

CUDA Programming

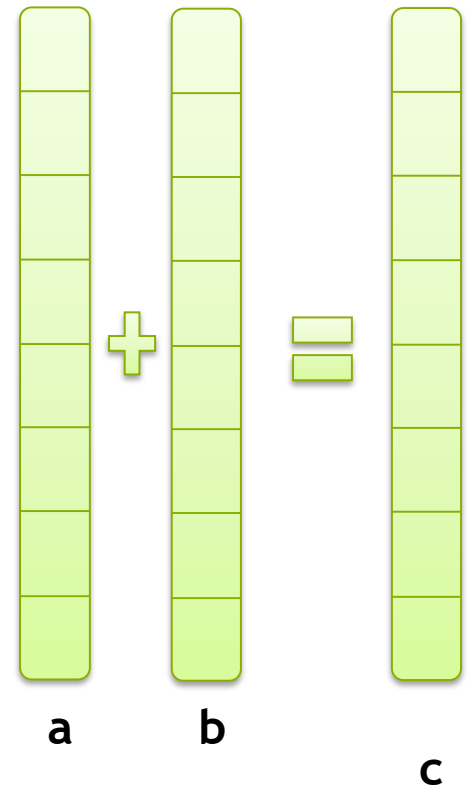
Sum of 2 Arrays

Outline

- ❑ Addition on the device
 - ❑ Moving to parallel using blocks
 - ❑ Moving to parallel using threads
 - ❑ Combining blocks and threads

Parallel Programming in CUDA C/C++

- GPU computing is about massive parallelism!
- We'll start by adding two integers and build up to vector addition



Addition on the Device

- A simple kernel to add two integers

```
__global__ void add(int *a, int *b, int *c) {  
    *c = *a + *b;  
}
```

- As before `__global__` is a CUDA C/C++ keyword meaning
 - `add()` will execute on the device
 - `add()` will be called from the host

Addition on the Device

- Note that we use pointers for the variables

```
__global__ void add(int *a, int *b, int *c) {  
    *c = *a + *b;  
}
```

- `add()` runs on the device, so `a`, `b` and `c` must point to device memory
- We need to allocate memory on the GPU

Memory Management

- Host and device memory are separate entities

- *Device* pointers point to GPU memory

- May be passed to/from host code

- May *not* be dereferenced in host code

- *Host* pointers point to CPU memory

- May be passed to/from device code

- May *not* be dereferenced in device code



- Simple CUDA API for handling device memory

- `cudaMalloc()`, `cudaFree()`, `cudaMemcpy()`

- Similar to the C equivalents `malloc()`, `free()`, `memcpy()`

Addition on the Device: `add()`

- Returning to our `add()` kernel

```
__global__ void add(int *a, int *b, int *c) {  
    *c = *a + *b;  
}
```

- Let's take a look at `main()`...

Addition on the Device: `main()`

```
int main(void) {  
    int a, b, c;           // host copies of a, b, c  
    int *d_a, *d_b, *d_c; // device copies of a, b, c  
    int size = sizeof(int);  
  
    // Allocate space for device copies of a, b, c  
    cudaMalloc((void **)&d_a, size);  
    cudaMalloc((void **)&d_b, size);  
    cudaMalloc((void **)&d_c, size);  
  
    // Setup input values  
    a = 2;  
    b = 7;
```


Addition on the Device: `main()`

```
// Copy inputs to device
```

```
cudaMemcpy(d_a, &a, size, cudaMemcpyHostToDevice);  
cudaMemcpy(d_b, &b, size, cudaMemcpyHostToDevice);
```

```
// Launch add() kernel on GPU
```

```
add<<<1,1>>>(d_a, d_b, d_c);
```

```
// Copy result back to host
```

```
cudaMemcpy(&c, d_c, size, cudaMemcpyDeviceToHost);
```

```
// Cleanup
```

```
cudaFree(d_a); cudaFree(d_b); cudaFree(d_c);
```

```
return 0;
```

```
}
```

Moving to Parallel

- GPU computing is about massive parallelism
 - So how do we run code in parallel on the device?

```
add<<< 1, 1 >>>() ;
```



```
add<<< N, 1 >>>() ;
```

