ECE408 /CS483/CSE408

Applied Parallel Programming

Lecture 2:
Introduction to CUDA and Data Parallel Programming

Course Reminders

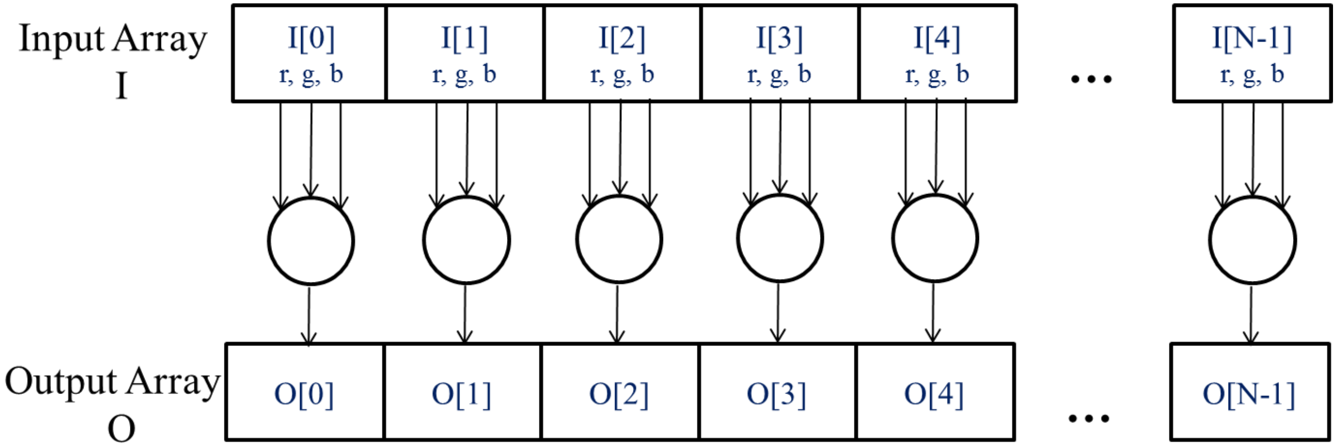
- Lab 0 is due Friday Sept 1st at 8pm US Central time
  - Will be released on Friday Sept 25th
  - Check Canvas / Github

Objectives

- Basic concept of data parallel computing
- Basic features of the CUDA C/C++ programming interface

A Data Parallel Computation Example: Conversion of a color image to grayscale

```
for each pixel {
     pixel = gsConvert(pixel)
}
// Every pixel is independent
// of every other pixel
```



CUDA Execution Model

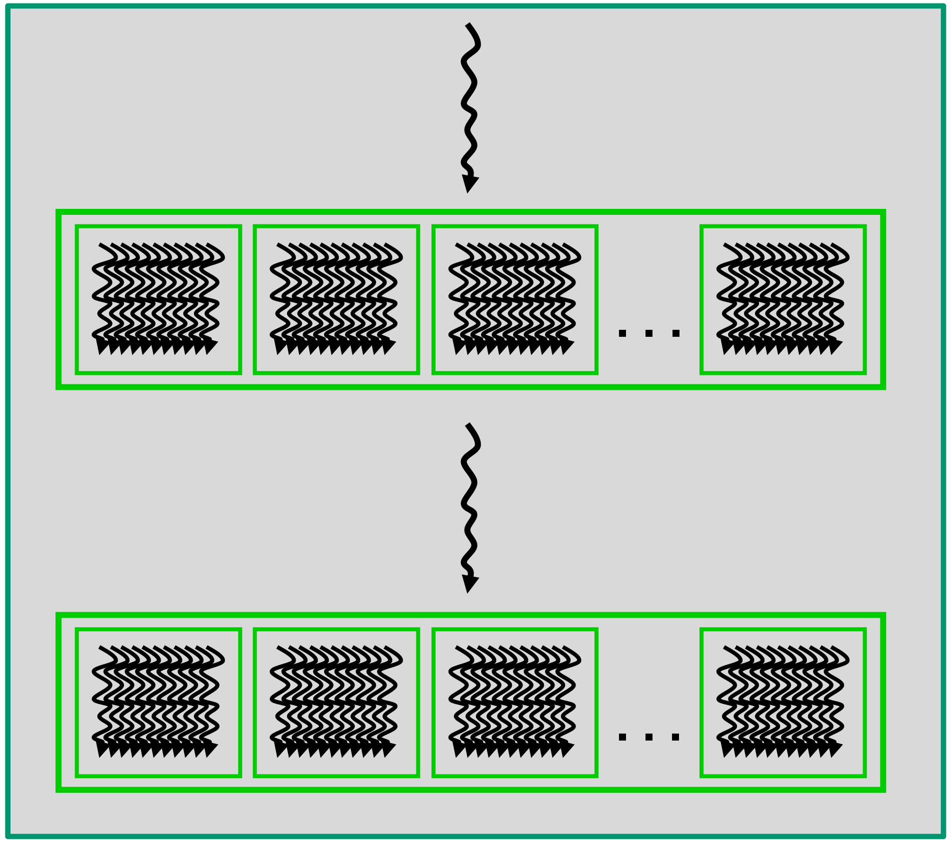
- Typical Compute-Intensive C/C++ code
  - Serial or modestly parallel parts
  - Highly parallel parts
- Serial parts → CPU (or Host)
- Highly Parallel parts → GPU (or Device)

Serial Code (CPU host)

Parallel Kernel (GPU device)

