

Introduction to CUDA C



What is CUDA?

- CUDA Architecture
 - Expose general-purpose GPU computing as first-class capability
 - Retain traditional DirectX/OpenGL graphics performance
- CUDA C
 - Based on industry-standard C
 - A handful of language extensions to allow heterogeneous programs
 - Straightforward APIs to manage devices, memory, etc.
- This talk will introduce you to CUDA C

Introduction to CUDA C

- What will you learn today?
 - Start from “Hello, World!”
 - Write and launch CUDA C kernels
 - Manage GPU memory
 - Run parallel kernels in CUDA C
 - Parallel communication and synchronization
 - Race conditions and atomic operations

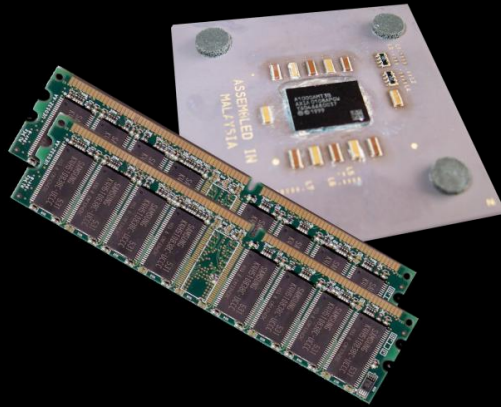
CUDA C Prerequisites

- You (probably) need experience with C or C++
- You do not need any GPU experience
- You do not need any graphics experience
- You do not need any parallel programming experience

CUDA C: The Basics

- Terminology
 - **Host** - The CPU and its memory (host memory)
 - **Device** - The GPU and its memory (device memory)

Host



Device



Note: *Figure Not to Scale*

Hello, World!

```
int main( void ) {  
    printf( "Hello, World!\n" );  
    return 0;  
}
```

- This basic program is just standard C that runs on the *host*
- NVIDIA's compiler (`nvcc`) will not complain about CUDA programs with no *device* code
- At its simplest, CUDA C is just C!

Hello, World! with Device Code

```
__global__ void kernel( void ) {  
}
```

```
int main( void ) {  
    kernel<<<1,1>>>();  
    printf( "Hello, World!\n" );  
    return 0;  
}
```

- Two notable additions to the original “Hello, World!”

Hello, World! with Device Code

```
__global__ void kernel( void ) {  
}
```

- CUDA C keyword `__global__` indicates that a function
 - Runs on the device
 - Called from host code
- `nvcc` splits source file into host and device components
 - NVIDIA's compiler handles device functions like `kernel()`
 - Standard host compiler handles host functions like `main()`
 - `gcc`
 - Microsoft Visual C

Hello, World! with Device Code

```
int main( void ) {  
    kernel<<< 1, 1 >>>();  
    printf( "Hello, World!\n" );  
    return 0;  
}
```

- Triple angle brackets mark a call from *host* code to *device* code
 - Sometimes called a “kernel launch”
 - We’ll discuss the parameters inside the angle brackets later
- This is all that’s required to execute a function on the GPU!
- The function `kernel()` does nothing, so this is fairly anticlimactic...

A More Complex Example

- 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 keyword meaning
 - `add()` will execute on the device
 - `add()` will be called from the host

A More Complex Example

- Notice that we use pointers for our 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
- How do we allocate memory on the GPU?

Memory Management

- Host and device memory are distinct entities
 - Device pointers point to GPU memory
 - May be passed to and from host code
 - May not be dereferenced from host code
 - Host pointers point to CPU memory
 - May be passed to and from device code
 - May not be dereferenced from device code
- Basic CUDA API for dealing with device memory
 - `cudaMalloc()`, `cudaFree()`, `cudaMemcpy()`
 - Similar to their C equivalents, `malloc()`, `free()`, `memcpy()`



A More Complex Example: add()

- Using our `add()` kernel:

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

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

A More Complex Example: `main()`

```
int main( void ) {  
    int a, b, c;                // host copies of a, b, c  
    int *dev_a, *dev_b, *dev_c; // device copies of a, b, c  
    int size = sizeof( int );   // we need space for an integer  
  
    // allocate device copies of a, b, c  
    cudaMalloc( (void**)&dev_a, size );  
    cudaMalloc( (void**)&dev_b, size );  
    cudaMalloc( (void**)&dev_c, size );  
  
    a = 2;  
    b = 7;
```

A More Complex Example: `main()` (cont)

```
// copy inputs to device
cudaMemcpy( dev_a, &a, size, cudaMemcpyHostToDevice );
cudaMemcpy( dev_b, &b, size, cudaMemcpyHostToDevice );

// launch add() kernel on GPU, passing parameters
add<<< 1, 1 >>>( dev_a, dev_b, dev_c );

// copy device result back to host copy of c
cudaMemcpy( &c, dev_c, size, cudaMemcpyDeviceToHost );

cudaFree( dev_a );
cudaFree( dev_b );
cudaFree( dev_c );
return 0;
}
```

Parallel Programming in CUDA C

- But wait...GPU computing is about massive parallelism
- So how do we run code in parallel on the device?
- Solution lies in the parameters between the triple angle brackets:

```
add<<< 1, 1 >>>( dev_a, dev_b, dev_c );
```



```
add<<< N, 1 >>>( dev_a, dev_b, dev_c );
```

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

Parallel Programming in CUDA C

- With `add()` running in parallel...let's do vector addition
- Terminology: Each parallel invocation of `add()` referred to as a *block*
- Kernel can refer to its block's index with the variable `blockIdx.x`
- Each block adds a value from `a[]` and `b[]`, storing the result in `c[]`:

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

- By using `blockIdx.x` to index arrays, each block handles different indices

Parallel Programming in CUDA C

- We write this code:

