Advanced Parallel Architecture

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GPU - Graphics Processing Units Part 2

Programming Massively Parallel Processors

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- Chapter 3 - Introduction to Data Parallelism and CUDA C
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- Chapter 4 - Data Parallel Execution Model
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Multicore and GPU Programming

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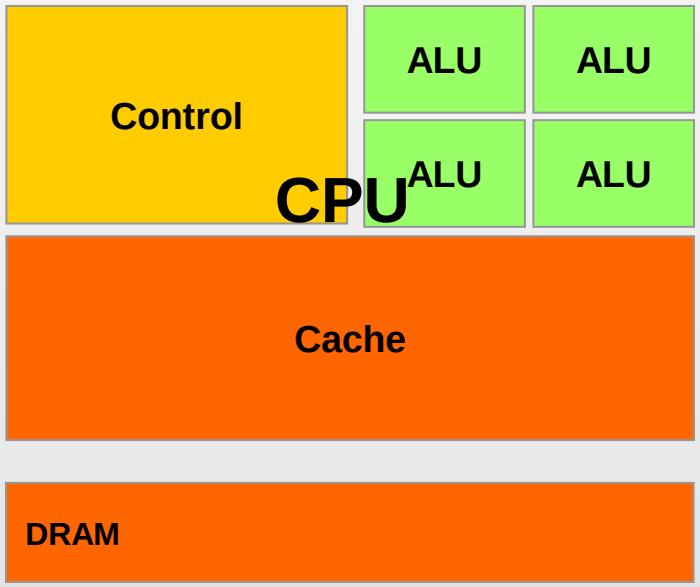
- Chapter 6 - GPU Programming
  - **Sections 6.2 - 6.7**

CUDA Programming Model

- The GPU is viewed as a compute **device** that:
  - Is a coprocessor to the CPU (**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

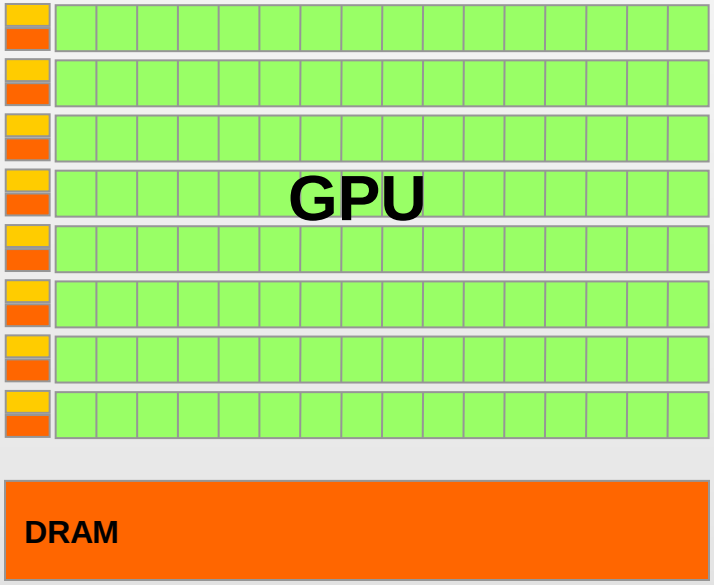
CPUs: Latency Oriented Design

- Large caches
  - Convert long latency memory accesses to short latency cache accesses
- Sophisticated control
  - Branch prediction for reduced branch latency
  - Data forwarding for reduced data latency
- Powerful ALU
  - Reduced operation latency



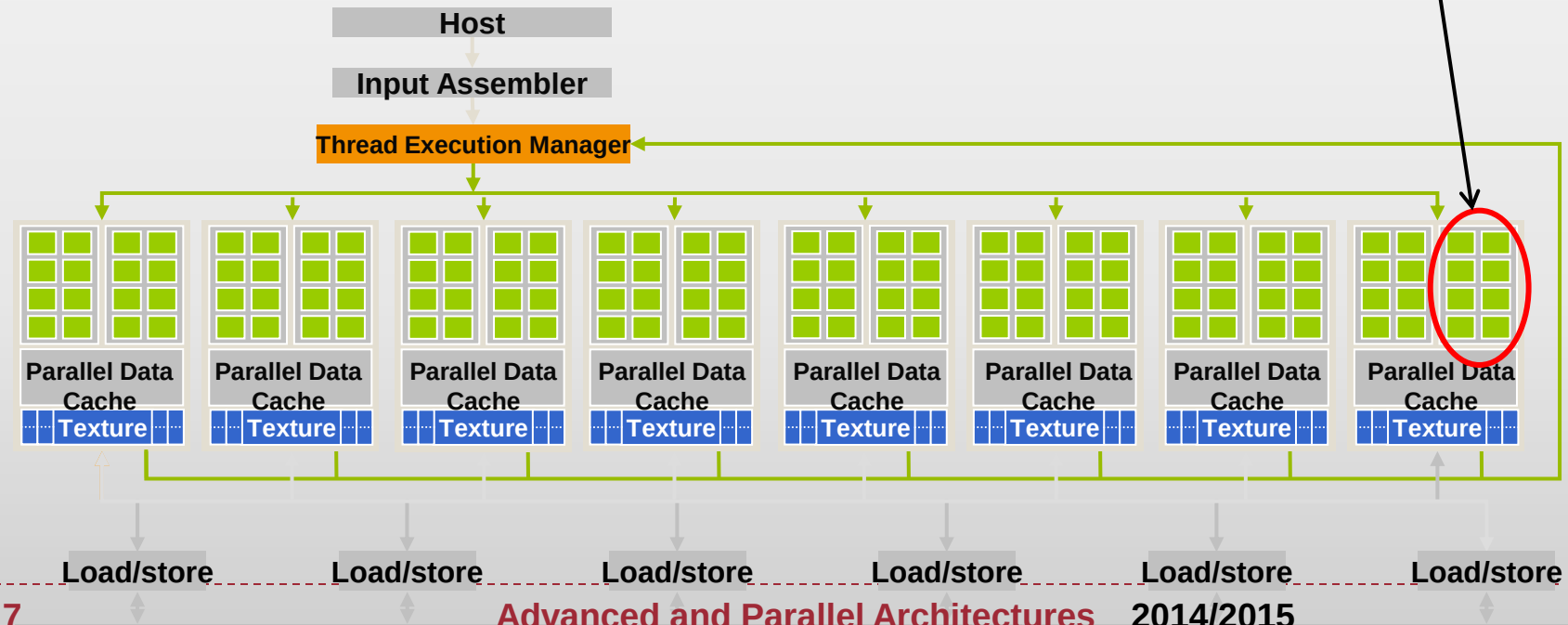
GPUs: Throughput Oriented Design

- Small caches
  - To boost memory throughput
- Simple control
  - No branch prediction
  - No data forwarding
- Energy efficient ALUs
  - Many, long latency but heavily pipelined for high throughput
- Require massive number of threads to tolerate latencies



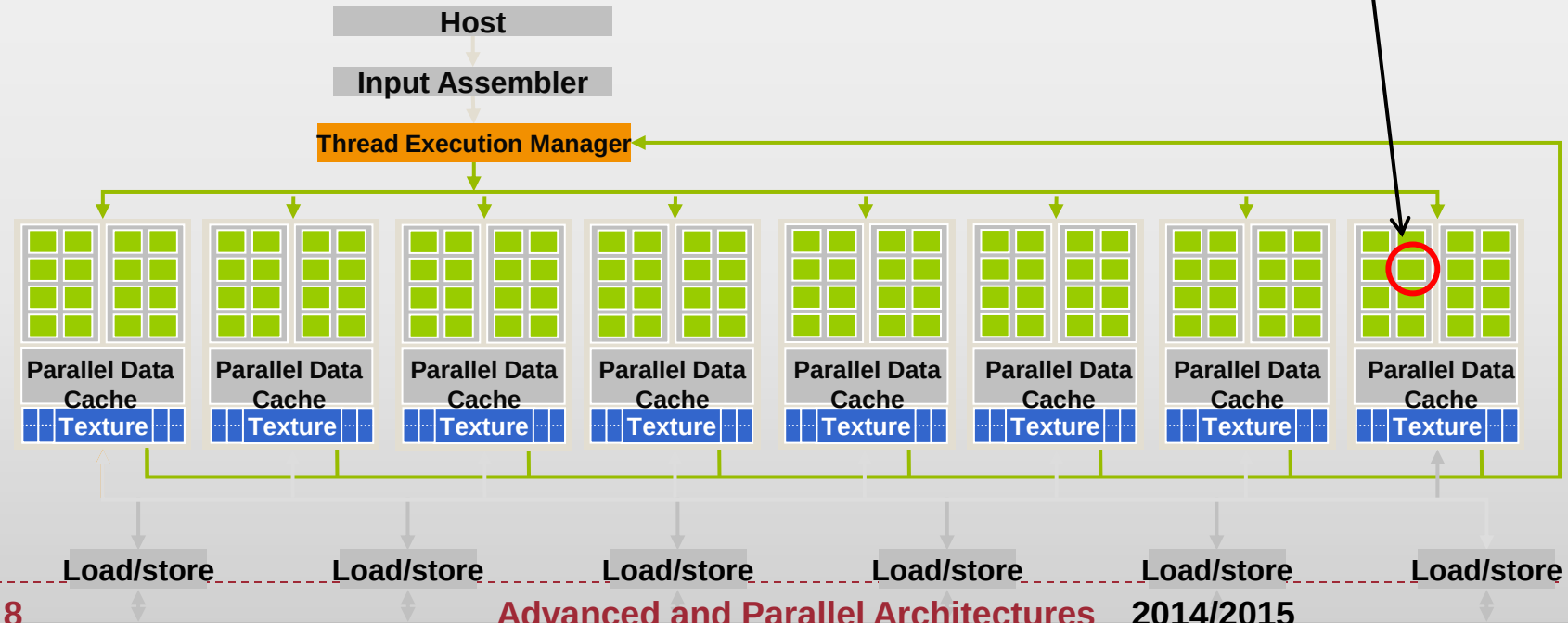
GPU Architecture

- A typical CUDA-capable GPU can be organized into
  - an array of highly threaded streaming multiprocessors (SMs)
  - in Figure, two SMs form a building block; but, the number of SMs in a building block can vary from one generation of CUDA GPUs to another generation



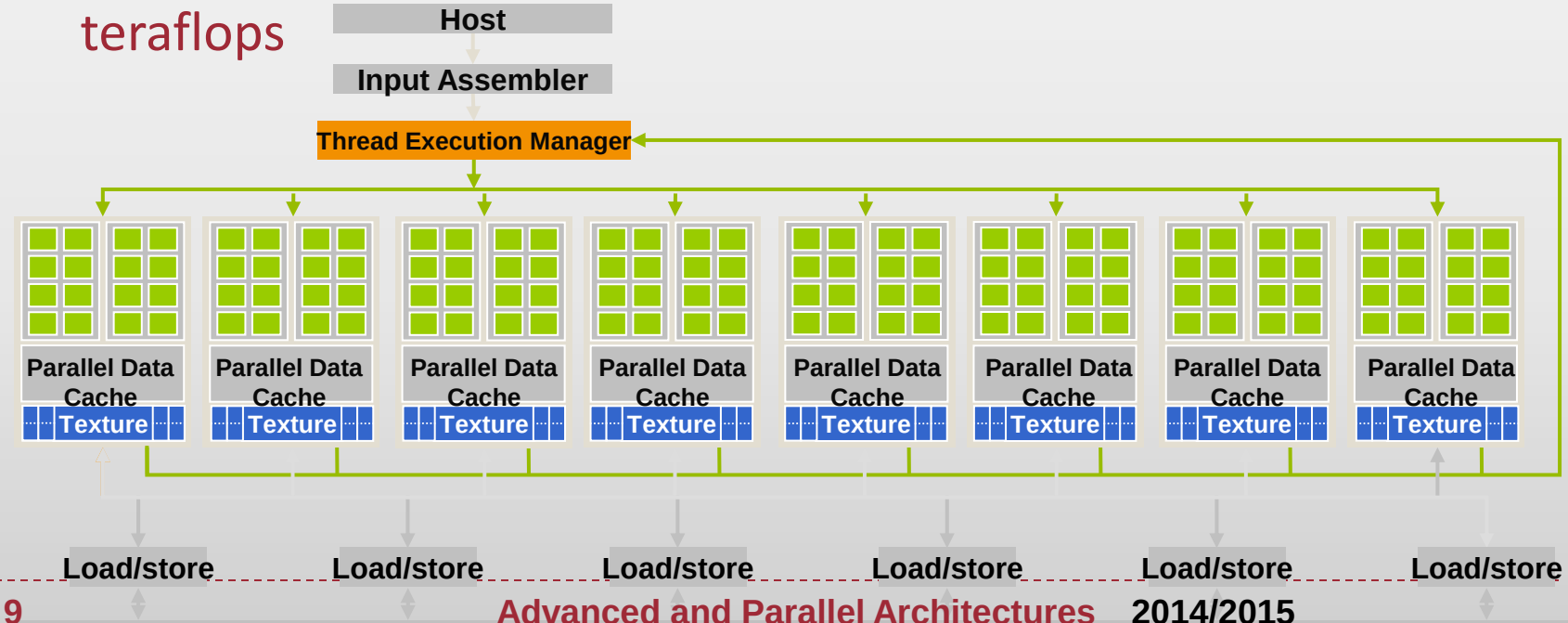
GPU Architecture

- Each SM has a number of streaming processors (SPs) that share control logic and instruction cache
- Each GPU currently comes with up to 4 gigabytes of graphics double data rate (GDDR) DRAM, referred to as global memory



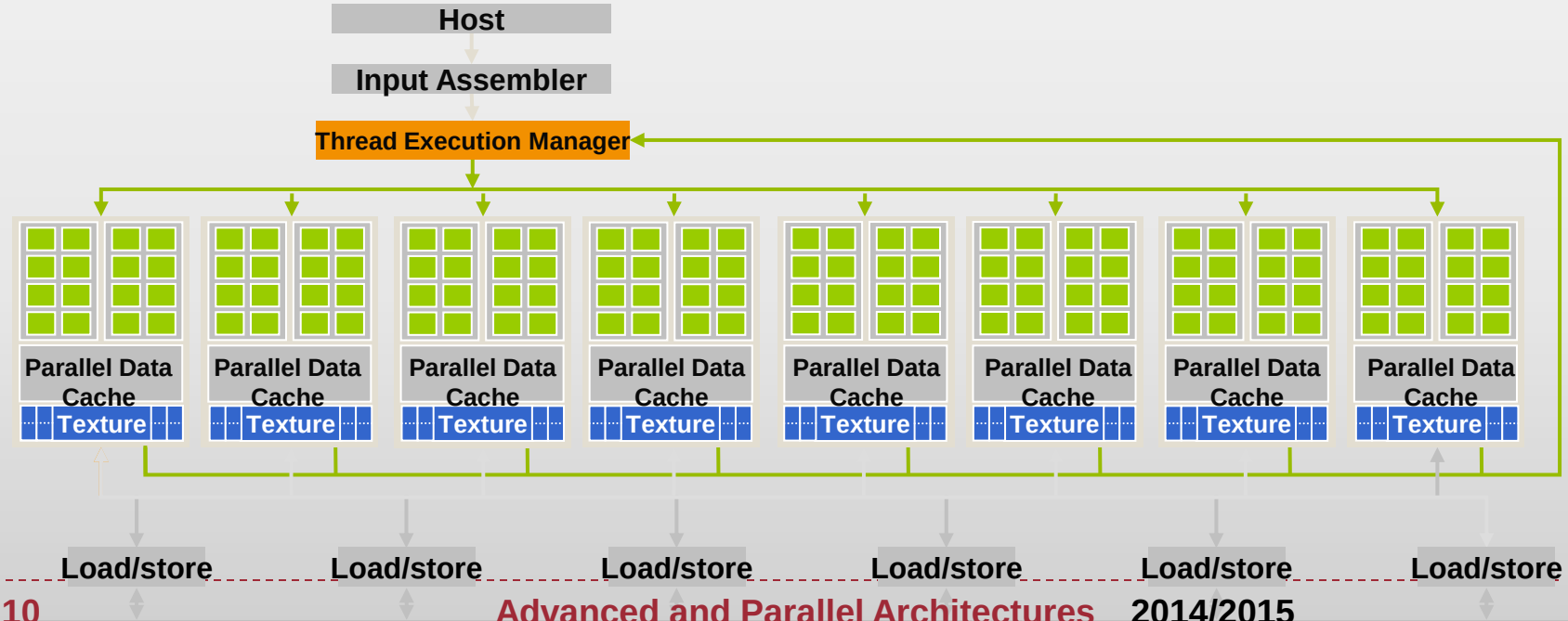
GPU Architecture

- The parallel **G80** chip has 128 SPs (16 SMs, 8 SPs)
- Each SP has a multiply–add (MAD) unit and an additional multiply unit.
  - With 128 SPs, the **G80** produces a total of over 500 gigaflops
  - The **GT200** (240 SPs) exceeds 1 teraflops and the **GTX680** 1,5 teraflops



GPU Architecture

- The **G80** chip supports up to **768 threads** per SM, which sums up to about 12,000 threads for this chip.
- The **GT200** supports **1024 threads** per SM and up to about 30,000 threads



