ECE408 /CS483/CSE408 Spring 2025
Applied Parallel Programming

Lecture 2:
Introduction to CUDA C and Data Parallel Programming

Course Reminders

- Delta access and Lab 0 are due this Friday at 8pm US Central time
  - It is an easy lab, but it may take some time to get the tools in place.
  - Its main purpose is to get familiar with the programming environment and the process.
  - If you miss this deadline, that's OK for Lab 0, but you must submit it anyway. Remember, Lab 0 will not be counted towards your overall grade.

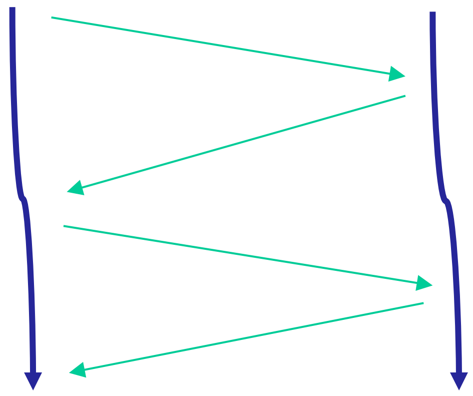
Objective

- To learn the basic concept of data parallel computing
- To learn the basic features of the CUDA C programming interface

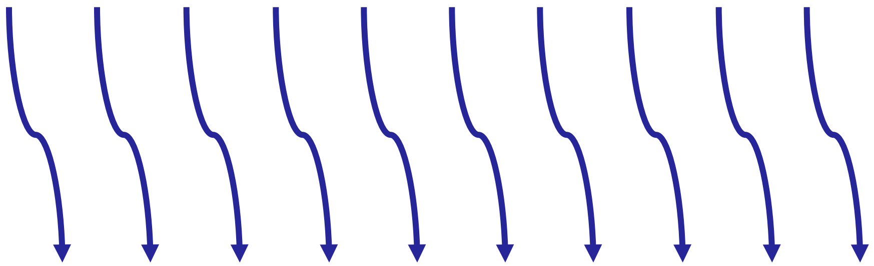
Thread as a basic unit of computing

- What is a thread?
  - Program
  - PC
  - Context
    - Memory
    - Registers
    - …

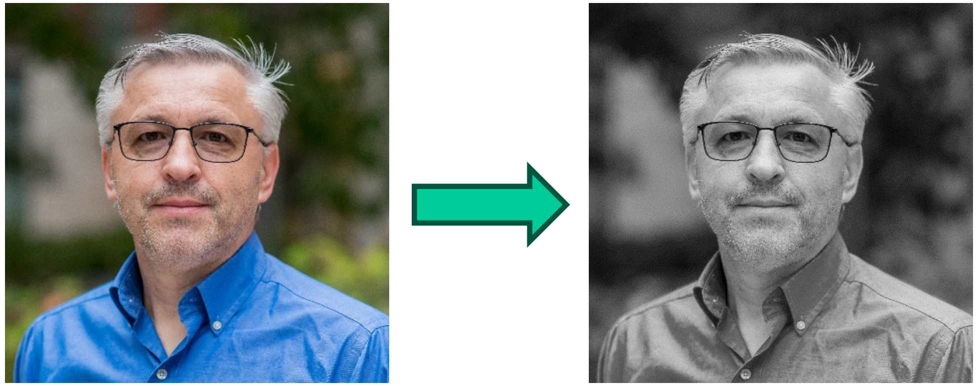
- Multiple threads



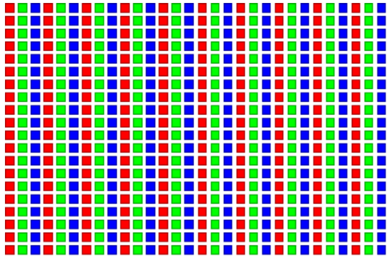
- Many threads



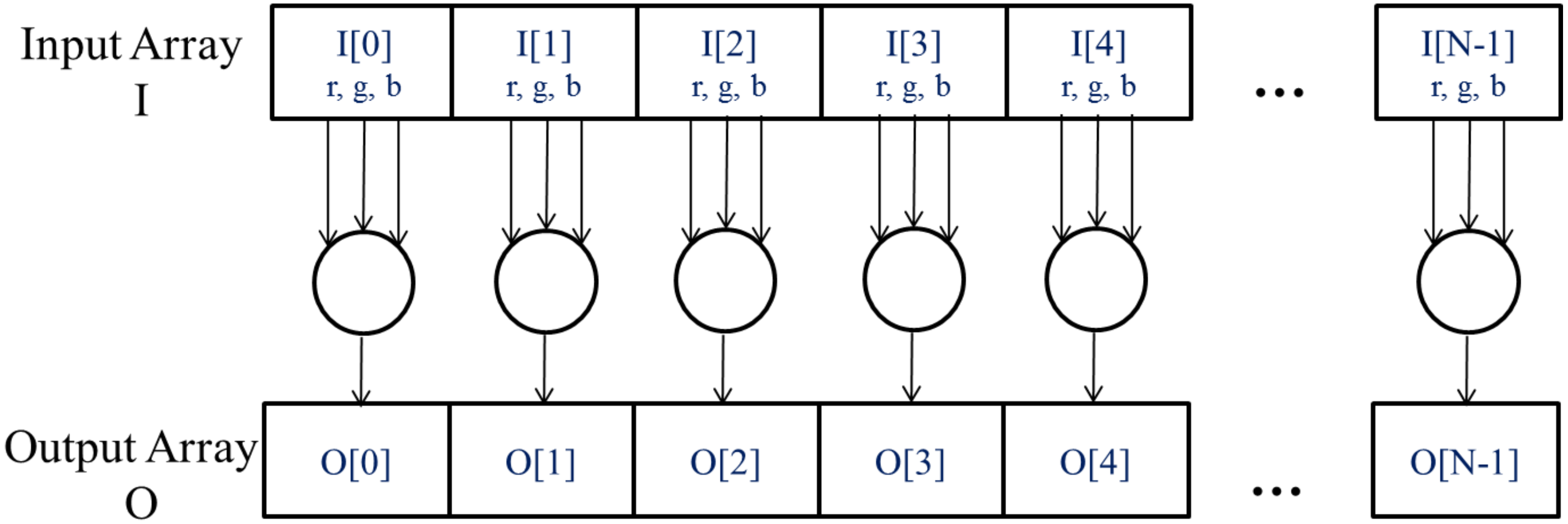
A Data Parallel Computation Example: Conversion of a color image to grey–scale image



