CSE 591: GPU Programming

Programmer Interface

Klaus Mueller

Computer Science Department

Stony Brook University

Compute Levels

Encodes the hardware capability of a GPU card

- newer cards have higher compute levels
- higher compute levels have more or faster features

Find a card's compute capability with CUDA runtime API

- *cudaGetDeviceProperties()* returns two fields: major and minor

Compute 1.0

- 8000 series of cards
- does not have atomic (un-interrupted completion) operations

Compute 1.1

- 9000 series of cards
- can overlap data transfer with kernel execution
- non-blocking kernel invocation
- will require more GPU memory (active + loading process)

Compute Levels

Compute 1.2

- GT 200 series of cards
- increased the number of warps from 24 to 32
- some memory management restrictions were also removed

Compute 1.3

- support of limited double-precision operations
- but watch out for significant performance drops

Compute Levels

Compute 2.0

- Fermi hardware
- New: L1 cache (6k-48k): encourages data re-use, locality
- New: shared L2 cache (up to 768k): enables inter-block communication
- ECC (Error Correcting Code): detect and correct single bit errors
- ECC only in Tesla boards, needed in data centers where the radiation of nearby processors could flip bits
- Dual copy engines and streams: run multiple asynchronous processes
- Switchable L1/shared memory (48k/16k or 16k/48k)
- Cache lining can be turned off
- Increase memory banks from 16 to 32: now an entire warp can write simultaneously

Compute Levels

Compute 2.1

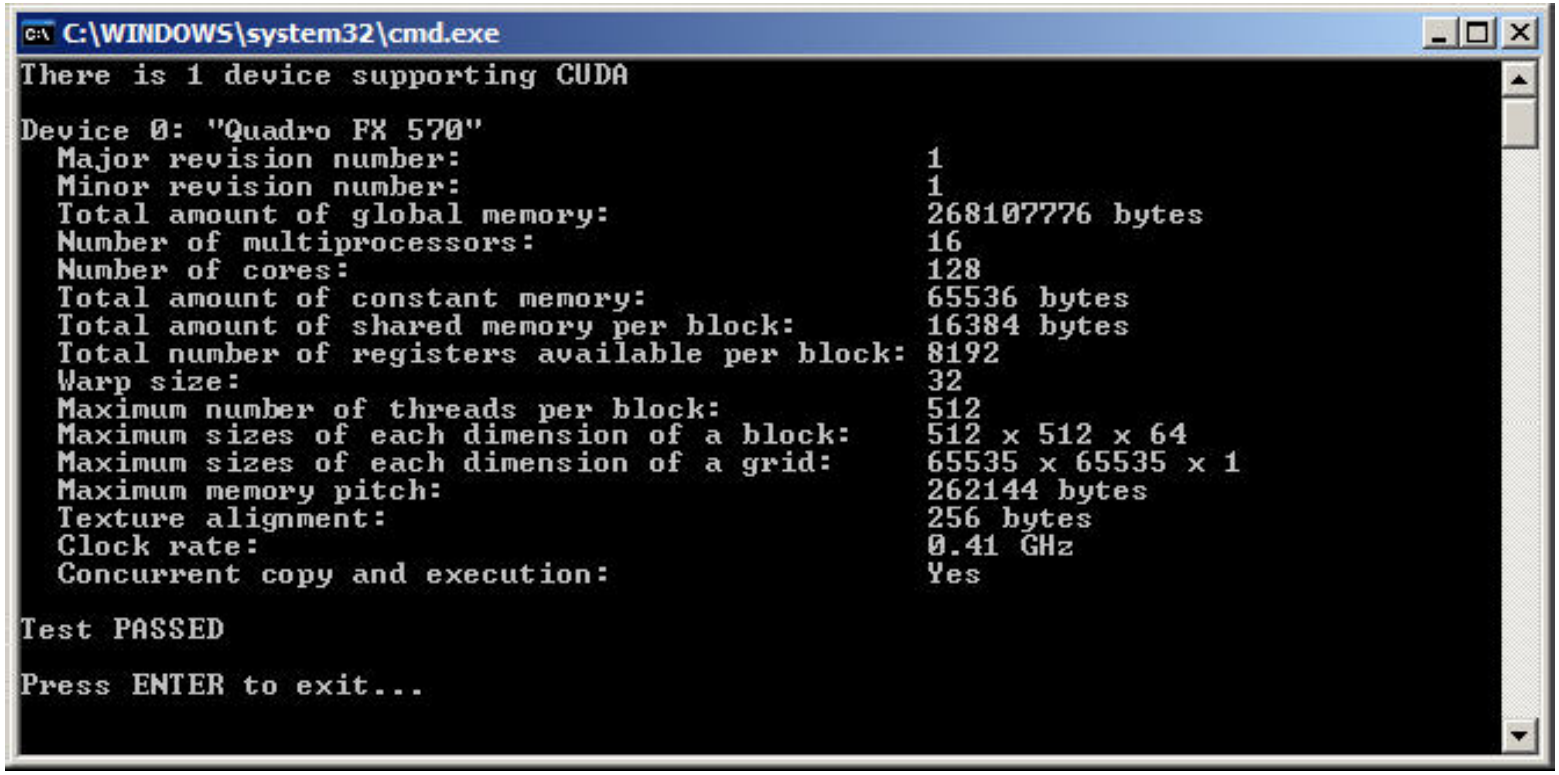
- GTX 480
- 48 CUDA cores per SM (instead of 32) but some are only single precision
- 8 instead of 4 single precision special function units
- dual warp dispatcher
- exploits instruction level parallelism (gives super-scalar speedups like Pentium, but needs independent instructions)

