance optimizations

→ https://github.com/nvidia/cuda-samples

Consider for example function assert()

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

int main()
{
    int i;

    for (i=0; i<10; i++) {
        assert(i < 5);
        printf("current i is %d \n", i);
    }

    return(0);
}
```

→ https://tinyurl.com/cudafordummies/ii/l3/smpl_assert.c

Consider for example function assert()

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#include <assert.h>

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{
    int i;

    for (i=0; i<10; i++) {
        assert(i < 5);
        printf("current i is %d \n", i);
    }

    return(0);
}
```

```
cuda-zen sh@n3073-009:~$  gcc ./smpl_assert.c
cuda-zen sh@n3073-009:~$  ./a.out
current i is 0
current i is 1
current i is 2
current i is 3
current i is 4
a.out: smpl_assert.c:20: main: Assertion `i < 5' failed.
Aborted (core dumped)
```

→ https://tinyurl.com/cudafordummies/ii/l3/smpl_assert.c

Basic Conventions

CUDA SDK cont.

Consider for example function assert()

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

int main()
{
    int i;

    for (i=0; i<10; i++) {
        assert(i < 5);
        printf("current i is %d \n", i);
    }

    return(0);
}
```

Developer's checkpoints: If expression is TRUE assert() does nothing. If FALSE, abortion and error message.

```
cuda-zen sh@n3073-009:~$  gcc ./smpl_assert.c
cuda-zen sh@n3073-009:~$  ./a.out
current i is 0
current i is 1
current i is 2
current i is 3
current i is 4
a.out: smpl_assert.c:20: main: Assertion `i < 5' failed.
Aborted (core dumped)
```

→ https://tinyurl.com/cudafordummies/ii/l3/smpl_assert.c

Basic Conventions

CUDA SDK cont.

There is also a CUDA SDK sample in 0_Introduction/simpleAssert/

Consider for example function assert()

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

int main()
{
    int i;

    for (i=0; i<10; i++) {
        assert(i < 5);
        printf("current i is %d \n", i);
    }

    return(0);
}
```

Developer's checkpoints: If expression is TRUE assert() does nothing. If FALSE, abortion and error message.

```
cuda-zen sh@n3073-009:~$  gcc ./smpl_assert.c
cuda-zen sh@n3073-009:~$  ./a.out
current i is 0
current i is 1
current i is 2
current i is 3
current i is 4
a.out: smpl_assert.c:20: main: Assertion `i < 5' failed.
Aborted (core dumped)
```

→ https://tinyurl.com/cudafordummies/ii/l3/smpl_assert.c

Basic Conventions

CUDA SDK cont. — 0_Introduction/simpleAssert

```
cuda-zen sh@n3073-009:~$ cd cuda-samples/Samples/0_Introduction/simpleAssert
cuda-zen sh@n3073-009:simpleAssert$ ls

Makefile           simpleAssert.cu              simpleAssert_vs2019.sln      simpleAssert_vs2022.vcxproj
NsightEclipse.xml  simpleAssert_vs2017.sln      simpleAssert_vs2019.vcxproj
README.md          simpleAssert_vs2017.vcxproj  simpleAssert_vs2022.sln

cuda-zen sh@n3073-009:simpleAssert$ cd ../
cuda-zen sh@n3073-009:0_Introduction$ cp -r ./simpleAssert ./my_simpleAssert
cuda-zen sh@n3073-009:0_Introduction$ cd ./my_simpleAssert
cuda-zen sh@n3073-009:my_simpleAssert$ export CUDA_PATH="/gpfs/opt/sw/cuda-zen/spack-0.19.0/opt/spack/linux-almalinux8-zen/gcc-9.5.0/cuda-11.6.2-2jmvqy2eamrpamnwll6mq5xccbe2xa7s"
cuda-zen sh@n3073-009:my_simpleAssert$ export SMS="70 75 80 86"
cuda-zen sh@n3073-009:my_simpleAssert$ make
```

→ https://github.com/nvidia/cuda-samples

Basic Conventions

CUDA SDK cont. — 0_Introduction/simpleAssert

```
cuda-zen sh@n3073-009: my_simpleAssert$ ./simpleAssert
simpleAssert starting...
OS_System_Type.release = 4.18.0-348.el8.x86_64
OS Info: <#1 SMP Tue Nov 9 06:28:28 EST 2021>

GPU Device 0: "Ampere" with compute capability 8.0

Launch kernel to generate assertion failures

-- Begin assert output

simpleAssert.cu:63: void testKernel(int): block: [1,0,0], thread: [28,0,0] Assertion `gtid < N` failed.
simpleAssert.cu:63: void testKernel(int): block: [1,0,0], thread: [29,0,0] Assertion `gtid < N` failed.
simpleAssert.cu:63: void testKernel(int): block: [1,0,0], thread: [30,0,0] Assertion `gtid < N` failed.
simpleAssert.cu:63: void testKernel(int): block: [1,0,0], thread: [31,0,0] Assertion `gtid < N` failed.

-- End assert output

Device assert failed as expected, CUDA error message is: device-side assert triggered

simpleAssert completed, returned OK
```

→ https://github.com/nvidia/cuda-samples

Basic Conventions

CUDA SDK cont. — 0_Introduction/simpleAssert

simpleAssert.cu

```
__global__ void testKernel(int N)
{
    int gtid = blockIdx.x*blockDim.x + threadIdx.x;
    assert(gtid < N);
}
int main(int argc, char **argv)
{
    ...
    runTest(argc, argv);
    ...
}
void runTest(int argc, char **argv)
{
    int Nblocks = 2;
    int Nthreads = 32;
    cudaError_t error;
    ...
    findCudaDevice(argc, (const char **)argv);
    dim3 dimGrid(Nblocks);
    dim3 dimBlock(Nthreads);
    testKernel <<< dimGrid, dimBlock >>> (60);
    error = cudaDeviceSynchronize();
}
```

→ https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__TYPES.html

Basic Conventions

CUDA SDK cont. — 0_Introduction/simpleAssert

simpleAssert.cu

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__global__ void testKernel(int N)
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Check is whether thread ID is < 60

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Basic Conventions

CUDA SDK cont. — 0_Introduction/simpleAssert

simpleAssert.cu

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    ...
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2 threadblocks with 32 threads

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Basic Conventions

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C++ style of initializing variables dimGrid and dimBlock

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kernel launch

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Device behaviour identical to host; lots of useful information !

simpleAssert.cu

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Basic Conventions

CUDA SDK cont. — 0_Introduction/simpleAssert

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New type (enum) for error variable

Check is whether thread ID is < 60

2 threadblocks with 32 threads

C++ style of initializing variables dimGrid and dimBlock

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simpleAssert.cu

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    runTest(argc, argv);
    ...
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void runTest(int argc, char **argv)
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    ...
    findCudaDevice(argc, (const char **)argv);
    dim3 dimGrid(Nblocks);
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    testKernel <<< dimGrid, dimBlock >>> (60);
    error = cudaDeviceSynchronize();
}
```

Device behaviour identical to host; lots of useful information !

New type (enum) for error variable

Generic function to identify GPU

Check is whether thread ID is < 60

2 threadblocks with 32 threads

C++ style of initializing variables dimGrid and dimBlock

kernel launch

→ https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__TYPES.html

simpleAssert.cu / error handling

```
void runTest(int argc, char **argv)
{
    ...
    printf("Launch kernel to generate assertion failures\n");
    testKernel <<< dimGrid, dimBlock >>> (60);

