ECE408/CS483/CSE408 Fall 2022

Applied Parallel Programming

Lecture 4:
Memory Model

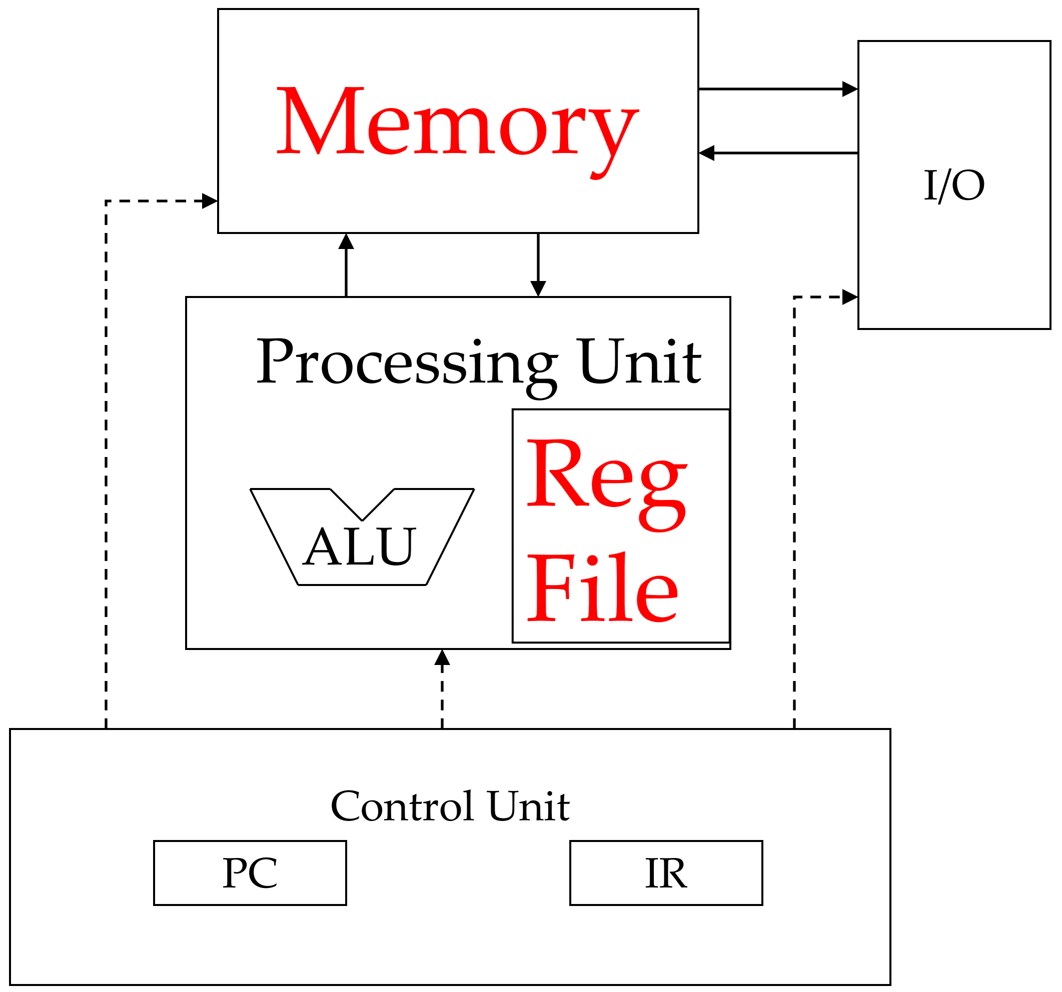
Course Reminders

- Lab 1 submission deadline is coming up
  - Instructions about how to submit will be posted any time now
  - Make sure to submit it by the deadline, no late submissions will be accepted
  - Make sure to submit the code **AND** only then answer the questions
- Lab 2 will be out soon, it is due next Friday
- The course staff only replies to questions posted on Campuswire
- Check out office hours schedule, there are many options

Objective

- To learn the basic features of the memories accessible by CUDA threads
- To prepare for MP-2 - basic matrix multiplication
- To learn to evaluate the performance implications of global memory accesses

The Von-Neumann Model



Instructions are Stored in Memory

- Every instruction needs to be fetched from memory, decoded, then executed.

- Instruction processing breaks into steps:

  Fetch | Decode | Execute | Memory

- Instructions come in three flavors:
  Operate, Data Transfer, and Control Flow.

Example: Processing an Add Instruction

- Example of an (LC-3) operate instruction:

  ADD R1, R2, R3
- meaning:
  - read R2 and R3
  - add them as unsigned/2's complement
  - write sum to R1

- Instruction processing for an operate instruction:

  Fetch | Decode | Execute | Memory

Example: Processing a Load Instruction

- Example of an (LC-3) data transfer instruction:

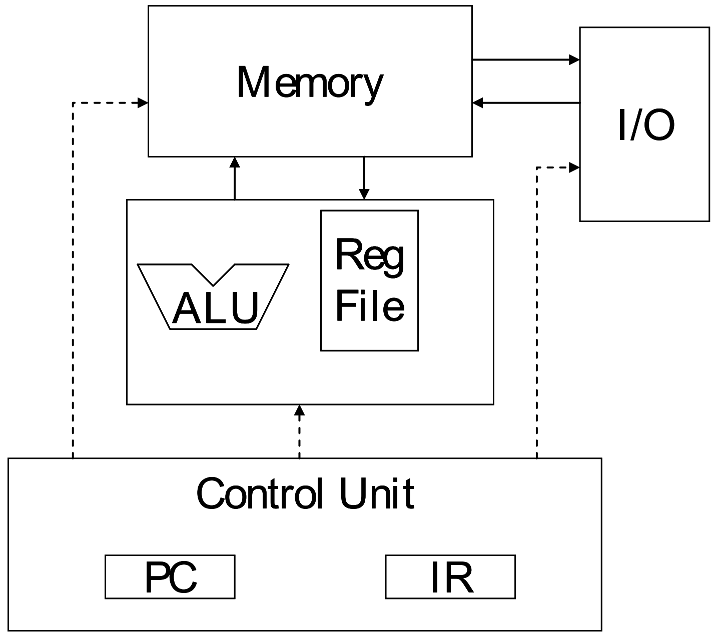
  LDR R4, R6, #3 ; a load

- meaning:
  - read R6
  - add the number 3 to it
  - load the contents of memory at the resulting address
  - write the bits to R4
- Instruction processing for a load instruction:

