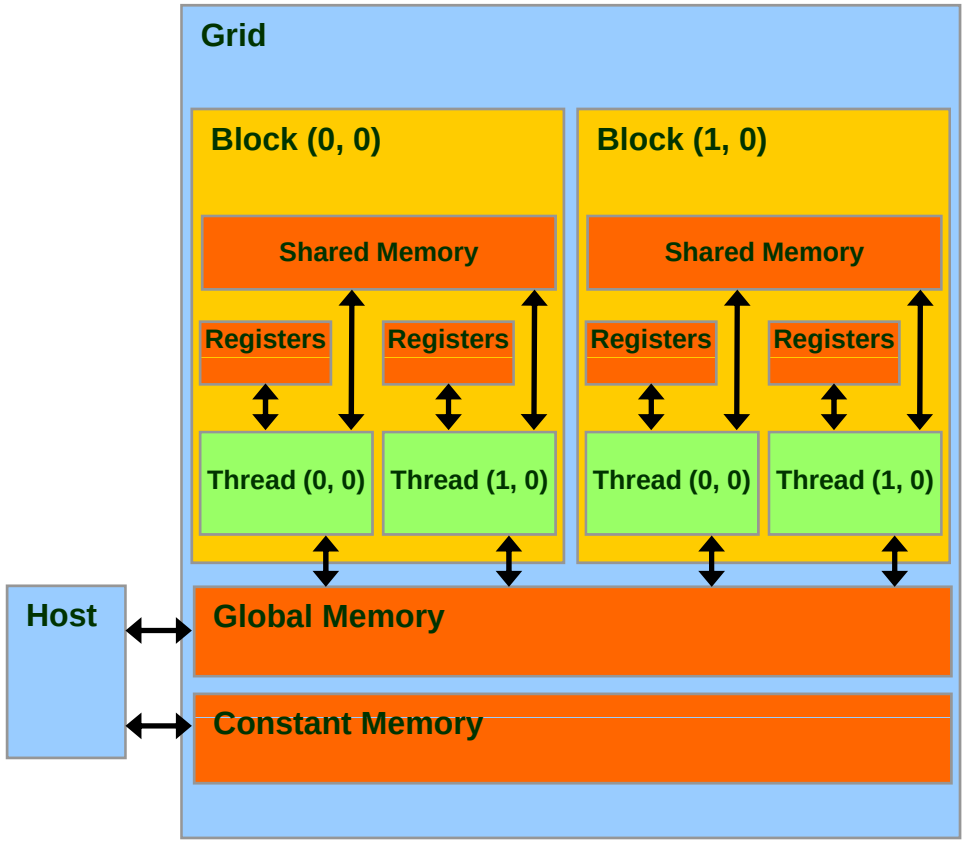
ECE 498AL

Programming Massively Parallel Processors

Lecture 5: CUDA Memories

G80 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**

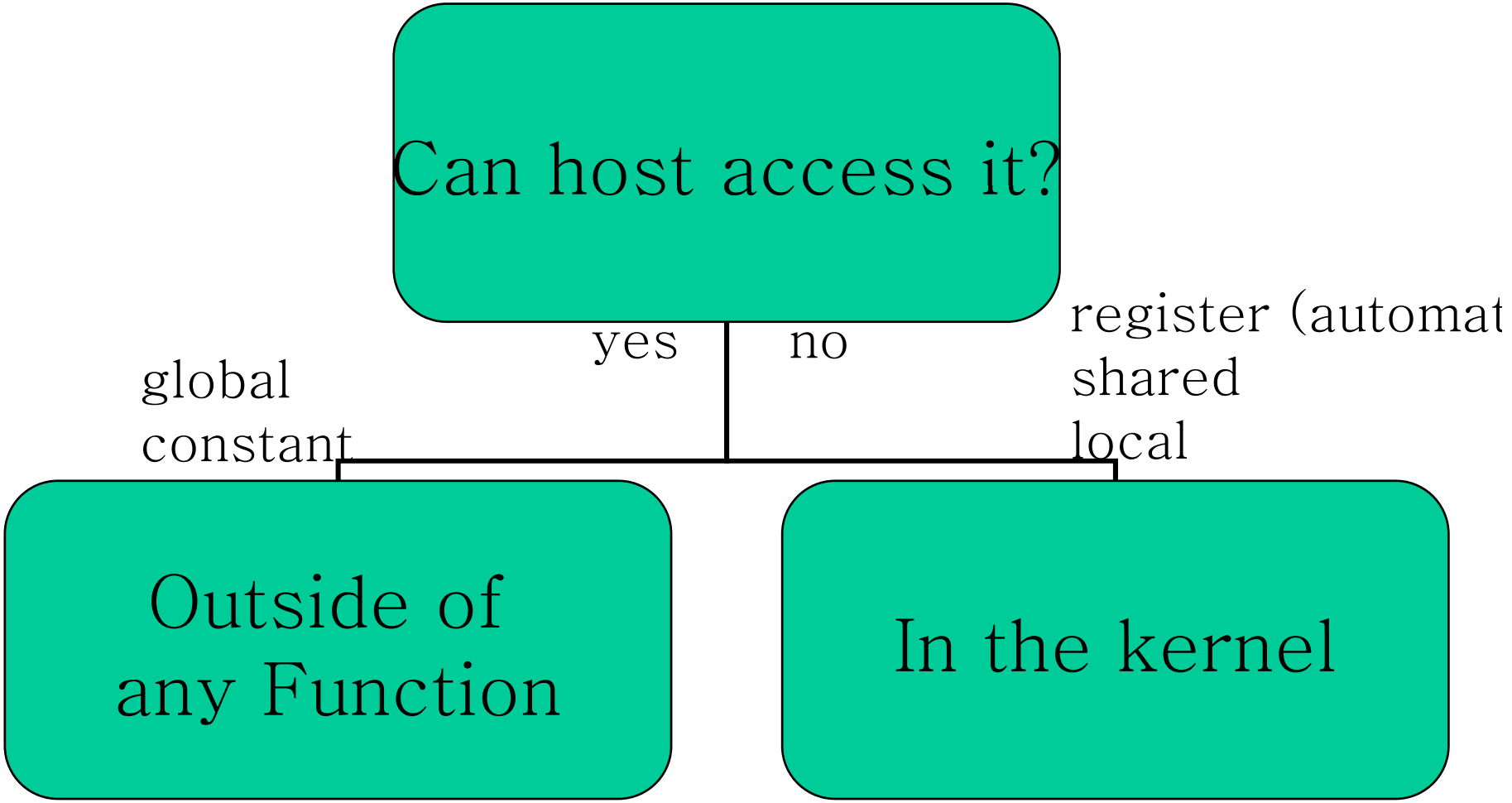


CUDA Variable Type Qualifiers

Variable declaration	Memory	Scope	Lifetime
`__device__ __local__ int LocalVar;`	local	thread	thread
`__device__ __shared__ int SharedVar;`	shared	block	block
`__device__ int GlobalVar;`	global	grid	application
`__device__ __constant__ int ConstantVar;`	constant	grid	application

- **`__device__`** is optional when used with **`__local__`**, **`__shared__`**, or **`__constant__`**
- Automatic variables without any qualifier reside in a register
  - Except arrays that reside in local memory

Where to Declare Variables?



Variable Type Restrictions

- Pointers can only point to memory allocated or declared in global memory:
  - Allocated in the host and passed to the kernel:

```
__global__ void KernelFunc(float* ptr)
```

  - Obtained as the address of a global variable:

```
float* ptr = &GlobalVar;
```

A Common Programming Strategy

- Global memory resides in device memory (DRAM) - much slower access than shared memory
- So, a profitable way of performing computation on the device is to tile data to take advantage of fast shared memory:
  - Partition data into subsets that fit into shared memory
  - Handle each data subset with one thread block by:
    - Loading the subset from global memory to shared memory, using multiple threads to exploit memory-level parallelism
    - Performing the computation on the subset from shared memory; each thread can efficiently multi-pass over any data element
    - Copying results from shared memory to global memory

A Common Programming Strategy (Cont.)

- Constant memory also resides in device memory (DRAM) - much slower access than shared memory
  - But… cached!
  - Highly efficient access for read-only data
- Carefully divide data according to access patterns
  - R/Only → constant memory (very fast if in cache)
  - R/W shared within Block → shared memory (very fast)
  - R/W within each thread → registers (very fast)
  - R/W inputs/results → global memory (very slow)

For texture memory usage, see NVIDIA document.

GPU Atomic Integer Operations

- Atomic operations on integers in global memory:
  - Associative operations on signed/unsigned ints
  - add, sub, min, max, ...
  - and, or, xor
  - Increment, decrement
  - Exchange, compare and swap
- Requires hardware with compute capability 1.1 and above.

