

# An Introduction to HPC and Scientific Computing

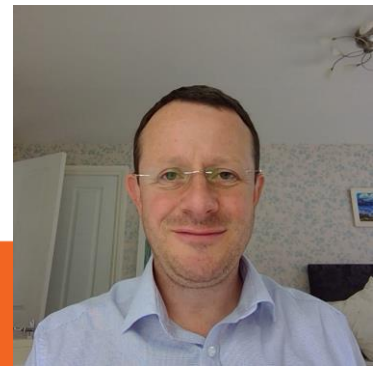
Lecture seven: An introduction to GPUs and how to use them.

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**Oxford e-Research Centre**

[www.oerc.ox.ac.uk](http://www.oerc.ox.ac.uk)



# Learning outcomes

In this lecture you will learn about:

- Different hardware generations of GPUs.
- How GPUs execute code.
- A more detailed look at the differences between GPUs and CPUs
- How GPUs hide memory latencies.
- The GPU software environment and useful tools.
- Finally we will cover the basics of how to use GPU libraries in your codes.

# Hardware overview



# CUDA capable hardware

NVIDIA has produced seven generations of GPU architectures that are capable of executing CUDA code.

Each generation has a different *compute capability*. Typically as the compute capability increases the functionality of the card increases.

Over the six generations memory capacity has increased by eight times, bandwidth to main memory by nine times, but compute throughput by 14 times.

Hardware generation	Card	# CUDA cores	Main memory (GB)	Bandwidth (GB/s)	Peak compute performance (Tflops)	CUDA compute capability
Tesla	C1060	240	4	103	0.93	1.3
Fermi	M2090	512	6	178	1.3	2
Kepler	K40	2880	12	288	4.2	3.5
Maxwell	M40	3072	12	288	5.8	5.2
Pascal	P100	3584	16	732	8.1	6
Volta	V100	5120	32	900	14	7

<https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html#compute-capabilities>

# CUDA capable hardware

Each generation has slightly different technical specifications, for example the maximum number of thread blocks per SM (multiprocessor). These specifications are often what limits the eventual performance of your GPU code.

Technical Specifications	Compute Capability										
	3	3.2	3.5	3.7	5	5.2	5.3	6	6.1	6.2	7
Maximum dimensionality of grid of thread blocks	3										
Maximum x-dimension of a grid of thread blocks	2 <sup>31</sup> -1										
Maximum y- or z-dimension of a grid of thread blocks	65535										
Maximum dimensionality of thread block	3										
Maximum x- or y-dimension of a block	1024										
Maximum z-dimension of a block	64										
Maximum number of threads per block	1024										
Warp size	32										
Maximum number of resident blocks per multiprocessor	16				32						
Maximum number of resident warps per multiprocessor	64										
Maximum number of resident threads per multiprocessor	2048										
Number of 32-bit registers per multiprocessor	64 K			128 K	64 K						
Maximum number of 32-bit registers per thread block	64 K	32 K	64 K				32 K	64 K		32 K	64 K
Maximum number of 32-bit registers per thread	63	255									
Maximum amount of shared memory per multiprocessor	48 KB			112 KB	64 KB	96 KB	64 KB		96 KB	64 KB	96 KB
Maximum amount of shared memory per thread block	48 KB										96 KB
Number of shared memory banks	32										

# NVIDIA Volta V100

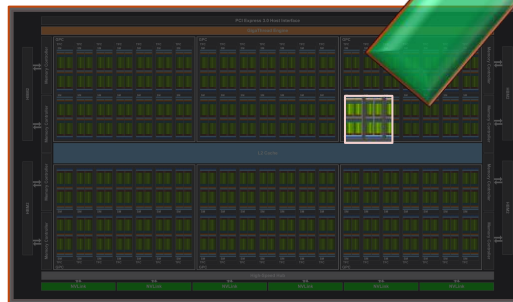


# NVIDIA Volta V100 – Streaming Multiprocessor (SM)

A V100 has 80 SMs (see right).

The GV100 SM incorporates 64 FP32 cores and 32 FP64 cores per SM.

The SM is partitioned into four processing blocks, each with 16 FP32 Cores, 8 FP64 Cores, 16 INT32 Cores, a new L0 instruction cache, one warp scheduler, one dispatch unit, and a 64 KB Register File.