  Fetch | Decode | Execute | Memory

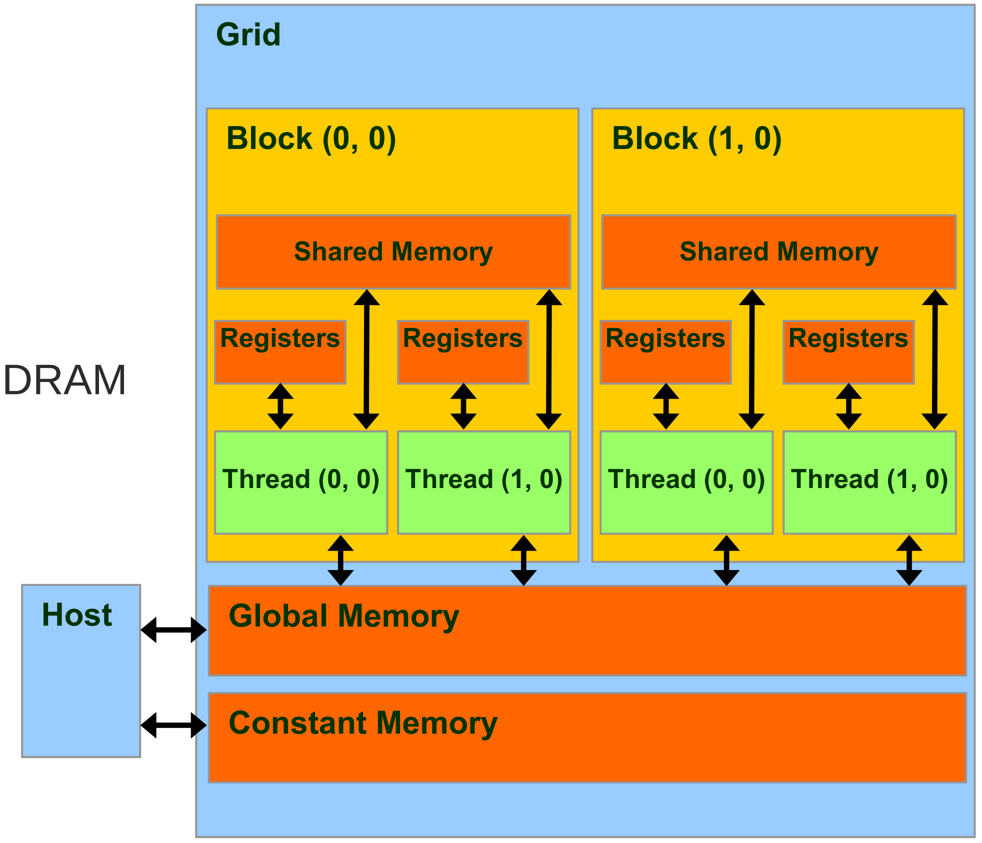
Registers vs Memory

- Registers
  - Fast: 1 cycle; no memory access required
  - Few: hundreds for CPU, O(10k) for GPU SM
- Memory
  - Slow: hundreds of cycles
  - Huge: GB or more



Programmer View of CUDA Memories

- Each thread can:
  - read/write per-thread **registers (~1 cycle)**
  - read/write per-block **shared memory (~5 cycles)**
  - read/write per-grid **global memory (~500 cycles)** off chip DRAM
  - read/only per-grid **constant memory (~5 cycles with caching)**



CUDA Variable Type Qualifiers

Variable declaration			Memory	Scope	Lifetime
		`int LocalVar;`	register	thread	thread
`__device__`	`__shared__`	`int SharedVar;`	shared	block	block
`__device__`		`int GlobalVar;`	global	app.	application
`__device__`	`__constant__`	`int ConstantVar;`	constant	app.	application

- `__device__`
  - optional with `__shared__` or `__constant__`
  - not allowed by itself within functions
- Automatic variables with no qualifiers
  - in registers for primitive types and structures
  - in global memory for per-thread arrays

Next Application: Matrix Multiplication

- Given two Width × Width matrices, M and N,
    - we can multiply M by N
    - to compute a third Width × Width matrix, P:
    - P = MN

