Parallel Computing with GPUs: Introduction to CUDA

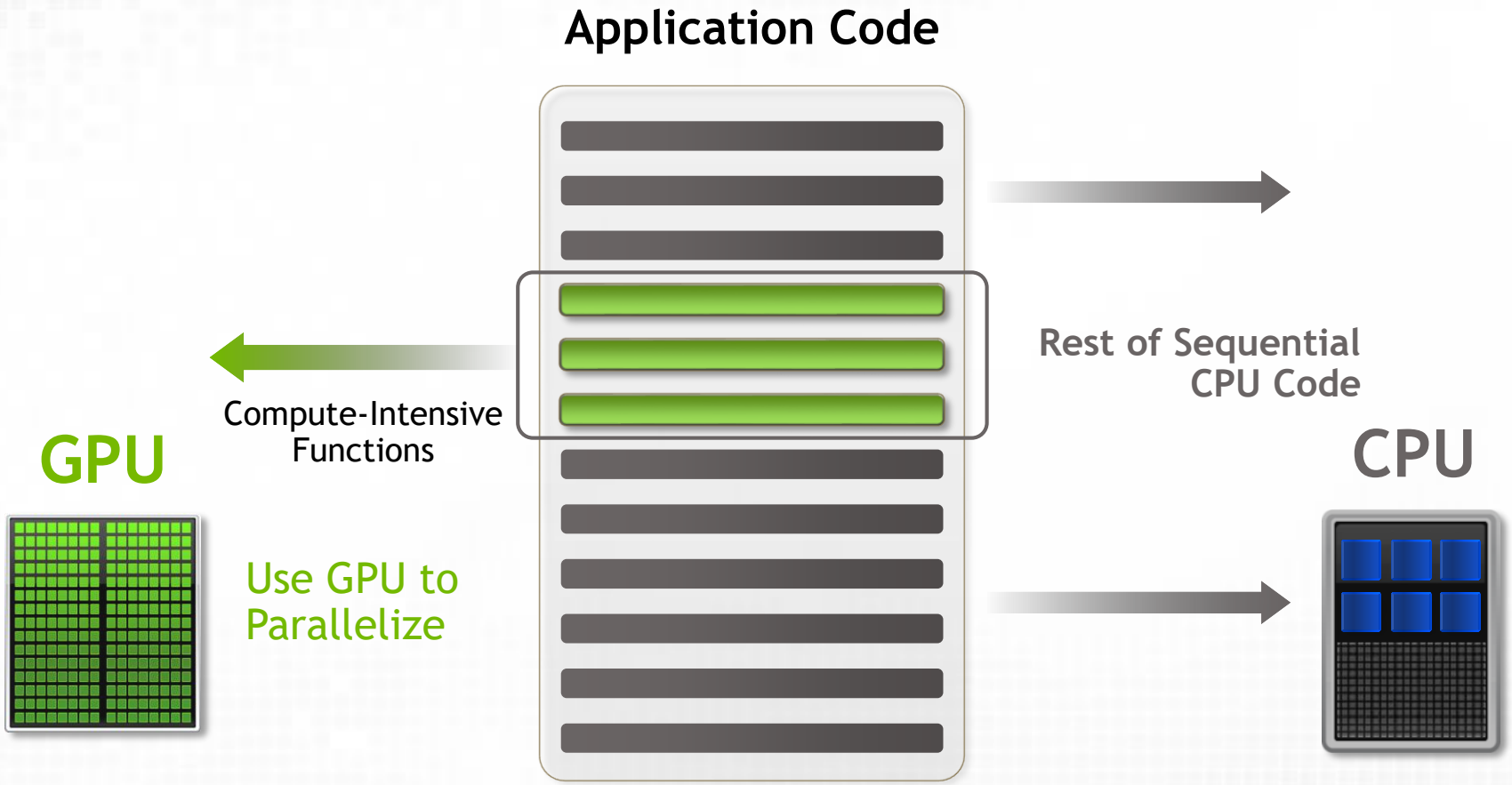
Dr Mozhgan Kabiri Chimeh

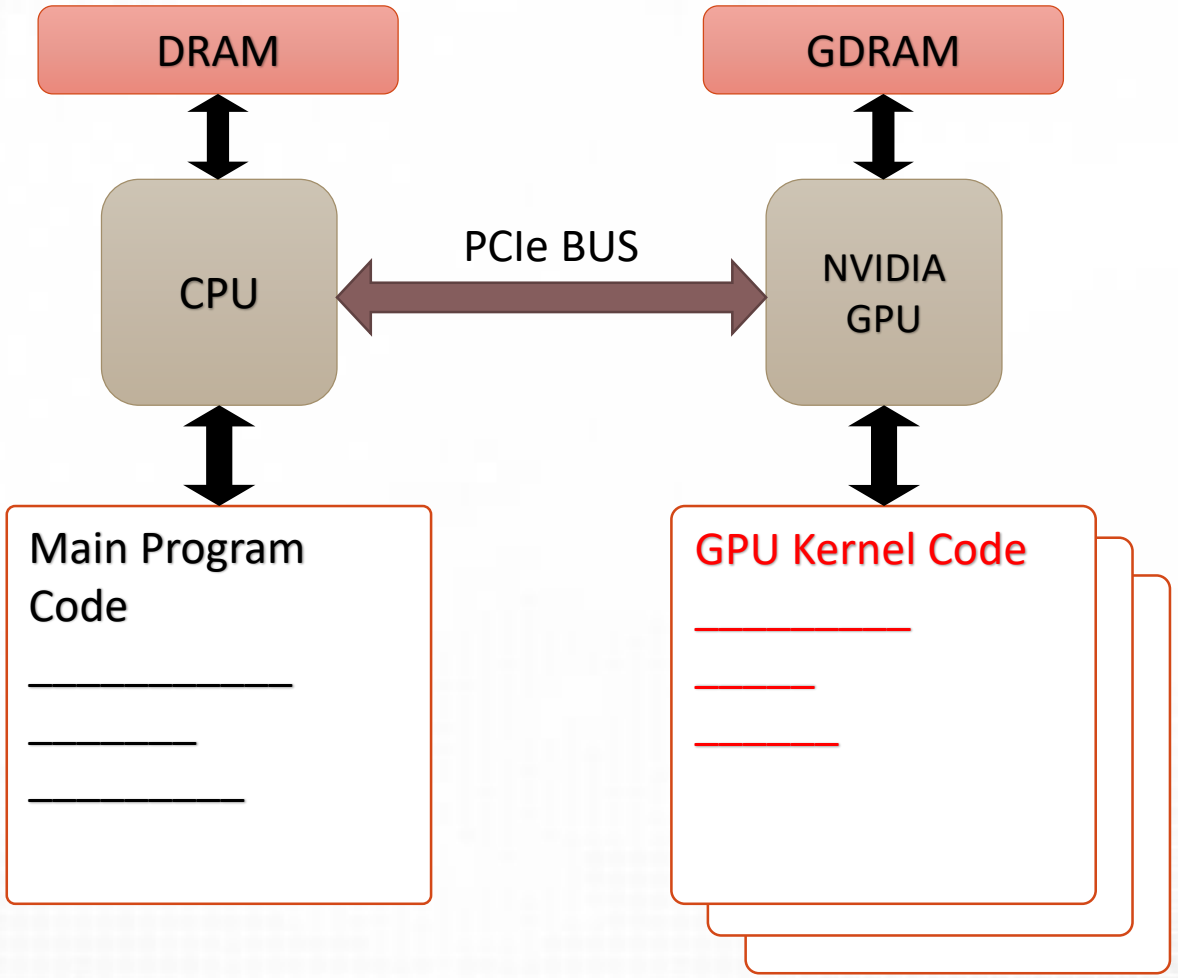
http://mkchimeh.staff.shef.ac.uk/teaching/COM4521