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



The pixels can be calculated independently of each other




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

CUDA/OpenCL – Execution Model

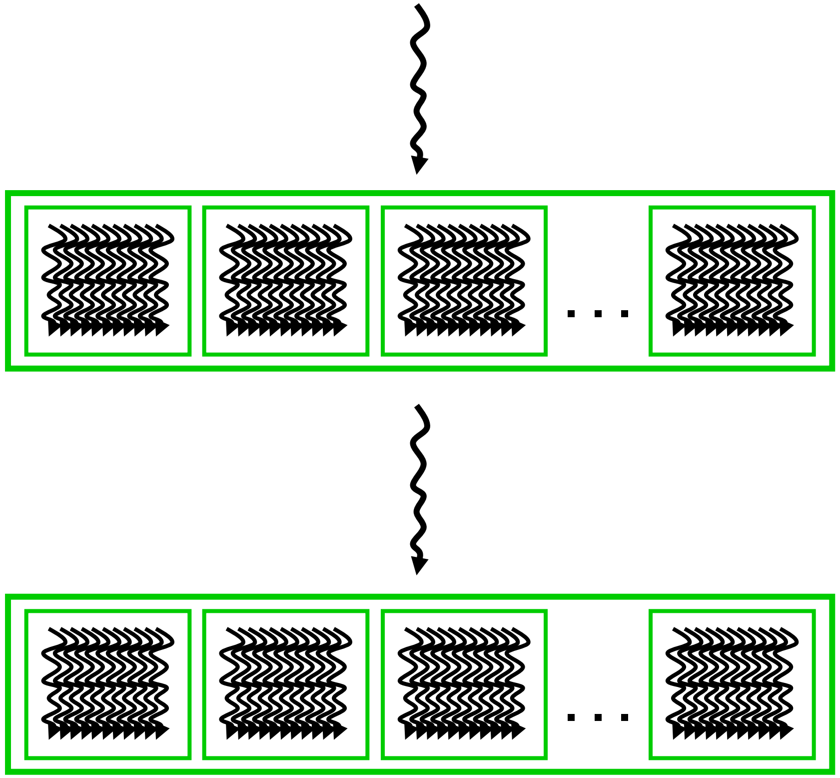
- Integrated host+device app C program
  - Serial or modestly parallel parts in **host** C code
  - Highly parallel parts in **device** SPMD kernel C code

Serial Code (host)

Parallel Kernel (device)
KernelA<<< nBlk, nTid >>>(args);

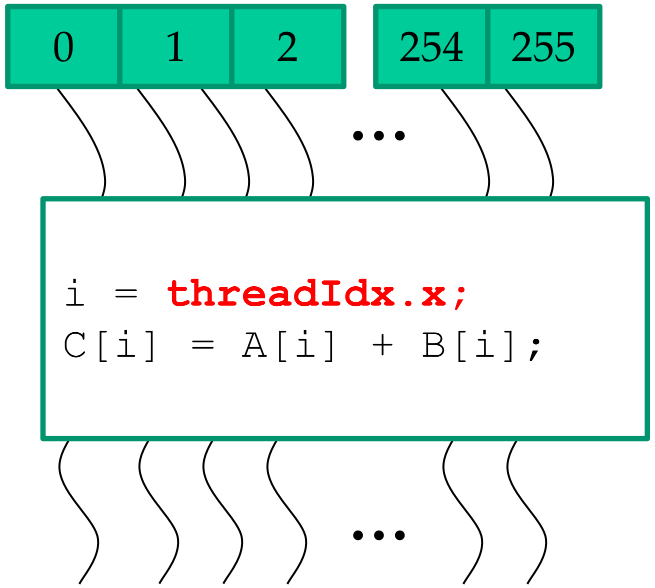
Serial Code (host)

Parallel Kernel (device)
KernelB<<< nBlk, nTid >>>(args);



