CS 677: Parallel Programming for Many-core Processors
Lecture 3

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Overview

• A Common Programming Strategy
• Threading Hardware
• Memory Hardware
• Control Flow
  – Simple Reduction
A Common Programming Strategy

• Global memory resides in device memory (DRAM)
  – Much slower access than shared memory

• Tile data to take advantage of fast shared memory:
  – Generalize from adjacent_difference example
    • Lecture 2, slides 35-40
  – Divide and conquer
A Common Programming Strategy

- Partition data into subsets that fit into shared memory
A Common Programming Strategy

- Handle each data subset with one thread block
Load the subset from global memory to shared memory, using multiple threads to exploit memory-level parallelism.
A Common Programming Strategy

• Perform the computation on the subset from shared memory
• Copy the result from *shared memory* back to global memory
A Common Programming Strategy

- Carefully partition data according to access patterns
- Read-only ➔ `__constant__` memory (fast)
- R/W & shared within block ➔ `__shared__` memory (fast)
- R/W within each thread ➔ registers (fast)
- Indexed R/W within each thread ➔ local memory (slow)
- R/W inputs/results ➔ `cudaMalloc`‘ed global memory (slow)
Communication Through Memory

• Question:

```c
__global__ void race(void) {
    __shared__ int my_shared_variable;
    my_shared_variable = threadIdx.x;

    // what is the value of
    // my_shared_variable?
}
```
This is a race condition
The result is undefined
The order in which threads access the variable is undefined without explicit coordination
Use barriers (e.g., `__syncthreads`) or atomic operations (e.g., `atomicAdd`) to enforce well-defined semantics
Threading Hardware
Single-Program Multiple-Data (SPMD)

- CUDA integrated CPU + GPU application C program
  - Serial C code executes on CPU
  - Parallel Kernel C code executes on GPU thread blocks

```
CPU Serial Code

GPU Parallel Kernel
KernelA<<< nBlk, nTid >>>(args);

CPU Serial Code

GPU Parallel Kernel
KernelB<<< nBlk, nTid >>>(args);
```
CUDA Thread Block: Review

• Programmer declares (Thread) Block:
  – Block size 1 to 512 concurrent threads
  – Block shape 1D, 2D, or 3D
  – Block dimensions in threads

• All threads in a Block execute the same thread program
• Threads share data and synchronize while doing their share of the work
• Threads have thread id numbers within Block
• Thread program uses thread id to select work and address shared data

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GeForce-8 Series HW Overview

Streaming Processor Array

Texture Processor Cluster

Streaming Multiprocessor

- Instruction L1
- Data L1
- Instruction Fetch/Dispatch
- Shared Memory
- SFU
- SP
- SFU
- SP
- SP
- SP
- SP
- SP
- SP
- SP
- SP

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CUDA Processor Terminology

- **SPA**
  - Streaming Processor Array

- **TPC**
  - Texture Processor Cluster (2 or more SM + TEX)

- **SM**
  - Streaming Multiprocessor (8 or more SP)
  - Multi-threaded processor core
  - Fundamental processing unit for CUDA thread block

- **SP**
  - Streaming Processor
  - Scalar ALU for a single CUDA thread
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
- texture and global memory access
Thread Lifecycle in HW

- Grid is launched on the SPA
- Thread Blocks are serially distributed to all the SM’s
  - Potentially >1 Thread Block per SM
- Each SM launches Warps of Threads
  - 2 levels of parallelism
- SM schedules and executes Warps that are ready to run
- As Warps and Thread Blocks complete, resources are freed
  - SPA can distribute more Thread Blocks
 Threads in Linear Order

<table>
<thead>
<tr>
<th>T(0,0)</th>
<th>T(1,0)</th>
<th>T(2,0)</th>
<th>T(3,0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T(0,1)</td>
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<td>T(3,2)</td>
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<td>T(1,3)</td>
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</table>

If the block was 3D, we would start with threads whose threadIdx.z=0, then threadIdx.z=1, etc.
SM Executes Blocks

- Threads are assigned to SMs 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 assigns/maintains thread id #s
  - SM manages/schedules thread execution
Thread Scheduling/Execution

