L2: Hardware Execution Model and Overview
January 11, 2012

Outline

• Execution Model
• Host Synchronization
• Single Instruction Multiple Data (SIMD)
• Multithreading
• Scheduling instructions for SIMD, multithreaded multiprocessor
• How it all comes together
• Reading:
  Ch 3 in Kirk and Hwu,
  http://courses.ece.illinois.edu/ece498/al/textbook/Chapter3-CudaThreadingModel.pdf
  Ch 4 in Nvidia CUDA Programming Guide

What is an Execution Model?

• Parallel programming model
  – Software technology for expressing parallel algorithms that target parallel hardware
  – Consists of programming languages, libraries, annotations, ...
  – Defines the semantics of software constructs running on parallel hardware
• Parallel execution model
  – Exposes an abstract view of hardware execution, generalized to a class of architectures
  – Answers the broad question of how to structure and name data and instructions and how to interrelate the two
  – Allows humans to reason about harnessing, distributing, and controlling concurrency
• Today’s lecture will help you reason about the target architecture while you are developing your code
  – How will code constructs be mapped to the hardware?

Administrative

• First assignment out, due next Friday at 5PM
  – Use handin on CADE machines to submit
    • "handin cs6235 lab1 <probfile>"
    • The file <probfile> should be a gzipped tar file of the CUDA program and output
  – Can implement on CADE machines, see provided makefile
• Grad lab is MEB 3161, must be sitting at machine
• Partners for people who have project ideas
• TA: Preethi Kotari, preethik@cs.utah.edu
• Mailing lists now visible:
  – cs6235s12@list.eng.utah.edu
    • Please use for all questions suitable for the whole class
    • Feel free to answer your classmates questions!
NVIDIA GPU Execution Model

I. SIMD Execution of warpsize-M threads (from single block)
   - Result is a set of instruction streams roughly equal to # blocks in thread divided by warpsize

II. Multithreaded Execution across different instruction streams within block
    - Also possibly across different blocks if there are more blocks than SMs

III. Each block mapped to single SM
    - No direct interaction across SMs

SIMT = Single-Instruction Multiple Threads

- Coined by Nvidia
- Combines SIMD execution within a Block (on an SM) with SPMD execution across Blocks (distributed across SMs)
- Terms to be defined...

CUDA Thread Block Overview

- All threads in a block execute the same kernel program (SPMD)
- Programmer declares block:
  - Block size 1 to 512 concurrent threads
  - Block shape 1D, 2D, or 3D
  - Block dimensions in threads
- Threads have thread id numbers within block
  - Thread program uses thread id to select work and address shared data
- Threads in the same block share data and synchronize while doing their share of the work
- Threads in different blocks cannot cooperate
  - Each block can execute in any order relative to other blocks

Calling a Kernel Function - Thread Creation in Detail

- A kernel function must be called with an execution configuration:
  
  ```
  __global__ void KernelFunc(...);
  dim3 DimGrid(100, 50); // 5000 thread blocks
  dim3 DimBlock(4, 8, 8); // 256 threads per block
  size_t SharedMemBytes = 64; // 64 bytes of shared memory
  KernelFunc<<<DimGrid, DimBlock, SharedMemBytes>>>(...);
  ```

- Any call to a kernel function is asynchronous from CUDA 1.0 on
- Explicit synchronization needed for blocking continued host execution (next slide)
Host Blocking: Common Examples

• How do you guarantee the GPU is done and results are ready?
• Timing example (excerpt from simpleStreams in CUDA SDK):
  
  ```
  cudaEvent_t start_event, stop_event;
  cudaEventCreate(&start_event);
  cudaEventCreate(&stop_event);
  cudaEventRecord(start_event, 0);
  int_array<<<blocks, threads>>>(d_a, d_c, niterations);
  cudaEventRecord(stop_event, 0);
  cudaEventSynchronize(stop_event);
  cudaEventElapsedTime(&elapsed_time, start_event, stop_event);
  ```

• A bunch of runs in a row example (excerpt from transpose in CUDA SDK)
  ```
  for (int i = 0; i < numIterations; ++i) {
    transpose<<<grid, threads>>>(d_odata, d_idata, size_x, size_y);
  }
  cudaThreadSynchronize();
  ```

