CSCI-GA.3033-004

Graphics Processing Units (GPUs): Architecture and Programming

Lecture 3: CUDA Programming Model

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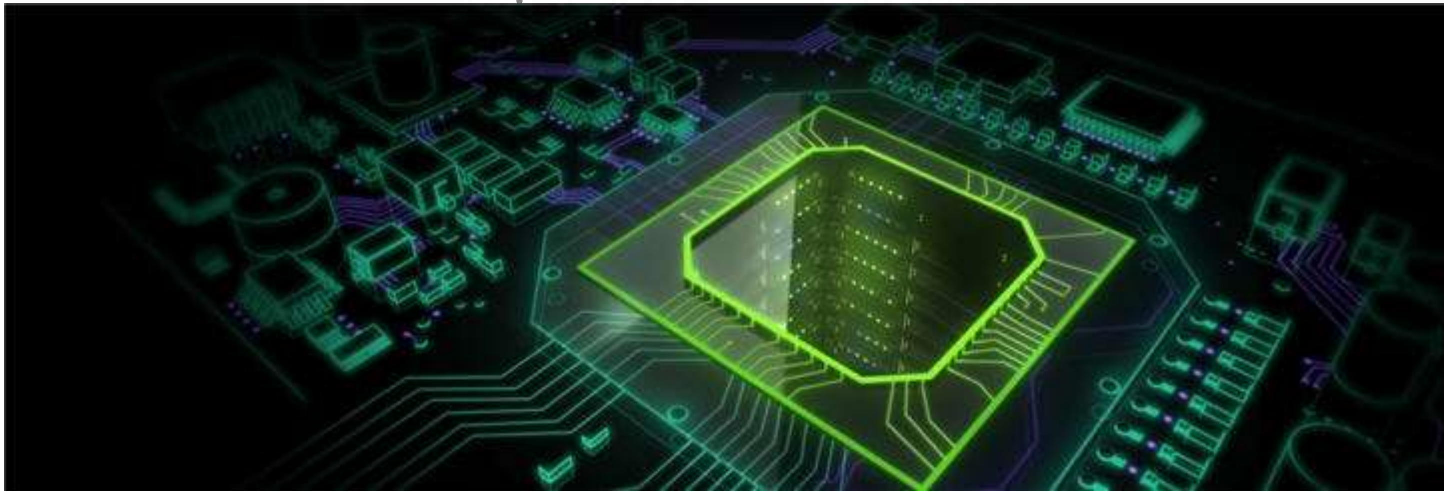


Behind CUDA

Source: http://hothardware.com/Reviews/Intel-Core-i5-and-i7-Processors-and-P55-Chipset/?page=4

Parallel Computing on a GPU

- GPUs deliver 25 to 200+ GFLOPS on compiled parallel C applications
  - Available in laptops, desktops, and clusters

- GPU parallelism is doubling every year
- Programming model scales transparently
  - Data parallelism

- Programmable in C with CUDA tools
- Multithreaded SPMD model uses application data parallelism and thread parallelism.

  [SPMD = Single Program Multiple Data]

GeForce 8800

Tesla D870

Tesla S870

CUDA

- Compute Unified Device Architecture
- Integrated host+device app C program
  - Serial or modestly parallel parts in **host** C code
  - Highly parallel parts in **device** SPMD kernel C code

Serial Code (host)

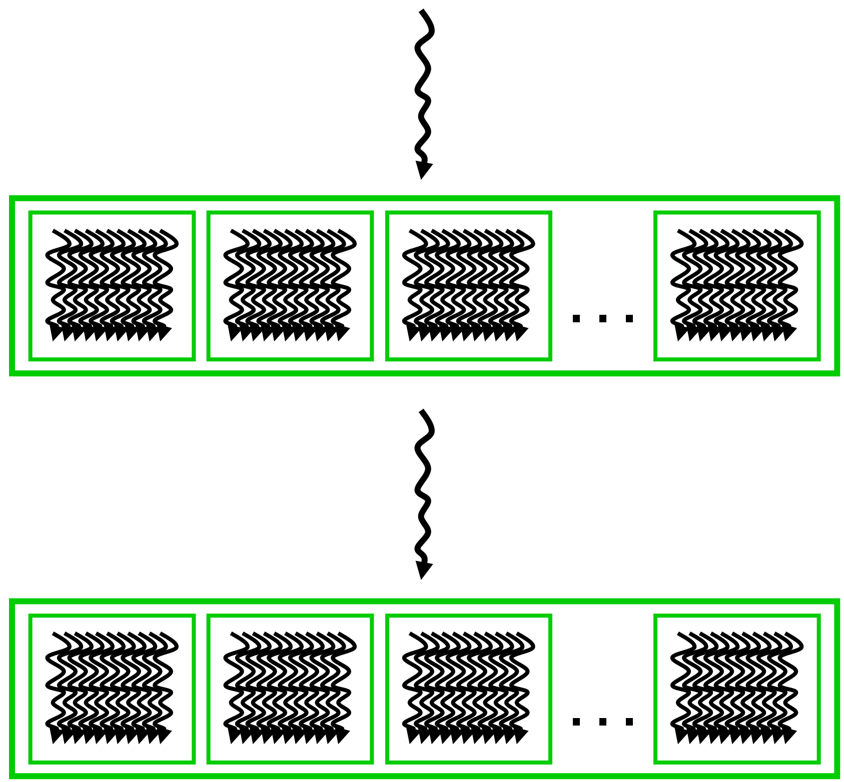
Parallel Kernel (device)

KernelA<<< nBlk, nTid >>>(args);

Serial Code (host)

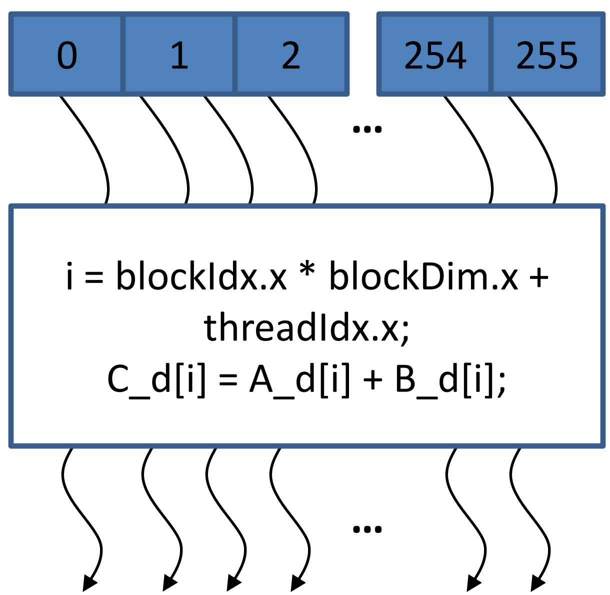
Parallel Kernel (device)

KernelB<<< nBlk, nTid >>>(args);



