ECE408 / CS483 / CSE408
Summer 2024

Applied Parallel Programming

Lecture 2: Introduction to CUDA C and Data Parallel Programming

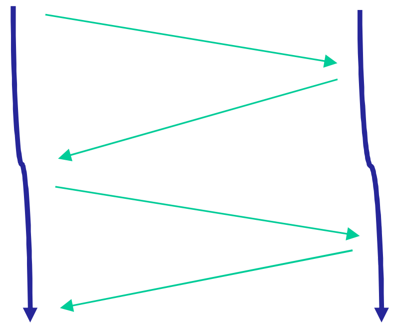
What Will You Learn Today?

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

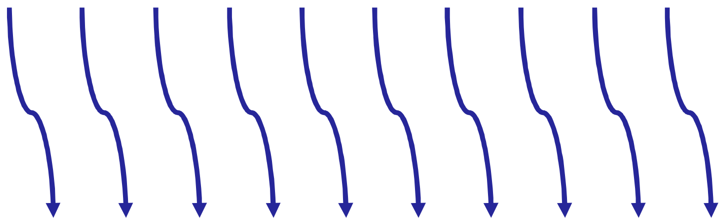
Thread as a Basic Unit of Computing

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

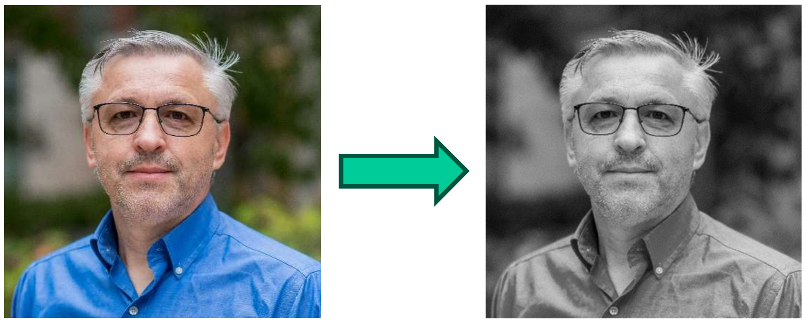
- Multiple threads



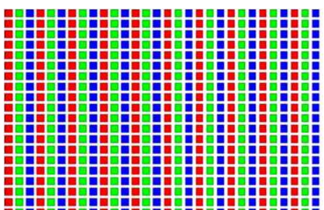
- Many threads



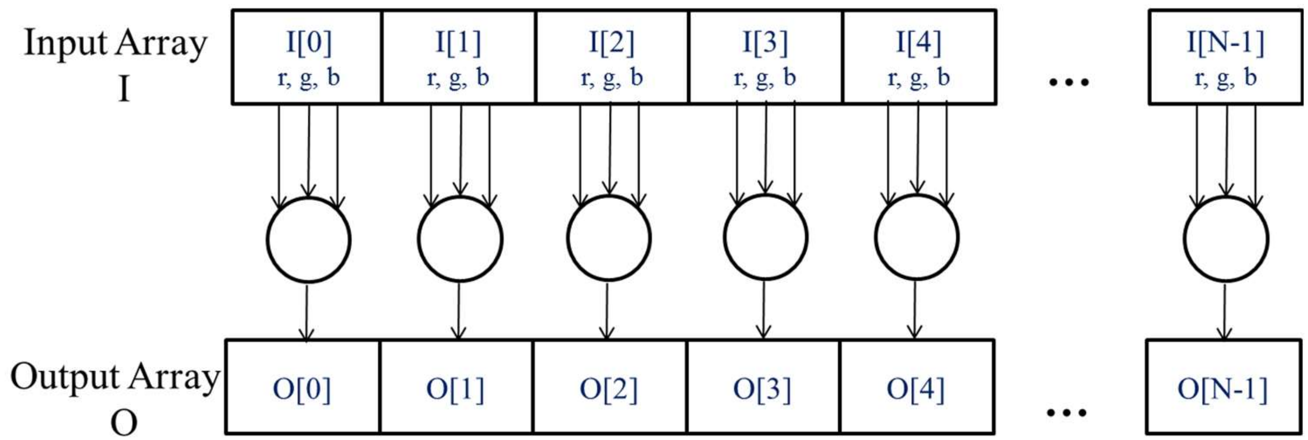
Parallel Example: Convert an Image to Black and White