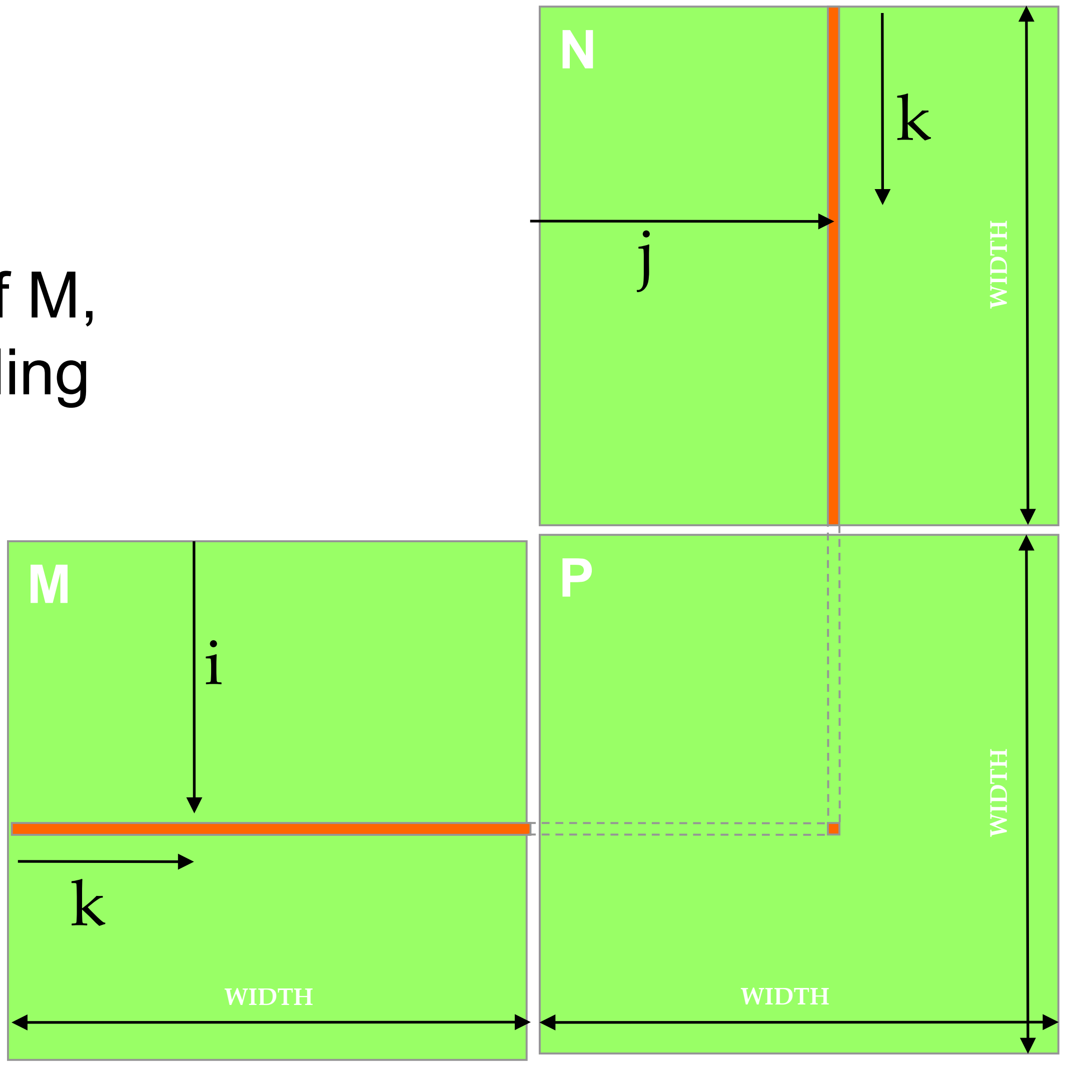
In terms of the elements of P, matrix multiplication implies computing…

$$P_{ij} = \sum_{k=1}^{Width} M_{ik} N_{kj}$$

Matrix Multiplication

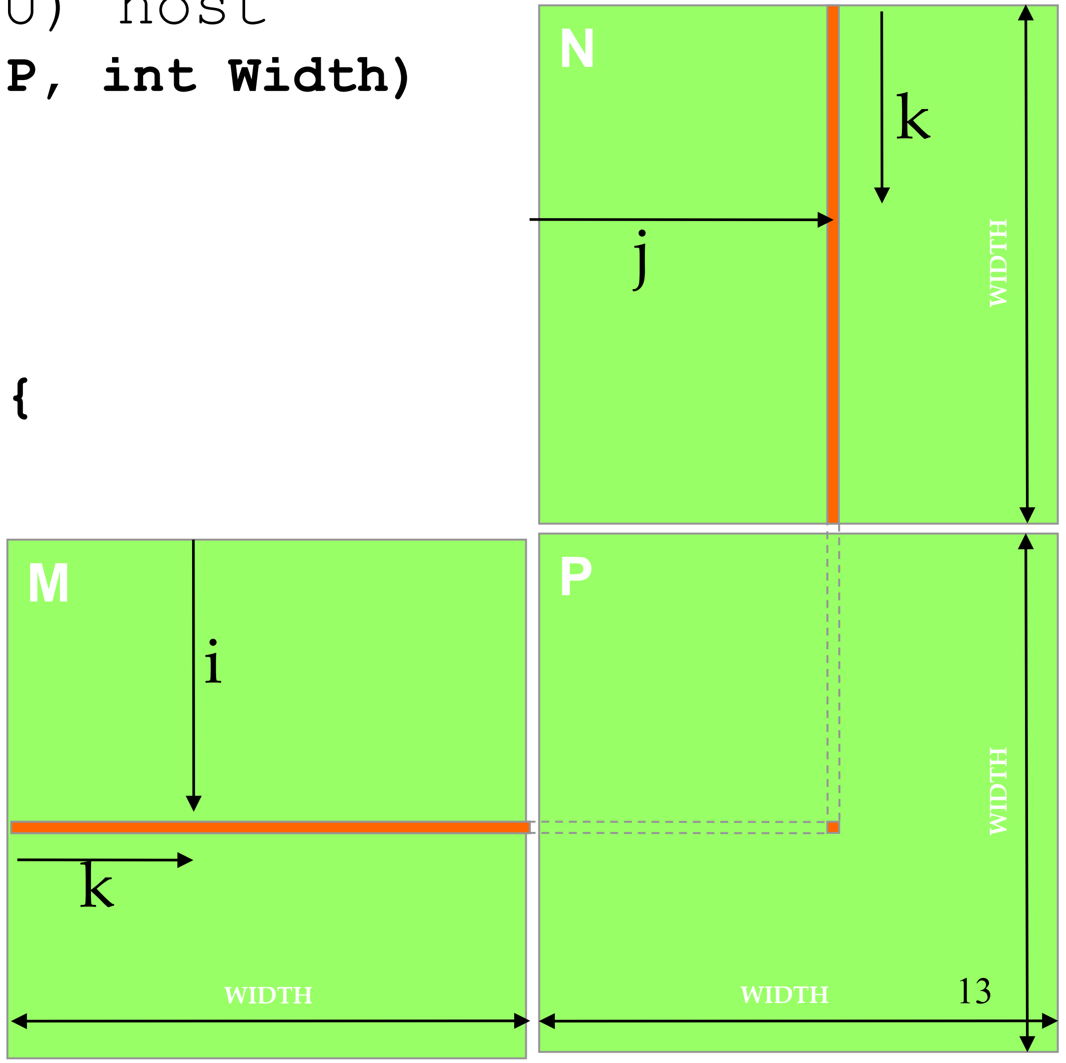
$$P_{ij} = \sum_{k=1}^{Width} M_{ik} N_{kj}$$

- Graphically, imagine
  - taking each element in a row of M,
  - multiplying it by the corresponding element in a column of N, and
  - summing up the products.
- Do that for every row and every column to produce P.