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

- This is what runs in parallel on the device:

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];
```

Parallel Addition: add()

- Using our newly 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()...

Parallel Addition: main()

```
#define N 512
int main( void ) {
    int *a, *b, *c;           // host copies of a, b, c
    int *dev_a, *dev_b, *dev_c; // device copies of a, b, c
    int size = N * sizeof( int ); // we need space for 512 integers

    // allocate device copies of a, b, c
    cudaMalloc( (void**)&dev_a, size );
    cudaMalloc( (void**)&dev_b, size );
    cudaMalloc( (void**)&dev_c, size );

    a = (int*)malloc( size );
    b = (int*)malloc( size );
    c = (int*)malloc( size );

    random_ints( a, N );
    random_ints( b, N );
```

Parallel Addition: main () (cont)

```
// copy inputs to device
cudaMemcpy( dev_a, a, size, cudaMemcpyHostToDevice );
cudaMemcpy( dev_b, b, size, cudaMemcpyHostToDevice );

// launch add() kernel with N parallel blocks
add<<< N, 1 >>>( dev_a, dev_b, dev_c );

// copy device result back to host copy of c
cudaMemcpy( c, dev_c, size, cudaMemcpyDeviceToHost );

free( a ); free( b ); free( c );
cudaFree( dev_a );
cudaFree( dev_b );
cudaFree( dev_c );
return 0;
}
```

Review

- Difference between “host” and “device”
 - Host = CPU
 - Device = GPU
- Using `__global__` to declare a function as device code
 - Runs on device
 - Called from host
- Passing parameters from host code to a device function

Review (cont)

- Basic device memory management
 - `cudaMalloc()`
 - `cudaMemcpy()`
 - `cudaFree()`
- Launching parallel kernels
 - Launch `N` copies of `add()` with: `add<<< N, 1 >>>();`
 - Used `blockIdx.x` to access block's index

Threads

- Terminology: A block can be split into parallel *threads*
- Let's change vector addition 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` in `add()`
- `main()` will require one change as well...

Parallel Addition (Threads): main()

```
#define N 512

int main( void ) {
    int *a, *b, *c;           //host copies of a, b, c
    int *dev_a, *dev_b, *dev_c; //device copies of a, b, c
    int size = N * sizeof( int ); //we need space for 512 integers

    // allocate device copies of a, b, c
    cudaMalloc( (void**)&dev_a, size );
    cudaMalloc( (void**)&dev_b, size );
    cudaMalloc( (void**)&dev_c, size );

    a = (int*)malloc( size );
    b = (int*)malloc( size );
    c = (int*)malloc( size );

    random_ints( a, N );
    random_ints( b, N );
```

Parallel Addition (Threads): main () (cont)

```
// copy inputs to device
cudaMemcpy( dev_a, a, size, cudaMemcpyHostToDevice );
cudaMemcpy( dev_b, b, size, cudaMemcpyHostToDevice );

// launch add() kernel with N threads
add<<< N, N >>>( dev_a, dev_b, dev_c );

// copy device result back to host copy of c
cudaMemcpy( c, dev_c, size, cudaMemcpyDeviceToHost );

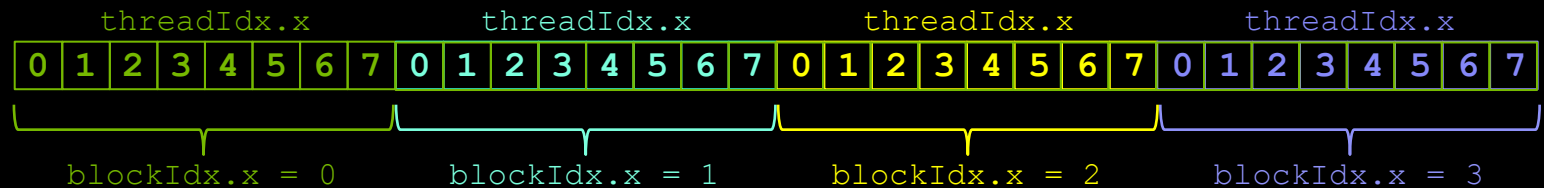
free( a ); free( b ); free( c );
cudaFree( dev_a );
cudaFree( dev_b );
cudaFree( dev_c );
return 0;
}
```

Using Threads And Blocks

- We've seen parallel vector addition using
 - Many blocks with 1 thread apiece
 - 1 block with many threads
- Let's adapt vector addition to use lots of *both* blocks and threads
- After using threads and blocks together, we'll talk about *why* threads
- First let's discuss data indexing...

Indexing Arrays With Threads And Blocks

- No longer as simple as just using `threadIdx.x` or `blockIdx.x` as indices
- To index array with 1 thread per entry (using 8 threads/block)



- If we have `M` threads/block, a unique array index for each entry given by

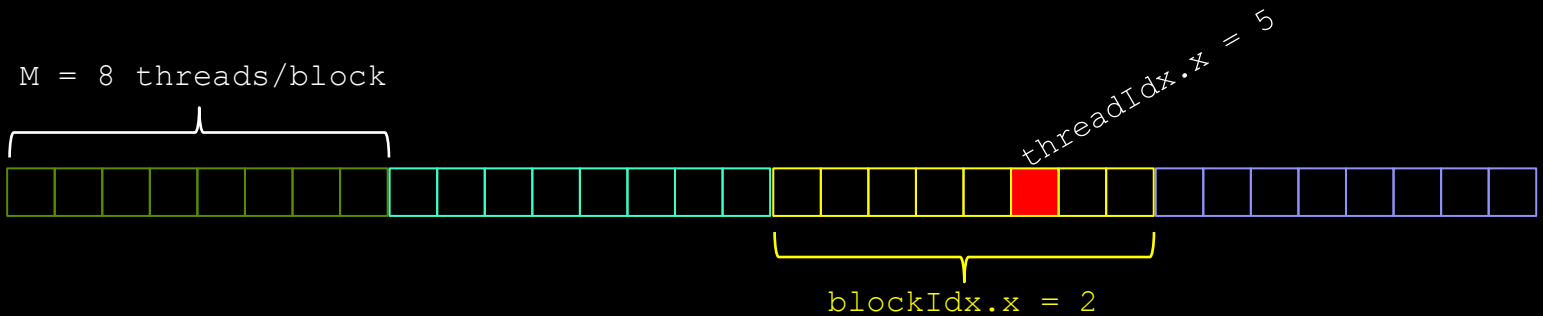
```
int index = threadIdx.x + blockIdx.x * M;
```

↓ ↓ ↓

