CS 677: Parallel Programming for Many-core Processors
Lecture 2

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Overview

• Simple encryption example
• Blocks, threads and warps
• CUDA memory types
• Matrix Multiplication using Shared Memory
• Thread Execution and Divergence
• Atomics
Encryption Example

```cpp
#include <iostream>
#include <cutil.h>

using namespace std;

__global__ void cuda_encrypt(char* m, int m_len, int shift)
{
    for (int i = 0; i < m_len; i++)
        m[i] = (((m[i] - 'a') + shift) % 26) + 'a';
}
```

Courtesy of Werner Backes
int main()
{
    char message[255];
    int message_len, shift;
    char* dev_message;

    cin >> message;
    cin >> shift;
    cout << "plaintext: " << message << endl;
    message_len = strlen(message);

    cudaMalloc(&dev_message, message_len+1);
    cudaMemcpy(dev_message, message, message_len+1, cudaMemcpyHostToDevice);
    cuda_encrypt<<<1,1>>>(dev_message, message_len, shift);
    cudaMemcpy(message, dev_message, message_len+1, cudaMemcpyDeviceToHost);

    cout << "ciphertext: " << message << endl;
    return 0;
}
Compilation and Execution

• Compile the example program hello world.cu using the CUDA compiler nvcc.
  – `nvcc -I. hello_world.cu -o hello_world`
  – The option `-I` is used to add an include path
  – `nvcc --help` outputs all available compiler options

• Output:
  – Execute `./hello_world`
    helloworld
    3
    plaintext: helloworld
ciphertext: khoorzruog
Parallel Encryption Example

```cpp
#include <iostream>
#include <cutil.h>

using namespace std;

__global__ void cuda_encrypt(char* m, int m_len, int shift)
{
    int tid = blockIdx.x * blockDim.x + threadIdx.x;
    if (tid < m_len)
        m[tid] = (((m[tid] - 'a') + shift) % 26) + 'a';
}
```
int main()
{
    char message[255];
    int message_len, shift;
    char* dev_message;

    cin >> message;
    cin >> shift;
    cout << "plaintext: " << message << endl;
    message_len = strlen(message);

    cudaMalloc(&dev_message, message_len+1);
    cudaMemcpy(dev_message, message, message_len+1, cudaMemcpyHostToDevice);
    cuda_encrypt<<<(message_len/32)+1,32>>>(dev_message, message_len, shift);
    cudaMemcpy(message, dev_message, message_len+1, cudaMemcpyDeviceToHost);

    cout << "ciphertext: " << message << endl;
    return 0;
}
Block IDs and Thread IDs

- Each thread uses IDs to decide what data to work on
  - Block ID: 1D, 2D or 3D
  - Thread ID: 1D, 2D, or 3D

- Simplifies memory addressing when processing multidimensional data
  - Image processing
  - Solving PDEs on volumes
  - ...

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Matrix Multiplication Using Multiple Blocks

- Break-up Pd into tiles
- Each block calculates one tile
  - Each thread calculates one element
  - Block size equal to tile size
A Small Example

TILE_WIDTH = 2

Block(0,0)          Block(1,0)

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P0,0</td>
<td>P1,0</td>
<td>P2,0</td>
<td>P3,0</td>
</tr>
<tr>
<td>P0,1</td>
<td>P1,1</td>
<td>P2,1</td>
<td>P3,1</td>
</tr>
<tr>
<td>P0,2</td>
<td>P1,2</td>
<td>P2,2</td>
<td>P3,2</td>
</tr>
<tr>
<td>P0,3</td>
<td>P1,3</td>
<td>P2,3</td>
<td>P3,3</td>
</tr>
</tbody>
</table>

Block(0,1)          Block(1,1)
A Small Example: Multiplication
Revised Matrix Multiplication Kernel using Multiple Blocks

```c
__global__ void MatrixMulKernel(float* Md, float* Nd, float* Pd, int Width)
{
    // Calculate the row index of the Pd element and M
    int Row = blockIdx.y*TILE_WIDTH + threadIdx.y;
    // Calculate the column idenx of Pd and N
    int Col = blockIdx.x*TILE_WIDTH + threadIdx.x;

    float Pvalue = 0;
    // each thread computes one element of the block sub-matrix
    for (int k = 0; k < Width; ++k)
        Pvalue += Md[Row*Width+k] * Nd[k*Width+Col];

    Pd[Row*Width+Col] = Pvalue;
}
```
Revised Step 5: Kernel Invocation (Host-side Code)

// Setup the execution configuration
dim3 dimGrid(Width/TILE_WIDTH, Width/TILE_WIDTH);
dim3 dimBlock(TILE_WIDTH, TILE_WIDTH);

// Launch the device computation threads
MatrixMulKernel<<<dimGrid, dimBlock>>>(Md, Nd, Pd, Width);
CUDA Thread Block

• 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!