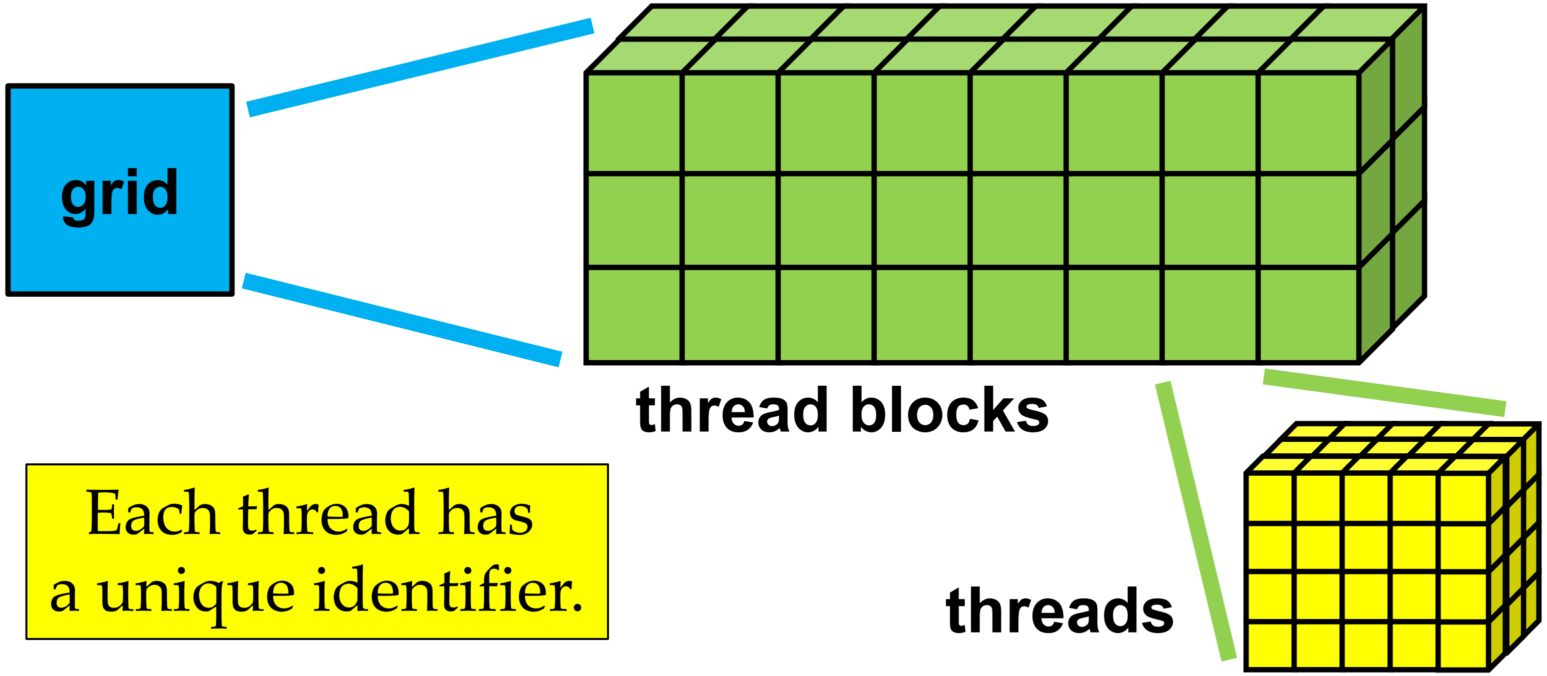
Arrays of Parallel Threads

- 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

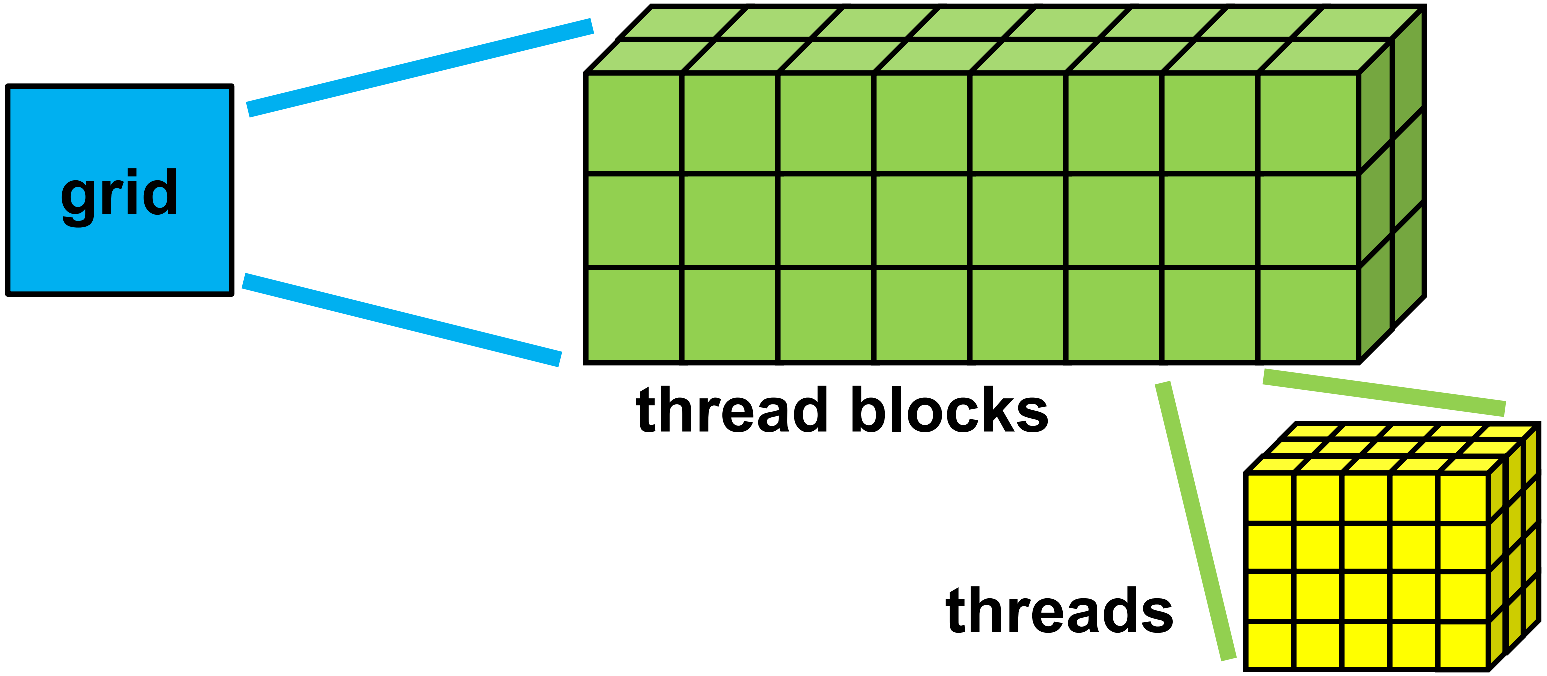
- Each CUDA kernel
  - is executed by a **grid**,
  - a 3D array of **thread blocks**, which are
  - 3D arrays of **threads**.



Each thread has
a unique identifier.

