

CUDA C/C++ BASICS

Modified from NVIDIA Corporation Slide Sets

What is CUDA?

- CUDA Architecture
 - Expose GPU parallelism for general-purpose computing
 - Retain performance
- CUDA C/C++
 - Based on industry-standard C/C++
 - Small set of extensions to enable heterogeneous programming
 - Straightforward APIs to manage devices, memory etc.
- This session introduces CUDA C/C++

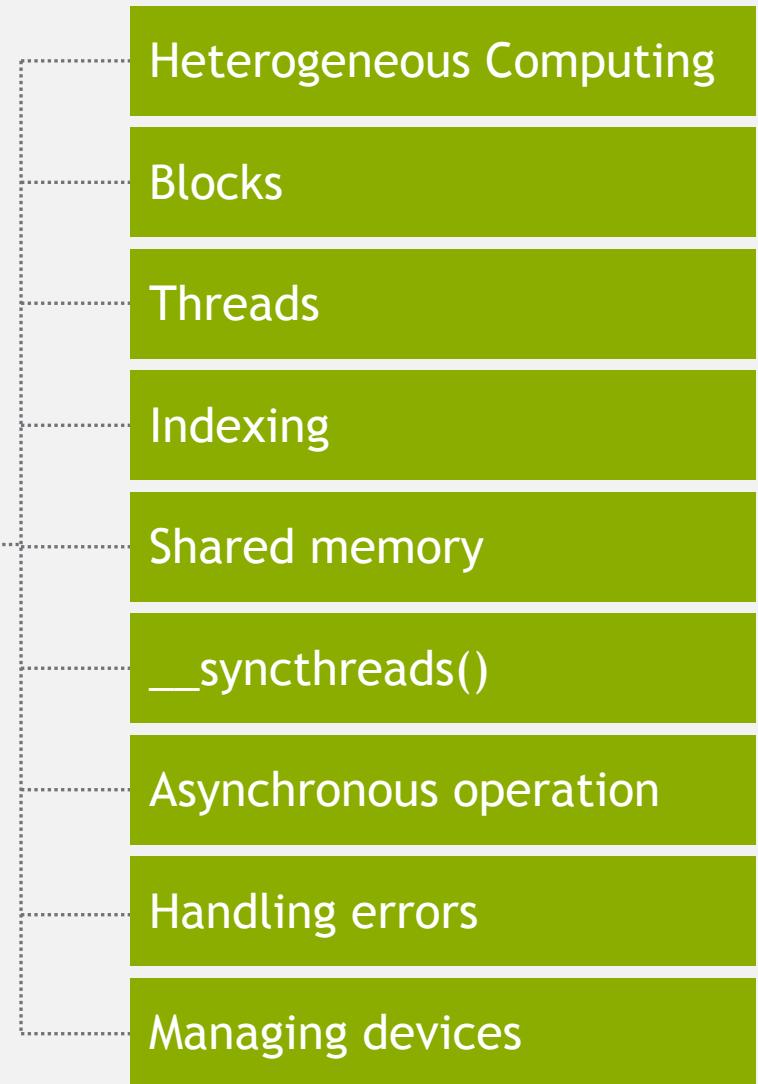
Introduction to CUDA C/C++

- What will you learn with this slide set?
 - Start from “Hello World!”
 - Write and launch CUDA C/C++ kernels
 - Manage GPU memory
 - Manage communication and synchronization

Prerequisites

- You (probably) need experience with C or C++
- You don't need GPU experience
- You don't need parallel programming experience
- You don't need graphics experience

CONCEPTS



HELLO WORLD!