Courtesy: John Nickolls, NVIDIA
Transparent Scalability

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

Each block can execute in any order relative to other blocks.
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
G80 Example: Thread Scheduling

- 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
G80 Example: Thread Scheduling (Cont.)

- SM 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
G80 Block Granularity Considerations

- For Matrix Multiplication using multiple blocks, should I use 8X8, 16X16 or 32X32 blocks?
  
  - For 8X8, we have 64 threads per Block. Since each SM can take up to 768 threads, there are 12 Blocks. However, each SM can only take up to 8 Blocks, only 512 threads will go into each SM!

  - For 16X16, we have 256 threads per Block. Since each SM can take up to 768 threads, it can take up to 3 Blocks and achieve full capacity unless other resource considerations overrule.

  - For 32X32, we have 1024 threads per Block. Not even one can fit into an SM!
## Technical Specifications per Compute Capability

<table>
<thead>
<tr>
<th>Technical specifications</th>
<th>Compute capability (version)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Maximum number of resident grids per device (concurrent kernel execution)</td>
<td>t.b.d.</td>
</tr>
<tr>
<td>Maximum dimensionality of grid of thread blocks</td>
<td>2</td>
</tr>
<tr>
<td>Maximum x-dimension of a grid of thread blocks</td>
<td>65535</td>
</tr>
<tr>
<td>Maximum y- or z-dimension of a grid of thread blocks</td>
<td>65535</td>
</tr>
<tr>
<td>Maximum dimensionality of thread block</td>
<td>3</td>
</tr>
<tr>
<td>Maximum x- or y-dimension of a block</td>
<td>512</td>
</tr>
<tr>
<td>Maximum z-dimension of a block</td>
<td>64</td>
</tr>
<tr>
<td>Maximum number of threads per block</td>
<td>512</td>
</tr>
<tr>
<td>Warp size</td>
<td>32</td>
</tr>
<tr>
<td>Maximum number of resident blocks per multiprocessor</td>
<td>8</td>
</tr>
<tr>
<td>Maximum number of resident warps per multiprocessor</td>
<td>24</td>
</tr>
<tr>
<td>Maximum number of resident threads per multiprocessor</td>
<td>768</td>
</tr>
<tr>
<td>Number of 32-bit registers per multiprocessor</td>
<td>8 K</td>
</tr>
<tr>
<td>Maximum number of 32-bit registers per thread block</td>
<td>N/A</td>
</tr>
<tr>
<td>Maximum number of 32-bit registers per thread</td>
<td>124</td>
</tr>
<tr>
<td>Maximum amount of shared memory per multiprocessor</td>
<td>16 KB</td>
</tr>
<tr>
<td>Maximum amount of shared memory per thread block</td>
<td>48 KB</td>
</tr>
<tr>
<td>Number of shared memory banks</td>
<td>16</td>
</tr>
<tr>
<td>Amount of local memory per thread</td>
<td>16 KB</td>
</tr>
<tr>
<td>Constant memory size</td>
<td></td>
</tr>
</tbody>
</table>

More Details of API Features
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 code
    - A host component to control and access one or more devices from the host
    - A device component providing device-specific functions
Language Extensions: Built-in Variables

• `dim3 gridSize;`
  – Dimensions of the grid in blocks
• `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. \( \_\_\sin(x) \))
  - \( \_\_\_\_\text{pow} \)
  - \( \_\_\_\_\text{log}, \_\_\_\text{log2}, \_\_\_\text{log10} \)
  - \( \_\_\_\_\text{exp} \)
  - \( \_\_\_\_\text{sin}, \_\_\_\text{cos}, \_\_\_\text{tan} \)
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
CUDA Memories
Hardware Implementation of CUDA Memories

• 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
CUDA Variable Type Qualifiers