# NVIDIA Volta V100 - SM

Lets look at this in more detail

We've talked about a Streaming Multiprocessor, this is a collection of hardware that our thread block executes on.

A FP32 core is the execution unit that performs single precision floating point arithmetic (floats).

A FP64 core performs double precision arithmetic (doubles).





# NVIDIA Volta V100 - SM

Lets look at this in more detail

A INT32 Core performs integer arithmetic

The warp scheduler selects which warp (group of 32 threads) to send to which execution units.

64 KB Register File – lots of transistors used for vary fast memory.

128KB of configurable L1 (data) cache or shared memory

Shared memory is a used manged cache.

LD/ST units load and store data from cores

SFU – special function units compute things like transcendentals.



# Code execution model

## Software

## Hardware

A thread executes on a core.

Thread



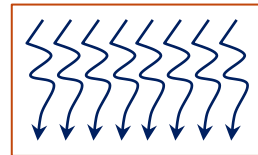
Core

A group of threads (thread block) is executed on a SM.

Thread blocks don't migrate between SMs.

Several concurrent thread blocks can reside on a SM.

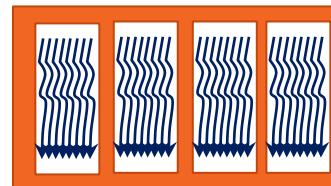
Thread Block



SM

A group of thread blocks form a grid and a grid runs on the device.

Grid



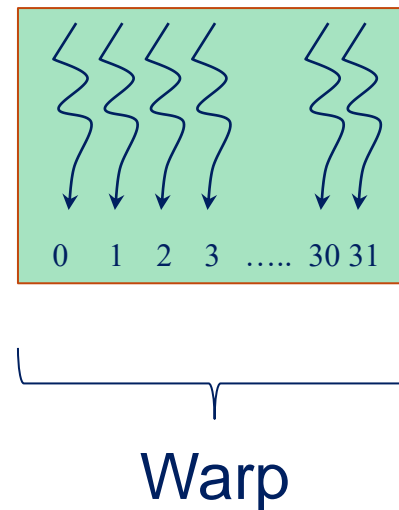
Device

*In CUDA this is a kernel launch.*

# Warps

Code executes on a GPU in groups of threads, the threads are naturally grouped into lots of 32, this is called a warp.

The reason that a warp has 32 elements is that the SIMD (recall lecture one) units on a GPU have 32 “lanes”.



# Warps

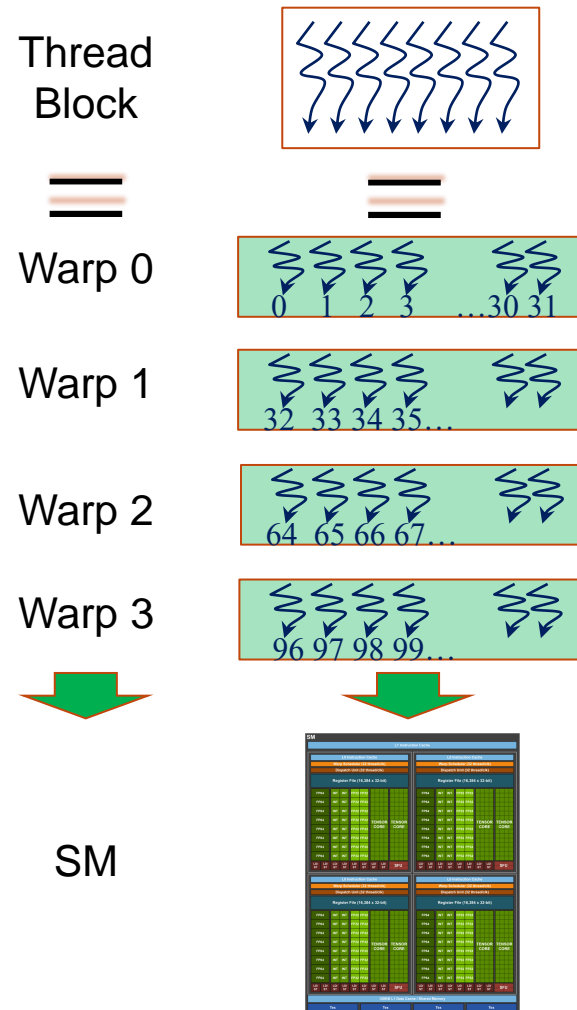
Thread blocks are formed from warps.