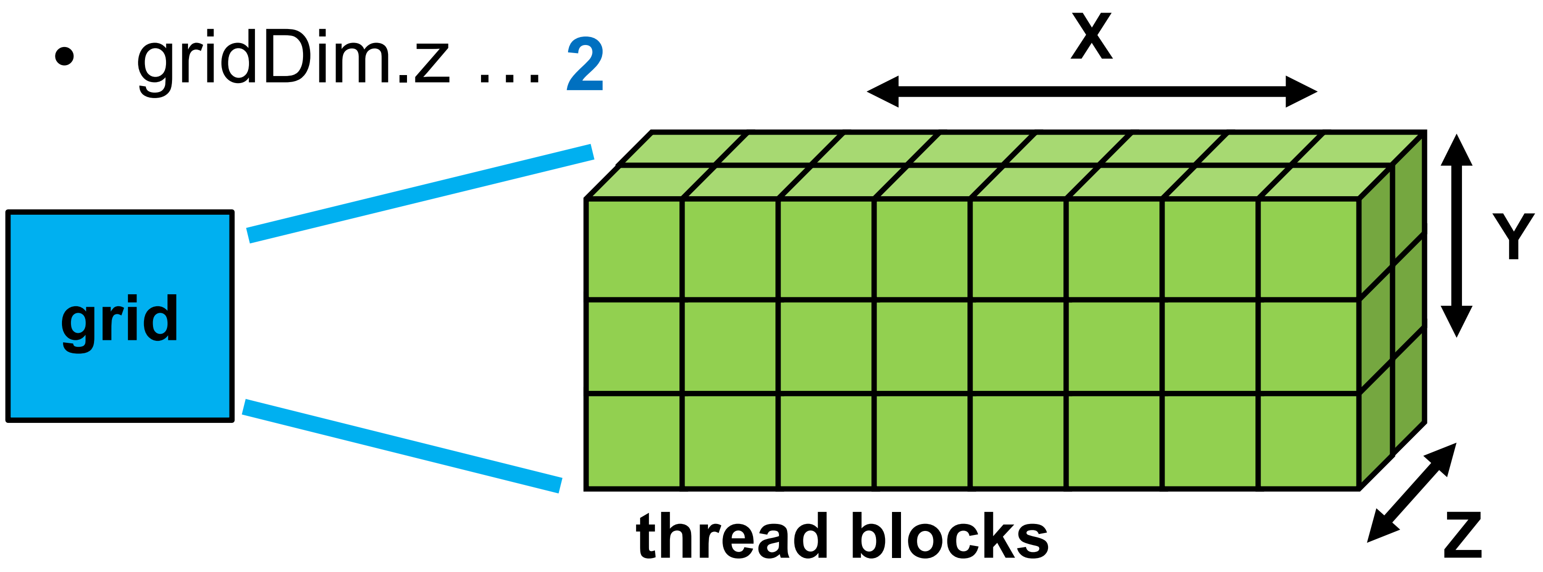
Single Program, Multiple Data

- Each thread
  - executes the **same program**
  - on **distinct data inputs**,
  - a single-program, multiple-data (**SPMD**) model



gridDim Gives Number of Blocks

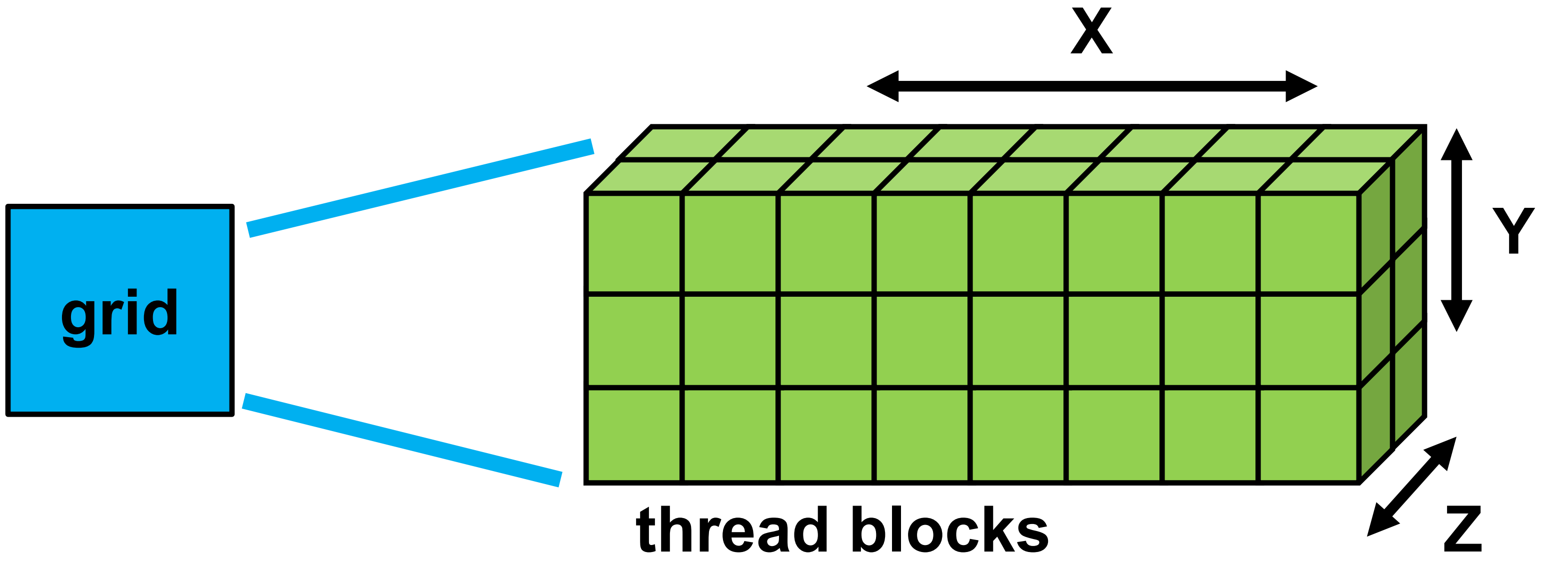
- Number of blocks in each dimension is
  - gridDim.x … **8**
  - gridDim.y … **3**
  - gridDim.z … **2**



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

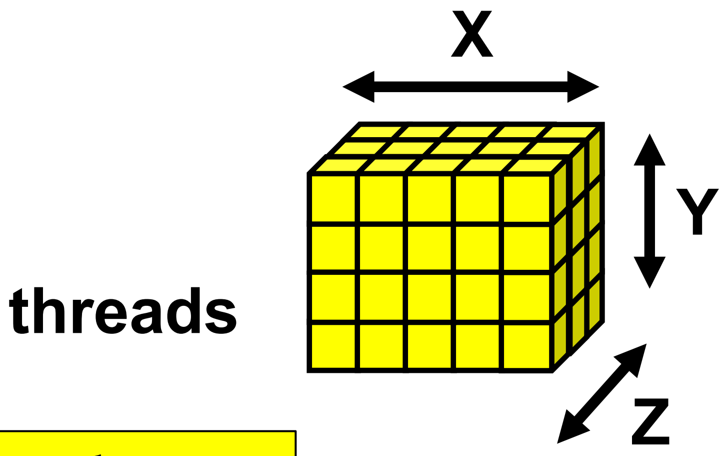
blockIdx is Unique for Each Block

- 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

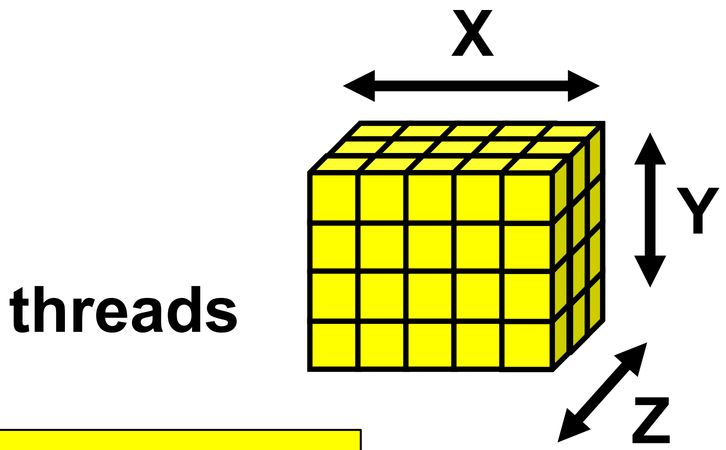
- Number of blocks in each dimension is
  - blockDim.x … **5**
  - blockDim.y … **4**
  - blockDim.z … **3**