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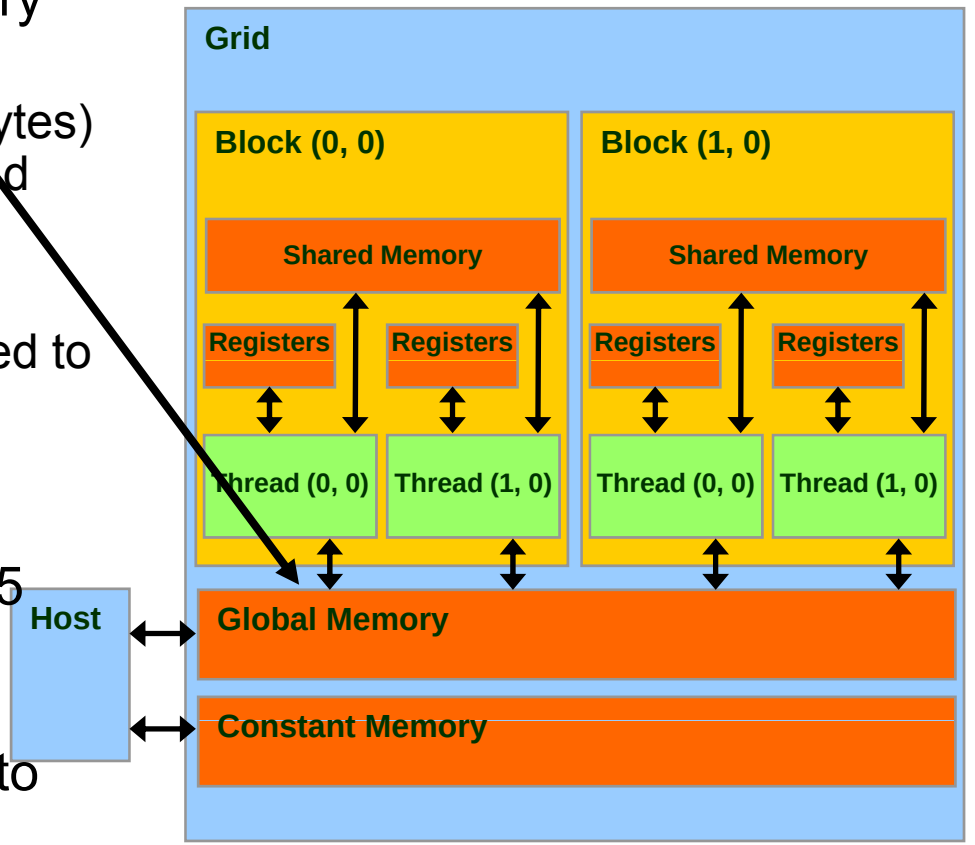
Matrix Multiplication using Shared Memory

Review: Matrix Multiplication Kernel using Multiple Blocks

```
__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;
}
```

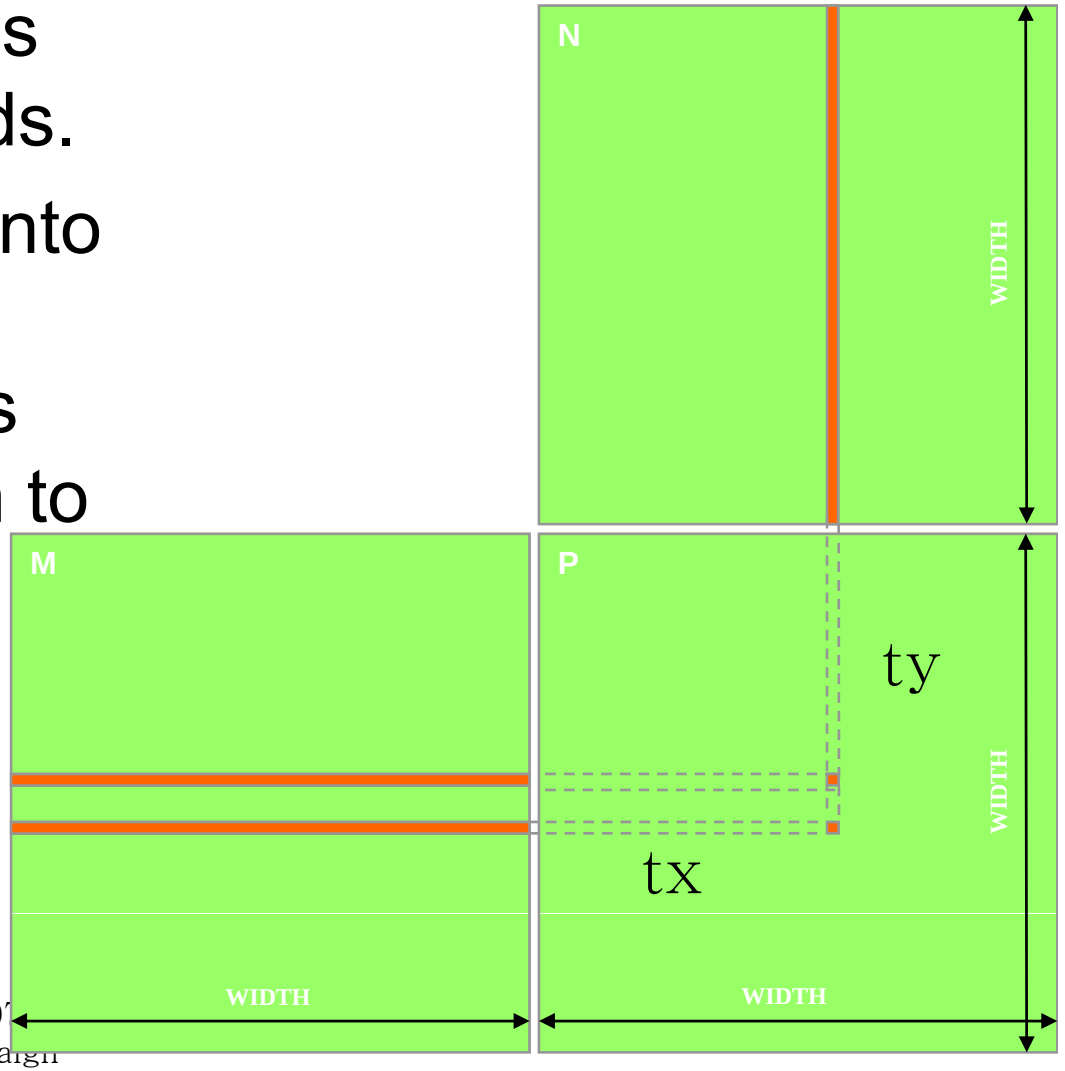
How about performance on G80?