The warp is executed in parallel on the SM.

By this we mean that everything that happens within a warp is lock-step.

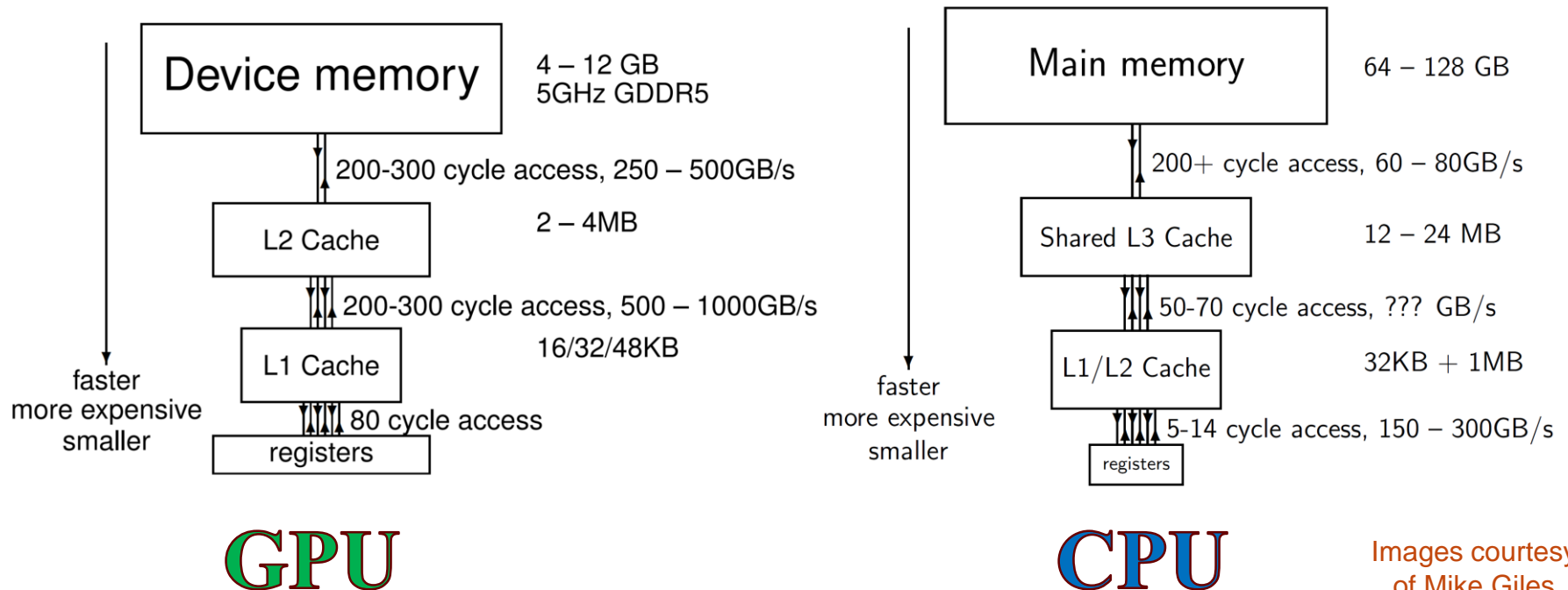
So the same operation (instruction) in thread 2, 3, 8 occurs in thread 7, 1, 4, 11... (from 0 to 31) at the same time.

So we have a Single Instruction Multiple Thread (SIMT) architecture.



# Memory architecture

In lecture one we looked at the memory architecture of CPUs. Let's compare this to that of GPUs. We see that although GPUs have greater bandwidth, they have less cache and (importantly) greater latencies (the time taken to get data from memory to the processing cores).



Images courtesy  
of Mike Giles

# Hiding memory latencies - SIMT

CPUs are optimised for low latency access to cached data sets.

Lots of transistors spent on control logic for out-of-order (OoO) and speculative execution.

