CUDA Thread Basics

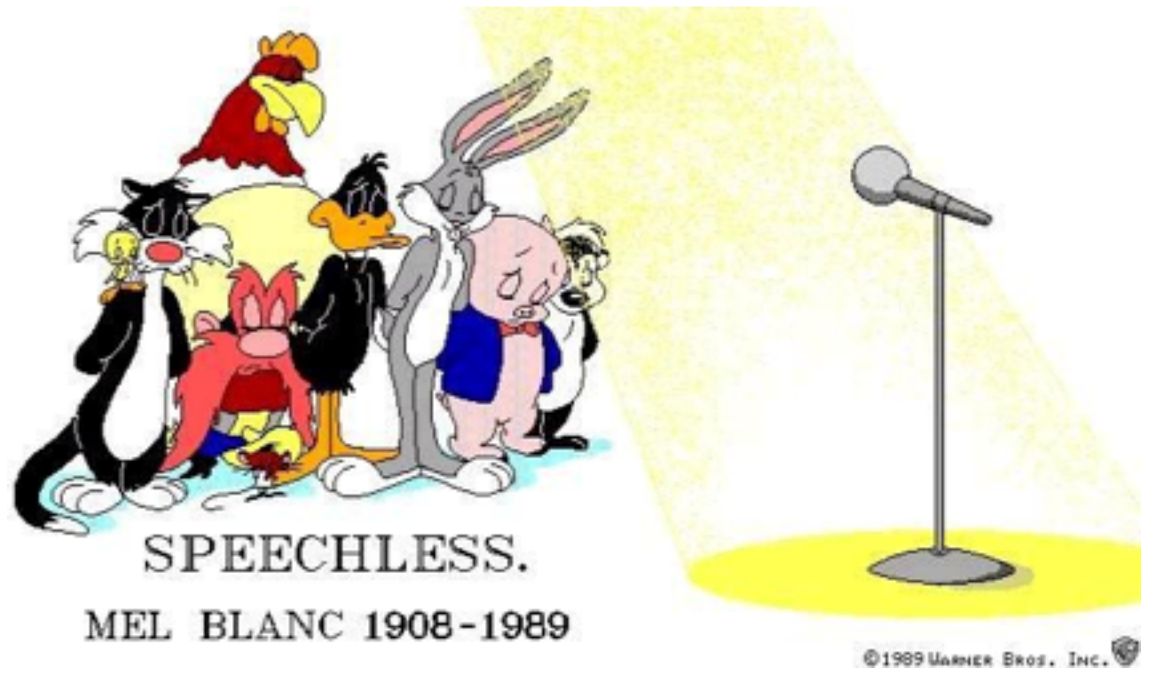
Hello World v.4.0: Vector Addition

```
#define N 256
#include <stdio.h>

__global__ void vecAdd (int *a, int *b, int *c);

int main() {
 int a[N], b[N], c[N];
 int *dev_a, *dev_b, *dev_c;

 // initialize a and b with real values (NOT SHOWN)

 size = N * sizeof(int);

 cudaMalloc((void**)&dev_a, size);
 cudaMalloc((void**)&dev_b, size);
 cudaMalloc((void**)&dev_c, size);

 cudaMemcpy(dev_a, a, size,cudaMemcpyHostToDevice);

 cudaMemcpy(dev_b, b, size,cudaMemcpyHostToDevice);

 vecAdd<<<1,N>>>(dev_a,dev_b,dev_c);

 cudaMemcpy(c, dev_c, size,cudaMemcpyDeviceToHost);

 cudaFree(dev_a);
 cudaFree(dev_b);
 cudaFree(dev_c);

 exit (0);
}

__global__ void vecAdd (int *a, int *b, int *c) {
 int i = threadIdx.x;
 c[i] = a[i] + b[i];
}
```

- CUDA gives each thread a unique ThreadID to distinguish between each other even though the kernel instructions are the same.

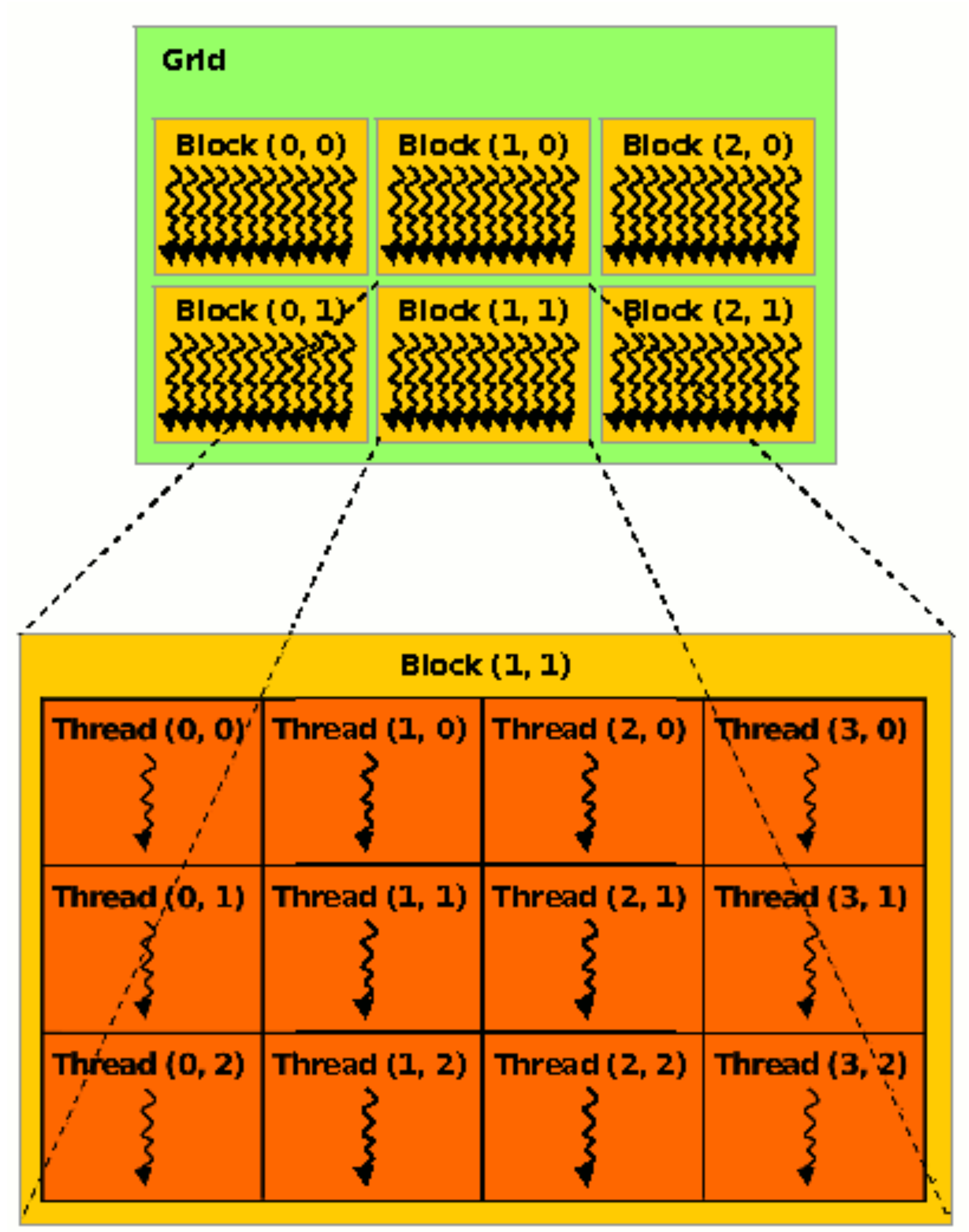
- In our example, in the kernel call the memory arguments specify 1 block and N threads.

```
OUTPUT:
```