- 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*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



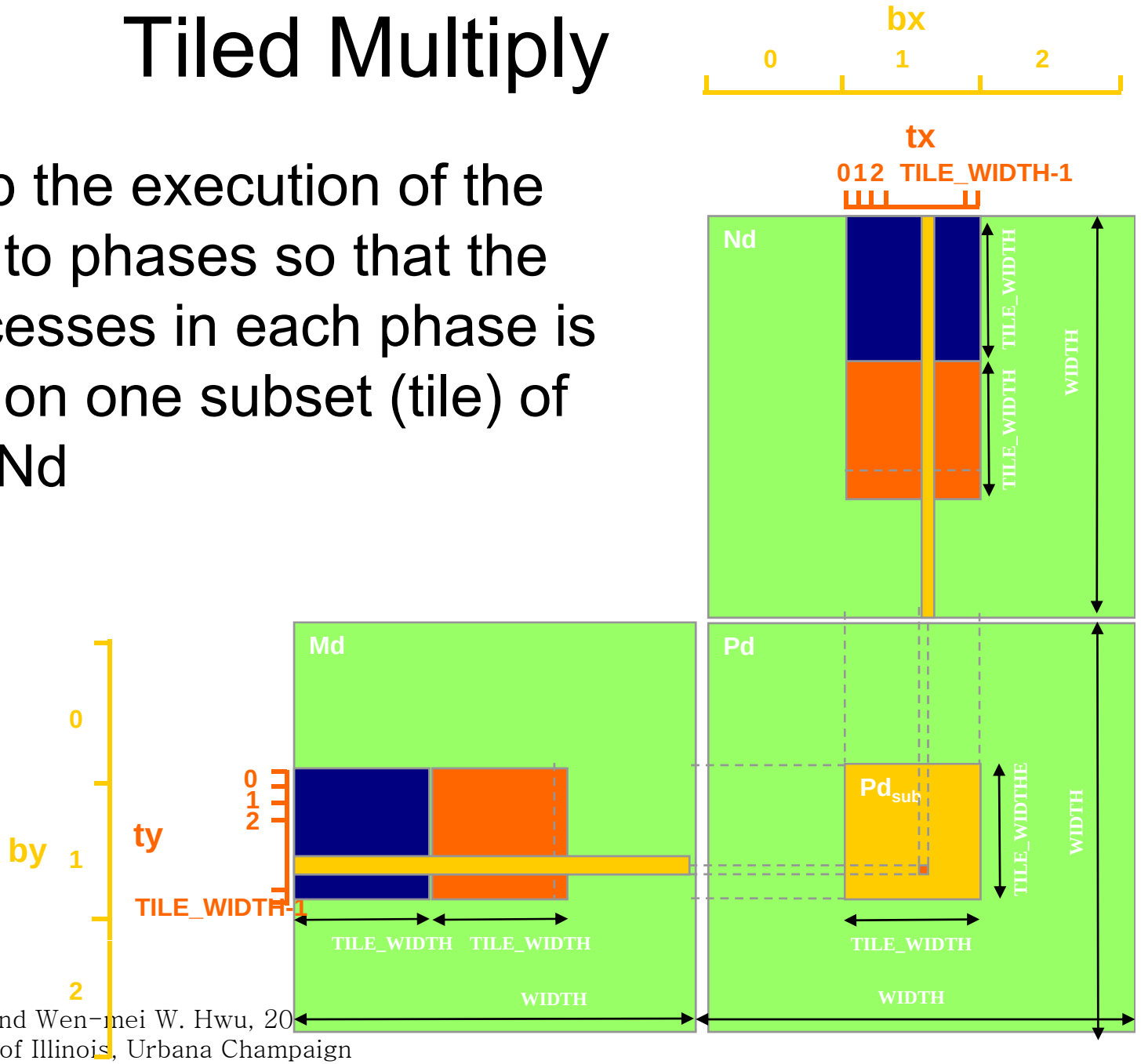
Idea: Use Shared Memory to reuse global memory data