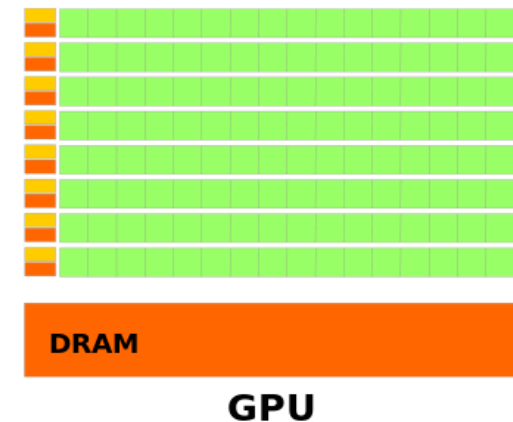
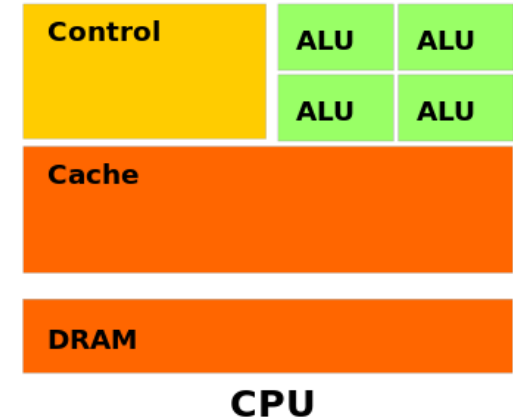
CPUs support 10's of threads.

GPUs are optimised for data parallel high throughput computation.

By having many thousands of memory requests *in flight* at any one time the larger latencies can be hidden.

Lots of transistors dedicated to computation.

GPUs support 1000's of threads.



By NVIDIA (NVIDIA CUDA Programming Guide version 3.0) [CC BY 3.0 (<https://creativecommons.org/licenses/by/3.0>)], via Wikimedia Commons

# Hiding memory latencies - SIMT

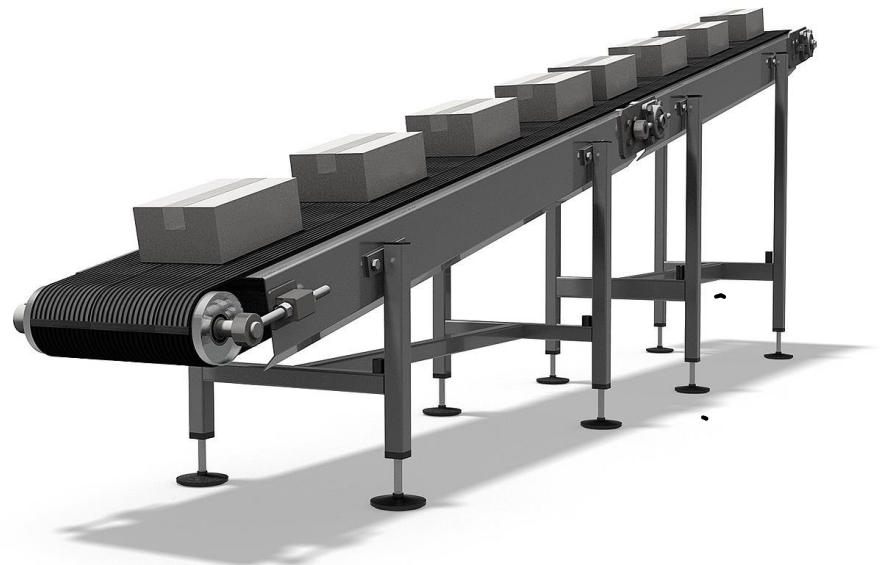
Lets think about our GPU memory pipe as a conveyor belt.

Every two seconds a container becomes available in which we can put a single piece of data.

***Bandwidth is one container per two seconds =  
0.5 containers per second***

Our conveyor belt has 8 containers on it at any one time.

***Latency is 8 containers / 0.5  
containers per second =  
16 seconds***



<http://on-demand.gputechconf.com/gtc/2018/presentation/s81006-volta-architecture-and-performance-optimization.pdf>



# Hiding memory latencies - SIMT

A CPU has only 10's of threads to make memory requests to hide it's memory latencies.

However a GPU has thousands of threads which can all make memory requests and so can hide larger latencies.

*A GPU hides the memory latencies of one warp with the computation of another warp*



# Hiding memory latencies - SIMT

A warp is executed on an SM, up to the point it stalls on a memory request.

The memory request is made and the warp removed.

The warp scheduler then looks to see what data has arrived through the memory pipe and then schedules the warp associated with that data for execution.

Eventually the data arrives for our stalled warp and then this is scheduled for execution.



# Memory coalescing

Global memory access happens in transactions of 32 or 128 bytes (cache line).