New compute capabilities

- 3.0 (680 GTX series) and 3.1 (Tesla K20)

Checking GPU Device Capabilities

Call *cudaGetDeviceProperties()*



Programmer Interface

C for CUDA

- most intuitive
- exposes programming model as a minimal set of operations
- define kernel as a C-function
- compile with **nvcc**
- **runtime API** provides various functions
- **runtime API** is implemented in **cudart** DLL (prefix cuda)

CUDA driver API

- expert interface
- allows finer control
- define kernels as modules of CUDA binary or assembly code
- **runtime API** is built on top of CUDA driver API

Programmer Interface

Compilation with **nvcc**

- any CUDA source file must be compiled with **nvcc**
- produces **PTX** assembler code
- produces **cubin** binary objects
- produces C code (host CPU code)

PTX assembler code

- can be ported to different GPUs
- but may include advanced functionality only recent GPUs support
- check the **compute capability**
- **PTX** is backward compatible

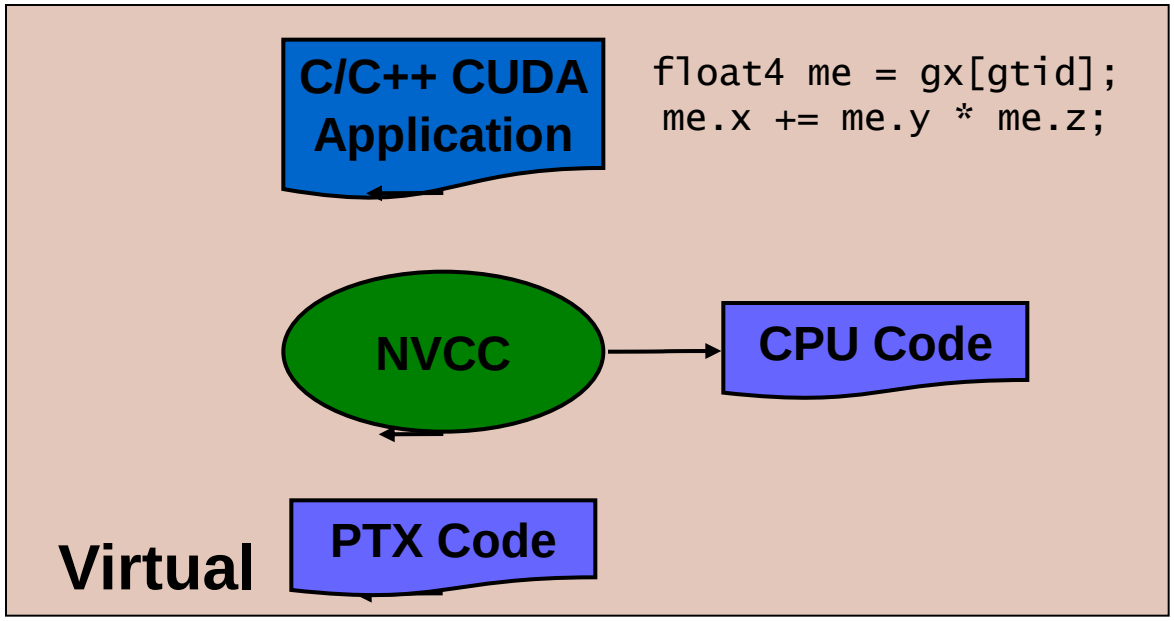
