L15: Introduction to CUDA

October 19,2010

A Few Words About Final Project

- Purpose:
  - A chance to dig in deeper into a parallel programming model and explore concepts.
  - Present results to work on communication of technical ideas
- Write a non-trivial parallel program that combines two parallel programming languages/models. In some cases, just do two separate implementations.
  - OpenMP + SSE-3
  - OpenMP + CUDA (but need to do this in separate parts of the code)
  - TBB + SSE-3
  - MPI + OpenMP
  - MPI + SSE-3
  - MPI + CUDA
- Present results in a poster session on the last day of class

Example Projects

- Look in the textbook or on-line
  - Recall Red/Blue from Ch. 4
    - Implement in MPI (+ SSE-3)
    - Implement main computation in CUDA
  - Algorithms from Ch. 5
  - SOR from Ch. 7
    - CUDA implementation?
  - FFT from Ch. 10
  - Jacobi from Ch. 10
  - Graph algorithms
  - Image and signal processing algorithms
  - Other domains…

Next Homework, due Monday, October 25 at 11:59PM

- Goal is Midterm Review
- You'll answer some questions from last year's midterm
- Handin
  - handin cs4961 hw03 <pdf file>
  - Problems IIa and IIc

Review for Quiz

- L1: Overview
  - Technology drivers for multi-core paradigm shift
  - Concerns in efficient parallelization
- L2:
  - Fundamental theorem of dependence
  - Reductions
- L3 & L4:
  - SIMD/MIMD, shared memory, distributed memory
  - Candidate Type Architecture Model
  - Parallel architectures
- L5 & L6:
  - Data parallelism and OpenMP
  - Red/Blue algorithm

Review for Quiz

- L7 & L8:
  - SIMD execution
  - Challenges with SIMD multimedia extensions
- L9-L12:
  - Red/Blue
  - Locality optimizations
- L13:
  - Task parallelism
- L14-L15:
  - Reasoning about Performance

Outline

- Overview of the CUDA Programming Model for NVIDIA systems
  - Presentation of basic syntax
- Simple working examples
  - See http://www.cs.utah.edu/~mhall/cs6963s09
- Architecture
- Execution Model
- Heterogeneous Memory Hierarchy

This lecture includes slides provided by:
Wen-mei Hwu (UIUC) and David Kirk (NVIDIA)
see http://courses.ece.uiuc.edu/ece498/al1/

and Austin Robison (NVIDIA)

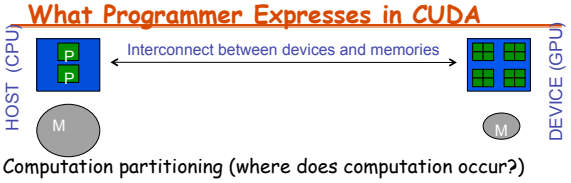
Reading

- David Kirk and Wen-mei Hwu manuscript (in progress)
  - http://www.toodoc.com/CUDA-textbook-by-David-Kirk-from-NVIDIA-and-Prof-Wen-mei-Hwu-pdf.html
- CUDA 2.x Manual, particularly Chapters 2 and 4 (download from nvidia.com/cudazone)
- Nice series from Dr. Dobbs Journal by Rob Farber
  - http://www.ddj.com/cpp/207200659

CUDA (Compute Unified Device Architecture)

- *Data-parallel* programming interface to GPU
  - Data to be operated on is discretized into independent partition of memory
  - Each thread performs roughly same computation to different partition of data
  - When appropriate, easy to express and very efficient parallelization
- Programmer expresses
  - Thread programs to be launched on GPU, and how to launch
  - Data organization and movement between host and GPU
  - Synchronization, memory management, testing, …
- CUDA is one of first to support *heterogeneous* architectures (more later in the semester)
- CUDA environment
  - Compiler, run-time utilities, libraries, emulation, performance