Matrix Multiplication Example
A Simple Host Version in C

```
// Matrix multiplication on the (CPU) host
void MatrixMul(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;
      }
}
```



Parallelize Elements of P

- What can we parallelize?
  - start with the **two outer loops**
  - parallelize **computation of elements of P**

- What about the inner loop?
  - Technically, floating-point is NOT associative.
  - The **parallel sum** is called a **reduction**—we'll come back to it in a few weeks.
  - For now, **use a single thread for each P_{ij}**.

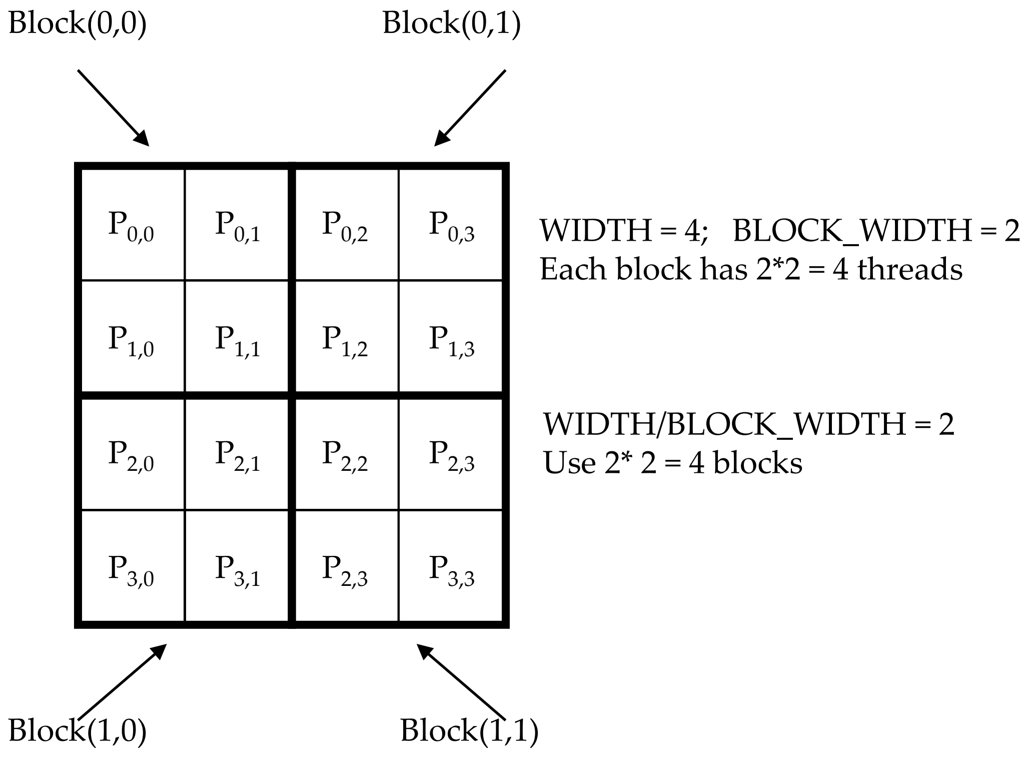
Compute Using 2D Blocks in a 2D Grid

- **P** is 2D, so organize threads in 2D as well:
  - Split the output **P** into square **tiles**
    - **of size TILE_WIDTH × TILE_WIDTH**
    - (a preprocessor constant).
  - **Each thread block produces one tile** of TILE_WIDTH^2 elements.
  - Create **[ceil (Width / TILE_WIDTH)]^2** thread **blocks** to cover the output matrix.