<table>
<thead>
<tr>
<th>Variable declaration</th>
<th>Memory</th>
<th>Scope</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>int var;</td>
<td>register</td>
<td>thread</td>
<td>thread</td>
</tr>
<tr>
<td>int array_var[10];</td>
<td>local</td>
<td>thread</td>
<td>thread</td>
</tr>
<tr>
<td><strong>shared</strong> int shared_var;</td>
<td>shared</td>
<td>block</td>
<td>block</td>
</tr>
<tr>
<td><strong>device</strong> int global_var;</td>
<td>global</td>
<td>grid</td>
<td>application</td>
</tr>
<tr>
<td><strong>constant</strong> int constant_var;</td>
<td>constant</td>
<td>grid</td>
<td>application</td>
</tr>
</tbody>
</table>

- “automatic” scalar variables without qualifier reside in a register
  – compiler will spill to thread local memory
- “automatic” array variables without qualifier reside in thread local memory
CUDA Variable Type Performance

<table>
<thead>
<tr>
<th>Variable declaration</th>
<th>Memory</th>
<th>Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>int var;</code></td>
<td>register</td>
<td>1x</td>
</tr>
<tr>
<td><code>int array_var[10];</code></td>
<td>local</td>
<td>100x</td>
</tr>
<tr>
<td><code>__shared__ int shared_var;</code></td>
<td>shared</td>
<td>1x</td>
</tr>
<tr>
<td><code>__device__ int global_var;</code></td>
<td>global</td>
<td>100x</td>
</tr>
<tr>
<td><code>__constant__ int constant_var;</code></td>
<td>constant</td>
<td>1x</td>
</tr>
</tbody>
</table>

- scalar variables reside in fast, on-chip registers
- shared variables reside in fast, on-chip memories
- thread-local arrays & global variables reside in uncached off-chip memory
  - Cache is now available, but there is still a significant drop off in speed
- constant variables reside in cached off-chip memory
CUDA Variable Type Scale

<table>
<thead>
<tr>
<th>Variable declaration</th>
<th>Instances</th>
<th>Visibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>int var;</td>
<td>100,000s</td>
<td>1</td>
</tr>
<tr>
<td>int array_var[10];</td>
<td>100,000s</td>
<td>1</td>
</tr>
<tr>
<td><strong>shared</strong> int shared_var;</td>
<td>100s</td>
<td>100s</td>
</tr>
<tr>
<td><strong>device</strong> int global_var;</td>
<td>1</td>
<td>100,000s</td>
</tr>
<tr>
<td><strong>constant</strong> int constant_var;</td>
<td>1</td>
<td>100,000s</td>
</tr>
</tbody>
</table>

- 100Ks per-thread variables, R/W by 1 thread
- 100s shared variables, each R/W by 100s of threads
- 1 global variable is R/W by 100Ks threads
- 1 constant variable is readable by 100Ks threads
Where to declare variables?

Can host access it?

- Yes
  - Outside of any function
    - __constant__ int constant_var;
    - __device__ int global_var;
  - In the kernel
    - int var;
    - int array_var[10];
    - __shared__ int shared_var;

- No
Example - thread-local variables

// Ten Nearest Neighbors application
__global__ void ten_nn(float2 *result, float2 *ps, float2 *qs,
                        size_t num_qs)
{
    // p goes in a register
    float2 p = ps[threadIdx.x];

    // per-thread heap goes in off-chip memory
    float2 heap[10];

    // read through num_qs points, maintaining
    // the nearest 10 qs to p in the heap
    ...
    // write out the contents of heap to result
    ...
}
Example - shared variables

// motivate shared variables with
// Adjacent Difference application:
// compute result[i] = input[i] - input[i-1]
__global__ void adj_diff_naive(int *result, int *input)
{
    // compute this thread’s global index
    unsigned int i = blockDim.x * blockIdx.x + threadIdx.x;

    if(i > 0)
    {
        int x_i = input[i];
        int x_i_minus_one = input[i-1];

        result[i] = x_i - x_i_minus_one;
    }
}
Example - shared variables

// motivate shared variables with
// Adjacent Difference application:
// compute result[i] = input[i] - input[i-1]
__global__ void adj_diff_naive(int *result, int *input)
{
    // compute this thread’s global index
    unsigned int i = blockDim.x * blockIdx.x + threadIdx.x;