This lecture

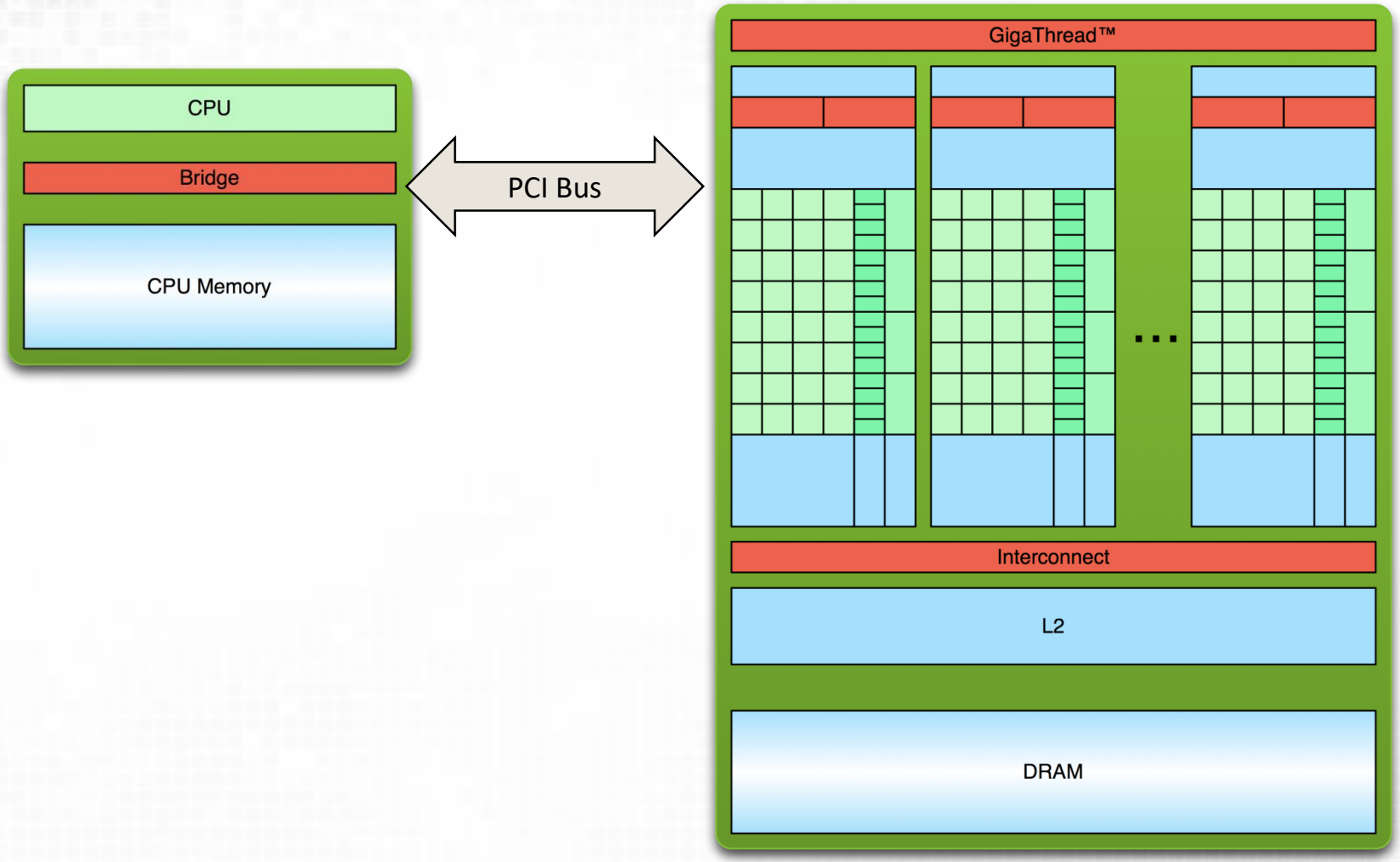
- CUDA Programming Model
- CUDA Device Code
- CUDA Host Code and Memory Management
- CUDA Compilation and execution in Visual Studio

Programming a GPU with CUDA



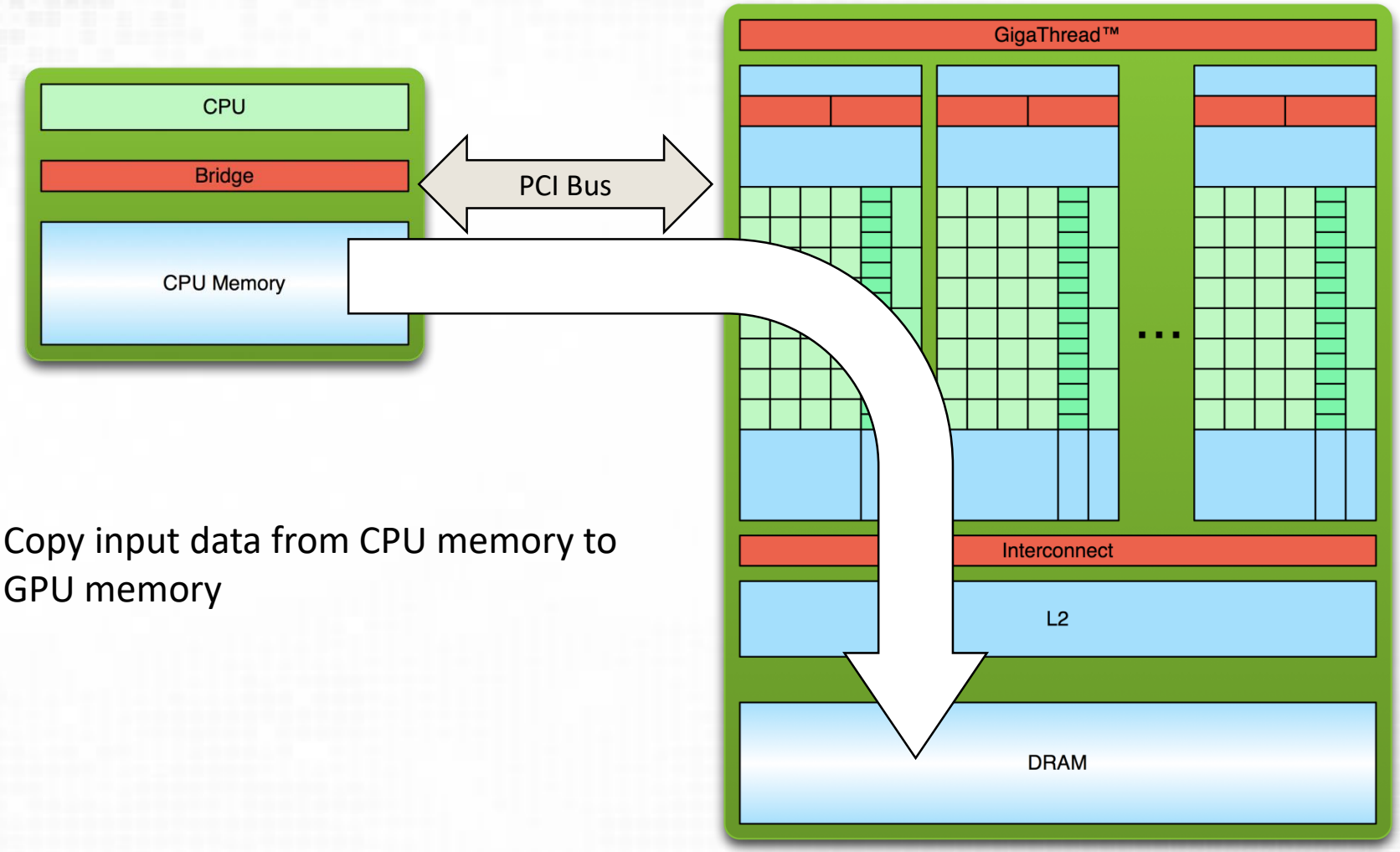


Simple processing flow



Images: Mark Harris (NVIDIA)