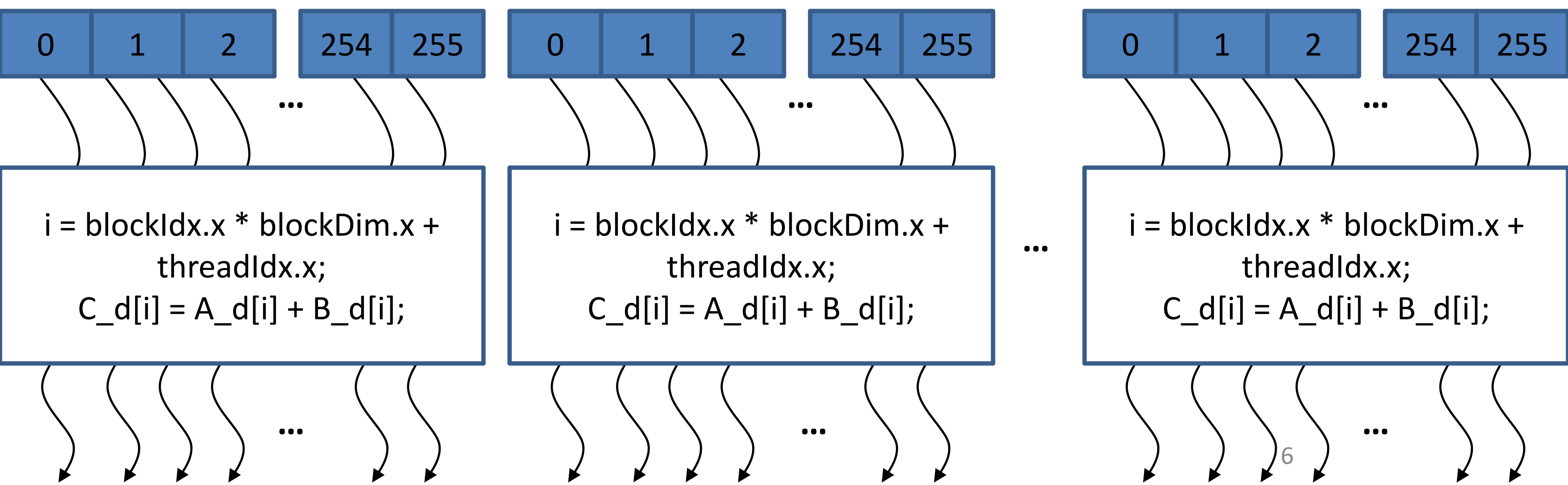
Parallel Threads

- A CUDA kernel is executed by an array of threads
  - All threads run the same code (the SP in SPMD)
  - Each thread has an ID that it uses to compute memory addresses and make control decisions



Thread Blocks

- Divide monolithic thread array into multiple blocks
  - Threads within a block cooperate via **shared memory, atomic operations** and **barrier synchronization, …**
  - Threads in different blocks cannot cooperate



Kernel

- Launched by the host
- Very similar to a C function
- To be executed on device
- All threads will execute that same code in the kernel.

Grid

- 1D or 2D (or 3D) organization of a block
- blockDim.x and blockDim.y
- gridDim.x and gridDim.y

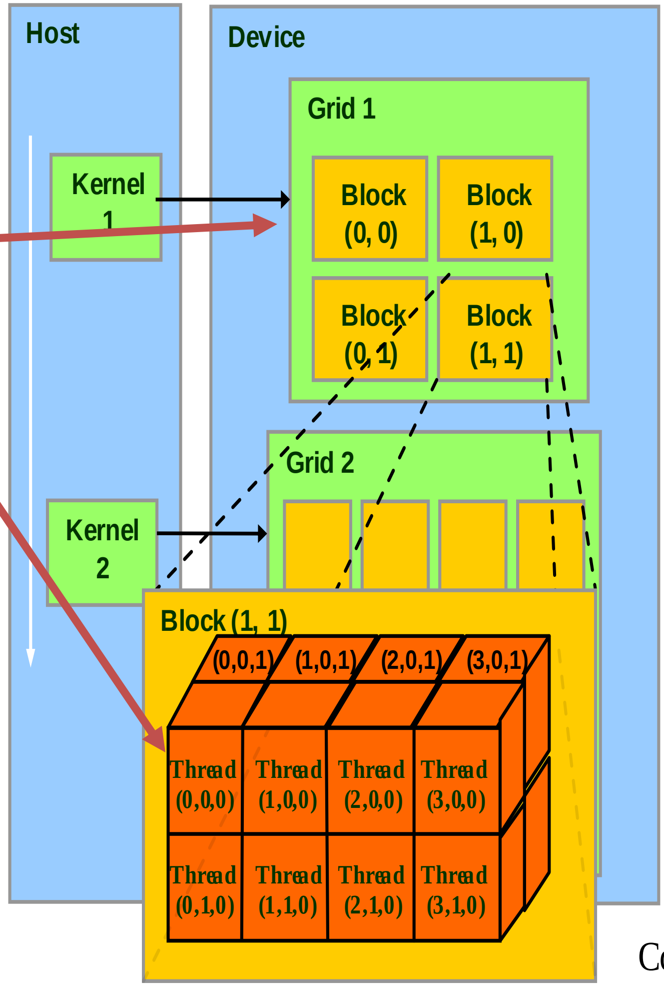
Block

- 1D, 2D, or 3D organization of a block
- Block is assigned to an SM
- blockIdx.x, blockIdx.y, and blockIdx.z