- Instead of executing `add()` once, execute N times in parallel

Vector Addition on the Device

- With `add()` running in parallel we can do vector addition
- Terminology: each parallel invocation of `add()` is referred to as a **block**
 - The set of blocks is referred to as a **grid**
 - Each invocation can refer to its block index using `blockIdx.x`

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

- By using `blockIdx.x` to index into the array, each block handles a different index

Vector Addition on the Device

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

- On the device, each block can execute in parallel:

Block 0

`c[0] = a[0] + b[0];`

Block 1

`c[1] = a[1] + b[1];`

Block 2

`c[2] = a[2] + b[2];`

Block 3

`c[3] = a[3] + b[3];`

Vector Addition on the Device: `add()`

- Returning to our parallelized `add()` kernel

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

- Let's take a look at `main()`...

Vector Addition on the Device: `main()`

```
#define N 512

int main(void) {
    int *a  *b  *c                // host copies of a, b, c
    int *d_a, *d_b, *d_c; // device copies of a, b, c
    int size = N * sizeof(int);

    // Alloc space for device copies of a, b, c
    cudaMalloc((void **)&d_a, size);
    cudaMalloc((void **)&d_b, size);
    cudaMalloc((void **)&d_c, size);

    // Alloc space for host copies of a, b, c and setup input values
    a = (int *)malloc(size); random_ints(a, N);
    b = (int *)malloc(size); random_ints(b, N);
    c = (int *)malloc(size);
```

Vector Addition on the Device: `main()`

```
// Copy inputs to device
```

```
cudaMemcpy(d_a, a, size, cudaMemcpyHostToDevice);
```

```
cudaMemcpy(d_b, b, size, cudaMemcpyHostToDevice);
```

```
// Launch add() kernel on GPU with N blocks
```

```
add<<<N,1>>>(d_a, d_b, d_c);
```

```
// Copy result back to host
```

```
cudaMemcpy(c, d_c, size, cudaMemcpyDeviceToHost);
```

```
// Cleanup
```

```
free(a); free(b); free(c);
```

```
cudaFree(d_a); cudaFree(d_b); cudaFree(d_c);
```

```
return 0;
```

```
}
```

CUDA Threads


- Terminology: a block can be split into parallel **threads**

Let's change `add()` to use parallel *threads* instead of parallel *blocks*

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

- We use **threadIdx.x** instead of **blockIdx.x**
- Need to make one change in `main()`...

```
add<<< 1, 1 >>>();  
add<<< 1, N >>>();
```



Vector Addition on the Device

- With `add()` running in parallel we can do vector addition
- Terminology: each parallel invocation of `add()` is referred to as a **thread**
 - Each invocation can refer to its thread index using `threadIdx.x`

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

- By using `threadIdx.x` to index into the array, each thread handles a different index

Vector Addition on the Device

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

- On the device, each thread can execute in parallel:

Thread 0

`c[0] = a[0] + b[0];`

Thread 1

`c[1] = a[1] + b[1];`

Thread 2

`c[2] = a[2] + b[2];`

Thread 3

`c[3] = a[3] + b[3];`

Vector Addition on the Device: `add()`

- Returning to our parallelized `add()` kernel

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

- Let's take a look at `main()`...

Vector Addition on the Device: `main()`

```
#define N 512

int main(void) {
    int *a  *b  *c                // host copies of a, b, c
    int *d_a, *d_b, *d_c; // device copies of a, b, c
    int size = N * sizeof(int);

    // Alloc space for device copies of a, b, c
    cudaMalloc((void **)&d_a, size);
    cudaMalloc((void **)&d_b, size);
    cudaMalloc((void **)&d_c, size);

    // Alloc space for host copies of a, b, c and setup input values
    a = (int *)malloc(size); random_ints(a, N);
    b = (int *)malloc(size); random_ints(b, N);
    c = (int *)malloc(size);
```

Vector Addition on the Device: `main()`

```
// Copy inputs to device
```

```
cudaMemcpy(d_a, a, size, cudaMemcpyHostToDevice);
```

```
cudaMemcpy(d_b, b, size, cudaMemcpyHostToDevice);
```

```
// Launch add() kernel on GPU with N blocks
```

```
add<<<1, N>>>(d_a, d_b, d_c);
```

```
// Copy result back to host
```

```
cudaMemcpy(c, d_c, size, cudaMemcpyDeviceToHost);
```

```
// Cleanup
```

```
free(a); free(b); free(c);
```

```
cudaFree(d_a); cudaFree(d_b); cudaFree(d_c);
```

```
return 0;
```