What Programmer Expresses in CUDA



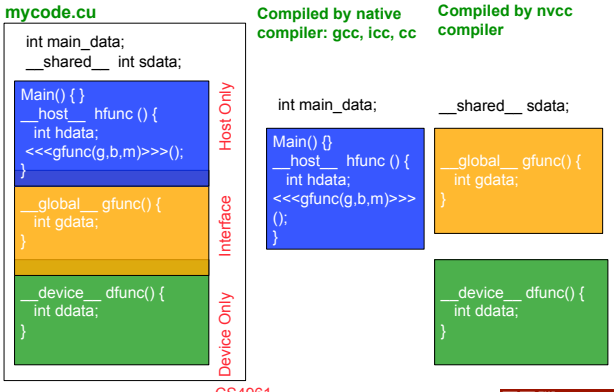
- Computation partitioning (where does computation occur?)
  - Declarations on functions __host__, __global__, __device__
  - Mapping of thread programs to device: compute <<<gs, bs>>>(<args>)
- Data partitioning (where does data reside, who may access it and how?)
  - Declarations on data __shared__, __device__, __constant__, …
- Data management and orchestration
  - Copying to/from host: *e.g.*, cudaMemcpy(h_obj,d_obj, cudaMemcpyDevicetoHost)
- Concurrency management
  - *E.g.* __synchthreads()

Minimal Extensions to C + API

- 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);
```


NVCC Compiler's Role: Partition Code and Compile for Device

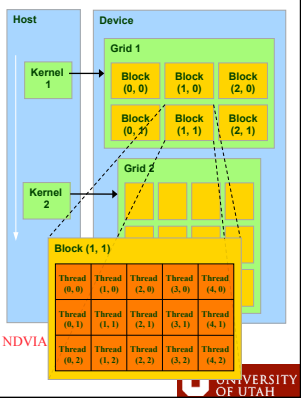


CUDA Programming Model: A Highly Multithreaded Coprocessor

- The GPU is viewed as a compute device that:
  - Is a coprocessor to the CPU or host
  - Has its own DRAM (device memory)
  - Runs many threads in parallel
- Data-parallel portions of an application are executed on the device as kernels which run in parallel on many threads
- Differences between GPU and CPU threads
  - GPU threads are extremely lightweight
    - Very little creation overhead
  - GPU needs 1000s of threads for full efficiency
    - Multi-core CPU needs only a few

Thread Batching: Grids and Blocks

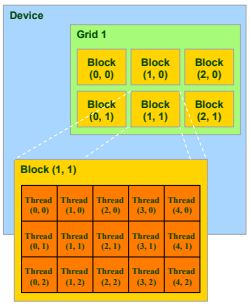
- A kernel is executed as a grid of thread blocks
  - All threads share data memory space
- A thread block is a batch of threads that can cooperate with each other by:
  - Synchronizing their execution
    - For hazard-free shared memory accesses
  - Efficiently sharing data through a low latency shared memory
- Two threads from two different blocks cannot cooperate



Courtesy: NDVIA

Block and Thread IDs

- Threads and blocks have IDs
  - So each thread can decide what data to work on
  - Block ID: 1D or 2D (blockIdx.x, blockIdx.y)
  - Thread ID: 1D, 2D, or 3D (threadIdx.{x,y,z})
- Simplifies memory addressing when processing multidimensional data
  - Image processing
  - Solving PDEs on volumes
  - …



Courtesy: NDVIA

Simple working code example: Count 3s

- Reminder
  - Scan elements of array of numbers (any of 0 to 9)
  - How many times does "3" appear?
  - Array of 16 elements, each thread examines 4 elements, 1 block in grid, 1 grid

threadIdx.x = 0 examines in_array elements 0, 4, 8, 12
threadIdx.x = 1 examines in_array elements 1, 5, 9, 13
threadIdx.x = 2 examines in_array elements 2, 6, 10, 14
threadIdx.x = 3 examines in_array elements 3, 7, 11, 15

Known as a cyclic data distribution

Key Concepts Compared to OpenMP

- Each thread executes on a separate "processor"
  - Conceptually, share a control unit
- Programmer expresses what happens at a thread
- Thread program has thread and block ID that is used to calculate work to perform.
- Synchronization:
  - Barrier between threads within a block
  - Atomic integer operations on global memory

Working through an example

- We'll write some message-passing pseudo code for Count3 (from Lecture 4)