Predominant Control Mechanisms: Some definitions

<table>
<thead>
<tr>
<th>Name</th>
<th>Meaning</th>
<th>Examples</th>
</tr>
</thead>
</table>
| Multiple Instruction, Multiple Data (MIMD) | Multiple threads of control, processors periodically synch              | OpenMP parallel loop: forall (i=0; i<n; i++) kernel func across blocks compute<<<gs, bs, msize>>>
| Single Program, Multiple Data (SPMD)     | Multiple threads of control, but each processor executes same code      | Processor-specific code: if ($threadId.x == 0) {                         |

Streaming Multiprocessor (SM)

• Streaming Multiprocessor (SM)
  - 8 Streaming Processors (SP)
  - 2 Super Function Units (SFU)
• Multi-threaded instruction dispatch
  - 1 to 512 threads active
  - Shared instruction fetch per 32 threads
  - Cover latency of texture/memory loads
• 20+ GFLOPS
• 16 KB shared memory
• DRAM texture and memory access

I. SIMD

• Motivation:
  - Data-parallel computations map well to architectures that apply the same computation repeatedly to different data
  - Conserve control units and simplify coordination
• Analogy to light switch
Example SIMD Execution

"Count 6" kernel function

```c
int val = d_in[SIZE/BLOCKSIZE * threadIdx.x];
d_out[threadIdx.x] += compare(val, 6);
```

Each "core" performs the same operations from its own registers.

Etc.

Example SIMD Execution

"Count 6" kernel function

```c
int val = d_in[SIZE/BLOCKSIZE * threadIdx.x];
d_out[threadIdx.x] += compare(val, 6);
```

LDC 0, &dout + threadIdx.x

Add R4, R1, R2

And R4, R1, RO
Overview of SIMD Programming

- Vector architectures
- Early examples of SIMD supercomputers
- TODAY Mostly
  - Multimedia extensions such as SSE-3
  - Graphics and games processors (example, IBM Cell)
  - Accelerators (e.g., ClearSpeed)
- Is there a dominant SIMD programming model?
  - Unfortunately, NO!!
- Why not?
  - Vector architectures were programmed by scientists
  - Multimedia extension architectures are programmed
    by systems programmers (almost assembly language)
    or code is automatically generated by a compiler
  - GPUs are programmed by games developers (domain-specific)
  - Accelerators typically use their own proprietary tools

Aside: Multimedia Extensions like SSE

- COMPLETELY DIFFERENT ARCHITECTURE!
- At the core of multimedia extensions
  - SIMD parallelism
  - Variable-sized data fields: Vector length = register width / type size

II. Multithreading: Motivation

- Each arithmetic instruction includes the following sequence

<table>
<thead>
<tr>
<th>Activity</th>
<th>Cost</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load operands</td>
<td>As much as O(100) cycles</td>
<td>Depends on location</td>
</tr>
<tr>
<td>Compute</td>
<td>O(1) cycles</td>
<td>Accesses registers</td>
</tr>
<tr>
<td>Store result</td>
<td>As much as O(100) cycles</td>
<td>Depends on location</td>
</tr>
</tbody>
</table>

- Memory latency, the time in cycles to access memory, limits utilization of compute engines
Thread-Level Parallelism

- **Motivation:**
  - A single thread leaves a processor under-utilized for most of the time
  - By doubling processor area, single thread performance barely improves
- **Strategies for thread-level parallelism:**
  - Multiple threads share the same large processor reduces under-utilization, efficient resource allocation
  - Multi-Threading
  - Each thread executes on its own mini processor: simple design, low interference between threads

What Resources are Shared?

- Multiple threads are simultaneously active (in other words, a new thread can start without a context switch)
- For correctness, each thread needs its own program counter (PC), and its own logical regs (on this hardware, each thread within block gets its own physical regs)
- Functional units, instruction unit, i-cache shared by all threads

Aside: Multithreading

- Historically, supercomputers targeting non-numeric computation
  - HEP, Tera MTA, Cray XMT
- Now common in commodity microprocessors
  - Simultaneous multithreading:
    - Multiple threads may come from different streams, can issue from multiple streams in single instruction issue
    - Alpha 21464 and Pentium 4 are examples
- CUDA somewhat simplified:
  - A full warp scheduled at a time

How is context switching so efficient?