CUDA Program Structure

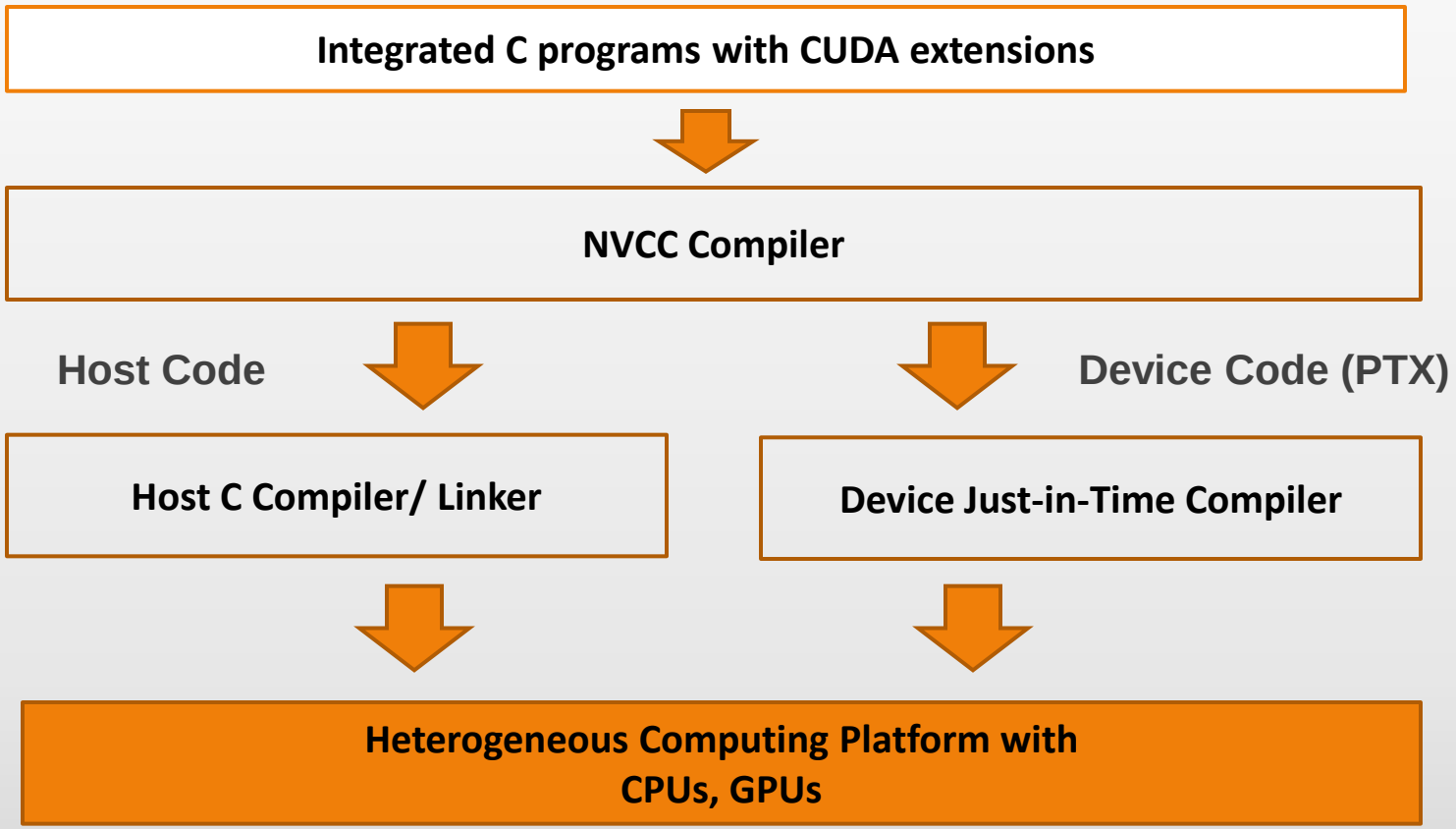
- The structure of a CUDA program reflects the computing system consisting of
  - a **host**, which is a traditional central processing unit (CPU)
  - one or more **devices** (GPUs)

- A CUDA program is a unified source code encompassing both host and device code
- The NVIDIA C compiler - **nvcc** - separates the two during the compilation process

CUDA Program Structure

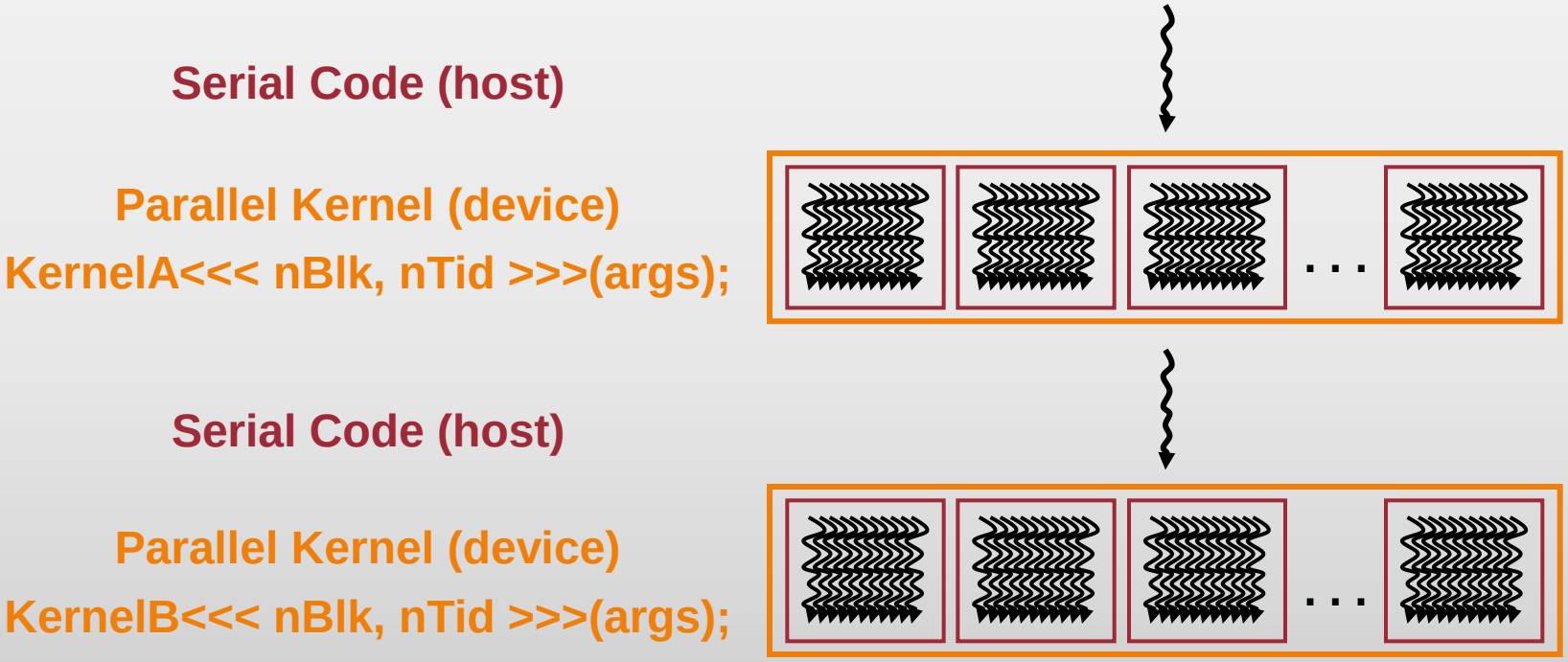
- The host code is:
  - straight ANSI C code
  - it is further compiled with the host's standard C compilers and runs as an ordinary CPU process
- The device code is:
  - written using ANSI C extended with **keywords** for labeling data-parallel functions, called **kernels**, and their associated **data structures**
  - The device code is typically further compiled by the **nvcc** and executed on a GPU device

Compiling A CUDA Program



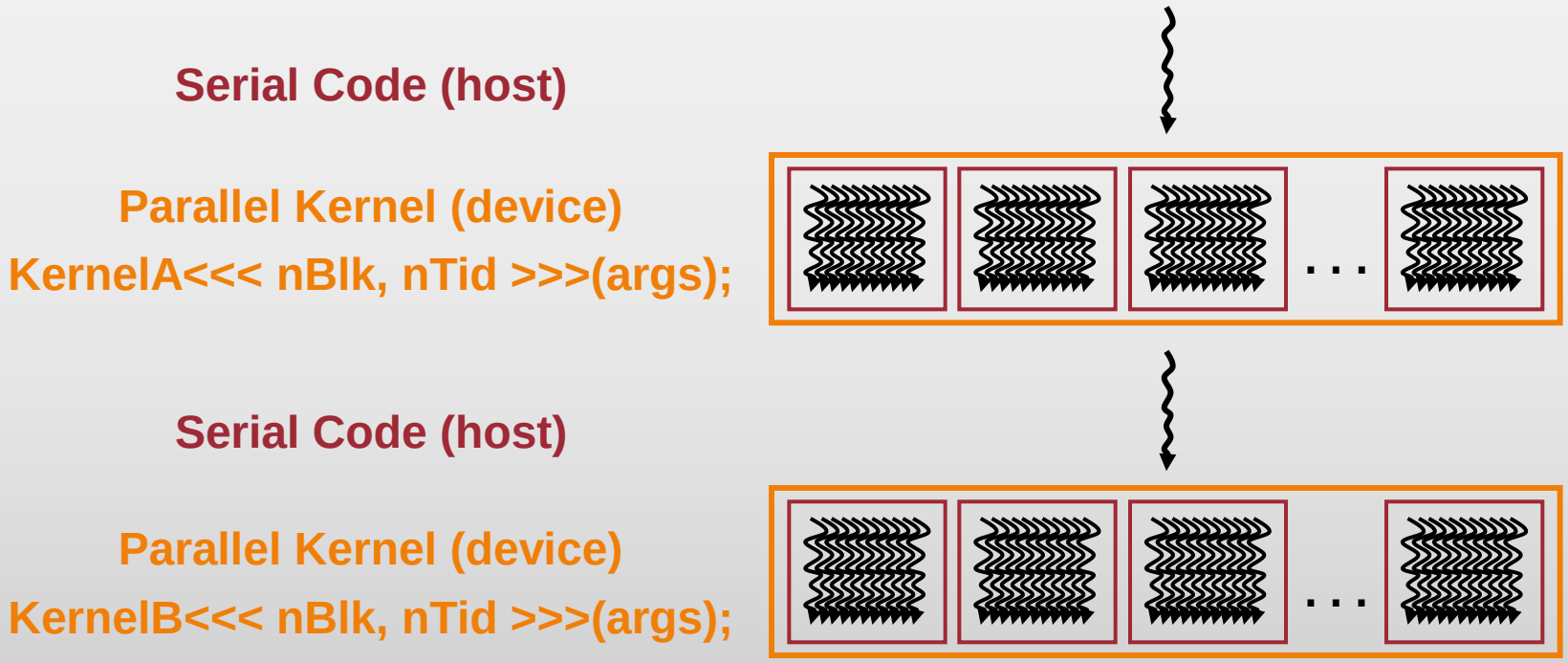
CUDA Execution Model

- The execution starts with host (CPU) execution
- When a kernel function is launched, the execution is moved to a device (GPU), where a large number of threads are generated to take advantage of abundant data parallelism



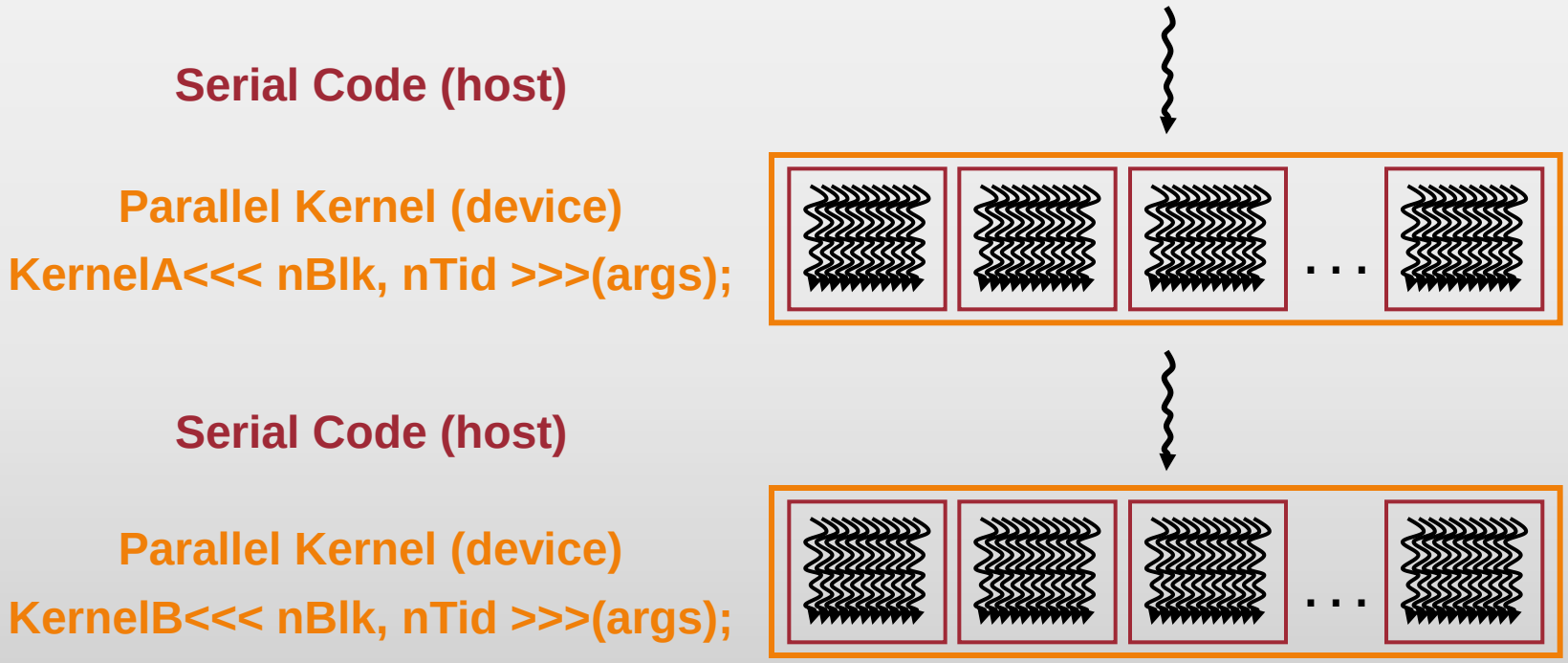
CUDA Execution Model

- All the threads that are generated by a kernel during an invocation are collectively called a **grid**
- Figure shows the execution of **two grids of threads**



CUDA Execution Model

- When all threads of a kernel complete their execution:
  - the corresponding grid terminates
  - the execution continues on the host until another kernel is invoked

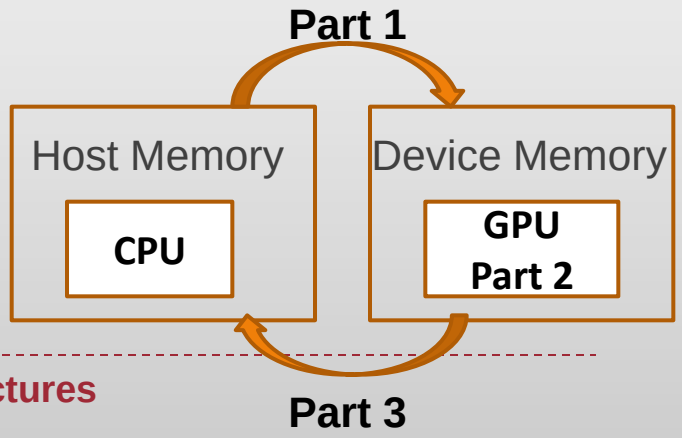


Vector Addition – Traditional C Code

```
// Compute vector sum C = A+B
void vecAdd(float* A, float* B, float* C, int n)
{
  for (i = 0, i < n, i++)
    C[i] = A[i] + B[i];
}

int main()
{
    // Memory allocation for A_h, B_h, and C_h
    // I/O to read A_h and B_h, N elements
    …
    vecAdd(A_h, B_h, C_h, N);
}
```

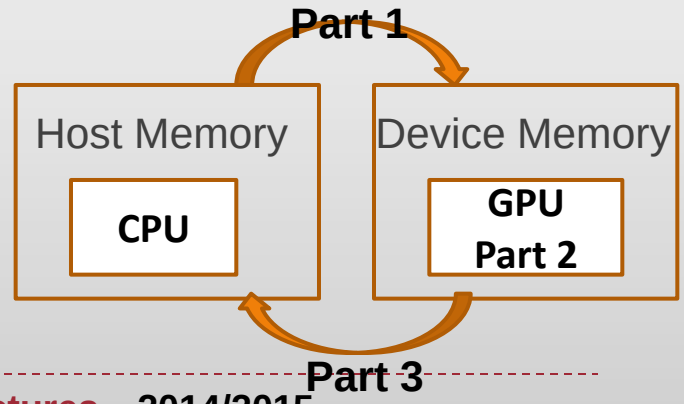
Vector Addition – Kernel

```
void vecAdd(float* h_A, float* h_B, float* h_C, int
n)
{
    int size = n* sizeof(float);
    float* d_A, d_B, d_C;
    …
1.  // Allocate device memory for A, B, and C
     // copy A and B to device memory

2.  // Kernel launch code – to have the device
     // to perform the actual vector addition

3.  // copy C from the device memory
     // Free device vectors
}
```



Device Memory and Data Transfer

- The host and devices have separate memory spaces
- To execute a kernel on a device
  - the programmer needs to **allocate memory on the device**
  - **transfer data** from the host memory to the allocated device memory
  - this corresponds to Part 1 of Figure
- After device execution
  - the programmer needs to **transfer result data** from the device memory back to the host memory
  - **free up** the device memory
  - this corresponds to Part 3 of Figure