```
int index =            x                      +            y                      * width;
```

Indexing Arrays: Example

- In this example, the red entry would have an index of 21:



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

Addition with Threads and Blocks

- The `blockDim.x` is a built-in variable for threads per block:

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

- A combined version of our vector addition kernel to use blocks *and* threads:

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

- So what changes in `main()` when we use both blocks and threads?

Parallel Addition (Blocks/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 *dev_a, *dev_b, *dev_c;    // device copies of a, b, c
    int size = N * sizeof( int );  // we need space for N integers

    // allocate device copies of a, b, c
    cudaMalloc( (void**)&dev_a, size );
    cudaMalloc( (void**)&dev_b, size );
    cudaMalloc( (void**)&dev_c, size );

    a = (int*)malloc( size );
    b = (int*)malloc( size );
    c = (int*)malloc( size );

    random_ints( a, N );
    random_ints( b, N );
```

Parallel Addition (Blocks/Threads): main()

```
// copy inputs to device
```

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

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

```
// launch add() kernel with blocks and threads
```

```
add<<< N/THREADS_PER_BLOCK, THREADS_PER_BLOCK >>>( dev_a, dev_b, dev_c );
```

```
// copy device result back to host copy of c
```

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

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

```
cudaFree( dev_a );
```

```
cudaFree( dev_b );
```

```
cudaFree( dev_c );
```

```
return 0;
```

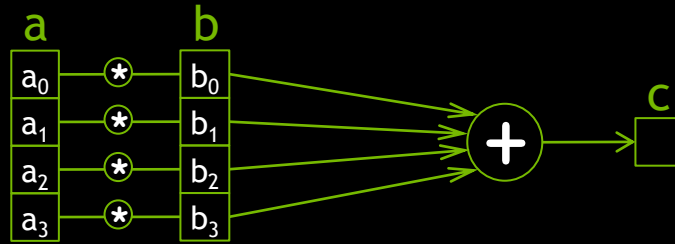
```
}
```


Why Bother With Threads?

- Threads seem unnecessary
 - Added a level of abstraction and complexity
 - What did we gain?
- Unlike parallel blocks, parallel threads have mechanisms to
 - Communicate
 - Synchronize
- Let's see how...

Dot Product

- Unlike vector addition, dot product is a *reduction* from vectors to a scalar



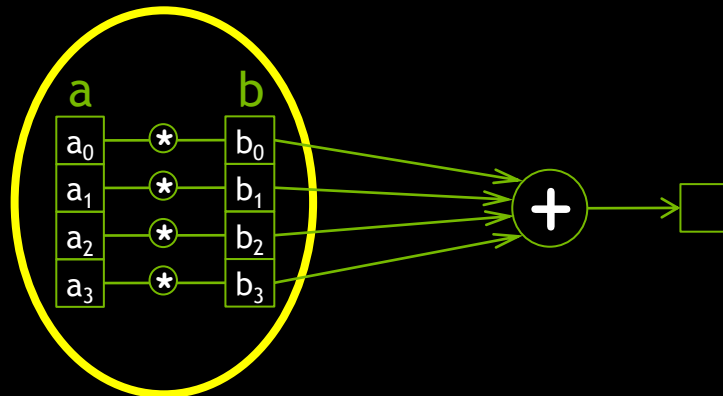
$$c = \vec{a} \cdot \vec{b}$$

$$= (a_0, a_1, a_2, a_3) \cdot (b_0, b_1, b_2, b_3)$$

$$= a_0 b_0 + a_1 b_1 + a_2 b_2 + a_3 b_3$$

Dot Product

- Parallel threads have no problem computing the pairwise products:

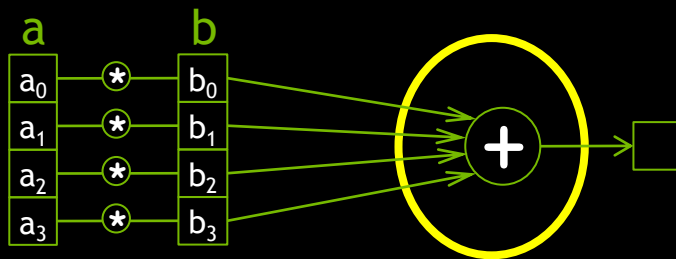


- So we can start a dot product CUDA kernel by doing just that:

```
__global__ void dot( int *a, int *b, int *c )    {  
    // Each thread computes a pairwise product  
    int temp = a[threadIdx.x] * b[threadIdx.x];
```