Thread

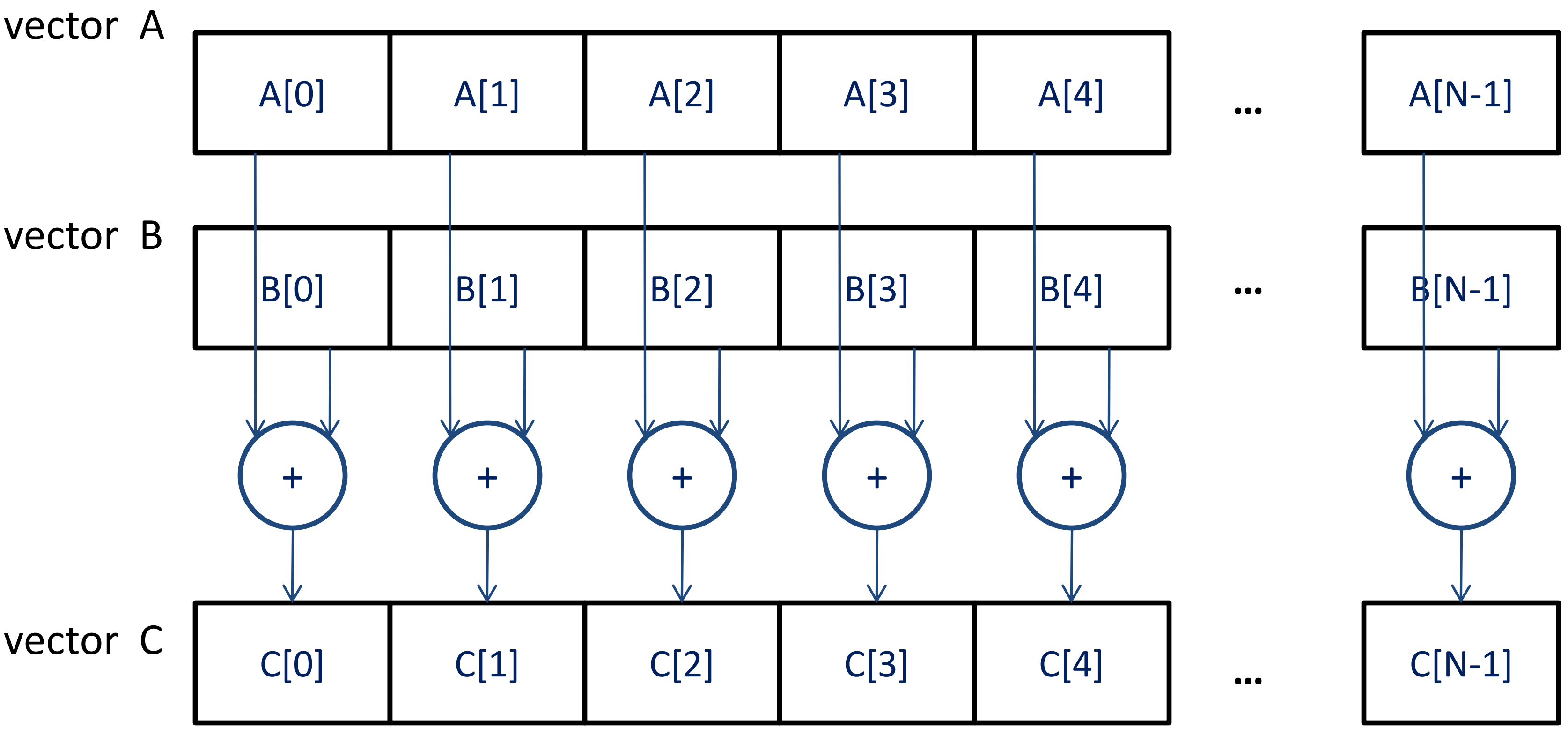
IDs

- Each thread uses IDs to decide what data to work on
  - Block ID: 1D or 2D (or 3D)
  - Thread ID: 1D, 2D, or 3D
- Simplifies memory addressing when processing multidimensional data
  - Image processing
  - Solving PDEs on volumes
  - …



Courtesy: NDVIA

A Simple Example: Vector Addition



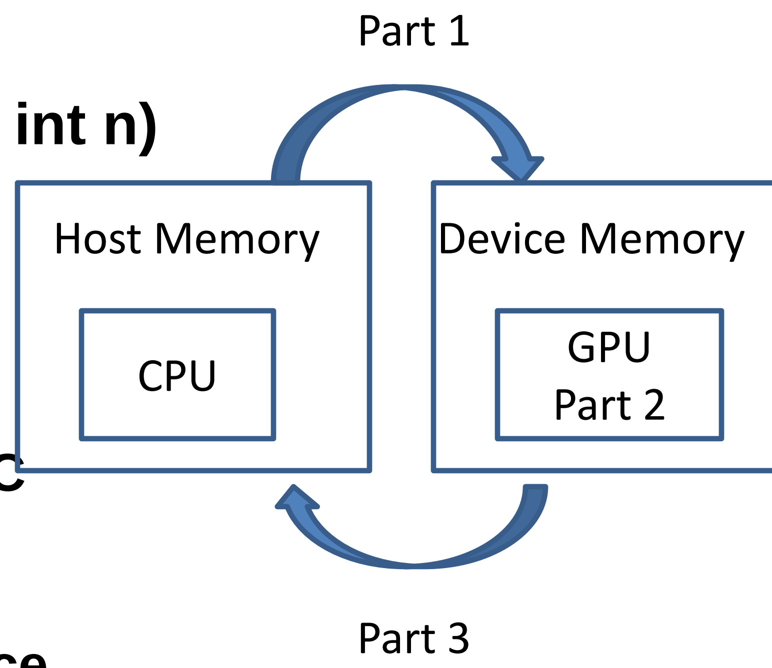
A Simple Example: Vector Addition

```
// 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);
}
```

GPU friendly!

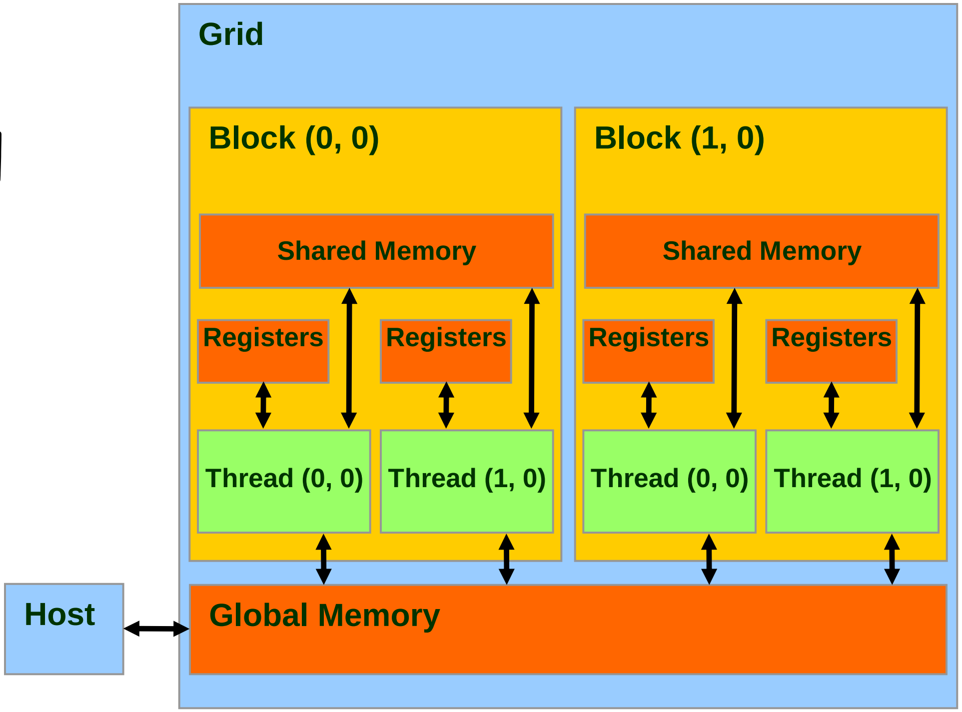
A Simple Example: Vector Addition

```
#include <cuda.h>
void vecAdd(float* A, float* B, float* C, int n)
{
  int size = n* sizeof(float);
  float* A_d, B_d, C_d;
  …
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
}
```



CUDA Memory Model

- Global memory
  - Main means of communicating R/W Data between host and device
  - Contents visible to all threads
  - Long latency access
- Device code can:
  - R/W per-thread registers
  - R/W per-grid global memory
- We will cover more later