NVIDIA GPU Memory Hierarchy

- Grids map to GPUs
- Blocks map to the MultiProcessors (MP)
- Threads map to Stream Processors (SP)
- Warps are groups of (32) threads that execute simultaneously



NVIDIA GPU Memory Architecture

- In a NVIDIA GTX 480:
  - Maximum number of threads per block: 1024
  - Maximum sizes of x-, y-, and z- dimensions of thread block: 1024 x 1024 x 64
  - Maximum size of each dimension of grid of thread blocks: 65535 x 65535 x 65535

Defining Grid/Block Structure

- Need to provide each kernel call with values for two key structures:
    - Number of blocks in each dimension
    - Threads per block in each dimension

- myKernel<<< B,T >>>(arg1, …);

- B – a structure that defines the number of blocks in grid in each dimension (1D or 2D).
- T – a structure that defines the number of threads in a block in each dimension (1D, 2D, or 3D).

1D Grids and/or 1D Blocks

- If want a 1-D structure, can use a integer for B and T in:
- myKernel<<< B, T >>>(arg1, …);
- B – An integer would define a 1D grid of that size
- T – An integer would define a 1D block of that size

- Example: myKernel<<< 1, 100 >>>(arg1, ...);

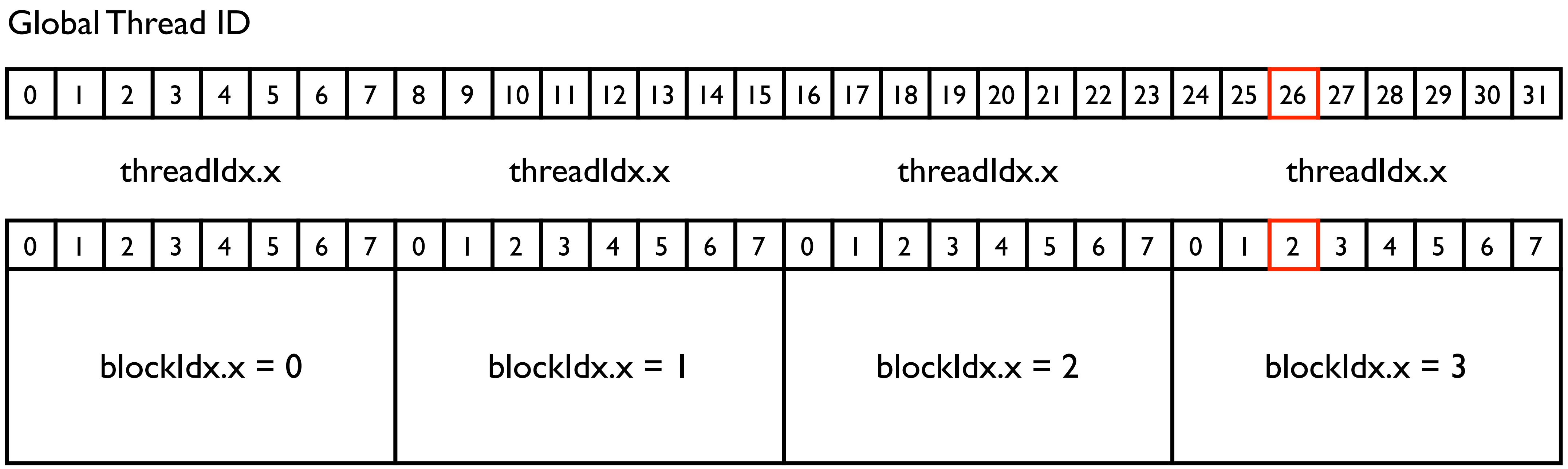
CUDA Built-In Variables

- **blockIdx.x**, **blockIdx.y**, **blockIdx.z** are built-in variables that returns the block ID in the x-axis, y-axis, and z-axis of the block that is executing the given block of code.
- **threadIdx.x**, **threadIdx.y**, **threadIdx.z** are built-in variables that return the thread ID in the x-axis, y-axis, and z-axis of the thread that is being executed by this stream processor in this particular block.
- **blockDim.x**, **blockDim.y**, **blockDim.z** are built-in variables that return the "block dimension" (i.e., the number of threads in a block in the x-axis, y-axis, and z-axis).

- So, you can express your collection of blocks, and your collection of threads within a block, as a 1D array, a 2D array or a 3D array.
- These can be helpful when thinking of your data as 2D or 3D.