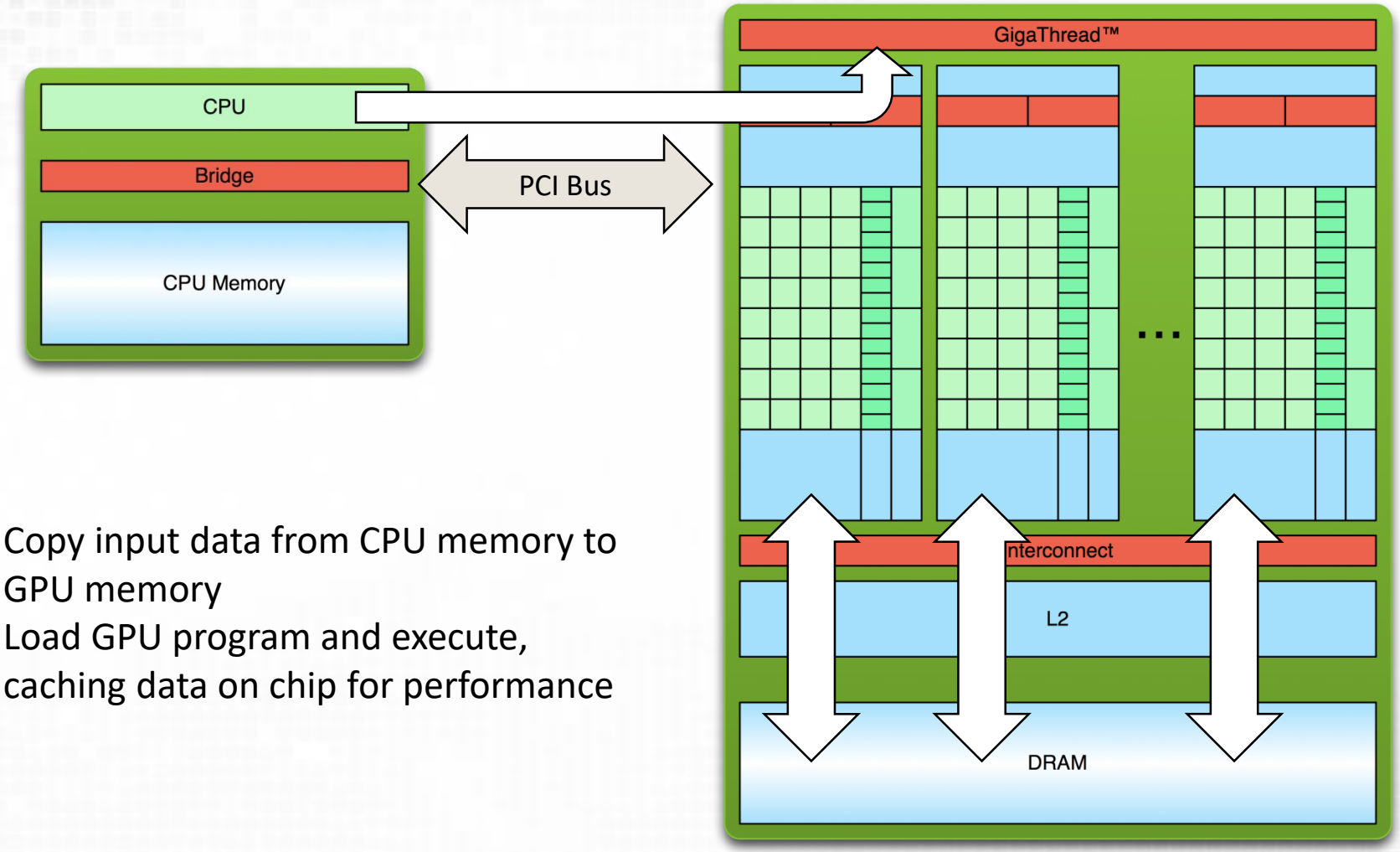
Simple processing flow



1. Copy input data from CPU memory to GPU memory

Images: Mark Harris (NVIDIA)

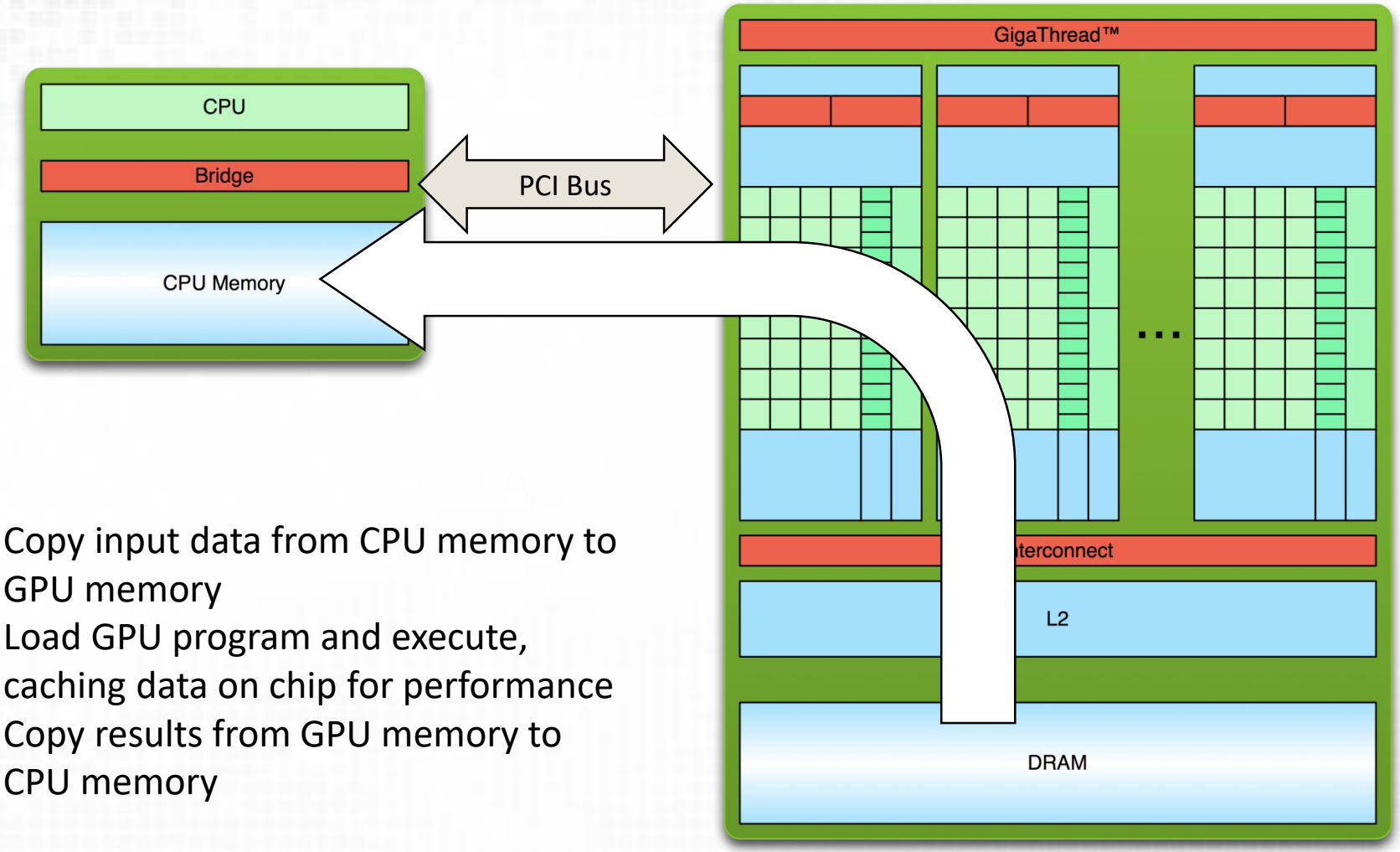
Simple processing flow



1. Copy input data from CPU memory to GPU memory
2. Load GPU program and execute, caching data on chip for performance

Images: Mark Harris (NVIDIA)

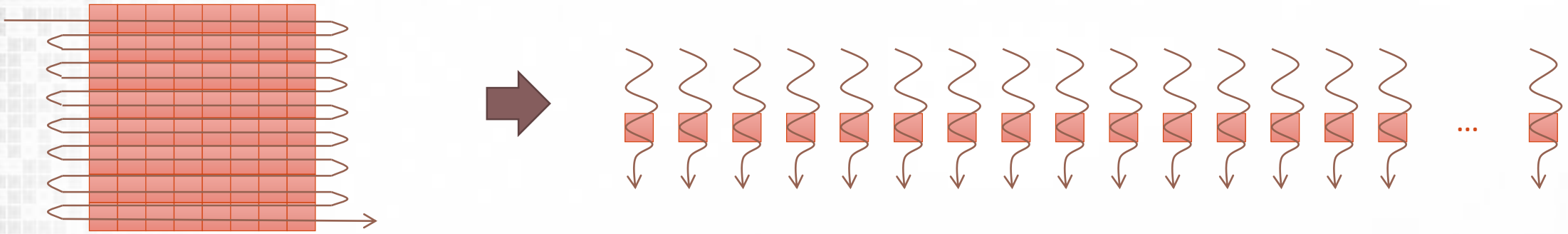
Simple processing flow



1. Copy input data from CPU memory to GPU memory
2. Load GPU program and execute, caching data on chip for performance
3. Copy results from GPU memory to CPU memory