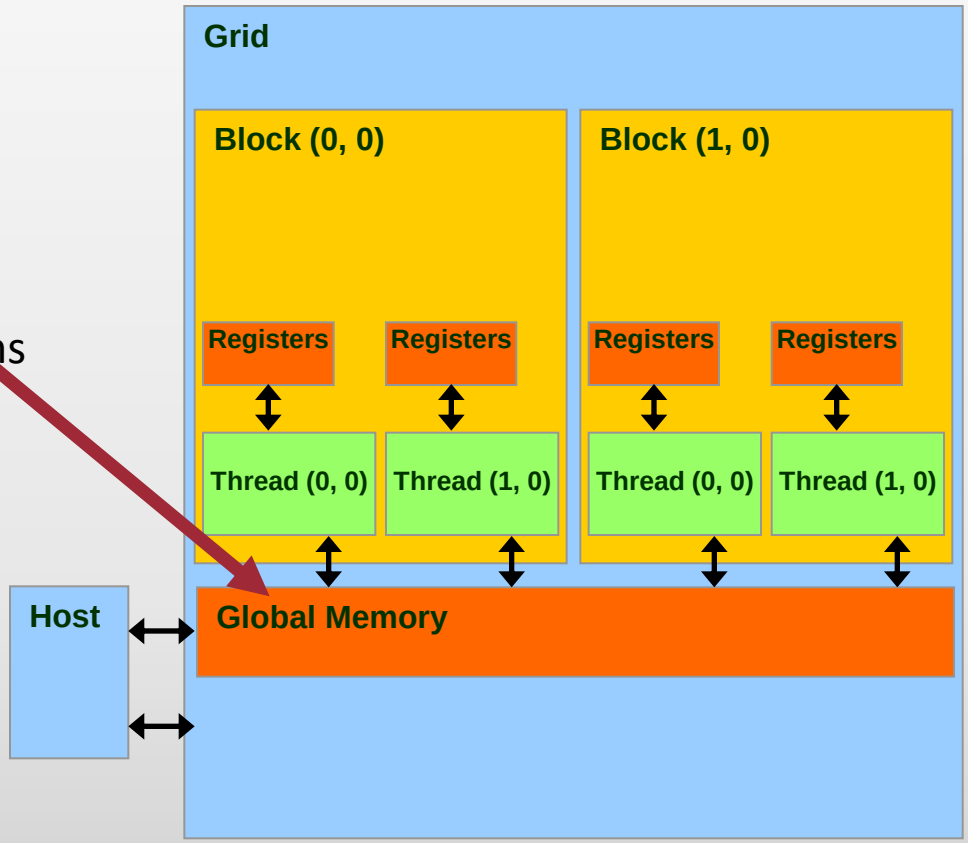


Device Memory and Data Transfer

- The CUDA memory model is supported by API functions that help programmers to manage data in memories
- The function **`cudaMalloc()`**:
  - called **from the host code** to allocate object in the device global memory
  - Two parameters:
    - **address of a pointer** variable to the allocated object after allocation
    - **size** of the allocated object in terms of bytes
- The function **`cudaFree()`**:
  - Frees object from device global memory
    - Pointer to freed object
- The function **`cudaMemcpy()`** for memory data transfer

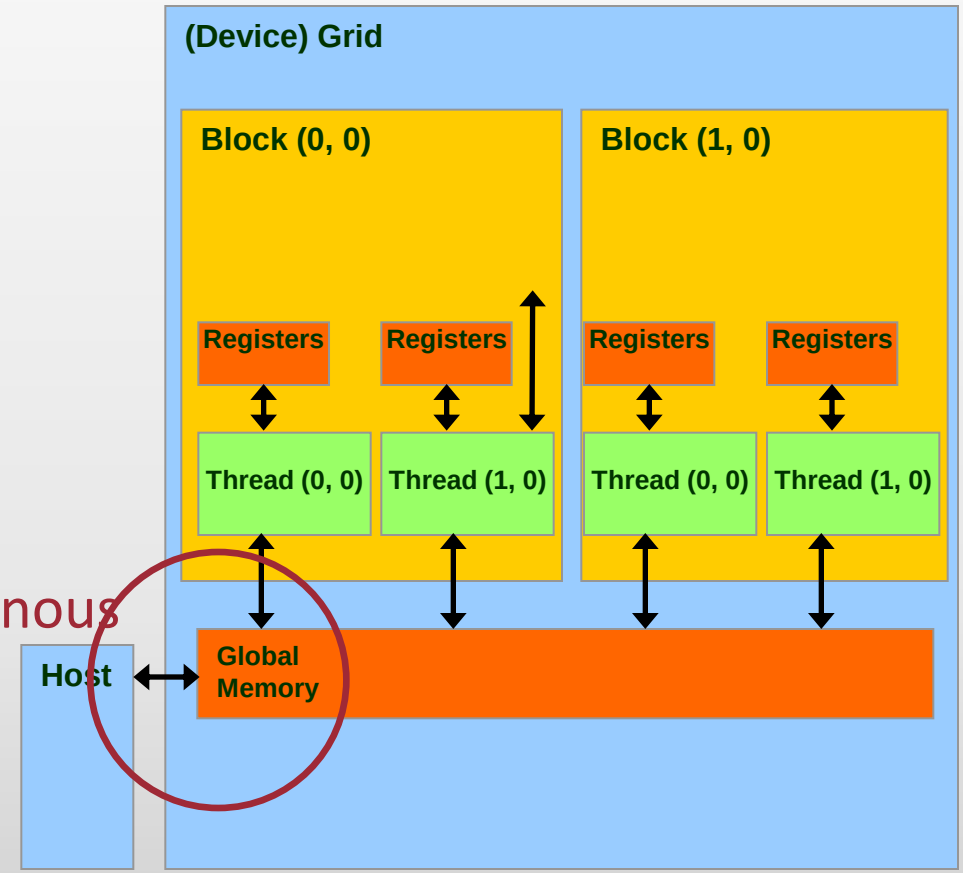
CUDA Device Memory Management API

- cudaMalloc()
  - Allocates object in the device global memory
  - Two parameters
    - **Address of a pointer** to the allocated object
    - **Size of** of allocated object in terms of bytes
- cudaFree()
  - Frees object from device global memory
    - **Pointer** to freed object



Host-Device Data Transfer API functions

- cudaMemcpy()
  - memory data transfer
  - requires four parameters
    - Pointer to destination
    - Pointer to source
    - Number of bytes copied
    - Type/Direction of transfer
  - Transfer to device is asynchronous

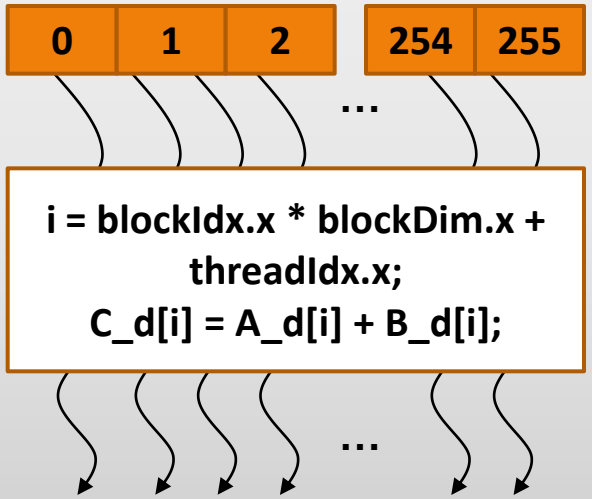


Vector Addition – Traditional C Code

```
void vecAdd(float* h_A, float* h_B, float* h_C, int n)
{
    int size = n * sizeof(float);
     float* d_A, d_B, d_C;

1. // Transfer A and B to device memory
     cudaMalloc((void **) &d_A, size);
     cudaMemcpy(d_A, h_A, size, cudaMemcpyHostToDevice);
     cudaMalloc((void **) &d_B, size);
     cudaMemcpy(d_B, h_B, size, cudaMemcpyHostToDevice);

   // Allocate device memory for
      cudaMalloc((void **) &d_C, size);

2. // Kernel invocation code – to be shown later
      …
3. // Transfer C from device to host
      cudaMemcpy(h_C, d_C, size, cudaMemcpyDeviceToHost);
    // Free device memory for A, B, C
      cudaFree(d_A); cudaFree(d_B); cudaFree (d_C);
}
```

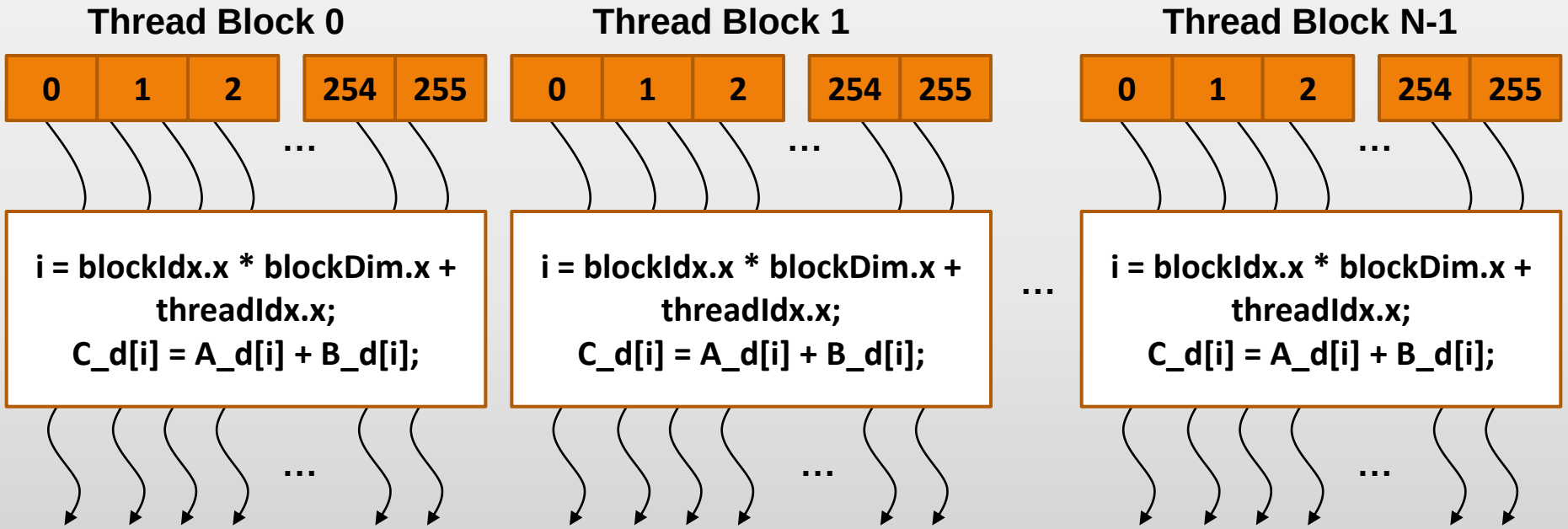
Arrays of Parallel Threads

- A **kernel** function specifies the code to be executed by all threads during a parallel phase
  - All of these threads execute the same code
- A CUDA kernel is executed by a grid (array) of threads
  - All threads in a grid run the same kernel code (SPMD)
  - Each thread has an index that it uses to compute memory addresses and make control decisions



Thread Blocks: Scalable Cooperation

- Thread array is divided into multiple blocks
  - Threads within a block cooperate via **shared memory, atomic operations** and **barrier synchronization**
  - Threads in different blocks cannot cooperate

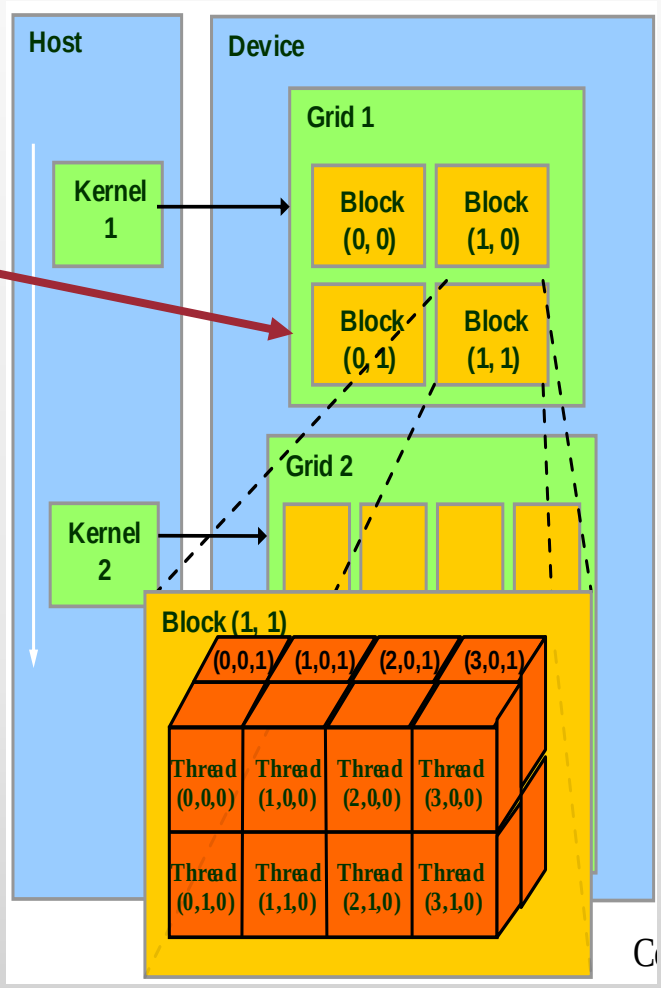


Arrays of Parallel Threads

- When a **kernel** is invoked, it is executed as **grid** of parallel threads
- Each CUDA thread grid typically is comprised of **thousands to millions** of lightweight GPU threads per kernel invocation
- Creating enough threads to fully utilize the hardware often requires a large amount of data parallelism

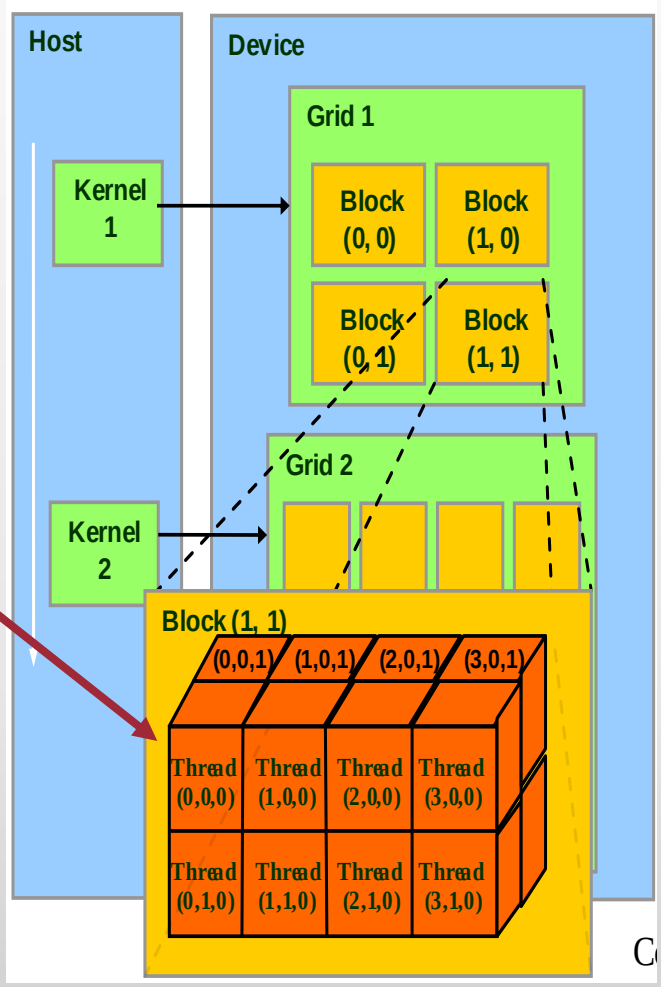
blockIdx and threadIdx

- Threads in a grid are organized into **a two-level hierarchy**
  - ***top level***, each **grid** consists of one or more thread blocks
  - All **blocks** in a grid have the **same number of threads** organized in the same manner
  - Each **grid** is organized as a as a **three-dimensional array** of blocks
  - Each **block** has a unique **three dimensional coordinate** given by the CUDA specific keywords **`blockIdx.x`**, **`blockIdx.y`** and **`blockIdx.z`**