- The full global thread ID in x dimension can be computed by:
  - x = blockIdx.x * blockDim.x + threadIdx.x;

Thread Identification Example: x-direction



- Assume a hypothetical 1D grid and 1D block architecture: 4 blocks, each with 8 threads.
- For Global Thread ID 26:
  - gridDim.x = 4 x 1
  - blockDim.x = 8 x 1
  - Global Thread ID = blockIdx.x * blockDim.x + threadIdx.x
  - = 3 x 8 + 2 = 26

Vector Addition Revisited

```
#define N 1618
#define T 1024 // max threads per block
#include <stdio.h>

__global__ void vecAdd (int *a, int *b, int *c);

int main() {
 int a[N], b[N], c[N];
 int *dev_a, *dev_b, *dev_c;

 // initialize a and b with real values (NOT SHOWN)

 size = N * sizeof(int);

 cudaMalloc((void**)&dev_a, size);
 cudaMalloc((void**)&dev_b, size);
 cudaMalloc((void**)&dev_c, size);

 cudaMemcpy(dev_a, a, size,cudaMemcpyHostToDevice);

 cudaMemcpy(dev_b, b, size,cudaMemcpyHostToDevice);

 vecAdd<<<(int)ceil(N/T),T>>>(dev_a,dev_b,dev_c);

 cudaMemcpy(c, dev_c, size,cudaMemcpyDeviceToHost);

 cudaFree(dev_a);
 cudaFree(dev_b);
 cudaFree(dev_c);

 exit (0);
}

__global__ void vecAdd (int *a, int *b, int *c) {
 int i = blockIdx.x * blockDim.x + threadIdx.x;
 if (i < N) {
  c[i] = a[i] + b[i];
 }
}
```

- Since the maximum number of threads per dimension in a block is 1024, if you must use more than one block to access more threads.
- Divide the work between different blocks.
- Notice that each block is reserved completely; in this example, two blocks are reserved even though most of the second block is not utilized.
- WARNING: CUDA does not issue warnings or errors if your thread bookkeeping is incorrect -- Use small test cases to verify that everything is okay.

Higher Dimensional Grids/Blocks

- 1D grids/blocks are suitable for 1D data, but higher dimensional grids/blocks are necessary for:
  - higher dimensional data.
  - data set larger than the hardware dimensional limitations of blocks.

- CUDA has built-in variables and structures to define the number of blocks in a grid in each dimension and the number of threads in a block in each dimension.

CUDA Built-In Vector Types and Structures

- uint3 and dim3 are CUDA-defined structures of unsigned integers: x, y, and z.
  - struct uint3 {x; y; z;};
  - struct dim3 {x; y; z;};
- The unsigned structure components are automatically initialized to 1.
- These vector types are mostly used to define grid of blocks and threads.
- There are other CUDA vector types (discussed later).

CUDA Built-In Variables for Grid/Block Sizes

- dim3 gridDim -- Grid dimensions, x and y (z not used).
- Number of blocks in grid =
  gridDim.x * gridDim.y

- dim3 blockDim -- Size of block dimensions x, y, and z.
- Number of threads in a block =
  blockDim.x * blockDim.y * blockDim.z

Example Initializing Values

- To set dimensions:
```
dim3 grid(16,16);        // grid = 16 x 16 blocks
dim3 block(32,32);       // block = 32 x 32 threads
myKernel<<<grid, block>>>(...);
```

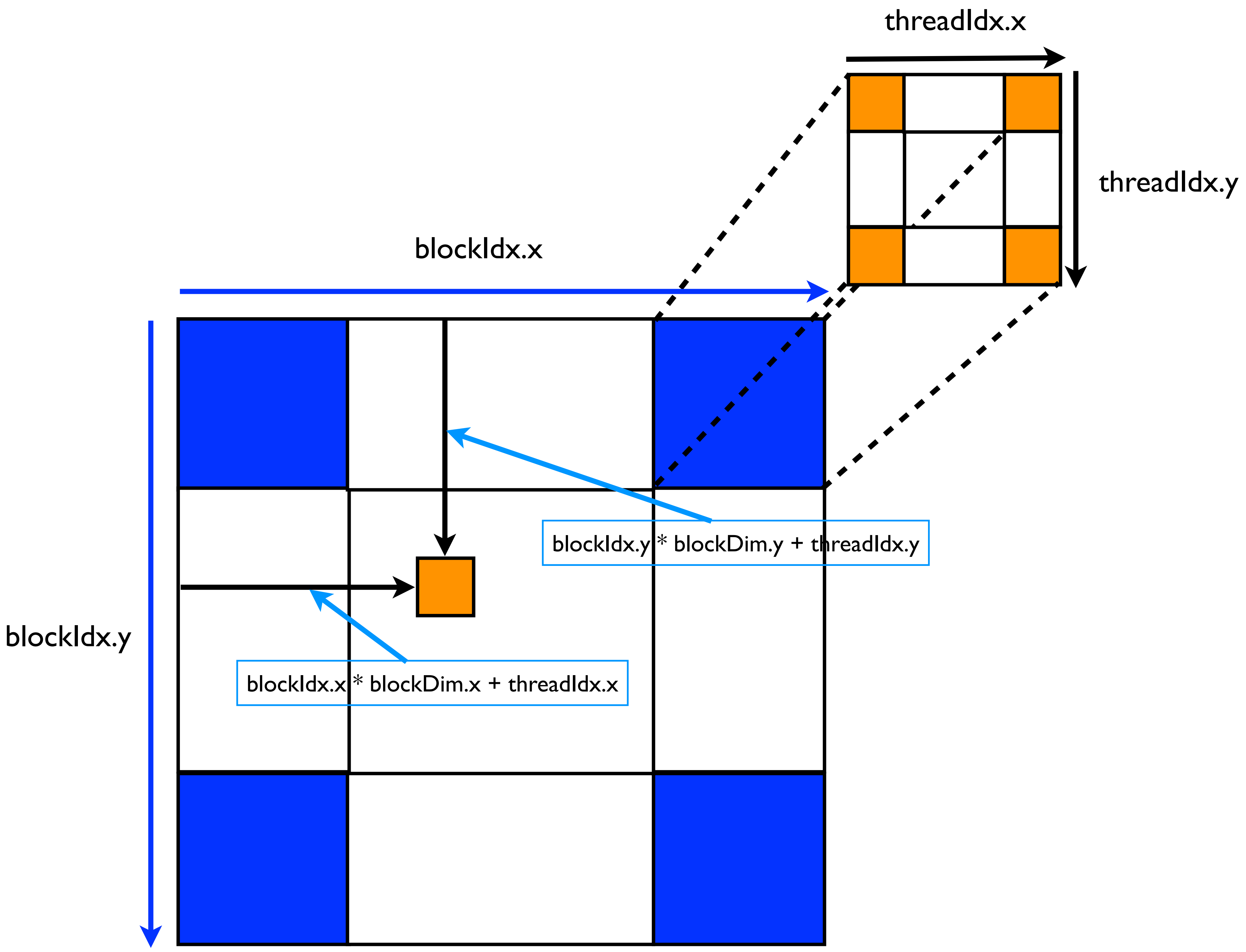
- which sets:
```
grid.x = 16;
grid.y = 16;
block.x = 32;
block.y = 32;
block.z = 1;
```