- Large register file (16K registers/block)
  - Each thread assigned a "window" of physical registers
  - Works if entire thread block’s registers do not exceed capacity (otherwise, compiler fails)
  - May be able to schedule from multiple blocks simultaneously
- Similarly, shared memory requirements must not exceed capacity for all blocks simultaneously scheduled
Example: Thread Scheduling on G80

- Each Block is executed as 32-thread Warps
  - An implementation decision, not part of the CUDA programming model
  - Warps are scheduling units in SM
- If 3 blocks are assigned to an SM and each block has 256 threads, how many Warps are there in an SM?
  - Each Block is divided into 256/32 = 8 Warps
  - There are 8 * 3 = 24 Warps

SM Warp Scheduling

- SM hardware implements zero-overhead Warp scheduling
  - Warps whose next instruction has its operands ready for consumption are eligible for execution
  - Eligible Warps are selected for execution on a prioritized scheduling policy
  - All threads in a Warp execute the same instruction when selected
- 4 clock cycles needed to dispatch the same instruction for all threads in a Warp in G80
  - If one global memory access is needed for every 4 instructions
  - A minimum of 13 Warps are needed to fully tolerate 200-cycle memory latency

SM Instruction Buffer - Warp Scheduling

- Fetch one warp instruction/cycle
  - from instruction cache
  - into any instruction buffer slot
- Issue one "ready-to-go" warp instruction/cycle
  - from any warp - instruction buffer slot
  - operand scoreboard used to prevent hazards
- Issue selection based on round-robin/age of warp
- SM broadcasts the same instruction to 32 Threads of a Warp

Scoreboarding

- How to determine if a thread is ready to execute?
- A scoreboard is a table in hardware that tracks
  - instructions being fetched, issued, executed
  - resources (functional units and operands) they need
  - which instructions modify which registers
- Old concept from CDC 6600 (1960s) to separate memory and computation
Scoreboarding

- All register operands of all instructions in the Instruction Buffer are scoreboarded
  - Status becomes ready after the needed values are deposited
  - prevents hazards
  - cleared instructions are eligible for issue
- Decoupled Memory/Processor pipelines
  - any thread can continue to issue instructions until scoreboarding prevents issue
  - allows Memory/Processor ops to proceed in shadow of Memory/Processor ops

Scoreboarding from Example

- Consider three separate instruction streams: warp1, warp3, and warp8

<table>
<thead>
<tr>
<th>Warp</th>
<th>Current Instruction</th>
<th>Instruction State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warp 1</td>
<td>42</td>
<td>Ready to write result</td>
</tr>
<tr>
<td>Warp 3</td>
<td>95</td>
<td>Computing</td>
</tr>
<tr>
<td>Warp 8</td>
<td>11</td>
<td>Computing</td>
</tr>
</tbody>
</table>

III. How it Comes Together

G80 Example: Executing Thread Blocks

- Threads are assigned to Streaming Multiprocessors in block granularity
  - Up to 8 blocks to each SM as resource allows
  - SM in G80 can take up to 768 threads
  - Could be 256 (threads/block) * 3 blocks
  - Or 128 (threads/block) * 6 blocks, etc.

- Threads run concurrently
  - SM maintains thread/block id #s
  - SM manages/schedules thread execution
**Details of Mapping**

- If #blocks in a grid exceeds number of SMs,
  - multiple blocks mapped to an SM
  - treated independently
  - provides more warps to scheduler so good as long as resources not exceeded
  - Possibly context switching overhead when scheduling between blocks (registers and shared memory)

- Thread Synchronization (more next time)
  - Within a block, threads observe SIMD model, and synchronize using `__syncthreads()`
  - Across blocks, interaction through global memory

**Transparent Scalability**

- Hardware is free to assigns blocks to any processor at any time
  - A kernel scales across any number of parallel processors

  ![Diagram](image)

  Each block can execute in any order relative to other blocks.

**Summary of Lecture**

- SIMT = SIMD+SPMD
- SIMD execution model within a warp, and conceptually within a block
- MIMD execution model across blocks
- Multithreading of SMs used to hide memory latency
  - Motivation for lots of threads to be concurrently active
  - Scoreboarding used to track warps ready to execute

**What’s Coming**

- Next few lectures:
  - Correctness of parallelization
  - Managing the memory hierarchy
  - Next assignment