- Each Thread Blocks is divided in 32-thread Warps
  - This is 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
  - At any point in time, only one of the 24 Warps will be selected for instruction fetch and execution.
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 L1 cache
  - into any instruction buffer slot
- Issue one “ready-to-go” warp instruction/cycle
  - from any warp - instruction buffer slot
  - operand **scoreboarding** 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 an instruction 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 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>Computing</td>
</tr>
<tr>
<td>Warp 3</td>
<td>95</td>
<td>Computing</td>
</tr>
<tr>
<td>Warp 8</td>
<td>11</td>
<td>Operands ready to go</td>
</tr>
</tbody>
</table>

- Schedule at time k

- Warp 8 instruction 11, t=k
- Warp 1 instruction 42, t=k+1
- Warp 3 instruction 95, t=k+2
- Warp 8 instruction 12, t=|k|
- Warp 3 instruction 96, t=|k+1|
Scoreboarding Example

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

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</tr>
<tr>
<td>Warp 8</td>
<td>11</td>
<td>Computing</td>
</tr>
</tbody>
</table>

Schedule at time k+1
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 other waiting Memory/Processor ops
Memory Hardware
CUDA Device Memory Space: Review

- Each thread can:
  - R/W per-thread registers
  - R/W per-thread local memory
  - R/W per-block shared memory
  - R/W per-grid global memory
  - Read only per-grid constant memory
  - Read only per-grid texture memory

- The host can R/W global, constant, and texture memories
Parallel Memory Sharing

- **Local Memory**: per-thread
  - Private per thread
  - Auto variables, register spill
- **Shared Memory**: per-Block
  - Shared by threads of the same block
  - Inter-thread communication
- **Global Memory**: per-application
  - Shared by all threads
  - Inter-Grid communication
SM Memory Architecture

- Threads in a block share data & results
  - In Memory and Shared Memory
  - Synchronize at barrier instruction

- Per-Block Shared Memory Allocation
  - Keeps data close to processor
  - Minimize trips to global Memory
  - Shared Memory is dynamically allocated to blocks, one of the limiting resources

Courtesy: John Nicols, NVIDIA
Texture Memory

- Read only
- More closely related to graphics pipeline
- Small, but can be faster than global memory due to cache
  - More relaxed coalescing requirements
  - Optimized for 2D spatial locality
  - Can pack 4 8-bit ints into 1 float
  - Converts data to [0.0 .. 1.0] or [-1.0 .. 1.0] range
  - Automatic boundary handling

⇒ out of scope for now

See http://cuda-programming.blogspot.com/2013/02/texture-memory-in-cuda-what-is-texture.html if interested
SM Register File

- Register File (RF)
  - 32 KB (8K entries) for each SM in G80
- TEX pipe can also read/write RF
  - 2 SMs share 1 TEX in G80, 3 SMs per TEX in GTX 200
  - Related to graphics mode (out of scope)
- Load/Store pipe can also read/write RF

MAD: Multiply and Add unit
SFU: Super Function Unit - where more complex instructions are executed
Programmer View of Register File

- There are 8192 registers in each SM in G80
  - This is an implementation decision, not part of CUDA
  - Registers are dynamically partitioned across all blocks assigned to the SM
  - Once assigned to a block, the register is NOT accessible by threads in other blocks
  - Each thread in the same block only access registers assigned to itself

(This has changed but the example is still useful)
Matrix Multiplication Example

• If each Block has 16X16 threads and each thread uses 10 registers, how many threads can run on each SM?
  – Each block requires $10 \times 256 = 2560$ registers
  – $8192 = 3 \times 2560 + \text{change}
  – So, three blocks can run on an SM as far as registers are concerned

• How about if each thread increases the use of registers by 1?
  – Each Block now requires $11 \times 256 = 2816$ registers
  – $8192 < 2816 \times 3$
  – Only two Blocks can run on an SM, $\frac{1}{3}$ reduction of parallelism!!!
More on Dynamic Partitioning

• Dynamic partitioning gives more flexibility to compilers/programmers
  – One can run a smaller number of threads that require many registers each or a large number of threads that require few registers each
  • This allows for finer grain threading than traditional CPU threading models
  – The compiler can tradeoff between instruction-level parallelism and thread level parallelism
ILP vs. TLP Example