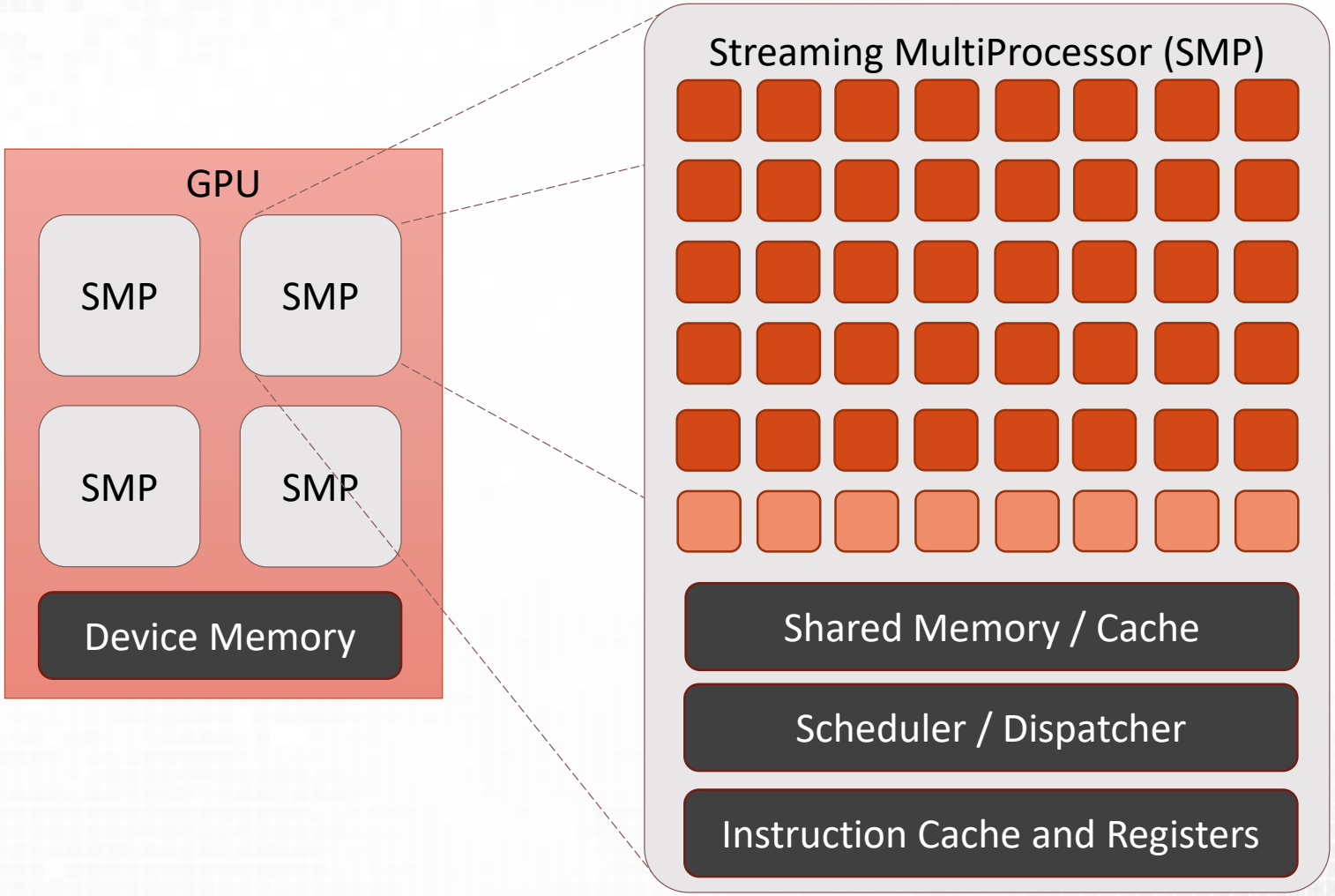
Images: Mark Harris (NVIDIA)

Stream Computing



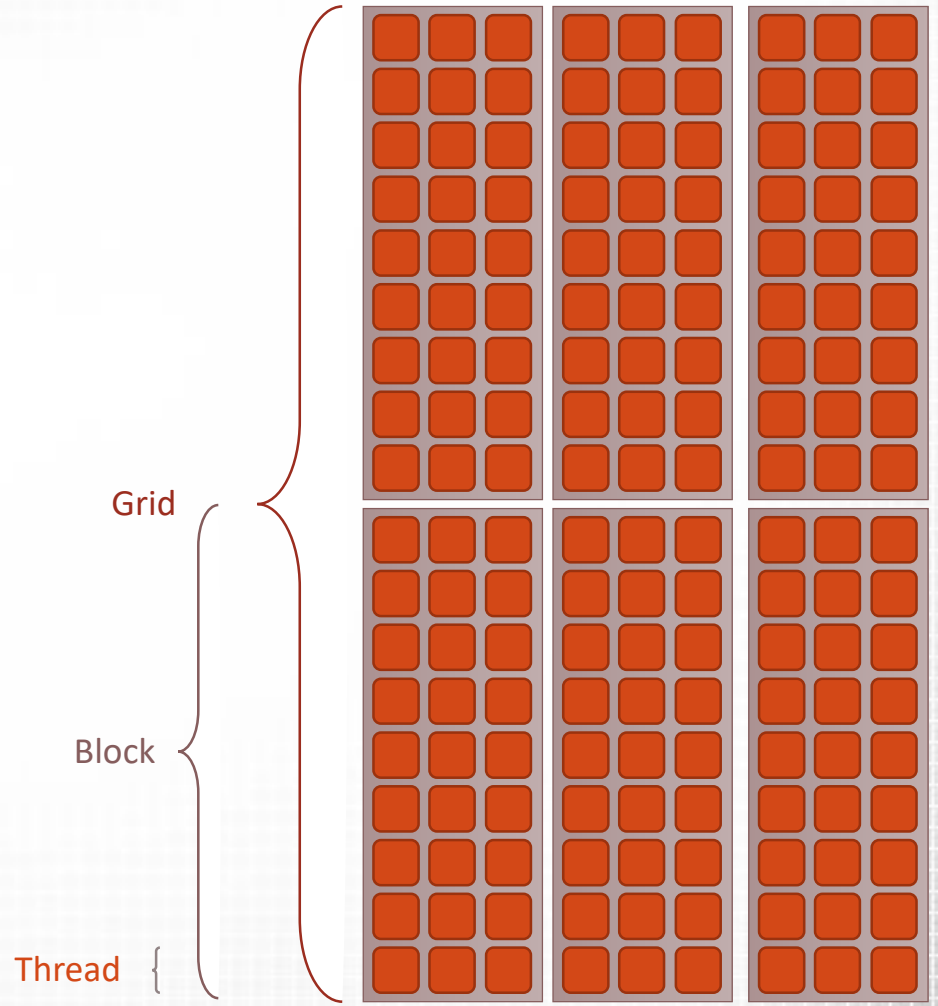
- Data set decomposed into a **stream** of elements
- A single computational function (**kernel**) operates on each element
  - A **thread** is the execution of a kernel on one data element
- Multiple Streaming Multiprocessor cores can operate on multiple elements in parallel
  - Many parallel threads
- Suitable for **Data Parallel** problems

- How does the stream computing principle map to the hardware model?



CUDA Software Model

- Hardware abstracted as a **Grid** of **Thread Blocks**
  - Blocks map to SMPs
  - Each thread maps onto a CUDA core
- Don't need to know the hardware characteristics
  - Code is portable across different GPU versions



CUDA Vector Types

- CUDA Introduces a new `dim` types. E.g. `dim2`, `dim3`, `dim4`
  - `dim3` contains a collection of three integers (X, Y, Z)

```
dim3 my_xyz (x_value, y_value, z_value);
```

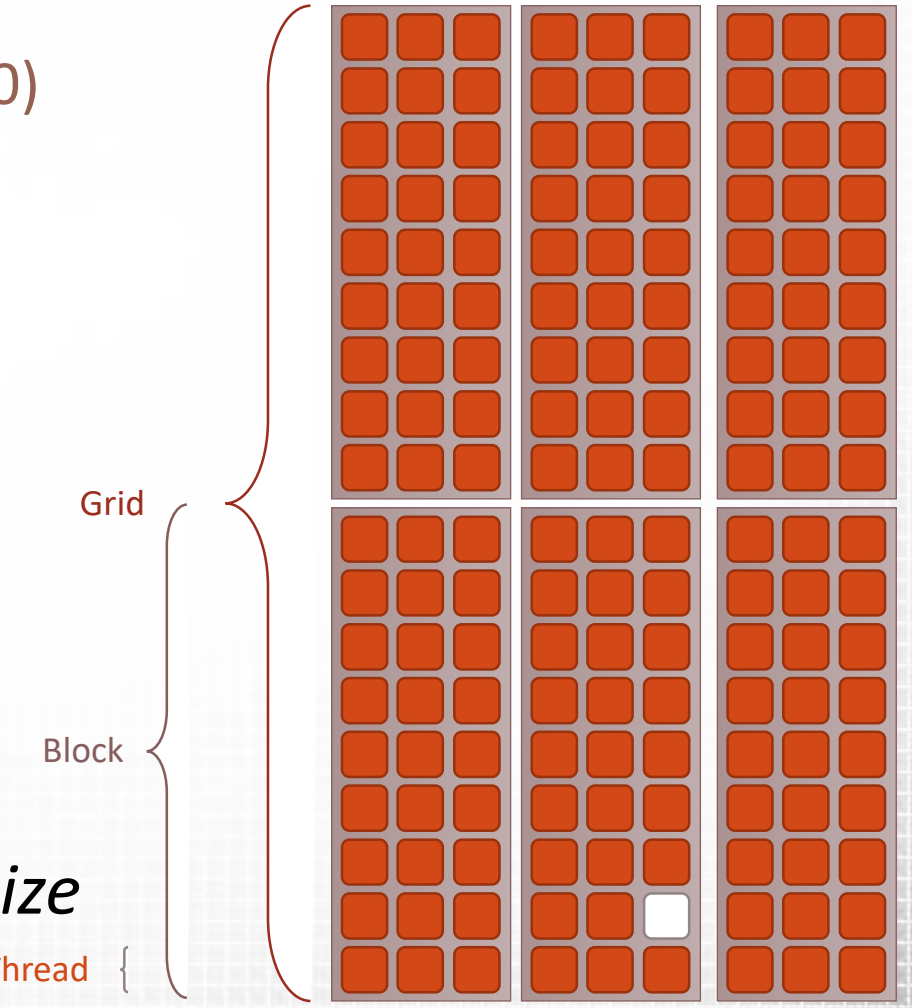
- Values are accessed as members

```
int x = my_xyz.x;
```