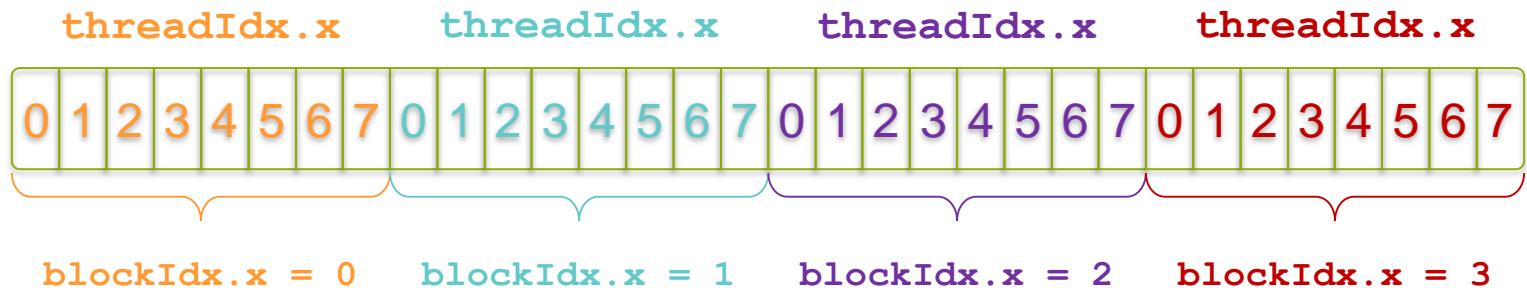
```
}
```

Combining Blocks and Threads

- We've seen parallel vector addition using:
 - Many blocks with one thread each
 - One block with many threads
- Let's adapt vector addition to use both blocks and threads
- Why? We'll come to that...
- First let's discuss data indexing...

Indexing Arrays with Blocks and Threads

- No longer as simple as using `blockIdx.x` and `threadIdx.x`
 - Consider indexing an array with one element per thread (8 threads/block)

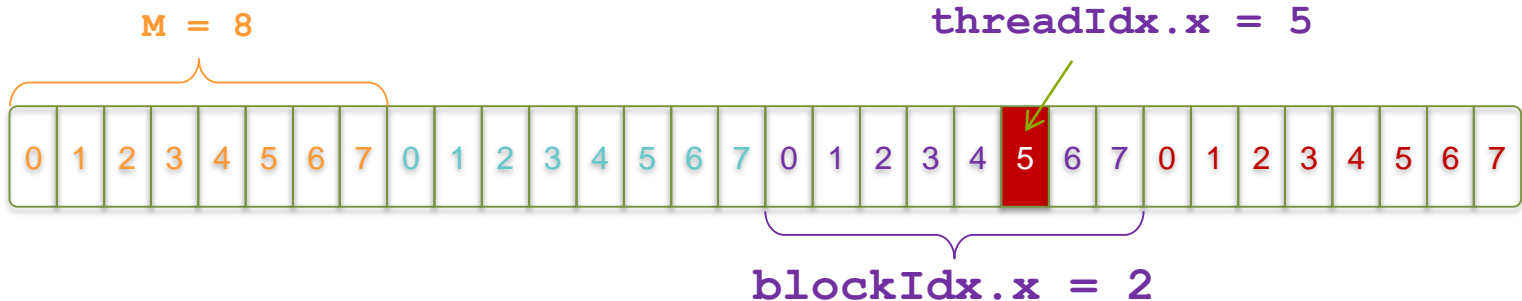


- With M threads/block a unique index for each thread is given by:

```
int index = threadIdx.x + blockIdx.x * M;
```

Indexing Arrays: Example

- Which thread will operate on the red element?



```
int index = threadIdx.x + blockIdx.x * M;  
          =           5      +           2      * 8;  
          = 21;
```


Vector Addition with Blocks and Threads

- Use the built-in variable `blockDim.x` for threads per block

```
int index = threadIdx.x + blockIdx.x * blockDim.x;
```

- Combined version of `add()` to use parallel threads *and* parallel blocks

```
__global__ void add(int *a, int *b, int *c) {  
    int index = threadIdx.x + blockIdx.x * blockDim.x;  
    c[index] = a[index] + b[index];  
}
```

- What changes need to be made in `main()`?