```
1  int array[length];                          The data is global
2  int t;                                      Number of desired threads
3  int total;                                  Result of computation, grand total
4  forall(j in(0..t-1))
5  {
6    int size=mySize(array,0);                 Figure size of local part of global data
7    int myData[size]=localize(array[]);
                                               Associate my part of global data with
                                               local variable
8    int i, priv_count=0;                      Local accumulation
9    for(i=0; i<size; i++)
10   {
11     if(myData[i]==3)
12     {
13       priv_count++;
14     }
15   }
16   total =+/priv_count;                      ompute grand total
17 }
```


CUDA Pseudo-Code

MAIN PROGRAM:

Initialization
- Allocate memory on host for input and output
- Assign random numbers to input array

Call *host* function

Calculate final output from per-thread output

Print result

HOST FUNCTION:

Allocate memory on device for copy of *input* and *output*

Copy input to *device*

Set up grid/block

Call *global* function

Copy *device* output to host

GLOBAL FUNCTION:

Thread scans subset of array elements

Call *device* function to compare with "3"

Compute local result

DEVICE FUNCTION:

Compare current element and "3"

Return 1 if same, else 0

Main Program: Preliminaries

MAIN PROGRAM:

Initialization
- Allocate memory on host for input and output
- Assign random numbers to input array

Call *host* function

Calculate final output from per-thread output

Print result

```
#include <stdio.h>
#define SIZE 16
#define BLOCKSIZE 4

int main(int argc, char **argv)
{
  int *in_array, *out_array;
  …
}
```

Main Program: Invoke Global Function

MAIN PROGRAM:

Initialization (OMIT)

- Allocate memory on host for input and output
- Assign random numbers to input array

Call *host* function

Calculate final output from per-thread output

Print result

```
#include <stdio.h>
#define SIZE 16
#define BLOCKSIZE 4
__host__ void outer_compute
        (int *in_arr, int *out_arr);
int main(int argc, char **argv)
{
  int *in_array, *out_array;
  /* initialization */ …
  outer_compute(in_array, out_array);
  …
}
```


Main Program: Calculate Output & Print Result

MAIN PROGRAM:

Initialization (OMIT)

- Allocate memory on host for input and output
- Assign random numbers to input array

Call *host* function

Calculate final output from per-thread output

Print result

```
#include <stdio.h>
#define SIZE 16
#define BLOCKSIZE 4
__host__ void outer_compute
        (int *in_arr, int *out_arr);
int main(int argc, char **argv)
{
  int *in_array, *out_array;
  int sum = 0;
  /* initialization */ …
  outer_compute(in_array, out_array);
  for (int i=0; i<BLOCKSIZE; i++) {
    sum+=out_array[i];
  }
  printf ("Result = %d\n",sum);
}
```


Host Function: Preliminaries & Allocation

HOST FUNCTION:

Allocate memory on device for copy of ***input*** and ***output***

Copy input to ***device***

Set up grid/block

Call ***global*** function

Copy ***device*** output to host

```
__host__ void outer_compute (int
*h_in_array, int *h_out_array) {

  int *d_in_array, *d_out_array;

  cudaMalloc((void **) &d_in_array,
        SIZE*sizeof(int));
  cudaMalloc((void **) &d_out_array,
        BLOCKSIZE*sizeof(int));

  …
}
```


Host Function: Copy Data To/From Host

HOST FUNCTION:

Allocate memory on device for copy of ***input*** and ***output***

Copy input to ***device***

Set up grid/block

Call ***global*** function

Copy ***device*** output to host

```
__host__ void outer_compute (int
*h_in_array, int *h_out_array) {
  int *d_in_array, *d_out_array;

  cudaMalloc((void **) &d_in_array,
        SIZE*sizeof(int));
  cudaMalloc((void **) &d_out_array,
        BLOCKSIZE*sizeof(int));
  cudaMemcpy(d_in_array, h_in_array,
        SIZE*sizeof(int),
        cudaMemcpyHostToDevice);
  … do computation …
  cudaMemcpy(h_out_array,d_out_array,
        BLOCKSIZE*sizeof(int),
        cudaMemcpyDeviceToHost);
}
```


Host Function: Setup & Call Global Function

HOST FUNCTION:

Allocate memory on device for copy of ***input*** and ***output***

Copy input to ***device***

Set up grid/block

Call ***global*** function

Copy ***device*** output to host