    if(i > 0)
    {
        // what are the bandwidth requirements of this kernel?
        int x_i = input[i];
        int x_i_minus_one = input[i-1];

        result[i] = x_i - x_i_minus_one;
    }
}
Example - shared variables

// motivate shared variables with
// Adjacent Difference application:
// compute result[i] = input[i] - input[i-1]
__global__ void adj_diff_naive(int *result, int *input)
{
    // compute this thread’s global index
    unsigned int i = blockDim.x * blockIdx.x + threadIdx.x;

    if(i > 0)
    {
        // How many times does this kernel load input[i]?
        int x_i = input[i]; // once by thread i
        int x_i_minus_one = input[i-1]; // again by thread i+1

        result[i] = x_i - x_i_minus_one;
    }
}
Example - shared variables

// optimized version of adjacent difference
__global__ void adj_diff(int *result, int *input)
{
    // shorthand for threadIdx.x
    int tx = threadIdx.x;
    // allocate a __shared__ array, one element per thread
    __shared__ int s_data[BLOCK_SIZE];
    // each thread reads one element to s_data
    unsigned int i = blockDim.x * blockIdx.x + tx;
    s_data[tx] = input[i];

    // avoid race condition: ensure all loads
    // complete before continuing
    __syncthreads();
    ...

Example - shared variables

```c
if(tx > 0)
    result[i] = s_data[tx] - s_data[tx-1];
else if(i > 0)
{
    // handle thread block boundary
    result[i] = s_data[tx] - input[i-1];
}
```
Example - shared variables

// when the size of the array isn’t known at compile time...
__global__ void adj_diff(int *result, int *input)
{
    // use extern to indicate a __shared__ array will be
    // allocated dynamically at kernel launch time
    extern __shared__ int s_data[];
    ...
}

// pass the size of the per-block array, in bytes, as the third
// argument to the triple chevrons
adj_diff<<<num_blocks, block_size, block_size * sizeof(int)>>>(r,i);

• Only one extern shared array can be declared
  • See CUDA programming guide for work-around
About Pointers - Outdated but Useful

• Yes, you can use them!
• You can point to any memory space:

```c
__device__ int my_global_variable;
__constant__ int my_constant_variable = 13;

__global__ void foo(void)
{
    __shared__ int my_shared_variable;

    int *ptr_to_global = &my_global_variable;
    const int *ptr_to_constant = &my_constant_variable;
    int *ptr_to_shared = &my_shared_variable;
    ...
    *ptr_to_global = *ptr_to_shared;
}
```
About Pointers - Outdated but Useful

- Pointers aren’t typed on memory space
  - `__shared__` int *ptr;
  - Where does `ptr` point?
  - `ptr` is a `__shared__` pointer variable, not a pointer to a `__shared__` variable!
Don’t confuse the compiler!

```c
__device__ int my_global_variable;
__global__ void foo(int *input)
{
    __shared__ int my_shared_variable;

    int *ptr = 0;
    if(input[threadIdx.x] % 2)
        ptr = &my_global_variable;
    else
        ptr = &my_shared_variable;
    // where does ptr point?
}
```
Advice

• Prefer dereferencing pointers in simple, regular access patterns
• Avoid propagating pointers
• Avoid pointers to pointers
  – The GPU would rather not pointer chase
  – Linked lists will not perform well
• Pay attention to compiler warning messages
  – Warning: Cannot tell what pointer points to, assuming global memory space
  – Crash waiting to happen
Unified Virtual Address Space

• The location of any memory on the host or on any of the devices which use the unified address space, can be determined from the value of the pointer using `cudaPointerGetAttributes()`

• When copying, the `cudaMemcpyKind` parameter of `cudaMemcpy*()` can be set to `cudaMemcpyDefault` to determine locations from the pointers. This also works for host pointers not allocated through CUDA, as long as the current device uses unified addressing.
Matrix Multiplication using Shared Memory
Review: Matrix Multiplication Kernel using Multiple Blocks

```c
__global__ void MatrixMulKernel(float* Md, float* Nd, float* Pd, int Width)
{
    // Calculate the row index of the Pd element and M
    int Row = blockIdx.y*TILE_WIDTH + threadIdx.y;
    // Calculate the column idenx of Pd and N
    int Col = blockIdx.x*TILE_WIDTH + threadIdx.x;

    float Pvalue = 0;
    // each thread computes one element of the block sub-matrix
    for (int k = 0; k < Width; ++k)
        Pvalue += Md[Row*Width+k] * Nd[k*Width+Col];

    Pd[Row*Width+Col] = Pvalue;
}
```
How about performance on GPU?