- 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

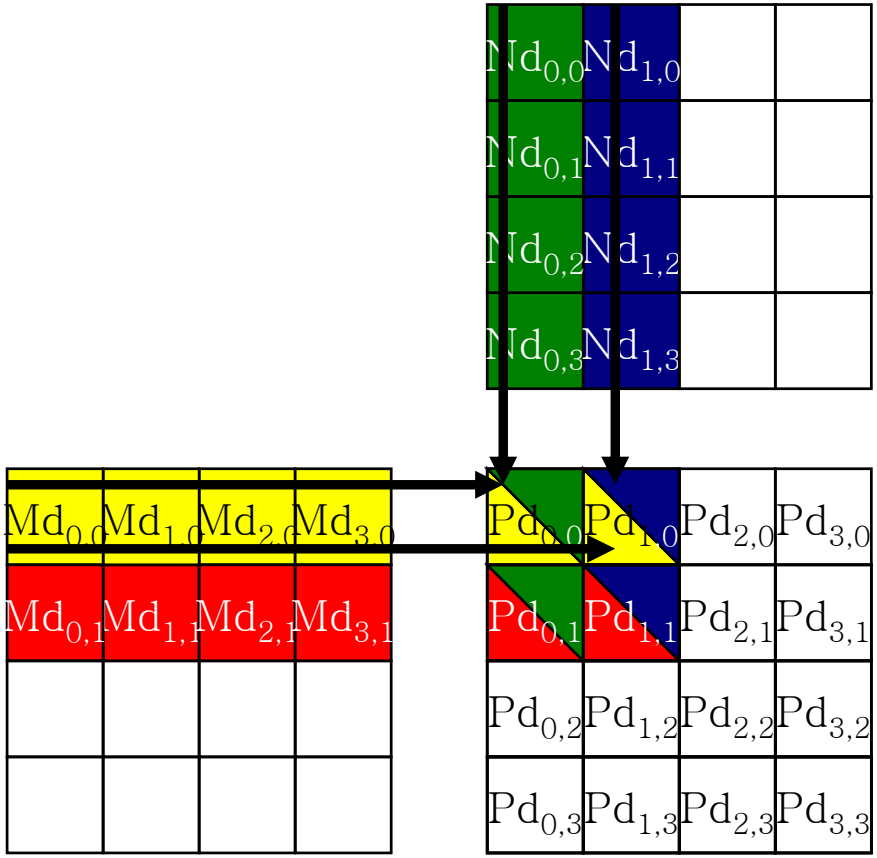


Tiled Multiply

- Break up the execution of the kernel into phases so that the data accesses in each phase is focused on one subset (tile) of Md and Nd