CONCEPTS

Heterogeneous Computing

Blocks

Threads

Indexing

Shared memory

`__syncthreads()`

Asynchronous operation

Handling errors

Managing devices

Heterogeneous Computing

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

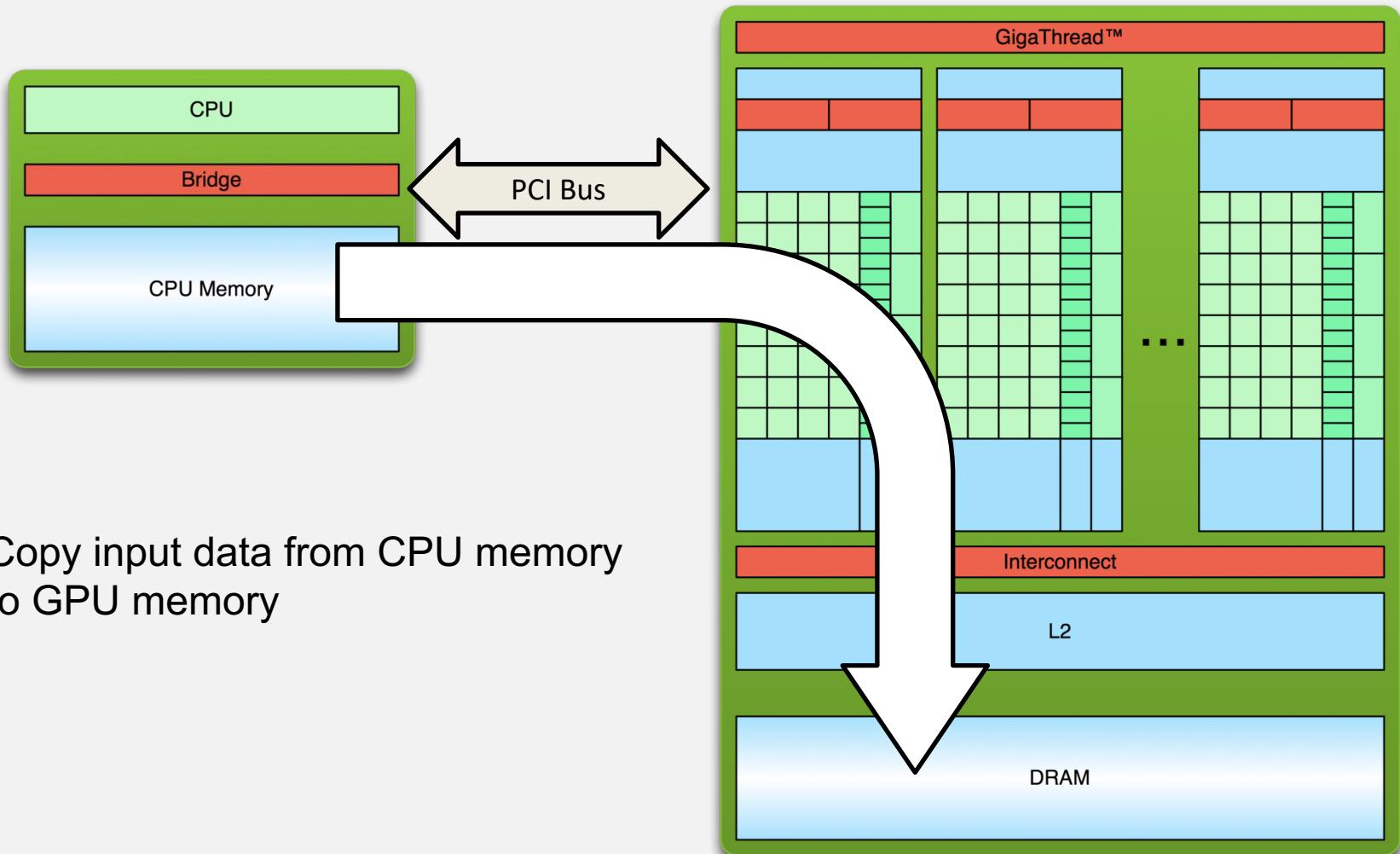


Host

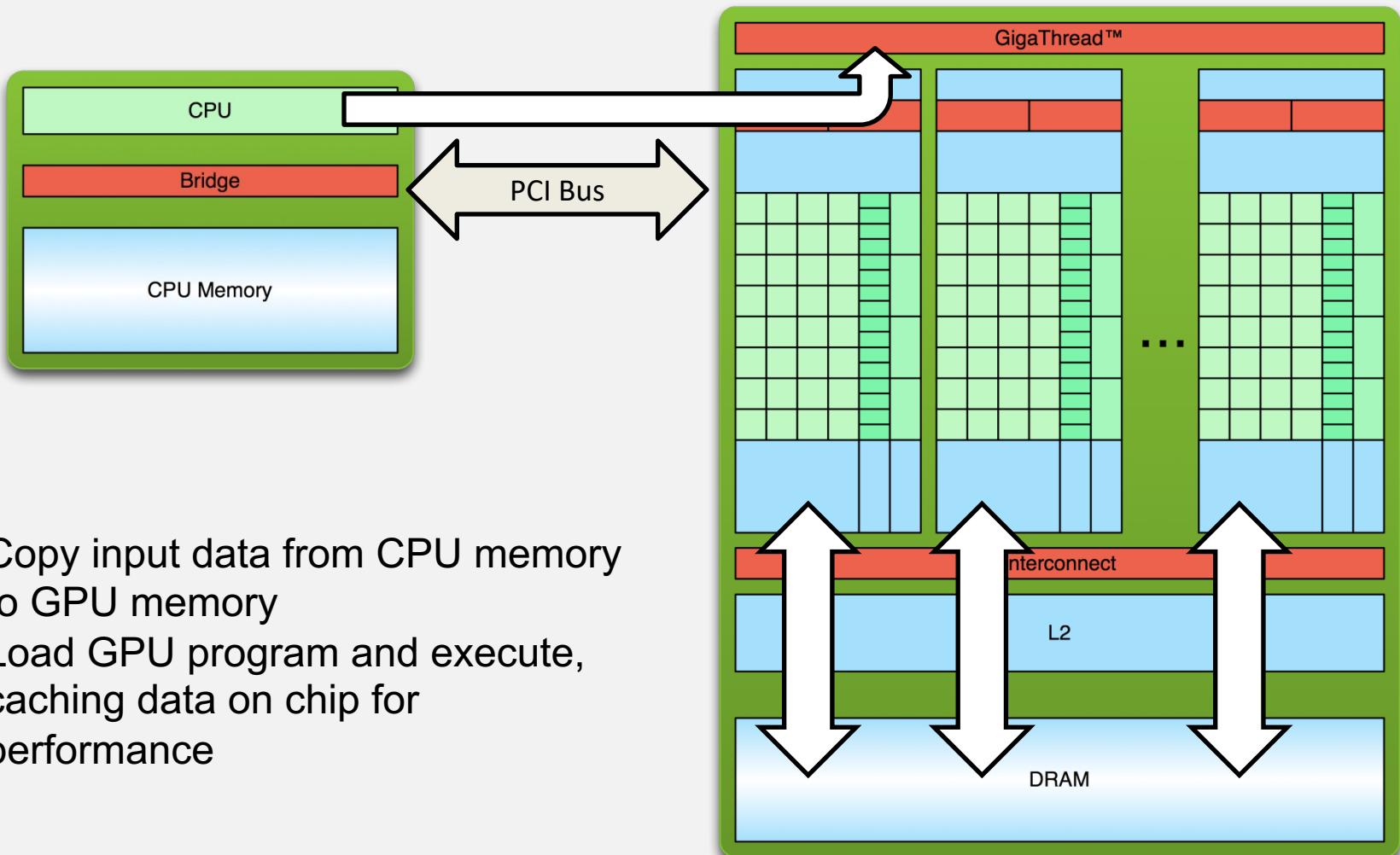


Device

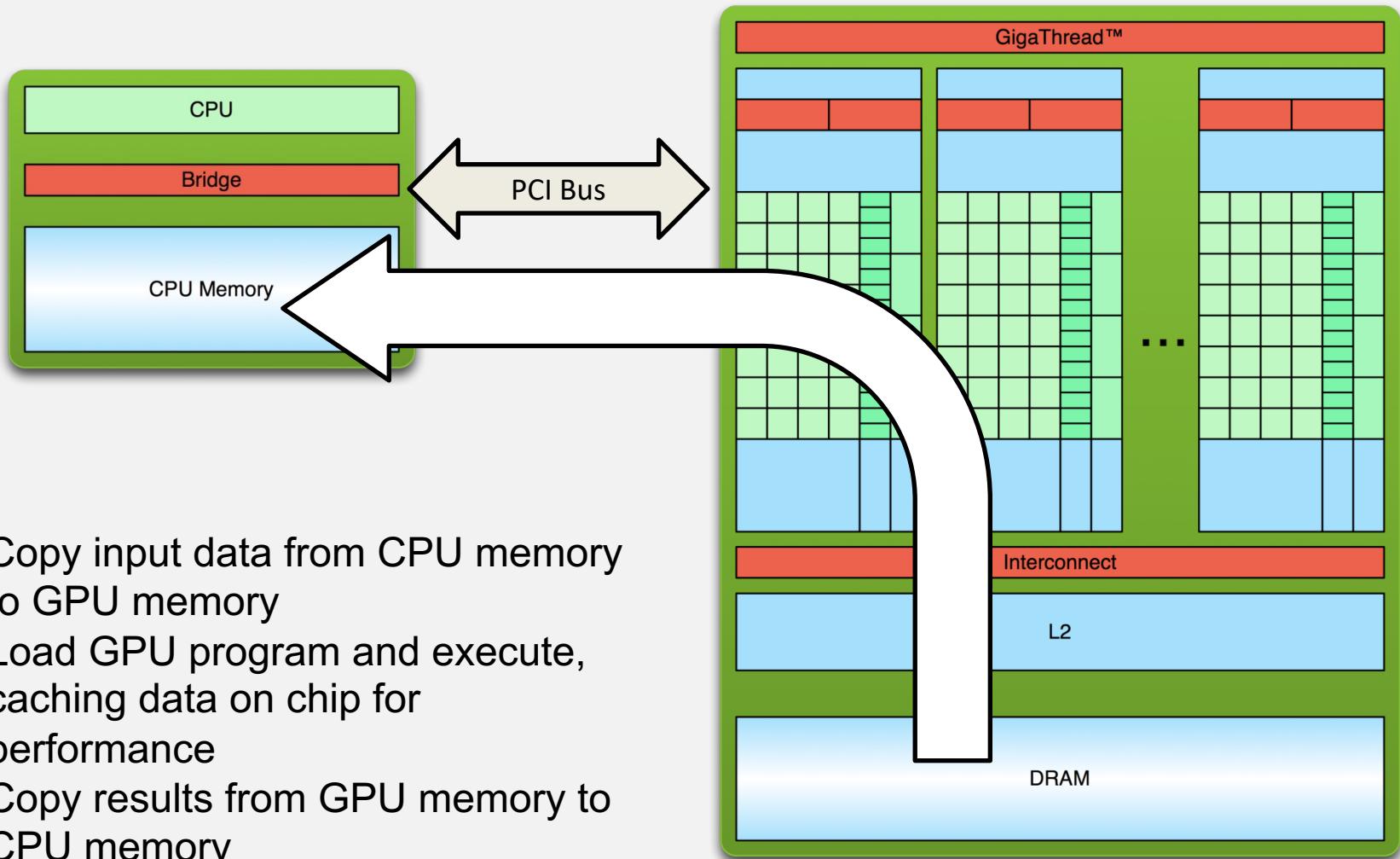
Simple Processing Flow



Simple Processing Flow



Simple Processing Flow



Hello World!

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

- Standard C that runs on the host
- NVIDIA compiler (nvcc) can be used to compile programs with no *device* code

Output:

```
$ nvcc  
hello_world.  
cu  
$ a.out  
Hello World!  
$
```

Hello World! with Device Code

```
__global__ void mykernel(void) { ... }

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

- Two new syntactic elements...

Hello World! with Device Code

```
__global__ void mykernel(void) {.....}
```

- CUDA C/C++ keyword `__global__` indicates a function that:
 - Runs on the device
 - Is called from host code
- nvcc separates source code into host and device components
 - Device functions (e.g. `mykernel()`) processed by NVIDIA compiler
 - Host functions (e.g. `main()`) processed by standard host compiler
 - `gcc, cl.exe`

Hello World! with Device Code

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

- Triple angle brackets mark a call from *host* code to *device* code
 - Also called a “kernel launch”
 - We’ll return to the parameters (1,1) in a moment
- That’s all that is required to execute a function on the GPU!

Hello World! with Device Code