Special dim3 Vectors

- `threadIdx`
  - The location of a thread within a block. E.g. (2,1,0)
- `blockIdx`
  - The location of a block within a grid. E.g. (1,0,0)
- `blockDim`
  - The dimensions of the blocks. E.g. (3,9,1)
- `gridDim`
  - The dimensions of the grid. E.g. (3,2,1)

`Idx` values use zero indices, Dim values are a size



Analogy

- Students arrive at halls of residence to check in
  - Rooms allocated in order
- Unfortunately admission rates are down!
  - Only half as many students as rooms
  - Each student can be moved from room i to room $2i$ so that no-one has a neighbour

Serial Solution

- Receptionist performs the following tasks
  1. Asks each student their assigned room number
  2. Works out their new room number
  3. Informs them of their new room number

Parallel Solution

"Everybody check your room number. Multiply it by 2 and go to that room"

- ❑CUDA Programming Model
- ❑CUDA Device Code
- ❑CUDA Host Code and Memory Management
- ❑CUDA Compilation and execution in Visual Studio

A First CUDA Example

- Serial solution

```
for (i=0;i<N;i++){
  result[i] = 2*i;
}
```

- We can parallelise this by assigning each iteration to a CUDA thread!

CUDA C Example: Device

```
__global__ void myKernel(int *result)
{
   int i = threadIdx.x;
   result[i] = 2*i;
}
```

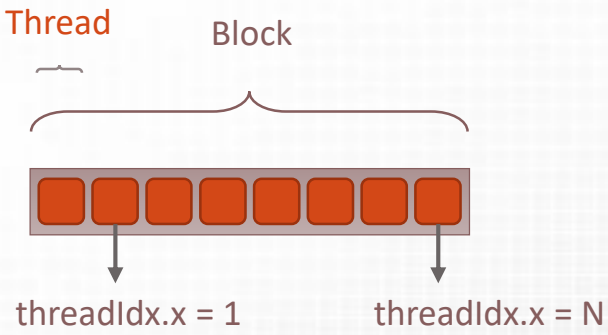
- Replace loop with a “kernel”
  - Use __global__ specifier to indicate it is GPU code
- Use threadIdx dim variable to get a unique index
  - Assuming for simplicity we have only **one block** which is **1-dimensional**
  - Equivalent to your door number at CUDA Halls of Residence

CUDA C Example: Host

- Call the kernel by using the CUDA kernel launch syntax
  - kernel<<<GRID OF BLOCKS, BLOCK OF THREADS>>>(arguments);

What should the dimensions be?

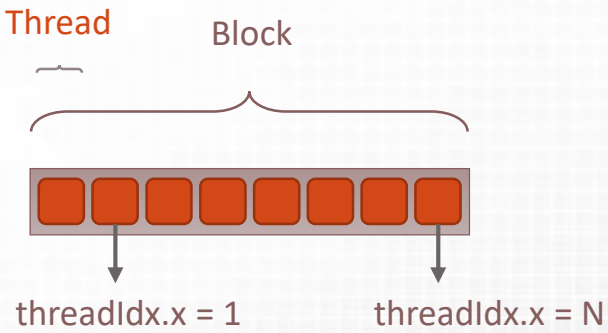
```
dim3 blocksPerGrid(?,?,?);
dim3 threadsPerBlock(?,?,?);

myKernel<<<blocksPerGrid, threadsPerBlock>>>(result);
```



CUDA C Example: Host

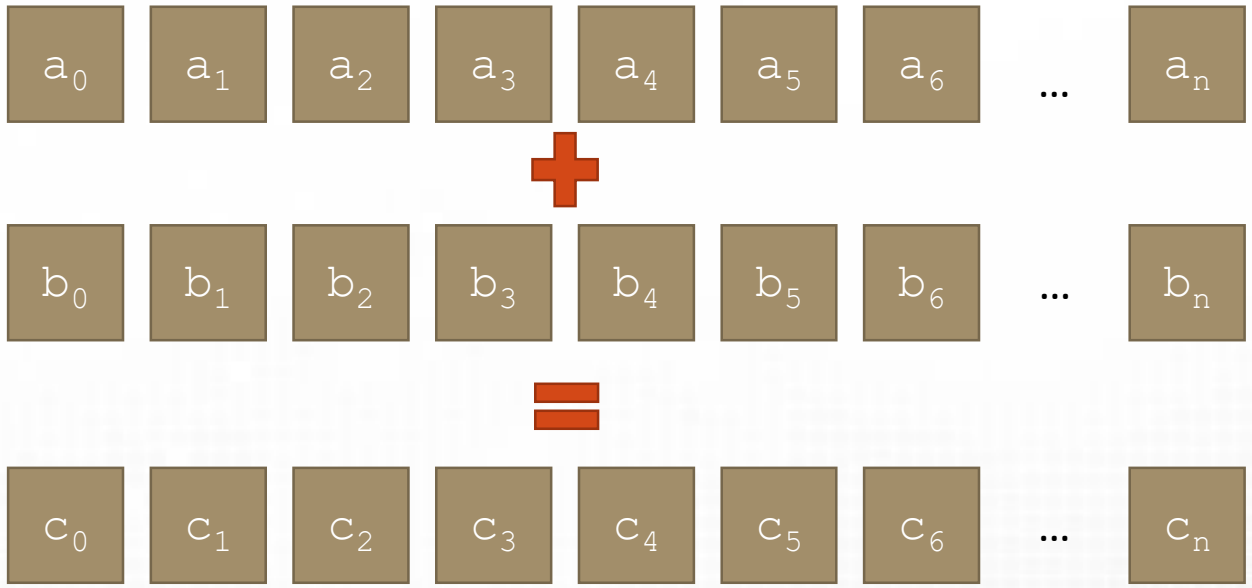
- Call the kernel by using the CUDA kernel launch syntax
  - kernel<<<GRID OF BLOCKS, BLOCK OF THREADS>>>(arguments);

```
dim3 blocksPerGrid(1,1,1);          //use only one block
dim3 threadsPerBlock(N,1,1);        //use N threads in the block

myKernel<<<blocksPerGrid, threadsPerBlock>>>(result);
```



Vector Addition Example

- Consider a more interesting example
  - Vector addition: e.g. `a + b = c`



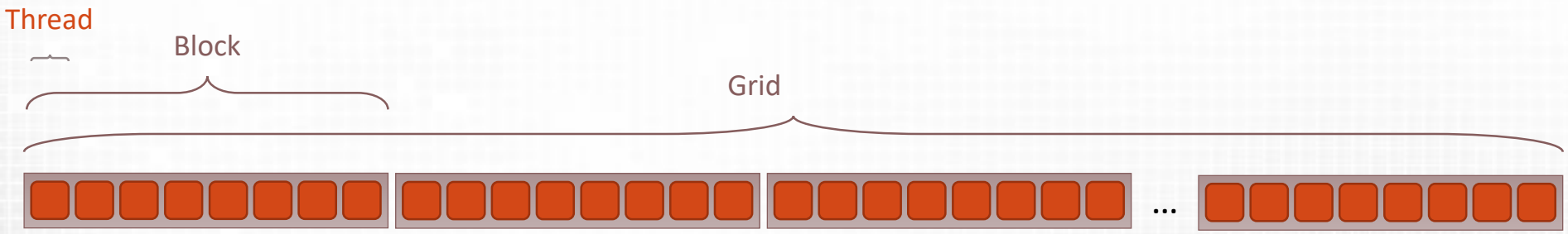
Vector Addition Example

```
//Kernel Code
__global__ void vectorAdd(float *a, float *b, float *c)
{
  int i = threadIdx.x;
  c[i] = a[i] + b[i];
}

//Host Code
...
dim3 blocksPerGrid(1,1,1);
dim3 threadsPerBlock(N,1,1); //single block of threads

vectorAdd<<<blocksPerGrid, threadsPerBlock>>>(a, b, c);
```

CUDA C Example: Host

- Only one block will give poor performance
  - A block gets allocated to a single SMP!
  - Solution: Use multiple blocks

```
dim3 blocksPerGrid(N/8,1,1);      //assumes 8 divides N exactly
dim3 threadsPerBlock(8,1,1);      //8 threads in the block

myKernel<<<blocksPerGrid, threadsPerBlock>>>(result);
```