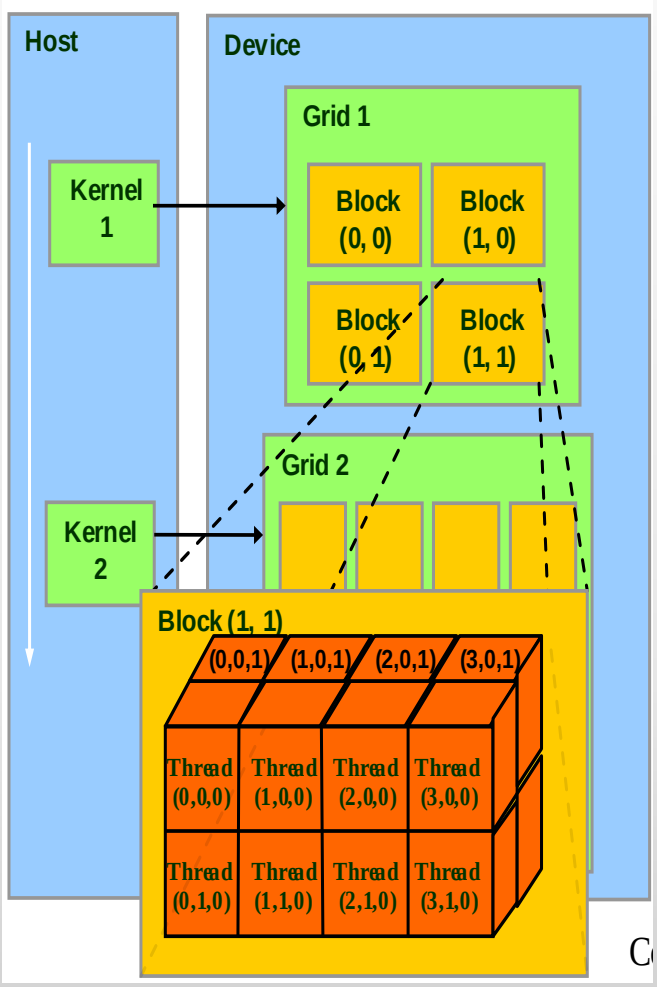
blockIdx and threadIdx

- Threads in a grid are organized into **a two-level hierarchy**
  - Each thread **block** is organized as a **three-dimensional array** of threads with a total size of up to 512 threads
  - The coordinates of threads in a block are uniquely defined by three thread indices: `threadIdx.x`, `threadIdx.y`, and `threadIdx.z`
  - Not all applications will use all three dimensions of a thread block
  - In Figure 3.13, each thread block is organized



blockIdx and threadIdx

- Threads in a grid are organized into **a two-level hierarchy**
- In Figure
  - each thread block is organized into a 4x2x2 three-dimensional array of threads
  - this gives Grid 1 a total of 4x16 = 64 threads
- Each thread uses indices to decide what data to work on
  - blockIdx: 1D, 2D, or 3D (CUDA 4.0)
  - threadIdx: 1D, 2D, or 3D



CUDA Thread Organization

- When a thread executes the kernel function, references to the `blockIdx` and `threadIdx` variables return the **coordinates of the thread**
- Additional built-in variables, `gridDim` and `blockDim`, provide the **dimension of the grid** and the **dimension of each block**

- `threadID = blockIdx.x * blockDim.x + threadIdx` identifies the part of the input data to read from and the part of the output data structure to write to
  - **Example** Thread 3 of Block 0 has a threadID value of 0*M + 3 = 3
  - **Example** Thread 3 of Block 5 has a threadID value of 5*M + 3

CUDA threads, blocks and grids

- Nvidia use the **Compute Capability** specification to encode what each generation of GPU chips is capable of
- The Compute Capability (CC) of a GPU can be discovered by running the `deviceQuery` utility

	Compute Capability			
Item	**1.x**	**2.x**	**3.x**	**5.x**
Max. number of grid dimensions	2	3		
Grid maximum x-dimension	$2^{16}-1$		$2^{31}-1$	
Grid maximum y/z-dimension	$2^{16}-1$			
Max. number of block dimensions	3			
Block max. x/y-dimension	512	1024		
Block max. z-dimension	64			
Max. threads per block	512	1024		
GPU example (GTX family chips)	8800	480	780	980

CUDA Thread Organization

- The exact organization of a grid is determined by the **execution configuration** provided at kernel launch
  - The first parameter specifies the dimensions of the grid as # blocks
  - The second specifies the dimensions of each block as # threads
  - Each such parameter is a **`dim3`** type, a C struct with three unsigned integer fields: x, y, and z
  - Example

```
dim3 dimGrid(128, 1, 1);
dim3 dimBlock(32, 1, 1);
vecAddKernel<<<dimGrid, dimBlock>>>(. . .);
```

oppure

```
dim3 cat(128, 1, 1);
dim3 dog(32, 1, 1);
KernelFunction<<<cat, dog>>>(. . .);
```

Execution Configuration Examples

Assuming we have

```
dim3 b(3,3,3);
dim3 g(20,100);
```

Different grid-block combination are possible

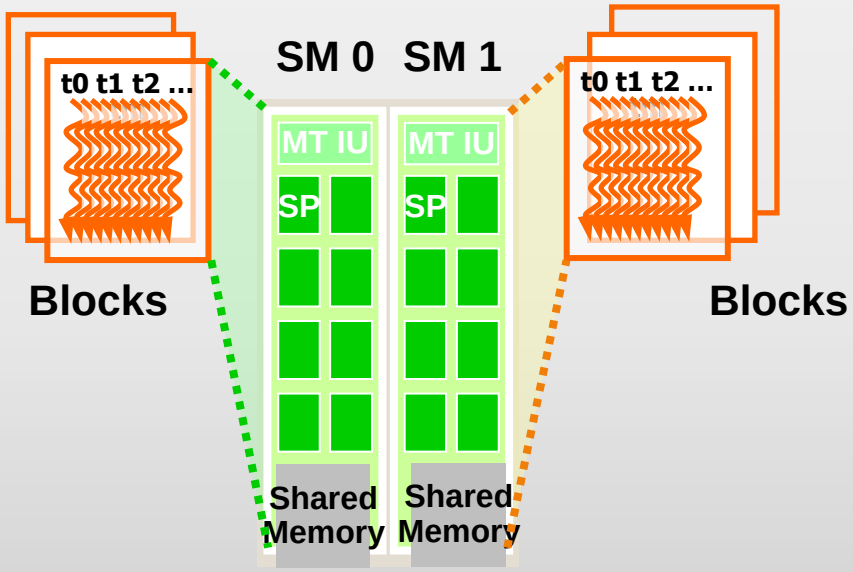
- `foo<<<g,b>>>();` // Run a 20x100 grid made of 3x3x3 blocks
- `foo<<<10,b>>>();` // Run a 10-block grid, each block made by 3x3x3 threads
- `foo<<<g,256>>>();` // Run a 20x100 grid, made of 256 threads
- `foo<<<g,2048>>>();` // An invalid example: maximum block size is 1024 threads even for compute capability 5.x
- `foo<<<5,g>>>();` // Another invalid example, that specifies a block size of 20x100=2000 threads
- `foo<<<10,256>>>;` // simplified configuration for a 1D grid of 1D blocks

Synchronization

- CUDA allows threads in the same block to coordinate their activities using a barrier synchronization function, `__syncthreads()`
  - the thread that executes the function call will be held at the calling location until every thread in the block reaches the location
- A `__syncthreads()` statement must be executed by all threads in a block of the kernel before any moves on to the next phase

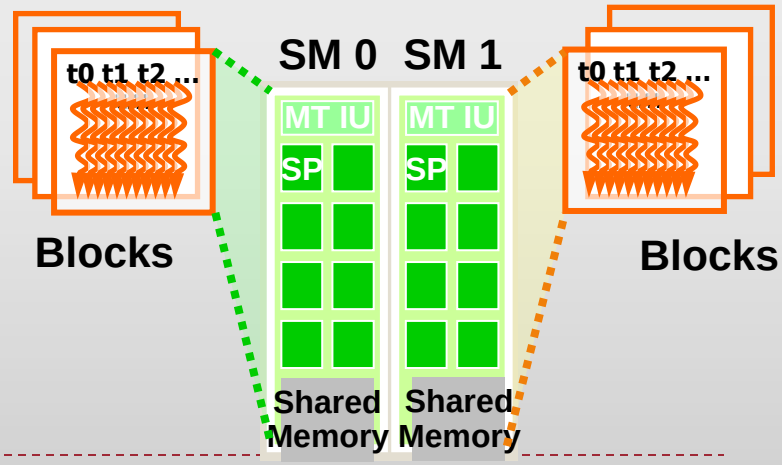
Thread and Block Assignment

- Once a **kernel is launched**, the CUDA runtime system generates the corresponding **grid of threads**
  - threads are assigned to execution resources on a block-by-block basis
- The execution resources are organized into streaming multiprocessors (SMs)
- Each device has a limit on the number of block that can be assigned to each SM



Thread and Block Assignment

- When an insufficient amount of any one or more types of resources needed for the simultaneous execution of blocks, the CUDA runtime automatically reduces the number of blocks assigned to each SM
- The runtime system maintains a list of blocks that need to execute and assigns new blocks to SMs as they complete the execution of blocks previously assigned to them

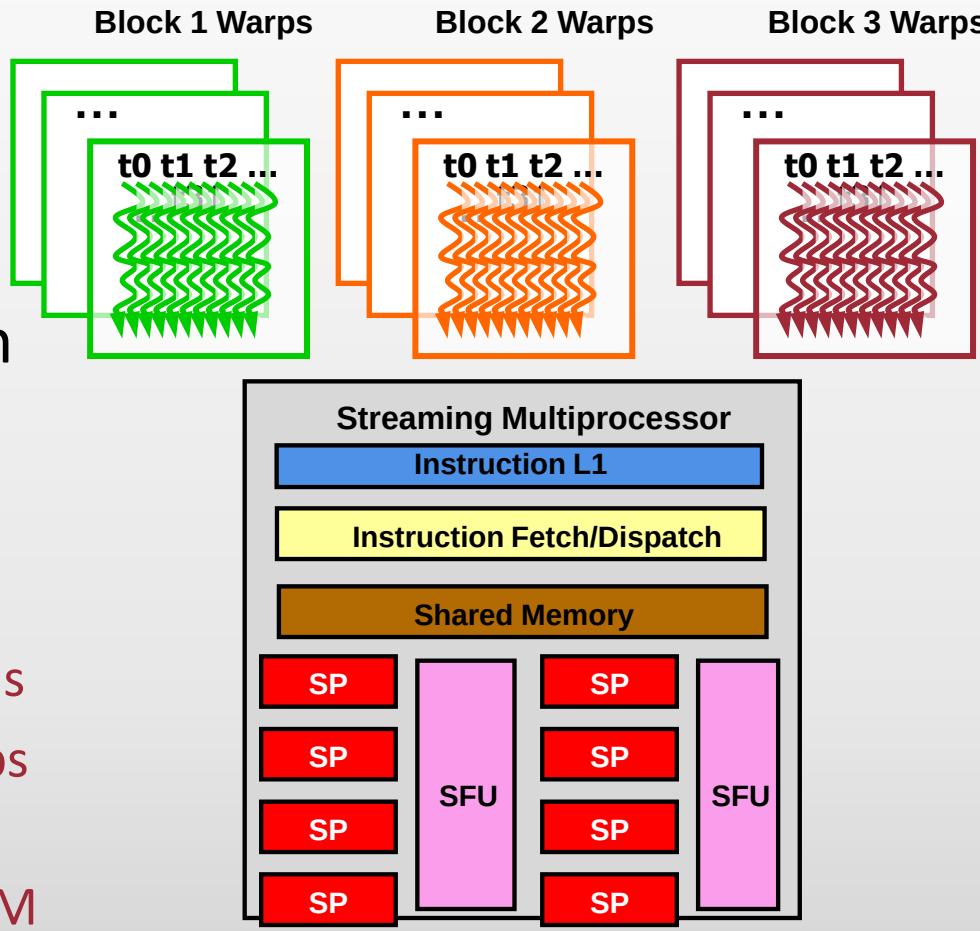


Thread Scheduling

- Once a block is assigned to a streaming multiprocessor, it is further divided into 32-thread units called **warps**
- The warp is the **unit of thread scheduling** in SMs
- Each warp consists of 32 threads of consecutive threadIdx values:
  - threads 0 through 31 form the first warp
  - threads 32 through 63 the second warp, and so on
- We can calculate the number of warps that reside in an SM for a given block size and a given number of blocks assigned to each SM

Thread Scheduling

- Each Block is executed as 32-thread Warps
  - Warps are scheduling units in SM
- **Example** If 3 blocks are assigned to an SM and each block has 256 threads, how many **warps** are there in an SM?
  - 3 blocks, each block 256 threads
  - each block has 256/32 = 8 warps
  - having 3 blocks in each SM, we have 8 x 3 = 24 warps in each SM



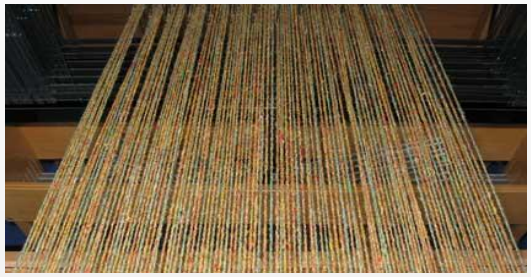
Thread Scheduling

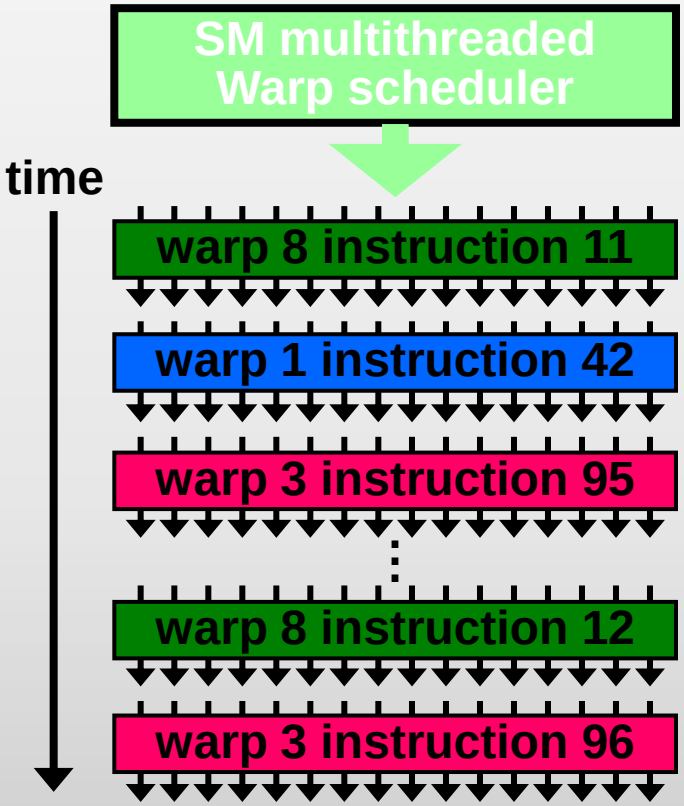
- **Why** do we need to have so many warps in an SM if there are only 8 SPs in an SM?
  - The answer is for **efficiently executing long-latency operations** such as global memory accesses
  - When an instruction executed by the threads in a warp needs to wait for the result of a previously initiated long-latency operation, the **warp is not selected for execution**
  - Another resident warp (that is no waiting for results) is selected for execution
  - If more than one warp is ready for execution, a **priority** mechanism is used to select one for execution
  - This mechanism of filling the latency of expensive operations with work from other threads is often referred to as ***latency hiding***

Thread Scheduling

- Note that **warp scheduling** is also used for tolerating other types of long latency operations such as *pipelined floating-point arithmetic* and *branch instructions*
- With enough warps around
  - the hardware will likely find a warp to execute at any point in time
  - full use of the execution hardware in spite of long-latency operations
- The selection of ready warps for execution
  - does not introduce any idle time into the execution timeline
  - ***zero-overhead thread scheduling***
- With warp scheduling, the long waiting time of warp instructions is hidden by executing instructions from other 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

Thread Scheduling

- List of GPU chips and their SM capabilty

	compute capability					
Item	**1.0, 1.1**	**1.2, 1.3**	**2.x**	**3.0**	**3.5**	**5.0**
Concurrent kernels/device	1		16		32	
Max. resident blocks/SM	8			16		32
Max. resident warps/SM	24	32	48	64		
Max. resident threads/SM	768	1024	1536	2048		
32-bit registers/SM	8k	16k	32k	64k		
Max. registers/thread	128		63		255	

Exercise

Simple exercise (register and shared memory not considered)

- Assume a CUDA device allowing 8 blocks, 1024 threads per SM and 512 thread in each block
- For matrix multiplication, should we use 8x8, 16x16, or 32x32 thread blocks?
- Analyze the pros and cons of each choice:
  - If we use **8x8 blocks**, each block would have only 64 threads, and we will need 1024/64 = 12 blocks to fully occupy an SM
  - We are limited to 8 blocks in each SM, we will end up with only 64 x 8 = 512 threads in each SM
  - Then the SM execution resources will likely be underutilized because there will be fewer warps to schedule around long-latency operations

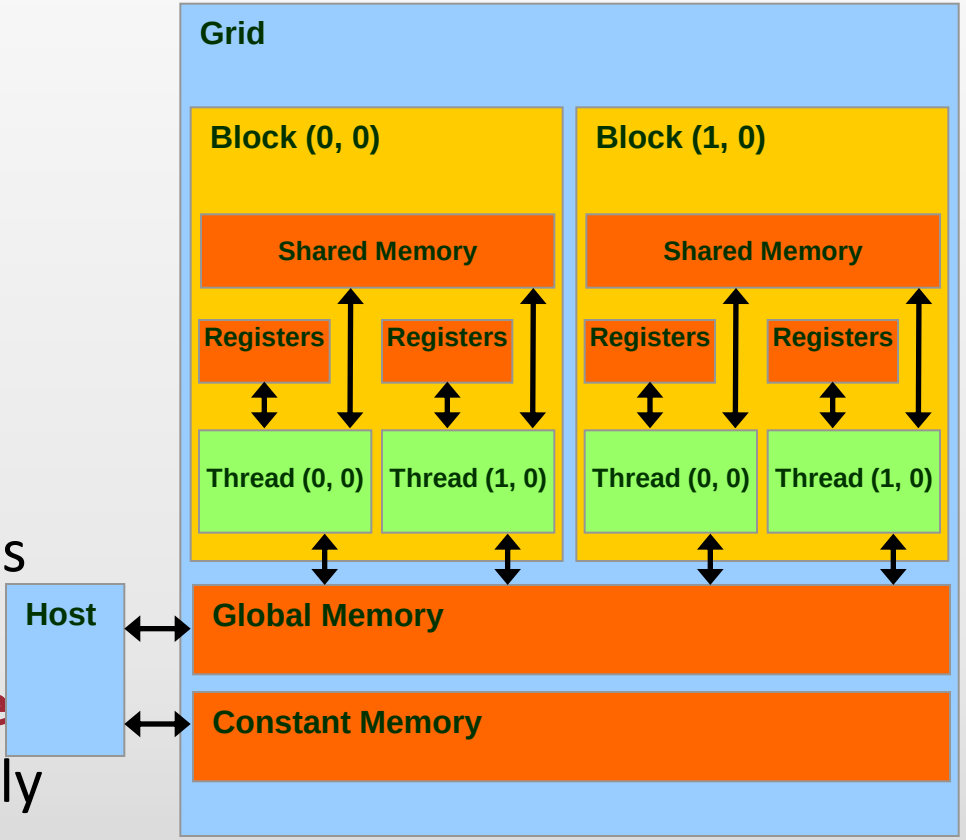
Exercise

Simple exercise (register and shared memory not considered)

