ACACES 2018 Summer School

GPU Architectures: Basic to Advanced Concepts

Adwait Jog, Assistant Professor

College of William & Mary
(http://adwaitjog.github.io/)

William & Mary

- Second oldest-institution of higher education in the USA

- Located in Williamsburg, VA, USA. *Recently hosted ASPLOS conference – one of the top venues for computer architecture research.*

- I am affiliated with Computer Science Department
  - Graduate Program (~65-70 Ph.D. students)
  - 25 Faculty Members

- Many graduated Ph.D. students have successfully established careers in academia & industry.

Brief Introduction

Adwait Jog
(Assistant Professor)

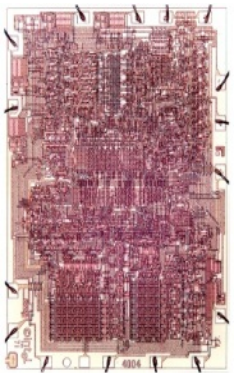
Interested in developing high-performance, energy-efficient and scalable systems that are low cost, reliable, and secure.

Special focus on GPU architectures and accelerators.

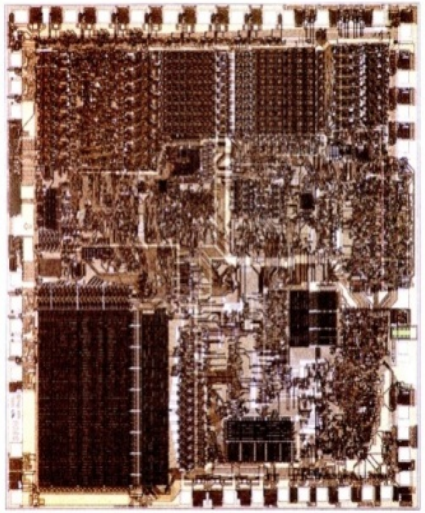
I lead Insight Computer Architecture Lab at College of William and Mary (http://insight-archlab.github.io/)

Our lab is funded by US National Science Foundation (NSF) and always looking to hire bright students at all levels.

Journey of CMPs: Scaling and Heterogeneity Trends

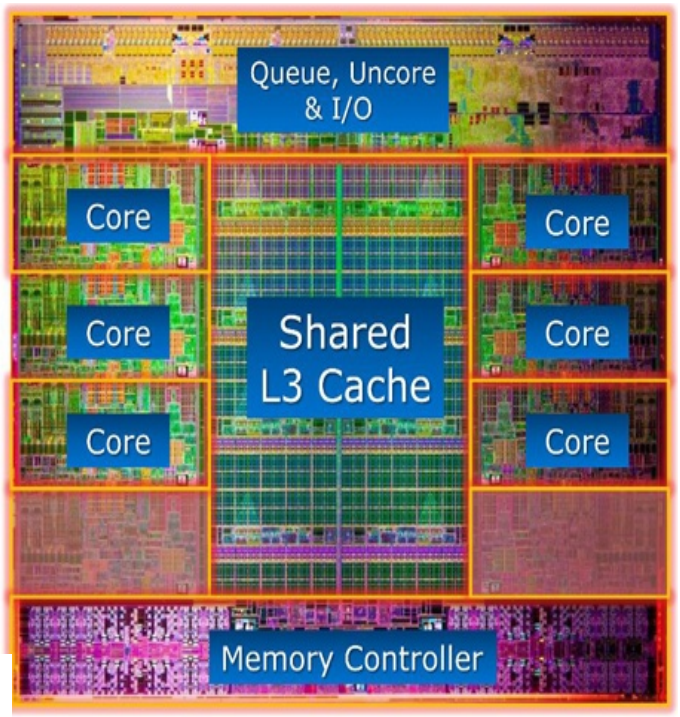


Intel 4004,
1971
1 core,
no cache
23K transistors



Intel 8088,
1978
1 core,
no cache
29K transistors

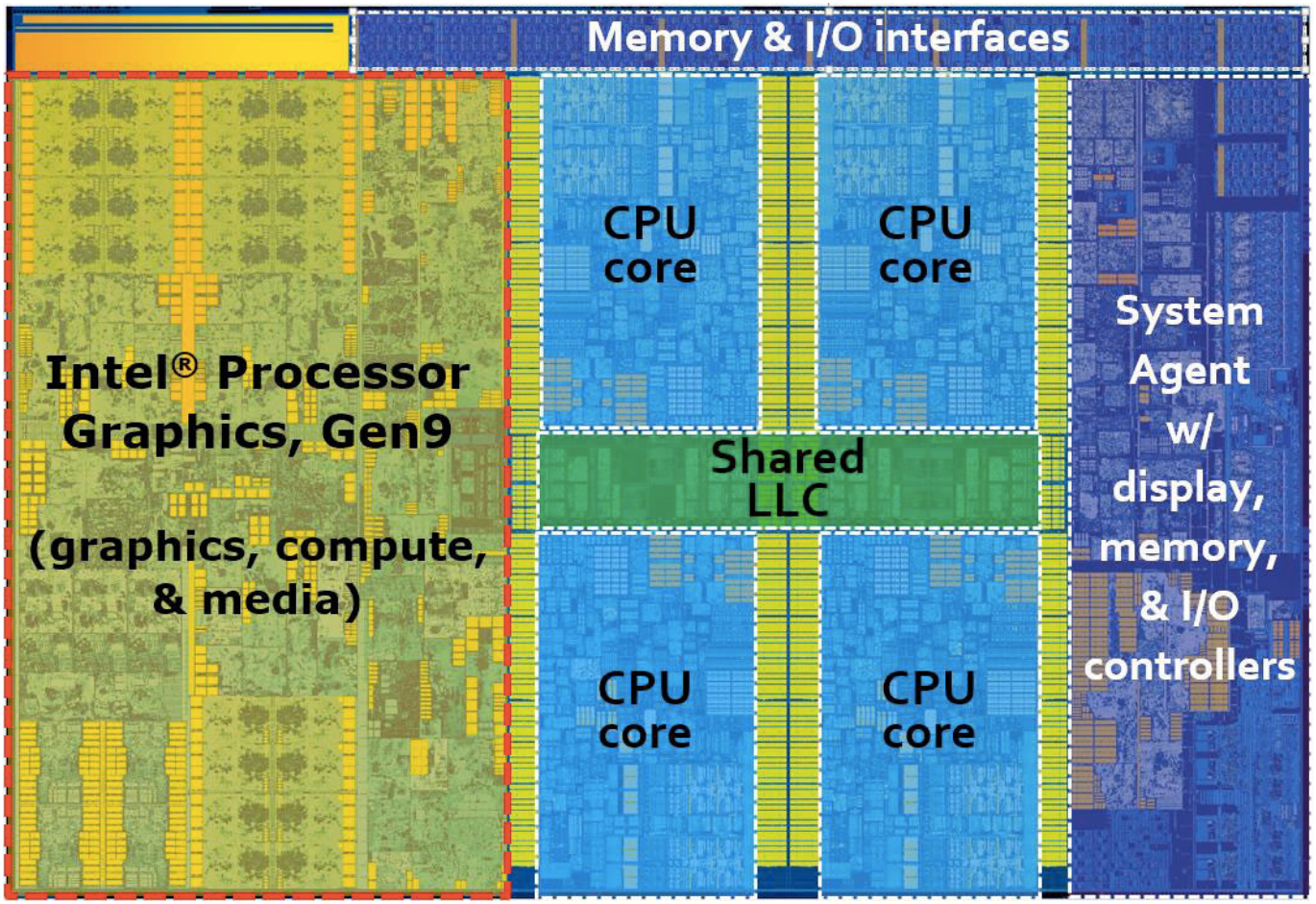
Intel Pentium 4,
2000
1 core
256 KB L2 cache
42M transistors