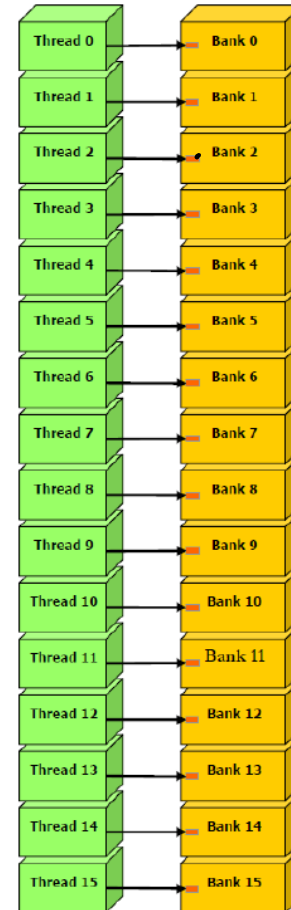
So to achieve peak memory bandwidth we need to use all of the data stored in the cache line.

## *Coalesced memory access*

A warp of threads access adjacent data (see right) in a cache line. In the best case this results in one memory transaction (best bandwidth).

## *Uncoalesced memory access*

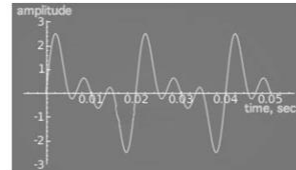
A warp of threads access scattered data all in different cache lines. This would result in 32 different memory transactions (giving poor bandwidth).



# Software overview

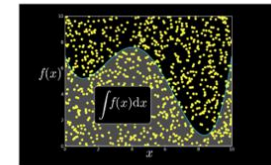
NVIDIA provides a rich ecosystem of software tools that allow you to easily utilise GPUs in your project.

During this course we will focus on the CUDA programming language, we will also look at some of the NVIDIA libraries that can be used to make programming GPUs easier.



## cuFFT

GPU-accelerated library for Fast Fourier Transforms



## cuRAND

GPU-accelerated random number generation (RNG)



## CUDA Toolkit

Provides a comprehensive environment for C/C++ developers building GPU-accelerated applications.



## cuBLAS

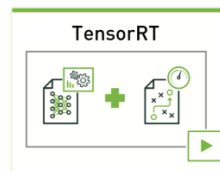
GPU-accelerated standard BLAS library

# Libraries

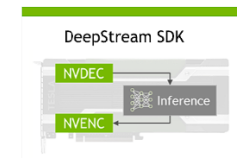
## Deep Learning Libraries



GPU-accelerated library of primitives for deep neural networks

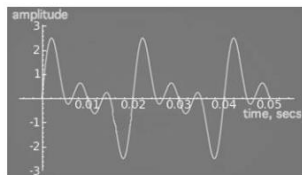


GPU-accelerated neural network inference library for building deep learning applications



Advanced GPU-accelerated video inference library

## Signal, Image and Video Libraries



### cuFFT

GPU-accelerated library for Fast Fourier Transforms



### NVIDIA Performance Primitives

GPU-accelerated library for image and signal processing



### NVIDIA Codec SDK

High-performance APIs and tools for hardware accelerated video encode and decode

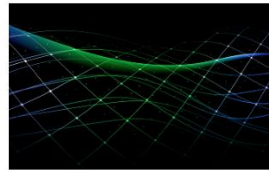
# Libraries

## Linear Algebra and Math Libraries



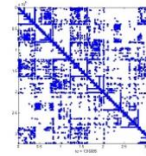
**cuBLAS**

GPU-accelerated standard BLAS library



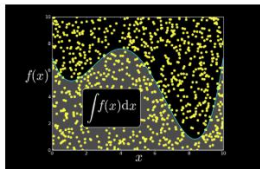
**CUDA Math Library**

GPU-accelerated standard mathematical function library



**cuSPARSE**

GPU-accelerated BLAS for sparse matrices



**cuRAND**

GPU-accelerated random number generation (RNG)



**cuSOLVER**

Dense and sparse direct solvers for Computer Vision, CFD, Computational Chemistry, and Linear Optimization applications

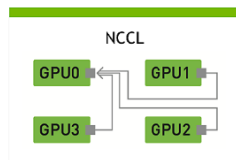


**AmgX**

GPU accelerated linear solvers for simulations and implicit unstructured methods

# Libraries

## Parallel Algorithm Libraries



### NCCL

Collective Communications Library for scaling apps across multiple GPUs and nodes



### nvGRAPH

GPU-accelerated library for graph analytics



### Thrust

GPU-accelerated library of parallel algorithms and data structures



# Languages



## CUDA Toolkit

Provides a comprehensive environment for C/C++ developers building GPU-accelerated applications.