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



Each Output Pixel's Value is Independent of Others




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

CUDA/OpenCL – Execution Model

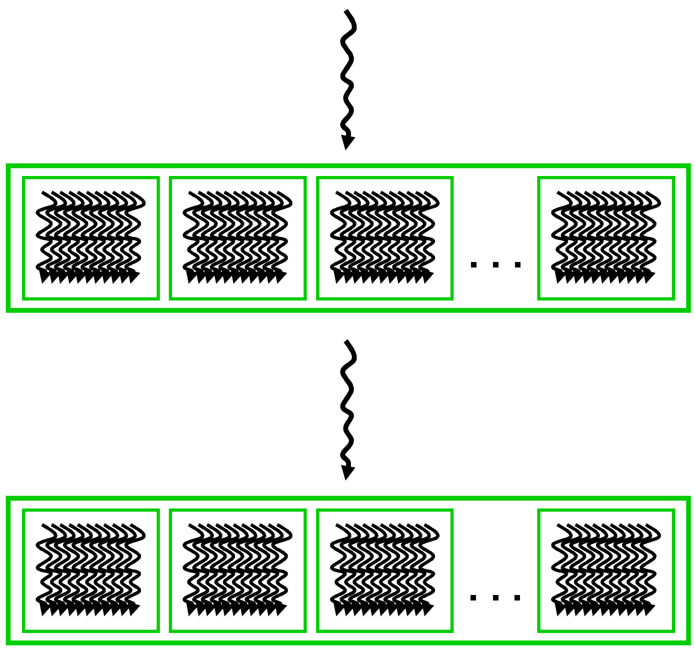
- Integrated host+device app C program
  - Serial or modestly parallel parts in **host** C code
  - Highly parallel parts in **device** SPMD kernel C code

Serial Code (host)

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

Serial Code (host)

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

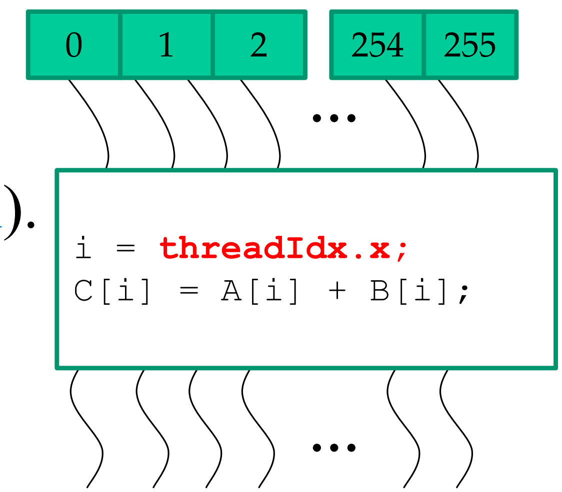


Kernel Executes as Grid of Uniquely Identified Threads

CUDA **kernel executes as a grid** (array) of threads.

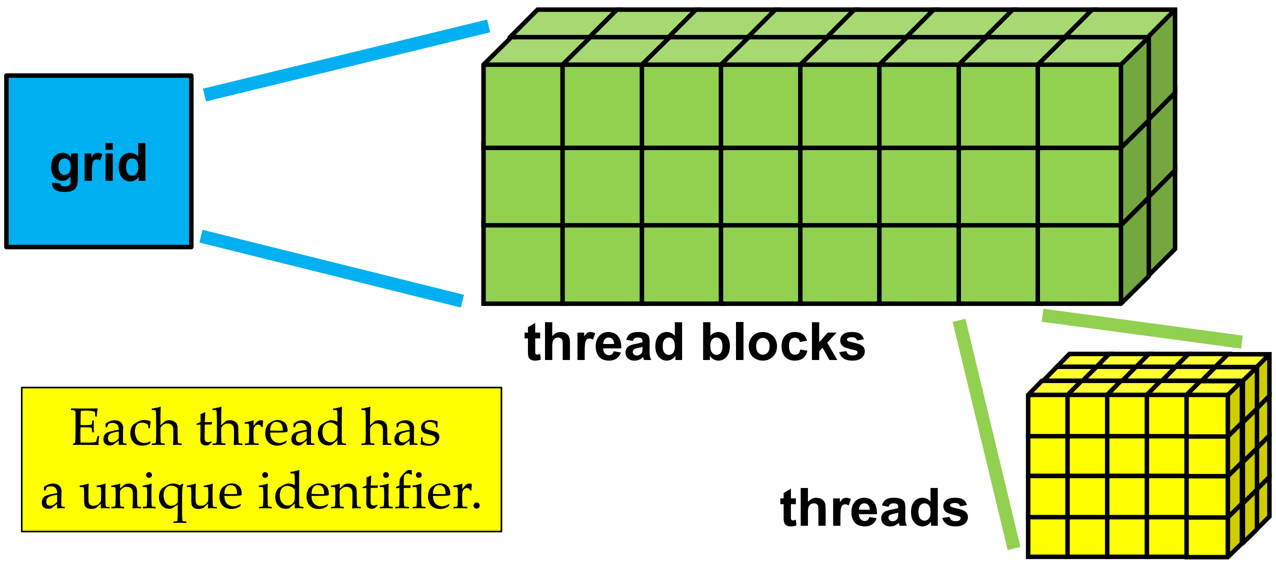
All threads in grid
- **run** the **same** kernel **code**; called a
- Single Program Multiple Data (**SPMD model**).