    //Synchronize (flushes assert output)
    printf("\n- Begin assert output\n\n");
    error = cudaDeviceSynchronize();
    printf("\n- End assert output\n\n");

    //Check for errors
    if (error == cudaErrorAssert) {
        printf("Device assert failed as expected, "
               "CUDA error message is: %s\n\n",
               cudaGetErrorString(error));
    }
    testResult = error == cudaErrorAssert;
}
```

→ https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__TYPES.html

simpleAssert.cu / error handling

```
void runTest(int argc, char **argv)
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    printf("Launch kernel to generate assertion failures\n");
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    }
    testResult = error == cudaErrorAssert;
}
```

Pick up return value from CUDA call

→ https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__TYPES.html

simpleAssert.cu / error handling

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               "CUDA error message is: %s\n\n",
               cudaGetErrorString(error));
    }
    testResult = error == cudaErrorAssert;
}
```

Pick up return value from CUDA call

Get specific info from returned error

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simpleAssert.cu / error handling

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void runTest(int argc, char **argv)
{
    ...
    printf("Launch kernel to generate assertion failures\n");
    testKernel <<< dimGrid, dimBlock >>> (60);

    //Synchronize (flushes assert output)
    printf("\n- Begin assert output\n\n");
    error = cudaDeviceSynchronize();
    printf("\n- End assert output\n\n");

    //Check for errors
    if (error == cudaErrorAssert) {
        printf("Device assert failed as expected, "
               "CUDA error message is: %s\n\n",
               cudaGetErrorString(error));
    }
    testResult = error == cudaErrorAssert;
}
```

Pick up return value from CUDA call

Get specific info from returned error

Set global variable to true/false

→ https://docs.nvidia.com/cuda/cuda-runtime-api/group__CUDART__TYPES.html

Basic Conventions

CUDA SDK cont. — 0_Introduction/simpleAssert

- assert() is a very simple and convenient way to do low-level debugging of kernel code

→ https://github.com/nvidia/cuda-samples

Basic Conventions

CUDA SDK cont. — 0_Introduction/simpleAssert

- assert() is a very simple and convenient way to do low-level debugging of kernel code
- Returns very detailed information, threadIdx, blockIdx, line number, function name

→ https://github.com/nvidia/cuda-samples

Basic Conventions

CUDA SDK cont. — 0_Introduction/simpleAssert

- assert() is a very simple and convenient way to do low-level debugging of kernel code
- Returns very detailed information, threadIdx, blockIdx, line number, function name
- With printf() — surprisingly — we do also get output written from kernel code sections, however only at full block level terminating correctly

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Basic Conventions

CUDA SDK cont. — 0_Introduction/simpleAssert

- assert() is a very simple and convenient way to do low-level debugging of kernel code
- Returns very detailed information, threadIdx, blockIdx, line number, function name
- With printf() — surprisingly — we do also get output written from kernel code sections, however only at full block level terminating correctly
- For example add another line after assert(gtid < N);
  printf("*** message from thread %d ***\n", gtid);

→ https://github.com/nvidia/cuda-samples

Basic Conventions

CUDA SDK cont. — 0_Introduction/simpleAssert

```
cuda-zen sh@n3073-009: my_simpleAssert$ ./simpleAssert

simpleAssert starting...
OS_System_Type.release = 4.18.0-348.el8.x86_64
OS Info: <#1 SMP Tue Nov 9 06:28:28 EST 2021>

GPU Device 0: "Ampere" with compute capability 8.0

Launch kernel to generate assertion failures

-- Begin assert output

*** message from thread 0 ***
*** message from thread 1 ***
*** message from thread 2 ***
......
*** message from thread 29 ***
*** message from thread 30 ***
*** message from thread 31 ***
simpleAssert.cu:63: void testKernel(int): block: [1,0,0], thread: [28,0,0] Assertion `gtid < N` failed.
simpleAssert.cu:63: void testKernel(int): block: [1,0,0], thread: [29,0,0] Assertion `gtid < N` failed.
simpleAssert.cu:63: void testKernel(int): block: [1,0,0], thread: [30,0,0] Assertion `gtid < N` failed.
simpleAssert.cu:63: void testKernel(int): block: [1,0,0], thread: [31,0,0] Assertion `gtid < N` failed.

-- End assert output
```

→ https://github.com/nvidia/cuda-samples

0_Introduction/simplePrintf

CUDA SDK cont.

- There is also another simple CUDA example demonstrating regular operation of printf() in kernel code sections running on the device
- Compute capability must be at least 2.0
- Otherwise an alternative cuPrintf() can be used
- This example is also a good exercise to recall basic builtin variables of the kernel code section, e.g. threadIdx, blockDim etc.

→ https://github.com/nvidia/cuda-samples

0_Introduction/simplePrintf

CUDA SDK cont.

```
cuda-zen sh@n3073-009: 0_Introduction$   cp -r ./simplePrintf ./my_simplePrintf
cuda-zen sh@n3073-009: 0_Introduction$   cd ./my_simplePrintf
cuda-zen sh@n3073-009: my_simplePrintf$   make
cuda-zen sh@n3073-009: my_simplePrintf$   ./simplePrintf
GPU Device 0: "Ampere" with compute capability 8.0

Device 0: "NVIDIA A100-PCIE-40GB" with Compute 8.0 capability
printf() is called. Output:

[1, 0]:         Value is:10             [0, 0]:         Value is:10
[1, 1]:         Value is:10             [0, 1]:         Value is:10
[1, 2]:         Value is:10             [0, 2]:         Value is:10
[1, 3]:         Value is:10             [0, 3]:         Value is:10
[1, 4]:         Value is:10             [0, 4]:         Value is:10
[1, 5]:         Value is:10             [0, 5]:         Value is:10
[1, 6]:         Value is:10             [0, 6]:         Value is:10
[1, 7]:         Value is:10             [0, 7]:         Value is:10
[2, 0]:         Value is:10             [3, 0]:         Value is:10
[2, 1]:         Value is:10             [3, 1]:         Value is:10
[2, 2]:         Value is:10             [3, 2]:         Value is:10
[2, 3]:         Value is:10             [3, 3]:         Value is:10
[2, 4]:         Value is:10             [3, 4]:         Value is:10
[2, 5]:         Value is:10             [3, 5]:         Value is:10
[2, 6]:         Value is:10             [3, 6]:         Value is:10
[2, 7]:         Value is:10             [3, 7]:         Value is:10
```

→ https://github.com/nvidia/cuda-samples

0_Introduction/simplePrintf

CUDA SDK cont.