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

threadIdx Unique for Each Thread

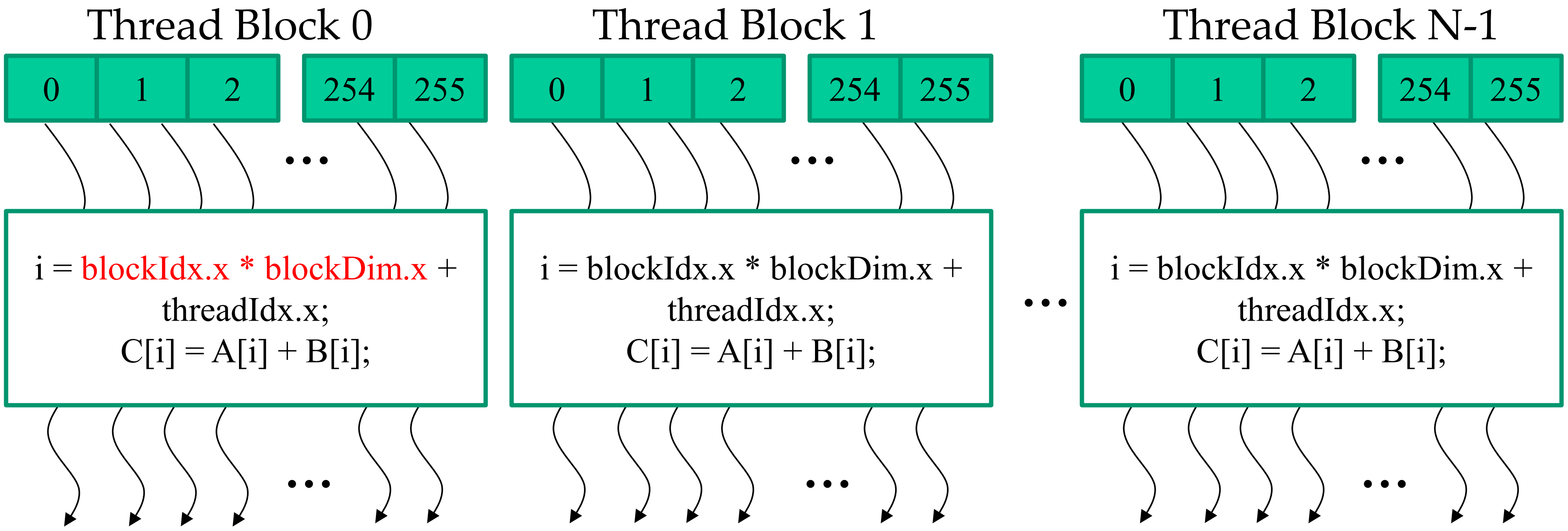
- Each thread has a unique index tuple
  - threadIdx.x (from 0 to (blockDim.x – 1))
  - threadIdx.y (from 0 to (blockDim.y – 1))
  - threadIdx.z (from 0 to (blockDim.z – 1))



threadIdx tuple is unique to each thread
WITHIN A BLOCK.

Thread Blocks: Scalable Cooperation

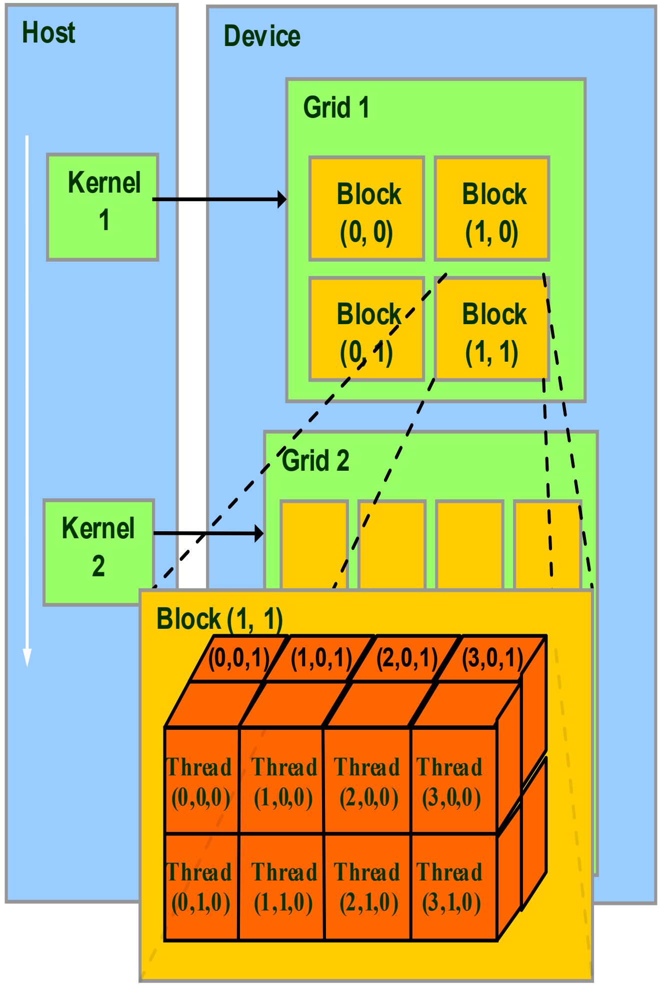
- Threads within a block cooperate via **shared memory, atomic operations** and **barrier synchronization** (to be covered later)
- Threads in different blocks cooperate less.