Each thread has a unique index used to
- compute memory addresses and
- make control decisions.



Logical Execution Model for CUDA

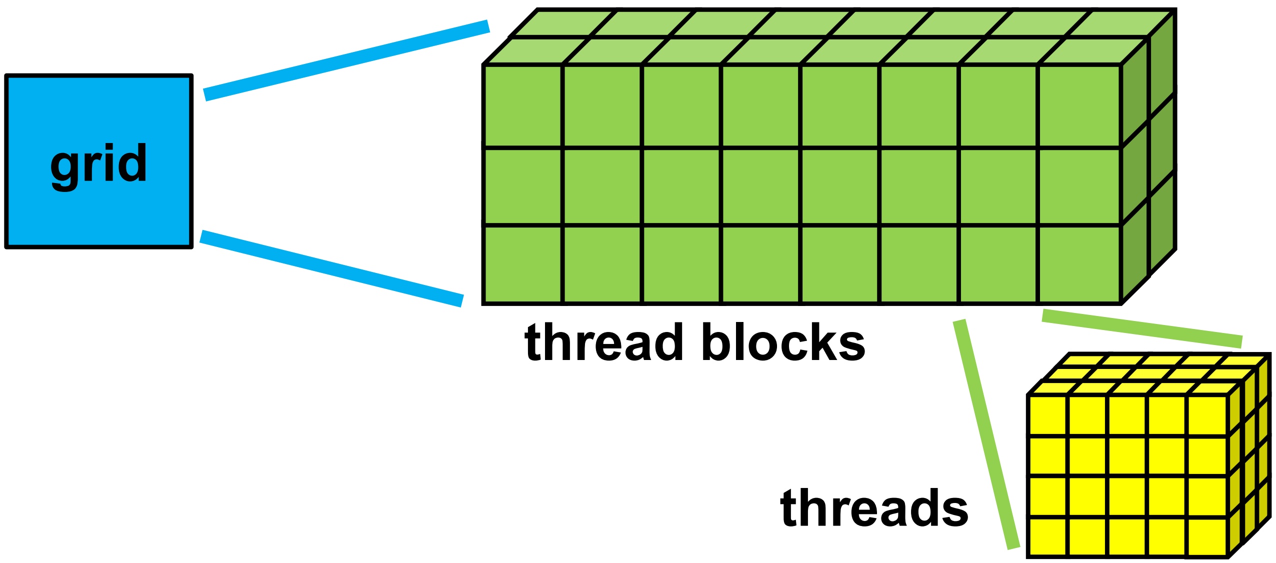
- Each CUDA kernel
  - is executed by a **grid**,
  - a 3D array of **thread blocks**, which are
  - 3D arrays of **threads**.



Each thread has
a unique identifier.