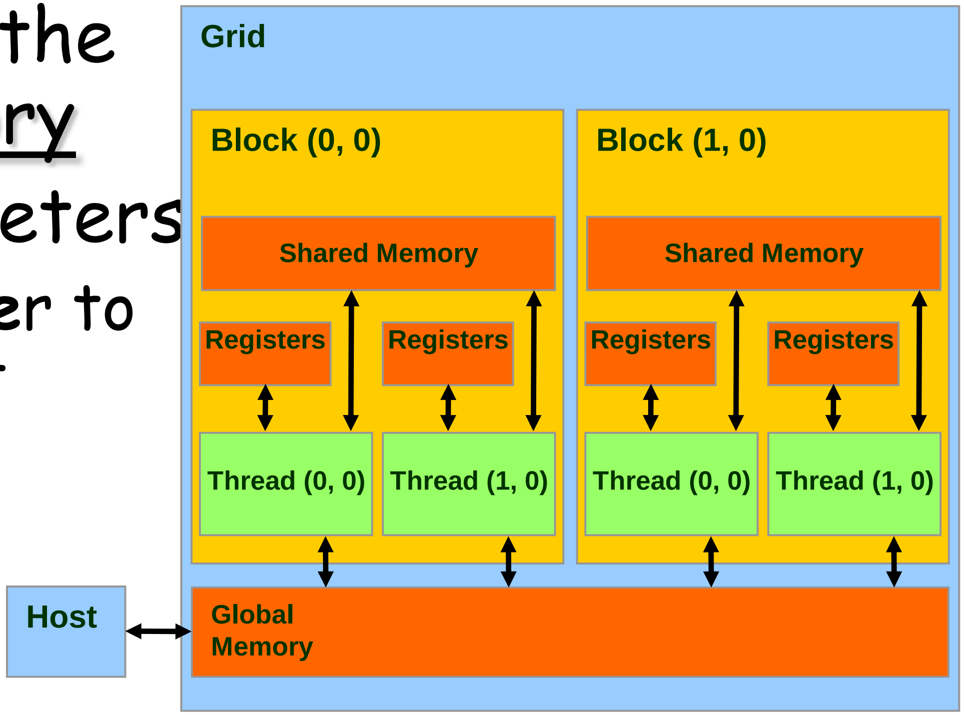


CPU & GPU Memory

- In CUDA, host and devices have separate memory spaces.
- If GPU and CPU are on the same chip, then they share memory space → fusion

CUDA Device Memory Allocation

- cudaMalloc()
  - Allocates object in the device Global Memory
  - Requires two parameters
    - **Address of a pointer** to the allocated object
    - **Size of** of allocated object
- cudaFree()
  - Frees object from device Global Memory
    - Pointer to freed object

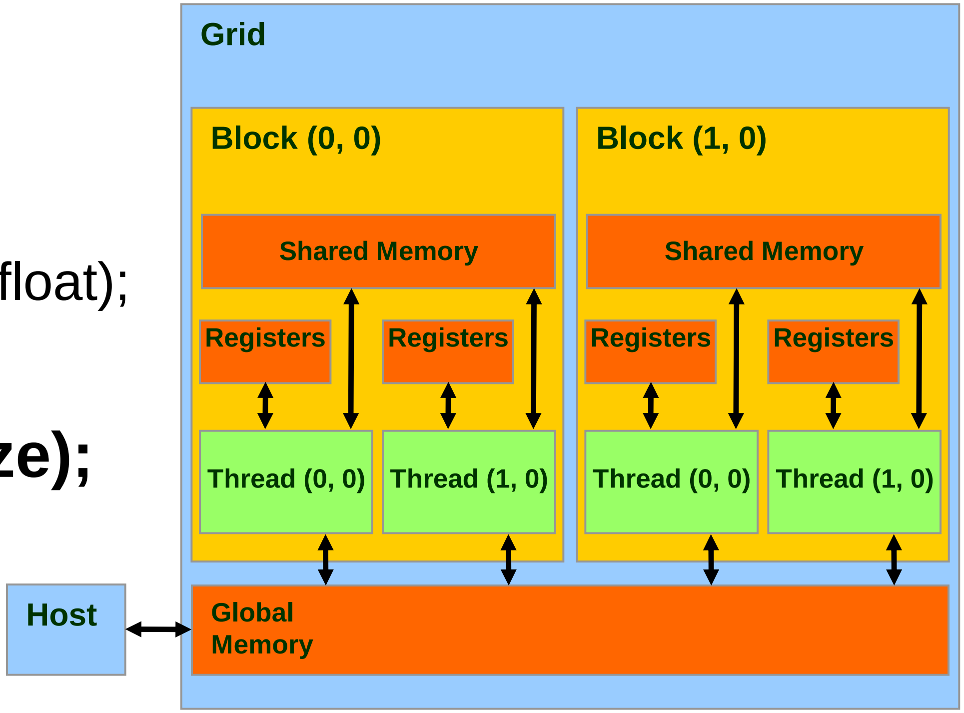


CUDA Device Memory Allocation

Example:

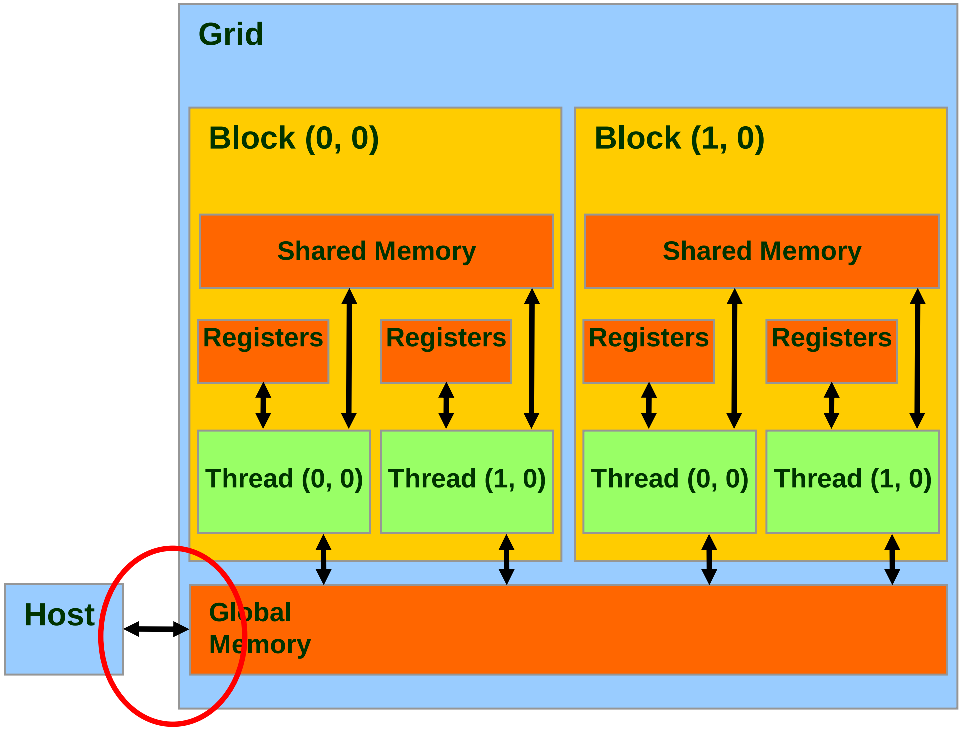
```
WIDTH = 64;
float *  Md;
int size = WIDTH * WIDTH * sizeof(float);
```

cudaMalloc((void)&Md, size);**
cudaFree(Md);