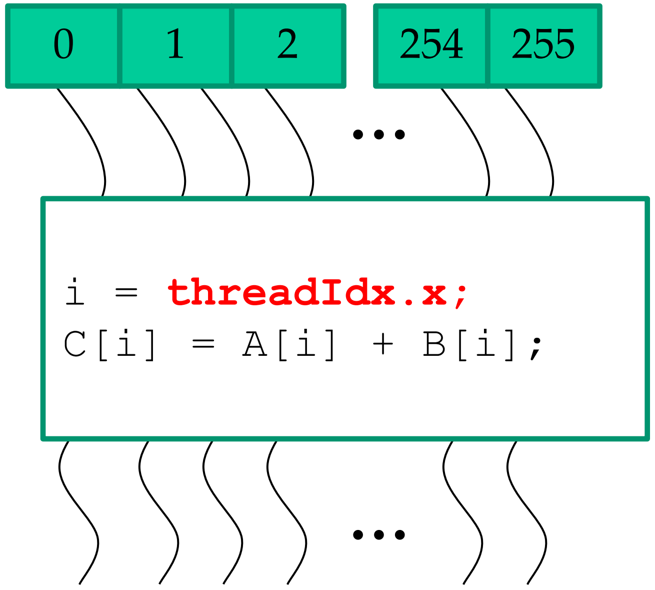
Serial Code (CPU host)

Parallel Kernel (GPU device)



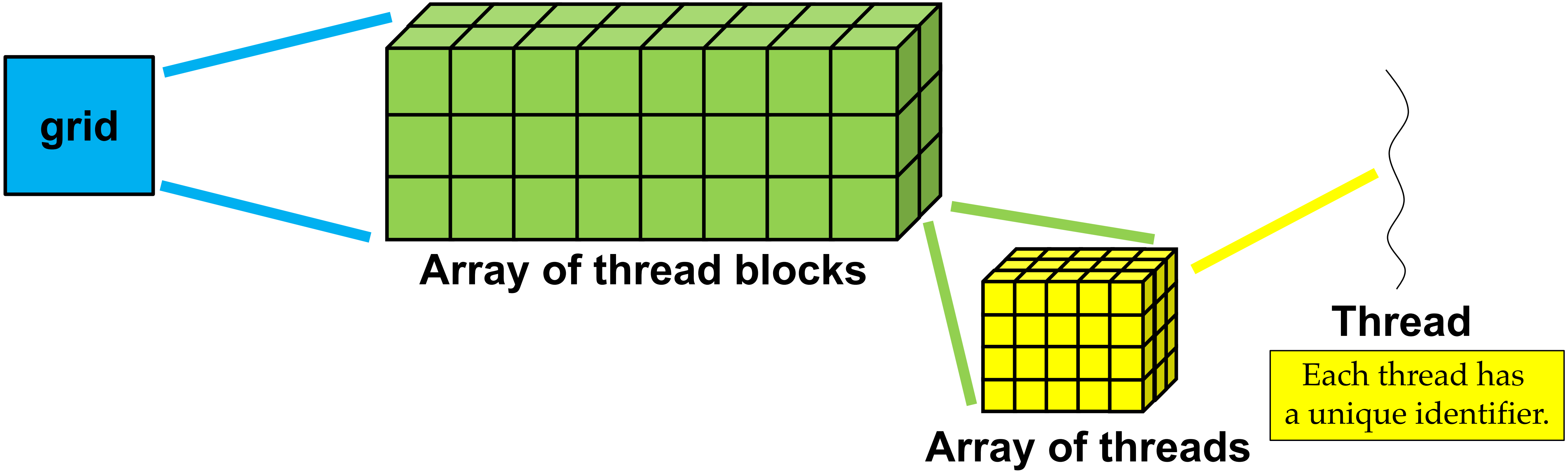
Arrays of Parallel Threads

- A CUDA kernel is executed as a grid (array) of threads
  - All threads in a grid run the same kernel code
  - Single Program Multiple Data (SPMD model)
  - Each thread has **a unique index** that it uses to compute memory addresses and make control decisions