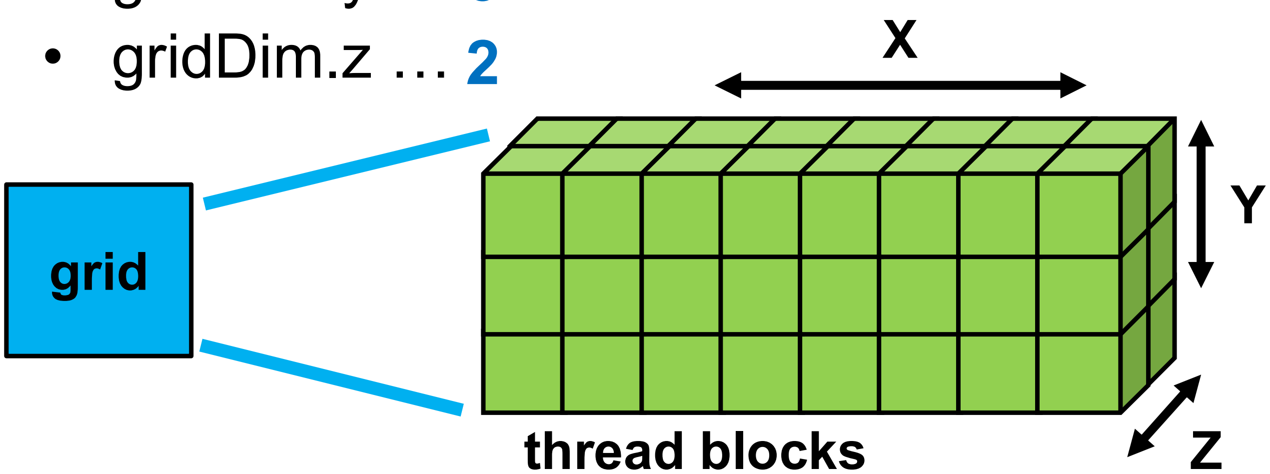
Single Program, Multiple Data

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



gridDim Gives Number of Blocks

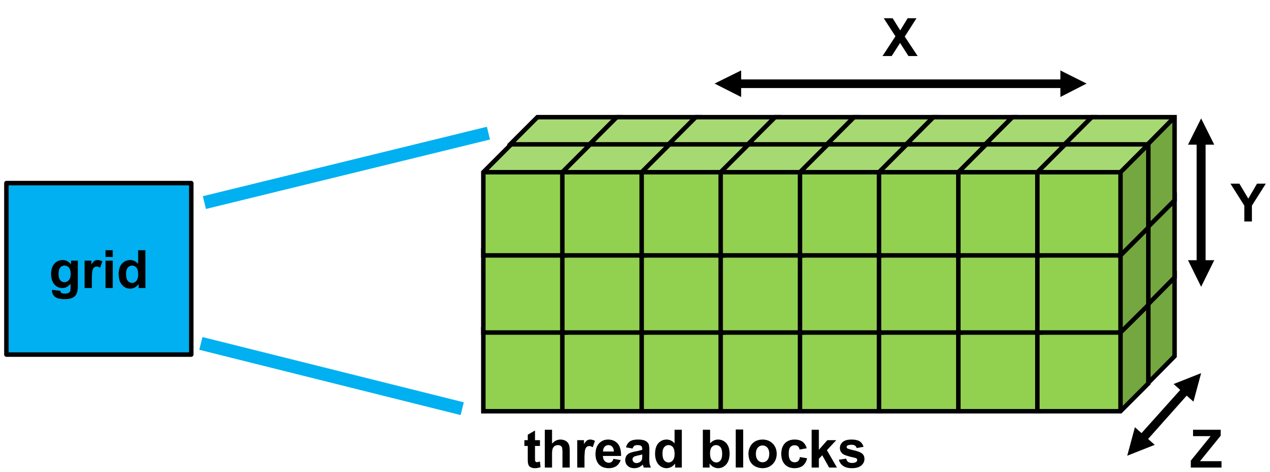
- Number of blocks in each dimension is
  - gridDim.x … **8**
  - gridDim.y … **3**
  - gridDim.z … **2**



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

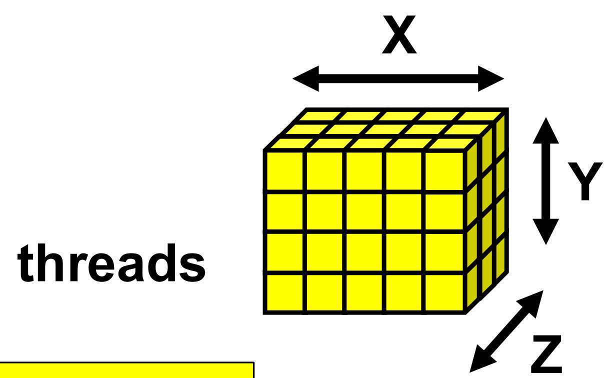
blockIdx is Unique for Each Block

- 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

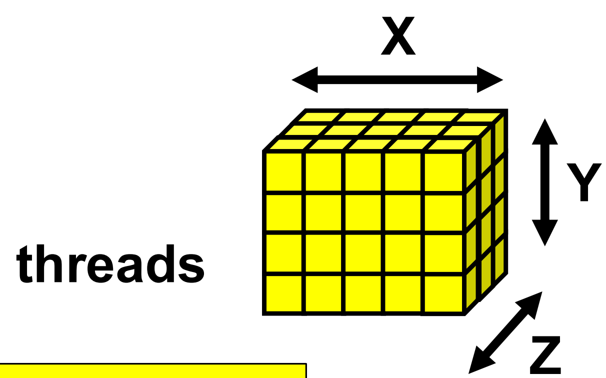
- Number of blocks in each dimension is
  - blockDim.x … **5**
  - blockDim.y … **4**
  - blockDim.z … **3**