Dot Product

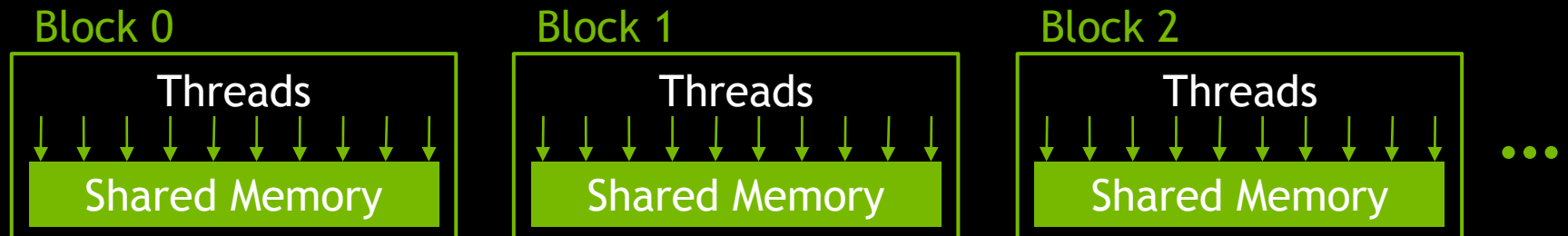
- But we need to share data between threads to compute the final sum:



```
__global__ void dot( int *a, int *b, int *c )    {  
    // Each thread computes a pairwise product  
    int temp = a[threadIdx.x] * b[threadIdx.x];  
  
    // Can't compute the final sum  
    // Each thread's copy of 'temp' is private  
}
```

Sharing Data Between Threads

- Terminology: A block of threads shares memory called...*shared memory*
- Extremely fast, on-chip memory (user-managed cache)
- Declared with the `__shared__` CUDA keyword
- Not visible to threads in other blocks running in parallel



Parallel Dot Product: dot()

- We perform parallel multiplication, serial addition:

```
#define N 512
__global__ void dot( int *a, int *b, int *c ) {
    // Shared memory for results of multiplication
    __shared__ int temp[N];
    temp[threadIdx.x] = a[threadIdx.x] * b[threadIdx.x];

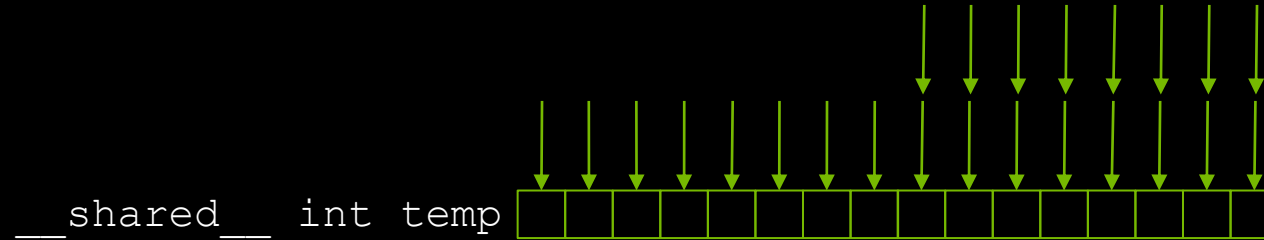
    // Thread 0 sums the pairwise products
    if( 0 == threadIdx.x ) {
        int sum = 0;
        for( int i = 0; i < N; i++ )
            sum += temp[i];
        *c = sum;
    }
}
```

Parallel Dot Product Recap

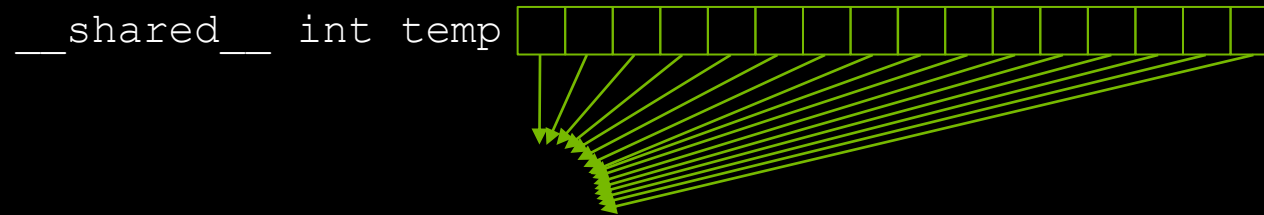
- We perform parallel, pairwise multiplications
- Shared memory stores each thread's result
- We sum these pairwise products from a single thread
- Sounds good...but we've made a huge mistake

Faulty Dot Product Exposed!

- Step 1: In parallel, each thread writes a pairwise product



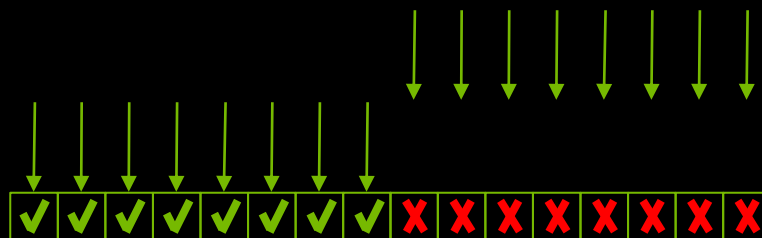
- Step 2: Thread 0 reads and sums the products



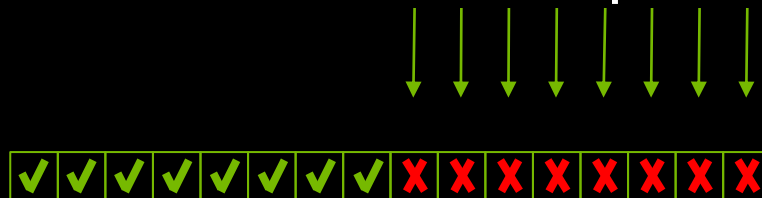
- But there's an assumption hidden in Step 1...