- Assume a CUDA device allowing 8 blocks, 1024 threads per SM and 512 thread in each block
- For matrix multiplication, should we use 8x8, 16x16, or 32x32 thread blocks?
  - The **16x16** blocks give 256 threads per block.
  - This means that each SM can take 1024/256 = 4 blocks.
  - This is within the 8-block limitation.
  - **Good configuration**:
    - full thread capacity in each SM and the
    - maximal number of warps for scheduling around the long-latency oper.
  - The **32x32** blocks exceed the limitation of up to 512 threads per block

Programmer View of CUDA Memories

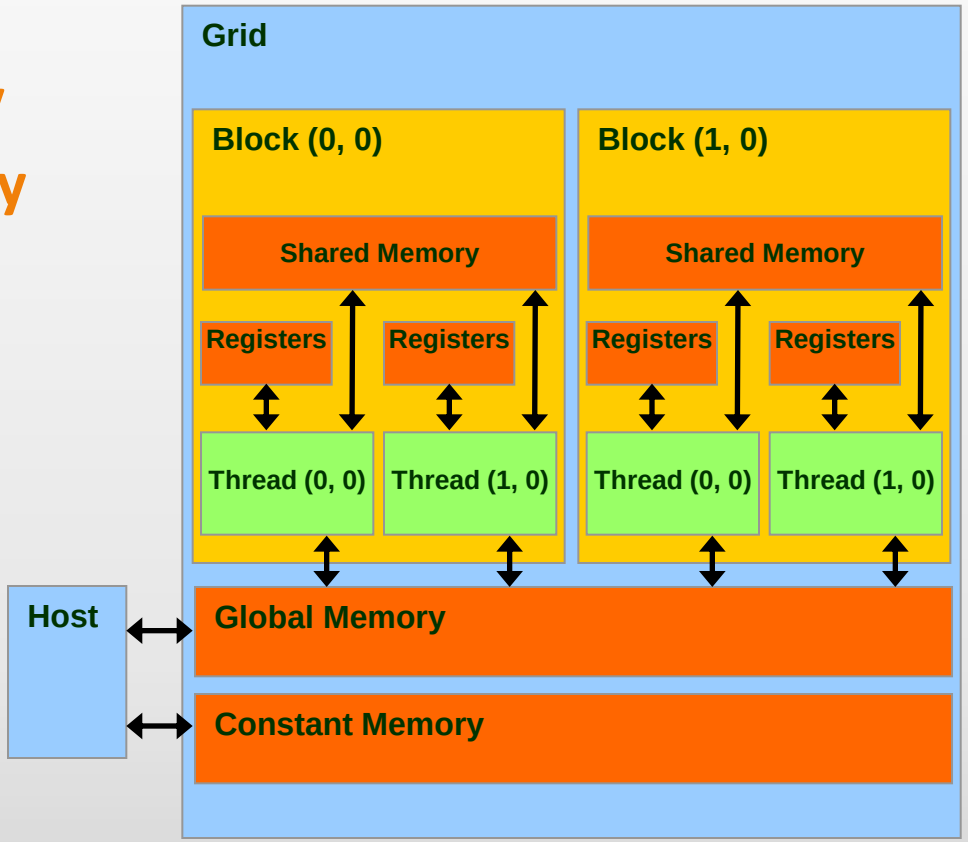
- At the bottom of the figure, we see global memory and constant memory
- These types of memory can be written (W) and read (R) by the host by calling API functions
- The **constant memory** supports short-latency, high-bandwidth, **read-only access by the device** when all threads simultaneously access the same location



Programmer View of CUDA Memories

Device code 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**

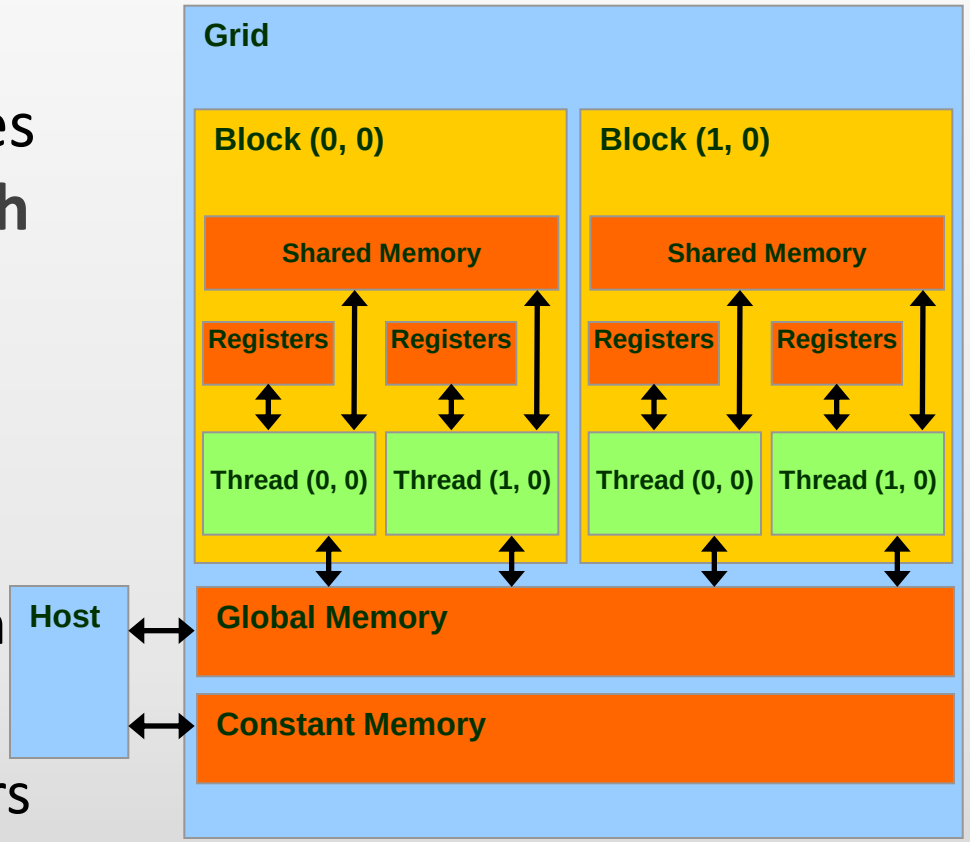


Host code can:

- Transfer data to/from per-grid global and constant memories

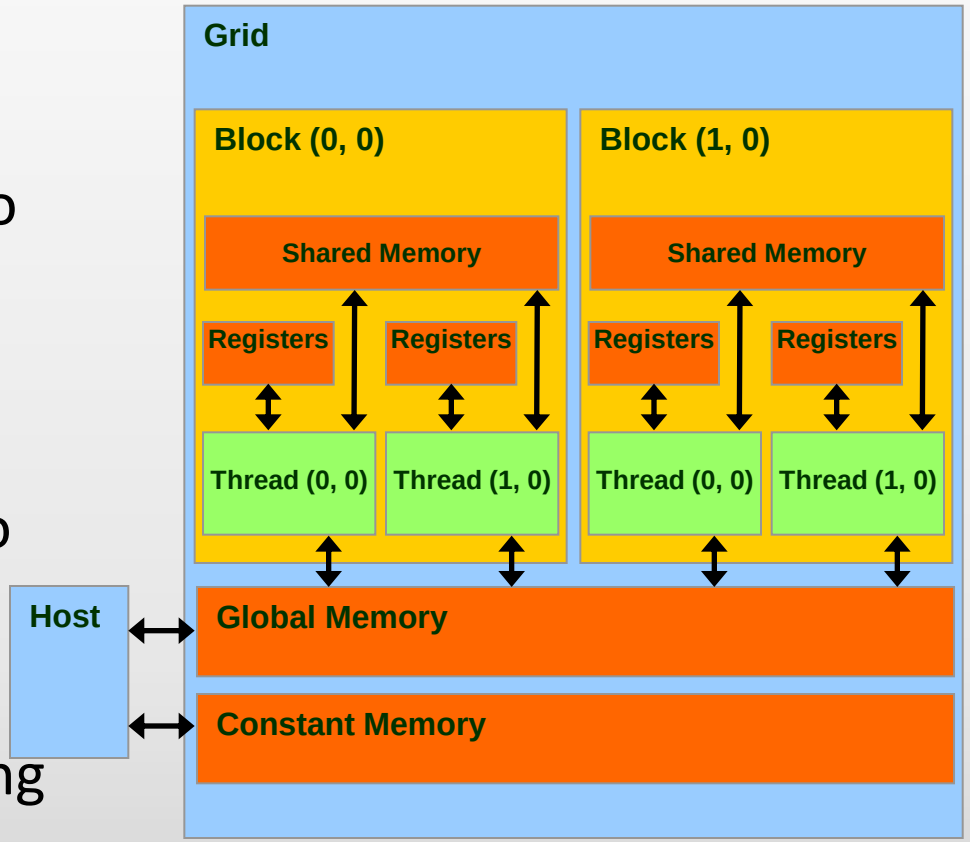
Programmer View of CUDA Memories

- **Registers** and **shared memory** are on-chip memories
- Variables on these memories can be **accessed at very high speed** in a highly parallel manner
- **Registers** are allocated to individual threads and each thread can only access its own registers
- A kernel function uses registers to hold frequently accessed variables private to each thread



Programmer View of CUDA Memories

- **Registers** and **shared memory** are on-chip memories
- **Shared memory** is allocated to thread blocks;
- **all threads in a block** can access variables in the **shared memory** locations allocated to the block
- Shared memory is used by threads to cooperate by sharing their input data and the intermediate results



Variables

- Table presents the CUDA syntax for declaring program variables into the various types of device memory
- Each declaration gives to CUDA variable:
  - A **scope** identifies the range of threads that can access the variable: single thread only, all threads of a block, or all threads of all grids
  - A **lifetime** specifies the portion of the program's execution duration when the variable is available for use: either within a kernel's invocation or throughout the entire application

Variable declaration	Memory	Scope	Lifetime
Automatic Variables	register	thread	kernel
`__device__ __shared__ int SharedVar;`	shared	block	kernel
`__device__ int GlobalVar;`	global	grid	application
`__device__ __constant__ int ConstantVar;`	constant	grid	application

A motivating example

- Lets assume that:
  - We have a kernel that requires 48 registers per thread
  - Target platform is a GTX 580 card (CC 2.0, 16SMs, 32k registers/SM)
  - Execution configuration is a grid of 4x5x3 blocks, each 100 threads
- Each block requires 100*48=4800 registers
- The grid is made of 4*5*3 = 60 blocks that need to be distributed to the 16 SMs of the card

A motivating example

- There will be 12 SMs that will receive 4 blocks and 4 SMs that will receive 3 blocks → Inefficient
- Additionally, each of the 100-thread blocks would be split into

$$\lceil \frac{100}{warpSize} \rceil = \lceil \frac{100}{32} \rceil = 4$$

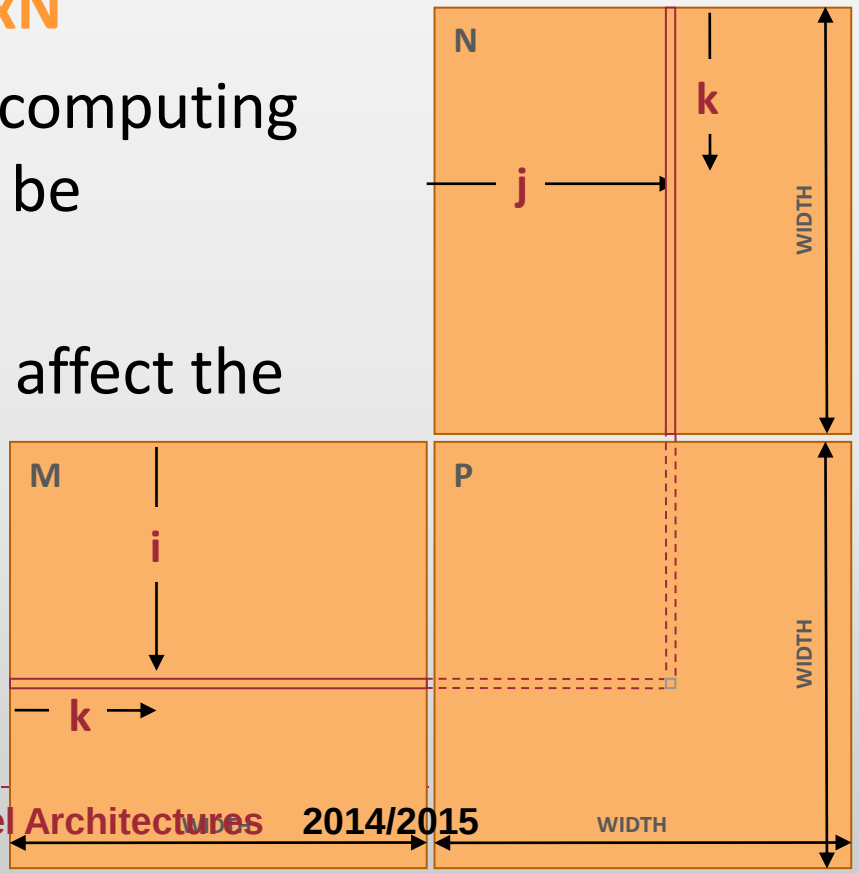
warps

- The first three warps would have 32 threads and the last would have 4 threads !
- So during the execution of the last warp of each block, of the SPs will be idle

$$\frac{32 - 4}{32} = 87.5\%$$

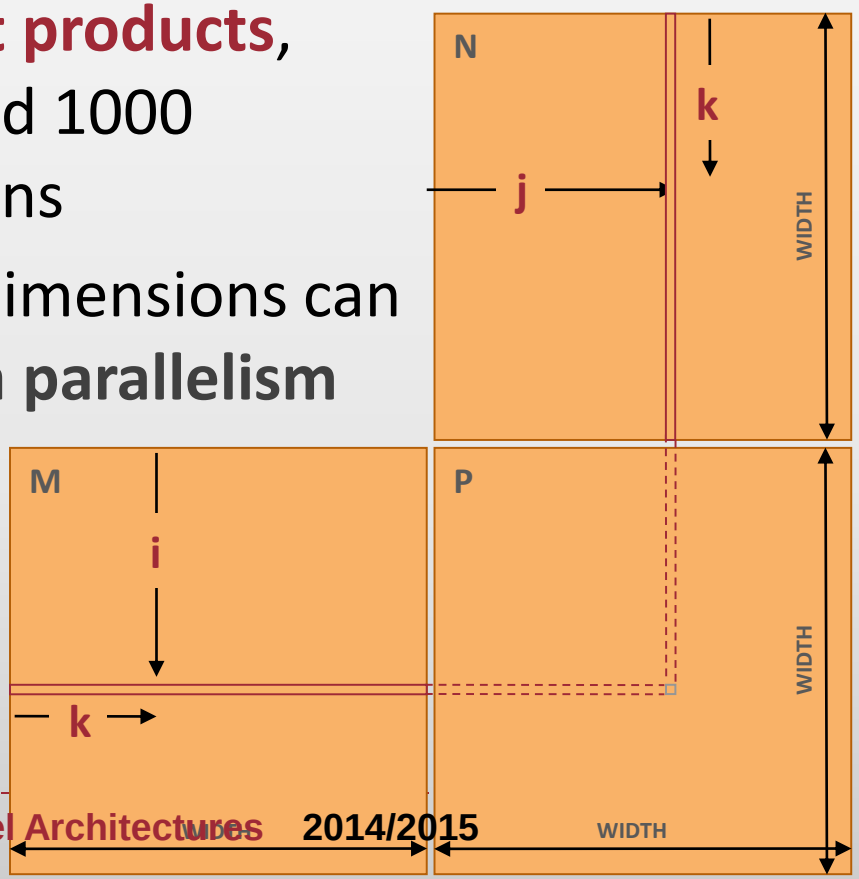
Matrix multiplication

- Each element of the product matrix P is generated by performing a dot product between a row of input matrix M and a column of input matrix N: **P=MxN**
- The dot product operations for computing different matrix P elements can be simultaneously performed
- None of these dot products will affect the results of each other