```
cuda-zen sh@n3073-009: 0_Introduction$   cp -r ./simplePrintf ./my_simplePrintf
cuda-zen sh@n3073-009: 0_Introduction$   cd ./my_simplePrintf
cuda-zen sh@n3073-009: my_simplePrintf$   make
cuda-zen sh@n3073-009: my_simplePrintf$   ./simplePrintf
GPU Device 0: "Ampere" with compute capability 8.0

Device 0: "NVIDIA A100-PCIE-40GB" with Compute 8.0 capability
printf() is called. Output:

[1, 0]:         Value is:10             [0, 0]:         Value is:10
[1, 1]:         Value is:10             [0, 1]:         Value is:10
[1, 2]:         Value is:10             [0, 2]:         Value is:10
[1, 3]:         Value is:10             [0, 3]:         Value is:10
[1, 4]:         Value is:10             [0, 4]:         Value is:10
[1, 5]:         Value is:10             [0, 5]:         Value is:10
[1, 6]:         Value is:10             [0, 6]:         Value is:10
[1, 7]:         Value is:10             [0, 7]:         Value is:10
[2, 0]:         Value is:10             [3, 0]:         Value is:10
[2, 1]:         Value is:10             [3, 1]:         Value is:10
[2, 2]:         Value is:10             [3, 2]:         Value is:10
[2, 3]:         Value is:10             [3, 3]:         Value is:10
[2, 4]:         Value is:10             [3, 4]:         Value is:10
[2, 5]:         Value is:10             [3, 5]:         Value is:10
[2, 6]:         Value is:10             [3, 6]:         Value is:10
[2, 7]:         Value is:10             [3, 7]:         Value is:10
```

4 x blocks with indices from 0-7

→ https://github.com/nvidia/cuda-samples

0_Introduction/simplePrintf

CUDA SDK cont.

```
cuda–zen sh@n3073–009: 0_Introduction$   cp -r ./simplePrintf ./my_simplePrintf
cuda–zen sh@n3073–009: 0_Introduction$   cd ./my_simplePrintf
cuda–zen sh@n3073–009: my_simplePrintf$  make
cuda–zen sh@n3073–009: my_simplePrintf$  ./simplePrintf
GPU Device 0: "Ampere" with compute capability 8.0

Device 0: "NVIDIA A100-PCIE-40GB" with Compute 8.0 capability
printf() is called. Output:

[1, 0]:         Value is:10             [0, 0]:         Value is:10
[1, 1]:         Value is:10             [0, 1]:         Value is:10
[1, 2]:         Value is:10             [0, 2]:         Value is:10
[1, 3]:         Value is:10             [0, 3]:         Value is:10
[1, 4]:         Value is:10             [0, 4]:         Value is:10
[1, 5]:         Value is:10             [0, 5]:         Value is:10
[1, 6]:         Value is:10             [0, 6]:         Value is:10
[1, 7]:         Value is:10             [0, 7]:         Value is:10
[2, 0]:         Value is:10             [3, 0]:         Value is:10
[2, 1]:         Value is:10             [3, 1]:         Value is:10
[2, 2]:         Value is:10             [3, 2]:         Value is:10
[2, 3]:         Value is:10             [3, 3]:         Value is:10
[2, 4]:         Value is:10             [3, 4]:         Value is:10
[2, 5]:         Value is:10             [3, 5]:         Value is:10
[2, 6]:         Value is:10             [3, 6]:         Value is:10
[2, 7]:         Value is:10             [3, 7]:         Value is:10
```

4 x blocks with indices from 0-7

stochastic order of blocks (1st index)

→ https://github.com/nvidia/cuda-samples

simplePrintf.cu

```
__global__ void testKernel(int val)
{
    int gtid = blockIdx.x*blockDim.x + threadIdx.x;
    printf("[%d, %d]:\t\tValue is:%d\n",
            blockIdx.y*gridDim.x+blockIdx.x,
            threadIdx.z*blockDim.x*blockDim.y+threadIdx.y*blockDim.x+threadIdx.x,
            val);
}

int main(int argc, char **argv)
{
    ...
    dim3 dimGrid(2, 2);
    dim3 dimBlock(2, 2, 2);
    testKernel <<< dimGrid, dimBlock >>> (10);
    error = cudaDeviceSynchronize();
    ...
}
```

→ https://github.com/nvidia/cuda-samples

simplePrintf.cu

```
__global__ void testKernel(int val)
{
    int gtid = blockIdx.x*blockDim.x + threadIdx.x;
    printf("[%d, %d]:\t\tValue is:%d\n",
           blockIdx.y*gridDim.x+blockIdx.x,
           threadIdx.z*blockDim.x*blockDim.y+threadIdx.y*blockDim.x+threadIdx.x,
           val);
}

int main(int argc, char **argv)
{
    ...
    dim3 dimGrid(2, 2);
    dim3 dimBlock(2, 2, 2);
    testKernel <<< dimGrid, dimBlock >>> (10);
    error = cudaDeviceSynchronize();
    ...
}
```

Linearizes 2D-grid

→ https://github.com/nvidia/cuda-samples

simplePrintf.cu

```
__global__ void testKernel(int val)
{
    int gtid = blockIdx.x*blockDim.x + threadIdx.x;
    printf("[%d, %d]:\t\tValue is:%d\n",
            blockIdx.y*gridDim.x+blockIdx.x,
            threadIdx.z*blockDim.x*blockDim.y+threadIdx.y*blockDim.x+threadIdx.x,
            val);
}

int main(int argc, char **argv)
{
    ...
    dim3 dimGrid(2, 2);
    dim3 dimBlock(2, 2, 2);
    testKernel <<< dimGrid, dimBlock >>> (10);
    error = cudaDeviceSynchronize();
    ...
}
```

Linearizes 2D-grid

Again, serialization of 3D-threadblocks

→ https://github.com/nvidia/cuda-samples

simplePrintf.cu

```
__global__ void testKernel(int val)
{
    int gtid = blockIdx.x*blockDim.x + threadIdx.x;
    printf("[%d, %d]:\t\tValue is:%d\n",
            blockIdx.y*gridDim.x+blockIdx.x,
            threadIdx.z*blockDim.x*blockDim.y+threadIdx.y*blockDim.x+threadIdx.x,
            val);
}

int main(int argc, char **argv)
{
    ...
    dim3 dimGrid(2, 2);
    dim3 dimBlock(2, 2, 2);
    testKernel <<< dimGrid, dimBlock >>> (10);
    error = cudaDeviceSynchronize();
    ...
}
```

Linearizes 2D-grid

Again, serialization of 3D-threadblocks

4 threadblocks (2D-grid) with 8 threads (3D-block)

→ https://github.com/nvidia/cuda-samples

- Good to see that printf() can be used also in kernel code
- Out of order execution of individual threadblocks in the blockgrid
- Only when the entire threadblock terminates correctly, printf() output will actually show up
- Important for the developmental stage, probably too expensive for production-ready runs

→ https://github.com/nvidia/cuda-samples

1_Utilities/bandwidthTest

CUDA SDK cont.

- 1_Utilities contains several CUDA examples that may also be regarded as simple tools to characterize the GPU hardware at hand

→ https://github.com/nvidia/cuda-samples

1_Utilities/bandwidthTest

CUDA SDK cont.

- 1_Utilities contains several CUDA examples that may also be regarded as simple tools to characterize the GPU hardware at hand
- deviceQuery has already been presented as a useful standard tool to list all device properties

→ https://github.com/nvidia/cuda-samples

1_Utilities/bandwidthTest

CUDA SDK cont.

- 1_Utilities contains several CUDA examples that may also be regarded as simple tools to characterize the GPU hardware at hand
- deviceQuery has already been presented as a useful standard tool to list all device properties
- A recurring issue with CUDA is bandwidth of data transfer — especially because there are so many different variants

→ https://github.com/nvidia/cuda-samples

1_Utilities/bandwidthTest

CUDA SDK cont.

- 1_Utilities contains several CUDA examples that may also be regarded as simple tools to characterize the GPU hardware at hand
- deviceQuery has already been presented as a useful standard tool to list all device properties
- A recurring issue with CUDA is bandwidth of data transfer — especially because there are so many different variants
- This example — bandwidthTest — may help to get a quick overview of what bandwidth we can expect on the current device

→ https://github.com/nvidia/cuda-samples

1_Utilities/bandwidthTest

CUDA SDK cont.

- 1_Utilities contains several CUDA examples that may also be regarded as simple tools to characterize the GPU hardware at hand
- deviceQuery has already been presented as a useful standard tool to list all device properties
- A recurring issue with CUDA is bandwidth of data transfer — especially because there are so many different variants
- This example — bandwidthTest — may help to get a quick overview of what bandwidth we can expect on the current device
- There are also several CL args that may provide guidance for size/type dependence

→ https://github.com/nvidia/cuda-samples

1_Utilities/bandwidthTest

CUDA SDK cont.