• Assume that a kernel has 256-thread Blocks, 4 independent instructions for each global memory load in the thread program, and each thread uses 10 registers, global loads take 200 cycles
  – 3 Blocks can run on each SM

• If a compiler can use one more register to change the dependence pattern so that 8 independent instructions exist for each global memory load
  – Only two can run on each SM
  – However, one only needs $200/(8*4) = 7$ Warps to tolerate the memory latency
  – Two blocks have 16 Warps. The performance can be actually higher!
Resource Allocation Example

(a) Pre-“optimization”
(b) Post-“optimization”

Increase in per-thread performance, but fewer threads:
Lower overall performance in this case
CUDA Occupancy Calculator

Memory Layout of a Matrix in C

M

\[
\begin{array}{cccc}
M_{0,0} & M_{1,0} & M_{2,0} & M_{3,0} \\
M_{0,1} & M_{1,1} & M_{2,1} & M_{3,1} \\
M_{0,2} & M_{1,2} & M_{2,2} & M_{3,2} \\
M_{0,3} & M_{1,3} & M_{2,3} & M_{3,3}
\end{array}
\]
Memory Coalescing*

- When accessing global memory, peak performance utilization occurs when all threads in a half warp access continuous memory locations.
Memory Layout of a Matrix in C

Access direction in Kernel code

Time Period 1
\[ T_1 \quad T_2 \quad T_3 \quad T_4 \]

Time Period 2
\[ T_1 \quad T_2 \quad T_3 \quad T_4 \]

\[ M \]

\[ M_{0,0} \quad M_{1,0} \quad M_{2,0} \quad M_{3,0} \]
\[ M_{0,1} \quad M_{1,1} \quad M_{2,1} \quad M_{3,1} \]
\[ M_{0,2} \quad M_{1,2} \quad M_{2,2} \quad M_{3,2} \]
\[ M_{0,3} \quad M_{1,3} \quad M_{2,3} \quad M_{3,3} \]
Memory Layout of a Matrix in C

Access direction in Kernel code

Time Period 2

Time Period 1

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Matrix Multiplication

__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;
}

Why this works:
• threads in warp have same ty
• adjacent threads read adjacent elements from memory

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Coalescing since 2013

- GPUs now have cache
  => Coalescing is less important as it is done by the hardware
- Make sure you have enough cache available for each warp
- There may still be some loss of performance (20-50%) due to uncoalesced access
Cache (Compute Capability 3.x)

- L1 cache for each multiprocessor
- L2 cache shared by all multiprocessors
- Both are used to cache accesses to local or global memory, including temporary register spills
- Cache behavior (e.g., whether reads are cached in both L1 and L2 or in L2 only) can be partially configured
Configuring the Cache

• The same on-chip memory is used for both L1 and shared memory. It can be configured as:
  – 48 KB of shared memory and 16 KB of L1 cache
  – 16 KB of shared memory and 48 KB of L1 cache
  – 32 KB of shared memory and 32 KB of L1 cache

• using `cudaFuncSetCacheConfig()`
Cache Preferences

// Host code

// cudaFuncCachePreferShared: shared memory is 48 KB
// cudaFuncCachePreferEqual: shared memory is 32 KB
// cudaFuncCachePreferL1: shared memory is 16 KB
// cudaFuncCachePreferNone: no preference
cudaFuncSetCacheConfig(MyKernel, cudaFuncCachePreferShared);
Cache Preferences

• The default cache configuration is "prefer none"
• If a kernel has no preference, then it will default to the preference of the current CPU thread/context
• If the current thread/context also has no preference, then most recent cache configuration will be used
  – unless a different cache configuration is required to launch the kernel (e.g., due to shared memory requirements)
• The initial configuration is 48 KB of shared memory and 16 KB of L1 cache
Constants

• Immediate address constants (#define)
• Indexed address constants
• Constants stored in DRAM, and cached on chip
  – L1 per SM
• A constant value can be broadcast to all threads in a warp
  – Extremely efficient way of accessing a value that is common for all threads in a block!