Read-Before-Write Hazard

- Suppose thread 0 finishes its write in step 1



- Then thread 0 reads index 12 in step 2



← This read returns garbage!

- Before thread 12 writes to index 12 in step 1?



Synchronization

- We need threads to wait between the sections of `dot()`:

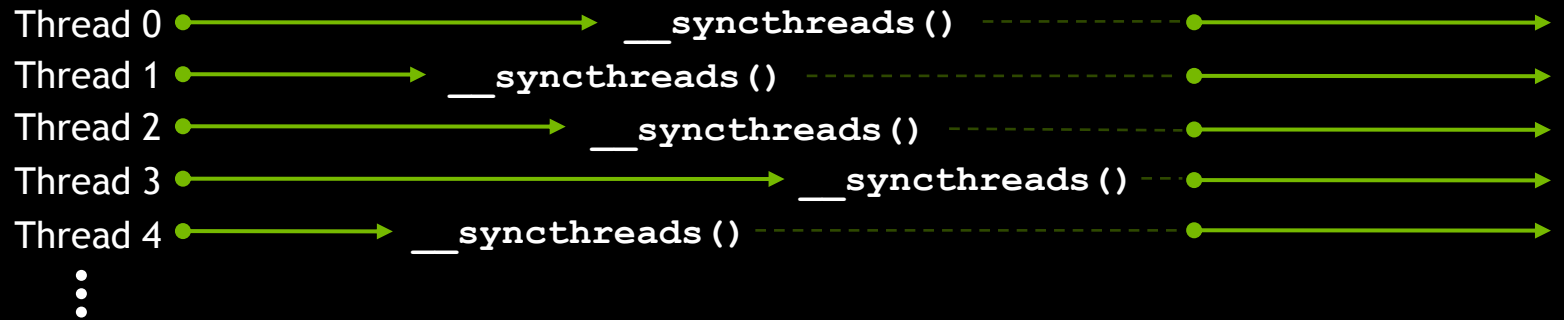
```
__global__ void dot( int *a, int *b, int *c ) {
    __shared__ int temp[N];
    temp[threadIdx.x] = a[threadIdx.x] * b[threadIdx.x];

    // * NEED THREADS TO SYNCHRONIZE HERE *
    // No thread can advance until all threads
    // have reached this point in the code

    // Thread 0 sums the pairwise products
    if( 0 == threadIdx.x ) {
        int sum = 0;
        for( int i = 0; i < N; i++ )
            sum += temp[i];
        *c = sum;
    }
}
```

`__syncthreads()`

- We can synchronize threads with the function `__syncthreads()`
- Threads in the block wait until *all* threads have hit the `__syncthreads()`



- Threads are *only* synchronized within a block

Parallel Dot Product: dot ()

```
__global__ void dot( int *a, int *b, int *c ) {  
    __shared__ int temp[N];  
    temp[threadIdx.x] = a[threadIdx.x] * b[threadIdx.x];  
  
    __syncthreads();  
  
    if( 0 == threadIdx.x ) {  
        int sum = 0;  
        for( int i = 0; i < N; i++ )  
            sum += temp[i];  
        *c = sum;  
    }  
}
```

- With a properly synchronized dot () routine, let's look at main ()

Parallel Dot Product: main()

```
#define N 512

int main( void ) {
    int *a, *b, *c;                // copies of a, b, c
    int *dev_a, *dev_b, *dev_c;    // device copies of a, b, c
    int size = N * sizeof( int );  // we need space for 512 integers

    // allocate device copies of a, b, c
    cudaMalloc( (void**)&dev_a, size );
    cudaMalloc( (void**)&dev_b, size );
    cudaMalloc( (void**)&dev_c, sizeof( int ) );

    a = (int *)malloc( size );
    b = (int *)malloc( size );
    c = (int *)malloc( sizeof( int ) );

    random_ints( a, N );
    random_ints( b, N );
```

Parallel Dot Product: main()

```
// copy inputs to device
cudaMemcpy( dev_a, a, size, cudaMemcpyHostToDevice );
cudaMemcpy( dev_b, b, size, cudaMemcpyHostToDevice );

// launch dot() kernel with 1 block and N threads
dot<<< 1, N >>>( dev_a, dev_b, dev_c );

// copy device result back to host copy of c
cudaMemcpy( c, dev_c, sizeof( int ) , cudaMemcpyDeviceToHost );

free( a ); free( b ); free( c );
cudaFree( dev_a );
cudaFree( dev_b );
cudaFree( dev_c );
return 0;
}
```

Review

- Launching kernels with parallel threads
 - Launch `add()` with `N` threads: `add<<< 1, N >>>()` ;
 - Used `threadIdx.x` to access thread's index
- Using both blocks and threads
 - Used `(threadIdx.x + blockIdx.x * blockDim.x)` to index input/output
 - `N/THREADS_PER_BLOCK` blocks and `THREADS_PER_BLOCK` threads gave us `N` threads total

Review (cont)

- Using `__shared__` to declare memory as shared memory
 - Data shared among threads in a block
 - Not visible to threads in other parallel blocks
- Using `__syncthreads()` as a barrier
 - No thread executes instructions after `__syncthreads()` until all threads have reached the `__syncthreads()`
 - Needs to be used to prevent *data hazards*