```
cuda-zen sh@n3073-009: 1_Utilities$   cp -r ./bandwidthTest ./my_bandwidthTest
cuda-zen sh@n3073-009: 1_Utilities$   cd ./my_bandwidthTest
cuda-zen sh@n3073-009: my_bandwidthTest$   make
cuda-zen sh@n3073-009: my_bandwidthTest$   ./bandwidthTest
[CUDA Bandwidth Test] - Starting...
Running on...

 Device 0: NVIDIA A100-PCIE-40GB
 Quick Mode

 Host to Device Bandwidth, 1 Device(s)
 PINNED Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     11.2

 Device to Host Bandwidth, 1 Device(s)
 PINNED Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     23.3

 Device to Device Bandwidth, 1 Device(s)
 PINNED Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     1163.9
```

→ https://github.com/nvidia/cuda-samples

1_Utilities/bandwidthTest

CUDA SDK cont.

```
cuda-zen sh@n3073-009: 1_Utilities$   cp -r ./bandwidthTest ./my_bandwidthTest
cuda-zen sh@n3073-009: 1_Utilities$   cd ./my_bandwidthTest
cuda-zen sh@n3073-009: my_bandwidthTest$   make
cuda-zen sh@n3073-009: my_bandwidthTest$   ./bandwidthTest
[CUDA Bandwidth Test] - Starting...
Running on...

 Device 0: NVIDIA A100-PCIE-40GB
 Quick Mode

 Host to Device Bandwidth, 1 Device(s)
 PINNED Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     11.2

 Device to Host Bandwidth, 1 Device(s)
 PINNED Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     23.3

 Device to Device Bandwidth, 1 Device(s)
 PINNED Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     1163.9
```

32MB (pinned) with ≈ 10-25 GB/s

→ https://github.com/nvidia/cuda-samples

1_Utilities/bandwidthTest

CUDA SDK cont.

```
cuda–zen sh@n3073–009: my_bandwidthTest$  ./bandwidthTest --help
cuda–zen sh@n3073–009: my_bandwidthTest$  ./bandwidthTest --mode=quick --memory=pageable --htod
[CUDA Bandwidth Test] - Starting...
Running on...

 Device 0: NVIDIA A100-PCIE-40GB
 Quick Mode

 Host to Device Bandwidth, 1 Device(s)
 PAGEABLE Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     2.2

cuda–zen sh@n3073–009: my_bandwidthTest$  ./bandwidthTest --mode=quick --memory=pinned --htod
[CUDA Bandwidth Test] - Starting...
Running on...

 Device 0: NVIDIA A100-PCIE-40GB
 Quick Mode

 Host to Device Bandwidth, 1 Device(s)
 PINNED Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     11.2
```

→ https://github.com/nvidia/cuda-samples

1_Utilities/bandwidthTest

CUDA SDK cont.

```
cuda–zen sh@n3073–009: my_bandwidthTest$ ./bandwidthTest --help
cuda–zen sh@n3073–009: my_bandwidthTest$ ./bandwidthTest --mode=quick --memory=pageable --htod
[CUDA Bandwidth Test] - Starting...
Running on...

 Device 0: NVIDIA A100-PCIE-40GB
 Quick Mode

 Host to Device Bandwidth, 1 Device(s)
 PAGEABLE Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     2.2

cuda–zen sh@n3073–009: my_bandwidthTest$ ./bandwidthTest --mode=quick --memory=pinned --htod
[CUDA Bandwidth Test] - Starting...
Running on...

 Device 0: NVIDIA A100-PCIE-40GB
 Quick Mode

 Host to Device Bandwidth, 1 Device(s)
 PINNED Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     11.2
```

PINNED is preferable to PAGEABLE

→ https://github.com/nvidia/cuda-samples

1_Utilities/bandwidthTest

CUDA SDK cont.

```
cuda–zen sh@n3073–009: my_bandwidthTest$  ./bandwidthTest --help
cuda–zen sh@n3073–009: my_bandwidthTest$  ./bandwidthTest --mode=quick --memory=pageable --htod
[CUDA Bandwidth Test] - Starting...
Running on...

 Device 0: NVIDIA A100-PCIE-40GB
 Quick Mode

 Host to Device Bandwidth, 1 Device(s)
 PAGEABLE Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     2.2

cuda–zen sh@n3073–009: my_bandwidthTest$  ./bandwidthTest --mode=quick --memory=pinned --htod
[CUDA Bandwidth Test] - Starting...
Running on...

 Device 0: NVIDIA A100-PCIE-40GB
 Quick Mode

 Host to Device Bandwidth, 1 Device(s)
 PINNED Memory Transfers
   Transfer Size (Bytes)        Bandwidth(GB/s)
   32000000                     11.2
```

Why so far off the promised 1555 GB/s ???

PINNED is preferable to PAGEABLE

→ https://github.com/nvidia/cuda-samples

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
float
testDeviceToHostTransfer(unsigned int memSize, memoryMode memMode, bool wc)
{
    StopWatchInterface *timer = NULL;
    float elapsedTimeInMs = 0.0f;
    float bandwidthInGBs = 0.0f;
    unsigned char *h_idata = NULL;
    unsigned char *h_odata = NULL;
    cudaEvent_t start, stop;

    sdkCreateTimer(&timer);
    checkCudaErrors(cudaEventCreate(&start));
    checkCudaErrors(cudaEventCreate(&stop));

    //allocate host memory
    if (PINNED == memMode)
    {
        //pinned memory mode - use special function to get OS-pinned memory
        checkCudaErrors(cudaHostAlloc((void **)&h_idata, memSize, (wc) ? cudaHostAllocWriteCombined : 0));
        checkCudaErrors(cudaHostAlloc((void **)&h_odata, memSize, (wc) ? cudaHostAllocWriteCombined : 0));
    }
    else {
        //pageable memory mode - use malloc
    }
```

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
float
testDeviceToHostTransfer(unsigned int memSize, memoryMode memMode, bool wc)
{
    StopWatchInterface *timer = NULL;
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    unsigned char *h_idata = NULL;
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    cudaEvent_t start, stop;

    sdkCreateTimer(&timer);
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        checkCudaErrors(cudaHostAlloc((void **)&h_idata, memSize, (wc) ? cudaHostAllocWriteCombined : 0));
        checkCudaErrors(cudaHostAlloc((void **)&h_odata, memSize, (wc) ? cudaHostAllocWriteCombined : 0));
    }
    else {
        //pageable memory mode - use malloc
    }
```

32000000

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
float
testDeviceToHostTransfer(unsigned int memSize, memoryMode memMode, bool wc)
{
    StopWatchInterface *timer = NULL;
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    unsigned char *h_idata = NULL;
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    cudaEvent_t start, stop;

    sdkCreateTimer(&timer);
    checkCudaErrors(cudaEventCreate(&start));
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    //allocate host memory
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    {
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        checkCudaErrors(cudaHostAlloc((void **)&h_idata, memSize, (wc) ? cudaHostAllocWriteCombined : 0));
        checkCudaErrors(cudaHostAlloc((void **)&h_odata, memSize, (wc) ? cudaHostAllocWriteCombined : 0));
    }
    else {
        //pageable memory mode - use malloc
    }
```