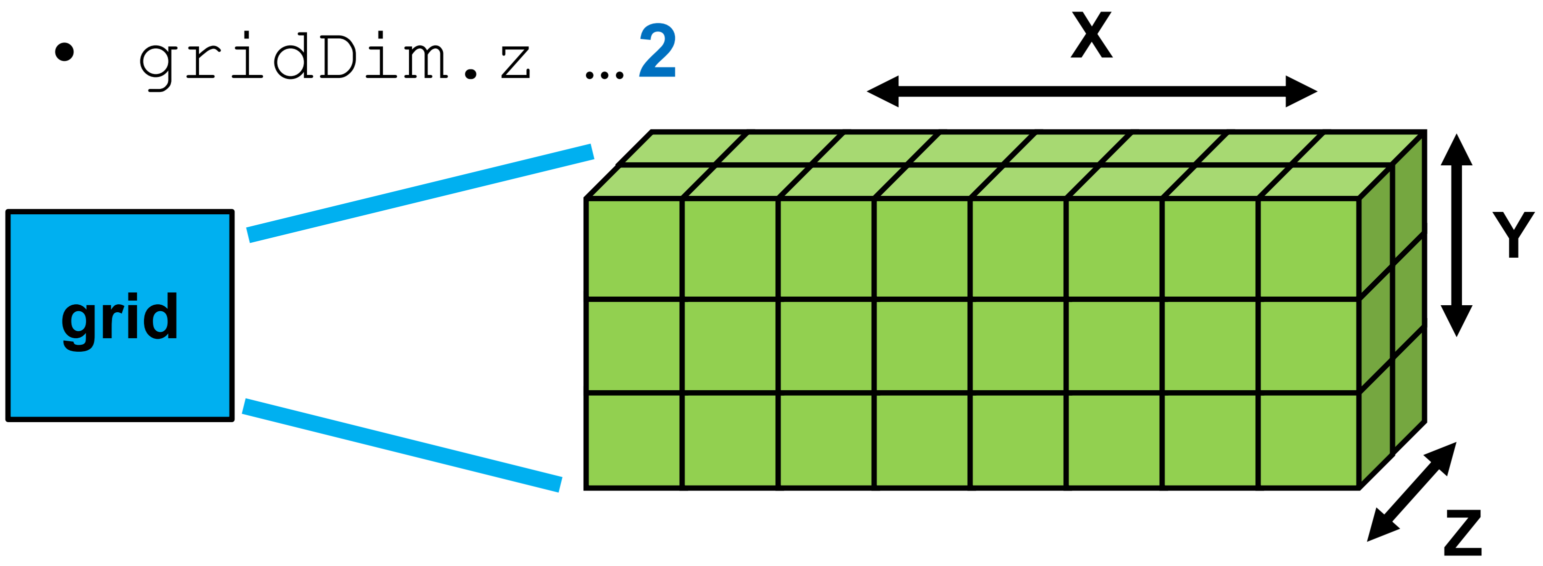
Logical Execution Model for CUDA

- Each CUDA kernel
  - is executed by a **grid**,
  - a 3D array of **thread blocks**, which are
  - 3D arrays of **threads**.



`gridDim` Gives Number of Blocks

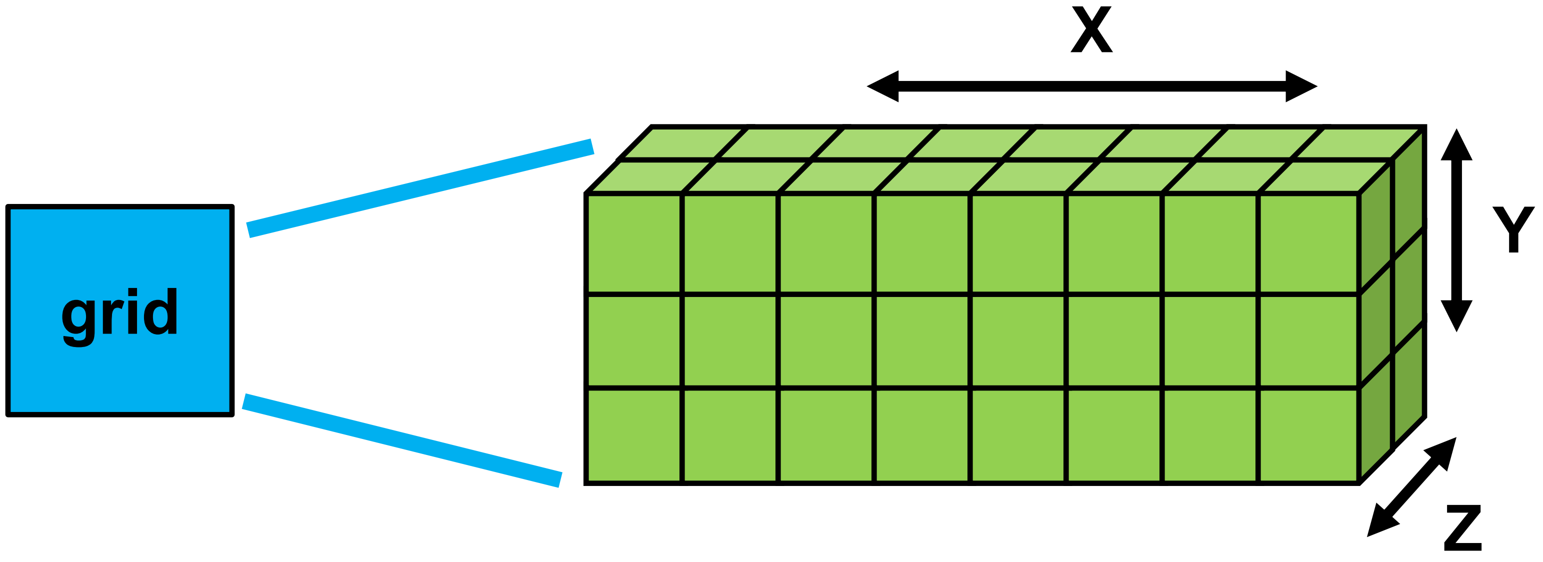
- Number of blocks in each dimension is
  - `gridDim.x` … 8
  - `gridDim.y` … 3
  - `gridDim.z` … 2



For 2D (and 1D) grids, simply use grid dimension 1 for Z (and Y).

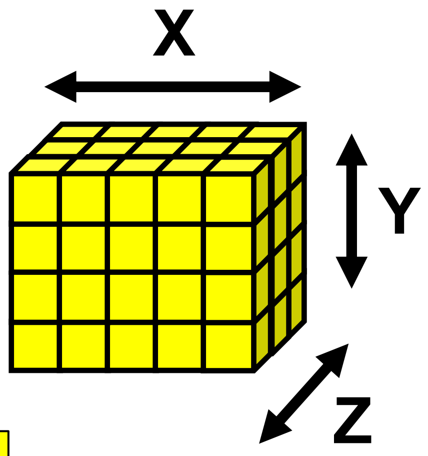
`blockIdx` is Unique for Each Block

- Each block has a unique index tuple
  - `blockIdx.x` (from 0 to (`gridDim.x` – 1))
  - `blockIdx.y` (from 0 to (`gridDim.y` – 1))
  - `blockIdx.z` (from 0 to (`gridDim.z` – 1))