Multiblock Dot Product

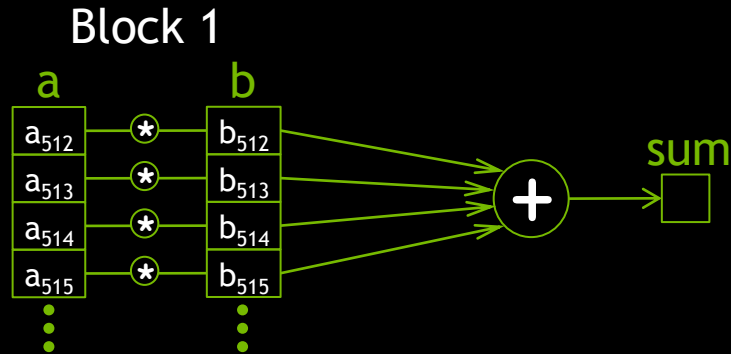
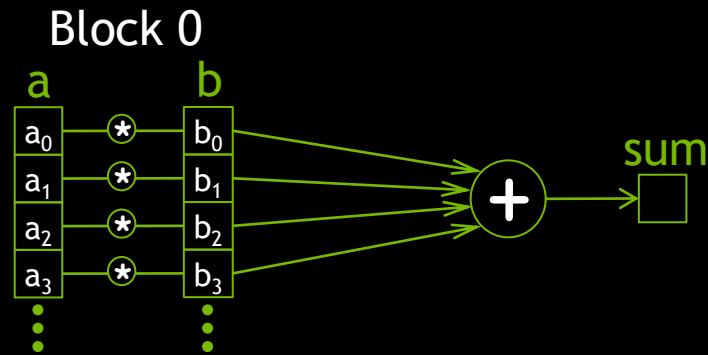
- Recall our dot product launch:

```
// launch dot() kernel with 1 block and N threads  
dot<<< 1, N >>>( dev_a, dev_b, dev_c );
```

- Launching with one block will not utilize much of the GPU
- Let's write a multiblock version of dot product

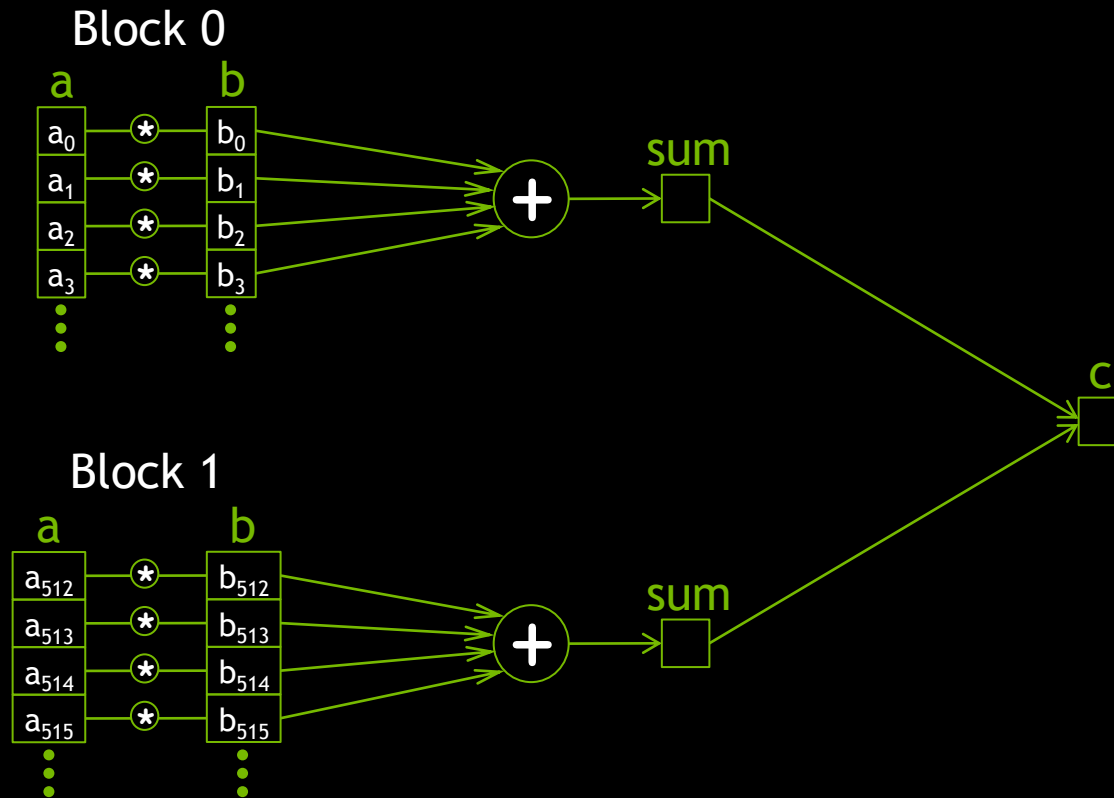
Multiblock Dot Product: Algorithm

- Each block computes a sum of its pairwise products like before:



Multiblock Dot Product: Algorithm

- And then contributes its sum to the final result:



Multiblock Dot Product: dot ()

```
#define N    (2048*2048)
#define THREADS_PER_BLOCK  512
__global__ void dot( int *a, int *b, int *c ) {
    __shared__ int temp[THREADS_PER_BLOCK];
    int index = threadIdx.x + blockIdx.x * blockDim.x;
    temp[threadIdx.x] = a[index] * b[index];

    __syncthreads();

    if( 0 == threadIdx.x ) {
        int sum = 0;
        for( int i = 0; i < THREADS_PER_BLOCK; i++ )
            sum += temp[i];
        atomicAdd( c , sum );
    }
}
```

- But we have a race condition...
- We can fix it with one of CUDA's atomic operations

Race Conditions

- Terminology: A *race condition* occurs when program behavior depends upon relative timing of two (or more) event sequences
- What actually takes place to execute the line in question: `*c += sum;`
 - Read value at address `c`
 - Add `sum` to value
 - Write result to address `c`