// specify as global variable
__device__ __constant__ float gpuGamma[2];
// copy gamma value to constant device memory
cudamemcpyToSymbol(gpuGamma, &gamma, sizeof(float));
...
// access as global variable in kernel
res = gpuGamma[0] * threadIdx.x;
Shared Memory

• Each SM has 16 or more KB of Shared Memory
  – 16 banks of 32-bit words
  – 64-bit access is also supported now

• CUDA uses Shared Memory as shared storage visible to all threads in a thread block
  – read and write access
Parallel Memory Architecture

• In a parallel machine, many threads access memory
  – Therefore, memory is divided into banks
  – Essential to achieve high bandwidth

• Each bank can service one address per cycle
  – A memory can service as many simultaneous accesses as it has banks

• Multiple simultaneous accesses to a bank result in a bank conflict
  – Conflicting accesses are serialized
Bank Addressing Examples

- **No Bank Conflicts**
  - Linear addressing
    - stride == 1

- **No Bank Conflicts**
  - Random 1:1 Permutation
Bank Addressing Examples

- 2-way Bank Conflicts
- 8-way Bank Conflicts

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How Addresses Map to Banks on G80

• Each bank has a bandwidth of 32 bits per clock cycle
• Successive 32-bit words are assigned to successive banks
• G80 has 16 banks
  – So bank = address % 16
  – Same as the size of a half-warp
    • No bank conflicts between different half-warps, only within a single half-warp
Shared Memory Bank Conflicts

- Shared memory is as fast as registers if there are no bank conflicts

- The fast case:
  - If all threads of a half-warp access different banks, there is no bank conflict
  - If all threads of a half-warp access an identical address, there is no bank conflict (broadcast)

- The slow case:
  - Bank Conflict: multiple threads in the same half-warp access the same bank
  - Must serialize the accesses
  - Cost = max # of simultaneous accesses to a single bank
Linear Addressing

• Given:

```c
__shared__ float shared[256];
float foo =
    shared[baseIndex + s * threadIdx.x];
```

• This is only bank-conflict-free if `s` shares no common factors with the number of banks
  – 16 on G80, so `s` must be odd
Compute Capability 3.x

- Left: Linear addressing with a stride of one 32-bit word (no bank conflict)
- Middle: Linear addressing with a stride of two 32-bit words (no bank conflict)
- Right: Linear addressing with a stride of three 32-bit words (no bank conflict)

- More flexible definition of alignment within banks enables last two examples
Compute Capability 3.x

- Left: Conflict-free access via random permutation
- Middle: Conflict-free access since threads 3, 4, 6, 7, and 9 access the same word within bank 5
- Right: Conflict-free broadcast access (threads access the same word within a bank)
Control Flow
Control Flow Instructions

• Main performance concern with branching is divergence
  – Threads within a single warp take different paths
  – Different execution paths are serialized on GPU
    • The control paths taken by the threads in a warp are traversed one at a time until there is no more.

• A common case: avoid divergence when branch condition is a function of thread ID
  – Example with divergence:
    • If (threadIdx.x > 2) { }
    • This creates two different control paths for threads in a block
    • Branch granularity < warp size; threads 0, 1 and 2 follow different path than the rest of the threads in the first warp
  – Example without divergence:
    • If (threadIdx.x / WARP_SIZE > 2) { }
    • Also creates two different control paths for threads in a block
    • Branch granularity is a whole multiple of warp size; all threads in any given warp follow the same path
Parallel Reduction

• Given an array of values, “reduce” them to a single value in parallel

• Examples
  – Sum reduction: sum of all values in the array
  – Max reduction: maximum of all values in the array

• Typically parallel implementation:
  – Recursively halve # threads, add two values per thread
  – Takes log(n) steps for n elements, requires n/2 threads
A Vector Reduction Example

• Assume an in-place reduction using shared memory
  – The original vector is in device global memory
  – The shared memory is used to hold a partial sum vector
  – Each iteration brings the partial sum vector closer to the final sum
  – The final solution will be in element 0
A simple implementation

• Assume we have already loaded array into

```
__shared__ float partialSum[]
```

```c
unsigned int t = threadIdx.x;
for (unsigned int stride = 1;
    stride < blockDim.x; stride *= 2)
{
    __syncthreads();
    if (t % (2*stride) == 0)
        partialSum[t] += partialSum[t+stride];
}
```
Vector Reduction with Branch Divergence