`blockDim`: # of Threads per Block

- Number of blocks in each dimension is
  - `blockDim.x` … **5**
  - `blockDim.y` … **4**
  - `blockDim.z` … **3**



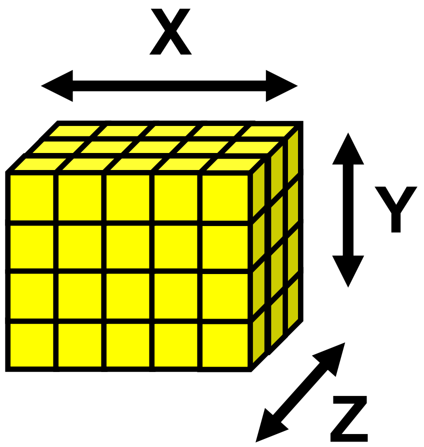
For 2D (and 1D) blocks, simply use block dimension 1 for Z (and Y).

`threadIdx` Unique for Each Thread

- Each thread has a unique index tuple
  - `threadIdx.x` (from 0 to (`blockDim.x` – 1))
  - `threadIdx.y` (from 0 to (`blockDim.y` – 1))
  - `threadIdx.z` (from 0 to (`blockDim.z` – 1))

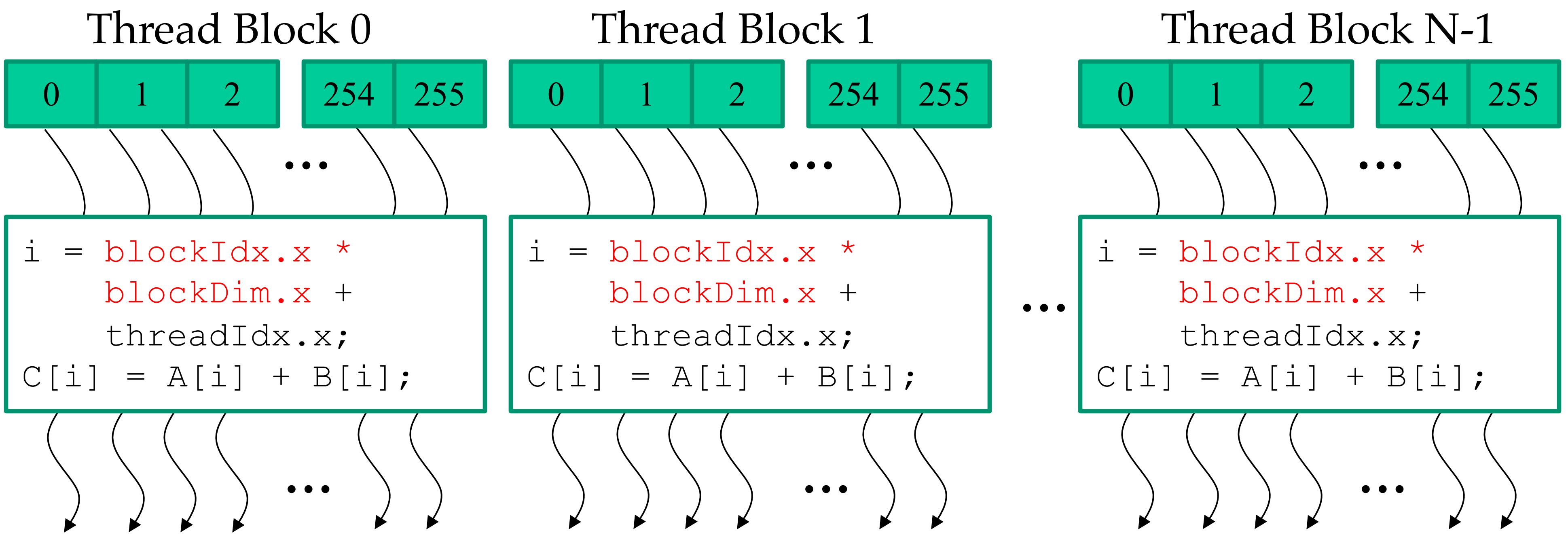
`threadIdx` tuple is unique to each thread
WITHIN A BLOCK.

`(threadIdx, blockIdx)` is unique to each thread
WITHIN A GRID.