Intel Sandy Bridge,
2011
6 cores
15 MB L3 cache
2270M transistors

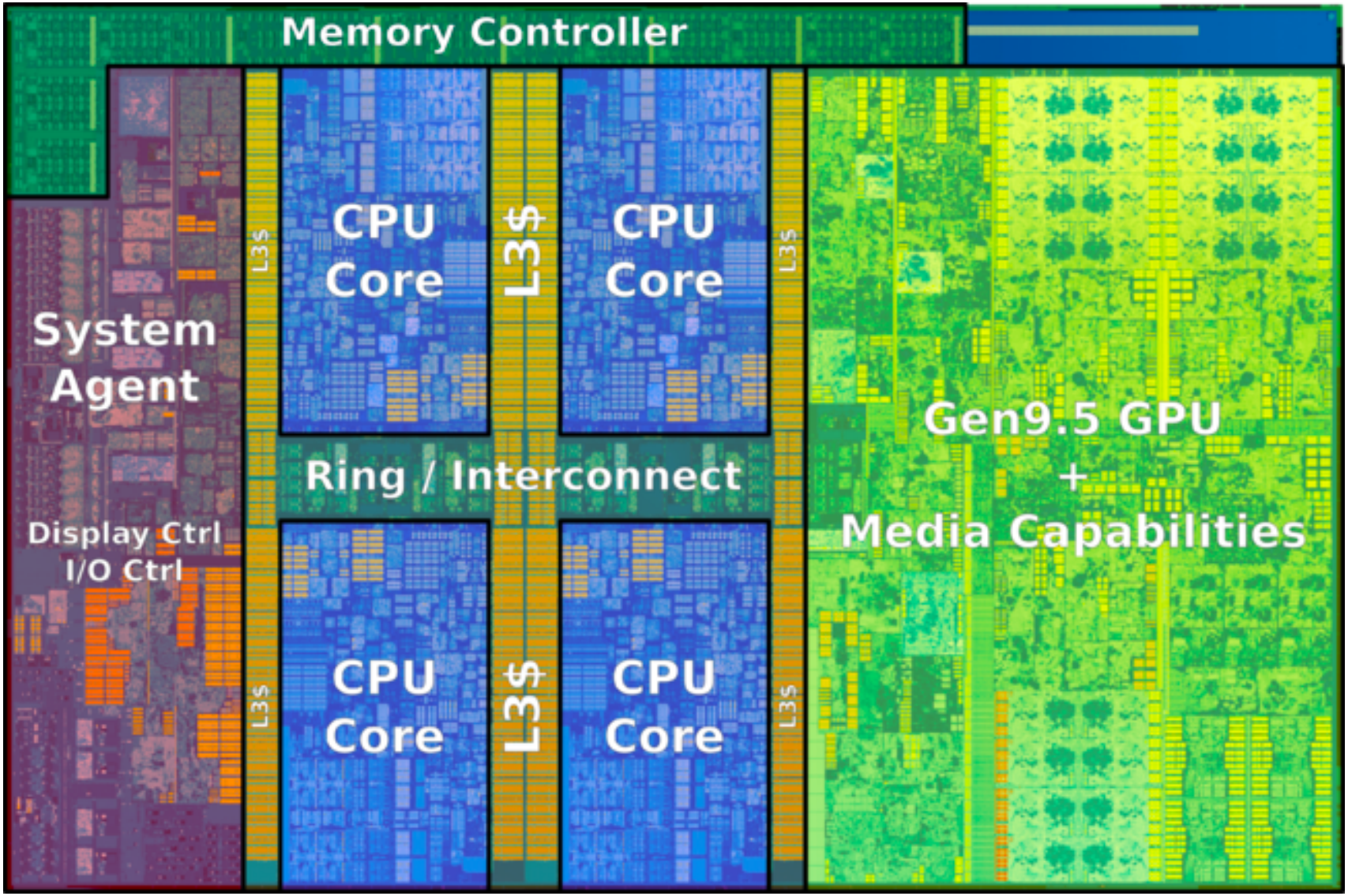
What's now?

Intel Core i7-6700K Processor, 2016 (Skylake)



1.7 billion transistors, 14 nm process, die size 122 mm^2

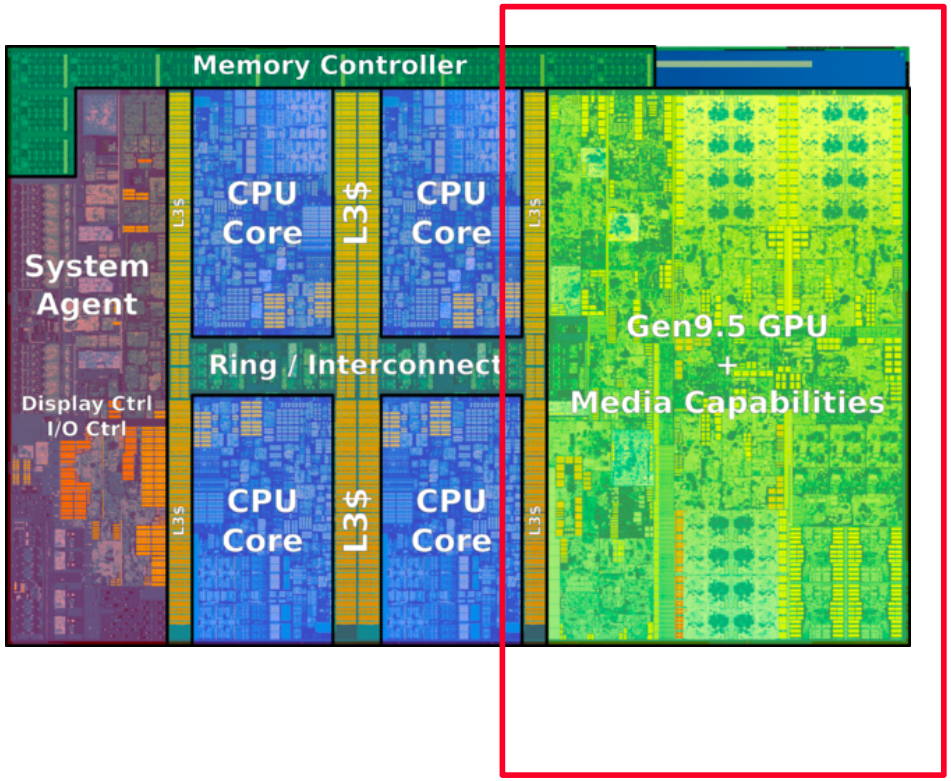
Intel Quad Core GT2, 2017 (Kaby Lake)