CUDA Built-In Variables for Grid/Block Indices

- uint3 blockIdx -- block index within grid:
  - blockIdx.x, blockIdx.y   (z not used)
- uint3 threadIdx -- thread index within block:
  - threadIdx.x, threadIdx.y, threadIdx.z

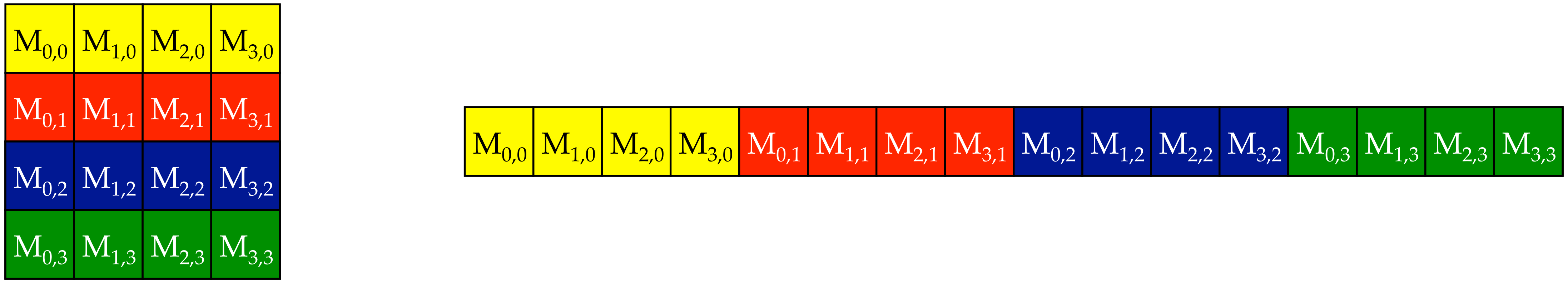
- Full global thread ID in x and y dimensions can be computed by:
  - x = blockIdx.x * blockDim.x + threadIdx.x;
  - y = blockIdx.y * blockDim.y + threadIdx.y;

2D Grids and 2D Blocks


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

Flatten Matrices into Linear Memory

- Generally memory allocated dynamically on device (GPU) and we cannot not use two-dimensional indices (e.g. A[row][column]) to access matrices.
- We will need to know how the matrix is laid out in memory and then compute the distance from the beginning of the matrix.
- C uses **row-major** order --- rows are stored one after the other in memory, i.e. row 0 then row 1 etc.


$M_{0,0}$ $M_{1,0}$ $M_{2,0}$ $M_{3,0}$
$M_{0,1}$ $M_{1,1}$ $M_{2,1}$ $M_{3,1}$
$M_{0,2}$ $M_{1,2}$ $M_{2,2}$ $M_{3,2}$
$M_{0,3}$ $M_{1,3}$ $M_{2,3}$ $M_{3,3}$
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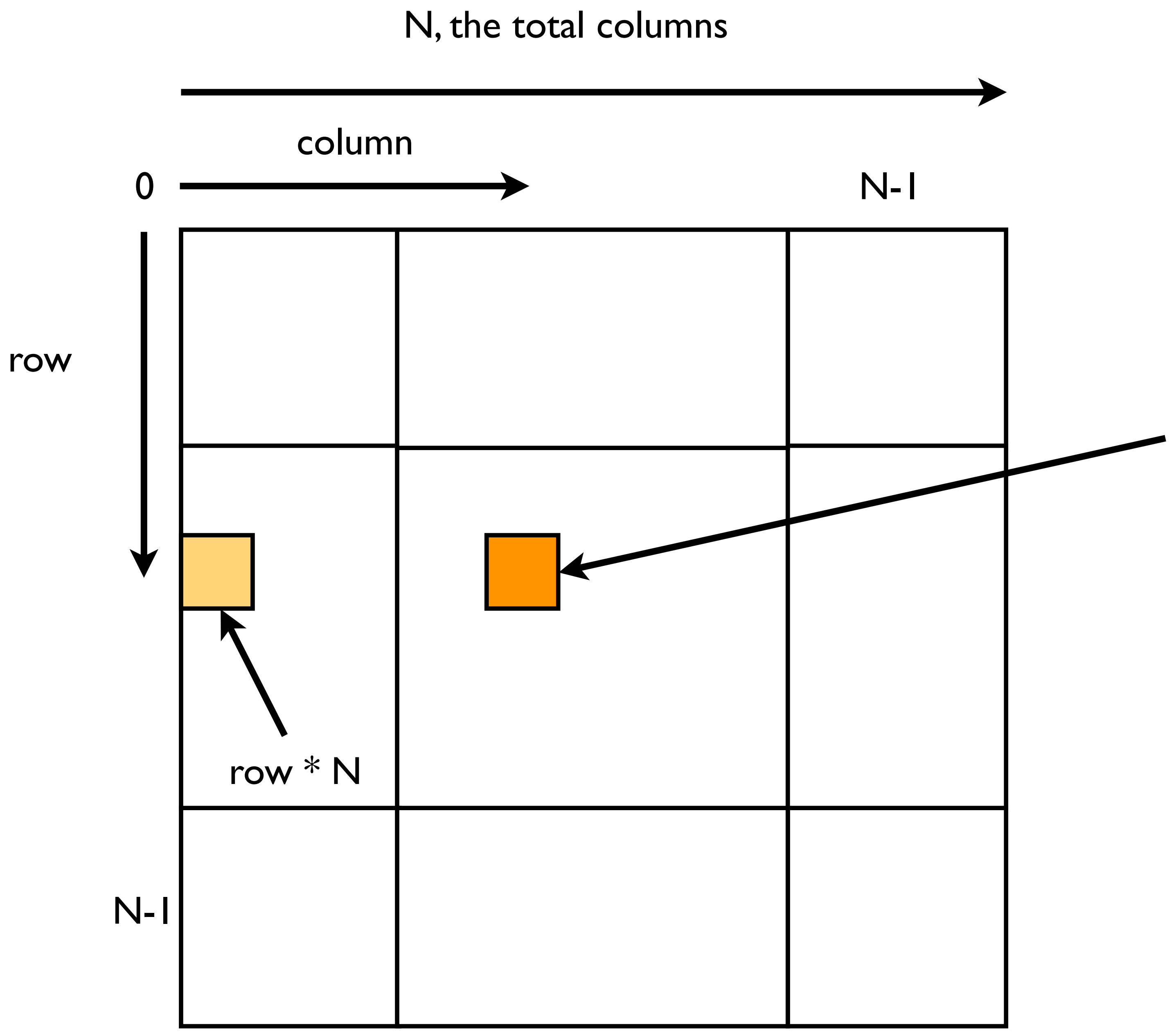
Accessing Matrices in Linear Memory



a[row][column] = a[offset]

offset = column + row * N

<u>In CUDA:</u>

```
int col = blockIdx.x*blockDim.x+threadIdx.x;
int row = blockIdx.y*blockDim.y+threadIdx.y;
int index = col + row * N;
A[index] = …
```