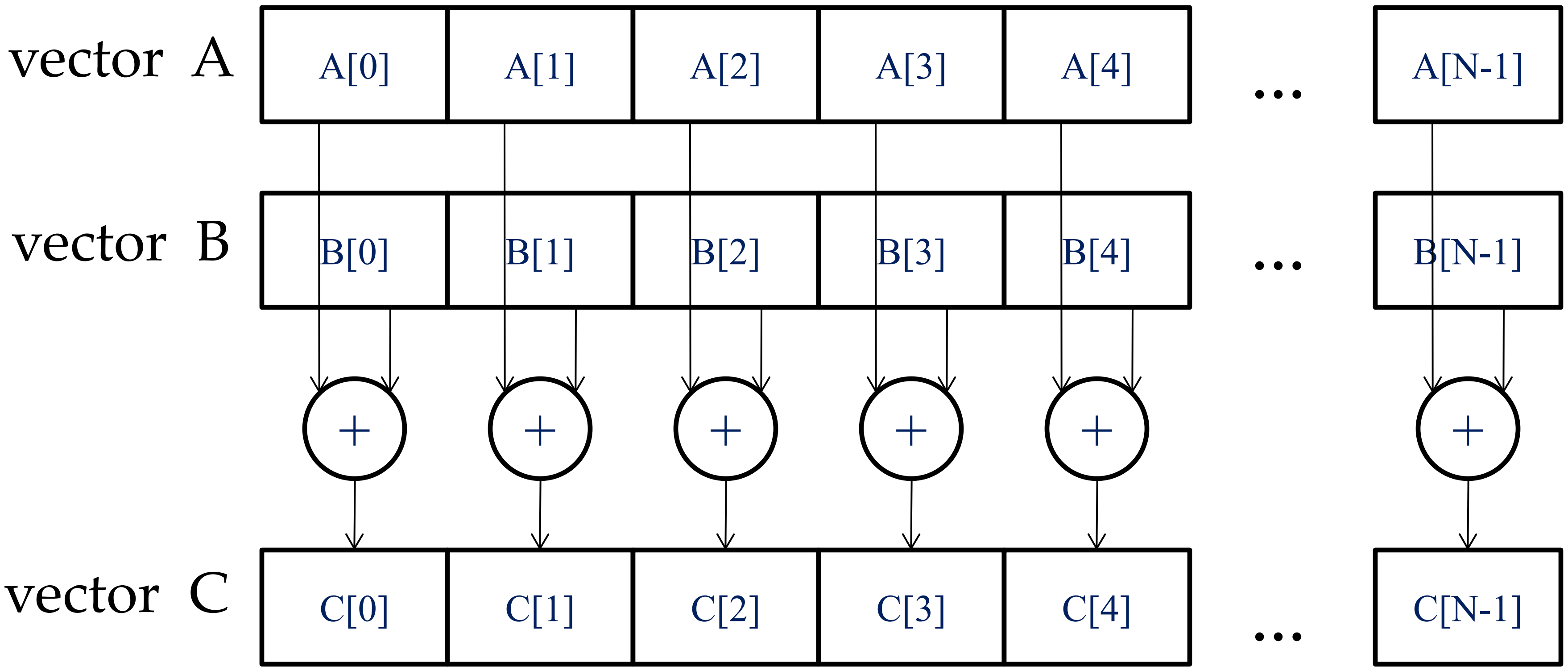
blockIdx and threadIdx

- Thread block and thread organization
  - simplifies memory addressing
  - when processing multidimensional data

– Image processing
– Vectors, matrices, tensors
– Solving PDEs on volumes
– …



Vector Addition – Conceptual View



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);
}
```

Heterogeneous Computing: vecAdd Host Code

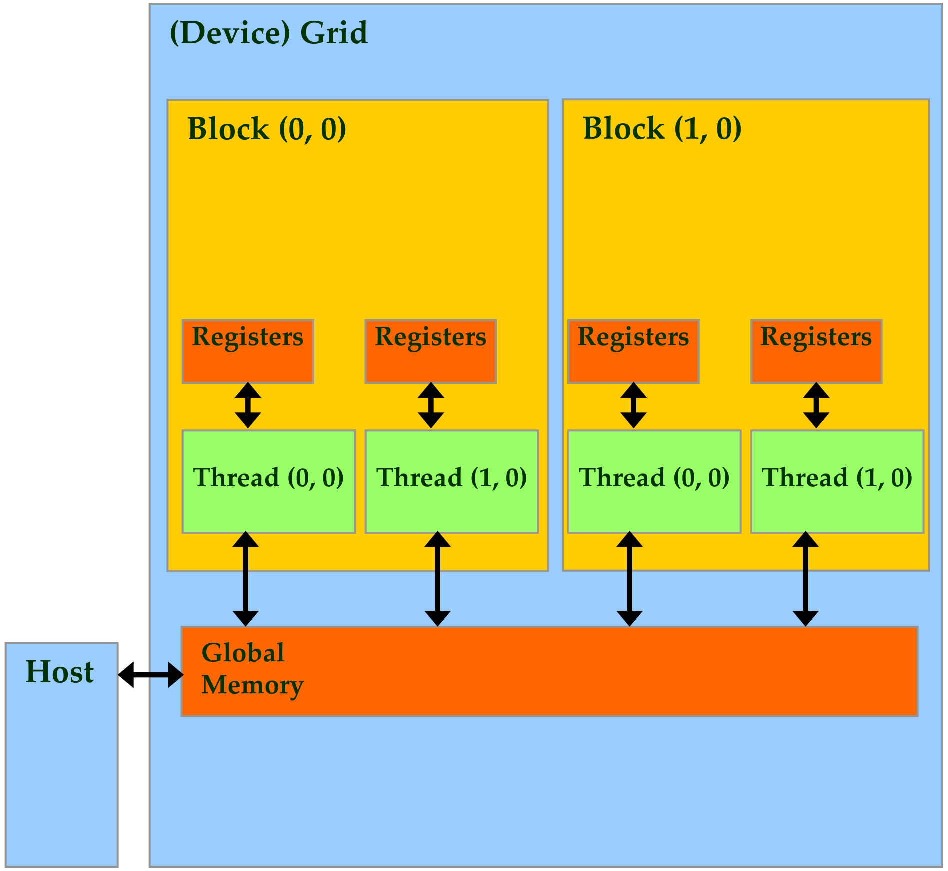
```
#include <cuda.h>
void vecAdd(float* A, float* B, float* C, int n)
{
     int size = n* sizeof(float);
     float *A_d, *B_d, *C_d;
  …
1. // Allocate device memory for A, B, and C
   // copy A and B to device memory