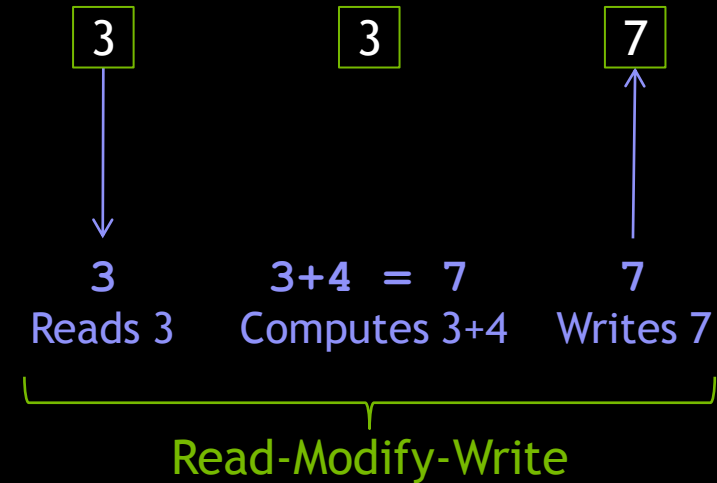
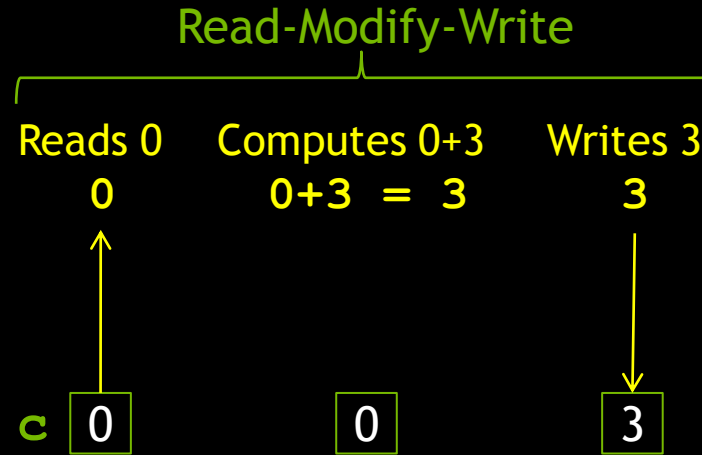
Terminology: *Read-Modify-Write*
- What if two threads are trying to do this at the same time?
 - Thread 0, Block 0
 - Read value at address `c`
 - Add `sum` to value
 - Write result to address `c`
 - Thread 0, Block 1
 - Read value at address `c`
 - Add `sum` to value
 - Write result to address `c`