```
__global__ void mykernel(void) {.....}

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

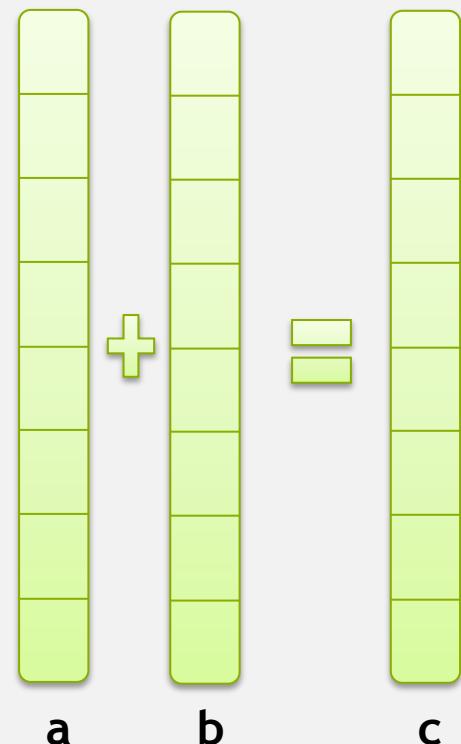
- `mykernel()` does nothing,
somewhat anticlimactic!

Output:

```
$ nvcc
hello.cu
$ a.out
Hello World!
$
```

Parallel Programming in CUDA C/C++

- But wait... GPU computing is about massive parallelism!
- We need a more interesting example...
- 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;
}
```

RUNNING IN PARALLEL

CONCEPTS

Heterogeneous Computing

Blocks

Threads

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Shared memory

`__syncthreads()`

Asynchronous operation

Handling errors

Managing devices

Moving to Parallel

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

```
add<<< 1, 1 >>>();  
      ^  
      |  
      v  
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;
}
```

Review (1 of 2)

- Difference between *host* and *device*
 - *Host* CPU
 - *Device* GPU
- Using `__global__` to declare a function as device code
 - Executes on the device
 - Called from the host
- Passing parameters from host code to a device function

Review (2 of 2)

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

INTRODUCING THREADS

CONCEPTS

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`__syncthreads()`

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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()` ...

Vector Addition Using Threads: 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 Using Threads: main()

```
// Copy inputs to device
cudaMemcpy(d_a, a, size, cudaMemcpyHostToDevice);
cudaMemcpy(d_b, b, size, cudaMemcpyHostToDevice);