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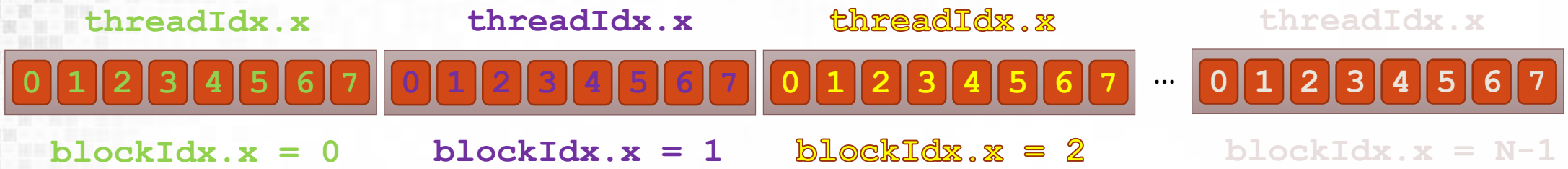
Vector Addition Example




```
//Kernel Code
__global__ void vectorAdd(float *a, float *b, float *c)
{
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  c[i] = a[i] + b[i];
}
```

- The integer `i` gives a unique thread Index used to access a unique value from the vectors `a`, `b` and `c`

A note on block sizes

- Thread block sizes can not be larger that `1024`
- Max grid size is `2147483647` for 1D
  - Grid y and z dimensions are limited to `65535`

- Block size should ideally be divisible by `32`
  - This is the warp size which threads are scheduled
  - Not less than `32` as in our trivial example!

- Varying the block size will result in different performance characteristics
  - Try incrementing by values of `32` and benchmark.

- Calling a kernel with scalar parameters assumes a `1D` grid of thread blocks.
  - E.g. `my_kernel<<<8, 128>>>(arguments);`

Device functions

- Kernels are always prefixed with `_global_`
- To call a function from a kernel the function must be a device function (i.e. it must be compiled for the GPU device)
  - A device function must be prefixed with `_device_`
- A device function is not available from the host
  - Unless it is also prefixed with `_host_`

```
int increment(int a){ return a + 1; }                          Host only

__device__ int increment(int a){ return a + 1; }               Device only

__device__ __host__ int increment(int a){ return a + 1; }      Host and device
```

Global functions are always `void` return type.

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- ❑CUDA Programming Model
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Memory Management

- GPU has separate dedicated memory from the host CPU
- Data accessed in kernels must be on GPU memory
  - Data must be explicitly copied and transferred
- **cudaMalloc()** is used to allocate memory on the GPU
- **cudaFree()** releases memory

```
float *d_a;
cudaMalloc(&d_a, N*sizeof(float));
...
cudaFree(d_a);
```

Memory Copying

- Once memory has been allocated we need to copy data to it and from it.
- **`cudaMemcpy()`** transfers memory from the host to device to host and vice versa

```
cudaMemcpy(array_device, array_host,
  N*sizeof(float), cudaMemcpyHostToDevice);
```

```
cudaMemcpy(array_host, array_device,
  N*sizeof(float), cudaMemcpyDeviceToHost);
```

- First argument is always the **destination** of transfer
- Transfers are relatively slow and should be minimised where possible

```
#define N 2048
#define THREADS_PER_BLOCK 128

__global__ void vectorAdd(float *a, float *b, float *c) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  c[i] = a[i] + b[i];
}

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

    cudaMalloc((void **)&d_a, size);
    cudaMalloc((void **)&d_b, size);
    cudaMalloc((void **)&d_c, size);

    a = (float *)malloc(size); random_floats(a, N);
    b = (float *)malloc(size); random_floats(b, N);
    c = (float *)malloc(size);

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

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

    cudaMemcpy(c, d_c, size, cudaMemcpyDeviceToHost);

    free(a); free(b); free(c);
    cudaFree(d_a); cudaFree(d_b); cudaFree(d_c);
    return 0;
}
```

Define macros

Define kernel

Define pointer variables

Allocate GPU memory

Allocate host memory and initialise contents

Copy input data to the device

Launch the kernel

Copy data back to host

Clean up

Statically allocated device memory

- How do we declare a large array on the host without using malloc?

Statically allocated device memory

- How do we declare a large array on the host without using malloc?
  - Statically allocate using compile time size

```
int array[N];
```

- We can do the same on the device. i.e.
  - Just like when applied to a function
  - Only available on the device
  - Must use `cudaMemCopyToSymbol()`
  - Must be a global variable

```
__device__ int array[N];
```

```
#define N 2048
#define THREADS_PER_BLOCK 128

__device__ float d_a[N];
__device__ float d_b[N];
__device__ float d_c[N];

__global__ void vectorAdd() {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  d_c[i] = d_a[i] + d_b[i];
}

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

    a = (float *)malloc(size); random_floats(a, N);
    b = (float *)malloc(size); random_floats(b, N);
    c = (float *)malloc(size);

    cudaMemcpyToSymbol(d_a, a, size);
    cudaMemcpyToSymbol(d_b, b, size);

    vectorAdd <<<N / THREADS_PER_BLOCK, THREADS_PER_BLOCK >>>();

    cudaMemcpyFromSymbol(c, d_c, size);

    free(a); free(b); free(c);
    return 0;
}
```

Define macros

Statically allocate GPU memory

Define kernel

Define pointer variables

Allocate host memory and initialise contents

Copy input data to the device

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Clean up

Device Synchronisation

- Kernel calls are non-blocking
  - Host continues after kernel launch
  - Overlaps CPU and GPU execution
- **`cudaDeviceSynchronise()`** call be called from the host to block until GPU kernels have completed

```
vectorAdd<<<blocksPerGrid, threadsPerBlock>>>(a, b, c);
//do work on host (that doesn't depend on c)
cudaDeviceSynchronise(); //wait for kernel to finish
```

- Standard **`cudaMemcpy`** calls are blocking
  - Non-blocking variants exist

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Compiling a CUDA program

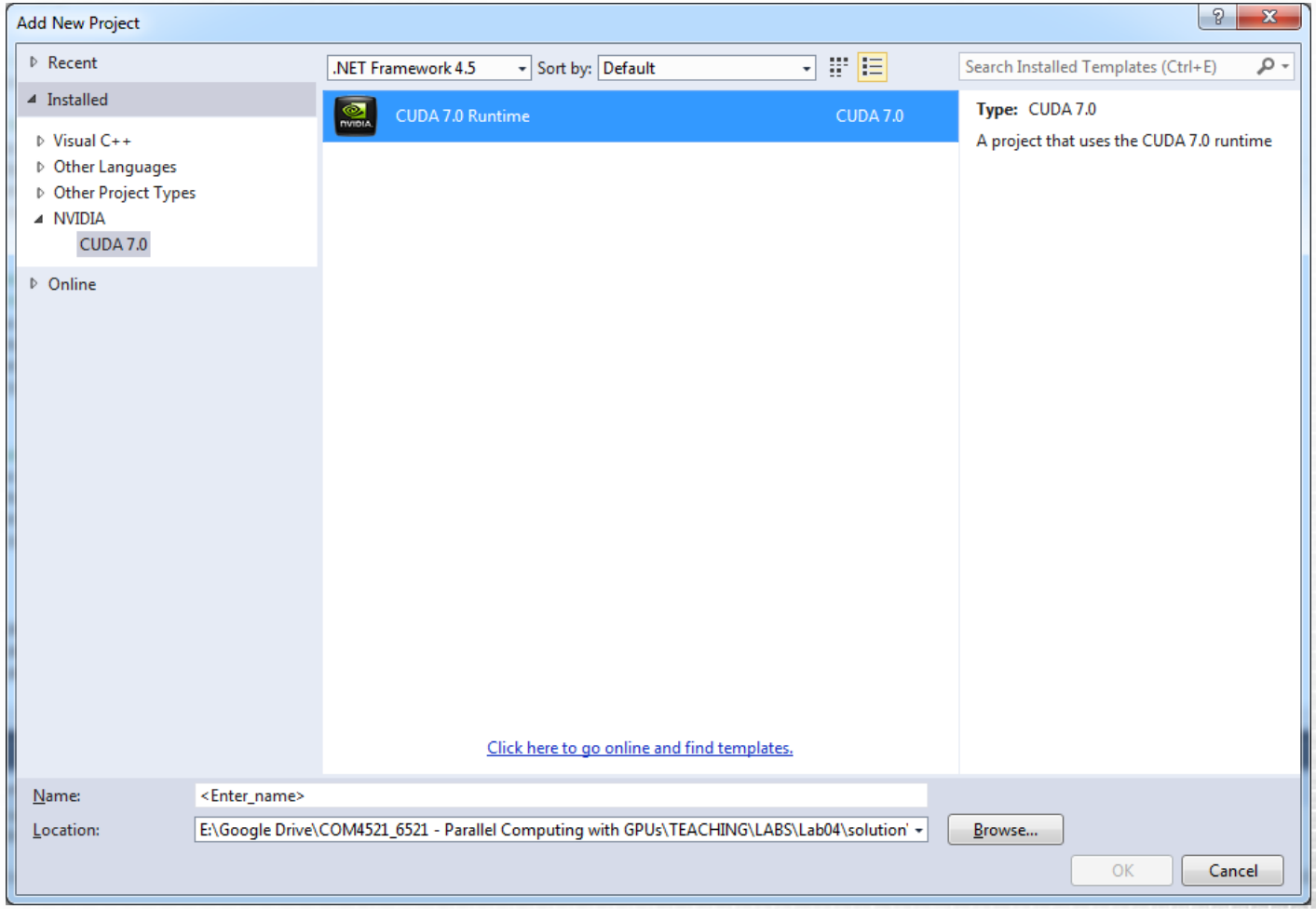
- CUDA C Code is compiled using **nvcc** e.g.
- Will compile host AND device code to produce an executable

```
nvcc -o example example.cu
```