A Small Example

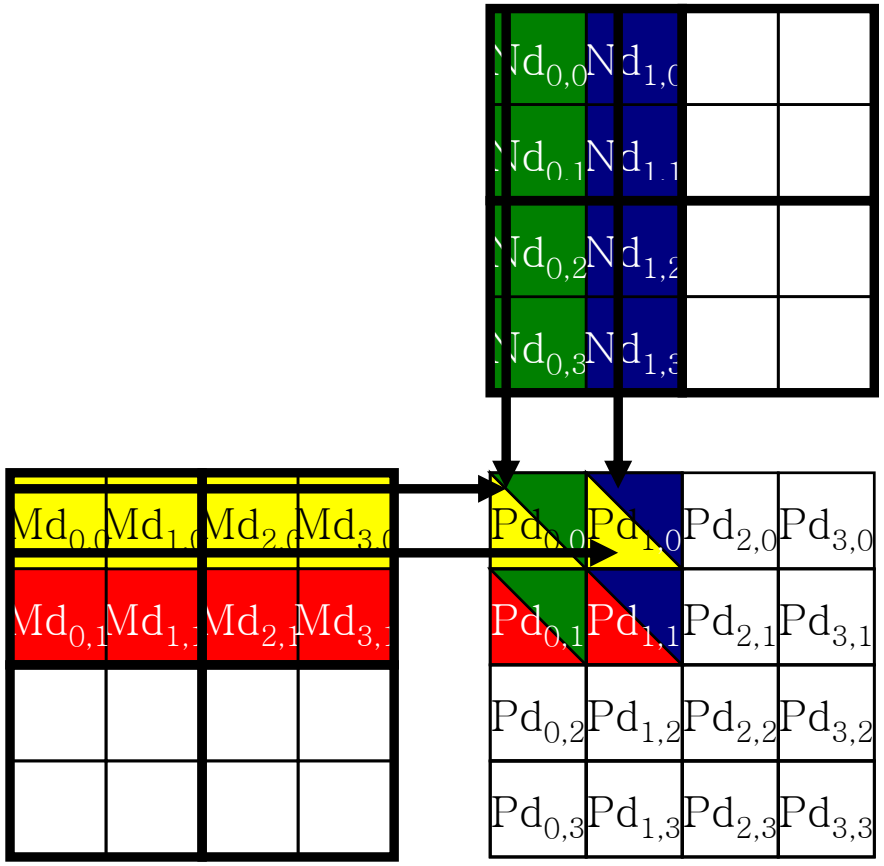


Every Md and Nd Element is used exactly twice in generating a 2X2 tile of P

Access order

$P_{0,0}$ $thread_{0,0}$	$P_{1,0}$ $thread_{1,0}$	$P_{0,1}$ $thread_{0,1}$	$P_{1,1}$ $thread_{1,1}$
$M_{0,0} * N_{0,0}$	$M_{0,0} * N_{1,0}$	$M_{0,1} * N_{0,0}$	$M_{0,1} * N_{1,0}$
$M_{1,0} * N_{0,1}$	$M_{1,0} * N_{1,1}$	$M_{1,1} * N_{0,1}$	$M_{1,1} * N_{1,1}$
$M_{2,0} * N_{0,2}$	$M_{2,0} * N_{1,2}$	$M_{2,1} * N_{0,2}$	$M_{2,1} * N_{1,2}$
$M_{3,0} * N_{0,3}$	$M_{3,0} * N_{1,3}$	$M_{3,1} * N_{0,3}$	$M_{3,1} * N_{1,3}$

Breaking Md and Nd into Tiles



Each phase of a Thread Block uses one tile from Md and one from Nd

	Phase 1			Phase 2		
$T_{0,0}$	**$Md_{0,0}$** ↓ $Mds_{0,0}$	**$Nd_{0,0}$** ↓ $Nds_{0,0}$	$PValue_{0,0}$ += $Mds_{0,0}$*$Nds_{0,0}$ + $Mds_{1,0}$*$Nds_{0,1}$	**$Md_{2,0}$** ↓ $Mds_{0,0}$	**$Nd_{0,2}$** ↓ $Nds_{0,0}$	$PValue_{0,0}$ += $Mds_{0,0}$*$Nds_{0,0}$ + $Mds_{1,0}$*$Nds_{0,1}$
$T_{1,0}$	**$Md_{1,0}$** ↓ $Mds_{1,0}$	**$Nd_{1,0}$** ↓ $Nds_{1,0}$	$PValue_{1,0}$ += $Mds_{0,0}$*$Nds_{1,0}$ + $Mds_{1,0}$*$Nds_{1,1}$	**$Md_{3,0}$** ↓ $Mds_{1,0}$	**$Nd_{1,2}$** ↓ $Nds_{1,0}$	$PValue_{1,0}$ += $Mds_{0,0}$*$Nds_{1,0}$ + $Mds_{1,0}$*$Nds_{1,1}$
$T_{0,1}$	**$Md_{0,1}$** ↓ $Mds_{0,1}$	**$Nd_{0,1}$** ↓ $Nds_{0,1}$	$PdValue_{0,1}$ += $Mds_{0,1}$*$Nds_{0,0}$ + $Mds_{1,1}$*$Nds_{0,1}$	**$Md_{2,1}$** ↓ $Mds_{0,1}$	**$Nd_{0,3}$** ↓ $Nds_{0,1}$	$PdValue_{0,1}$ += $Mds_{0,1}$*$Nds_{0,0}$ + $Mds_{1,1}$*$Nds_{0,1}$
$T_{1,1}$	**$Md_{1,1}$** ↓ $Mds_{1,1}$	**$Nd_{1,1}$** ↓ $Nds_{1,1}$	$PdValue_{1,1}$ += $Mds_{0,1}$*$Nds_{1,0}$ + $Mds_{1,1}$*$Nds_{1,1}$	**$Md_{3,1}$** ↓ $Mds_{1,1}$	**$Nd_{1,3}$** ↓ $Nds_{1,1}$	$PdValue_{1,1}$ += $Mds_{0,1}$*$Nds_{1,0}$ + $Mds_{1,1}$*$Nds_{1,1}$

time →

First-order Size Considerations in G80

- 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
- Each thread block perform 2*256 = 512 float loads from global memory for 256 * (2*16) = 8,192 mul/add operations.
  - Memory bandwidth no longer a limiting factor