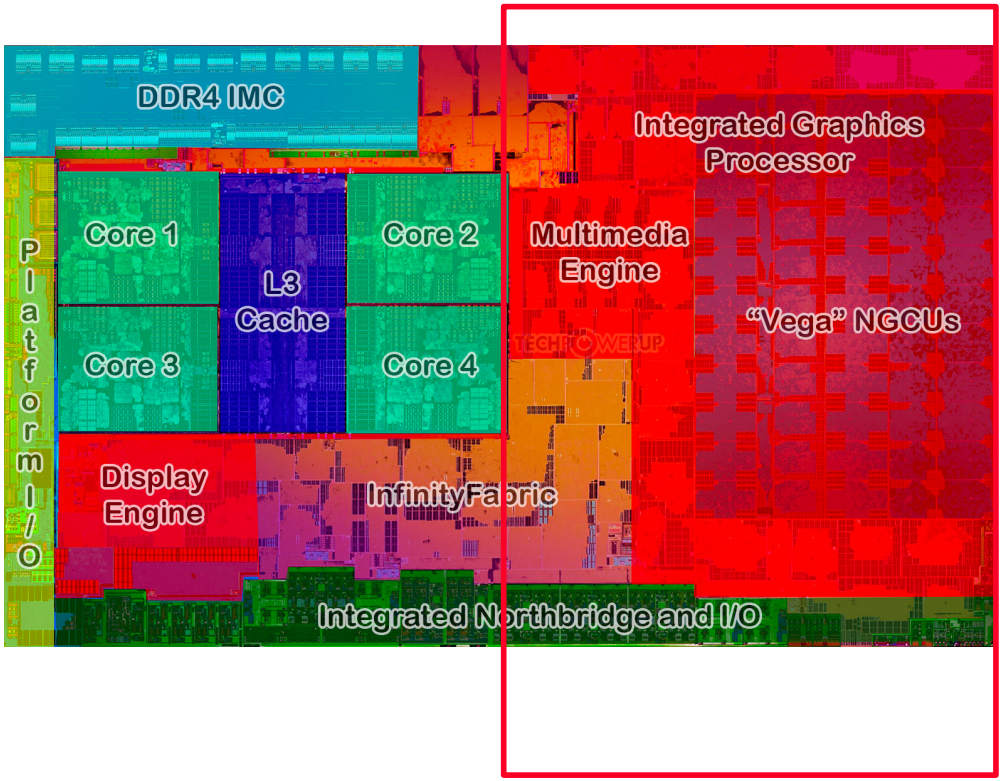
14 nm process, die size 126 mm^2

I) Graphics Portions on CMPs are Growing

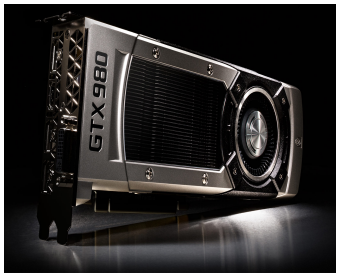
Intel Coffee Lake



AMD Raven Ridge



II) Graphics Cards are Becoming More Powerful

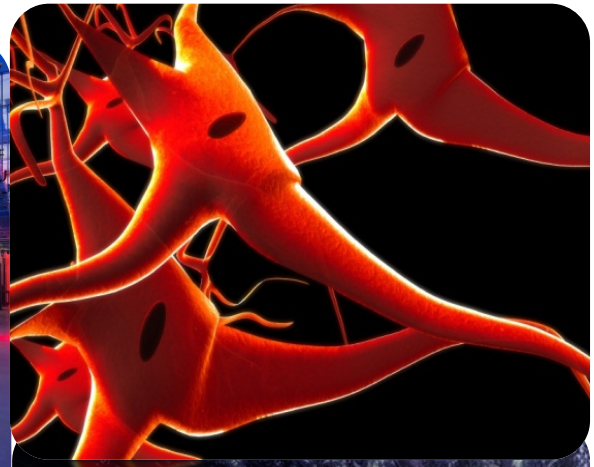
2008	2010	2012	2014	2016	2018
					
GTX 275 *(Tesla)* 240 CUDA Cores (127 GB/sec)	GTX 480 *(Fermi)* 448 CUDA Cores (139 GB/sec)	GTX 680 *(Kepler)* 1536 CUDA Cores (192 GB/sec)	GTX 980 *(Maxwell)* 2048 CUDA Cores (224 GB/sec)	GP 100 *(Pascal)* 3584 CUDA Cores (720 GB/sec)	GV 100 *(Volta)* 5120 CUDA Cores (900 GB/sec)