Cubin binary objects

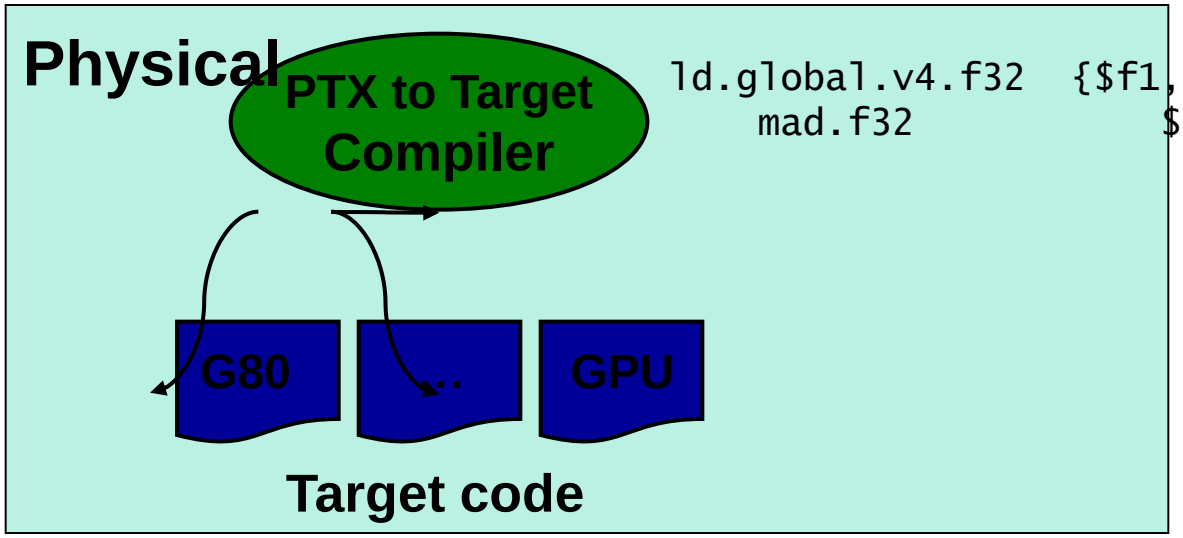
- specific to a particular GPU model
- generate by recompiling **PTX** (or higher level code)

Linking

- CUDA runtime library (**cudart**) and CUDA core library (**cuda**)

More Graphically





Debugging Using the Device Emulation Mode

An executable compiled in device emulation mode (**`nvcc -deviceemu`**)

- runs completely on the host using the CUDA runtime
- no need of any device and CUDA driver
- each device thread is emulated with a host thread

Running in device emulation mode, one can:

- use host native debug support (breakpoints, inspection, etc.)
- access any device-specific data from host code and vice-versa
- call any host function from device code (e.g. `printf`) and vice-versa
- detect deadlock situations caused by improper usage of `__syncthreads`

Device Emulation Mode Pitfalls

Emulated device threads execute sequentially,

- simultaneous accesses of the same memory location by multiple threads could produce different results.