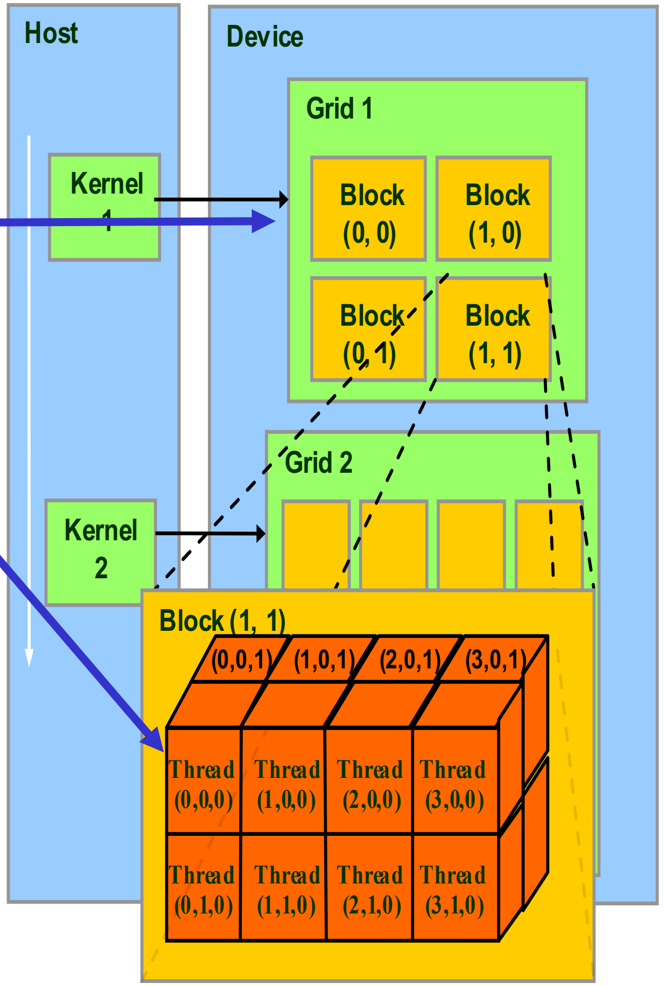
Thread Blocks: Scalable Cooperation

- Divide thread array into multiple blocks
  - Threads within a block cooperate via **shared memory, atomic operations** and **barrier synchronization** (to be covered later)
  - Threads in different blocks cooperate less (later)

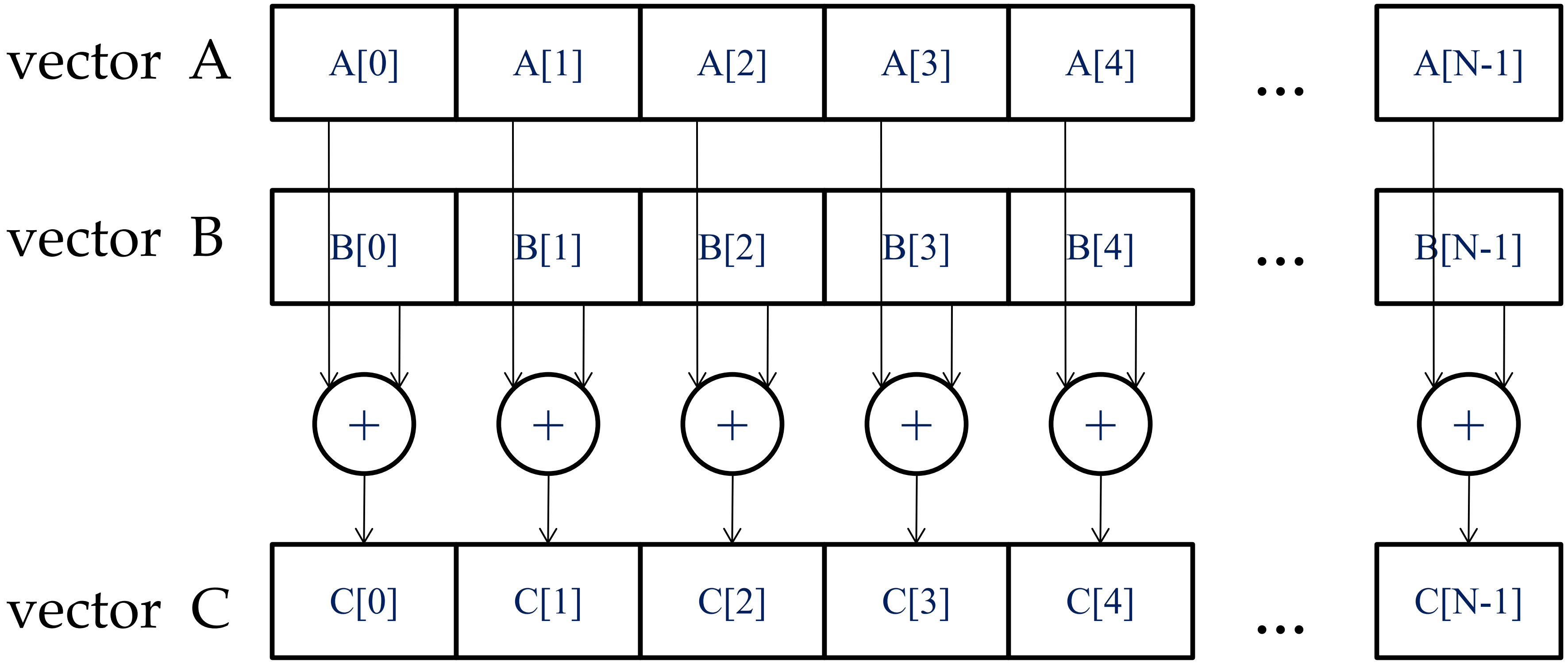


`blockIdx` and `threadIdx`

- Each thread uses indices to decide what data to work on
  - `blockIdx`: 1D, 2D, or 3D
    `threadIdx`: 1D, 2D, or 3D
- Simplifies memory addressing when processing multidimensional data
  - Image processing
  - Vectors, matrices, tensors
  - Solving PDEs on volumes
  - …