// Launch add() kernel on GPU with N threads
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;
}
```

CONCEPTS

COMBINING THREADS AND BLOCKS

Heterogeneous Computing

Blocks

Threads

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Shared memory

`__syncthreads()`

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Handling errors

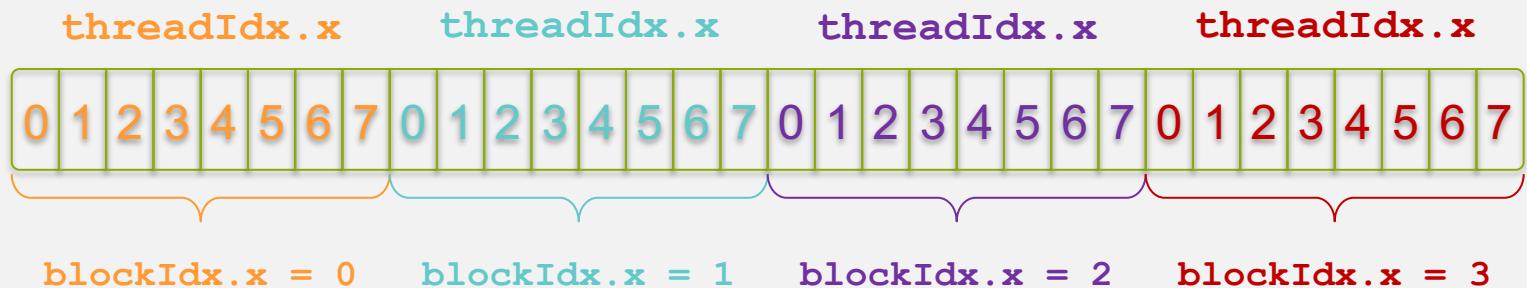
Managing devices

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)

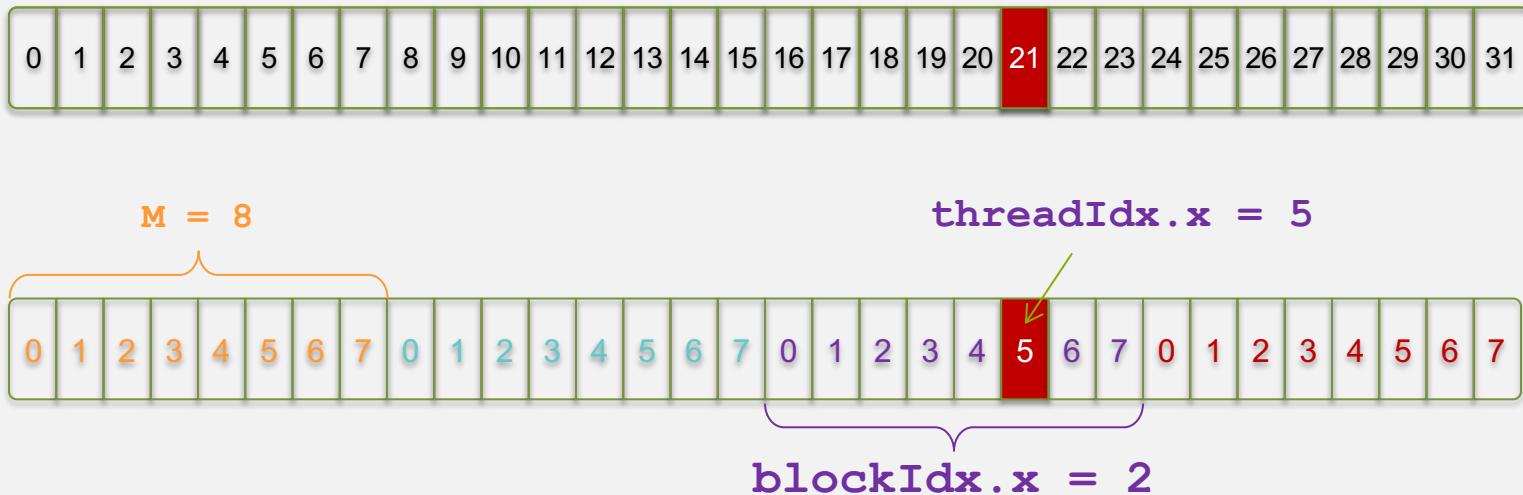


- With M threads/block a unique index for each thread is given by:

```
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);
```

Why Bother with Threads?

- Threads seem unnecessary
 - They add a level of complexity
 - What do we gain?
- Unlike parallel blocks, threads have mechanisms to:
 - Communicate
 - Synchronize
- To look closer, we need a new example...

COOPERATING THREADS

CONCEPTS

Heterogeneous Computing

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`__syncthreads()`

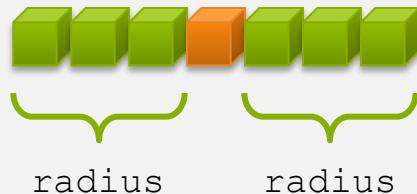
Asynchronous operation

Handling errors

Managing devices

1D Stencil

- Consider applying a 1D stencil to a 1D array of elements
 - Each output element is the sum of input elements within a radius
- If radius is 3, then each output element is the sum of 7 input elements:



Implementing Within a Block

- Each thread processes one output element
 - `blockDim.x` elements per block
- Input elements are read several times
 - With radius 3, each input element is read seven times

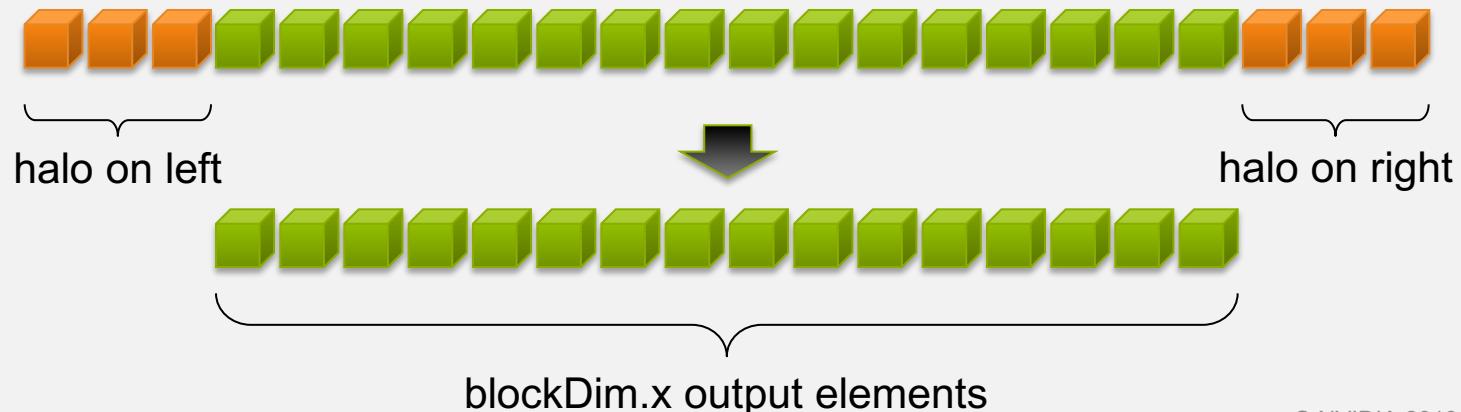


Sharing Data Between Threads

- Terminology: within a block, threads share data via **shared memory**
- Extremely fast on-chip memory, user-managed
- Declare using **__shared__**, allocated per block
- Data is not visible to threads in other blocks

Implementing With Shared Memory

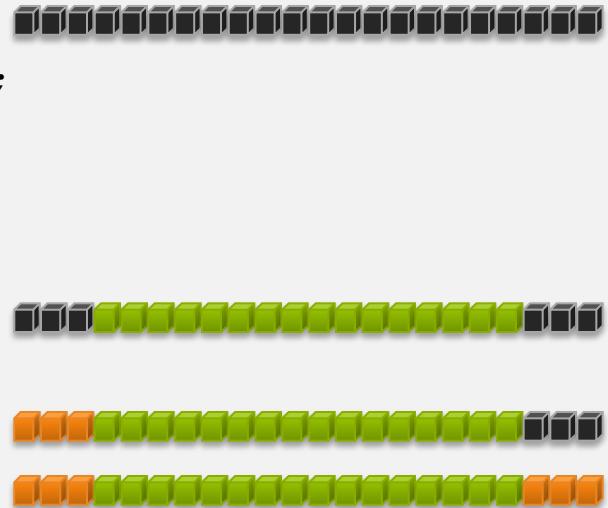
- Cache data in shared memory
 - Read $(blockDim.x + 2 * radius)$ input elements from global memory to shared memory
 - Compute $blockDim.x$ output elements
 - Write $blockDim.x$ output elements to global memory
 - Each block needs a **halo** of $radius$ elements at each boundary



Stencil Kernel

```
__global__ void stencil_1d(int *in, int *out) {
    __shared__ int temp[BLOCK_SIZE + 2 * RADIUS];
    int gindex = threadIdx.x + blockIdx.x * blockDim.x;
    int lindex = threadIdx.x + RADIUS;

    // Read input elements into shared memory
    temp[lindex] = in[gindex];
    if (threadIdx.x < RADIUS) {
        temp[lindex - RADIUS] = in[gindex - RADIUS];
        temp[lindex + BLOCK_SIZE] =
            in[gindex + BLOCK_SIZE];
    }
}
```



Stencil Kernel

```
// Apply the stencil
int result = 0;
for (int offset = -RADIUS ; offset <= RADIUS ; offset++)
    result += temp[lindex + offset];

// Store the result
out[gindex] = result;
}
```

Data Race!

- The stencil example will not work...
- Suppose thread 15 reads the halo before thread 0 has fetched it...