Dereferencing device pointers on the host or host pointers on the device

- can produce correct results in device emulation mode
- but will generate an error in device execution mode

A Word of Caution: Floating Point

Results of floating-point computations will slightly differ because of:

- different compiler outputs, instruction sets
- use of extended precision for intermediate results
  - there are various options to force strict single precision on the host

Application Programming Interface

The API is an extension to the C programming language

It consists of:

- language extensions
  - to target portions of the code for execution on the device
- a runtime library split into:
  - a common component providing built-in vector types and a subset of the C runtime library in both host and device codes
  - a host component to control and access one or more devices from the host
  - a device component providing device-specific functions

Extended C

Declspecs

- **global, device, shared, local, constant**

Keywords

- **threadIdx, blockIdx**

Intrinsics

- **__syncthreads**

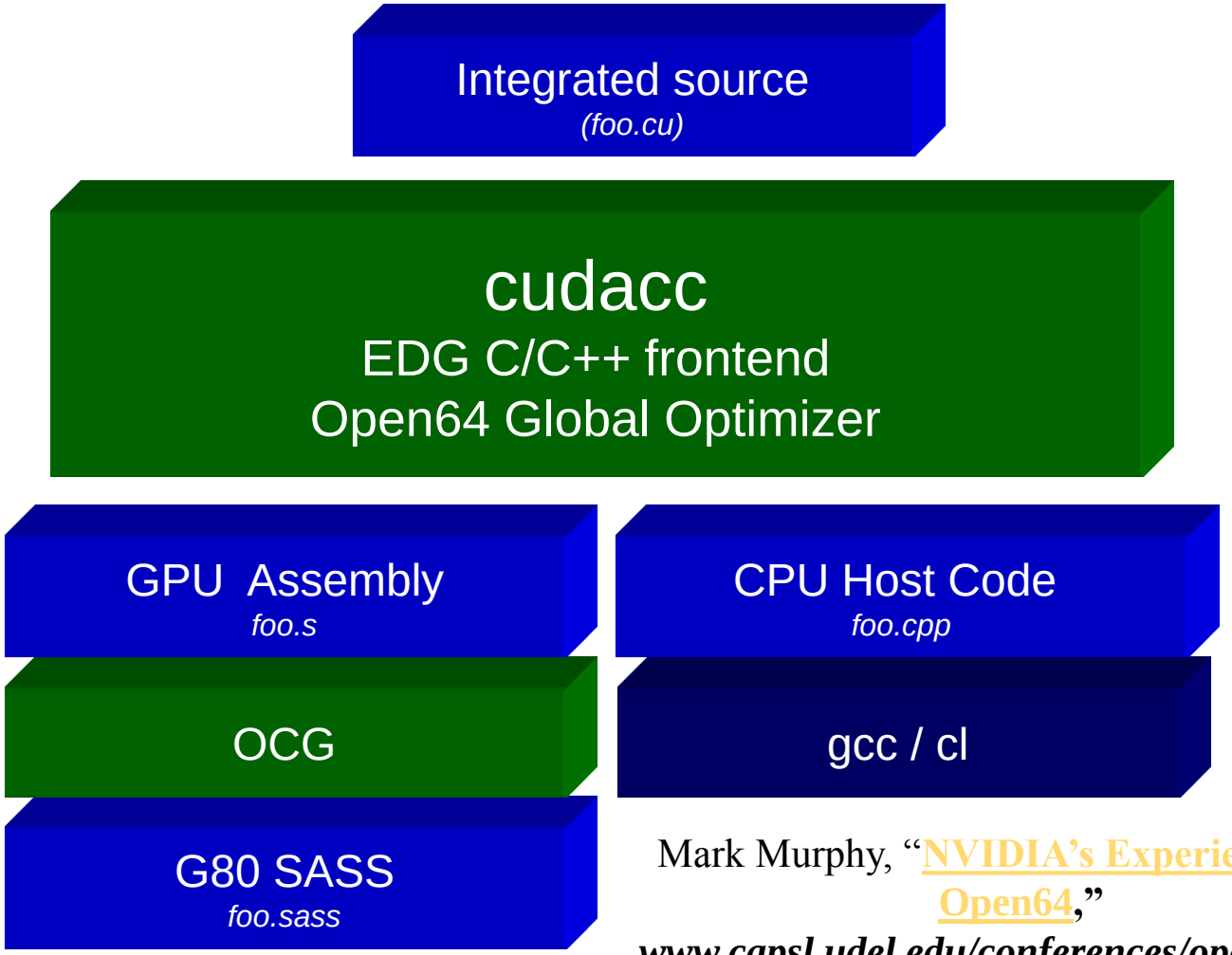
Runtime API

- **Memory, symbol, execution management**

Function launch

```
__device__ float filter[N];

__global__ void convolve (float *image)  {

  __shared__ float region[M];
  ...

  region[threadIdx] = image[i];

  __syncthreads()
  ...

  image[j] = result;
}

// Allocate GPU memory
void *myimage = cudaMalloc(bytes)

// 100 blocks, 10 threads per block
convolve<<<100, 10>>> (myimage);
```

Extended C



Mark Murphy, "NVIDIA's Experience with Open64,"
www.capsl.udel.edu/conferences/open64/2008/Papers/101.doc

Language Extensions: Built-in Variables

dim3 gridDim;

- dimensions of the grid in blocks (**gridDim.z** unused)

dim3 blockDim;

- dimensions of the block in threads

dim3 blockIdx;

- block index within the grid

dim3 threadIdx;

- thread index within the block