Addition with Blocks and Threads: `main()`

```
#define N (2048*2048)
#define THREADS_PER_BLOCK 512
int main(void) {
    int *a, *b, *c;                // host copies of a, b, c
    int *d_a, *d_b, *d_c;          // device copies of a, b, c
    int size = N * sizeof(int);

    // Alloc space for device copies of a, b, c
    cudaMalloc((void **)&d_a, size);
    cudaMalloc((void **)&d_b, size);
    cudaMalloc((void **)&d_c, size);

    // Alloc space for host copies of a, b, c and setup input values
    a = (int *)malloc(size); random_ints(a, N);
    b = (int *)malloc(size); random_ints(b, N);
    c = (int *)malloc(size);
```

Addition with Blocks and Threads: `main()`

```
// Copy inputs to device
```

```
cudaMemcpy(d_a, a, size, cudaMemcpyHostToDevice);
```

```
cudaMemcpy(d_b, b, size, cudaMemcpyHostToDevice);
```

```
// Launch add() kernel on GPU
```

```
add<<<N/THREADS_PER_BLOCK, THREADS_PER_BLOCK>>>(d_a, d_b, d_c);
```

```
// Copy result back to host
```

```
cudaMemcpy(c, d_c, size, cudaMemcpyDeviceToHost);
```

```
// Cleanup
```

```
free(a); free(b); free(c);
```

```
cudaFree(d_a); cudaFree(d_b); cudaFree(d_c);
```

```
return 0;
```

```
}
```

Handling Arbitrary Vector Sizes

- Typical problems are not friendly multiples of `blockDim.x`
- Avoid accessing beyond the end of the arrays:

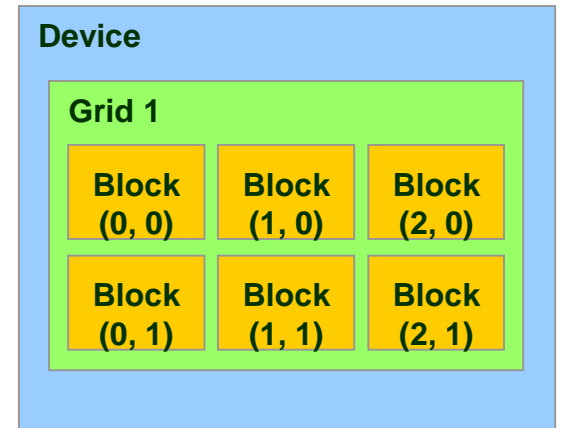
```
__global__ void add(int *a, int *b, int *c, int n) {  
    int index = threadIdx.x + blockIdx.x * blockDim.x;  
    if (index < n)  
        c[index] = a[index] + b[index];  
}
```

- Update the kernel launch:

```
add<<<(N + M-1) / M, M>>>(d_a, d_b, d_c, N);
```