Kernel Function - A Small Example

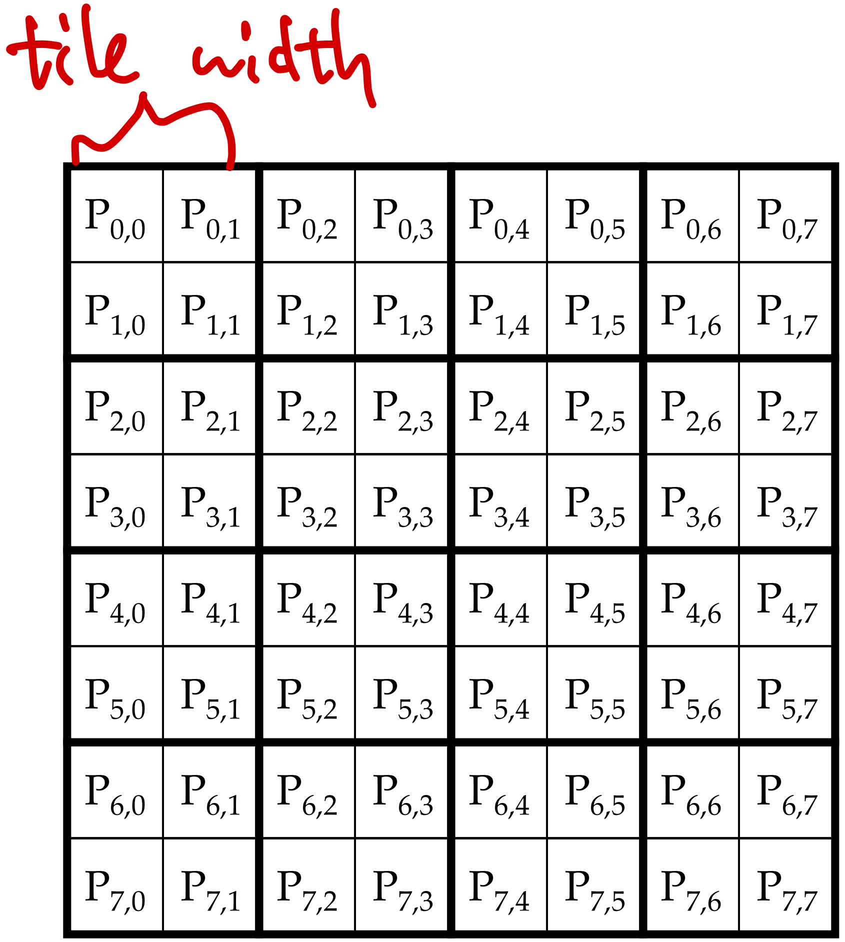
一个block的边长是BLOCK_WIDTH

- Have each 2D thread block to compute a $(\text{BLOCK\_WIDTH})^2$ sub-matrix of the result matrix
  - Each block has $(\text{BLOCK\_WIDTH})^2$ threads
- Generate a 2D Grid of $(\text{WIDTH/BLOCK\_WIDTH})^2$ blocks
- This concept is called **tiling**. Each block represents a **tile**.



Block(0,0)
Block(0,1)
$P_{0,0}$ $P_{0,1}$ $P_{0,2}$ $P_{0,3}$
$P_{1,0}$ $P_{1,1}$ $P_{1,2}$ $P_{1,3}$
$P_{2,0}$ $P_{2,1}$ $P_{2,2}$ $P_{2,3}$
$P_{3,0}$ $P_{3,1}$ $P_{2,3}$ $P_{3,3}$
WIDTH = 4; BLOCK_WIDTH = 2
Each block has 2*2 = 4 threads
WIDTH/BLOCK_WIDTH = 2
Use 2* 2 = 4 blocks
Block(1,0)
Block(1,1)

Example: Width 8, TILE_WIDTH 2



$P_{0,0}$	$P_{0,1}$	$P_{0,2}$	$P_{0,3}$	$P_{0,4}$	$P_{0,5}$	$P_{0,6}$	$P_{0,7}$
$P_{1,0}$	$P_{1,1}$	$P_{1,2}$	$P_{1,3}$	$P_{1,4}$	$P_{1,5}$	$P_{1,6}$	$P_{1,7}$
$P_{2,0}$	$P_{2,1}$	$P_{2,2}$	$P_{2,3}$	$P_{2,4}$	$P_{2,5}$	$P_{2,6}$	$P_{2,7}$
$P_{3,0}$	$P_{3,1}$	$P_{3,2}$	$P_{3,3}$	$P_{3,4}$	$P_{3,5}$	$P_{3,6}$	$P_{3,7}$
$P_{4,0}$	$P_{4,1}$	$P_{4,2}$	$P_{4,3}$	$P_{4,4}$	$P_{4,5}$	$P_{4,6}$	$P_{4,7}$
$P_{5,0}$	$P_{5,1}$	$P_{5,2}$	$P_{5,3}$	$P_{5,4}$	$P_{5,5}$	$P_{5,6}$	$P_{5,7}$
$P_{6,0}$	$P_{6,1}$	$P_{6,2}$	$P_{6,3}$	$P_{6,4}$	$P_{6,5}$	$P_{6,6}$	$P_{6,7}$
$P_{7,0}$	$P_{7,1}$	$P_{7,2}$	$P_{7,3}$	$P_{7,4}$	$P_{7,5}$	$P_{7,6}$	$P_{7,7}$

Each block has
2*2 = 4 threads.

WIDTH/TILE_WIDTH = 4
Use 4×4 = 16 blocks.

Example: Same Matrix, Larger Tiles
(Width 8, TILE_WIDTH 4)

$P_{0,0}$	$P_{0,1}$	$P_{0,2}$	$P_{0,3}$	$P_{0,4}$	$P_{0,5}$	$P_{0,6}$	$P_{0,7}$
$P_{1,0}$	$P_{1,1}$	$P_{1,2}$	$P_{1,3}$	$P_{1,4}$	$P_{1,5}$	$P_{1,6}$	$P_{1,7}$
$P_{2,0}$	$P_{2,1}$	$P_{2,2}$	$P_{2,3}$	$P_{2,4}$	$P_{2,5}$	$P_{2,6}$	$P_{2,7}$
$P_{3,0}$	$P_{3,1}$	$P_{3,2}$	$P_{3,3}$	$P_{3,4}$	$P_{3,5}$	$P_{3,6}$	$P_{3,7}$
$P_{4,0}$	$P_{4,1}$	$P_{4,2}$	$P_{4,3}$	$P_{4,4}$	$P_{4,5}$	$P_{4,6}$	$P_{4,7}$
$P_{5,0}$	$P_{5,1}$	$P_{5,2}$	$P_{5,3}$	$P_{5,4}$	$P_{5,5}$	$P_{5,6}$	$P_{5,7}$
$P_{6,0}$	$P_{6,1}$	$P_{6,2}$	$P_{6,3}$	$P_{6,4}$	$P_{6,5}$	$P_{6,6}$	$P_{6,7}$
$P_{7,0}$	$P_{7,1}$	$P_{7,2}$	$P_{7,3}$	$P_{7,4}$	$P_{7,5}$	$P_{7,6}$	$P_{7,7}$

Each block has
4*4 =16 threads.

WIDTH/TILE_WIDTH = 2
Use 2* 2 = 4 blocks.