32000000

CUDA types

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
float
testDeviceToHostTransfer(unsigned int memSize, memoryMode memMode, bool wc)
{
    StopWatchInterface *timer = NULL;
    float elapsedTimeInMs = 0.0f;
    float bandwidthInGBs = 0.0f;
    unsigned char *h_idata = NULL;
    unsigned char *h_odata = NULL;
    cudaEvent_t start, stop;

    sdkCreateTimer(&timer);
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    //allocate host memory
    if (PINNED == memMode)
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        //pinned memory mode - use special function to get OS-pinned memory
        checkCudaErrors(cudaHostAlloc((void **)&h_idata, memSize, (wc) ? cudaHostAllocWriteCombined : 0));
        checkCudaErrors(cudaHostAlloc((void **)&h_odata, memSize, (wc) ? cudaHostAllocWriteCombined : 0));
    }
    else {
        //pageable memory mode - use malloc
    }
```

32000000

CUDA types

CUDA time measurement

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
float
testDeviceToHostTransfer(unsigned int memSize, memoryMode memMode, bool wc)
{
    StopWatchInterface *timer = NULL;
    float elapsedTimeInMs = 0.0f;
    float bandwidthInGBs = 0.0f;
    unsigned char *h_idata = NULL;
    unsigned char *h_odata = NULL;
    cudaEvent_t start, stop;

    sdkCreateTimer(&timer);
    checkCudaErrors(cudaEventCreate(&start));
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    //allocate host memory
    if (PINNED == memMode)
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        //pinned memory mode - use special function to get OS-pinned memory
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        checkCudaErrors(cudaHostAlloc((void **)&h_odata, memSize, (wc) ? cudaHostAllocWriteCombined : 0));
    }
    else {
        //pageable memory mode - use malloc
    }
```

32000000

CUDA types

CUDA time measurement

Error handling via encapsulation

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
//initialize the memory
for (unsigned int i = 0; i < memSize/sizeof(unsigned char); i++)
{
    h_idata[i] = (unsigned char)(i & 0xff);
}
// allocate device memory
unsigned char *d_idata;
checkCudaErrors(cudaMalloc((void **) &d_idata, memSize));

//initialize the device memory
checkCudaErrors(cudaMemcpy(d_idata, h_idata, memSize,
                           cudaMemcpyHostToDevice));

//copy data from GPU to Host
sdkStartTimer(&timer);
checkCudaErrors(cudaEventRecord(start, 0));
if (PINNED == memMode)
{
    for (unsigned int i = 0; i < MEMCOPY_ITERATIONS; i++)
    {
        checkCudaErrors(cudaMemcpyAsync(h_odata, d_idata, memSize,
                                        cudaMemcpyDeviceToHost, 0));
    }
} else { ... }
```

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
//initialize the memory
for (unsigned int i = 0; i < memSize/sizeof(unsigned char); i++)
{
    h_idata[i] = (unsigned char)(i & 0xff);
}
// allocate device memory
unsigned char *d_idata;
checkCudaErrors(cudaMalloc((void **) &d_idata, memSize));

//initialize the device memory
checkCudaErrors(cudaMemcpy(d_idata, h_idata, memSize,
                           cudaMemcpyHostToDevice));

//copy data from GPU to Host
sdkStartTimer(&timer);
checkCudaErrors(cudaEventRecord(start, 0));
if (PINNED == memMode)
{
    for (unsigned int i = 0; i < MEMCOPY_ITERATIONS; i++)
    {
        checkCudaErrors(cudaMemcpyAsync(h_odata, d_idata, memSize,
                                        cudaMemcpyDeviceToHost, 0));
    }
} else { ... }
```

Loop over 32M items

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
//initialize the memory
for (unsigned int i = 0; i < memSize/sizeof(unsigned char); i++)
{
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}
// allocate device memory
unsigned char *d_idata;
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//initialize the device memory
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//copy data from GPU to Host
sdkStartTimer(&timer);
checkCudaErrors(cudaEventRecord(start, 0));
if (PINNED == memMode)
{
    for (unsigned int i = 0; i < MEMCOPY_ITERATIONS; i++)
    {
        checkCudaErrors(cudaMemcpyAsync(h_odata, d_idata, memSize,
                                        cudaMemcpyDeviceToHost, 0));
    }
} else { ... }
```

Loop over 32M items

bitwise add like (i % 255)

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
//initialize the memory
for (unsigned int i = 0; i < memSize/sizeof(unsigned char); i++)
{
    h_idata[i] = (unsigned char)(i & 0xff);
}
// allocate device memory
unsigned char *d_idata;
checkCudaErrors(cudaMalloc((void **) &d_idata, memSize));

//initialize the device memory
checkCudaErrors(cudaMemcpy(d_idata, h_idata, memSize,
                           cudaMemcpyHostToDevice));

//copy data from GPU to Host
sdkStartTimer(&timer);
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if (PINNED == memMode)
{
    for (unsigned int i = 0; i < MEMCOPY_ITERATIONS; i++)
    {
        checkCudaErrors(cudaMemcpyAsync(h_odata, d_idata, memSize,
                                        cudaMemcpyDeviceToHost, 0));
    }
} else { ... }
```

Loop over 32M items

bitwise add like (i % 255)

Memory set up on GPU

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
//initialize the memory
for (unsigned int i = 0; i < memSize/sizeof(unsigned char); i++)
{
    h_idata[i] = (unsigned char)(i & 0xff);
}
// allocate device memory
unsigned char *d_idata;
checkCudaErrors(cudaMalloc((void **) &d_idata, memSize));

//initialize the device memory
checkCudaErrors(cudaMemcpy(d_idata, h_idata, memSize,
                           cudaMemcpyHostToDevice));

//copy data from GPU to Host
sdkStartTimer(&timer);
checkCudaErrors(cudaEventRecord(start, 0));
if (PINNED == memMode)
{
    for (unsigned int i = 0; i < MEMCOPY_ITERATIONS; i++)
    {
        checkCudaErrors(cudaMemcpyAsync(h_odata, d_idata, memSize,
                                        cudaMemcpyDeviceToHost, 0));
    }
} else { ... }
```

Loop over 32M items

bitwise add like (i % 255)

Memory set up on GPU

Timing begin

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
//initialize the memory
for (unsigned int i = 0; i < memSize/sizeof(unsigned char); i++)
{
    h_idata[i] = (unsigned char)(i & 0xff);
}
// allocate device memory
unsigned char *d_idata;
checkCudaErrors(cudaMalloc((void **) &d_idata, memSize));

//initialize the device memory
checkCudaErrors(cudaMemcpy(d_idata, h_idata, memSize,
                           cudaMemcpyHostToDevice));

//copy data from GPU to Host
sdkStartTimer(&timer);
checkCudaErrors(cudaEventRecord(start, 0));
if (PINNED == memMode)
{
    for (unsigned int i = 0; i < MEMCOPY_ITERATIONS; i++)
    {
        checkCudaErrors(cudaMemcpyAsync(h_odata, d_idata, memSize,
                                        cudaMemcpyDeviceToHost, 0));
    }
} else { ... }
```