Vector Addition – Conceptual View



Vector Addition – Traditional C/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);
}
```

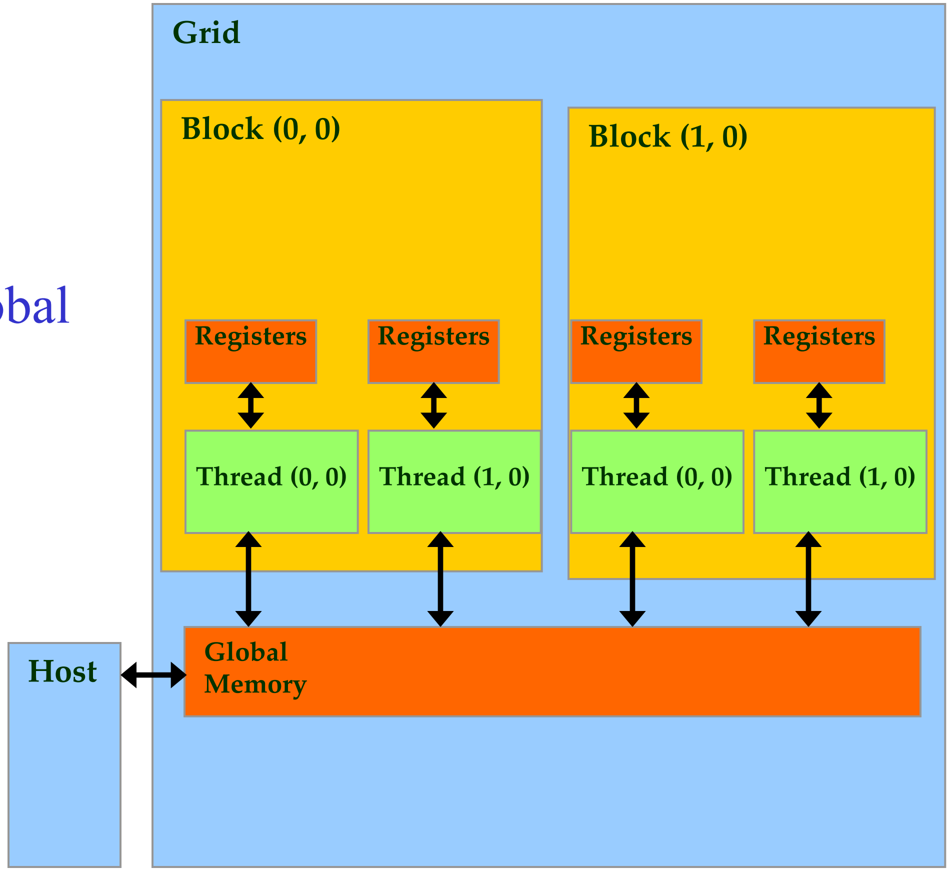
CUDA `vecAdd` Host Code

```
#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
}
```

Partial Overview of CUDA Memories

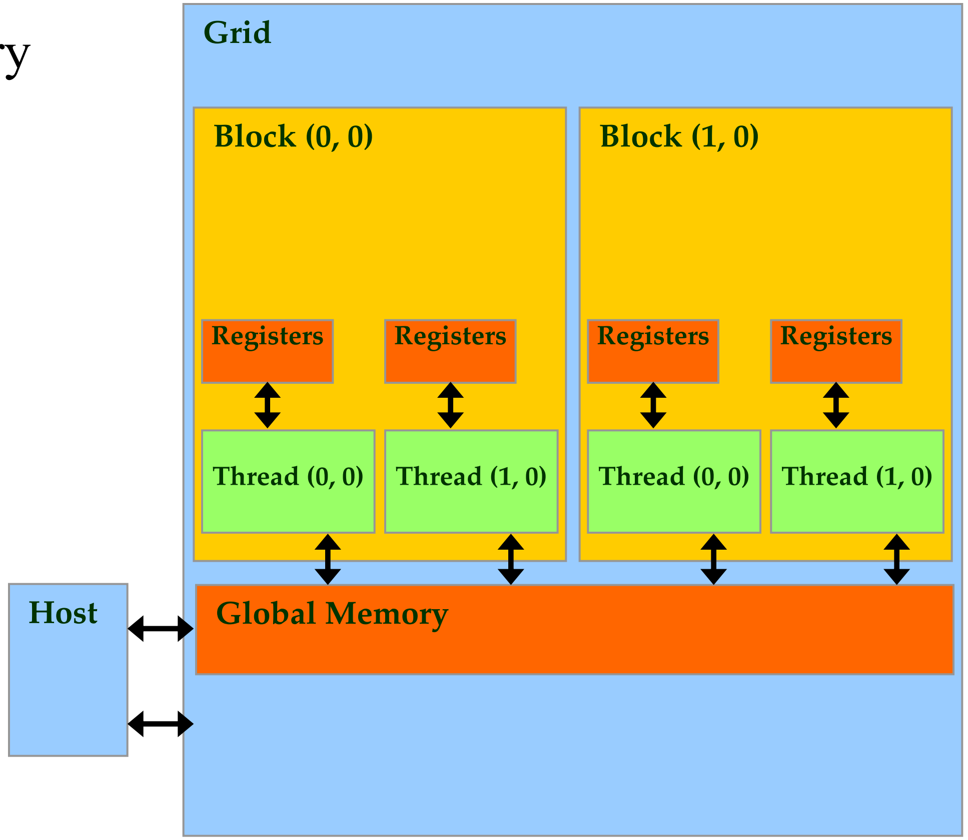
- Device code can:
  - R/W per-thread registers
  - R/W per-grid global memory
- Host code can
  - Transfer data to/from per grid global memory

We will cover more later.



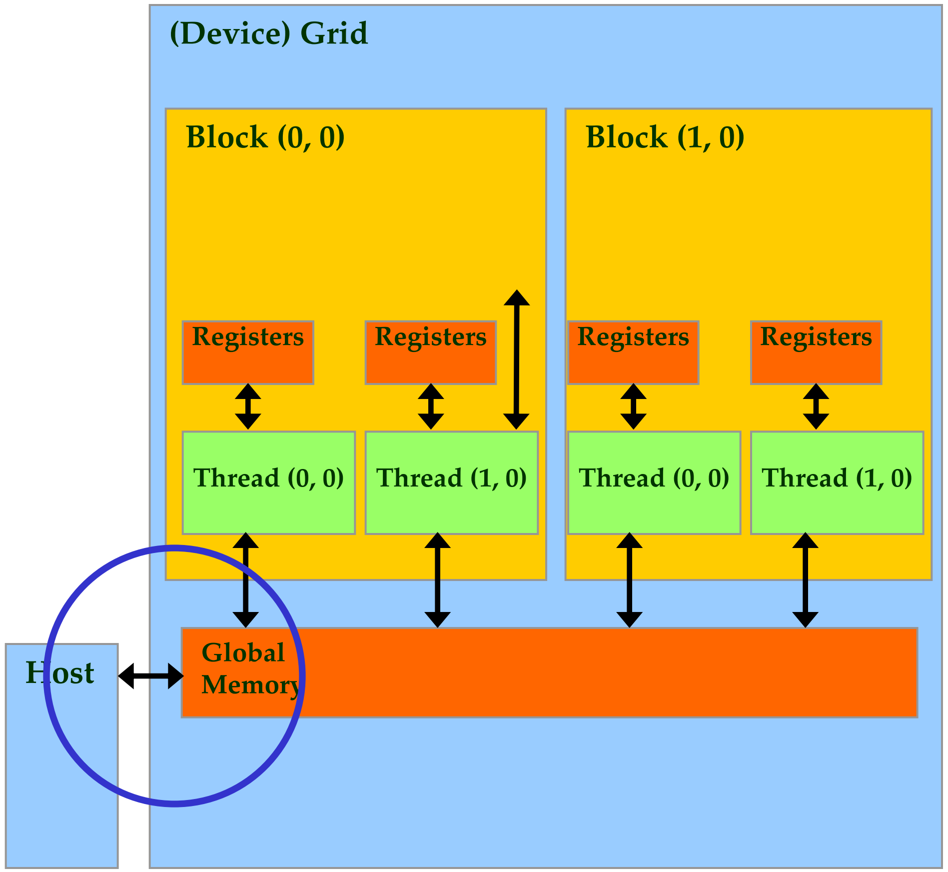
CUDA Device Memory Management API

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



Host-Device Data Transfer API

- `cudaMemcpy()`
  - memory data transfer
  - Requires four parameters
    - Pointer to destination
    - Pointer to source
    - Number of bytes copied
    - Type/Direction of transfer