```
temp[lindex] = in[gindex];           Store at temp[18]   
if (threadIdx.x < RADIUS) {  
    temp[lindex - RADIUS] = in[gindex - RADIUS];    Skipped, threadIdx > RADIUS  
    temp[lindex + BLOCK_SIZE] = in[gindex + BLOCK_SIZE];  
}  
  
int result = 0;  
result += temp[lindex + 1];           Load from temp[19] 
```

__syncthreads()

- `void __syncthreads();`
- Synchronizes all threads within a block
 - Used to prevent RAW / WAR / WAW hazards
- All threads must reach the barrier
 - In conditional code, the condition must be uniform across the block

Stencil Kernel

```
__global__ void stencil_1d(int *in, int *out) {
    __shared__ int temp[BLOCK_SIZE + 2 * RADIUS];
    int gindex = threadIdx.x + blockIdx.x * blockDim.x;
    int lindex = threadIdx.x + radius;

    // Read input elements into shared memory
    temp[lindex] = in[gindex];
    if (threadIdx.x < RADIUS) {
        temp[lindex - RADIUS] = in[gindex - RADIUS];
        temp[lindex + BLOCK_SIZE] = in[gindex + BLOCK_SIZE];
    }

    // Synchronize (ensure all the data is available)
    __syncthreads();
}
```

Stencil Kernel

```
// Apply the stencil
int result = 0;
for (int offset = -RADIUS ; offset <= RADIUS ; offset++)
    result += temp[lindex + offset];

// Store the result
out[gindex] = result;
}
```

Review (1 of 2)

- Launching parallel threads
 - Launch N blocks with M threads per block with
`kernel<<<N,M>>>(...);`
 - Use `blockIdx.x` to access block index within grid
 - Use `threadIdx.x` to access thread index within block
- Allocate elements to threads:

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

Review (2 of 2)

- Use `__shared__` to declare a variable/array in shared memory
 - Data is shared between threads in a block
 - Not visible to threads in other blocks
- Use `__syncthreads()` as a barrier
 - Use to prevent data hazards

CONCEPTS

MANAGING THE DEVICE

Heterogeneous Computing

Blocks

Threads

Indexing

Shared memory

`__syncthreads()`

Asynchronous operation

Handling errors

Managing devices

Coordinating Host & Device

- Kernel launches are **asynchronous**
 - Control returns to the CPU immediately
- CPU needs to synchronize before consuming the results

`cudaMemcpy()`

Blocks the CPU until the copy is complete
Copy begins when all preceding CUDA calls have completed

`cudaMemcpyAsync()`

Asynchronous, does not block the CPU

`cudaDeviceSynchronize()`

Blocks the CPU until all preceding CUDA calls have completed

Reporting Errors

- All CUDA API calls return an error code (`cudaError_t`)
 - Error in the API call itself
 - Error in an earlier asynchronous operation (e.g. kernel)
OR
- Get the error code for the last error:
`cudaError_t cudaGetLastError(void)`
- Get a string to describe the error:
`char *cudaGetErrorString(cudaError_t)`

`printf("%s\n", cudaGetErrorString(cudaGetLastError()));`

Device Management

- Application can query and select GPUs

```
cudaGetDeviceCount(int *count)  
cudaSetDevice(int device)  
cudaGetDevice(int *device)  
cudaGetDeviceProperties(cudaDeviceProp *prop, int device)
```

- Multiple threads can share a device
- A single thread can manage multiple devices

```
cudaSetDevice(i) to select current device  
cudaMemcpy(...) for peer-to-peer copies†
```

[†] requires OS and device support

Introduction to CUDA C/C++

- What have we learned?
 - Write and launch CUDA C/C++ kernels
 - `__global__`, `blockIdx.x`, `threadIdx.x`, `<<>>>`
 - Manage GPU memory
 - `cudaMalloc()`, `cudaMemcpy()`, `cudaFree()`
 - Manage communication and synchronization
 - `__shared__`, `__syncthreads()`
 - `cudaMemcpy()` VS `cudaMemcpyAsync()`,
`cudaDeviceSynchronize()`

IDs and Dimensions

- A kernel is launched as a grid of blocks of threads

- `blockIdx` and `threadIdx` are 3D
- We showed only one dimension (x)

- Built-in variables:

- `threadIdx`
- `blockIdx`
- `blockDim`
- `gridDim`