CUDA Device Memory Allocation

- cudaMemcpy()
  - memory data transfer
  - Requires four parameters
    - Pointer to destination
    - Pointer to source
    - Number of bytes copied
    - Type of transfer
      - Host to Host
      - Host to Device
      - Device to Host
      - Device to Device
- Asynchronous transfer

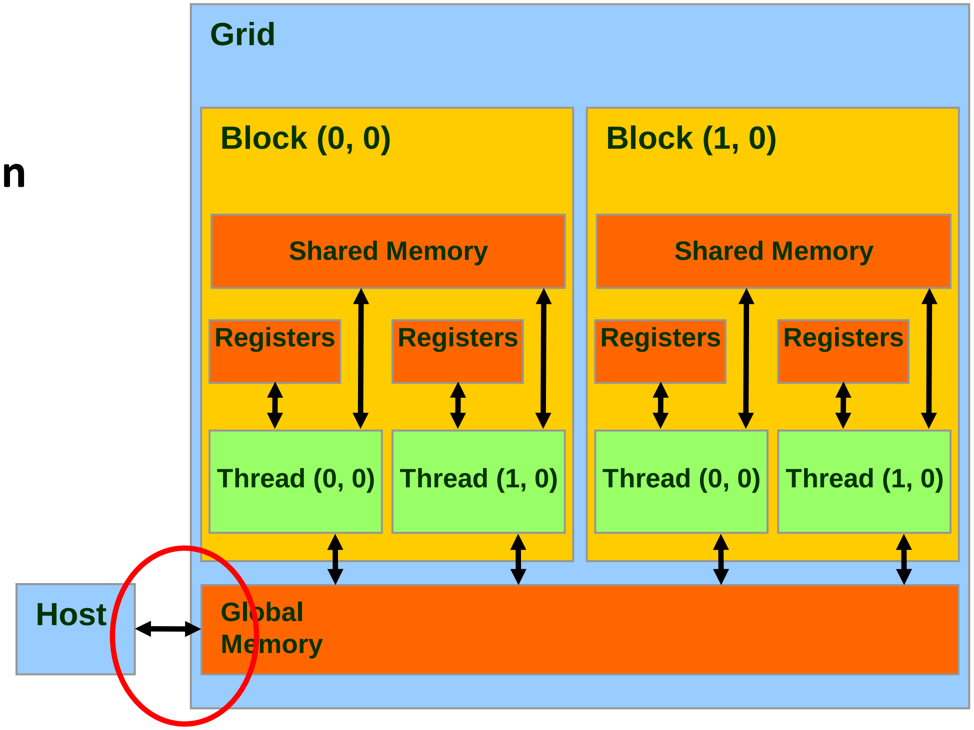


Important!
cudaMemcpy() cannot be used to copy between different GPUs in multi-GPUs system

CUDA Device Memory Allocation

Example:

Destination pointer **Source pointer** **Size in bytes** **Direction**



cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);

cudaMemcpy(M, Md, size, cudaMemcpyDeviceToHost);

A Simple Example: Vector Addition

```
void vecAdd(float* A, float* B, float* C, int n)
{
  int size = n * sizeof(float);
   float* A_d,  * B_d, * C_d;

1. // Transfer A and B to device memory
   cudaMalloc((void **) &A_d, size);
   cudaMemcpy(A_d, A, size, cudaMemcpyHostToDevice);
   cudaMalloc((void **) &B_d, size);
   cudaMemcpy(B_d, B, size, cudaMemcpyHostToDevice);

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

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

How to launch a kernel?

```
int vecAdd(float* A, float* B, float* C, int n)
{
 // A_d, B_d, C_d allocations and copies omitted
 // Run ceil(n/256) blocks of 256 threads each
  vecAddKernel<<<ceil(n/256),256>>>(A_d, B_d, C_d, n);
}
```

#blocks **#threads/blks**

```
// Each thread performs one pair-wise addition
__global__
void vecAddkernel(float* A_d, float* B_d, float* C_d, int n)
{
   int i = threadIdx.x + blockDim.x * blockIdx.x;
   if(i<n) C_d[i] = A_d[i] + B_d[i];
}
```

Unique ID

Unique ID
1D grid of 1D blocks

```
blockIdx.x *blockDim.x + threadIdx.x;
```

Unique ID
1D grid of 2D blocks

```
blockIdx.x * blockDim.x * blockDim.y +
threadIdx.y * blockDim.x +
threadIdx.x;
```

Unique ID
1D grid of 3D blocks

blockIdx.x * blockDim.x * blockDim.y * blockDim.z +

threadIdx.z * blockDim.y * blockDim.x +
threadIdx.y * blockDim.x +
threadIdx.x;

Unique ID
2D grid of 1D blocks

int blockId = blockIdx.y * gridDim.x + blockIdx.x;

int threadId = blockId * blockDim.x + threadIdx.x;

Unique ID
2D grid of 2D blocks

int blockId = blockIdx.x + blockIdx.y * gridDim.x;

int threadId = blockId * (blockDim.x * blockDim.y) + (threadIdx.y * blockDim.x) + threadIdx.x;

Unique ID
2D grid of 3D blocks

```
int blockId = blockIdx.x  +
              blockIdx.y * gridDim.x;

int threadId = blockId * (blockDim.x *
blockDim.y * blockDim.z) +
 (threadIdx.z * (blockDim.x * blockDim.y))
  + (threadIdx.y * blockDim.x)
  + threadIdx.x;
```

Unique ID
3D grid of 1D blocks

```
int blockId = blockIdx.x
  + blockIdx.y * gridDim.x
  + gridDim.x * gridDim.y * blockIdx.z;

int threadId = blockId * blockDim.x +
  threadIdx.x;
```

Unique ID
3D grid of 2D blocks

```
int blockId = blockIdx.x
            + blockIdx.y * gridDim.x
   + gridDim.x * gridDim.y * blockIdx.z;

int threadId = blockId * (blockDim.x *
      blockDim.y)
    + (threadIdx.y * blockDim.x)
    + threadIdx.x;
```

Unique ID
3D grid of 3D blocks