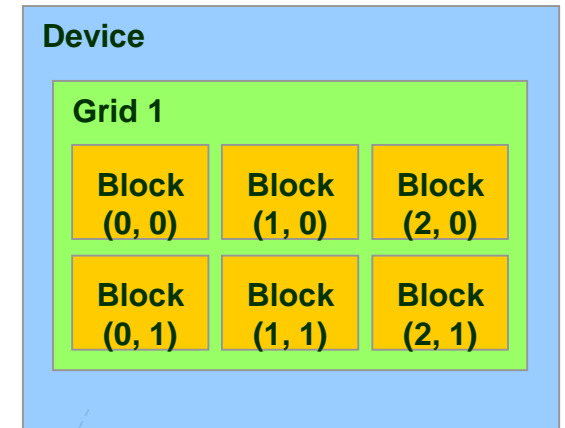
Formatting the grid as a Matrix

- `dim3 grid(3,2);`
- `kernel<<grid, 1>>(...);`



Formatting the grid as a Matrix

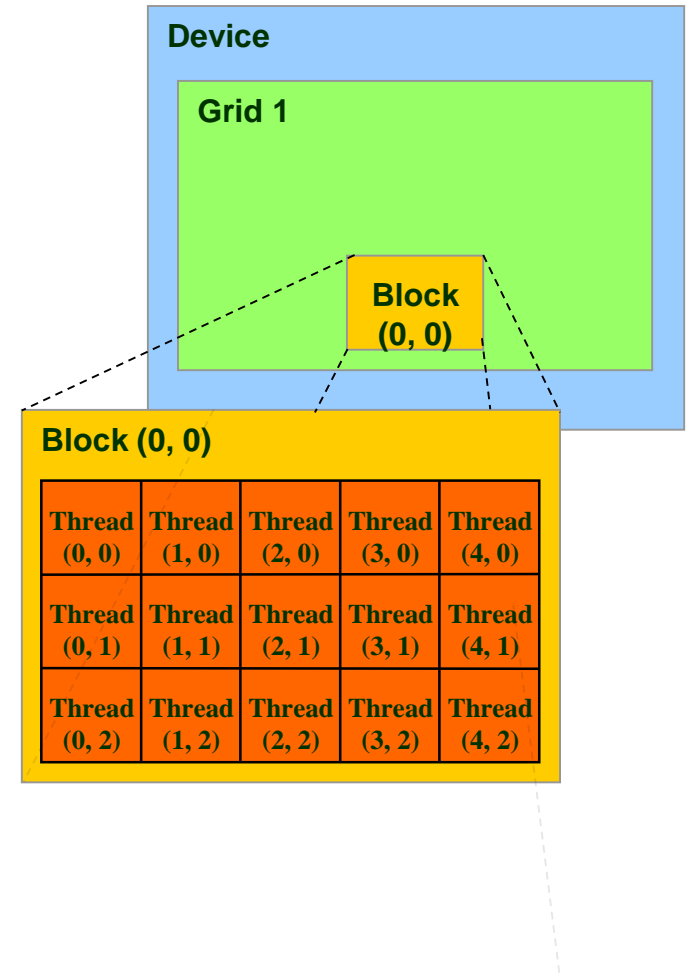
- `dim3 grid (3,2);`
- `kernel<<<grid, 1>>>(...);`