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

threadIdx Unique for Each Thread

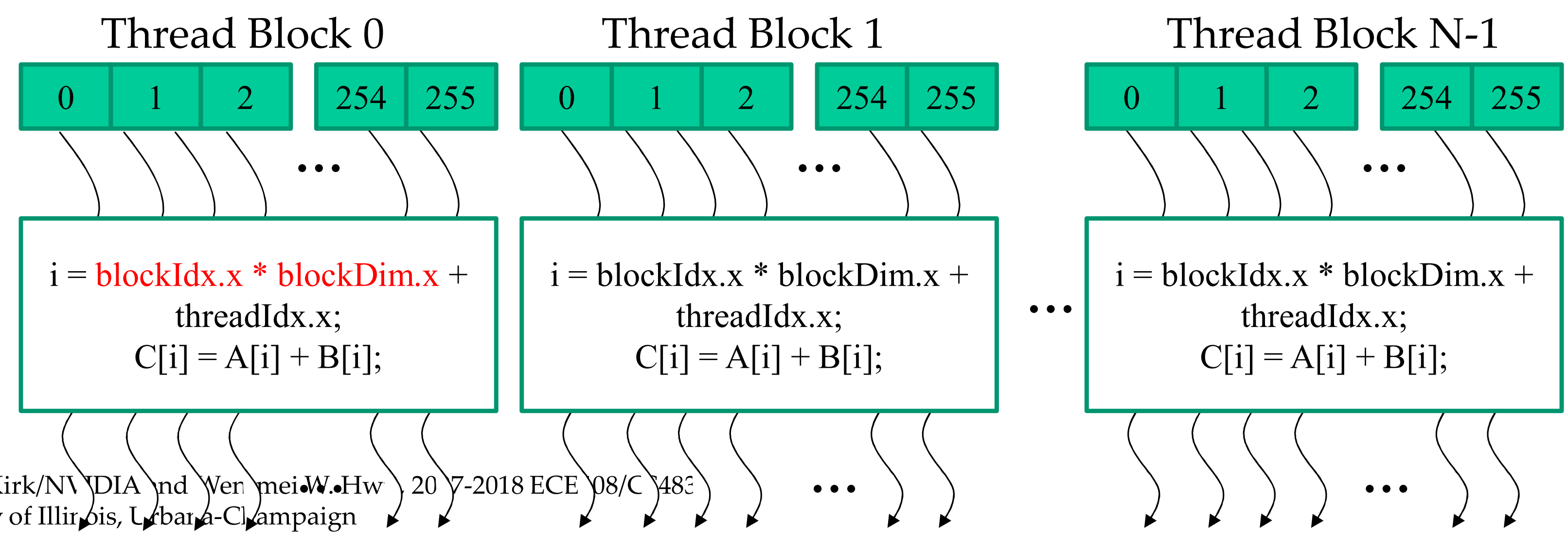
- Each thread has a unique index tuple
  - threadIdx.x (from 0 to (blockDim.x – 1))
  - threadIdx.y (from 0 to (blockDim.y – 1))
  - threadIdx.z (from 0 to (blockDim.z – 1))



threadIdx tuple is unique to each thread
WITHIN A BLOCK.

Thread Blocks: Scalable Cooperation

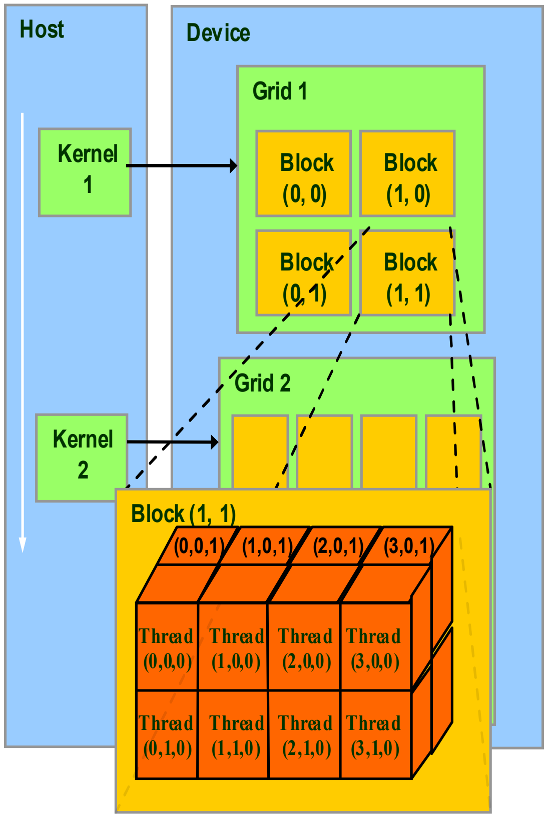
- Threads within a block cooperate via **shared memory, atomic operations** and **barrier synchronization** (to be covered later)
- Threads in different blocks cooperate less.