```
int blockId = blockIdx.x
   + blockIdx.y * gridDim.x
   + gridDim.x * gridDim.y * blockIdx.z;

int threadId = blockId * (blockDim.x *
   blockDim.y * blockDim.z) +
   (threadIdx.z * (blockDim.x * blockDim.y))
    + (threadIdx.y * blockDim.x)
    + threadIdx.x;
```

The *Hello World* of Parallel Programming: **Matrix Multiplication**

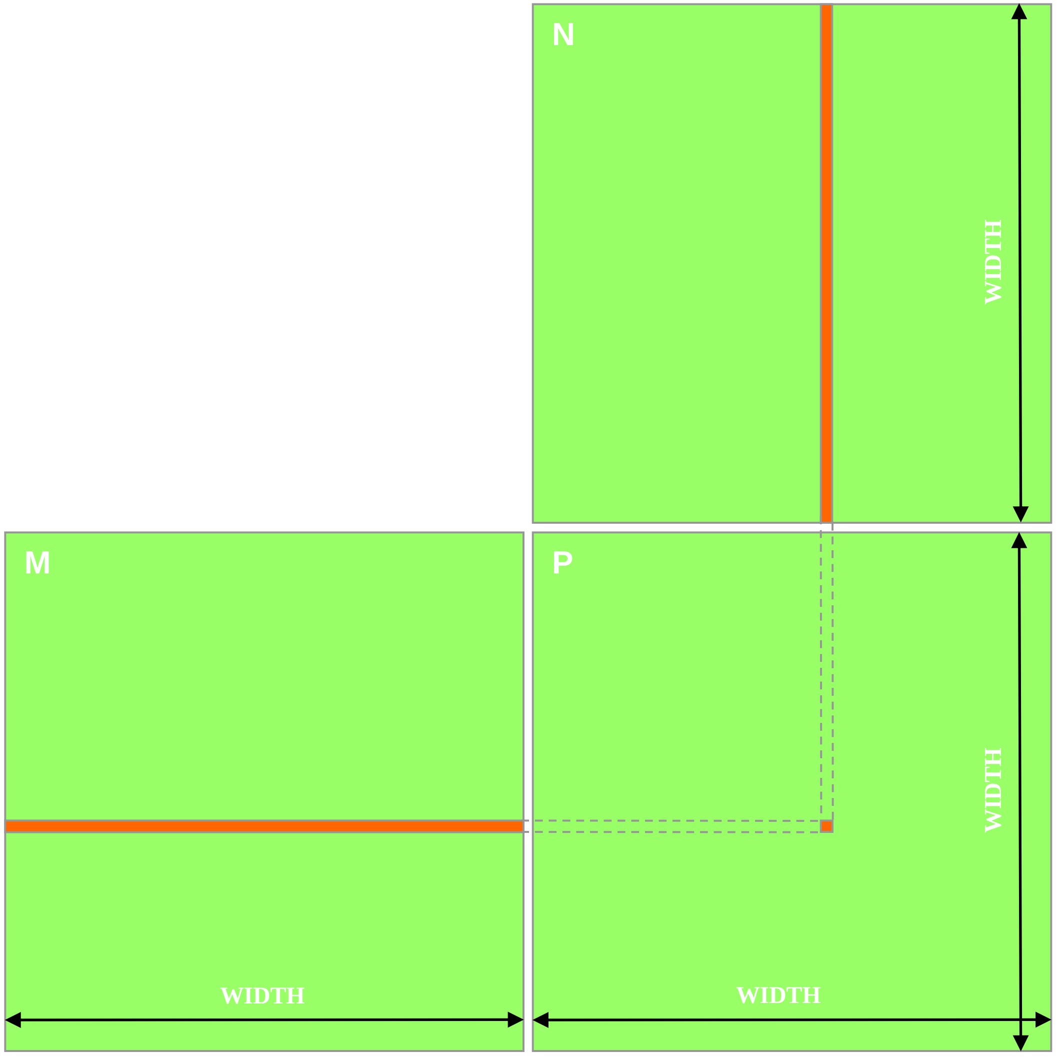
	Executed on the:	Only callable from the:
`__device__ float DeviceFunc()`	device	device
`__global__ void KernelFunc()`	device	host
`__host__ float HostFunc()`	host	host

- `__global__` defines a kernel function. Must return `void`
- `__device__` and `__host__` can be used together

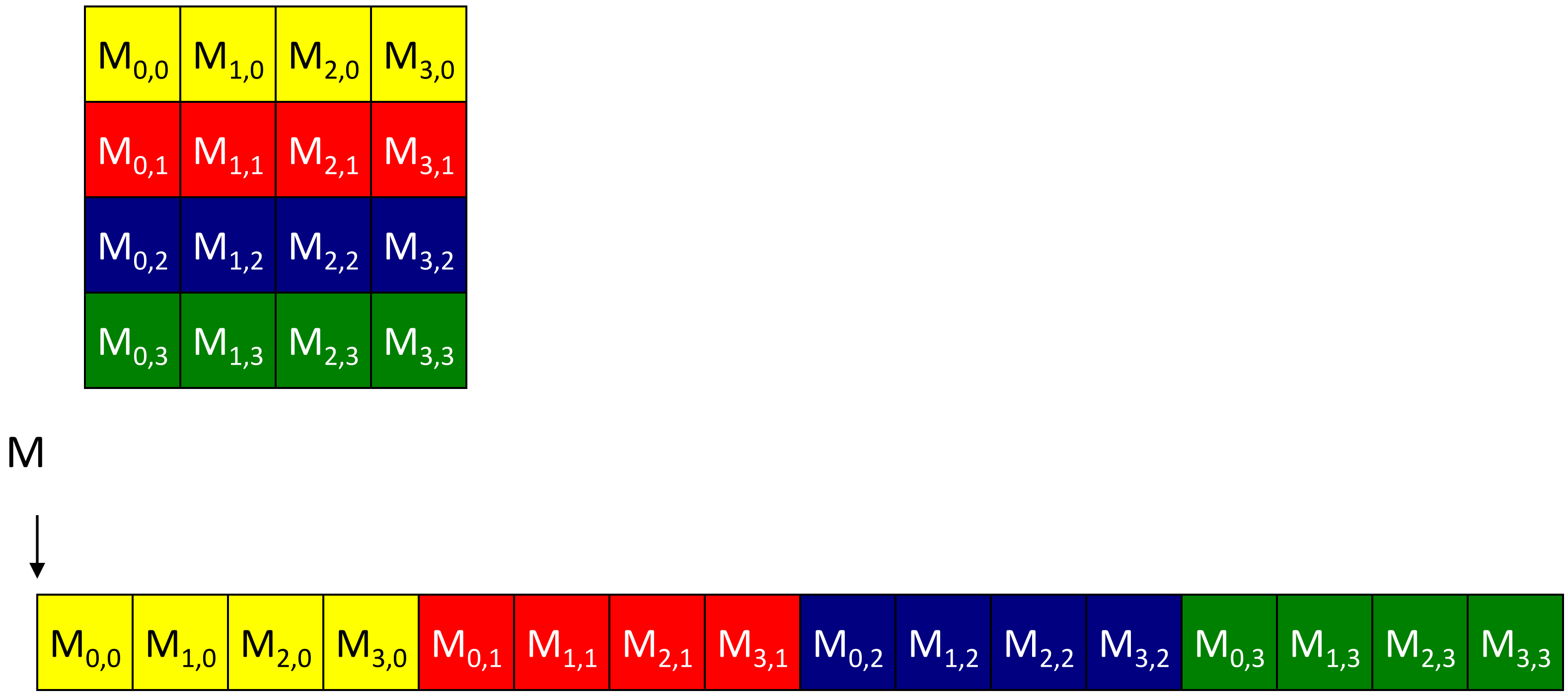
- For functions executed on the device:
  - No recursion
  - No static variable declarations inside the function
  - No indirect function calls through pointers

The *Hello World* of Parallel Programming: **Matrix Multiplication**

Data Parallelism:
We can safely perform many arithmetic operations on the data structures in a simultaneous manner.



The *Hello World* of Parallel Programming: **Matrix Multiplication**



C adopts raw-major placement approach
when storing 2D matrix in linear memory address.

The *Hello World* of Parallel Programming: **Matrix Multiplication**

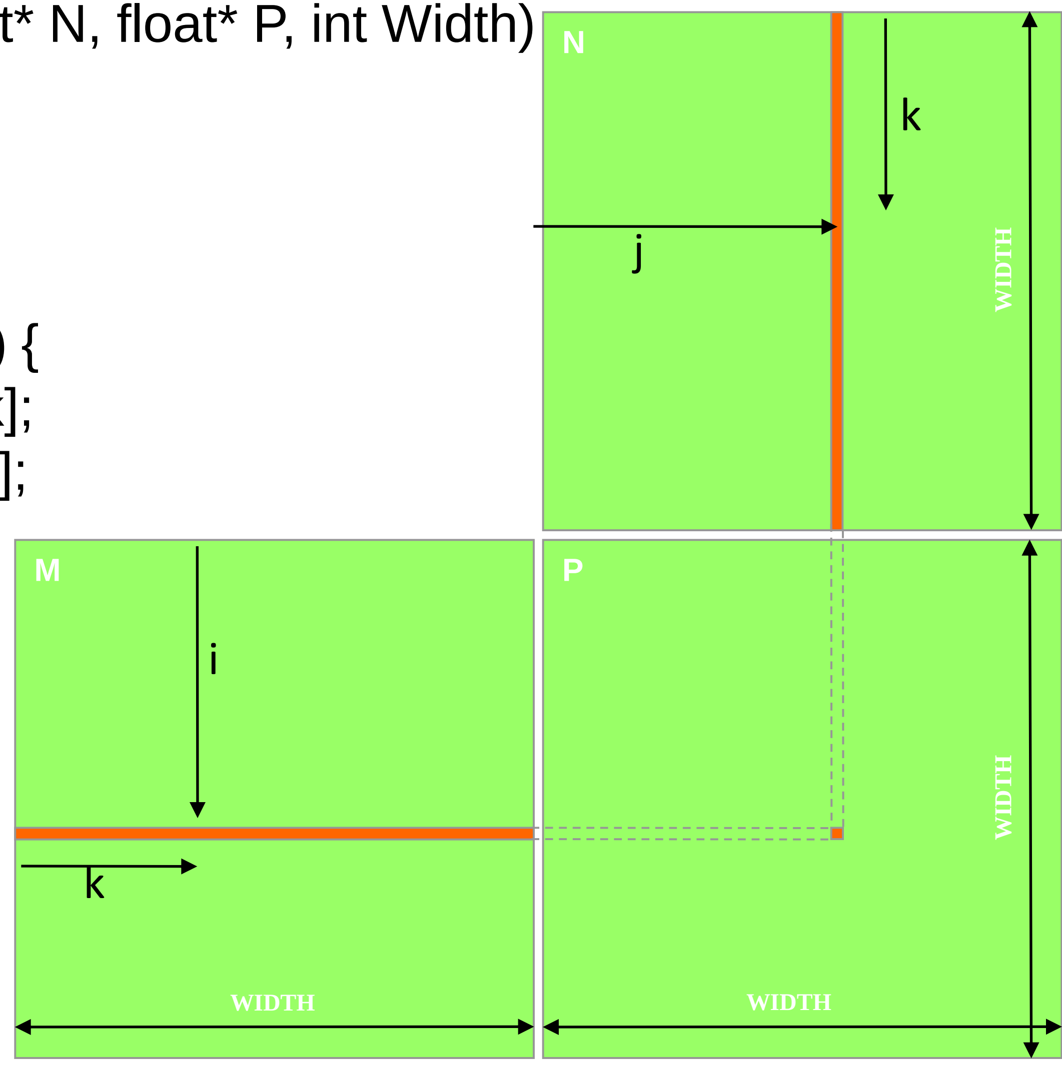
```
int main(void) {
1.   // Allocate and initialize the matrices M, N, P
     // I/O to read the input matrices M and N
....