Common Runtime Component: Mathematical Functions

`pow, sqrt, cbrt, hypot`

`exp, exp2, expm1`

`log, log2, log10, log1p`

`sin, cos, tan, asin, acos, atan, atan2`

`sinh, cosh, tanh, asinh, acosh, atanh`

`ceil, floor, trunc, round`

etc.

- when executed on the host, a given function uses the C runtime implementation if available
- these functions are only supported for scalar types, not vector types

Device Runtime Component: Mathematical Functions

Some mathematical functions (e.g. `sin(x)`) have a less accurate, but faster device-only version (e.g. `__sin(x)`)

- `__pow`
- `__log`, `__log2`, `__log10`
- `__exp`
- `__sin`, `__cos`, `__tan`

Host Runtime Component

Provides functions to deal with:

- device management (including multi-device systems)
- memory management
- error handling

Initializes the first time a runtime function is called

A host thread can invoke device code on only one device

- multiple host threads required to run on multiple devices

Device Runtime Component: Synchronization Function

```
void __syncthreads();
```

Synchronizes all threads in a block

Once all threads have reached this point, execution resumes normally

Used to avoid RAW / WAR / WAW hazards when accessing shared or global memory

Allowed in conditional constructs only if the conditional is uniform across the entire thread block

Setup CUDA

Compute Unified Device Architecture

- Hardware compatibility: http://www.nvidia.com/object/cuda_gpus.html
- Driver, Toolkit (7.0) and SDK : https://developer.nvidia.com/cuda-toolkit
- Toolkit includes:
  - -- Compiler
  - -- Development tools
  - -- Libraries for scientific computation
    (CUBLAS, CUFFT, CUSPARSE, CURAND, etc.)
  - -- User guides and documents

Compilation and Linking

Any source file containing CUDA language extensions must be compiled with NVCC

NVCC is a compiler

- Compile device code
- Invoking the necessary compilers for host code like, g++, cl, ...