CUDA Code – Kernel Execution Configuration

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

Tiled Matrix Multiplication Kernel

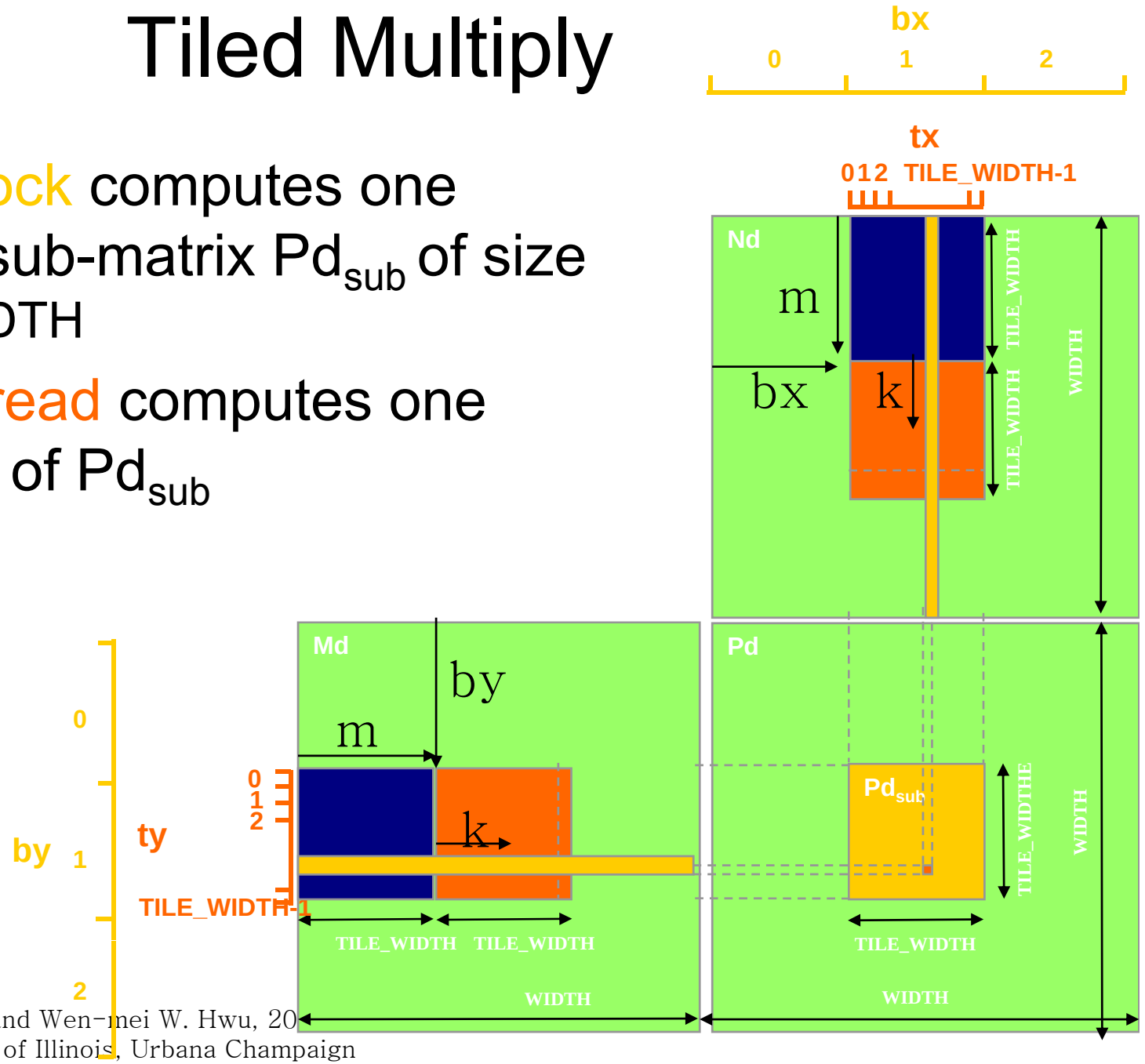
```
__global__ void MatrixMulKernel(float* Md, float* Nd, float* Pd, int Width)
{
1.  __shared__float Mds[TILE_WIDTH][TILE_WIDTH];
2.  __shared__float Nds[TILE_WIDTH][TILE_WIDTH];

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) {
// Coolaborative loading of Md and Nd tiles into shared memory
9.     Mds[ty][tx] = Md[Row*Width + (m*TILE_WIDTH + tx)]; //Width*Width memory
10.    Nds[ty][tx] = Nd[Col + (m*TILE_WIDTH + ty)*Width];//Width*Width (Tile)
11.    __syncthreads(); //wait until fetching two tiles Mds, Nds for each block

11.   for (int k = 0; k < TILE_WIDTH; ++k)
12.   Pvalue += Mds[ty][k] * Nds[k][tx];
13.   Synchthreads();//wait here to finish the job for the current input tile
14.  }
13.   Pd[Row*Width+Col] = Pvalue;
}  //?? How much space do we need for Pvalue? 1M x 4 bytes?
```