2.   // M * N on the device
     MatrixMultiplication(M, N, P, Width);


3.   // I/O to write the output matrix P
     // Free matrices M, N, P
...
return 0;
}
```

A Simple main function: executed at the host

The *Hello World* of Parallel Programming: **Matrix Multiplication**

// Matrix multiplication on the (CPU) host

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

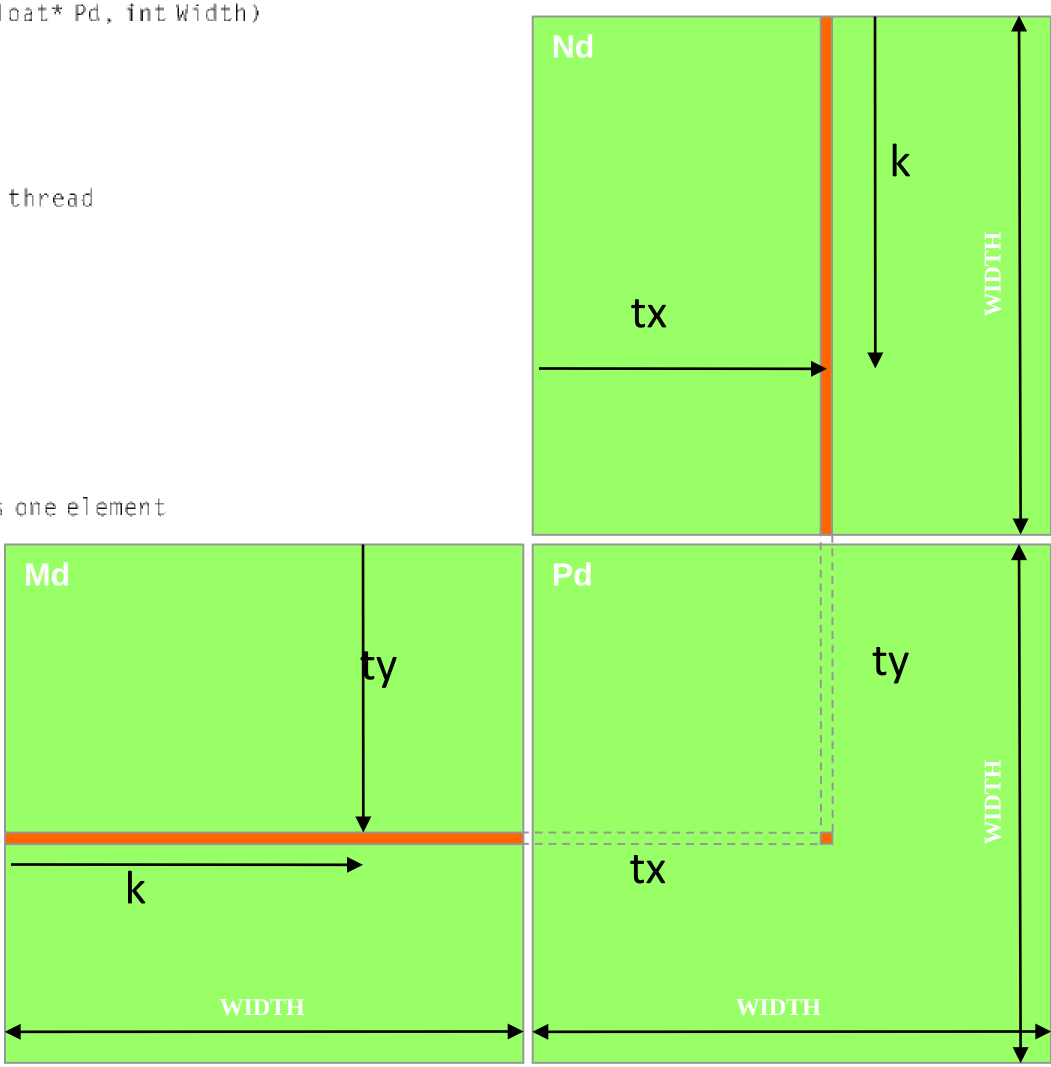


The *Hello World* of Parallel Programming: **Matrix Multiplication**