Loop over 32M items

bitwise add like (i % 255)

Memory set up on GPU

Timing begin

100

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
    checkCudaErrors(cudaEventRecord(stop, 0));

    // make sure GPU has finished copying
    checkCudaErrors(cudaDeviceSynchronize());
    //get the total elapsed time in ms
    sdkStopTimer(&timer);
    checkCudaErrors(cudaEventElapsedTime(&elapsedTimeInMs, start, stop));

    //calculate bandwidth in GB/s
    double time_s = elapsedTimeInMs / 1e3;
    bandwidthInGBs = (memSize * (float)MEMCOPY_ITERATIONS) / (double)1e9;
    bandwidthInGBs = bandwidthInGBs / time_s;
    //clean up memory
    checkCudaErrors(cudaEventDestroy(stop));
    checkCudaErrors(cudaEventDestroy(start));
    sdkDeleteTimer(&timer);

    ... freeing allocated memory

    return bandwidthInGBs;
}
```

1_Utilities/bandwidthTest

CUDA SDK cont.

bandwidthTest.cu (essentials)

```
    checkCudaErrors(cudaEventRecord(stop, 0));

    // make sure GPU has finished copying
    checkCudaErrors(cudaDeviceSynchronize());
    //get the total elapsed time in ms
    sdkStopTimer(&timer);
    checkCudaErrors(cudaEventElapsedTime(&elapsedTimeInMs, start, stop));

    //calculate bandwidth in GB/s
    double time_s = elapsedTimeInMs / 1e3;
    bandwidthInGBs = (memSize * (float)MEMCOPY_ITERATIONS) / (double)1e9;
    bandwidthInGBs = bandwidthInGBs / time_s;
    //clean up memory
    checkCudaErrors(cudaEventDestroy(stop));
    checkCudaErrors(cudaEventDestroy(start));
    sdkDeleteTimer(&timer);

    ... freeing allocated memory

    return bandwidthInGBs;
}
```

Timing end

1_Utilities/bandwidthTest

CUDA SDK cont.

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Timing end

Exe time in ms

1_Utilities/bandwidthTest

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Timing end

Exe time in ms

Convert and compute bw

1_Utilities/bandwidthTest

CUDA SDK cont.

- Data transfer between host and device is the slowest link involved in GPU computing
- Needs to be carefully designed/minimized case-by-case
- Peak bandwidth disparity between device memory $\leftrightarrow$ GPU cores (1555 GB/s on A100) and host memory $\leftrightarrow$ device memory (25 GB/s PCIe Gen4)
- GPU receives pinned memory only, which is a temporary translation of pageable host memory
- That's why the directly allocated memory in pinned form is transferred faster
- Another optimization strategy is to overlap memory transfer with computing

→ https://devblogs.nvidia.com/how-optimize-data-transfers-cuda-cc

- Efficiency comes with concurrently executing functions on all sorts of processing elements including CPU- and GPU-cores

→ https://devblogs.nvidia.com/gpu-pro-tip-cuda-7-streams-simplify-concurrency

- Efficiency comes with concurrently executing functions on all sorts of processing elements including CPU- and GPU-cores
- CUDA applications manage concurrency with streams

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0_Introduction/simpleStreams

CUDA SDK cont.

- Efficiency comes with concurrently executing functions on all sorts of processing elements including CPU- and GPU-cores
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- A stream is a sequence of commands executed in order
- Several streams may execute their respective sequences of commands concurrently/asynchronously
- With CUDA 7 control over more than one (default stream) was introduced, so that multiple host threads can now have their own associated default stream for launching kernels

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- Several streams may execute their respective sequences of commands concurrently/asynchronously
- With CUDA 7 control over more than one (default stream) was introduced, so that multiple host threads can now have their own associated default stream for launching kernels
- Asynchronous commands in CUDA return control to the calling host thread before the device has finished the requested task (non-blocking), e.g. kernel launches, memory copies performed by functions with the Async suffix, etc.

→ https://devblogs.nvidia.com/gpu-pro-tip-cuda-7-streams-simplify-concurrency

CUDA streams

```
KrnlDmmy <<< numBlocks, threadsPerBlock, numBytes  >>> ();      // default stream
KrnlDmmy <<< numBlocks, threadsPerBlock, numBytes, 0  >>> ();   // stream 0
```

→ https://devblogs.nvidia.com/gpu-pro-tip-cuda-7-streams-simplify-concurrency
→ https://stackoverflow.com/questions/27162408/shared-memory-and-streams-when-launching-kernel

CUDA streams

Specifying a stream for a kernel launch (or memcopy) is optional

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Stream 0 is the default stream

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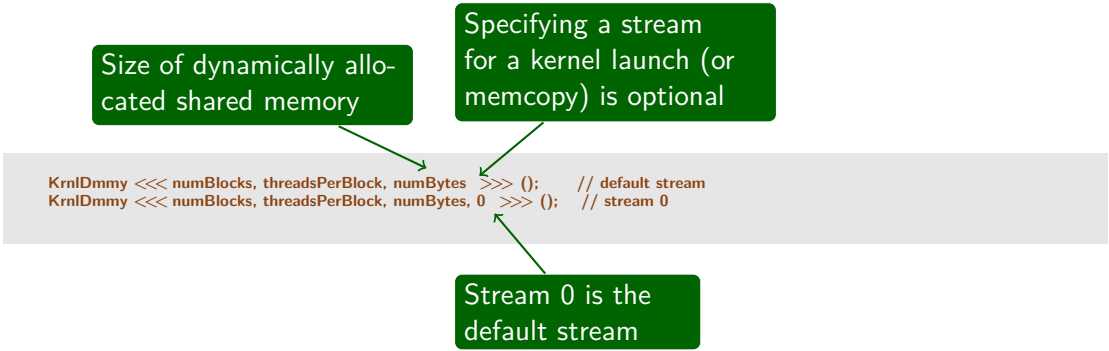
CUDA streams



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CUDA streams

Size of dynamically allocated shared memory

Specifying a stream for a kernel launch (or memcopy) is optional

```
KrnlDmmy <<< numBlocks, threadsPerBlock, numBytes  >>> ();      // default stream
KrnlDmmy <<< numBlocks, threadsPerBlock, numBytes, 0  >>> ();   // stream 0
```

Since CUDA 7 per-(host)thread default streams may be used

Stream 0 is the default stream

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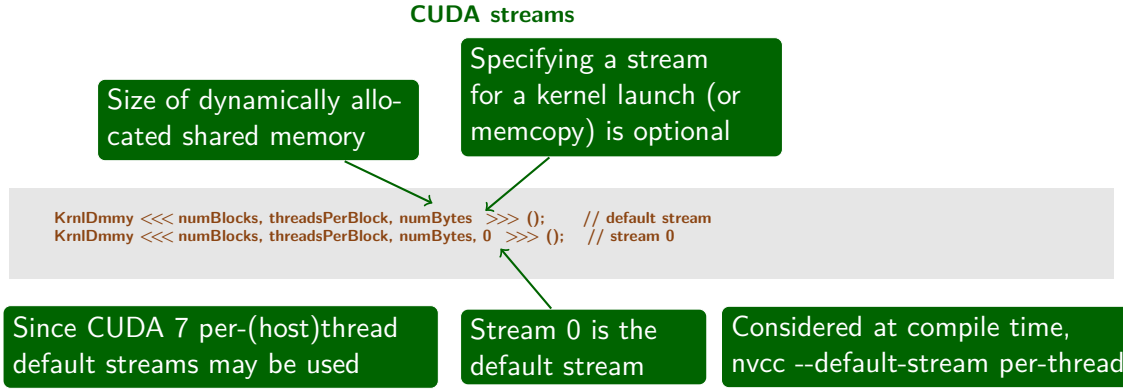

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0_Introduction/simpleStreams

CUDA SDK cont.