- All threads access global memory for their input matrix elements
  - Two memory accesses (8 bytes) per floating point multiply-add
  - 4B/s of memory bandwidth/FLOPS
  - $4 \times 346.5 = 1386$ GB/s required to achieve peak FLOP rating
  - 86.4 GB/s limits the code at 21.6 GFLOPS

- The actual code runs at about 15 GFLOPS

- Need to drastically cut down memory accesses to get closer to the peak 346.5 GFLOPS (on G80 - ignore specific numbers)
Idea: Use Shared Memory to reuse global memory data

- Each input element is read by Width threads
- Load each element into Shared Memory and have several threads use the local version to reduce the memory bandwidth
  - Tiled algorithms
Tiled Multiply

- Break up the execution of the kernel into phases so that the data accesses in each phase is focused on one subset (tile) of $M_d$ and $N_d$
A Small Example
Every Md and Nd Element is used exactly twice in generating a 2X2 tile of $P$

<table>
<thead>
<tr>
<th>$P_{0,0}$ thread$_{0,0}$</th>
<th>$P_{1,0}$ thread$_{1,0}$</th>
<th>$P_{0,1}$ thread$_{0,1}$</th>
<th>$P_{1,1}$ thread$_{1,1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{0,0} \times N_{0,0}$</td>
<td>$M_{0,0} \times N_{1,0}$</td>
<td>$M_{0,1} \times N_{0,0}$</td>
<td>$M_{0,1} \times N_{1,0}$</td>
</tr>
<tr>
<td>$M_{1,0} \times N_{0,1}$</td>
<td>$M_{1,0} \times N_{1,1}$</td>
<td>$M_{1,1} \times N_{0,1}$</td>
<td>$M_{1,1} \times N_{1,1}$</td>
</tr>
<tr>
<td>$M_{2,0} \times N_{0,2}$</td>
<td>$M_{2,0} \times N_{1,2}$</td>
<td>$M_{2,1} \times N_{0,2}$</td>
<td>$M_{2,1} \times N_{1,2}$</td>
</tr>
<tr>
<td>$M_{3,0} \times N_{0,3}$</td>
<td>$M_{3,0} \times N_{1,3}$</td>
<td>$M_{3,1} \times N_{0,3}$</td>
<td>$M_{3,1} \times N_{1,3}$</td>
</tr>
</tbody>
</table>
Breaking Md and Nd into Tiles

- Break up the inner product loop of each thread into phases
- At the beginning of each phase, load the Md and Nd elements that everyone needs during the phase into shared memory
- Everyone accesses the Md and Nd elements from shared memory during the phase
Work for Block (0,0)
Work for Block (0,0)

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N₀,₀</td>
<td>N₀,₁</td>
<td>N₀,₂</td>
<td>N₀,₃</td>
</tr>
<tr>
<td>N₁,₀</td>
<td>N₁,₁</td>
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Work for Block (0,0)

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Work for Block (0,0)
Work for Block (0,0)
Tiled Matrix Multiplication Kernel

```c
__global__ void MatrixMulKernel(float* Md, float* Nd, float* Pd, int Width)
{
  1. __shared__ float Mds[TILE_WIDTH][TILE_WIDTH];
  2. __shared__ float Nds[TILE_WIDTH][TILE_WIDTH];

  3. int bx = blockIdx.x;  int by = blockIdx.y;
  4. int tx = threadIdx.x;  int ty = threadIdx.y;

  // Identify the row and column of the Pd element to work on
  5. int Row = by * TILE_WIDTH + ty;
  6. int Col = bx * TILE_WIDTH + tx;

  7. float Pvalue = 0;
  // Loop over the Md and Nd tiles required to compute the Pd element
  8. for (int m = 0; m < Width/TILE_WIDTH; ++m) {

    // Collaborative loading of Md and Nd tiles into shared memory
    9.   Mds[ty][tx] = Md[Row*Width + (m*TILE_WIDTH + tx)];
    10.  Nds[ty][tx] = Nd[(m*TILE_WIDTH + ty)*Width + Col];
    11.  __syncthreads();

    12.  for (int k = 0; k < TILE_WIDTH; ++k)
    13.    Pvalue += Mds[ty][k] * Nds[k][tx];
    14.    __syncthreads();
  }
  15. Pd[Row*Width + Col] = Pvalue;
}
```