Any executable with CUDA code requires dynamic libraries:

- The CUDA runtime library (**`cudart`**) OR
- The CUDA core library (**`cuda`**)

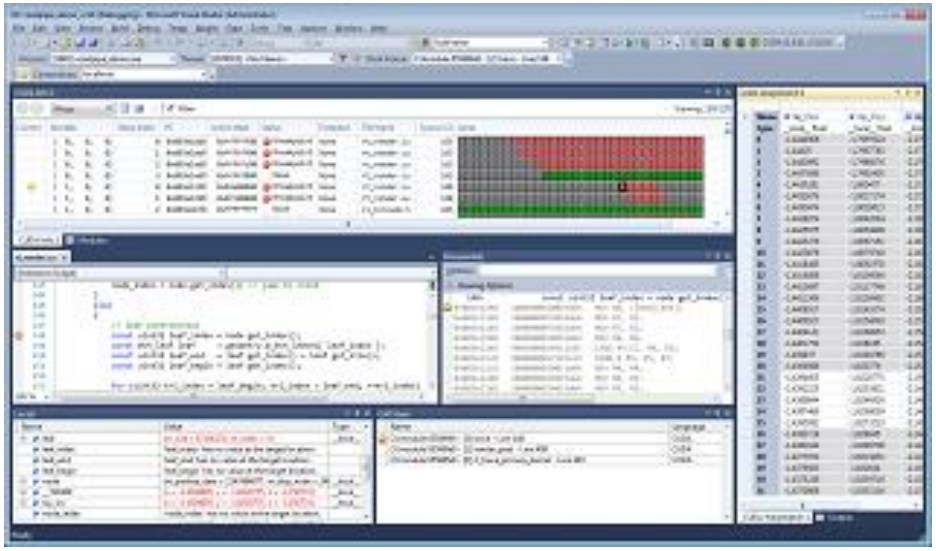
Development Tools

NVIDIA Nsight (Windows)

- Visual Studio Based GPU Development Environment
  https://developer.nvidia.com/nvidia-nsight-visual-studio-edition
- Debug CUDA C/C++ source code directly on the GPU
- Use the familiar Visual Studio Locals, Watches, Memory and Breakpoints windows
- Integrated analysis tool to isolate performance bottleneck
- support for Visual Studio, Eclipse

CUDA-GDB debugger

for Linux and MacOS



Visual Profiler

transpose - CUDA Visual Profiler - [Session2 - Device_0 - Context]

File Session View Options Window Help

Profiler Output | Summary Table | GPU Time Summary Plot | GPU Time Width Plot | GPU Time Height Plot

Session1
Device
Co
Session2
Device
Co

	Method	GPU Time	CPU Time	Occupancy	grid size X	grid size Y	block size X	block size Y	block size Z	static shared memory per block	registers per thread	mem transfer size (bytes)	ran	gld coalesced	gst uncoalesced	gst coalesced	branch	instructions
1	memcopy	1573.92	4390.85									4194304	0					
2	transpose_na...	3041.95	3062.27	1	256	16	16	16	16	32	6			8192	262144	0	2048	32591
3	transpose	341.92	364.64	1	256	16	16	16	16	1120	8			8192	0	32768	10240	42873
4	transpose_na...	2945.89	2959.24	1	256	16	16	16	16	32	6			8192	262144	0	2048	32479
5	transpose	343.808	356.759	1	256	16	16	16	16	1120	8			8192	0	32768	10240	43116
6	memcopy	4034.91	4880.18									4194304	1					

A graphical profiling tool to measure and benchmark performance

tracks events with hardware counters on signals in the chip

Fine Tuning Performance by watching the following metric

- Coalescing
- Occupancy
- Branch diversity
- Instruction throughput
- Computing / Data transfer ratio
- Share memory and register per thread