Kernel Invocation (Host-side Code)

每个dimension有几个block

```
// TILE_WIDTH is a #define constant
dim3 dimGrid(ceil((1.0*Width)/TILE_WIDTH),
         ceil((1.0*Width)/TILE_WIDTH), 1);

dim3 dimBlock(TILE_WIDTH, TILE_WIDTH, 1);



// Launch the device computation threads!
MatrixMulKernel<<<dimGrid, dimBlock>>>(Md, Nd, Pd, Width);
```

2D grid
x，y需要多少个block

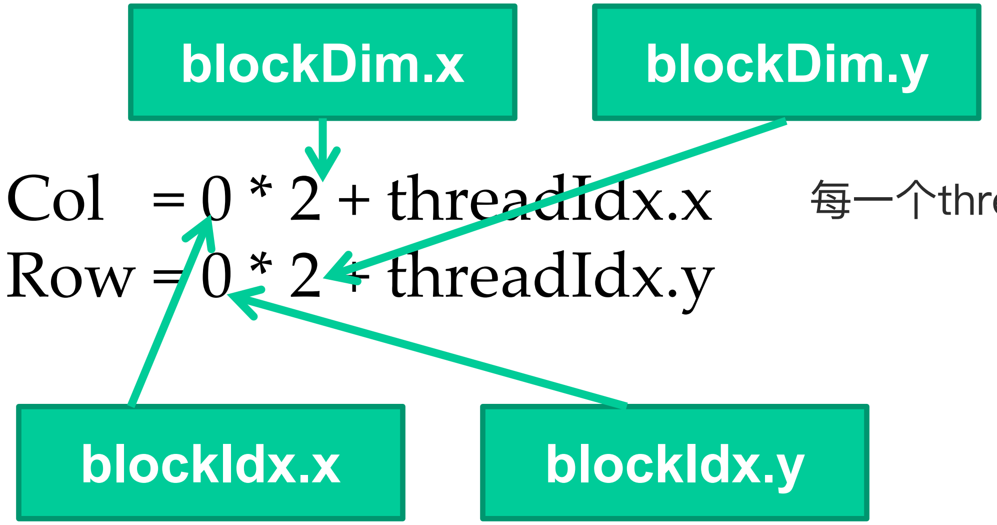
三个矩阵，width

Kernel Function

```
// Matrix multiplication kernel – per thread code
                                   input                    output
__global__
void MatrixMulKernel(float* d_M, float* d_N, float* d_P, int Width)
{

     // Pvalue is used to store the element of the matrix
     // that is computed by the thread
     float Pvalue = 0;
     ...
     ...
     d_P[  ] = Pvalue;
```

Work for Block (0,0) with TILE_WIDTH 2



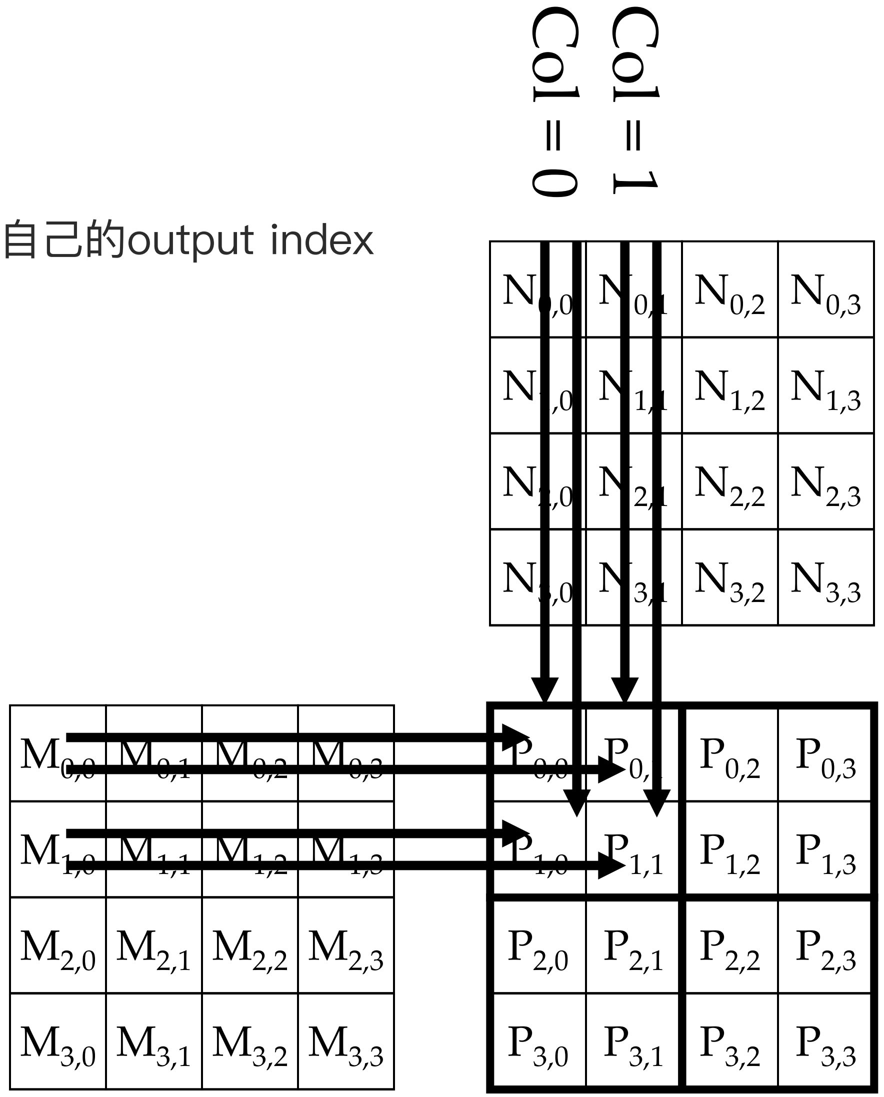
Col $= 0 * 2 + \text{threadIdx.x}$
Row $= 0 * 2 + \text{threadIdx.y}$

每一个thread计算自己的output index

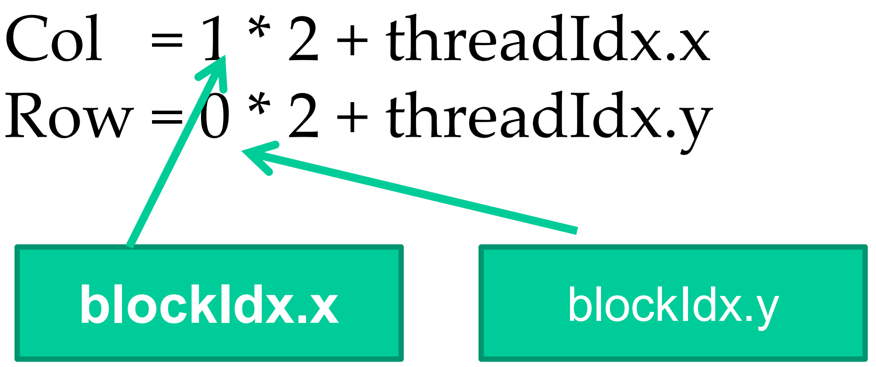
mapping from thread index
to the location