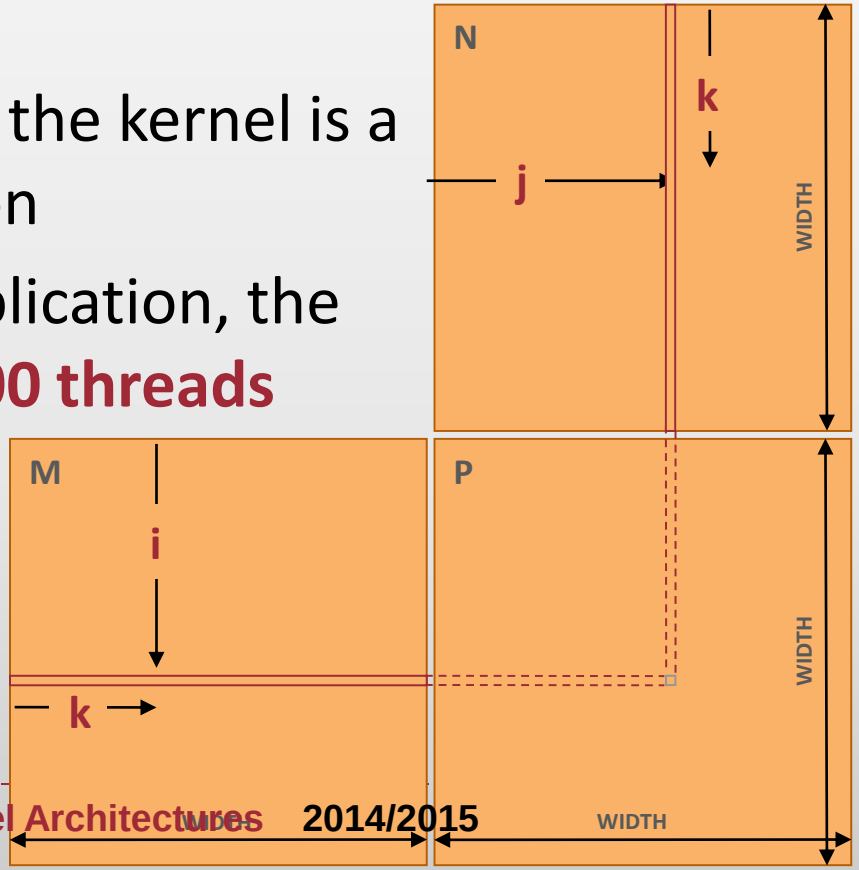
Matrix multiplication

- For large matrices, the number of dot products can be very large
- Example, a **1000 x 1000 matrix multiplication** has **1,000,000 independent dot products**, each involving 1000 multiply and 1000 accumulate arithmetic operations
- **Matrix multiplication** of large dimensions can have **very large amount of data parallelism**



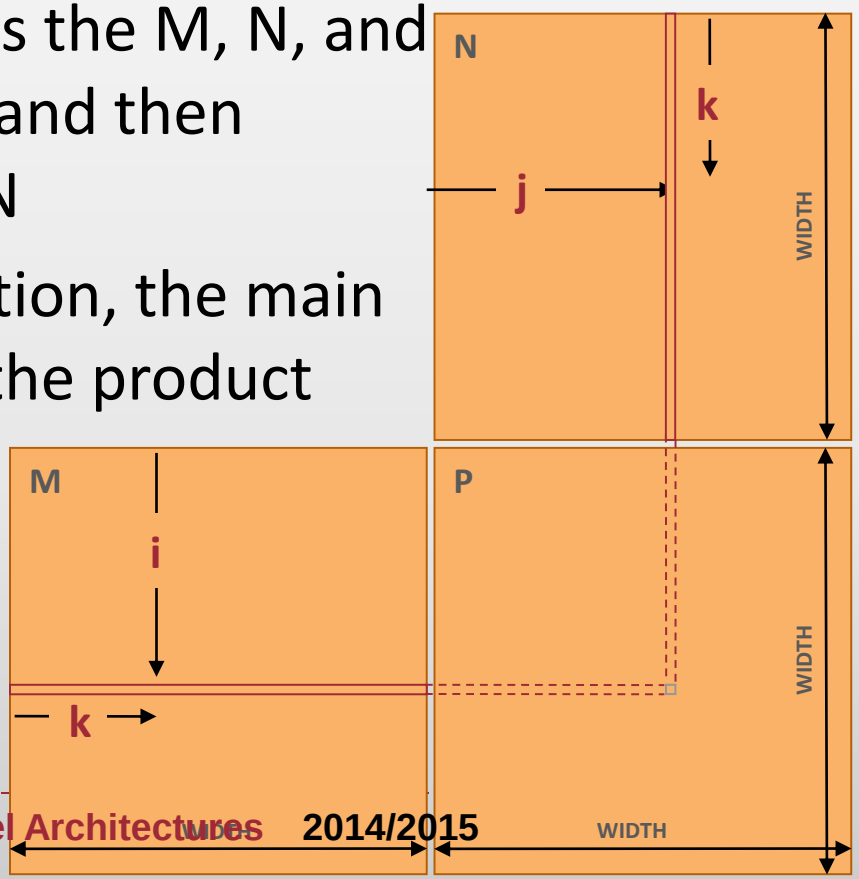
Matrix multiplication

- the entire **matrix multiplication computation** can be implemented as a **kernel**
- **Each thread** is used to compute **one element** of output matrix P
- The number of threads used by the kernel is a function of the matrix dimension
- For a 1000 x 1000 matrix multiplication, the kernel would generate **1,000,000 threads** when it is invoked



Matrix multiplication

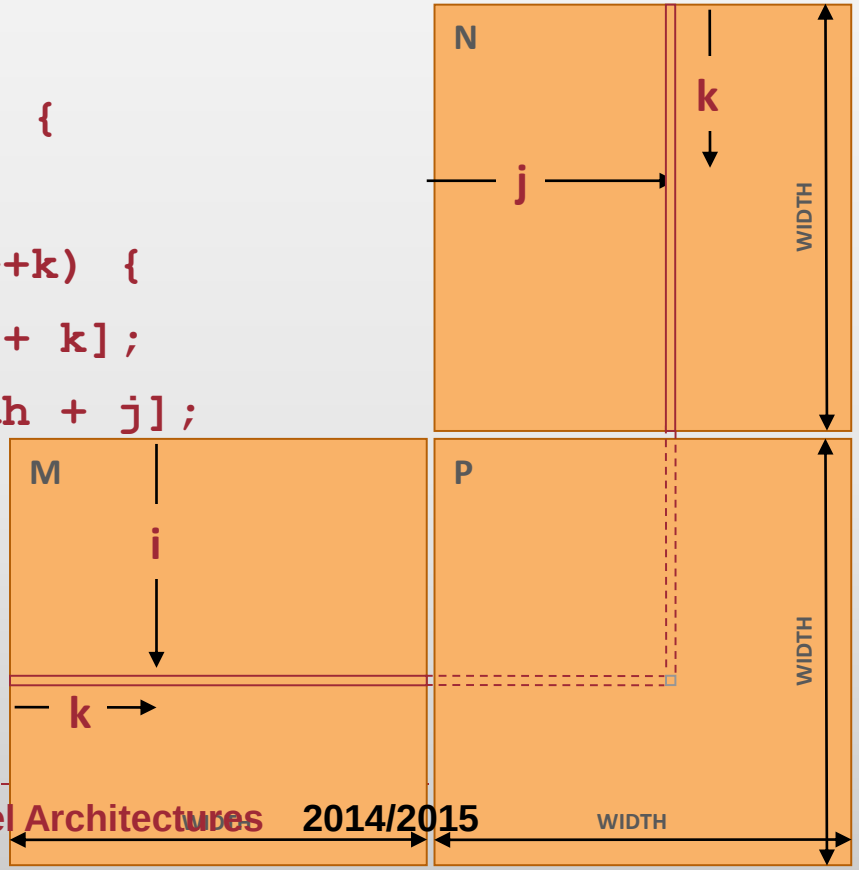
- Assume that the **matrices are square** in shape, and the dimension of each matrix is specified by the parameter **WIDTH**
- The **main program** first allocates the M, N, and P matrices in the host memory and then performs I/O to read in M and N
- After completing the multiplication, the main function performs I/O to write the product matrix P and to free memory



Matrix multiplication

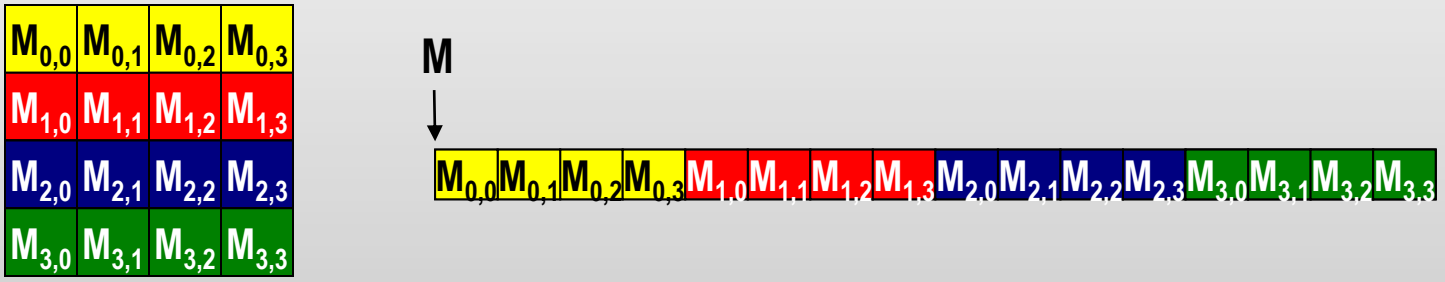
CPU-only matrix multiplication function

```
void MatrixMulOnHost(float* M, float* N,
  float* P, int Width)
{
for (int i = 0; i < Width; ++i)
  for (int j = 0; j < Width; ++j) {
     float sum = 0;
     for (int k = 0; k < Width; ++k) {
          float a = M[i  * width + k];
             float b = N[k * width + j];
             sum += a * b;
          }
          P[i * Width + j] = sum;
       }
}
```



Matrix multiplication

- The index used for accessing the M matrix in the innermost loop is i*Width+k
- The M matrix elements are placed into the system memory according to the row-major convention:
  - All elements of a row are placed into consecutive memory locations
  - The rows are then placed one after another



Matrix multiplication

- To port the matrix multiplication function into CUDA, we can modify the MatrixMultiplication() function to move the bulk o the calculation to a CUDA device

```
void MatrixMulOnDevice(float* M, float* N, float* P, int Width)
{
    int size = Width * Width * sizeof(float);
     float* Md, Nd, Pd;
   …
1.// Allocate device memory for M, N, P and
       // load M, N to device memory
2.// Kernel invocation code to have the device to perform
       // the actual matrix multiplication
3.// copy P from the device
         // Free device matrices
}
```

Matrix multiplication

- To port the matrix multiplication funct… can modify the MatrixMultiplication() fun… ulk o… the calculation to a CUDA device

```
void MatrixMulOnDevice(float* M, float… idth)
{
    int size = Width * Width …
     float* Md, Nd, …
   …
1.// Allocate device memory for M, N, P and
       // load M, N to device memory
2.// Kernel invocation code to have the device to perform
       // the actual matrix multiplication
3.// copy P from the device
         // Free device matrices
}
```

Part 1
- **allocates** device (GPU) memory to hold copies of the M, N, and P matrices, and
- **copies** these matrices over to the device memory

Matrix multiplication

- To port the matrix multiplication functi… can modify the MatrixMultiplication() fun… ulk o… the calculation to a CUDA device

```
void MatrixMulOnDevice(float* M, float… idth)
{
    int size = Width * Width * si…
     float* Md, Nd, Pd;
   …
1.// Allocate d… e memory for M, N, P and
       // load M, N to device memory
2.// Kernel invocation code to have the device to perform
       // the actual matrix multiplication
3.// copy P from the device
         // Free device matrices
}
```

Part 2
- invokes a kernel that launches parallel execution of the actual matrix multiplication on the device

Matrix multiplication

- To port the matrix multiplication functi… can modify the MatrixMultiplication() fun… ulk o… the calculation to a CUDA device

```
void MatrixMulOnDevice(float* M, float… idth)
{
    int size = Width * Width * siz…
     float* Md, Nd, Pd;
   …
1.// Allocate device …y for M, N, P and
       // load M … to device memory
2.// Kernel …vocation code to have the device to perform
       // the actual matrix multiplication
3.// copy P from the device
         // Free device matrices
}
```

Part 3
- copies the product matrix P from the device memory back to the host memory

Matrix multiplication

Assume M, N and P are on the **host** and Md, Nd and Pd on **device**

```
void MatrixMulOnDevice(float* M, float* N, float* P, int Width)
{
    int size = Width * Width * sizeof(float);
     float* Md, Nd, Pd;
    …
1. // Allocate and Load M, N to device memory
      cudaMalloc(&Md, size);
      cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);
      cudaMalloc(&Nd, size);
      cudaMemcpy(Nd, N, size, cudaMemcpyHostToDevice);
      // Allocate P on the device
      cudaMalloc(&Pd, size);
```

Matrix multiplication

Assume M, N and P are on the **host** and

```
void MatrixMulOnDevice(float* M, floa
{
    int size = Width * Width * sizeof(
     float* Md, Nd, Pd;
    …
1. // Allocate and Load M, N to device me
     cudaMalloc(&Md, size);
     cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);
     cudaMalloc(&Nd, size);
     cudaMemcpy(Nd, N, size, cudaMemcpyHostToDevice);
     // Allocate P on the device
     cudaMalloc(&Pd, size);
```

The two symbolic constants, `cudaMemcpyHostToDevice` and `cudaMemcpyDeviceToHost` are predefined constants of the CUDA programming environment, recognized by `cudaMemcpy`

Matrix multiplication

```
2.    // Kernel invocation code – to be shown later
      …
3.     // Read P from the device
       cudaMemcpy(P, Pd, size, cudaMemcpyDeviceToHost);
        // Free device matrices
       cudaFree(Md);
       cudaFree(Nd);
       cudaFree (Pd);
      }
```

- the product data is copied from device memory to host memory so the value will be available to main() by a call to the `cudaMemcpy()` function
- Then Md, Nd, and Pd are freed from the device memoryby calls to the `cudaFree()` functions

Matrix multiplication

```
// Matrix multiplication kernel – thread specification
__global__ void MatrixMulKernel(float* Md, float* Nd, float* Pd, int
   Width)
{
// 2D Thread ID
int tx = threadIdx.x;
int ty = threadIdx.y;
// Pvalue stores the Pd element that is computed by the thread
float Pvalue = 0;
for (int k = 0; k < Width; ++k)
   {
   float Mdelement = Md[ty * Md.width + k];
   float Ndelement = Nd[k * Nd.width + tx];
   Pvalue += Mdelement * Ndelement;
   }
// Write the matrix to device memory each thread writes one element
Pd[ty * Width + tx] = Pvalue;
}
```

Matrix multiplication

```
// Matrix multiplication kernel – thread specification
__global__ void MatrixMulKernel(float* Md, float* Nd, float*
   Pd, int Width)
{
// 2D Thread ID
int tx = threadIdx.x;
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float Pvalue = 0;
for (int k = 0; k < Width; ++k)
   {
   float Mdelement = Md[ty * Md.width + k];
   float Ndelement = Nd[k * Nd.width + tx];
   Pvalue += Mdelement * Ndelement;
   }
// Write the matrix to device memory each thread writes one element
Pd[ty * Width + tx] = Pvalue;
}
```

The CUDA-specific keyword `__global__` in front of the declaration of `MatrixMulKernel()` indicates that the function is a kernel and that it can be called from a host functions to generate a grid of threads on a device

Matrix multiplication

```
// Matrix multiplication kernel –
__global__ void MatrixMulKernel(fl
   Width)
{
// 2D Thread ID
int tx = threadIdx.x;
int ty = threadIdx.y;
// Pvalue stores the Pd eleme
float Pvalue = 0;
for (int k = 0; k < Width; ++k)
   {
   float Mdelement = Md[ty * Md.width + k];
   float Ndelement = Nd[k * Nd.width + tx];
   Pvalue += Mdelement * Ndelement;
   }
// Write the matrix to device memory each thread writes one element
Pd[ty * Width + tx] = Pvalue;
}
```

- The keywords `threadIdx.x` and `threadIdx.y` refer to the thread indices of a thread
- The original loop variables i and j are now replaced with `threadIdx.x` and `threadIdx.y`
- The CUDA threading hardware generates all of the `threadIdx.x` and `threadIdx.y` values for each thread, instead of the loop increment the values of i and j for loop iteration

Matrix

```
// Matri
__global
   Width
{
// 2D Th
int tx =
int ty =
// Pvalu
float Pv
for (int
   {
   float
   float
   Pvalu
   }
// Write
Pd[ty * Wid
}
```