III) GPUs are Becoming Ubiquitous

IVa) GPUs are Becoming More Useful

HELPS UNDERSTAND UNIVERSE

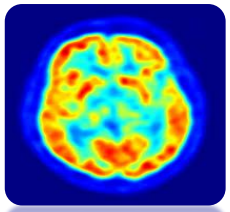
BACKEND OF "GOOGLE" & MANY OTHERS



ENABLING SCIENTIFIC COMPUTING & BREAKTHROUGHS

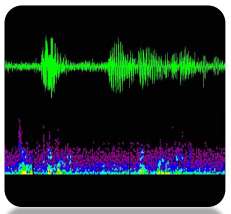
IVb) GPUs are Becoming More Useful

Astronomy



Medical Imaging

Physics Simulation



Audio Processing

Machine Learning

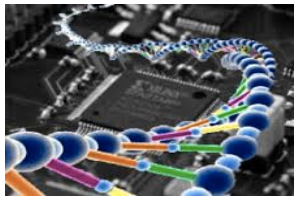
Data-Level Parallelism

Large Data Sets

Games

Image Processing

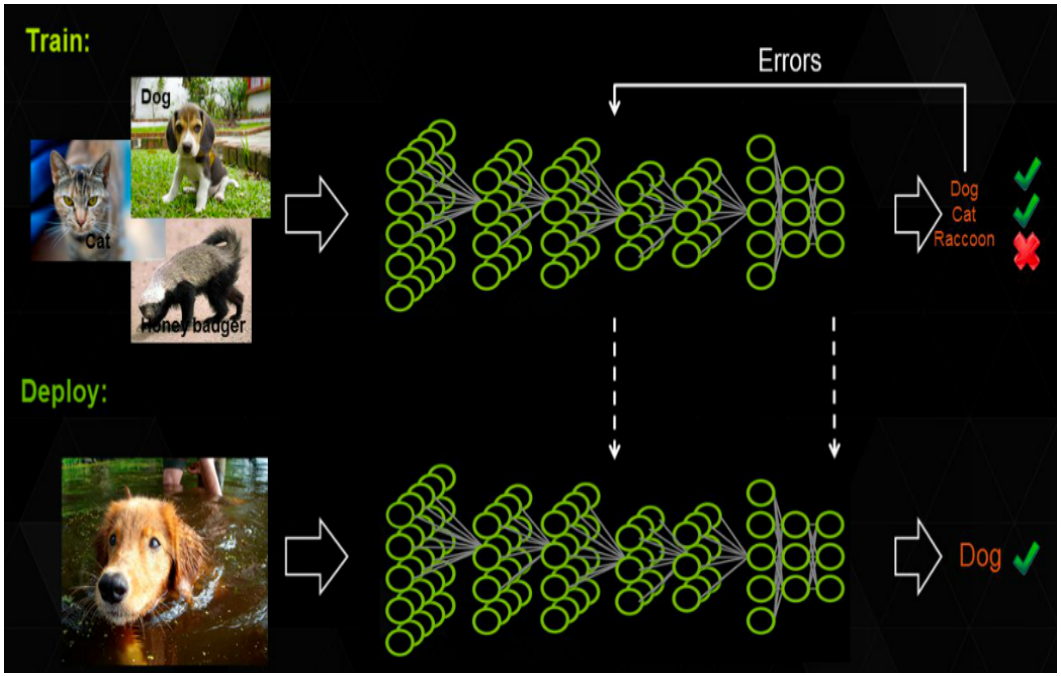
Financial Computing

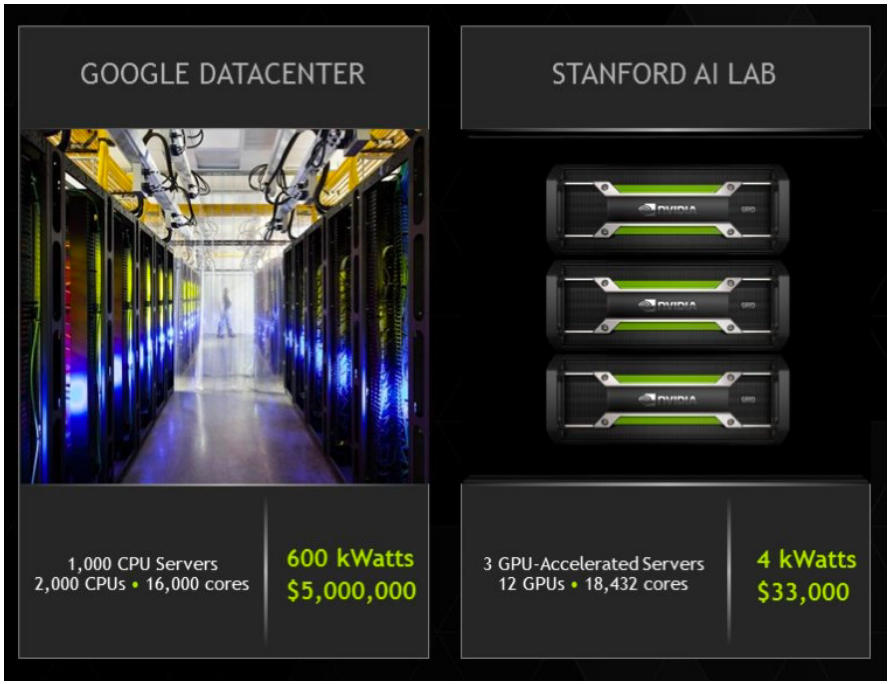


Genomics

IVc) GPUs are Becoming More Useful

- Deep Learning and Artificial Intelligence





Credit: NVIDIA AI

- **However, there are several compute and memory bottlenecks in GPU-based systems that need to be addressed via software- and/or hardware-based solutions**

Course Outline

- Lectures 1 and 2: Basics Concepts
  - Basics of GPU Programming
  - Basics of GPU Architecture
- Lecture 3: GPU Performance Bottlenecks
  - Memory Bottlenecks
  - Compute Bottlenecks
  - Possible Software and Hardware Solutions
- Lecture 4: GPU Security Concerns
  - Timing channels
  - Possible Software and Hardware Solutions

Lecture Material

- Available at my webpage (http://adwaitjog.github.io/). Navigate to the teaching tab
- Direct link: *http://adwaitjog.github.io/teach/acaces2018.html*
- Material will updated over the week – so keep checking the website periodically
- The lecture material is currently **preliminary** and small changes are likely. Follow the class lectures!

Course Objectives

- By the end of this (short) course, I hope you can appreciate
  - the benefits of GPUs
  - the architectural differences between CPU and GPU
  - the key research challenges in the context of GPUs
  - some of the existing research directions
- I encourage questions during/after the class
  - Ample time for discussions during the week
  - Find me during breaks or email me

Background

- My assumption is that students have some background on basic computer organization and design.

- Question 1: How many of you have taken undergraduate-level course on computer architecture?

- Question 2: How many of you have taken graduate-level course on computer architecture?

- Question 3: How many of you have taken a GPU course before?

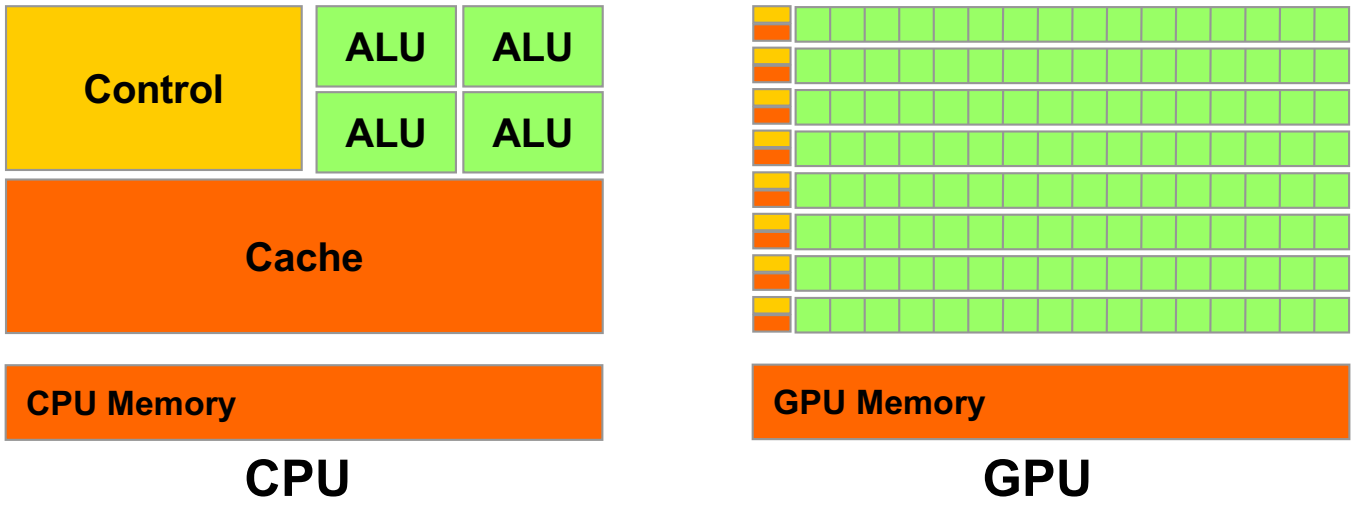
Reading Material (Books & Docs)

- D. Kirk and W. Hwu, "Programming Massively Parallel Processors – A Hands-on Approach, 3rd Edition"
- *Patterson and Hennesy, Computer Organization and Design, 5th Edition, Appendix C-2 on GPUs*
- *Aamodt, Fung, Rogers, "General-Purpose Graphics Processing Architectures" – Morgan & Claypool Publishers, 1st Edition (New book!)*
- *Nvidia CUDA C Programming Guide*
  - *https://docs.nvidia.com/cuda/cuda-c-programming-guide/*