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// Setup the execution configuration

dim3 dimBlock(TILE_WIDTH, TILE_WIDTH);
dim3 dimGrid(Width / TILE_WIDTH,
          Width / TILE_WIDTH);
First-order Size Considerations

• Each **thread block** should have many threads
  – TILE_WIDTH of 16 gives 16*16 = 256 threads

• There should be many thread blocks
  – A 1024*1024 Pd gives 64*64 = 4096 Thread Blocks
  – TILE_WIDTH of 16 gives each SM 3 blocks, 768 threads (full capacity)

• Each thread block performs 2*256 = 512 float loads from global memory for 256 * (2*16) = 8,192 mul/add operations (lines 9-14)
  – Memory bandwidth no longer a limiting factor
Tiled Multiply

• Each block computes one square sub-matrix $P_{d_{sub}}$ of size $\text{TILE_WIDTH}$

• Each thread computes one element of $P_{d_{sub}}$
Shared Memory and Threading

• Each SM in G80 has 16KB shared memory
  – SM size is implementation-dependent!
  – For TILE_WIDTH = 16, each thread block uses 2*256*4B = 2KB of shared memory.
  – The SM can potentially have up to 8 Thread Blocks actively executing
    • This allows up to 8*512 = 4,096 pending loads. (2 per thread, 256 threads per block)
    • The threading model limits the number of thread blocks to 3 so shared memory is not the limiting factor here
  – The next TILE_WIDTH 32 would lead to 2*32*32*4B= 8KB shared memory usage per thread block, allowing only up to two thread blocks active at the same time

• Using 16x16 tiling, we reduce the accesses to the global memory by a factor of 16
  – The 86.4B/s bandwidth can now support (86.4/4)*16 = 347.6 GFLOPS

• Each SM in Fermi has 16KB or 48KB shared memory
  – Configurable vs L1 cache, total 64KB
Tiling Size Effects

![Tiling Size Effects Graph]

- **GFLOPS**
- **tiled only**
- **tiled & unrolled**

- **not tiled**
- **4x4 tiles**
- **8x8 tiles**
- **12x12 tiles**
- **16x16 tiles**

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Memory Resources as Limit to Parallelism

- Effective use of different memory resources reduces the number of accesses to global memory.
- These resources are finite!
- The more memory locations each thread requires → the fewer threads an SM can accommodate → what if each thread required 22 registers and each block had 256 threads?

<table>
<thead>
<tr>
<th>Resource</th>
<th>Per GT200 SM</th>
<th>Full Occupancy on GT200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Registers</td>
<td>16384</td>
<td>( \leq \frac{16384}{768} ) threads = 21 per thread</td>
</tr>
<tr>
<td><strong>shared</strong> Memory</td>
<td>16KB</td>
<td>( \leq \frac{16KB}{8} ) blocks = 2KB per block</td>
</tr>
</tbody>
</table>
Final Thoughts on Memory

• Effective use of CUDA memory hierarchy decreases bandwidth consumption to increase throughput
• Use \texttt{__shared__} memory to eliminate redundant loads from global memory
  – Use \texttt{__syncthreads} barriers to protect \texttt{__shared__} data
  – Use atomics if access patterns are sparse or unpredictable
• Optimization comes with a development cost
• Memory resources ultimately limit parallelism
Thread Execution and Divergence
Scheduling Blocks onto SMs

- HW Schedules thread blocks onto available SMs
  - No guarantee of ordering among thread blocks
  - HW will schedule thread blocks as soon as a previous thread block finishes
Mapping of Thread Blocks

- Each thread block is mapped to one or more warps
- The hardware schedules each warp independently

Thread Block N (128 threads) → TB N W1 → TB N W2 → TB N W3 → TB N W4
Thread Scheduling Example

- SM implements zero-overhead warp scheduling
  - At any time, only one of the warps is executed by SM
  - Warps whose next instruction has its inputs 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

![Diagram](image)

TB = Thread Block, W = Warp
Control Flow Divergence

• What happens if you have the following code?

```c
if (foo(threadIdx.x))
{
    do_A();
}
el
```
Control Flow Divergence