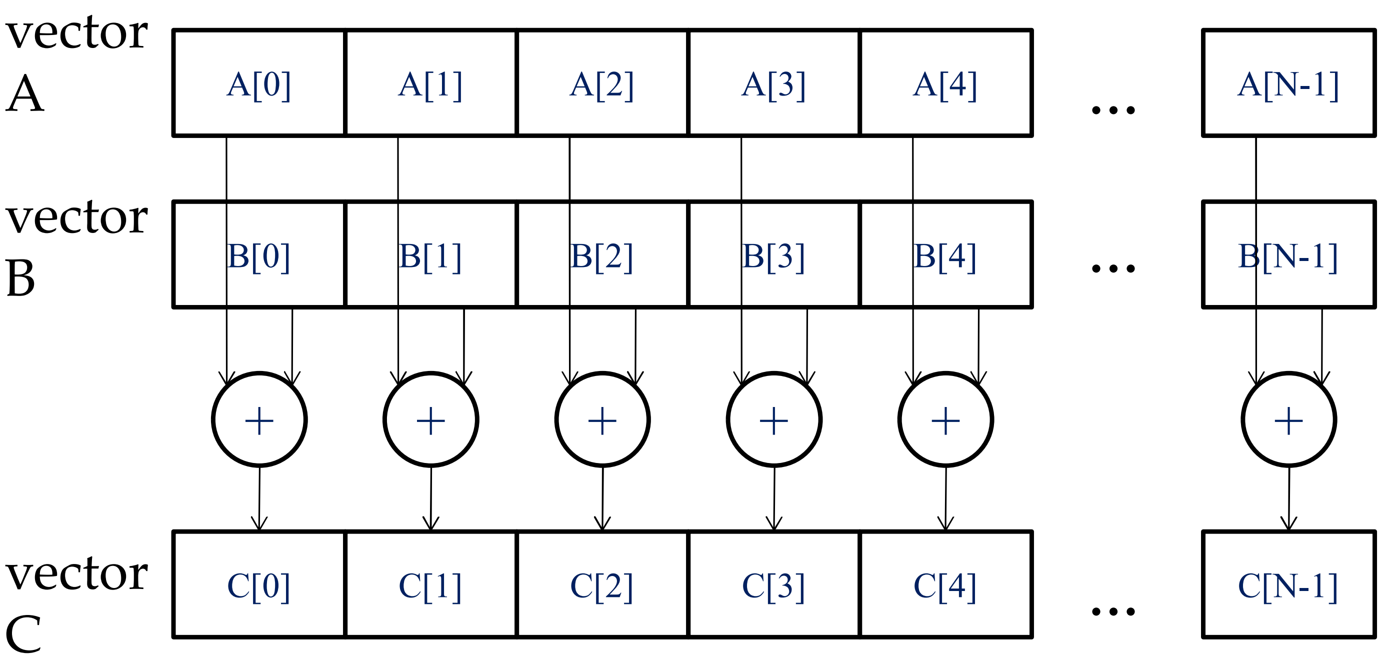
blockIdx and threadIdx

- 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);
}
```

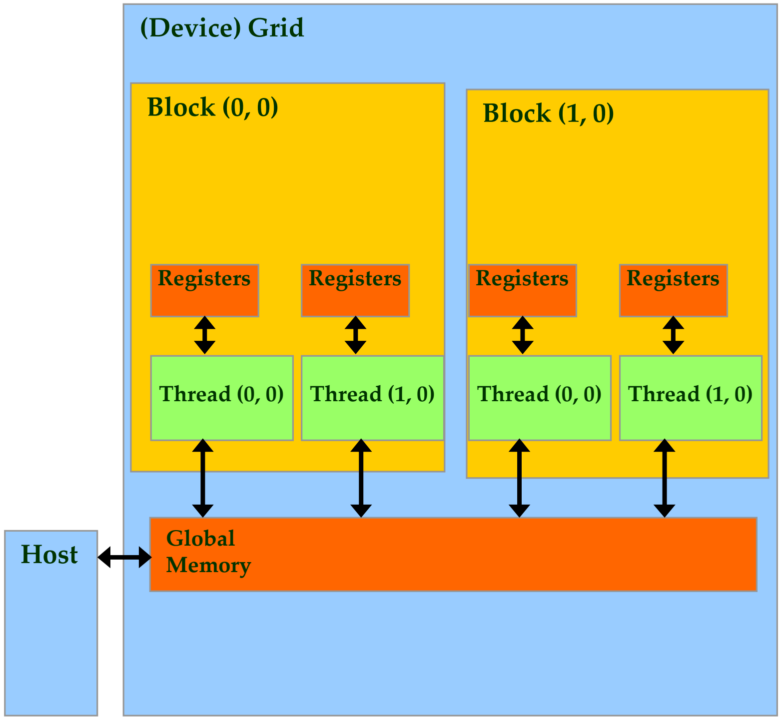
Heterogeneous Computing vecAdd Host Code

```
#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
  - **Allocate memory** for per-grid global memory.
  - **Transfer data to/from** per-grid **global memory**

We will cover more later.