Matrix Addition: Add two 2D matrices

- Corresponding elements of each array (a,b) added together to form element of third array (c):

$$c_{i,j} = a_{i,j} + b_{i,j}$$

$$(0 \leq i < n, 0 \leq j < m)$$

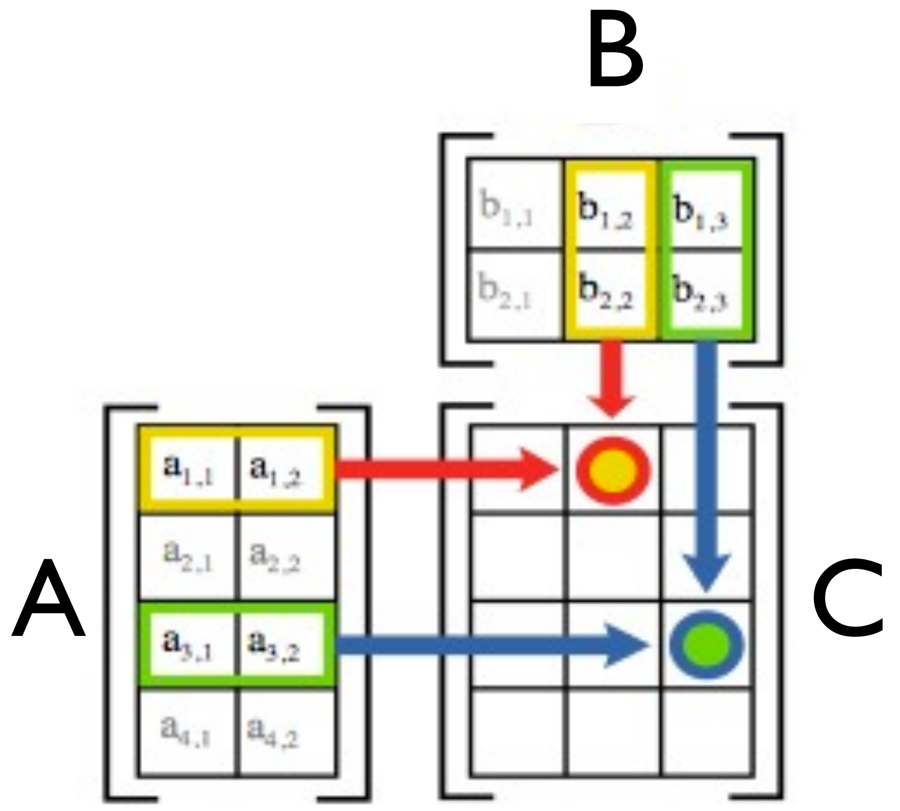
Matrix Addition

```
#define N 512
#define BLOCK_DIM 512

__global__ void matrixAdd (int *a, int *b, int *c);

int main() {
 int a[N][N], b[N][N], c[N][N];
 int *dev_a, *dev_b, *dev_c;

 int size = N * N * sizeof(int);

 // initialize a and b with real values (NOT SHOWN)

 cudaMalloc((void**)&dev_a, size);
 cudaMalloc((void**)&dev_b, size);
 cudaMalloc((void**)&dev_c, size);

 cudaMemcpy(dev_a, a, size, cudaMemcpyHostToDevice);
 cudaMemcpy(dev_b, b, size, cudaMemcpyHostToDevice);

 dim3 dimBlock(BLOCK_DIM, BLOCK_DIM);
 dim3 dimGrid((int)ceil(N/dimBlock.x),(int)ceil(N/dimBlock.y));

 matrixAdd<<<dimGrid,dimBlock>>>(dev_a,dev_b,dev_c);

 cudaMemcpy(c, dev_c, size, cudaMemcpyDeviceToHost);

 cudaFree(dev_a); cudaFree(dev_b); cudaFree(dev_c);
}

__global__ void matrixAdd (int *a, int *b, int *c) {
 int col = blockIdx.x * blockDim.x + threadIdx.x;
 int row = blockIdx.y * blockDim.y + threadIdx.y;

 int index = col + row * N;

 if (col < N && row < N) {
  c[index] = a[index] + b[index];
 }
}
```

- 2D matrices are added to form a sum 2D matrix.
- We use dim3 variables to set the Grid and Block dimensions.
- We calculate a global thread ID to index the column and row of the matrix.
- We calculate the linear index of the matrix.
- Voila~!

Matrix Multiplication Review

$$c_{i,j} = \sum_{k=0}^{l-1} a_{i,k} b_{k,j}$$



- To calculate the product of two matrices A and B, we multiply the rows of A by the columns of B and add them up.
- Then place the sum in the appropriate position in the matrix C.

$$AB = \begin{bmatrix} 1 & 0 & -2 \\ 0 & 3 & -1 \end{bmatrix} \begin{bmatrix} 0 & 3 \\ -2 & -1 \\ 0 & 4 \end{bmatrix}$$

$$= \begin{bmatrix} (1*0)+(0*-2)+(-2*0) & (1*3)+(0*-1)+(-2*4) \\ (0*0)+(3*-2)+(-1*0) & (0*3)+(3*-1)+(-1*4) \end{bmatrix}$$

$$= \begin{bmatrix} 0+0+0 & 3+0+-8 \\ 0+-6+0 & 0+-3+-4 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & -5 \\ -6 & -7 \end{bmatrix} = C$$