Row = 0

Row = 1

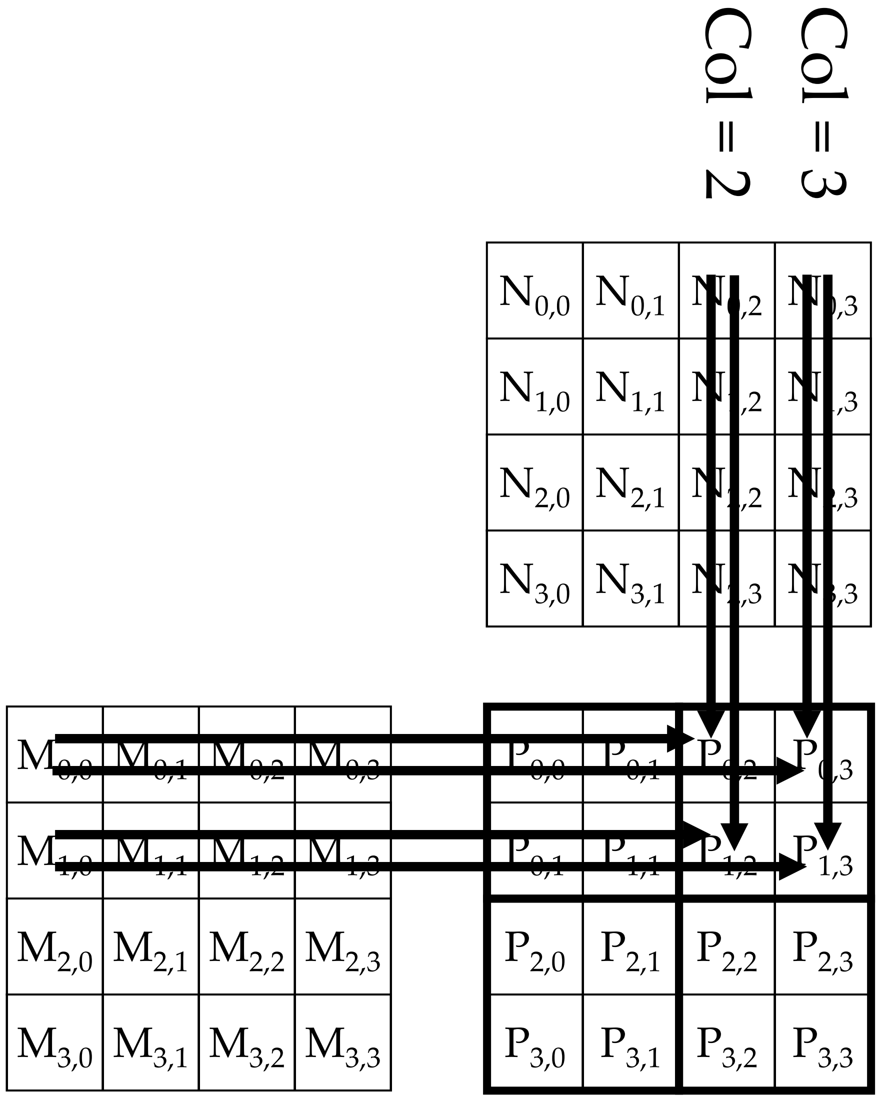

Col = 0
Col = 1
$N_{0,0}$ $N_{0,1}$ $N_{0,2}$ $N_{0,3}$
$N_{1,0}$ $N_{1,1}$ $N_{1,2}$ $N_{1,3}$
$N_{2,0}$ $N_{2,1}$ $N_{2,2}$ $N_{2,3}$
$N_{3,0}$ $N_{3,1}$ $N_{3,2}$ $N_{3,3}$
$M_{0,0}$ $M_{0,1}$ $M_{0,2}$ $M_{0,3}$
$M_{1,0}$ $M_{1,1}$ $M_{1,2}$ $M_{1,3}$
$M_{2,0}$ $M_{2,1}$ $M_{2,2}$ $M_{2,3}$
$M_{3,0}$ $M_{3,1}$ $M_{3,2}$ $M_{3,3}$
$P_{0,0}$ $P_{0,1}$ $P_{0,2}$ $P_{0,3}$
$P_{1,0}$ $P_{1,1}$ $P_{1,2}$ $P_{1,3}$
$P_{2,0}$ $P_{2,1}$ $P_{2,2}$ $P_{2,3}$
$P_{3,0}$ $P_{3,1}$ $P_{3,2}$ $P_{3,3}$

Work for Block (0,1)

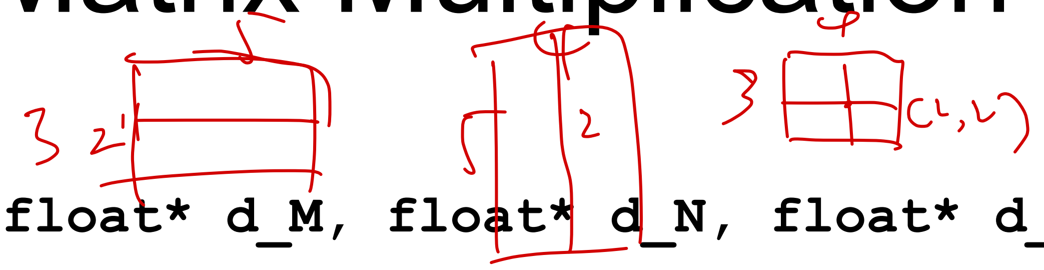


Row = 0

Row = 1



A Simple Matrix Multiplication Kernel



```
__global__
void MatrixMulKernel(float* d_M, float* d_N, float* d_P, int Width)
{
  // Calculate the row index of the d_P element and d_M
 int Row = blockIdx.y*blockDim.y+threadIdx.y;
  // Calculate the column idenx of d_P and d_N
 int Col = blockIdx.x*blockDim.x+threadIdx.x;

 if ((Row < Width) && (Col < Width)) {
     float Pvalue = 0;
     // each thread computes one element of the block sub-matrix
     for (int k = 0; k < Width; ++k)
        Pvalue += d_M[Row*Width+k] * d_N[k*Width+Col];
     d_P[Row*Width+Col] = Pvalue;
 }
}
```

17×19×4

每一个thread计算对应在output中的index

然后累加

通过row和column找到在input中的index

Memory Bandwidth is Overloaded!