Course Outline

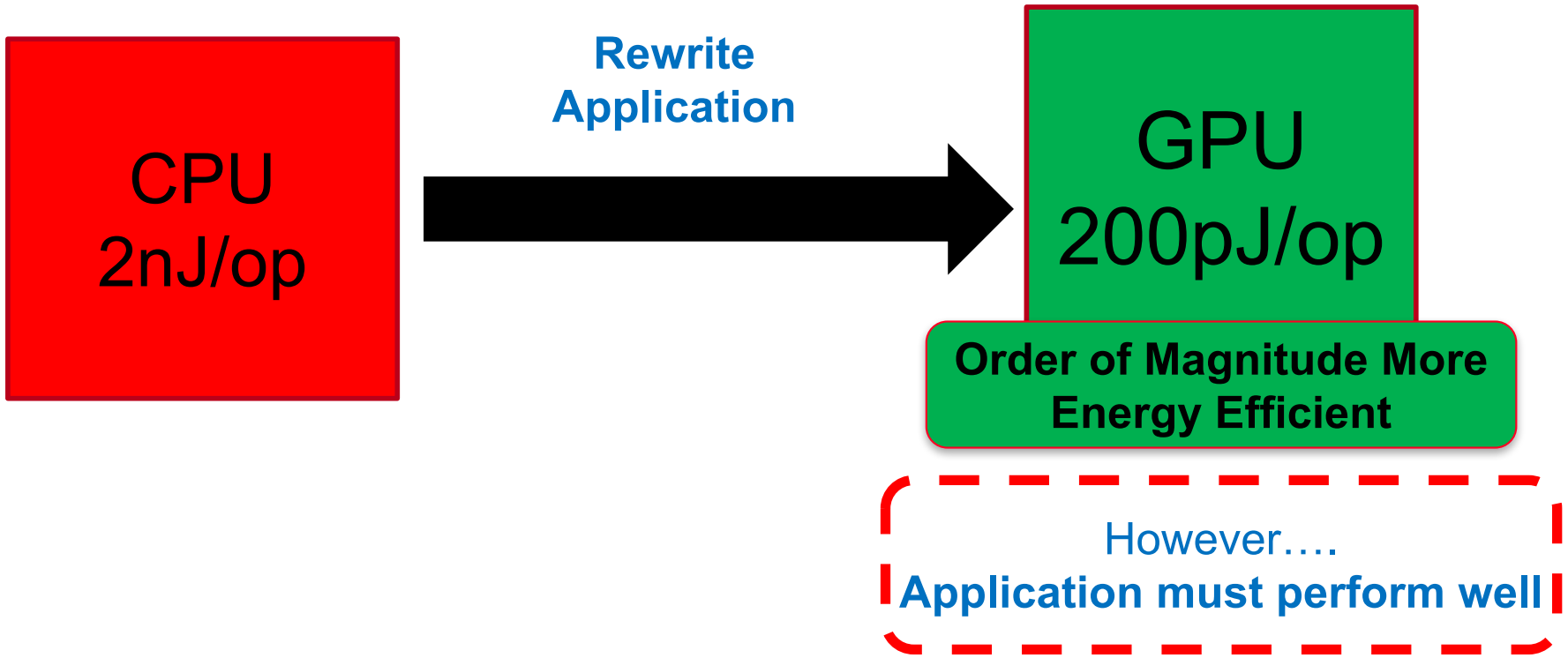
- Lectures 1 and 2: Basics Concepts
  - **Basics of GPU Programming**
  - Basics of GPU Architecture
- Lecture 3: GPU Performance Bottlenecks
  - Memory Bottlenecks
  - Compute Bottlenecks
  - Possible Software and Hardware Solutions
- Lecture 4: GPU Security Concerns
  - Timing channels
  - Possible Software and Hardware Solutions

GPU vs. CPU

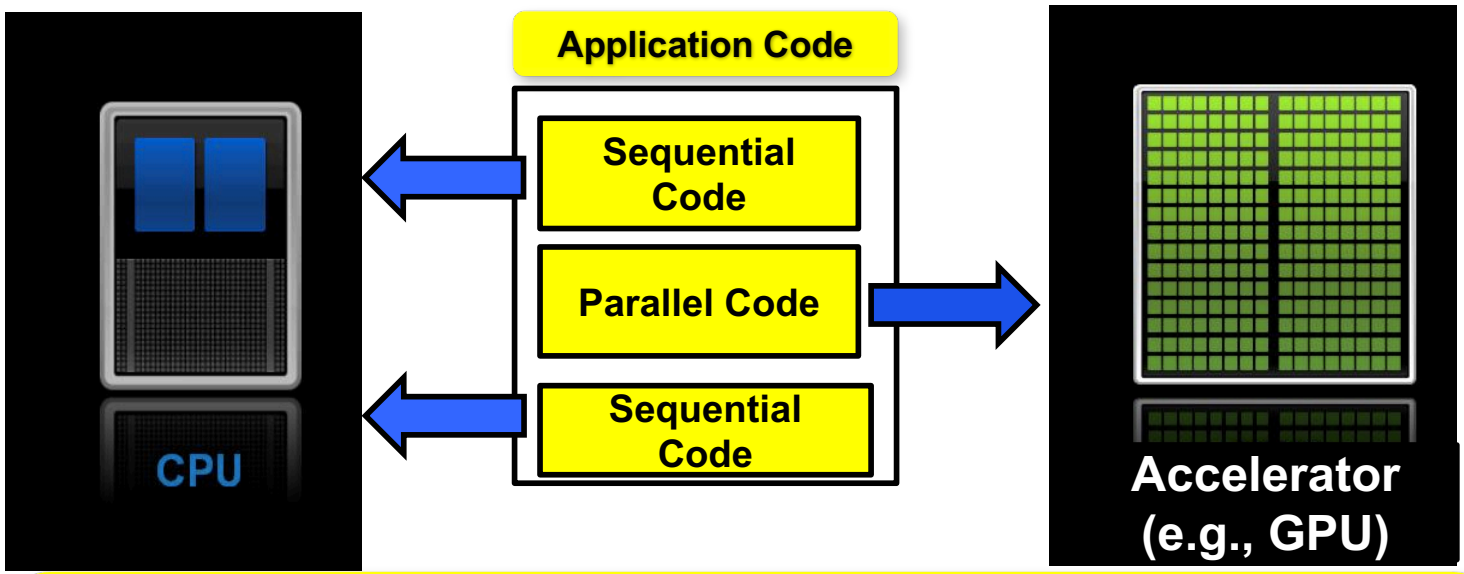


Why use a GPU for computing?

- GPU uses larger fraction of silicon for computation than CPU.
- At peak performance GPU uses order of magnitude less energy per operation than CPU.



How Acceleration Works



Many Top 20 supercomputers in the green500 list employ accelerators.