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

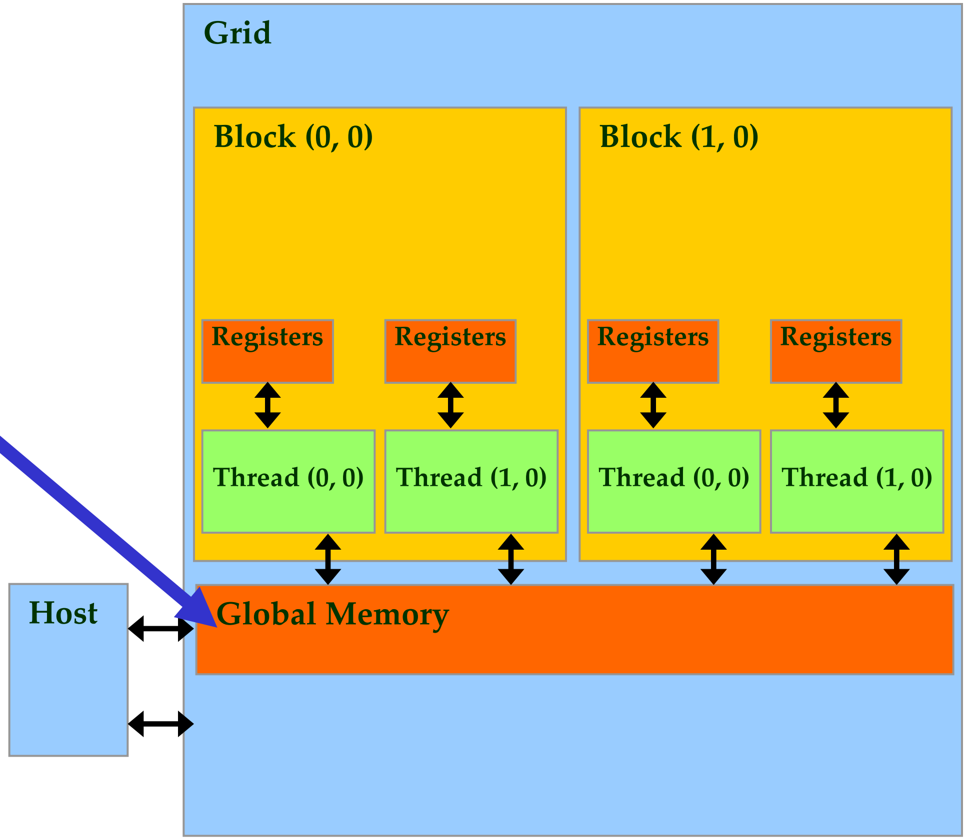
- Host code can
  - Transfer data to/from per grid global memory

We will cover more later.



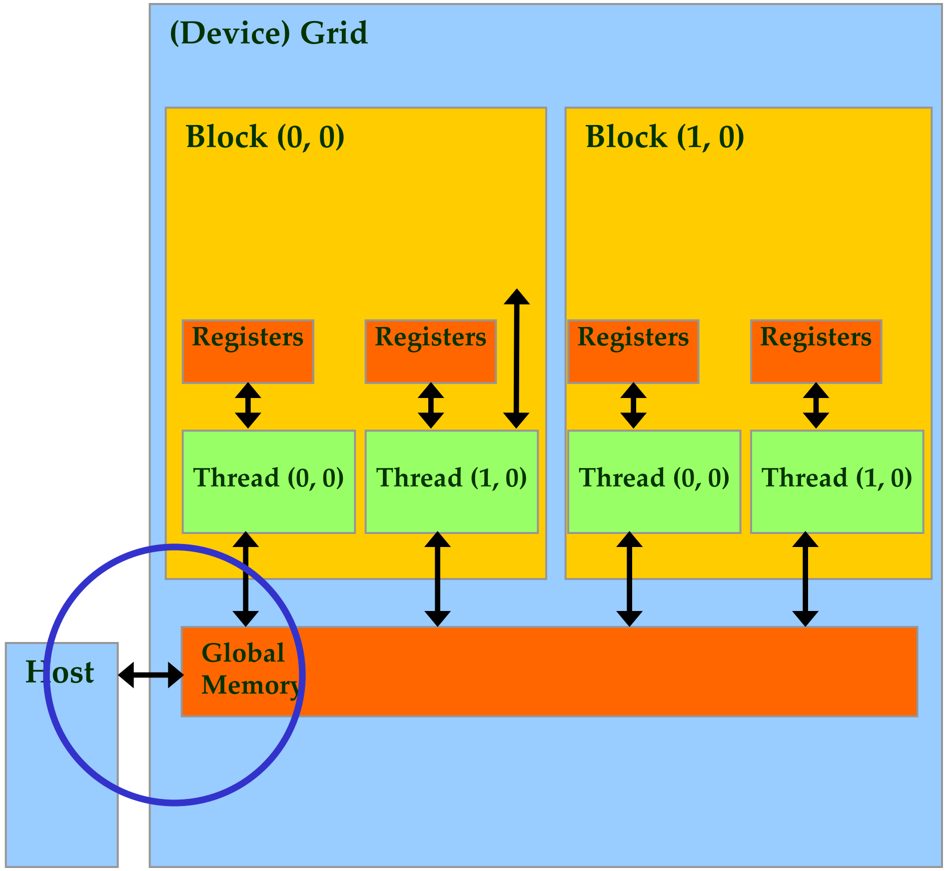
CUDA Device Memory Management API functions

- cudaMalloc()
  - Allocates object in the device global memory
  - Two parameters
    - **Address of a pointer** 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 functions

- 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
   // (error-checking omitted)
    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) 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) 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) blocks of 256 threads each
  dim3 DimGrid(n/256, 1, 1);
  if (0 != (n % 256)) { DimGrid.x++; }
  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 on, explicit synch needed for blocking

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) blocks of 256 threads each
  dim3 DimGrid(ceil(n/256), 1, 1);
  dim3 DimBlock(256, 1, 1);