Global Memory Contention

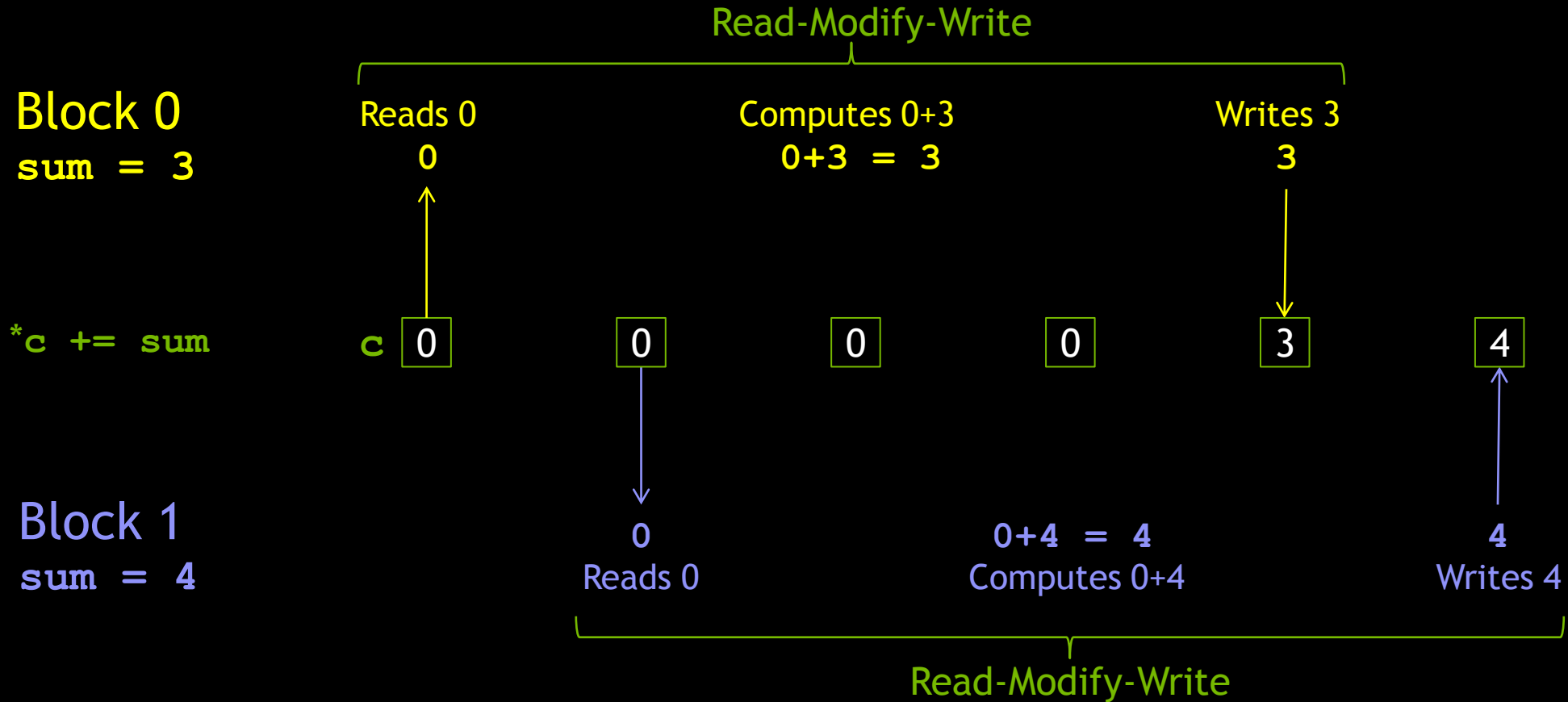
Block 0
sum = 3

*c += sum

Block 1
sum = 4



Global Memory Contention



Atomic Operations

- Terminology: Read-modify-write uninterruptible when *atomic*
- Many *atomic operations* on memory available with CUDA C
 - `atomicAdd()`
 - `atomicSub()`
 - `atomicMin()`
 - `atomicMax()`
 - `atomicInc()`
 - `atomicDec()`
 - `atomicExch()`
 - `atomicCAS()`
- Predictable result when simultaneous access to memory required
- We need to atomically add `sum` to `c` in our multiblock dot product

Multiblock Dot Product: dot ()

```
__global__ void dot( int *a, int *b, int *c ) {  
    __shared__ int temp[THREADS_PER_BLOCK];  
    int index = threadIdx.x + blockIdx.x * blockDim.x;  
    temp[threadIdx.x] = a[index] * b[index];  
  
    __syncthreads();  
  
    if( 0 == threadIdx.x ) {  
        int sum = 0;  
        for( int i = 0; i < THREADS_PER_BLOCK; i++ )  
            sum += temp[i];  
        atomicAdd( c , sum );  
    }  
}
```

- Now let's fix up `main()` to handle a multiblock dot product

Parallel Dot Product: main()

```
#define N    (2048*2048)
#define THREADS_PER_BLOCK 512
int main( void ) {
    int *a, *b, *c;                // host copies of a, b, c
    int *dev_a, *dev_b, *dev_c;    // device copies of a, b, c
    int size = N * sizeof( int );  // we need space for N ints

    // allocate device copies of a, b, c
    cudaMalloc( (void**)&dev_a, size );
    cudaMalloc( (void**)&dev_b, size );
    cudaMalloc( (void**)&dev_c, sizeof( int ) );

    a = (int *)malloc( size );
    b = (int *)malloc( size );
    c = (int *)malloc( sizeof( int ) );

    random_ints( a, N );
    random_ints( b, N );
```

Parallel Dot Product: main()

```
// copy inputs to device
cudaMemcpy( dev_a, a, size, cudaMemcpyHostToDevice );
cudaMemcpy( dev_b, b, size, cudaMemcpyHostToDevice );

// launch dot() kernel
dot<<< N/THREADS_PER_BLOCK, THREADS_PER_BLOCK >>>( dev_a, dev_b, dev_c );

// copy device result back to host copy of c
cudaMemcpy( c, dev_c, sizeof( int ) , cudaMemcpyDeviceToHost );

free( a ); free( b ); free( c );
cudaFree( dev_a );
cudaFree( dev_b );
cudaFree( dev_c );
return 0;
}
```

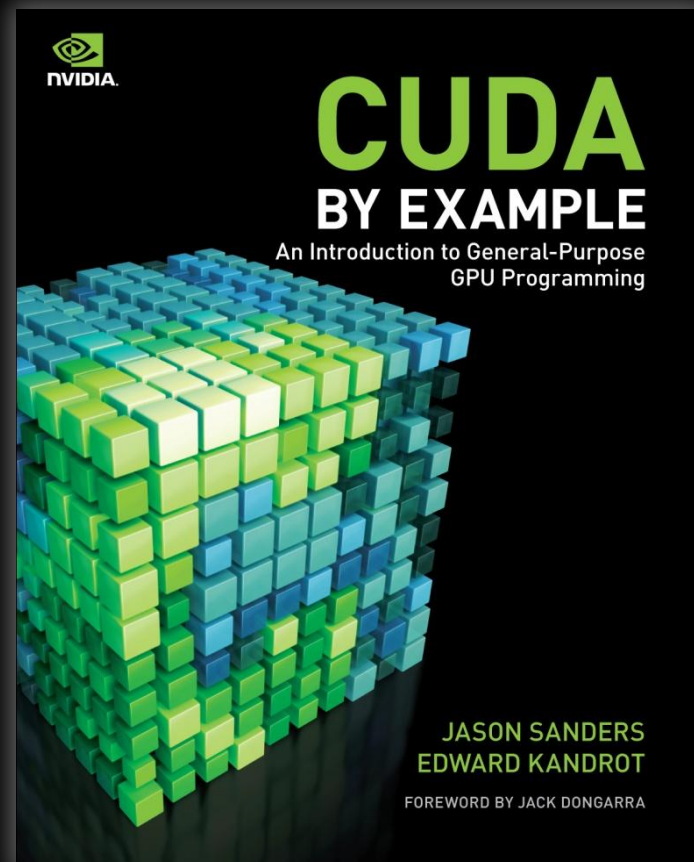
Review

- Race conditions
 - Behavior depends upon relative timing of multiple event sequences
 - Can occur when an implied read-modify-write is interruptible
- Atomic operations
 - CUDA provides read-modify-write operations guaranteed to be atomic
 - Atomics ensure correct results when multiple threads modify memory

To Learn More CUDA C

- Check out *CUDA by Example*

- Parallel Programming in CUDA C
- Thread Cooperation
- Constant Memory and Events
- Texture Memory
- Graphics Interoperability
- Atomics
- Streams
- CUDA C on Multiple GPUs
- Other CUDA Resources



- <http://developer.nvidia.com/object/cuda-by-example.html>

Questions

- First my questions
- Now your questions...