Thread 0

Thread 2

Thread 4

Thread 6

Thread 8

Thread 10

0

1

2

3

4

5

6

7

8

9

10

11

0+1

2+3

4+5

6+7

8+9

10+11

0...3

4..7

8..11

8..15

iterations

Array elements

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Some Observations

• In each iteration, two control flow paths will be sequentially traversed for each warp
  – Threads that perform addition and threads that do not
  – Threads that do not perform addition may cost extra cycles depending on the implementation of divergence

• No more than half of threads will be executing at any time
  – All odd index threads are disabled right from the beginning!
  – On average, less than ¼ of the threads will be activated for all warps over time.
  – After the 5th iteration, entire warps in each block will be disabled, poor resource utilization but no divergence
    • This can go on for a while, up to 4 more iterations (512/32=16= 2^4), where each iteration only has one thread activated until all warps retire
Shortcomings of the implementation

• Assume we have already loaded array into

```c
__shared__ float partialSum[]

unsigned int t = threadIdx.x;
for (unsigned int stride = 1;
    stride < blockDim.x; stride *= 2)
{
    __syncthreads();
    if (t % (2*stride) == 0)
        partialSum[t] += partialSum[t+stride];
} 
```

BAD: Divergence due to interleaved branch decisions
A better implementation

- Assume we have already loaded array into
  
  ```
  __shared__ float partialSum[]
  
  unsigned int t = threadIdx.x;
  for (unsigned int stride = blockDim.x/2;
       stride > 0; stride >>= 1)
  {
    __syncthreads();
    if (t < stride)
      partialSum[t] += partialSum[t+stride];
  }
  ```
No Divergence until $\leq 16$ sub-sums

<table>
<thead>
<tr>
<th>Thread 0</th>
<th>Thread 1</th>
<th>Thread 2</th>
<th>Thread 14</th>
<th>Thread 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>...</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>15+16</td>
<td>14</td>
<td>15</td>
<td>15+31</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>15+31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0+16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
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Prefetching and Instruction Mix
Prefetching

• One could double buffer the computation, getting better instruction mix within each thread
  – This is classic software pipelining in ILP compilers

```
Loop {
  Load current tile to shared memory
  syncthreads()
  Compute current tile
  syncthreads()
}
```

```
Load next tile from global memory

Loop {
  Deposit current tile to shared memory
  syncthreads()
  Load next tile from global memory
  Compute current tile
  syncthreads()
}
```
Prefetch

- Deposit blue tile from register into shared memory
- Syncthreads
- Load orange tile into register
- Compute Blue tile
- Deposit orange tile into shared memory
- ....
Instruction Mix Considerations

```c
for (int k = 0; k < BLOCK_SIZE; ++k)
    Pvalue += Ms[ty][k] * Ns[k][tx];
```

There are very few mul/add between branches and address calculation

Loop unrolling can help. (Be aware that any local arrays used after unrolling will be dumped into Local Memory)

```c
Pvalue += Ms[ty][k] * Ns[k][tx] + ... 
    Ms[ty][k+15] * Ns[k+15][tx];
```
Unrolling

(b) Tiled Version

Ctemp = 0;
for (...) {
  __shared__ float As[16][16];
  __shared__ float Bs[16][16];

  // load input tile elements
  As[ty][tx] = A[indexA];
  Bs[ty][tx] = B[indexB];
  indexA += 16;
  indexB += 16 * widthB;
  __syncthreads();

  // compute results for tile
  for (i = 0; i < 16; i++)
  {
    Ctemp += As[ty][i] * Bs[i][tx];
  }
  __syncthreads();
}
C[indexC] = Ctemp;

(c) Unrolled Version

Ctemp = 0;
for (...) {
  __shared__ float As[16][16];
  __shared__ float Bs[16][16];

  // load input tile elements
  As[ty][tx] = A[indexA];
  Bs[ty][tx] = B[indexB];
  indexA += 16;
  indexB += 16 * widthB;
  __syncthreads();

  // compute results for tile
  Ctemp +=
    As[ty][0] * Bs[0][tx];
  ...
  Ctemp +=
    As[ty][15] * Bs[15][tx];
  __syncthreads();
}
C[indexC] = Ctemp;

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