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

A Number of blocks per dimension

B Number of threads per dimension in a block

C Unique block # in x dimension

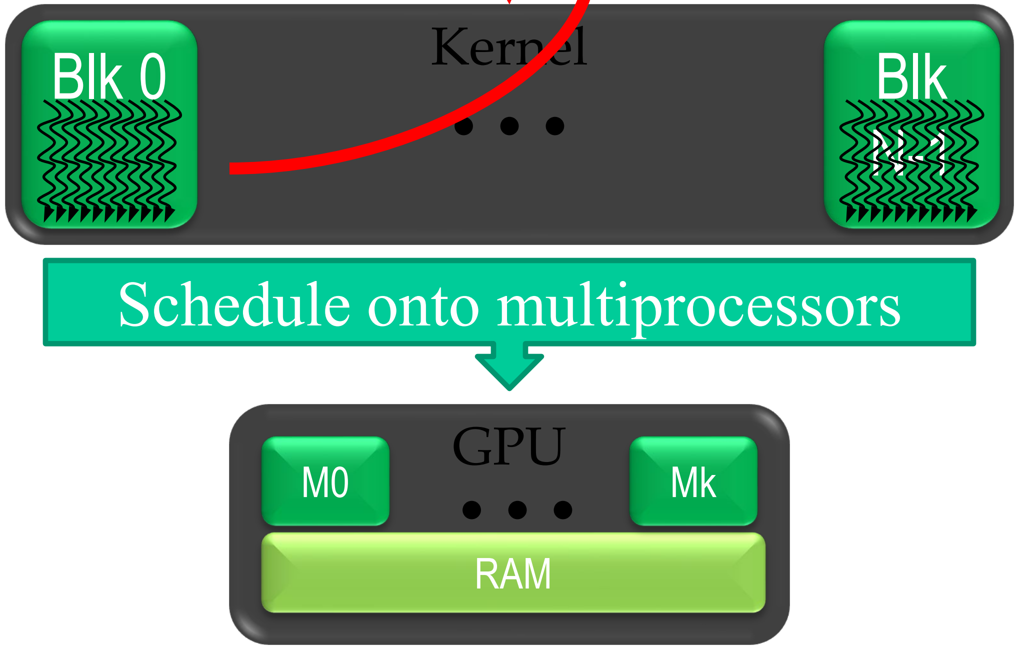
D Number of threads per block in x dimension

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];
}
```

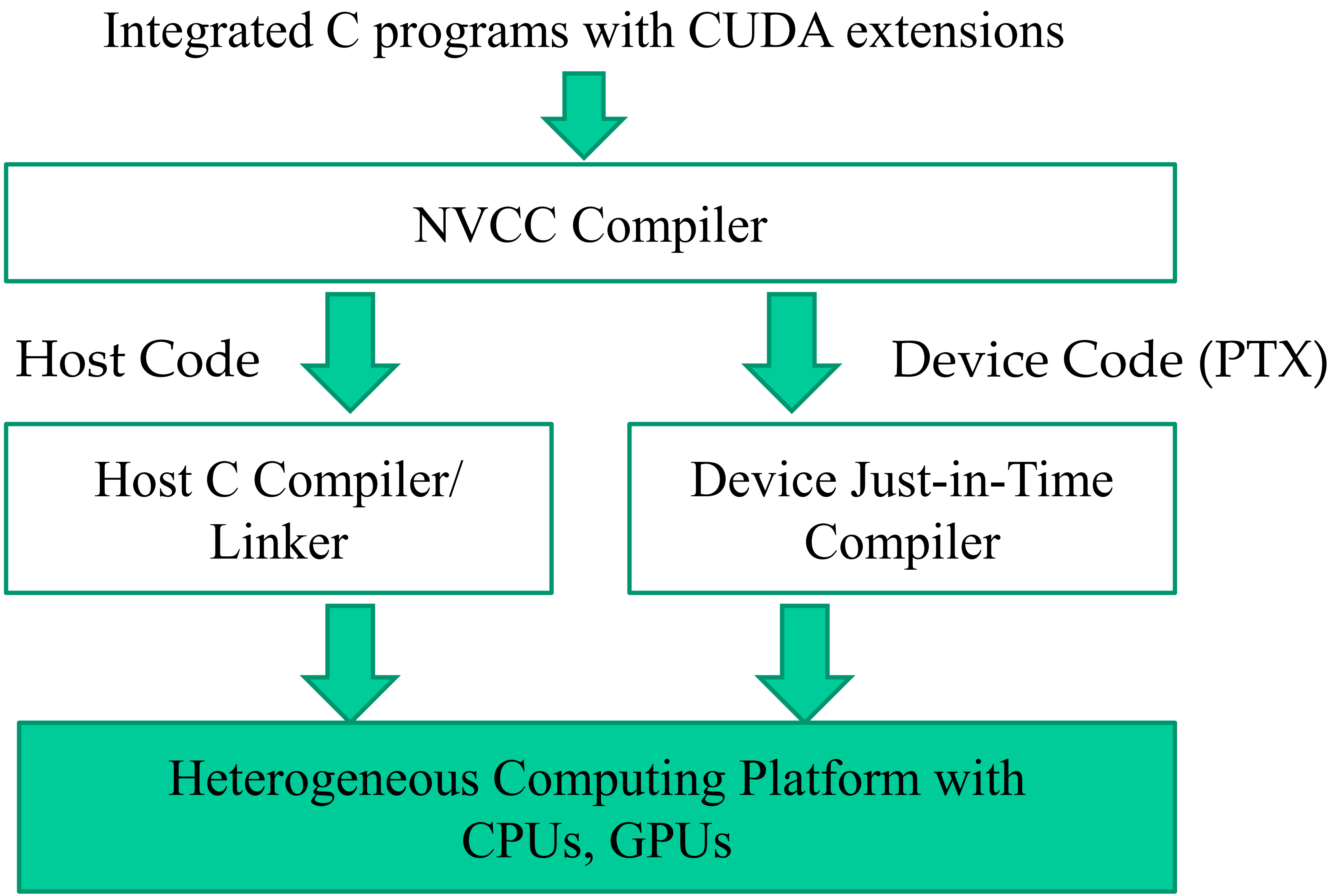


More on CUDA Function Declarations

	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



ANY MORE QUESTIONS?
READ CHAPTER 2

Problem Solving

- Consider the following code:

```
kernel<<VECTOR_N, ELEMENT_N>>>(d_C, d_A, d_B, ELEMENT_N);
```

- Q: How many CUDA threads are in each block as the result of the following kernel call?
- A: **`ELEMENT_N`**

- Q: How many CUDA threads will be created as the result of the following kernel call?
- A: **`VECTOR_N * ELEMENT_N`**

Problem Solving

- Q: For a vector addition, assume that the vector length is 16000, each thread calculates 8 output elements, and the thread block size is 256 threads. The programmer configures the kernel launch to have a minimal number of thread blocks to cover all output elements. How many **threads** will be in the **grid**?
- A:
  - How many threads do we need? 16000/8 = 2000
  - How many blocks of threads do we need to run 2000 threads? ceil(2000/256) = 8
  - Thus, how many threads will be running? 8 * 256 = 2048

Problem Solving

- Q: A CUDA kernel is launched with 512 thread blocks each of which has 256 threads. If a variable is declared as a local variable in the kernel, how many versions of the variable will be created through the lifetime of the execution of the kernel?
- A:
  - How many threads will be created? 512 * 256 = 131072
  - So, there will be as many copies of the local variable, one in each thread.