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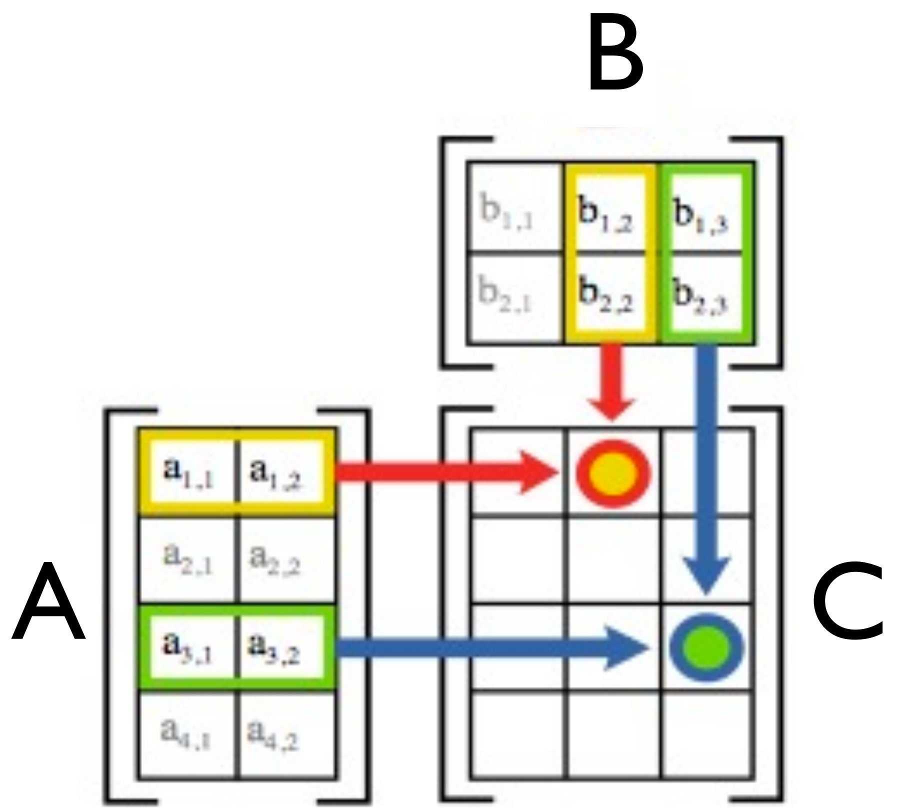

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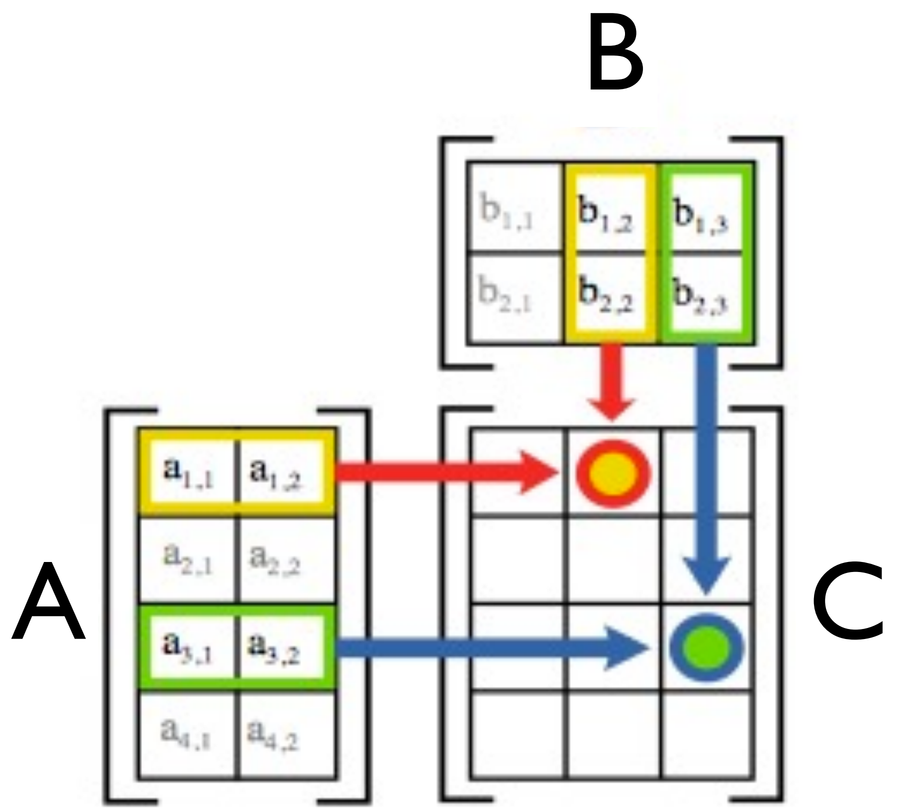

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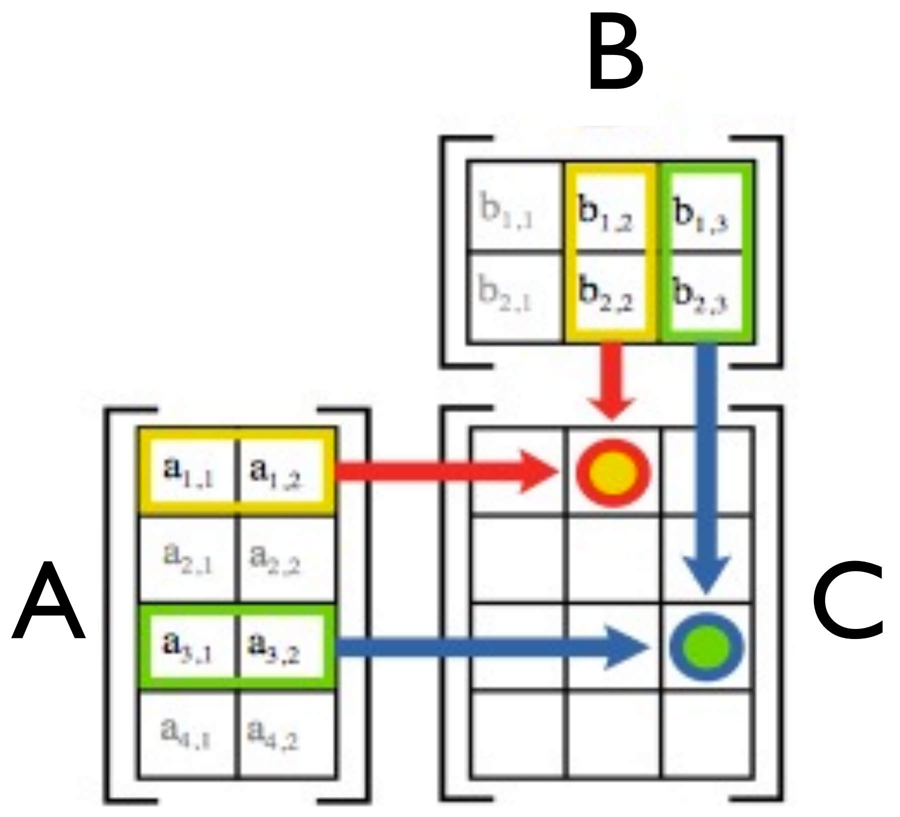