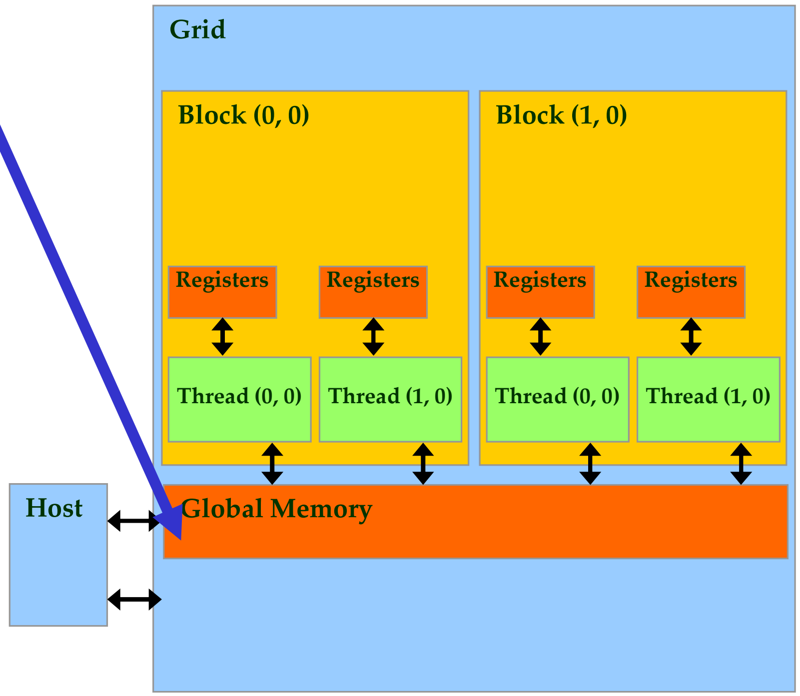
CUDA Device Memory Management API Functions

`cudaMalloc`

- **Allocate in device global memory**
- Two parameters
  - Address in which to store pointer to allocated memory
  - Size in bytes of allocated memory

`cudaFree`

- **Free device global memory**
- One parameter:
  - **pointer** to memory to free
  - (as returned from `cudaMalloc`)

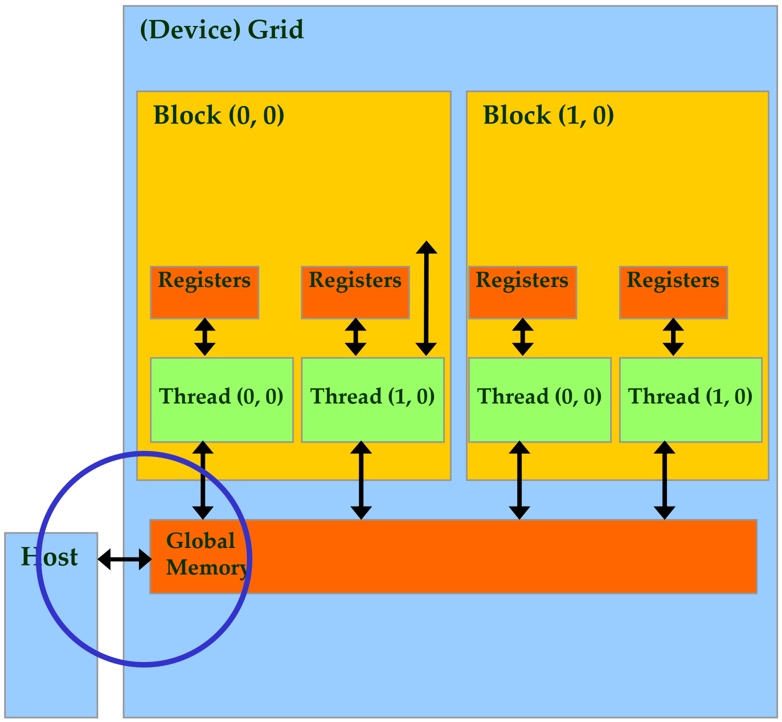


```
void vecAdd(float* A, float* B, float* C, int N)
{
      int size = N * sizeof(float);
      float *A_d, *B_d, *C_d;

1. // Allocate device memory for A, B, and C
    cudaMalloc((void **) &A_d, size);
    cudaMalloc((void **) &B_d, size);
    cudaMalloc((void **) &C_d, size);

   // copy A and B to device memory



2. // Kernel invocation code – to be shown later
     …
3. // Transfer C from device to host

   // Free device memory for A, B, C
   cudaFree(A_d); cudaFree(B_d); cudaFree (C_d);
}
```

Host-Device Data Transfer API Functions

cudaMemcpy

- **memory data transfer**
- 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. // Allocate device memory for A, B, and C
    cudaMalloc((void **) &A_d, size);
    cudaMalloc((void **) &B_d, size);
    cudaMalloc((void **) &C_d, size);

   // copy A and B to device memory
    cudaMemcpy(A_d, A, size, cudaMemcpyHostToDevice);
    cudaMemcpy(B_d, B, size, cudaMemcpyHostToDevice);