From Fung et al. MICRO ‘07
Control Flow Divergence

- Nested branches

```c
if (foo(threadIdx.x))
{
    if (bar(threadIdx.x))
        do_A();
    else
        do_B();
}
else
    do_C();
```
Control Flow Divergence
Control Flow Divergence

- You don’t have to worry about divergence for correctness (*)
- You might have to think about it for performance
  - Depends on your branch conditions

* Mostly true, except corner cases (for example intra-warp locks)
Control Flow Divergence

• Performance drops off with the degree of divergence

```c
switch(threadIdx.x % N) {
    case 0:
        ...
        ...
    case 1:
        ...
        ...
}
```
Atomics
The Problem

• How do you do global communication?
• Finish a grid and start a new one
Global Communication

• Finish a kernel and start a new one
• All writes from all threads complete before a kernel finishes

stepl<grid1,blk1>>>(...);
// The system ensures that all
// writes from step1 complete.
step2<grid2,blk2>>>(...);
Global Communication

• Would need to decompose kernels into before and after parts
Race Conditions

• Or, write to a predefined memory location
  – Race condition! Updates can be lost
Race Conditions

threadId: 0

// vector[0] was equal to 0
vector[0] += 5;
...
a = vector[0];

threadId: 1917

vector[0] += 1;
...
a = vector[0];

• What is the value of $a$ in thread 0?
• What is the value of $a$ in thread 1917?
Race Conditions

• Thread 0 could have finished execution before 1917 started
• Or the other way around
• Or both are executing at the same time

• Answer: not defined by the programming model, can be arbitrary
• CUDA provides atomic operations to deal with this problem
Atomics

• An atomic operation guarantees that only a single thread has access to a piece of memory while an operation completes
• The name atomic comes from the fact that it is uninterruptable
• No dropped data, but ordering is still arbitrary
• Different types of atomic instructions
  • atomic{Add, Sub, Exch, Min, Max, Inc, Dec, CAS, And, Or, Xor}
• More types in newer architectures
Compare and Swap

```c
int compare_and_swap(int* register,
    int oldval, int newval)
{
    int old_reg_val = *register;
    if(old_reg_val == oldval)
        *register = newval;

    return old_reg_val;
}
```

- Most general type of atomic
- Can emulate all others with CAS
Example: Histogram

// Determine frequency of colors in a picture
// colors have already been converted into ints
// Each thread looks at one pixel and increments
// a counter atomically
__global__ void histogram(int* color,
                          int* buckets)
{
    int i = threadIdx.x
             + blockDim.x * blockIdx.x;
    int c = colors[i];
    atomicAdd(&buckets[c], 1);
}
Example: Workqueue

// For algorithms where the amount of work per item
// is highly non-uniform, it often makes sense
// to continuously grab work from a queue

__global__
void workq(int* work_q, int* q_counter,
            int* output, int queue_max)
{
    int i = threadIdx.x + blockDim.x * blockIdx.x;
    int q_index = atomicInc(q_counter, queue_max);
    int result = do_work(work_q[q_index]);
    output[i] = result;
}
Atoms

- Atomics are slower than normal load/store
- You can have the whole machine queuing on a single location in memory
- Atomics unavailable on G80
Example: Global Min/Max (Naive)

// If you require the maximum across all threads
// in a grid, you could do it with a single global
// maximum value, but it will be VERY slow
__global__
void global_max(int* values, int* gl_max)
{
    int i = threadIdx.x
    + blockDim.x * blockIdx.x;
    int val = values[i];
    atomicMax(gl_max, val);
}
Example: Global Min/Max (Better)

// introduce intermediate maximum results, so that
// most threads do not try to update the global max
__global__
void global_max(int* values, int* max,
                int *regional_maxes,
                int num_regions)
{
    // i and val as before ...
    int region = i % num_regions;
    if(atomicMax(&reg_max[region],val) < val)
    {
        atomicMax(max,val);
    }
}
Global Min/Max

- Single value causes serial bottleneck
- Create hierarchy of values for more parallelism
- Performance will still be slow, so use judiciously
Atomics - Summary

• Can’t use normal load/store for inter-thread communication because of **race conditions**

• Use **atomic instructions** for sparse and/or unpredictable global communication

• **Decompose data** (very limited use of single global sum/max/min/etc.) for more parallelism