Fastest Super Computer* -- SUMMIT @ Oak Ridge

Multiple Volta GPUs

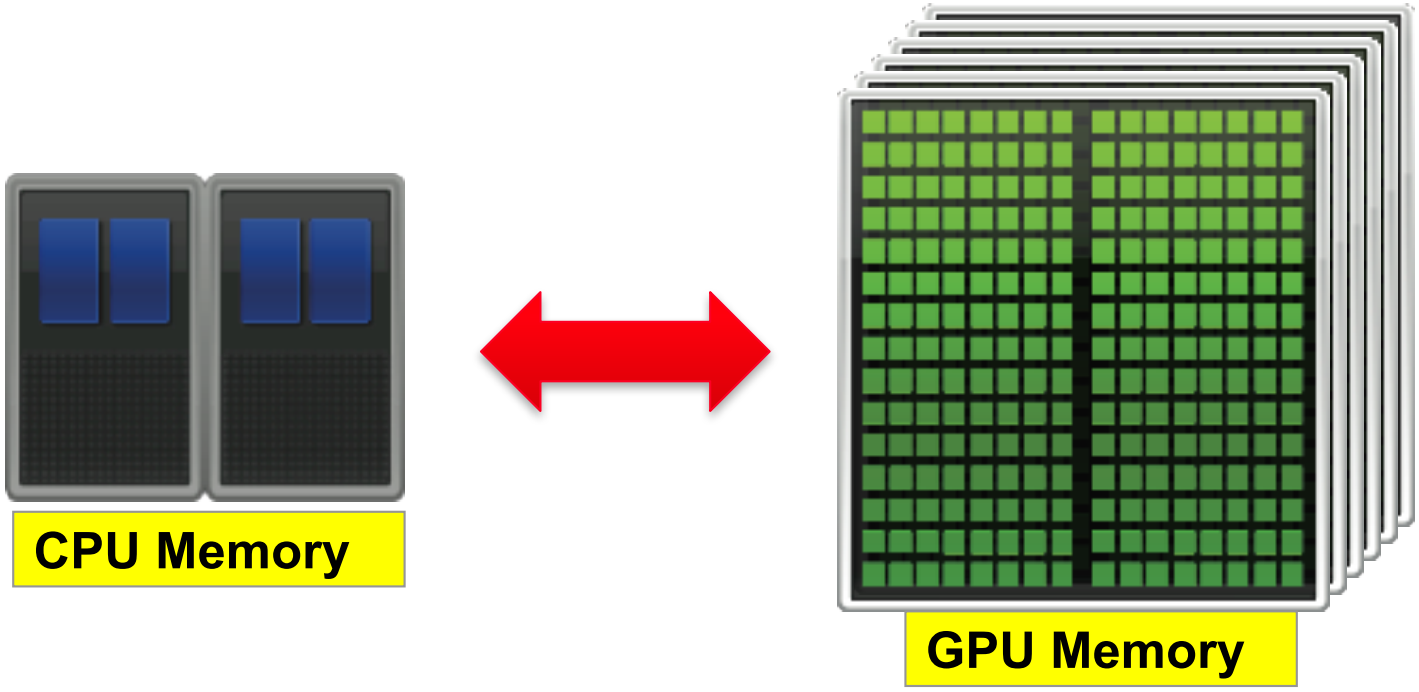
NVLink

HBM + DDR4

https://www.olcf.ornl.gov/olcf-resources/compute-systems/summit/

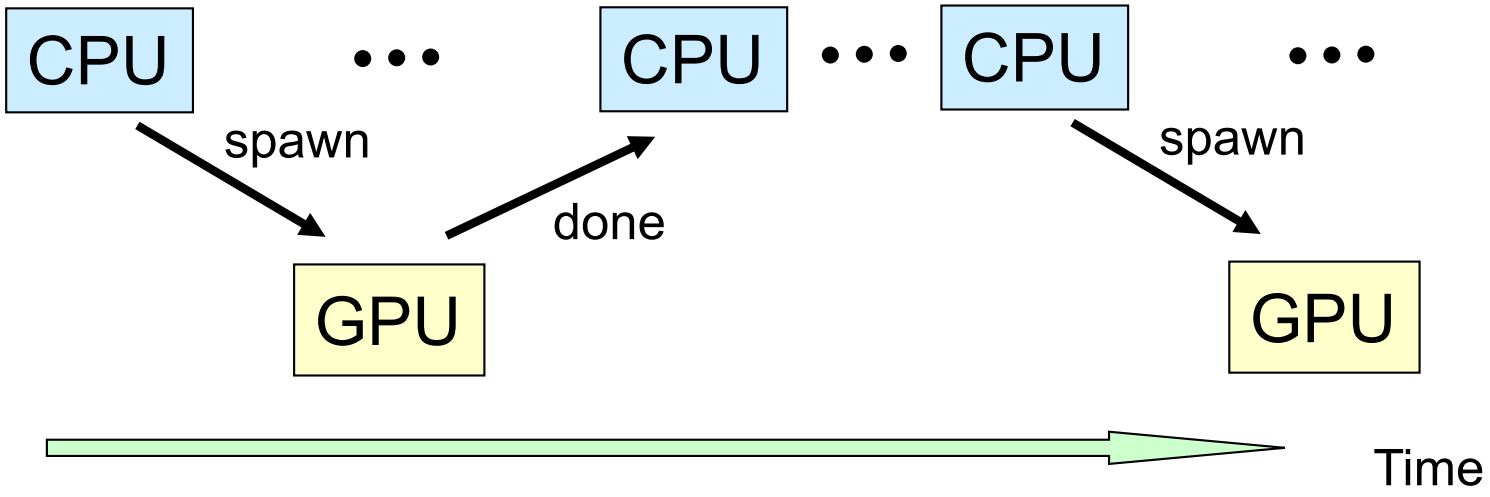
* As of June 2018

How is this system programmed (today)?



GPU Programming Model

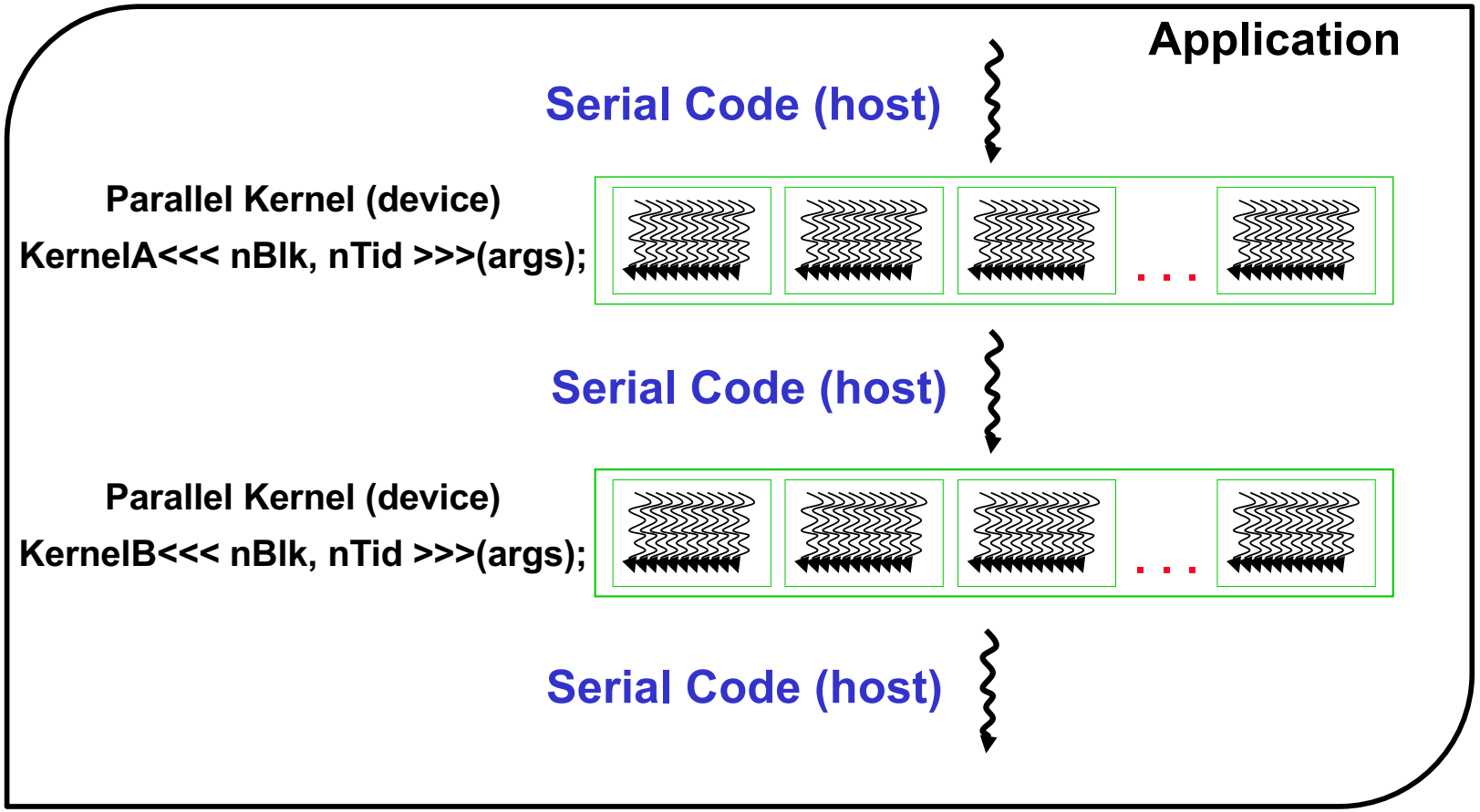
- CPU (host) “off-load” parallel kernels to GPU (device)