```
__host__ void outer_compute (int
*h_in_array, int *h_out_array) {
int *d_in_array, *d_out_array;

 cudaMalloc((void **) &d_in_array,
        SIZE*sizeof(int));
cudaMalloc((void **) &d_out_array,
        BLOCKSIZE*sizeof(int));
cudaMemcpy(d_in_array, h_in_array,
        SIZE*sizeof(int),
        cudaMemcpyHostToDevice);

compute<<<(1,BLOCKSIZE,0)>>>
        (d_in_array, d_out_array);
cudaMemcpy(h_out_array, d_out_array,
        BLOCKSIZE*sizeof(int),
        cudaMemcpyDeviceToHost);
}
```


Global Function

GLOBAL FUNCTION:

Thread scans subset of array elements

Call ***device*** function to compare with "3"

Compute local result

```
__global__ void compute(int
*d_in,int *d_out) {
d_out[threadIdx.x] = 0;
for (int i=0; i<SIZE/BLOCKSIZE;
        i++)
 {
  int val = d_in[i*BLOCKSIZE +
threadIdx.x];
  d_out[threadIdx.x] +=
compare(val, 3);
 }
}
```


Device Function

DEVICE FUNCTION:

Compare current element and "3"

Return 1 if same, else 0

```
__device__ int
compare(int a, int b) {
 if (a == b) return 1;
 return 0;
}
```


Advanced Topics

- Programming model within blocks is SIMD
- Across blocks?
  - SPMD
  - Barrier does not work
  - State of global memory not guaranteed to be consistent
- Nvidia calls the combined programming model SIMT (single instruction multiple threads)
- Other options for implementing count3s

Another Example: Adding Two Matrices

CPU C program

```
void add_matrix_cpu(float *a, float *b,
   float *c, int N)
{
int i, j, index;
for (i=0;i<N;i++) {
    for (j=0;j<N;j++) {
        index =i+j*N;
        c[index]=a[index]+b[index];
     }
  }
}

void main() {
    .....
    add_matrix(a,b,c,N);
}
```

CUDA C program

```
__global__ void add_matrix_gpu(float *a,
float *b, float *c, int N)
{
    int i =blockIdx.x*blockDim.x+threadIdx.x;
    int j=blockIdx.y*blockDim.y+threadIdx.y;
    int index =i+j*N;
    if( i <N && j <N)
      c[index]=a[index]+b[index];
}

void main() {
    dim3 dimBlock(blocksize,blocksize);
    dim3 dimGrid(N/dimBlock.x,N/dimBlock.y);

add_matrix_gpu<<<dimGrid,dimBlock>>>(a,b,c
,N);
}
```


Example source: Austin Robison, NVIDIA

Closer Inspection of Computation and Data Partitioning

- Define 2-d set of blocks, and 2-d set of threads per block

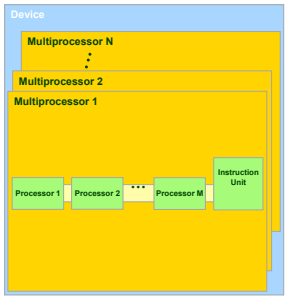
```
dim3 dimBlock(blocksize,blocksize);
dim3 dimGrid(N/dimBlock.x,N/dimBlock.y);
```

- Each thread identifies what element of the matrix it operates on