- `int index = blockIdx.x + blockIdx.y * gridDim.x;`

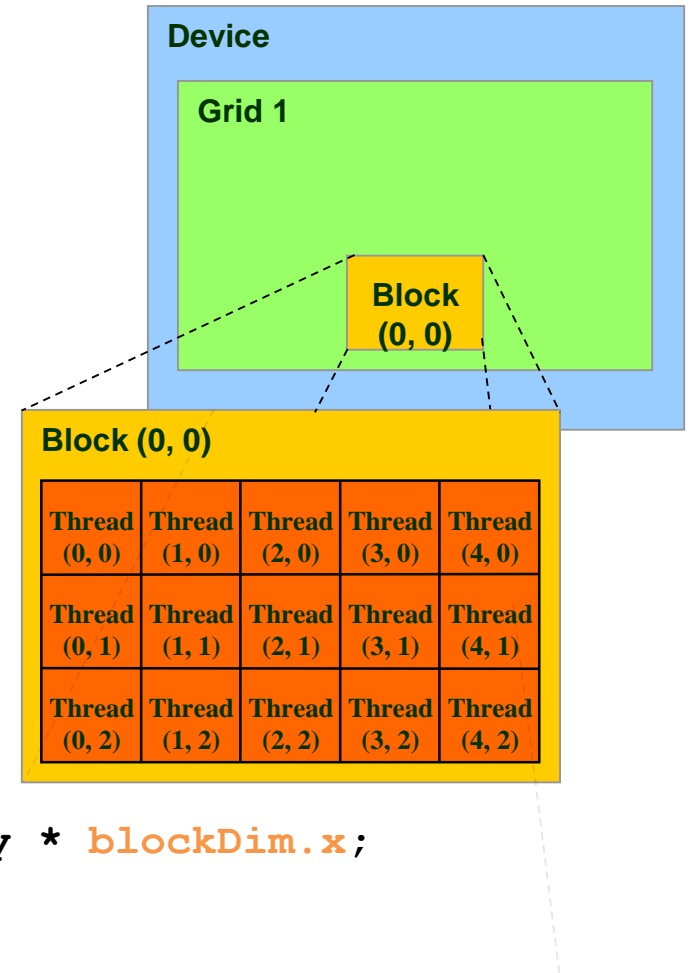
Formatting the grid as a Matrix

- `dim3 threads(5,3);`
- `kernel<<<1, threads>>>(...);`



Formatting the grid as a Matrix

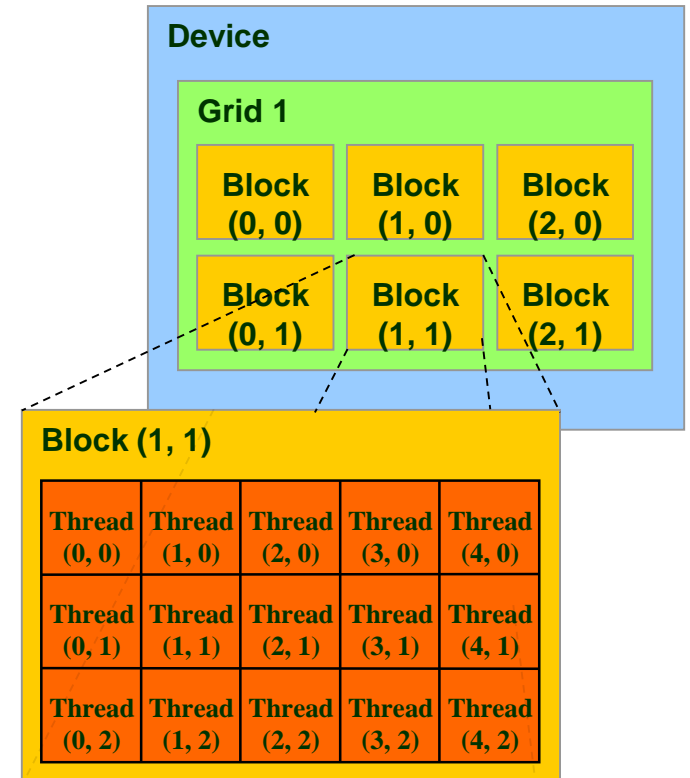
- `dim3 threads(5,3);`
- `kernel<<1, threads>>(...);`



- `int index = threadIdx.x + threadIdx.y * blockDim.x;`

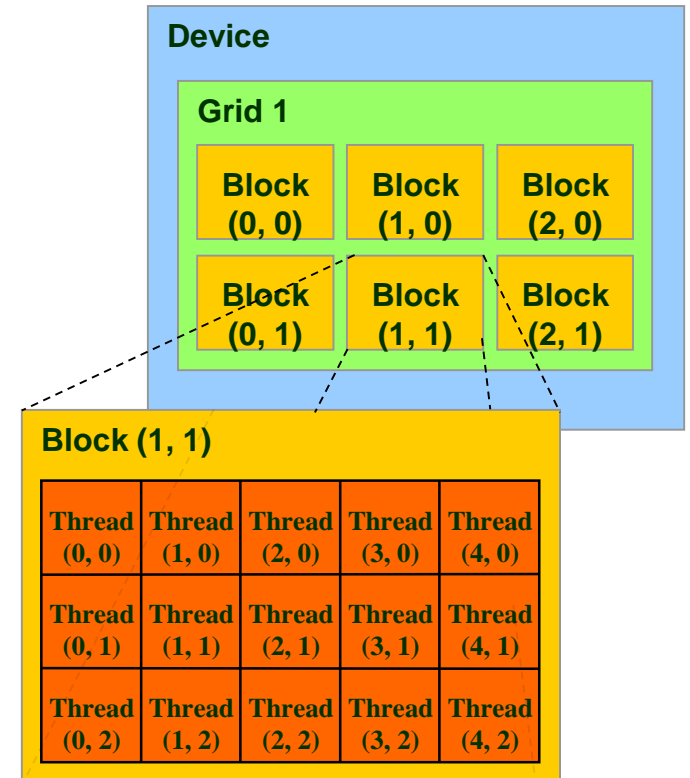
Formatting the grid as a Matrix

- `dim3 grid (3,2);`
- `dim3 block(5,3);`
- `kernel<<<grid, block>>>(...);`



Formatting the grid as a Matrix

- `dim3 grid(3,2);`
- `dim3 block(5,3);`
- `kernel<<<grid, block>>>(...);`



- ```
int index = (blockIdx.x + blockIdx.y * gridDim.x)
 * (blockDim.x * blockDim.y)
 + threadIdx.y * blockDim.x + threadIdx.x;
```