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

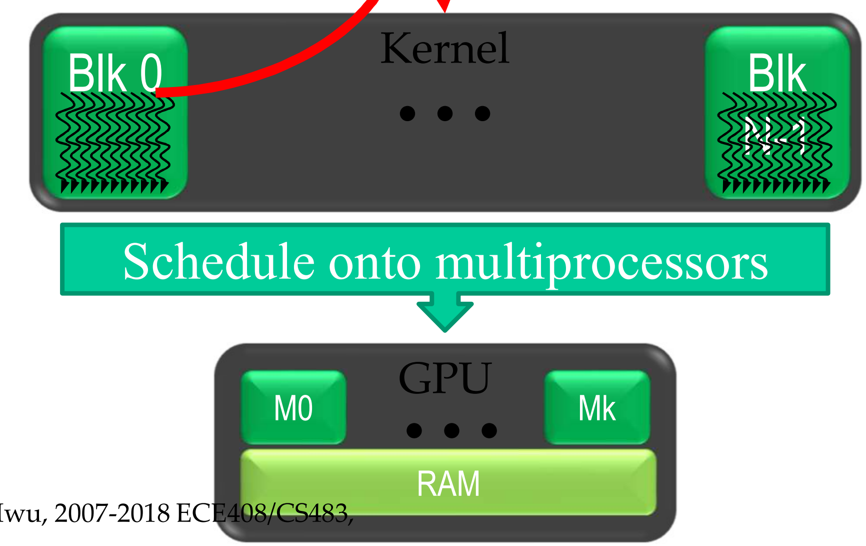
D Number of threads per block in x dimension

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];
}
```

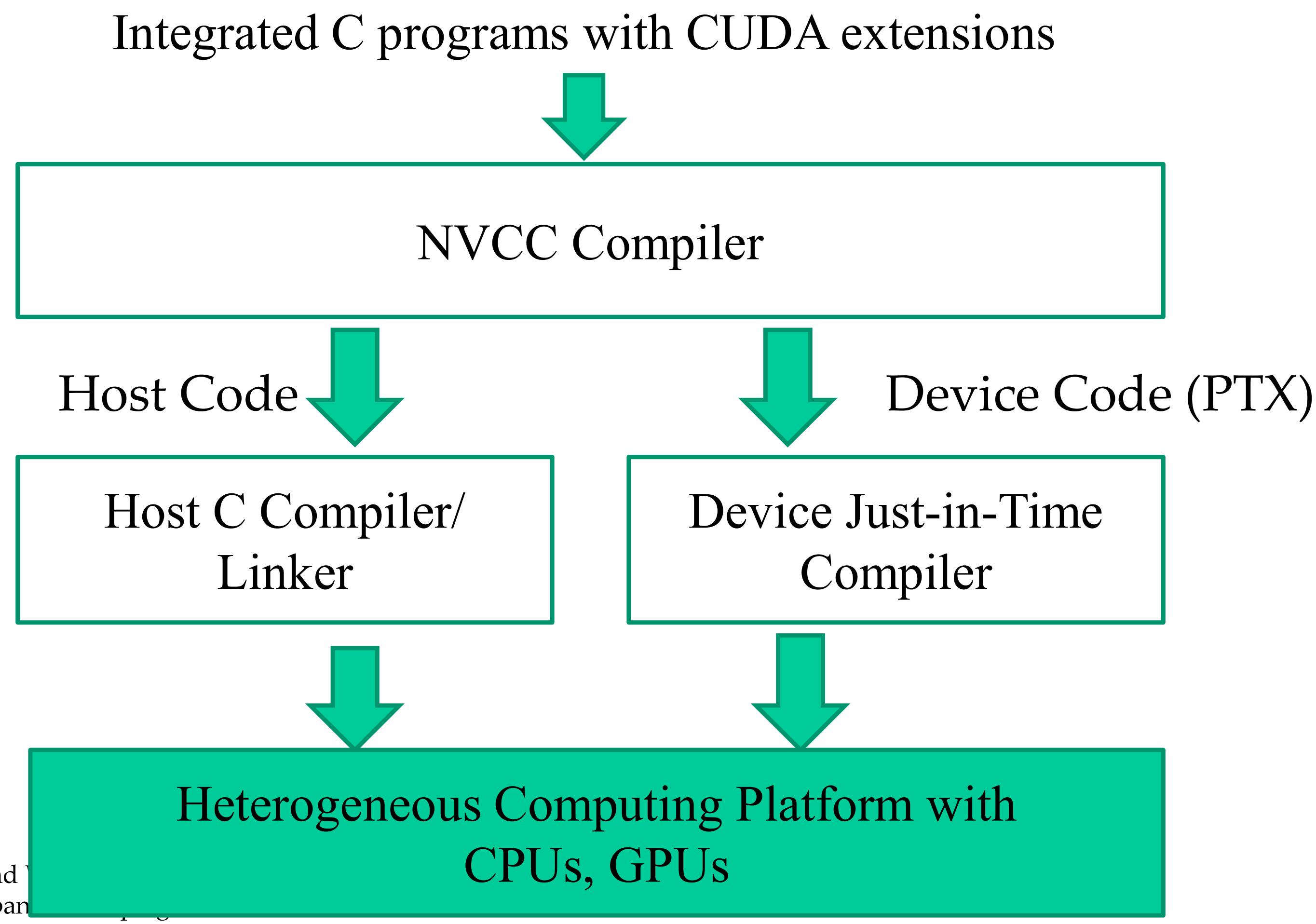


More on CUDA Function Declarations

	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



QUESTIONS?