```
const int N = 1048576;

__global__ void kernel(float *x, int n)
{
    int tid = blockIdx.x * blockDim.x + threadIdx.x;
    for (int i = tid; i <n; i += blockDim.x) {
        x[i] = sqrt(pow(3.14159,i));
    }
}
int main()
{
    const int num_streams = 8;
    cudaStream_t streams[num_streams];
    float *data[num_streams];
    for (int i = 0; i <num_streams; i++) {
        cudaStreamCreate(&streams[i]);
        cudaMalloc(&data[i], N * sizeof(float));
        // launch one worker kernel per stream
        kernel <<< 1, 64, 0, streams[i]  >>> (data[i], N);
        // launch a dummy kernel on the default stream
        kernel <<< 1, 1 >>> (0, 0);
    }
    cudaDeviceReset();
    return 0;
}
```

Thread-specific run through array x[] with stride blockDim.x

→ https://tinyurl.com/cudafordummies/ii/t/stream_test.cu

0_Introduction/simpleStreams

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Thread-specific run through array x[] with stride blockDim.x

Special type declaration

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0_Introduction/simpleStreams

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Thread-specific run through array x[] with stride blockDim.x

Special type declaration

Stream creation and specific memory allocation

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0_Introduction/simpleStreams

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}
```

Thread-specific run through array x[] with stride blockDim.x

Special type declaration

Stream creation and specific memory allocation

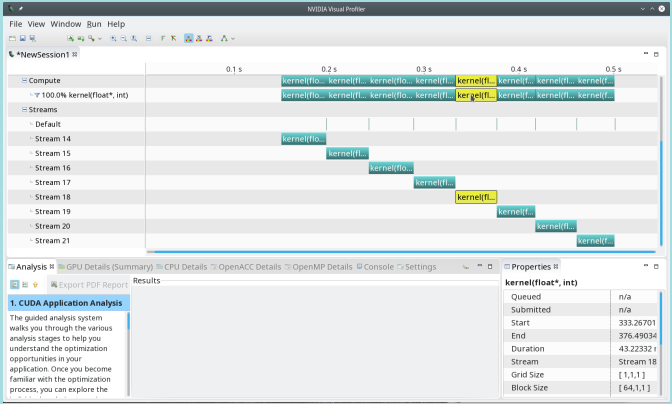
Kernel launch via streams

→ https://tinyurl.com/cudafordummies/ii/t/stream_test.cu

0_Introduction/simpleStreams

CUDA SDK cont.

```
cuda–zen  sh@n3073–009:~$  nvcc ./stream_test.cu -o ./stream_legacy
cuda–zen  sh@n3073–009:~$  nvvp ./stream_legacy
```



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0_Introduction/simpleStreams

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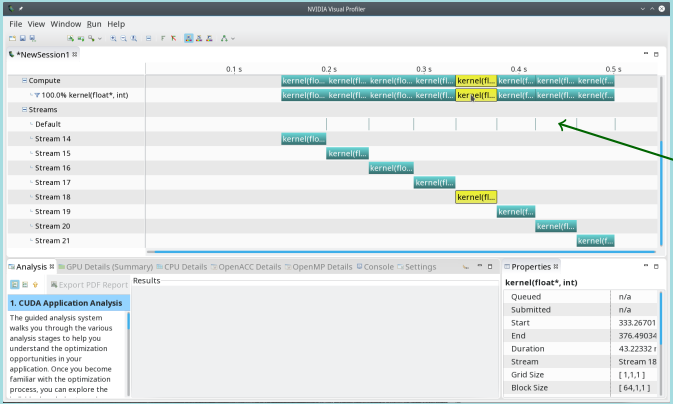

Interleaved dummy kernel sent to the default stream → no concurrency

→ https://devblogs.nvidia.com/gpu-pro-tip-cuda-7-streams-simplify-concurrency

0_Introduction/simpleStreams

CUDA SDK cont.

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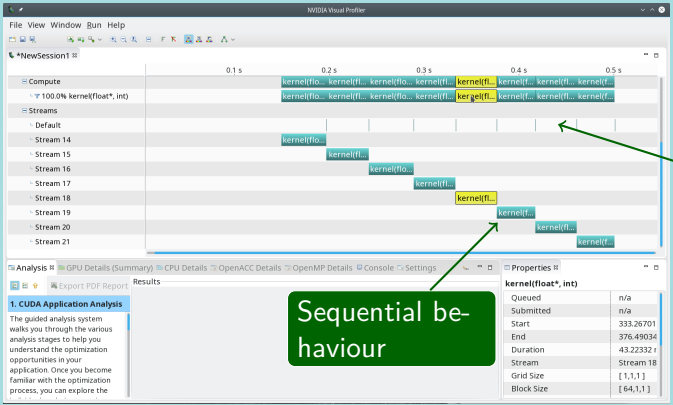

Sequential behaviour

Interleaved dummy kernel sent to the default stream → no concurrency

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0_Introduction/simpleStreams

CUDA SDK cont.

```
cuda–zen sh@n3073–009:~$ nvcc --default-stream per-thread ./stream_test.cu -o ./stream_per-thread
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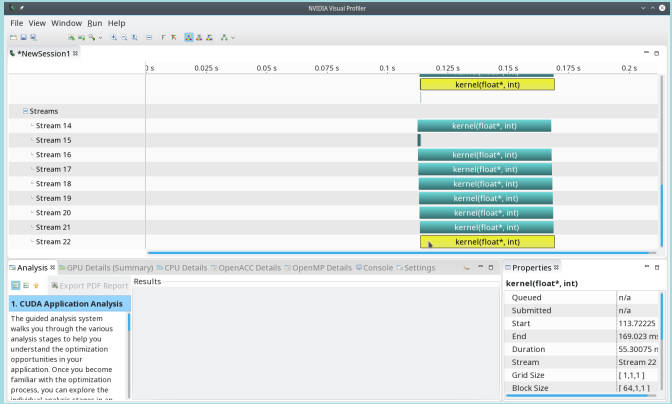

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0_Introduction/simpleStreams

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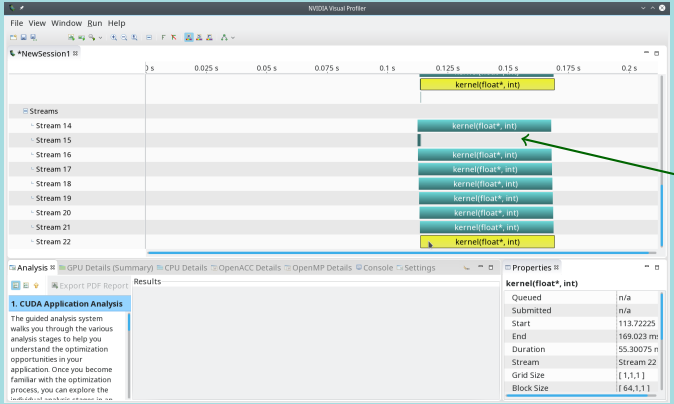

Dummy kernel (sent to the default stream) in parallel

→ https://devblogs.nvidia.com/gpu-pro-tip-cuda-7-streams-simplify-concurrency

0_Introduction/simpleStreams

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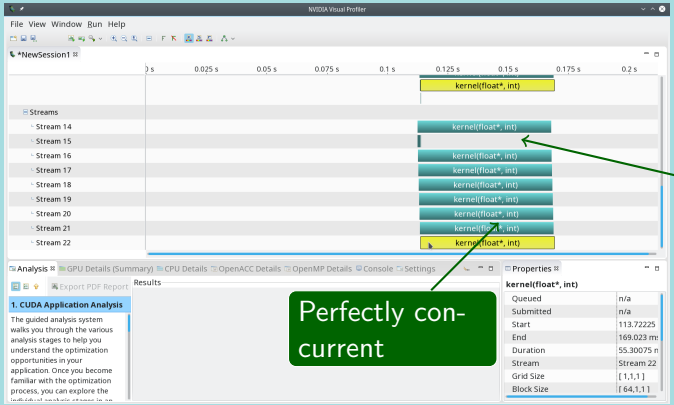

Dummy kernel (sent to the default stream) in parallel

Perfectly concurrent

→ https://devblogs.nvidia.com/gpu-pro-tip-cuda-7-streams-simplify-concurrency

0_Introduction/simpleStreams

CUDA SDK cont.