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$$= \begin{bmatrix} 0+0+0 & 3+0+-8 \\ 0+-6+0 & 0+-3+-4 \end{bmatrix}$$

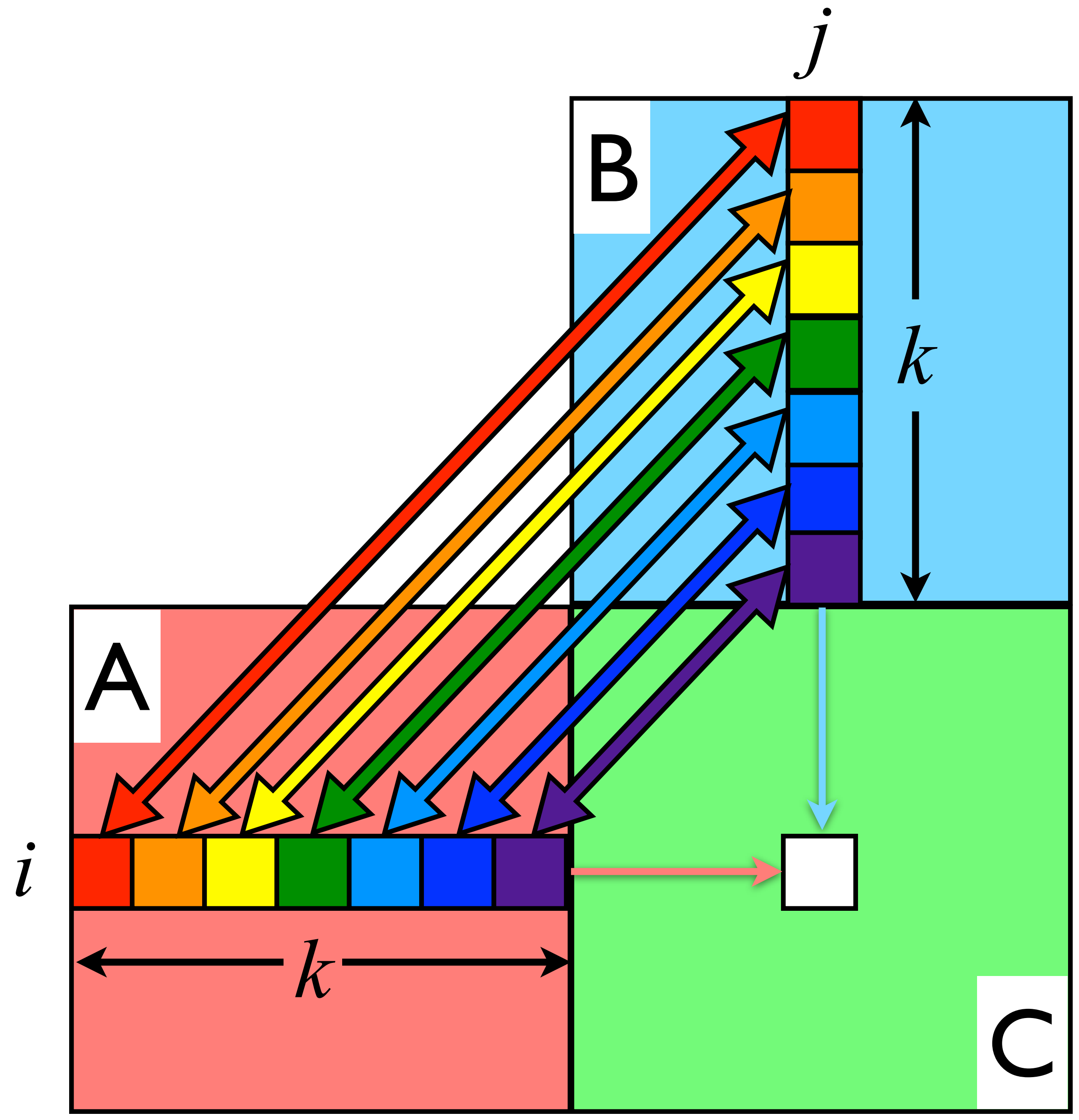
$$= \begin{bmatrix} 0 & -5 \\ -6 & -7 \end{bmatrix} = C$$

Square Matrix Multiplication C Code

```
void matrixMult (int a[N][N], int b[N][N], int c[N][N], int width)
{
  for (int i = 0; i < width; i++) {
    for (int j = 0; j < width; j++) {
      int sum = 0;
      for (int k = 0; k < width; k++) {
        int m = a[i][k];
        int n = b[k][j];
        sum += m * n;
      }
      c[i][j] = sum;
    }
  }
}
```

- Sequential algorithm consists of multiple nested for loops.
- Both multiplications and additions are in $O(N^3)$.
- Can it be parallelized?

Motivation for Parallel Matrix Multiplication Algorithm



- To compute a single value of C(i,j), only a single thread be necessary to traverse the ith row of A and the jth column of B.
- Therefore, the number of threads needed to compute a square matrix multiply is O(N^2).