```
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
         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);
}
```

Example: Vector Addition Kernel

Device Code

```
// Compute vector sum C = A+B
// Each thread performs one pair-wise addition
__global__
void vecAddKernel(float* A_d, float* B_d, float* C_d, int n)
{
    int i = blockIdx.x * blockDim.x + threadIdx.x ;
    if(i<n) C_d[i] = A_d[i] + B_d[i];
}
int vectAdd(float* A, float* B, float* C, int n)
{
    // A_d, B_d, C_d allocations and copies omitted
    // Run ceil(n/256.0) blocks of 256 threads each
    vecAddKernel<<<ceil(n/256.0), 256>>>(A_d, B_d, C_d, n);
}
```

Example: Vector Addition Kernel

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

Host Code

```
int vecAdd(float* A, float* B, float* C, int n)
{
  // A_d, B_d, C_d allocations and copies omitted
  // Run ceil(n/256.0) blocks of 256 threads each
  vecAddKernel<<<ceil(n/256.0),256>>>(A_d, B_d, C_d, n);
}
```

More on Kernel Launch

Equivalent Host Code

```
int vecAdd(float* A, float* B, float* C, int n)
{
 // A_d, B_d, C_d allocations and copies omitted
 // Run ceil(n/256.0) blocks of 256 threads each
  dim3 DimGrid(ceil(n/256.0), 1, 1);
  dim3 DimBlock(256, 1, 1);

  vecAddKernel<<<DimGrid,DimBlock>>>(A_d, B_d, C_d, n);
}
```

- Any call to a kernel function is asynchronous from CUDA 1.0 onward, explicit synch needed to block

Vector Addition Kernel

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

int vecAdd(float* A, float* B, float* C, int n)
{
  // A_d, B_d, C_d allocations and copies omitted
  // Run ceil(n/256.0) blocks of 256 threads each
  dim3 DimGrid(ceil(n/256.0), 1, 1);
  dim3 DimBlock(256, 1, 1);

  vecAddKernel<<<DimGrid,DimBlock>>>(A_d, B_d, C_d, n);
}
```

A Number of blocks per dimension in the grid

B Number of threads per dimension in a block

C Unique block # in x dimension

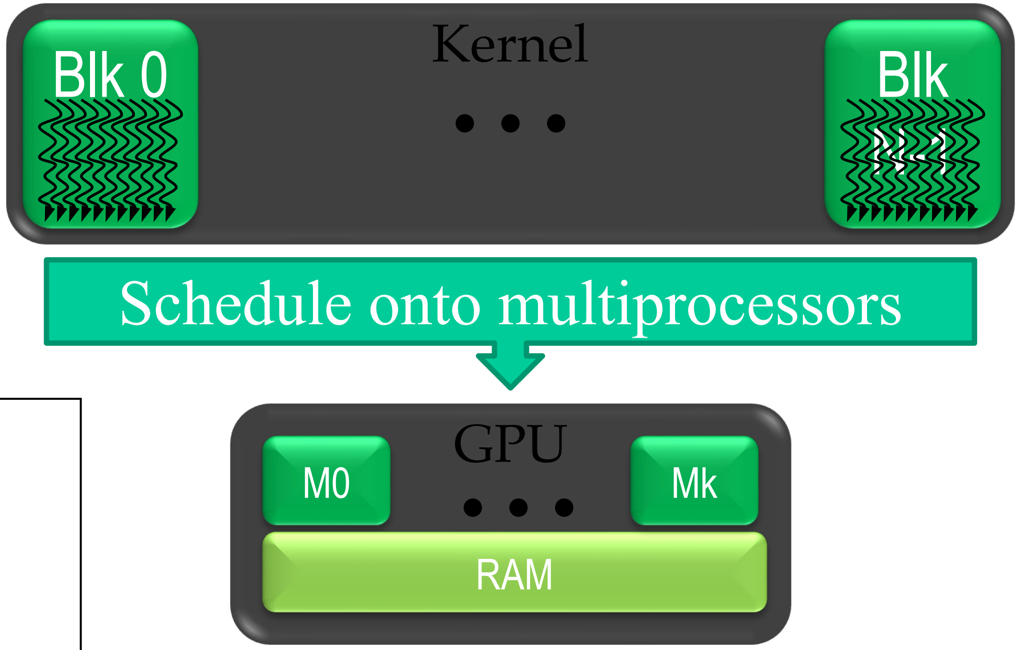
D Number of threads per block in x dimension