```
void MatrixMultiplication(float* M, float* N, float* P, int Width)
{
  int size = Width * Width * sizeof(float);
  float* Md, Nd, Pd;

1. // Transfer M and N to device memory
  cudaMalloc((void**) &Md, size);
  cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);
  cudaMalloc((void**) &Nd, size);
  cudaMemcpy(Nd, N, size, cudaMemcpyHostToDevice);

  // Allocate P on the device
  cudaMalloc((void**) &Pd, size);

  MatrixMulKernel(Md, Nd, Pd, Width);
  ...
3. // Transfer P from device to host
  cudaMemcpy(P, Pd, size, cudaMemcpyDeviceToHost);
  // Free device matrices
  cudaFree(Md); cudaFree(Nd); cudaFree (Pd);
  }
```

The *Hello World* of Parallel Programming: **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 * Width + k];
      float Ndelement = Nd[k * Width + tx];
      Pvalue += Mdelement * Ndelement;
   }

   // Write the matrix to device memory each thread writes one element
   Pd[ty * Width + tx] = Pvalue;
}
```



The Kernel Function

More On Specifying Dimensions

```
// Setup the execution configuration
  dim3 dimGrid(x, y);
  dim3 dimBlock(x, y, z);
```

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

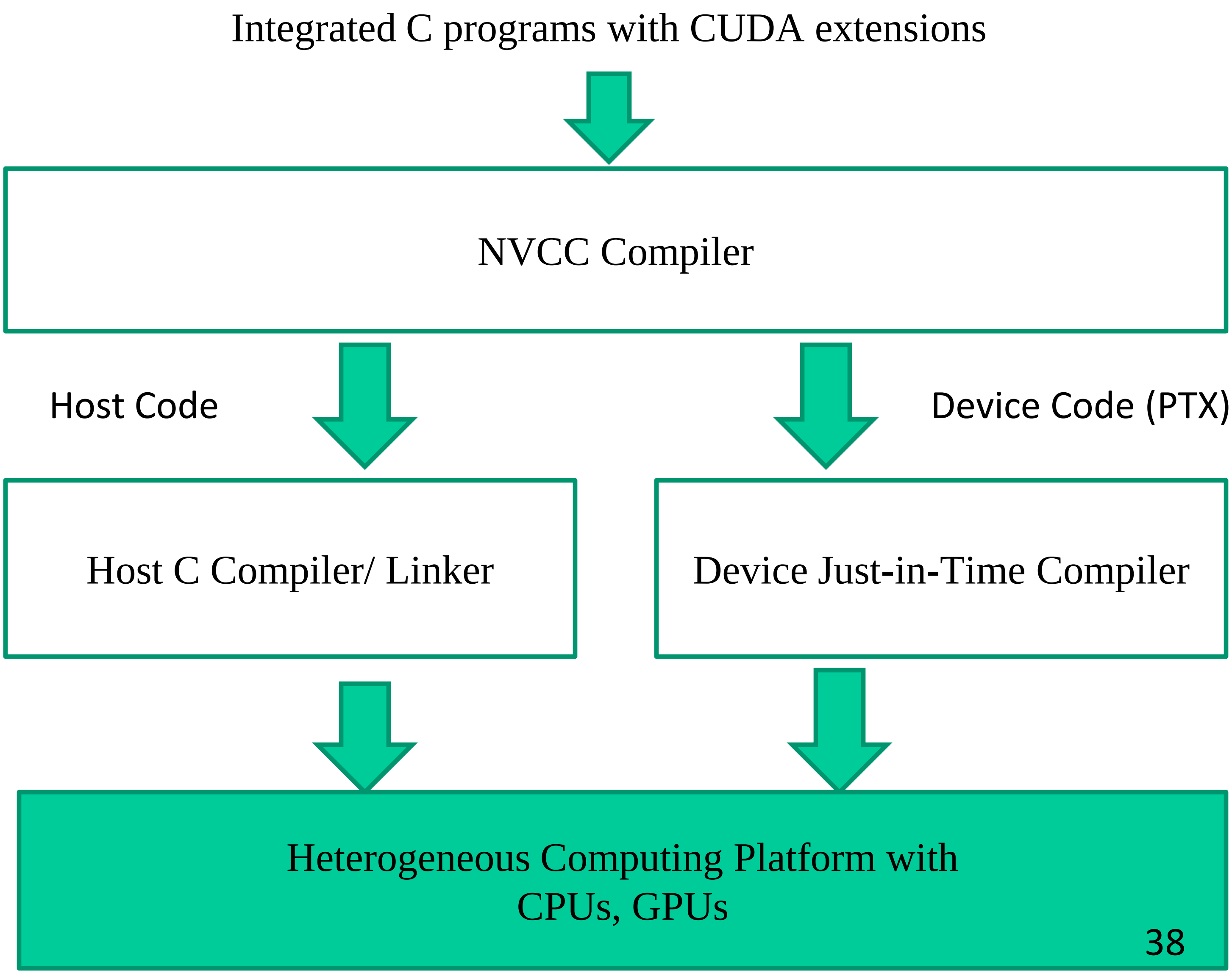
Important:

- dimGrid and dimBlock are user defined
- **gridDim** and **blockDim** are built-in predefined variable accessible in kernel functions

Be Sure To Know:

- Maximum dimensions of a block
- Maximum number of threads per block
- Maximum dimensions of a grid
- Maximum number of blocks per thread

Tools


Integrated C programs with CUDA extensions
NVCC Compiler
Host Code
Device Code (PTX)
Host C Compiler/ Linker
Device Just-in-Time Compiler
Heterogeneous Computing Platform with
CPUs, GPUs

Conclusions

- Data parallelism is the main source of scalability for parallel programs
- Each CUDA source file can have a mixture of both host and device code.
- What we learned today about CUDA:
  - KernelA<<< nBlk, nTid >>>(args)
  - cudaMalloc()
  - cudaFree()
  - cudaMemcpy()
  - gridDim and blockDim
  - threadIdx.x and threadIdx.y
  - dim3