```
int i=blockIdx.x*blockDim.x+threadIdx.x;
int j=blockIdx.y*blockDim.y+threadIdx.y;
int index =i+j*N;
if( i <N && j <N)
  c[index]=a[index]+b[index];
```


Hardware Implementation: A Set of SIMD Multiprocessors

- A device has a set of multiprocessors
- Each multiprocessor is a set of 32-bit processors with a Single Instruction Multiple Data architecture
  - Shared instruction unit
- At each clock cycle, a multiprocessor executes the same instruction on a group of threads called a warp
- The number of threads in a warp is the warp size

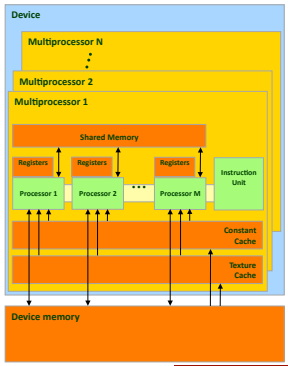


Hardware Execution Model

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

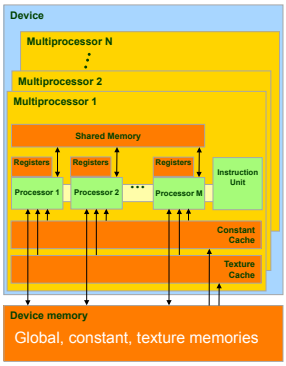
II. Multithreaded Execution across different instruction streams within block
  - Also possibly across different blocks if there are more blocks than SMs

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



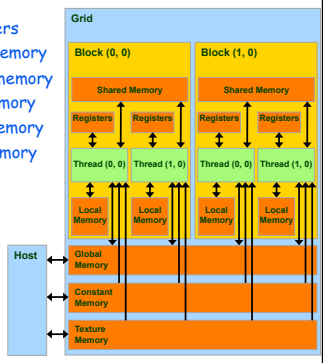
Hardware Implementation: Memory Architecture

- The local, global, constant, and texture spaces are regions of device memory
- Each multiprocessor has:
  - A set of 32-bit registers per processor
  - On-chip shared memory
    - Where the shared memory space resides
  - A read-only constant cache
    - To speed up access to the constant memory space
  - A read-only texture cache
    - To speed up access to the texture memory space



Programmer's View: Memory Spaces

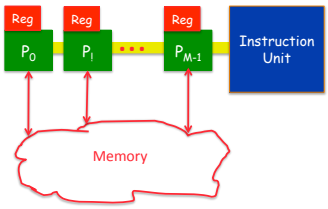
- Each thread can:
  - Read/write per-thread registers
  - Read/write per-thread local memory
  - Read/write per-block shared memory
  - Read/write per-grid global memory
  - Read only per-grid constant memory
  - Read only per-grid texture memory
- The host can read/write global, constant, and texture memory



Example SIMD Execution

"Count 3" kernel function

```
d_out[threadIdx.x] = 0;
for (int i=0; i<SIZE/BLOCKSIZE; i++) {
  int val = d_in[i*BLOCKSIZE + threadIdx.x];
  d_out[threadIdx.x] += compare(val, 3);
}
```



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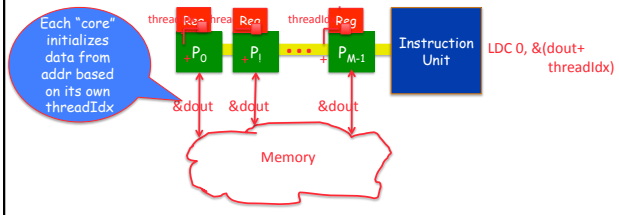

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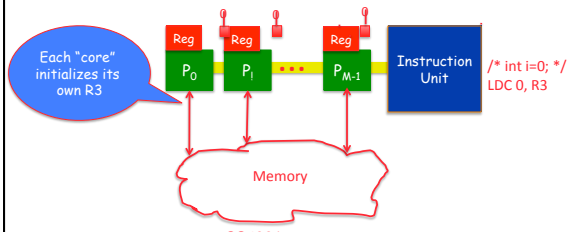

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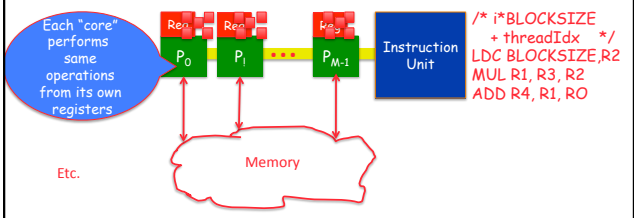
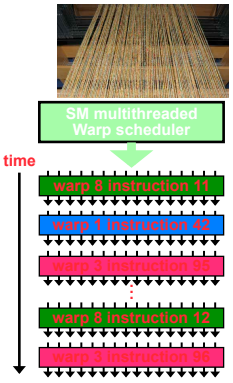


SM Warp Scheduling



- 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 minimal of 13 Warps are needed to fully tolerate 200-cycle memory latency

Summary of Lecture

- Introduction to CUDA
- Essentially, a few extensions to C + API supporting heterogeneous data-parallel CPU+GPU execution
  - Computation partitioning
  - Data partitioning (parts of this implied by decomposition into threads)
  - Data organization and management
  - Concurrency management
- Compiler nvcc takes as input a .cu program and produces
  - C Code for host processor (CPU), compiled by native C compiler
  - Code for device processor (GPU), compiled by nvcc compiler
- Two examples
  - Parallel reduction, count3s
  - Embarassingly/Pleasingly parallel computation