- We will be using Visual Studio to build our CUDA code so we will not need to compile at the command line (unless you are running on ShARC)

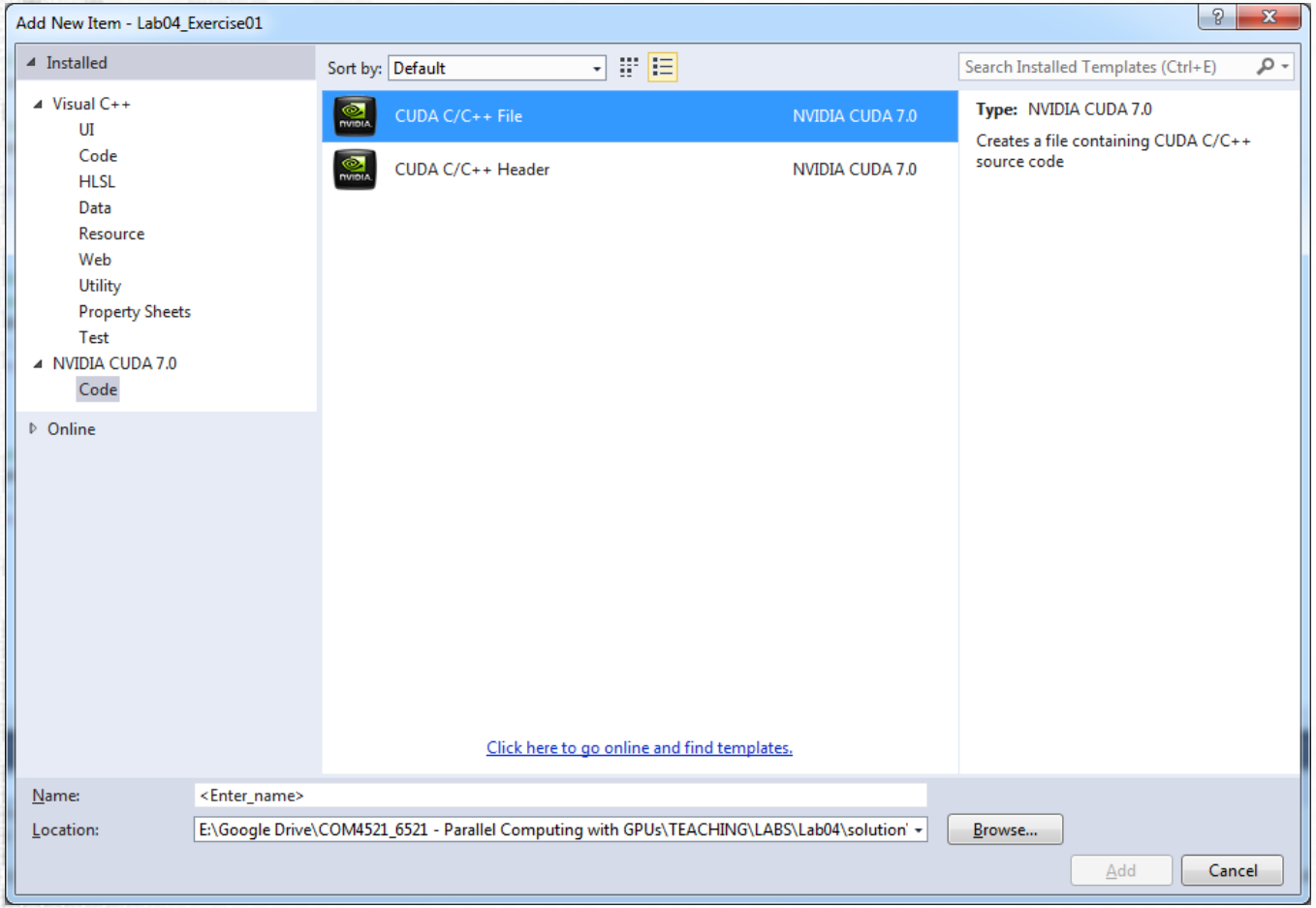
Creating a CUDA Project

- Create New CUDA Project
  - Select *NVIDIA -> CUDA 10*
  - This will create a project with a default kernels.cu file containing a basic vector addition example



Preferred Method!

Adding a CUDA source file



- Alternatively add a CUDA source file to an existing application
- If you do this you must modify the project properties to include CUDA build customisations
  - http://developer.download.nvidia.com/compute/cuda/6_5/rel/docs/CUDA_Getting_Started_Windows.pdf (section 3.4)

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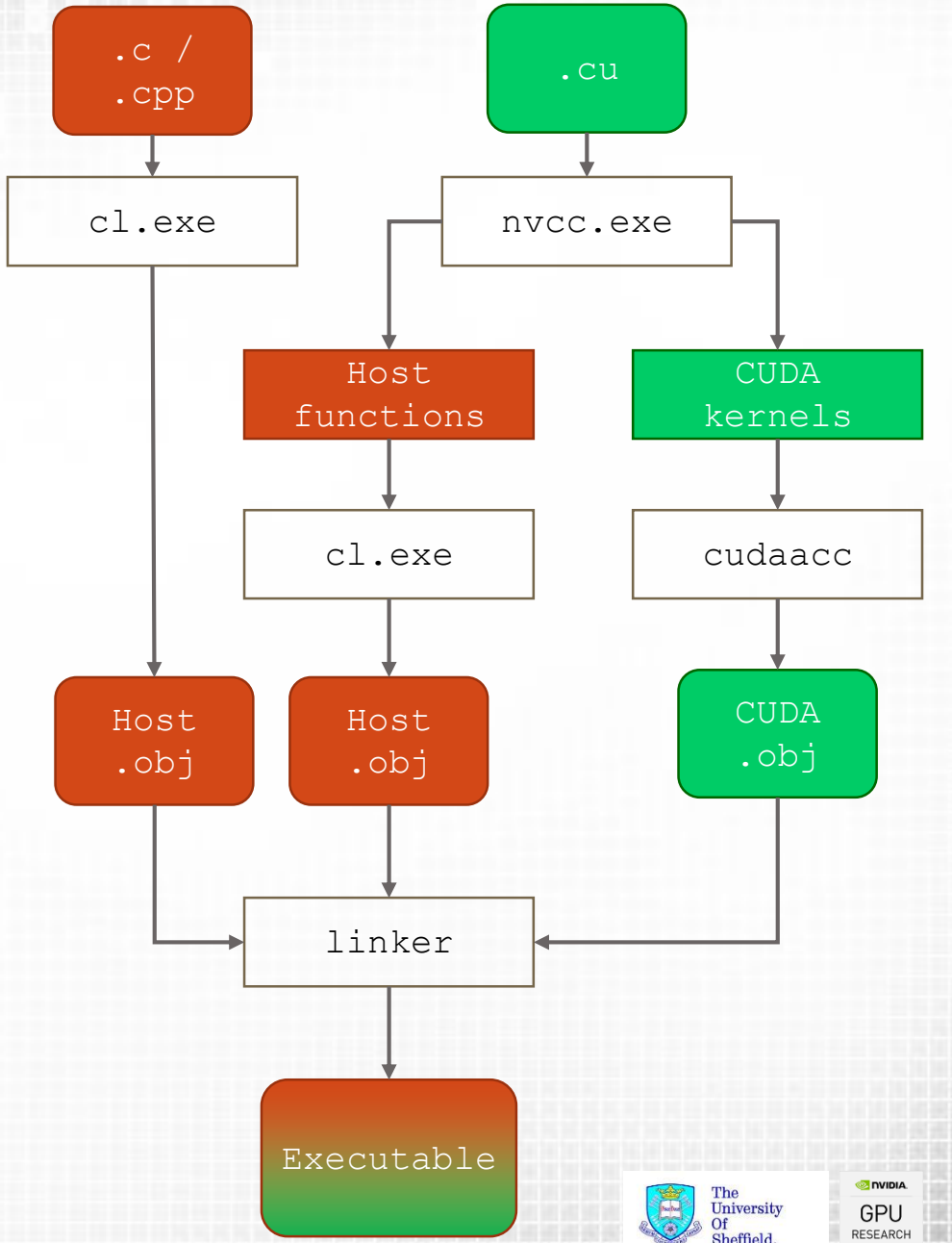
Compilation