```
#include <omp.h>
const int N = 1048576;
__global__ void kernel(float *x, int n)
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}
int main()
{
    const int num_streams = 8;
    cudaStream_t streams[num_streams];
    float *data[num_streams];
    omp_set_num_threads(num_streams);
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Individual host-threads on separate CPU cores with associated stream

→ https://tinyurl.com/cudafordummies/ii/t/stream_test_v5.cu

0_Introduction/simpleStreams

CUDA SDK cont.

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```

Individual host-threads on separate CPU cores with associated stream

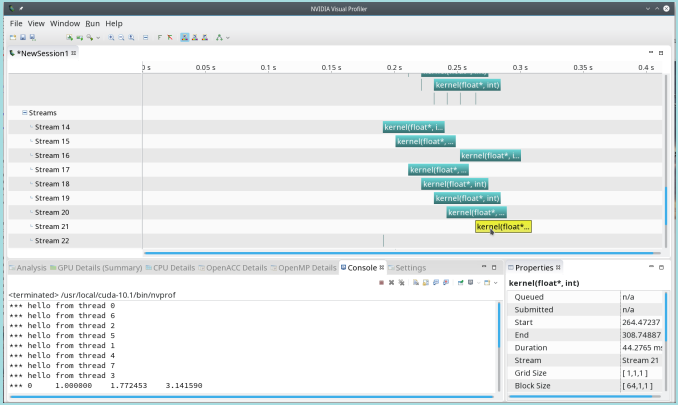
Simplest way of exhausting all available CPU/GPU resources

→ https://tinyurl.com/cudafordummies/ii/t/stream_test_v5.cu

0_Introduction/simpleStreams

CUDA SDK cont.

```
cuda–zen  sh@n3073–009:~$  nvcc --default-stream per-thread -ccbin g++ -m64 -Xcompiler -fopenmp ./stream_test_v5.cu -o ./stream_v5_pt
cuda–zen  sh@n3073–009:~$  nvvp ./stream_v5_pt
```



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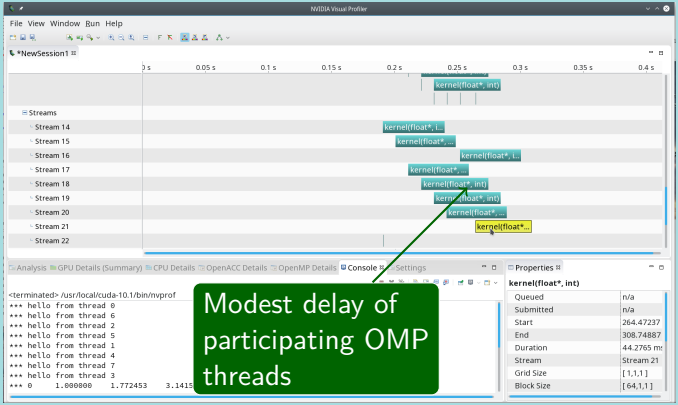

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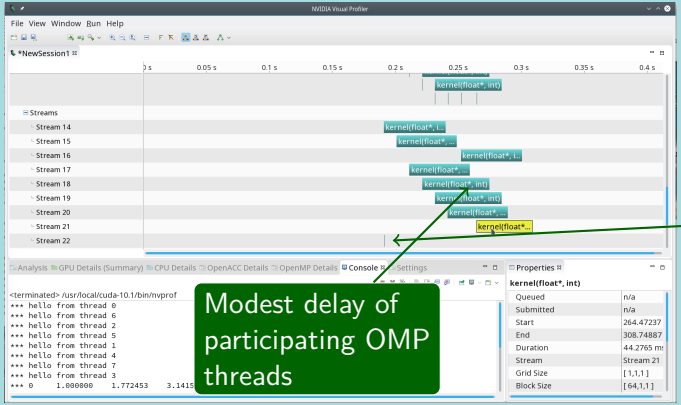

→ https://devblogs.nvidia.com/gpu-pro-tip-cuda-7-streams-simplify-concurrency

- Streams enable a lot of flexibilty in CUDA workloads
- Only the legacy default stream can pose problems
- Compiler flag --default-stream per-thread needs to be applied to all *.cu units involved
- cudaDeviceSynchronize() continues to synchronize everything on the device
- Individual streams may be synchronized via cudaStreamSynchronize()
- Ruling out interference by the default stream completely may be achieved with non-blocking streams, i.e. by passing the flag cudaStreamNonBlocking to cudaStreamCreate()

→ https://devblogs.nvidia.com/gpu-pro-tip-cuda-7-streams-simplify-concurrency

4_CUDA_Libraries/randomFog

CUDA SDK cont.

- CUDA is for graphics cards, so there are a lot of graphics examples too
- Example 4_CUDA_Libraries/randomFog
- Random number generation (200k) with CURAND
- Spherical polar coordinates are used (radius, rho, theta) normalized and presented as uniform distribution on the sphere
- Several options to display the data set

→ /usr/local/cuda/extras/demo_suite/randomFog

5_Domain_Specific/nbody

CUDA SDK cont.

- nbody is a CUDA demo of a gravitational n-body simulation
- Rather efficient scaling (strong) with multiple GPUs
- OpenGL rendering
- Command line args like -numbodies=10000 or -fp64 or -fullscreen or -cpu

→ /usr/local/cuda/extras/demo_suite/nbody

4_CUDA_Libraries/oceanFFT

CUDA SDK cont.

- oceanFFT is a graphical demo of an ocean surface
- Height field is computed with the help of the CUFFT library (CUDA Fast Fourier Transform)
- OpenGL rendering
- 'w' — toggle wireframe

→ cd /usr/local/cuda/extras/demo_suite; ./oceanFFT

Take Home Messages

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- An exploratory space (memory management, error-handling...)
- PCIe bandwidth remains a critical limitation in GPU computing
- CUDA streams bring in another level of flexibility, especially when run concurrently (perhaps from individual OpenMP threads on the host)
- Graphical demos — nice to have them too !