- That's a **simple implementation**:
  - GPU kernel is the **CPU code** with the **outer loops replaced with** per-thread **index calculations**!
- Unfortunately, performance is quite bad.
- Why?
- With the given approach,
  - global **memory bandwidth can't** supply enough data to **keep the SMs busy**!

Where Do We Access Global Memory?

```
__global__
void MatrixMulKernel(float* d_M, float* d_N, float* d_P, int Width)
{
  // Calculate the row index of the d_P element and d_M
 int Row = blockIdx.y*blockDim.y+threadIdx.y;
  // Calculate the column idenx of d_P and d_N
 int Col = blockIdx.x*blockDim.x+threadIdx.x;

 if ((Row < Width) && (Col < Width)) {
     float Pvalue = 0;
     // each thread computes one element of the block sub-matrix
     for (int k = 0; k < Width; ++k)
        Pvalue += d_M[Row*Width+k] * d_N[k*Width+Col];
     d_P[Row*Width+Col] = Pvalue;
 }
}
```

accesses to global memory

Each Thread Requires 4B of Data per FLOP

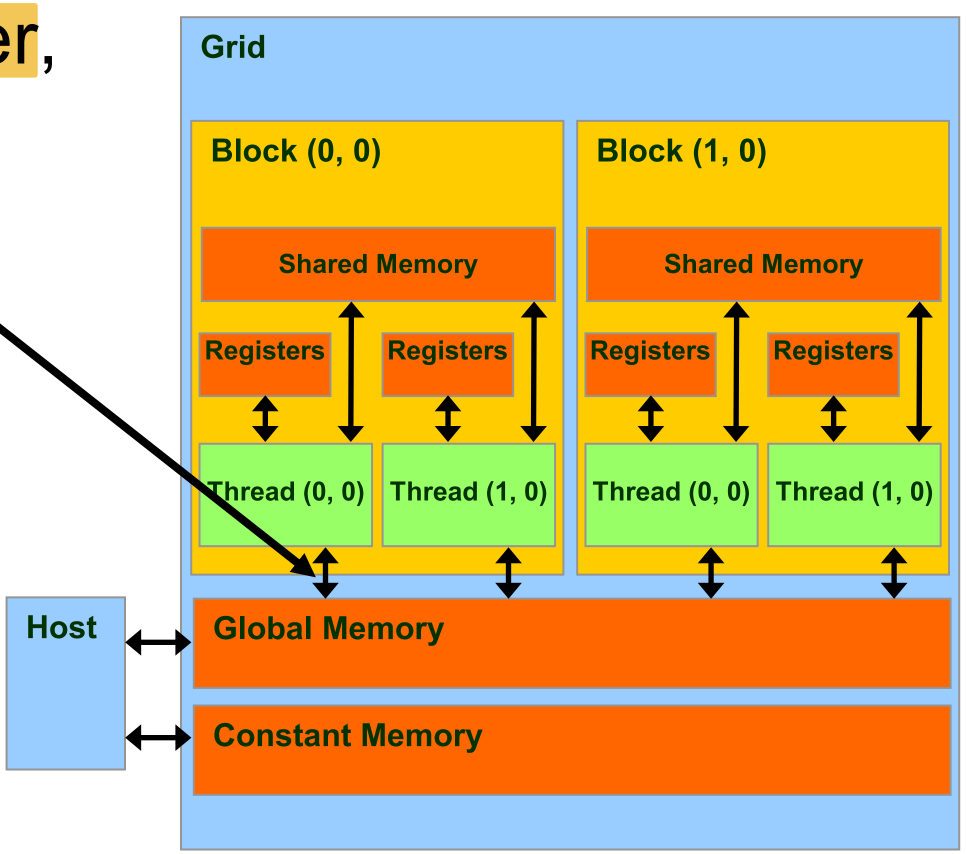
- Each threads access global memory
  - for elements of **M** and **N**:
  - **4B each**, or **8B per pair**.
  - (And once TOTAL to **P** per thread—ignore it.)
- With each pair of elements,
  - a thread does a single multiply-add,
  - **2 FLOP**—floating-point operations.
- So for every FLOP,
  - **a thread needs** 4B from memory:
  - **4B / FLOP**.

对于两个数据，
每个thread做一次multiply，一次add
也就是两个FLOP

8B / 2FLOP = 4B/FLOP
对于每一次FLOP，需要4B的数据

150 GB/s Bandwidth Implies 37.5 GFLOPs

- One generation of GPUs:
  - **1,000 GFLOP/s** of compute power, and
  - **150 GB/s** of memory bandwidth.



- Dividing bandwidth by memory requirements:

$$\frac{150\ GB/s}{4\ B/FLOP} = 37.5\ \text{GFLOP/s}$$

which **limits computation**!

通过GB/s除以B/FLOP,
得到的GFLOP/S远远小于GPU的compute power
被memory bound了

What to Do? Reuse Memory Accesses!

But **37.5 GFLOPs is a limit**.

In an **actual execution**,

- memory is not busy all the time, and
- the code **runs at** about **25 GFLOPs**.

To get closer to 1,000 GFLOPs

- we **need to** drastically **cut down**
- **accesses to global memory**.

ANY MORE QUESTIONS? READ CHAPTER 4!