## CUDA FORTRAN

Enjoy GPU acceleration directly from your Fortran program using CUDA Fortran from The Portland Group.



## OpenCL™

OpenCL is a low-level API for GPU computing that can run on CUDA-powered GPUs.

## OpenACC

### OpenACC

Directives for parallel computing, is a new open parallel programming standard designed to enable all scientific and technical programmers.



## Anaconda Accelerate

Enables acceleration on your GPU or multi-core processor using Python.



## Alea GPU

This is a novel approach to develop GPU applications on .NET, combining the CUDA with Microsoft's F#.



## PGI Accelerator Fortran and C Compilers

Accelerate applications on GPU platforms by adding compiler directives to existing code.



## PyCUDA

Gives you access to CUDA functionality from your Python code.



## The PGI CUDA C/C++ compiler for x86

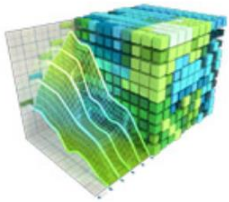
Compile and optimize their CUDA applications to run on x86-based workstations, servers and clusters.



## Altimesh Hybridizer™

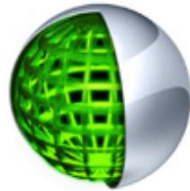
An advanced productivity tool that generates vectorized C++ (AVX) and CUDA C code from .NET assemblies (MSIL) or Java archives (bytecode)

# Tools



## NVIDIA Visual Profiler

This is a cross-platform performance profiling tool that delivers developers vital feedback for optimizing CUDA C/C++ applications. First introduced in 2008, Visual Profiler supports all CUDA capable NVIDIA GPUs shipped since 2006 on Linux, Mac OS X, and Windows.



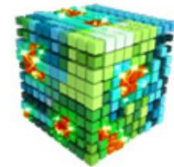
## NVIDIA® Nsight™

The ultimate development platform for heterogeneous computing. Work with powerful debugging and profiling tools, optimize the performance of your CPU and GPU code. Find out about the Eclipse Edition and the graphics debugging enabled Visual Studio Edition.



## CUDA-GDB

Delivers a seamless debugging experience that allows you to debug both the CPU and GPU portions of your application simultaneously. Use CUDA-GDB on Linux or MacOS, from the command line, DDD or EMACS.



## CUDA-MEMCHECK

Identifies memory access errors in your GPU code and allows you to locate and resolve problems quickly. CUDA-MEMCHECK also reports runtime execution errors, identifying situations that could result in an “unspecified launch failure” error while your application is running.

# CUDA

CUDA (Compute Unified Device Architecture) provides a set of programming extensions based on the C/C++ family of languages.

If you have a basic understanding of C and understand the concept of threads and SIMD execution, then CUDA is easy to pick up.

An introduction to the CUDA programming language will be given in lecture eight.



## CUDA Toolkit

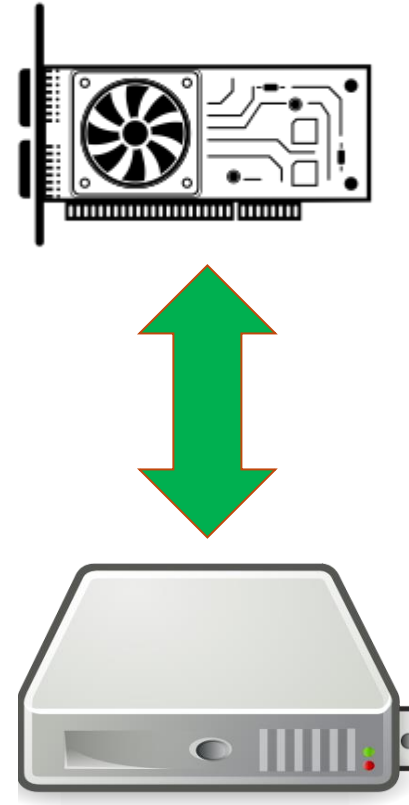
Provides a comprehensive environment for C/C++ developers building GPU-accelerated applications.