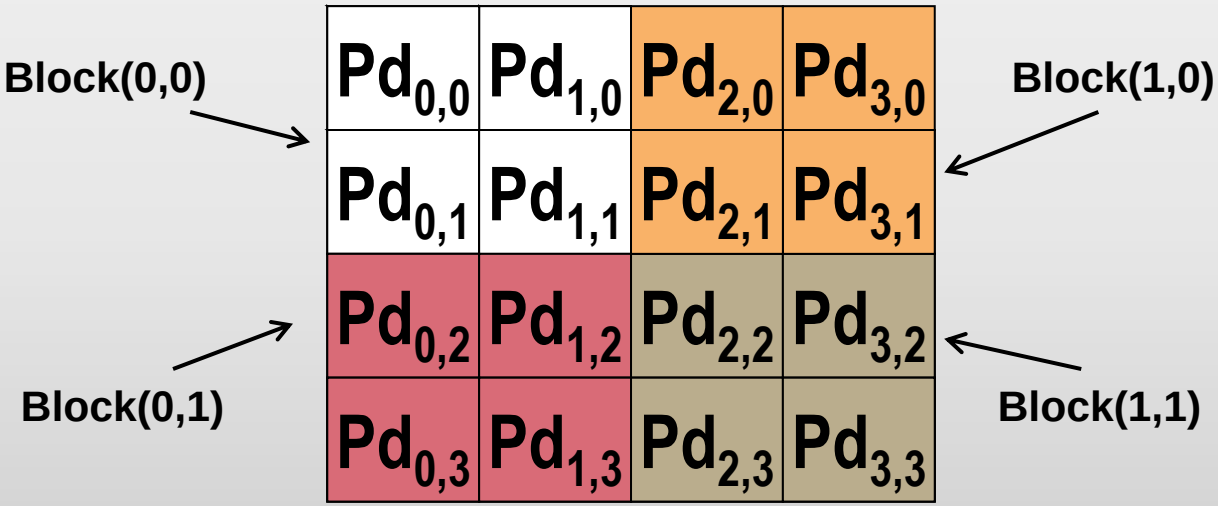
- One limitation of this simple code is that it can only handle matrices of up to 16x16
- This limitation comes from the fact that **the kernel function does not use** `blockIdx`
- As a result, we are limited to using **only one block of threads**
- Even if we used more blocks, threads from different blocks would calculate the same Pd element if they have the same threadIdx value
- Because a thread block can have only up to 512 threads, and each thread calculates one element of the product matrix, **the code can only calculate a product matrix of up to 512 elements**
- For square matrices, we are limited to 16x16 because 32x32 requires more than 512 threads per block
- This is obviously **not acceptable**
- The product matrix must have millions of elements in order to have a sufficient amount of data parallelism to benefit from execution on a device
- **We revise the matrix multiplication kernel function using multiple blocks**

Matrix multiplication

- In order to accommodate larger matrices, we need to use **multiple thread blocks**
- Conceptually, **we break Pd into square tiles**
- All the Pd **elements of a tile** are computed by a **block of threads**
- By keeping the dimensions of these Pd tiles small, we keep the total number of threads in each block under 512, the maximal allowable block size
- We abbreviate `threadIdx.x` and `threadIdx.y` as `tx` and `ty`, and `blockIdx.x` and `blockIdx.y` as `bx` and `by`

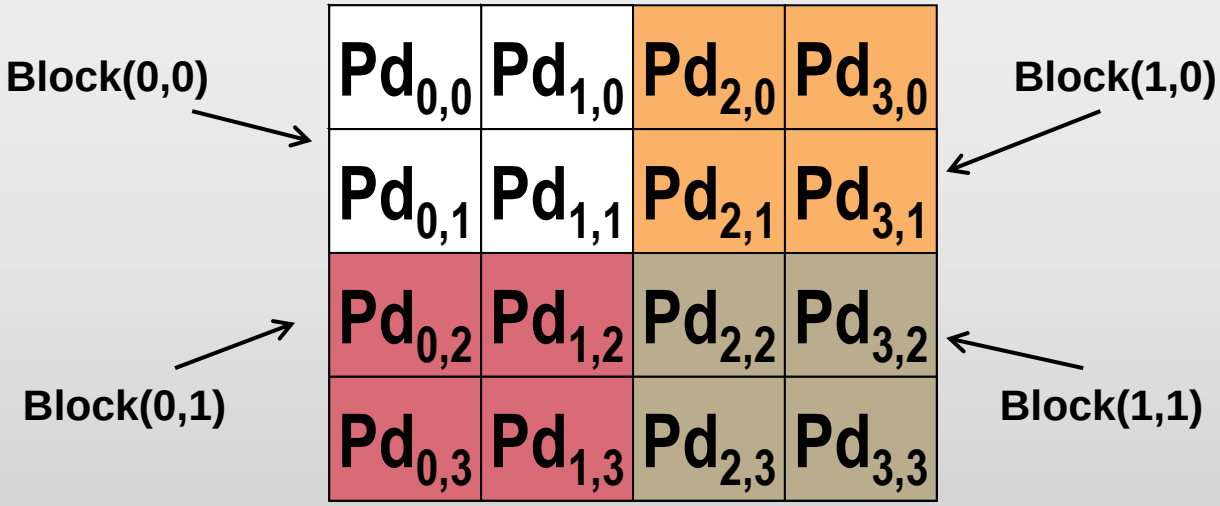
Matrix multiplication

- Consider a matrix 4x4, a very small TILE_WIDTH value (2) and divide the matrix into 4 tiles
- We create blocks organized into 2x2 arrays of threads
- Each block calculates 4 Pd elements



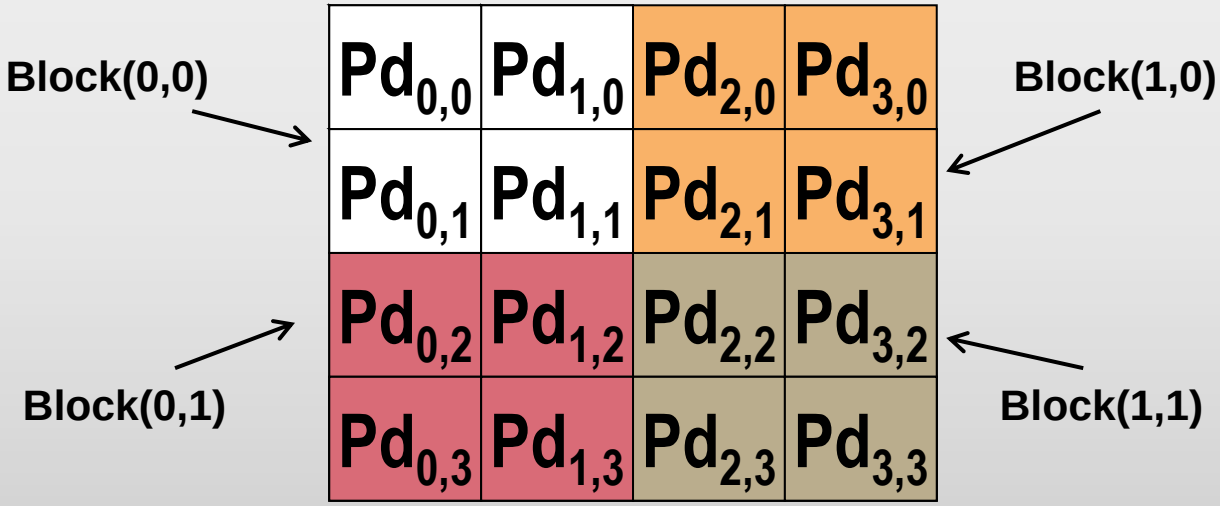
Matrix multiplication

- Thread (0, 0) of block (0, 0) calculates Pd0,0, whereas thread (0, 0) of block (1, 0) calculates Pd2,0
- the Pd element calculated by thread (0, 0) of block (1, 0) can be computed by
- Pd[bx* TILE_WIDTH + tx] [by* TILE_WIDTH + ty] =Pd[1*2 + 0][0*2 + 0] = Pd[2][0]



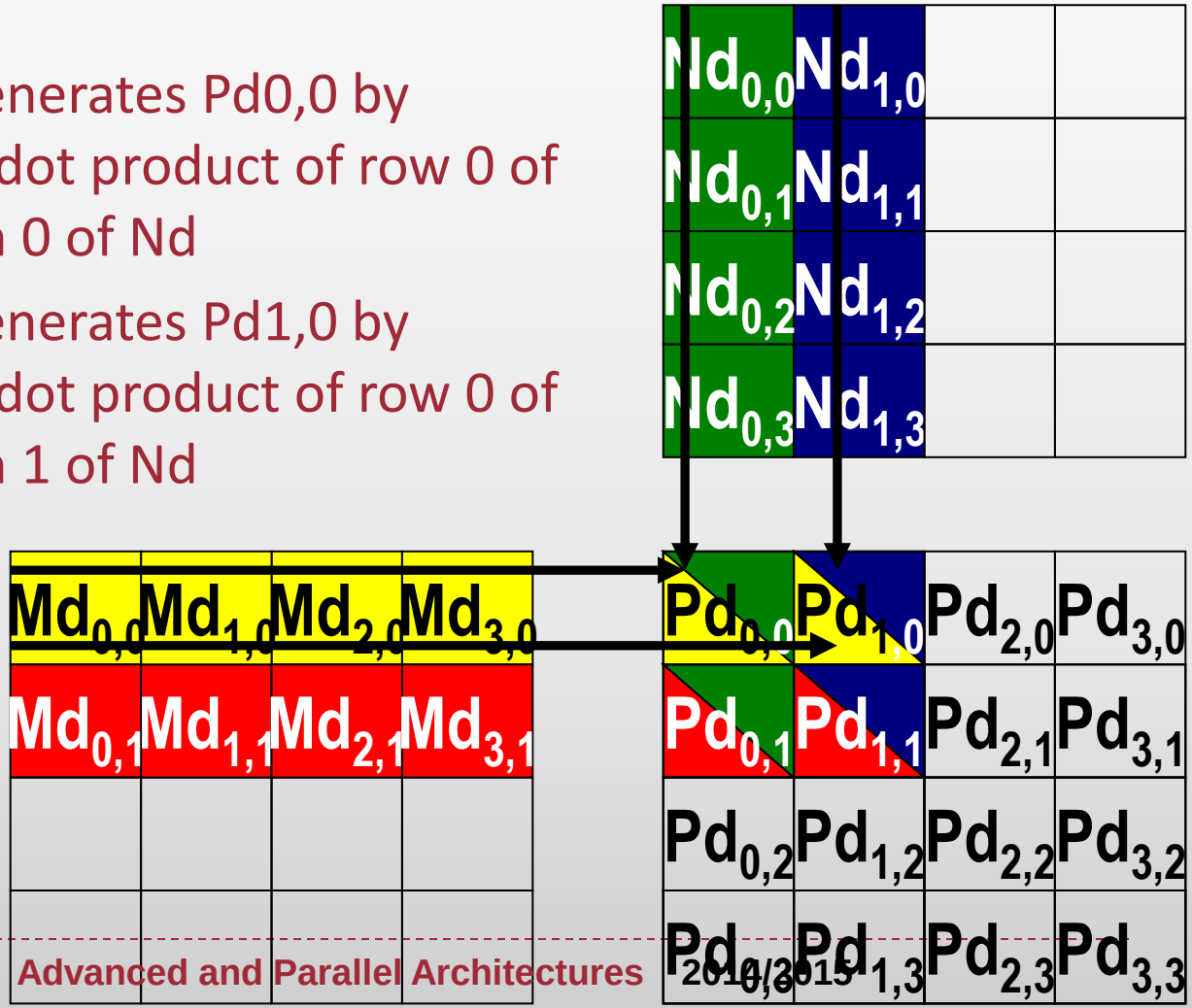
Matrix multiplication

- We also need the row (y) index of Md and the column (x) index of Nd for input values
- the row index of Md used by thread (tx, ty) of block (bx, by) is (by*TILE_WIDTH + ty)
- The column index of Nd used by the same thread is (bx*TILE_WIDTH + tx)



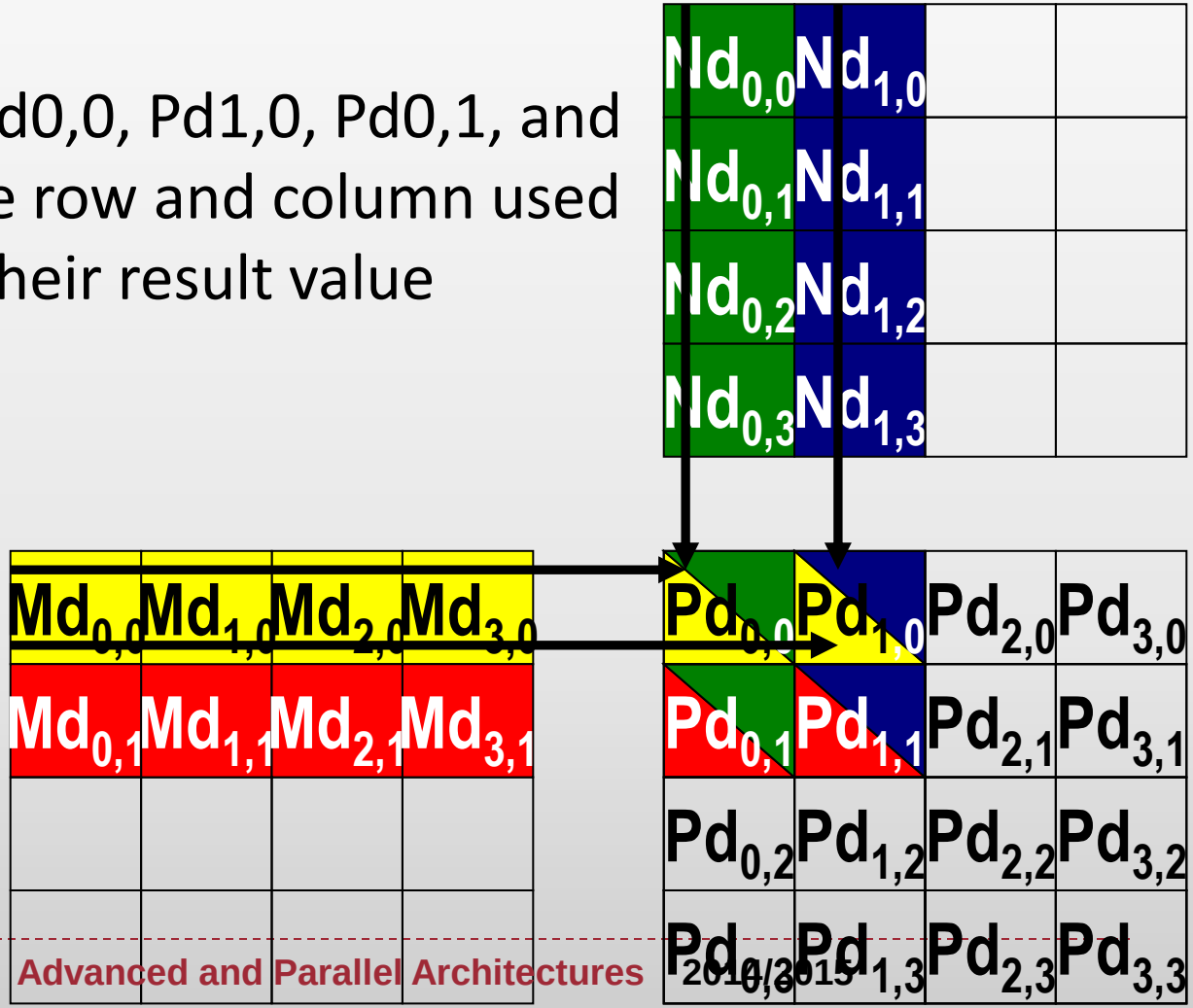
Matrix multiplication

- Threads in block (0, 0) produce four dot products:
  - Thread (0, 0) generates Pd0,0 by calculating the dot product of row 0 of Md and column 0 of Nd
  - Thread (1, 0) generates Pd1,0 by calculating the dot product of row 0 of Md and column 1 of Nd
  - …



Matrix multiplication

- The arrows of Pd0,0, Pd1,0, Pd0,1, and Pd1,1 shows the row and column used for generating their result value



Matrix multiplication

- Revised matrix multiplication kernel function with 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 index of Pd and N
int Col = blockIdx.x*TILE_WIDTH + threadIdx.x;

float Pvalue = 0;
// each thread computes one e    ent
    sub-matrix
for (int k = 0; k < Width; ++k)
  Pvalue += Md[Row*Width+k] * Nd[k

  Pd[Row*Width+Col] = Pvalue;
```

each thread uses its `blockIdx` and `threadIdx` values to identify the row index (Row) and the column index (Col) of the Pd element

Matrix multiplication

- Revised matrix multiplication kernel funct

```
__global__ void MatrixMulKernel(flo
    Nd, float* Pd, int Width)
{
// Calculate the row index of the P
int Row = blockIdx.y*TILE_WIDTH + t
// Calculate the column index of
int Col = blockIdx.x*TILE_WIDT

float Pvalue = 0;
// each thread compute 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;
```

It then performs a dot product on the row of Md and column of Nd to generate the value of the Pd element It eventually writes the Pd value to the appropriate global memory location

Matrix multiplication

- This kernel can handle matrices of up to 16 x 65,535 elements in each dimension
- In the situation where matrices larger than this new limit are to be multiplied, one can divide the Pd matrix into submatrices of a size permitted by the kernel
- All blocks can run in parallel with each other and will fully utilize parallel execution resources

Matrix multiplication

- Revised host code to be used in the MatrixMultiplication() to launch the revised kernel MatrixMulKernel() with multiple blocks
- Note that the dimGrid is Width/TILE_WIDTH for both the x dimension and the y dimension

```
// Set up the execution configuration
dim3 dimGrid(Width/TILE_WIDTH,Width/TILE_WIDTH)
dim3 dimBlock(TILE_WIDTH,TILE_WIDTH)