Single processor code

```
__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.   for (blockIdx.y = 0; blockIdx.y < Width/TILE_WIDTH; blockIdx.y++){
4.     for (blockIdx.x = 0; blockIdx.x < Width/TILE_WIDTH; blockIdx.x++){
5.       for (threadIdx.y = 0; threadIdx.y < TILE_WIDTH; threadIdx.y++){
6.         for (threadIdx.x = 0; threadIdx.x < TILE_WIDTH; threadIdx.x++){
7.     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) {
9.     Mds[ty][tx] = Md[Row*Width + (m*TILE_WIDTH + tx)];
10.    Nds[ty][tx] = Nd[Col + (m*TILE_WIDTH + ty)*Width];

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

Tiled Multiply

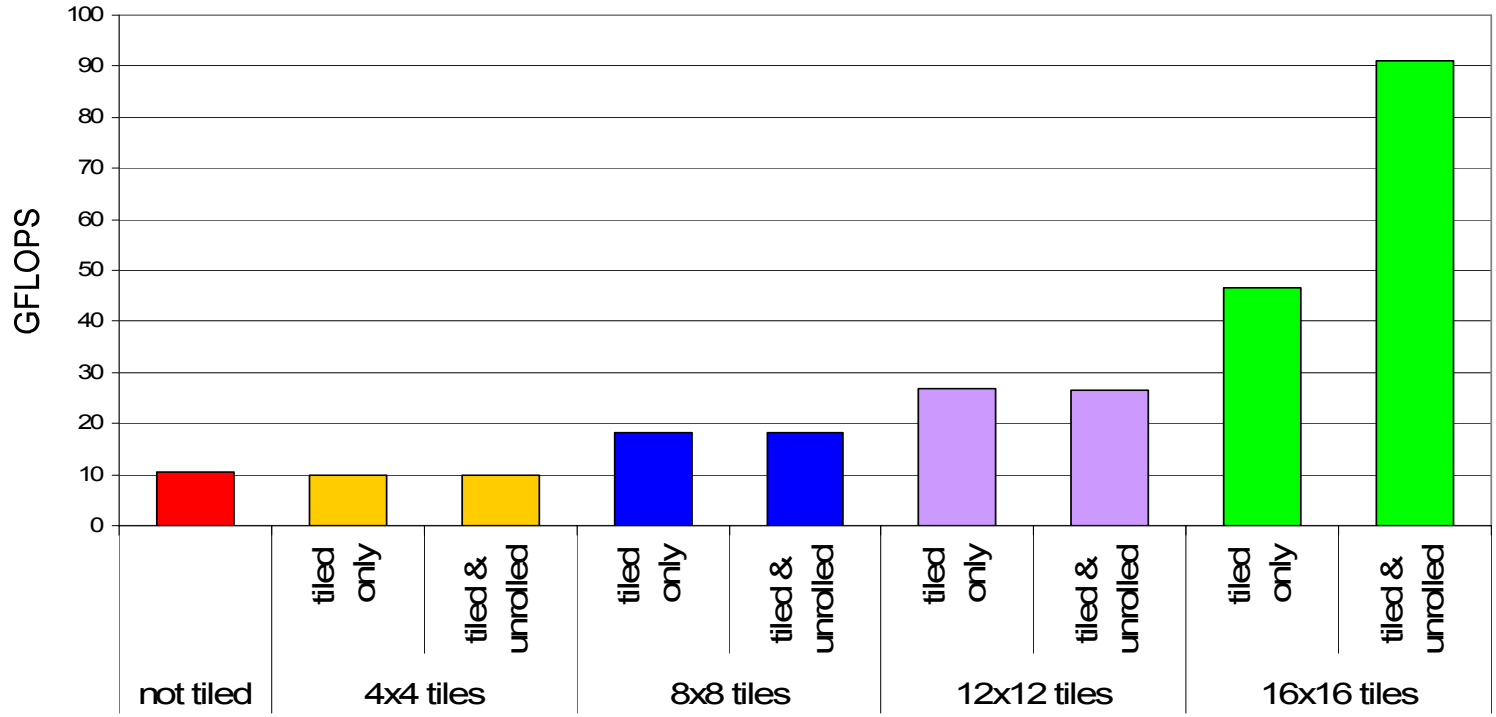
- Each block computes one square sub-matrix Pd_{sub} of size TILE_WIDTH
- Each thread computes one element of Pd_{sub}



G80 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.
  - 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 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!

Tiling Size Effects



Summary- Typical Structure of a CUDA Program

- Global variables declaration
  - __host__
  - __device__... __global__, __constant__, __texture__
- Function prototypes
  - __global__ void kernelOne(…)
  - float handyFunction(…)
- Main ()
  - allocate memory space on the device – cudaMalloc(&d_GlblVarPtr, bytes)
  - transfer data from host to device – cudaMemCpy(d_GlblVarPtr, h_Gl…)
  - execution configuration setup
  - kernel call – kernelOne<<<execution configuration>>>(args…);
  - transfer results from device to host – cudaMemCpy(h_GlblVarPtr,…)
  - optional: compare against golden (host computed) solution
- Kernel – void kernelOne(type args,…)
  - variables declaration - __local__, __shared__
    - automatic variables transparently assigned to registers or local memory
  - syncthreads()…
- Other functions
  - float handyFunction(int inVar…);

repeat as needed