# Working with GPUs

Recall for our first lecture (and earlier in these slides), a GPU is attached to the computer by a PCIe bus.

It also has its own memory (for example a V100 has 16GB of HBM2 memory). So the GPU has a separate address space.

This means that for us to work with the GPU we need to allocate memory on the card (device) and then transfer data to and from the device.



By RRZEicons [CC BY-SA 3.0 (<https://creativecommons.org/licenses/by-sa/3.0/>)], from Wikimedia Commons

# Working with GPUs

To allocate memory on the device  
CUDA provides a function just like  
`malloc()` called `cudaMalloc()`

To free memory CUDA provides a  
function like `free()` called  
`cudaFree()`

Examples are given in the code  
snippit on the right.

```
// Allocate pointers for host and device memory
float *h_input, *h_output;
float *d_input, *d_output;

// malloc() host memory (this is in your RAM)
h_input = (float*) malloc(mem_size);
h_output = (float*) malloc(mem_size);

// allocate device memory input and output arrays
cudaMalloc((void**)&d_input, mem_size);
cudaMalloc((void**)&d_output, mem_size);

// Do something here!

// cleanup memory
free(h_input);
free(h_output);
cudaFree(d_input);
cudaFree(d_output);
```

# Working with GPUs

To transfer data to and from the GPU CUDA provides a function to do this called `cudaMemcpy()`

As arguments `cudaMemcpy()` takes:

```
cudaMemcpy(destination pointer, origin pointer, size of memory to move, direction)
```

Examples below

```
// Copy host memory to device input array
cudaMemcpy(d_input, h_input, mem_size, cudaMemcpyHostToDevice);

// Do something on the GPU

// copy result from device to host
cudaMemcpy(h_output, d_output, mem_size, cudaMemcpyDeviceToHost);
```

# An example - cuRAND

The example on the right shows how to generate a distribution of random normal number using cuRAND.

This code could replace

// Do something here

In the previous slides. Combining this will `cudaMemcpy()` allows you to start building a GPU program.

```
// random number generation
#include <cuda.h>
#include <curand.h>

// Declare variable
curandGenerator_t gen;

// Create random number generator
curandCreateGenerator(&gen, CURAND_RNG_PSEUDO_DEFAULT) );

// Set the generator options
curandSetPseudoRandomGeneratorSeed(gen, 1234ULL) );

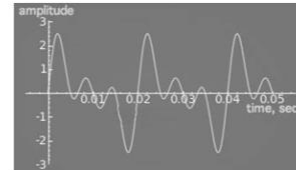
// Generate the randoms
curandGenerateNormal(gen, d_input, NUM_ELS, 0.0f, 1.0f) );
```

<https://docs.nvidia.com/cuda/curand/introduction.html#introduction>



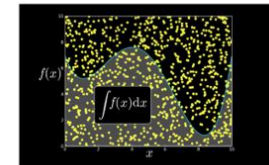
# Practical 5

In practical 5 you will work with different codes to familiarise yourselves with cuRAND, cuFFT and cuBLAS.



cuFFT

GPU-accelerated library for Fast Fourier Transforms



cuRAND

GPU-accelerated random number generation (RNG)



CUDA Toolkit

Provides a comprehensive environment for C/C++ developers building GPU-accelerated applications.



cuBLAS

GPU-accelerated standard BLAS library

# What have we learnt?

In this lecture you have learnt about different hardware generations of GPUs and some of their differences.

We've looked at how GPUs execute code.

We have looked at the differences between GPUs and CPUs in greater detail, we have also looked at how GPUs hide memory latencies.

We've looked at the GPU software environment and useful tools.

Finally we have covered the basics of how to use GPU libraries in your codes.



# Further reading

<http://docs.nvidia.com/cuda/curand/index.html>

<https://developer.nvidia.com/curand>

<http://docs.nvidia.com/cuda/cufft/index.html>

<https://developer.nvidia.com/cufft>

<http://docs.nvidia.com/cuda/cublas/index.html>

<https://developer.nvidia.com/cublas>

<https://docs.nvidia.com/cuda/>

<https://developer.nvidia.com/about-cuda>

# In the next lecture...

In the next lecture you will learn about the CUDA programming language and how to write a CUDA code.