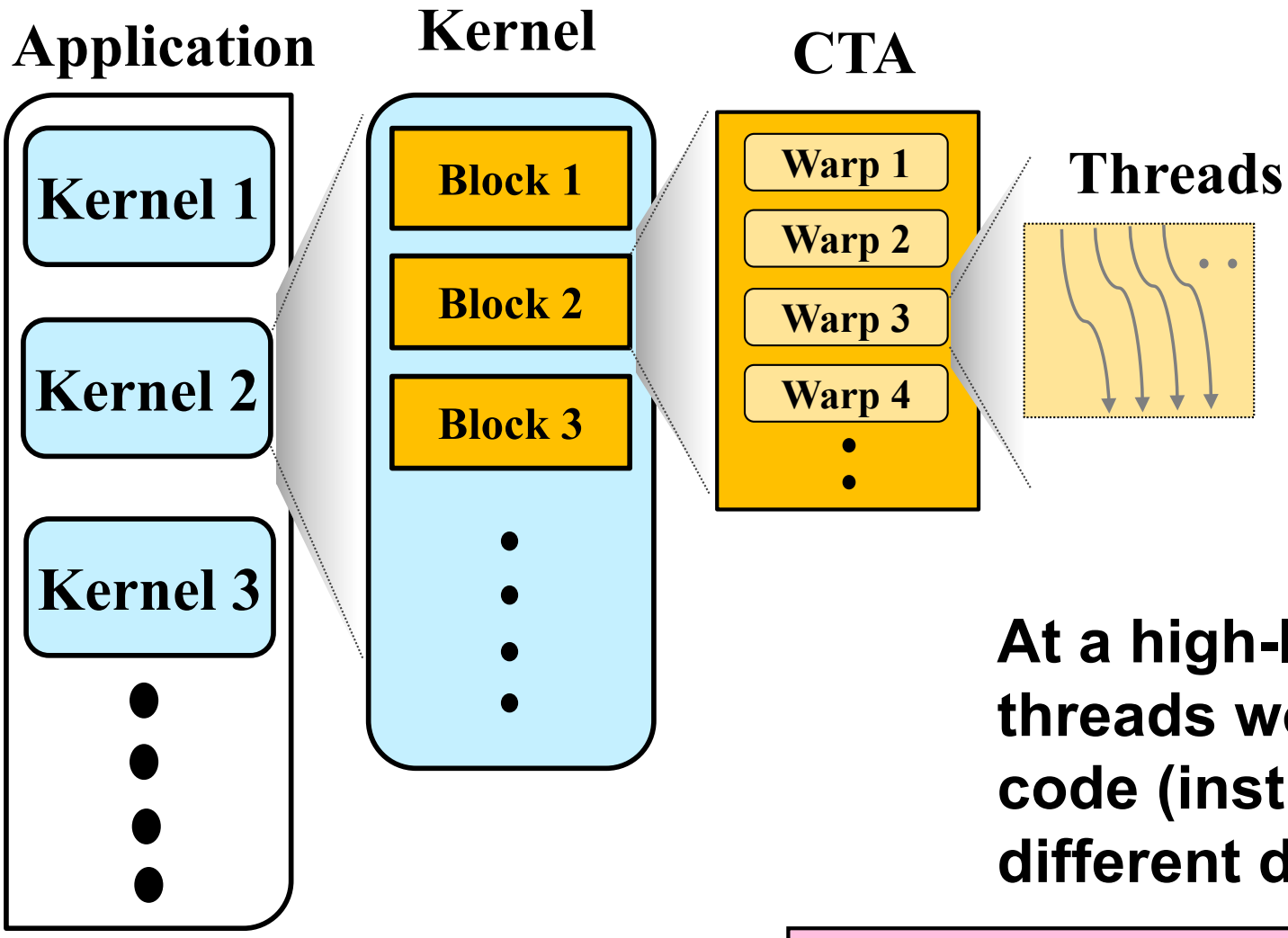
- Transfer data to GPU memory
- GPU spawns threads
- Need to transfer result data back to CPU main memory

CUDA Execution Model

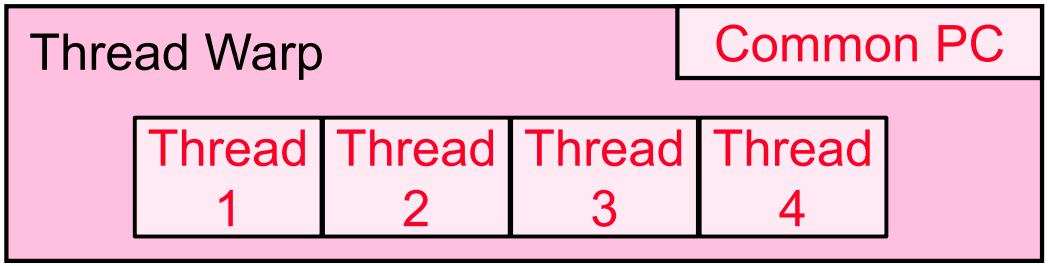
- **Application Code**
  - Serial parts (C code) in CPU (host)
  - Parallel parts (Kernel code) in GPU (device)



GPU as SIMD machine

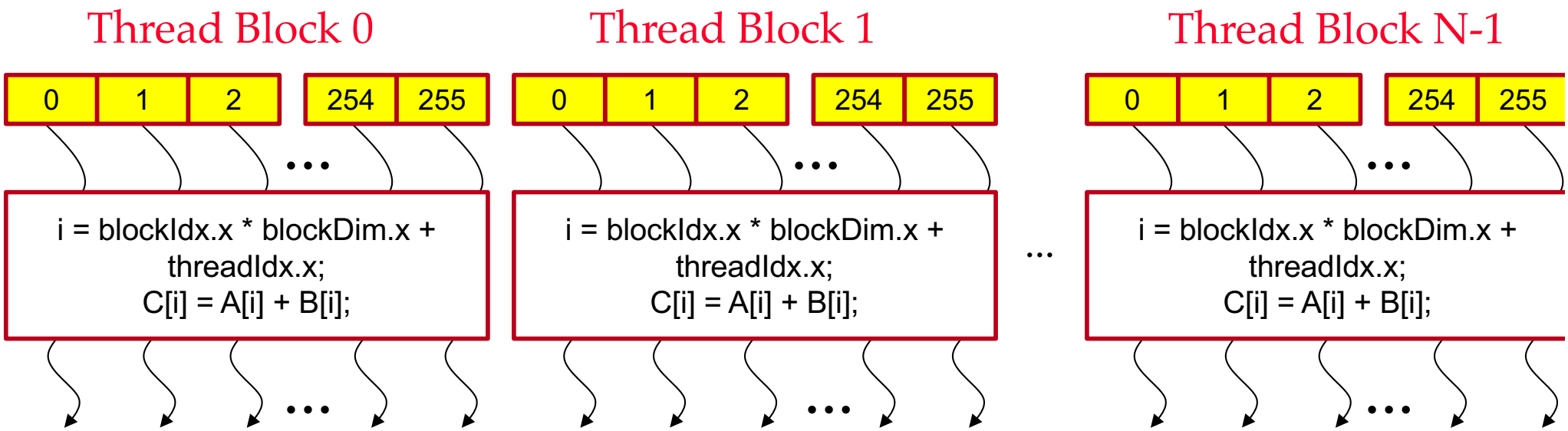


At a high-level, multiple threads work on same code (instructions) but different data