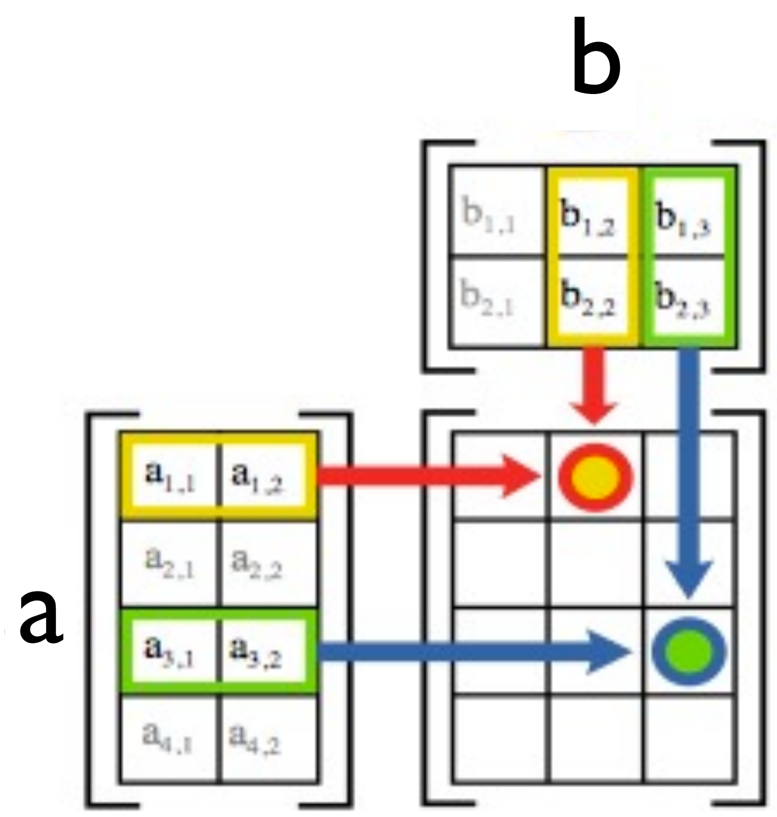
C to CUDA for Dummies
Step 1: Write the Kernel

C Function

```
void matrixMult (int a[N][N], int b[N][N], int c[N][N], int width)
{
  for (int i = 0; i < width; i++) {
    for (int j = 0; j < width; j++) {
      int sum = 0;
      for (int k = 0; k < width; k++) {
        int m = a[i][k];
        int n = b[k][j];
        sum += m * n;
      }
      c[i][j] = sum;
    }
  }
}
```

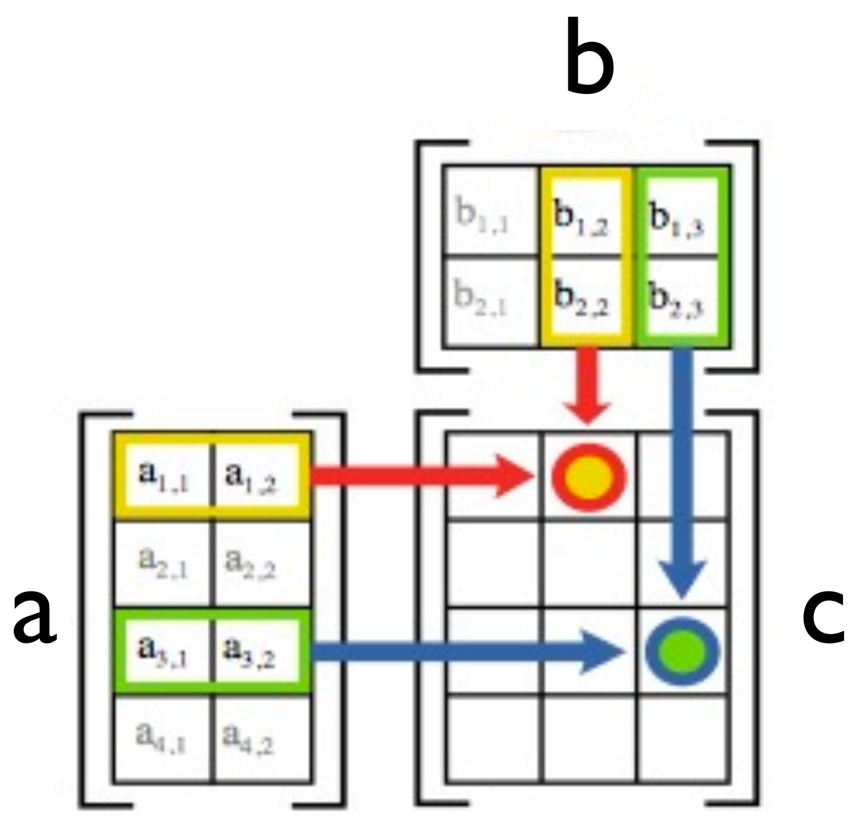
CUDA Kernel

```
__global__ void matrixMult (int *a, int *b, int *c, int width) {
 int k, sum = 0;

 int col = threadIdx.x + blockDim.x * blockIdx.x;
 int row = threadIdx.y + blockDim.y * blockIdx.y;

 if(col < width && row < width) {
  for (k = 0; k < width; k++)
   sum += a[row * width + k] * b[k * width + col];
   c[row * width + col] = sum;
 }
}
```



C to CUDA for Dummies
Step 2: Do the Rest

```
#define N 16
#include <stdio.h>

__global__ void matrixMult (int *a, int *b, int *c, int width);

int main() {
 int a[N][N], b[N][N], c[N][N];
 int *dev_a, *dev_b, *dev_c;

 // initialize matrices a and b with appropriate values

 int size = N * N * sizeof(int);
 cudaMalloc((void **) &dev_a, size);
 cudaMalloc((void **) &dev_b, size);
 cudaMalloc((void **) &dev_c, size);

 cudaMemcpy(dev_a, a, size, cudaMemcpyHostToDevice);
 cudaMemcpy(dev_b, b, size, cudaMemcpyHostToDevice);

 dim3 dimGrid(1, 1);
 dim3 dimBlock(N, N);

 matrixMult<<<dimGrid, dimBlock>>>(dev_a, dev_b, dev_c, N);

 cudaMemcpy(c, dev_c, size, cudaMemcpyDeviceToHost);

 cudaFree(dev_a); cudaFree(dev_b); cudaFree(dev_c);

__global__ void matrixMult (int *a, int *b, int *c, int width) {
 int k, sum = 0;

 int col = threadIdx.x + blockDim.x * blockIdx.x;
 int row = threadIdx.y + blockDim.y * blockIdx.y;

 if(col < width && row < width) {
  for (k = 0; k < width; k++)
   sum += a[row * width + k] * b[k * width + col];
   c[row * width + col] = sum;
 }
}
```


b
$b_{1,1}$
$b_{1,2}$
$b_{1,3}$
$b_{2,1}$
$b_{2,2}$
$b_{2,3}$
a
$a_{1,1}$
$a_{1,2}$
$a_{2,1}$
$a_{2,2}$
$a_{3,1}$
$a_{3,2}$
$a_{4,1}$
$a_{4,2}$
c