E Unique thread # in x dimension in the block

Kernel execution in a nutshell

```
__host__
Void vecAdd()
{
  dim3 DimGrid(ceil(n/256.0),1,1);
  dim3 DimBlock(256,1,1);

  vecAddKernel<<<DimGrid,DimBlock>>>(A_d, B_d, C_d, n);
}
```

```
__global__
void vecAddKernel(float *A_d, float *B_d, float *C_d, int n)
{
   int i = blockIdx.x * blockDim.x + threadIdx.x;

   if( i<n ) C_d[i] = A_d[i]+B_d[i];
}
```

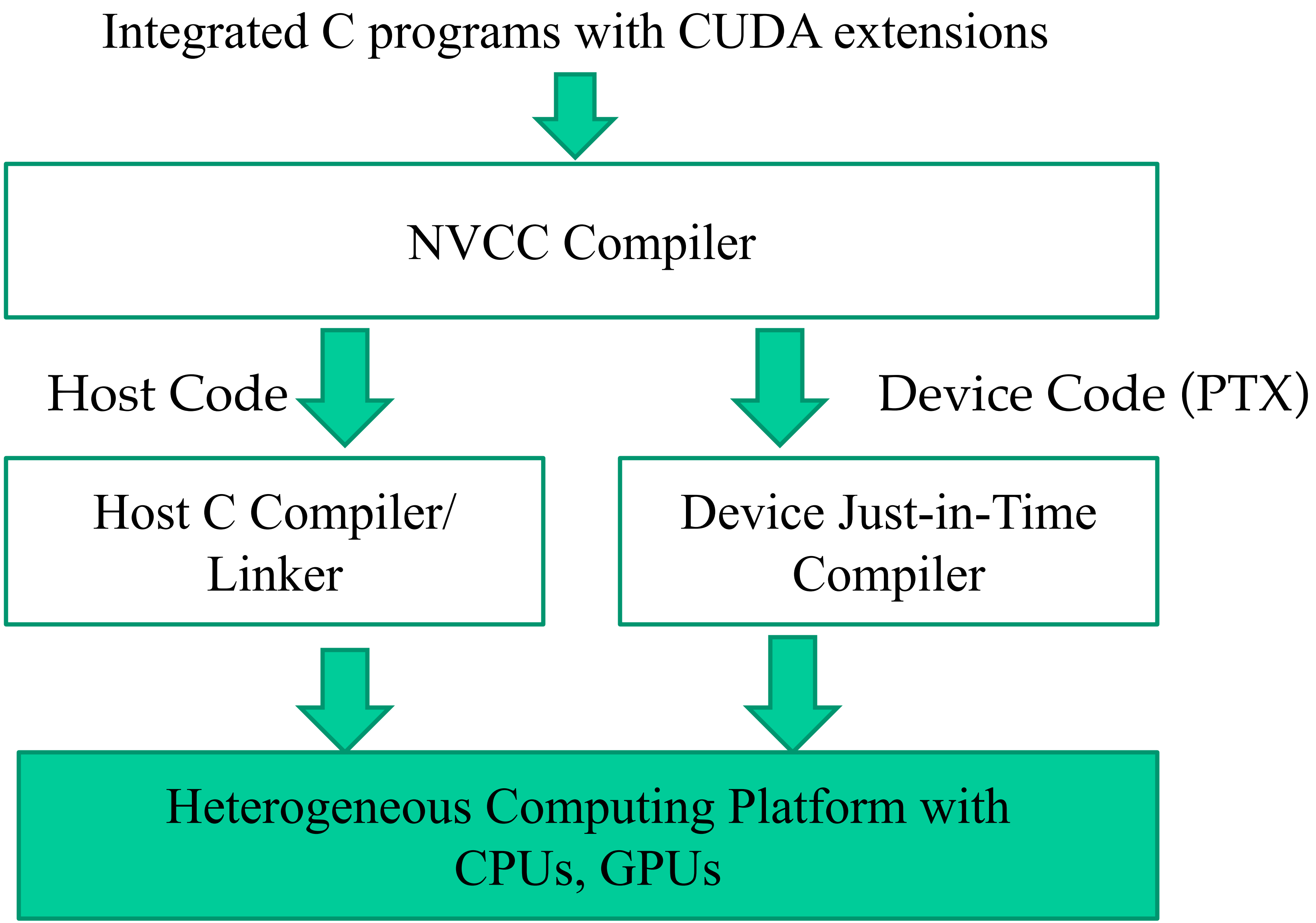


More on CUDA Function Declarations

	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
  - Each "__" consists of two underscore characters
  - A kernel function must return `void`
- `__device__` and `__host__` can be used together

Compiling A CUDA Program



QUESTIONS?