// launch the device computation thread
MatrixMulKernel<<<dimGrid, dimBlock>>>(Md,Nd,Pd,Width);
```

Matrix multiplication

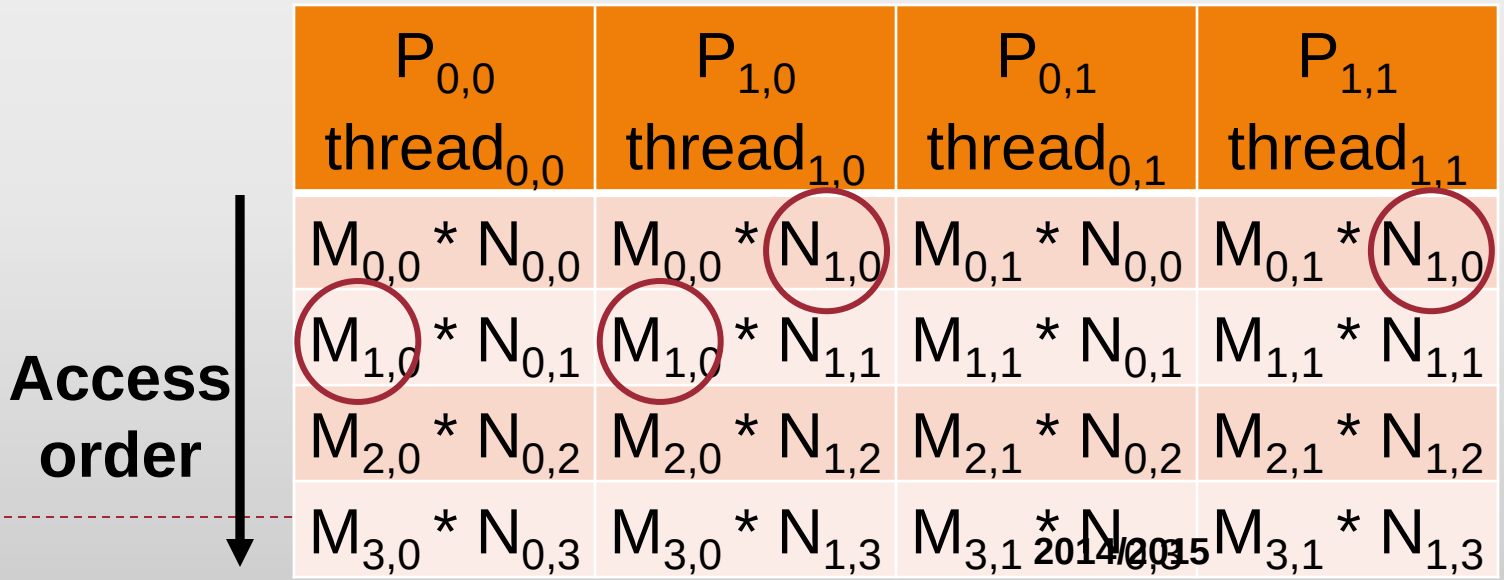
- The table shows the global memory accesses done by all threads in block(0,0)
- The threads are listed in the horizontal direction, with the time of access increasing downward in the vertical direction
- Each thread accesses **4 elements of Md** and **4 elements of Nd** during its execution.

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

Access order

Matrix multiplication

- Among the four threads highlighted, there is a significant **overlap** in terms of the Md and Nd elements they access:
  - thread(0,0) and thread(1,0) both access Md1,0 as well as the rest of row 0 of Md
  - thread(1,0) and thread(1,1) both access Nd1,0 as well as the rest of column 1 of Nd

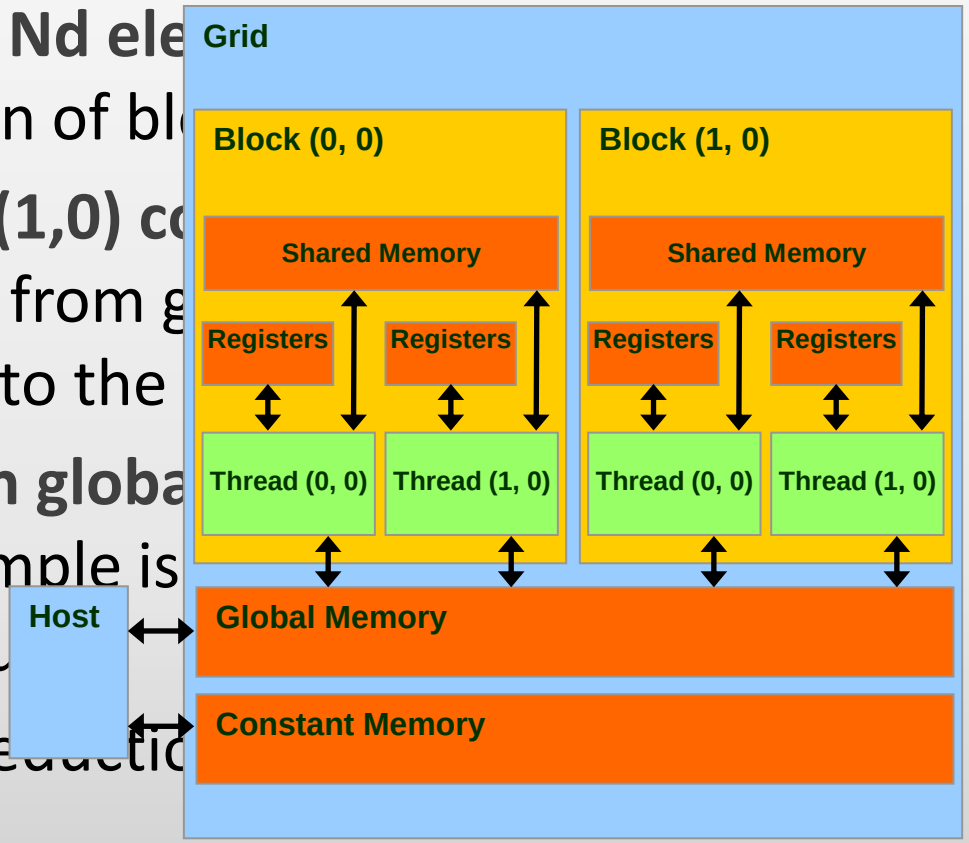


Matrix multiplication

- The kernel is written so both thread(0,0) and thread(1,0) access these Md row 0 elements from the **global memory**
- In general, **every Md and Nd element** is accessed exactly **twice** during the execution of block(0,0)
- If **thread(0,0) and thread(1,0) collaborate** so that Md elements are only loaded from global memory once, the total number of accesses to the global memory by half
- The potential **reduction in global memory traffic** in the matrix multiplication example is **proportional** to the **dimension of the blocks** used
- NxN blocks → potential reduction of global memory is N

Matrix multiplication

- The kernel is written so both thread(0,0) and thread(1,0) access these Md row 0 elements from the **global memory**
- In general, **every Md and Nd ele**
  twice during the execution of bl
- If **thread(0,0) and thread(1,0) c**
  elements are only loaded from g
  total number of accesses to the
- The potential **reduction in globa**
  matrix multiplication example is
  dimension of the blocks u
- NxN blocks → potential reductio

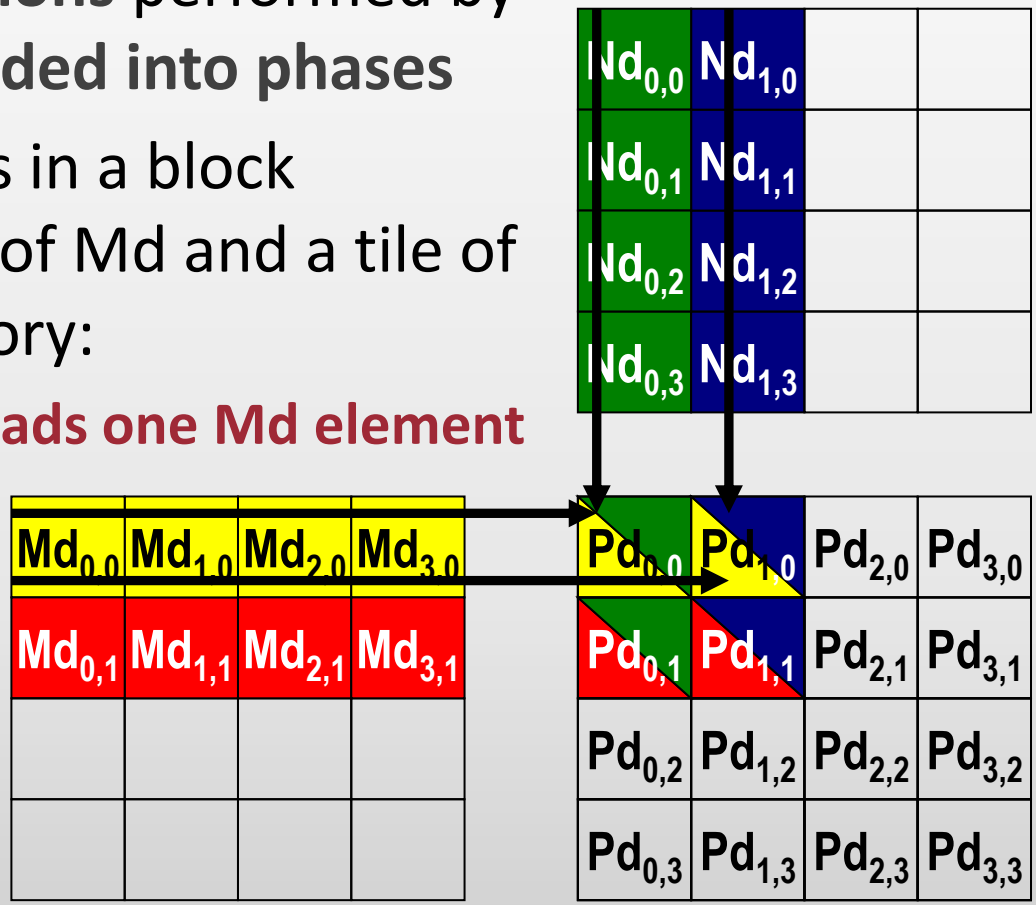


Matrix multiplication

- Algorithm where threads collaborate to reduce the traffic to the global memory:
  - threads collaboratively load Md and Nd elements into the **shared memory** before they individually use these elements in their dot product calculation.
- The size of the **shared memory is quite small**
- To no exceed the capacity of the shared memory when loading Md and Nd elements we can divide the Md and Nd matrices into **smaller tiles**

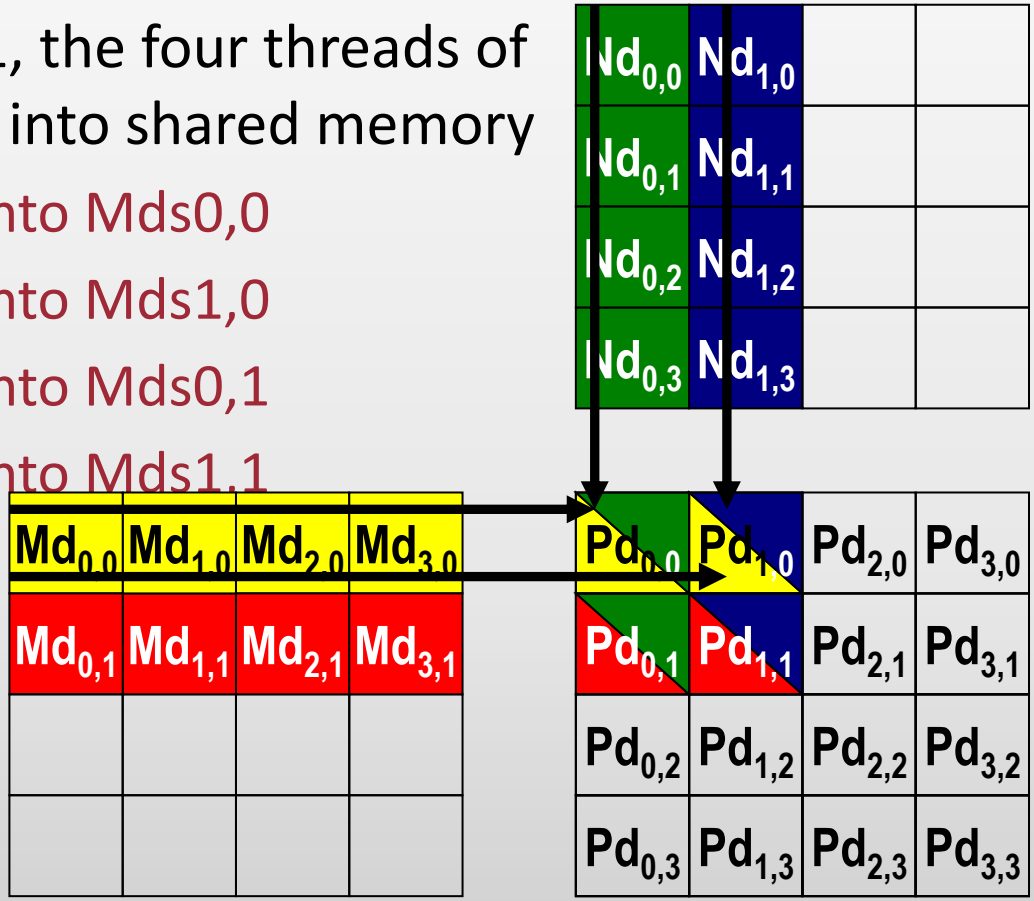
Matrix multiplication

- Divide Md and Nd into 2x2 tiles
- The **dot product calculations** performed by each thread are now **divided into phases**
- In each phase, all threads in a block collaborate to load a tile of Md and a tile of Nd into the shared memory:
  - **every thread in a block loads one Md element and one Nd element**



Matrix multiplication

- Activities of threads in block(0,0) (other blocks are the same)
- At the beginning of Phase 1, the four threads of block(0,0) load a tile of Md into shared memory
  - thread(0,0) loads Md0,0 into Mds0,0
  - thread(1,0) loads Md1,0 into Mds1,0
  - thread(0,1) loads Md0,1 into Mds0,1
  - thread(1,1) loads Md1,1 into Mds1,1



Matrix multiplication

- The shared memory array for the **Md** elements is called **Mds**, for the **Nd** elements is called **Nds**

	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 →

Matrix multiplication

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

- At the beginning of **Phase 1**, the four threads of block(0,0) load a tile of **Md** into the shared memory and a tile of **Nd**
- These values are used in the calculation of the dot product
- **Note that** each value in the shared memory is used **twice**

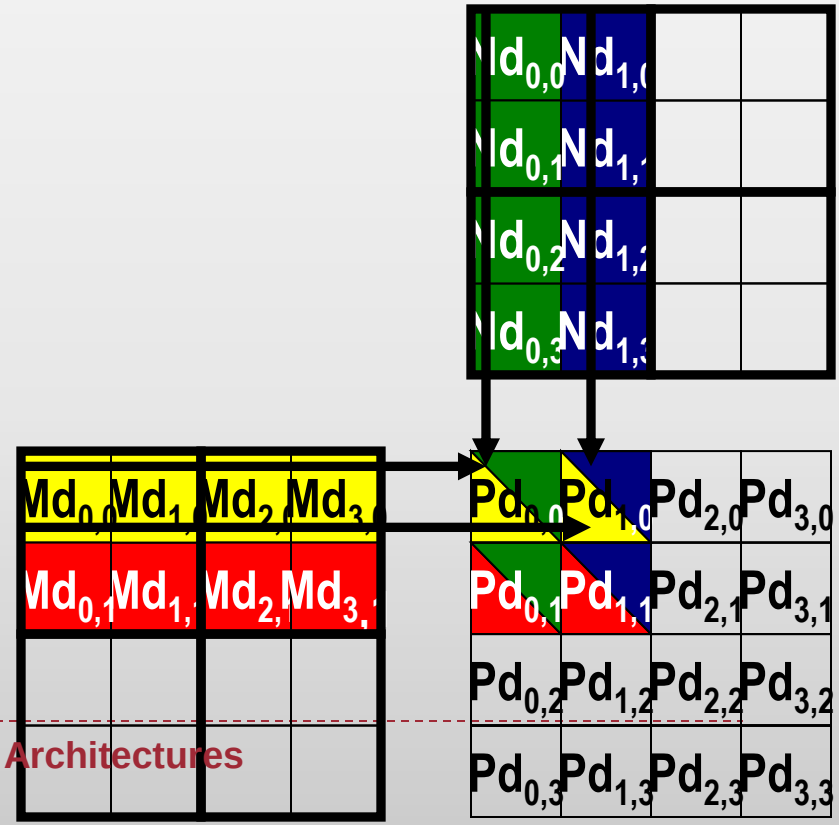
Example

- $Md_{0,1}$ is loaded by $thread_{0,1}$ into $Mds_{1,1}$ and is used once by $thread_{0,1}$ and once by $thread_{1,1}$
- **$Nd_{1,0}$** is loaded by $thread_{1,0}$ into $Nds_{1,0}$ and is used once by $thread_{1,0}$ and once by $thread_{1,1}$

Matrix multiplication

	Phase2		
$T_{0,0}$	**$Md_{2,0}$** ↓ $Mds_{0,0}$	**$Nd_{0,2}$** ↓ $Nds_{0,0}$	$PValue_{0,0}$ += $Mds_{0,0}$*$Nds_{0,0}$ + $Mds_{1,0}$*$Nds_{0,1}$
$T_{1,0}$	**$Md_{3,0}$** ↓ $Mds_{1,0}$	**$Nd_{1,2}$** ↓ $Nds_{1,0}$	$PValue_{1,0}$ += $Mds_{0,0}$*$Nds_{1,0}$ + $Mds_{1,0}$*$Nds_{1,1}$
$T_{0,1}$	**$Md_{2,1}$** ↓ $Mds_{0,1}$	**$Nd_{0,3}$** ↓ $Nds_{0,1}$	$PdValue_{0,1}$ += $Mds_{0,1}$*$Nds_{0,0}$ + $Mds_{1,1}$*$Nds_{0,1}$
$T_{1,1}$	**$Md_{3,1}$** ↓ $Mds_{1,1}$	**$Nd_{1,3}$** ↓ $Nds_{1,1}$	$PdValue_{1,1}$ += $Mds_{0,1}$*$Nds_{1,0}$ + $Mds_{1,1}$*$Nds_{1,1}$

- **Phase 2** is similar and it allow to complete the computation
- **Note that** the two phases use the same Mds e Nds.



Matrix multiplication

Tiled matrix multiplication **kernel** using **shared memories**

```
__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;
```

Matrix multiplication

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