- CUDA source file (`*.cu`) are compiled by `nvcc`
- An existing cuda.rules file creates property page for CUDA source files
  - Configures `nvcc` in the same way as configuring the C compiler
  - Options such as optimisation and include directories can be inherited from project defaults
- C and C++ files are compiled with `cl` (MSVCC compiler)



Device Versions

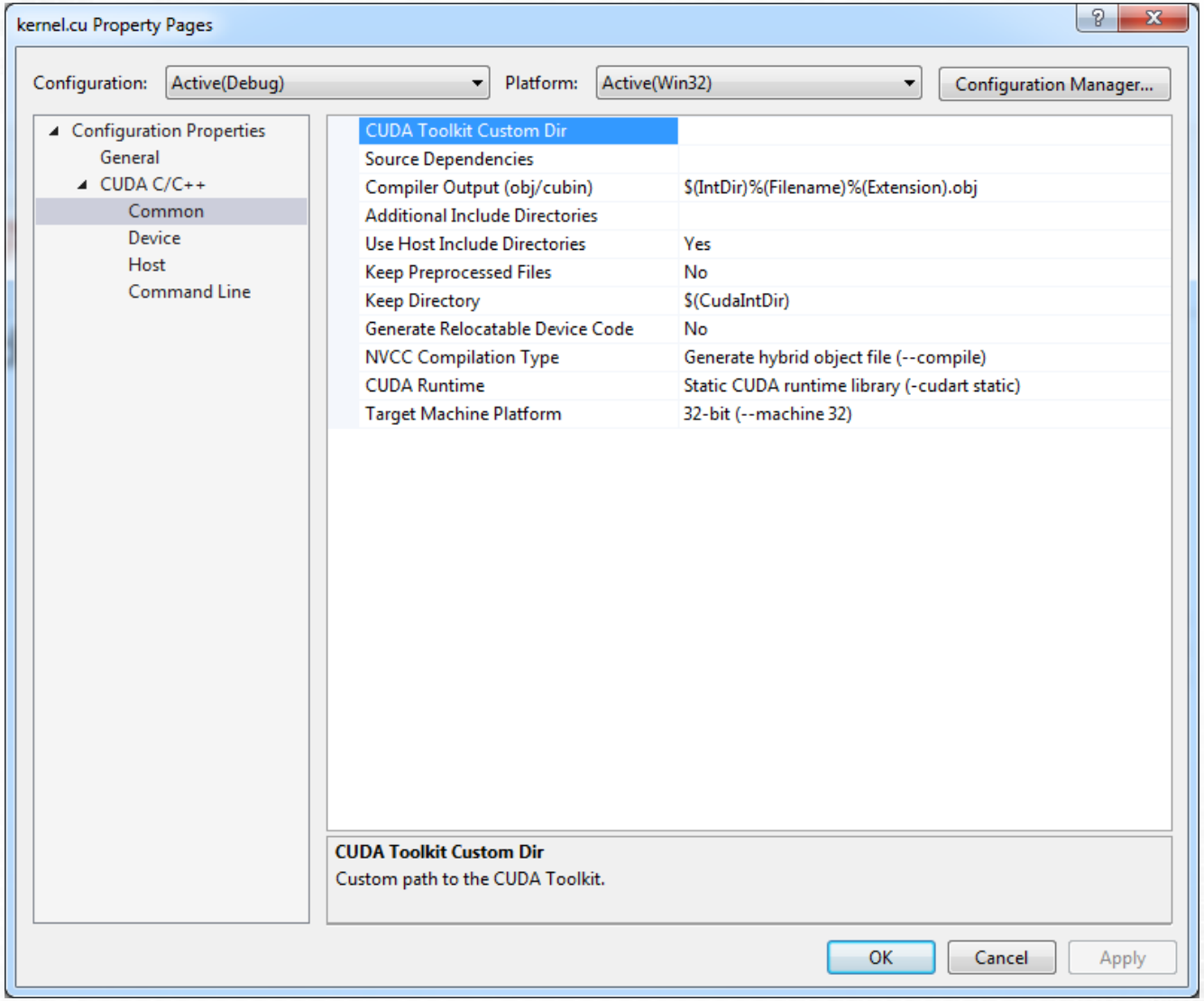
- Different generations of NVIDIA hardware have different compatibility
  - In the last lecture we saw product families and chip variants
  - These are classified by **CUDA compute versions**
- Compilation normally builds for CUDA compute version 2
  - See Project Properties, *CUDA C/C++Device->Code Generation*
  - Default value is "`compute_20,sm_20`" - deprecated from CUDA 9
  - Any hardware with greater than the compiled compute version can execute the code (backwards compatibility)
- You can build for multiple versions using separator
  - E.g. "`compute_30,sm_30;compute_35,sm_35`"
    - All Diamond and Lewin Labs GPUs
  - This will increase build time and execution file size
  - Runtime will select the best version for your hardware

https://en.wikipedia.org/wiki/CUDA#Supported_GPUs

Device Versions of Available GPUs

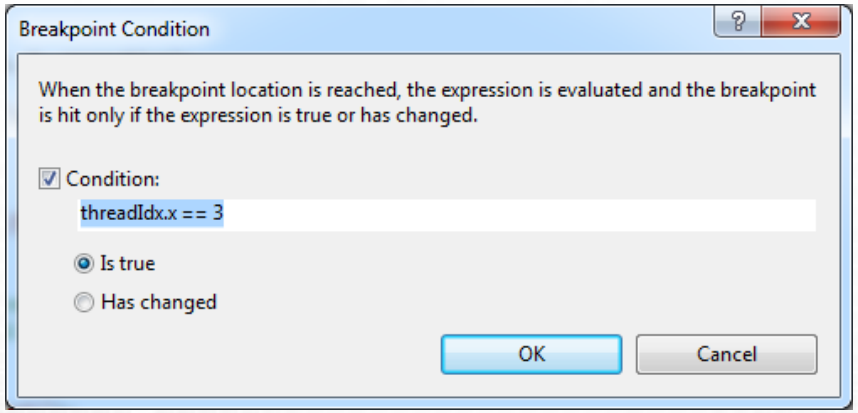
- Diamond High Spec Lab (lab machines)
  - Quadro P4000
    - `compute_61,sm_61;`
- ShARC
  - Tesla K80
    - `compute_50,sm_50;`
  - P100
    - `compute_60,sm_60;`

CUDA Properties



Debugging

- NSIGHT is a GPU debugger for debugging GPU kernel code
  - It does not debug breakpoints in host code
- To launch select insert a breakpoint and select NSIGHT-> Start CUDA Debugging
  - You must be in the debug build configuration.
  - When stepping all warps except the debugger focus will be paused
- Use conditional breakpoints to focus on specific threads
  - Right click on break point and select Condition



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Error Checking

- `cudaError_t`: enumerator for runtime errors
  - Can be converted to an error string (`const char *`) using `cudaGetErrorString(cudaError_t)`
- Many host functions (e.g. `cudaMalloc`, `cudaMemcpy`) return a `cudaError_t` which can be used to handle errors gracefully

```
cudaError_t cudaStatus;

cudaStatus = cudaMemcpy(dev_a, a, size * sizeof(int), cudaMemcpyHostToDevice);
if (cudaStatus != cudaSuccess) {
    //handle error
}
```

- Kernels do not return an error but if one is raised it can be queried using the `cudaGetLastError()` function

```
addKernel<<<1, size>>>(dev_c, dev_a, dev_b);
cudaStatus = cudaGetLastError();
```

Summary

- CUDA is a C like programming language
- Programming a GPU requires moving data to and from the device
- Parallel regions are executed using Kernel
- Kernels require high levels of parallelism
  - Exposed as many threads grouped into blocks
  - Thread blocks are mapped to SMs
- Host and device code are compiled separately and linked into a single executable

Acknowledgements and Further Reading

- Some of the content in this lecture material has been provided by;

1. GPUComputing@Sheffield Introduction to CUDA Teaching Material
   - Originally from content provided by Alan Gray at EPCC
2. NVIDIA Educational Material
   - Specifically Mark Harris's (Introduction to CUDA C)

- **Further Reading**
  - Essential Reading: CUDA C Programming Guide
    - http://docs.nvidia.com/cuda/cuda-c-programming-guide/