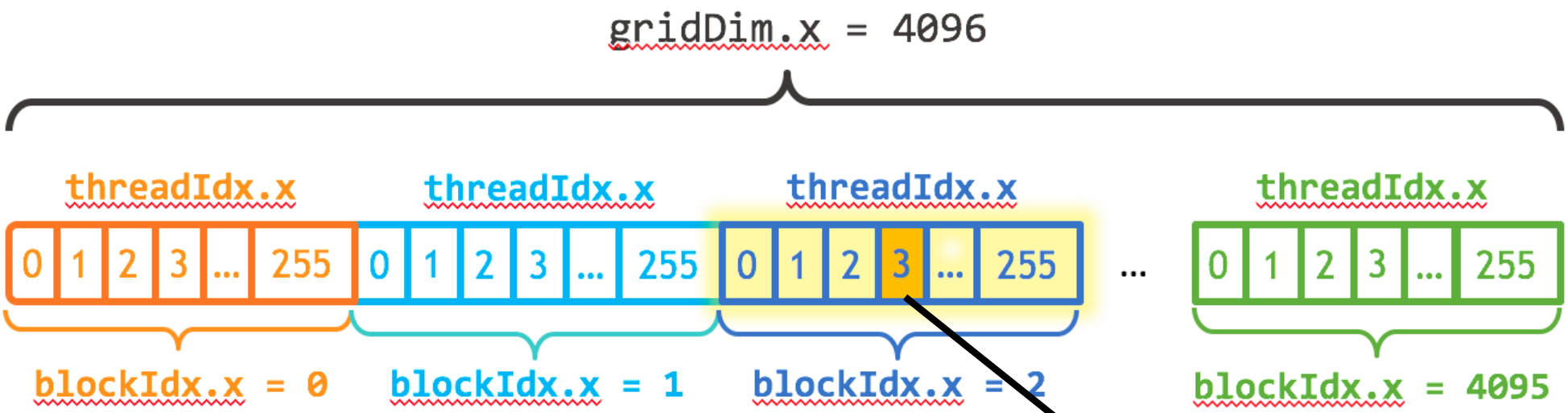


Kernel: Arrays of Parallel Threads

- A CUDA kernel is executed by a grid of threads
  - All threads in a grid run the same kernel code (Single Program Multiple Data)
  - Each thread has indexes that it uses to compute memory addresses and make control decisions

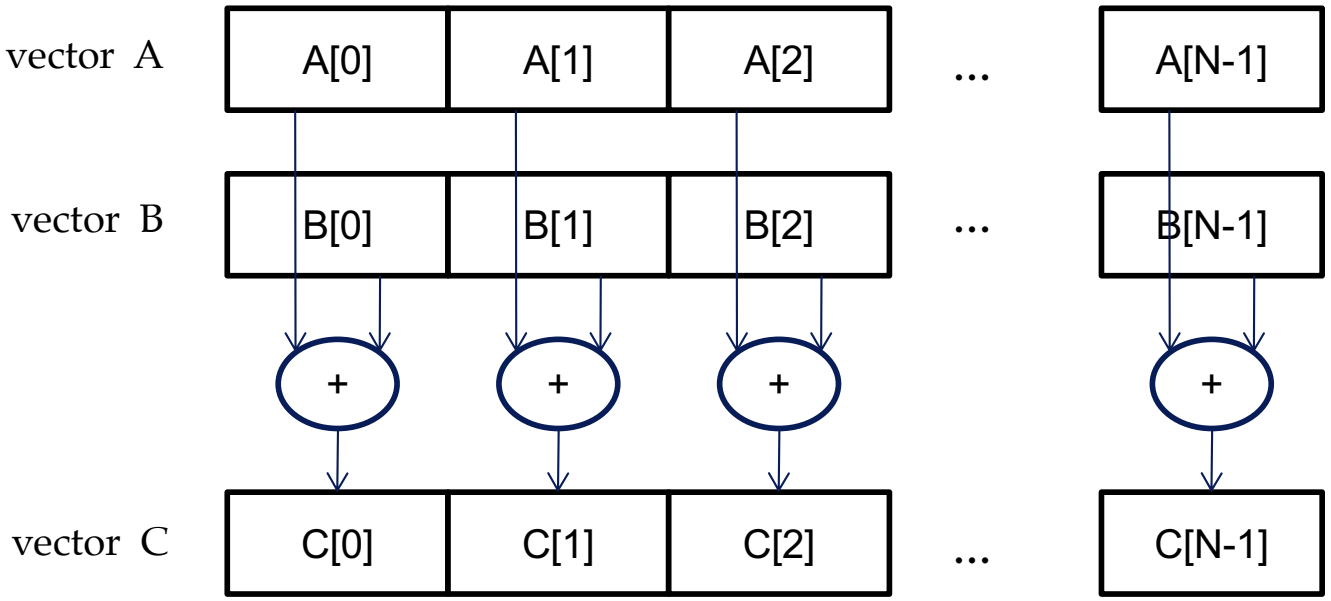


Kernel, Blocks, Threads




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

index =    (2)      *   (256)    +     (3)      = 515
```

Vector Addition Example



Vector Addition – Traditional C Code

```
// Compute vector sum C = A + B
void vecAdd(float *h_A, float *h_B, float *h_C, int n)
{
    int i;
    for (i = 0; i<n; i++) h_C[i] = h_A[i] + h_B[i];
}

int main()
{
    // Memory allocation for h_A, h_B, and h_C
    // I/O to read h_A and h_B, N elements
    …
    vecAdd(h_A, h_B, h_C, N);
}
```

vecAdd CUDA Host Code

```
#include <cuda.h>

void vecAdd(float *h_A, float *h_B, float *h_C, int n)

{

   int size = n* sizeof(float);

   float *d_A, *d_B, *d_C;

   // Part 1

            // Allocate device memory for A, B, and C

             // copy A and B to GPU (device) memory

   // Part 2

            // Kernel launch code – the device performs the vector addition

   // Part 3

             // copy C from the device memory

             // Free device vectors

}
```

Vector Addition (Host Side)

```
void vecAdd(float *h_A, float *h_B, float *h_C, int n)
{
    int size = n * sizeof(float); float *d_A, *d_B, *d_C;

    cudaMalloc((void **) &d_A, size);
    cudaMalloc((void **) &d_B, size);
    cudaMalloc((void **) &d_C, size);

    cudaMemcpy(d_A, h_A, size, cudaMemcpyHostToDevice);
    cudaMemcpy(d_B, h_B, size, cudaMemcpyHostToDevice);

    // Kernel invocation code – to be shown later

    cudaMemcpy(h_C, d_C, size, cudaMemcpyDeviceToHost);

    // do processing of results
    cudaFree(d_A); cudaFree(d_B); cudaFree (d_C);
}
```

Kernel Invocation code (Host Side)

```
void vecAdd(float *h_A, float *h_B, float *h_C, int n)
{
    ….. Preparation code (See previous slide)

    int blockSize, gridSize;
    // Number of threads in each thread block
    blockSize = 1024;

    // Number of thread blocks in grid
    gridSize = (int)ceil((float)n/blockSize);

    // Execute the kernel
    vecAdd<<<gridSize, blockSize>>>(d_A, d_B, d_C, n);

     … Post-processing (See previous slide)
}
```

Kernel Code (Device Side)

```
__global__ void vecAdd(double *a, double *b, double *c, int n)
{
    // Get our global thread ID
    int id = blockIdx.x*blockDim.x+threadIdx.x;

    // Make sure we do not go out of bounds
    if (id < n)
        c[id] = a[id] + b[id];
}
```

Same code is run by several threads

Important CUDA Syntax Extensions

- Declaration specifiers

  __global__ void foo(...); // kernel entry point (runs on GPU)

- Syntax for kernel launch

  foo<<<500, 128>>>(...); // 500 thread blocks, 128 threads each

- Built in variables for thread identification

  dim3 threadIdx; dim3 blockIdx; dim3 blockDim;

Example: Original C Code

```
void saxpy_serial(int n, float a, float *x, float
   *y)
{
   for (int i = 0; i < n; ++i)
      y[i] = a*x[i] + y[i];
}

int main() {
   // omitted: allocate and initialize memory
   saxpy_serial(n, 2.0, x, y); // Invoke serial SAXPY
   kernel
   // omitted: using result
}
```

CUDA Code

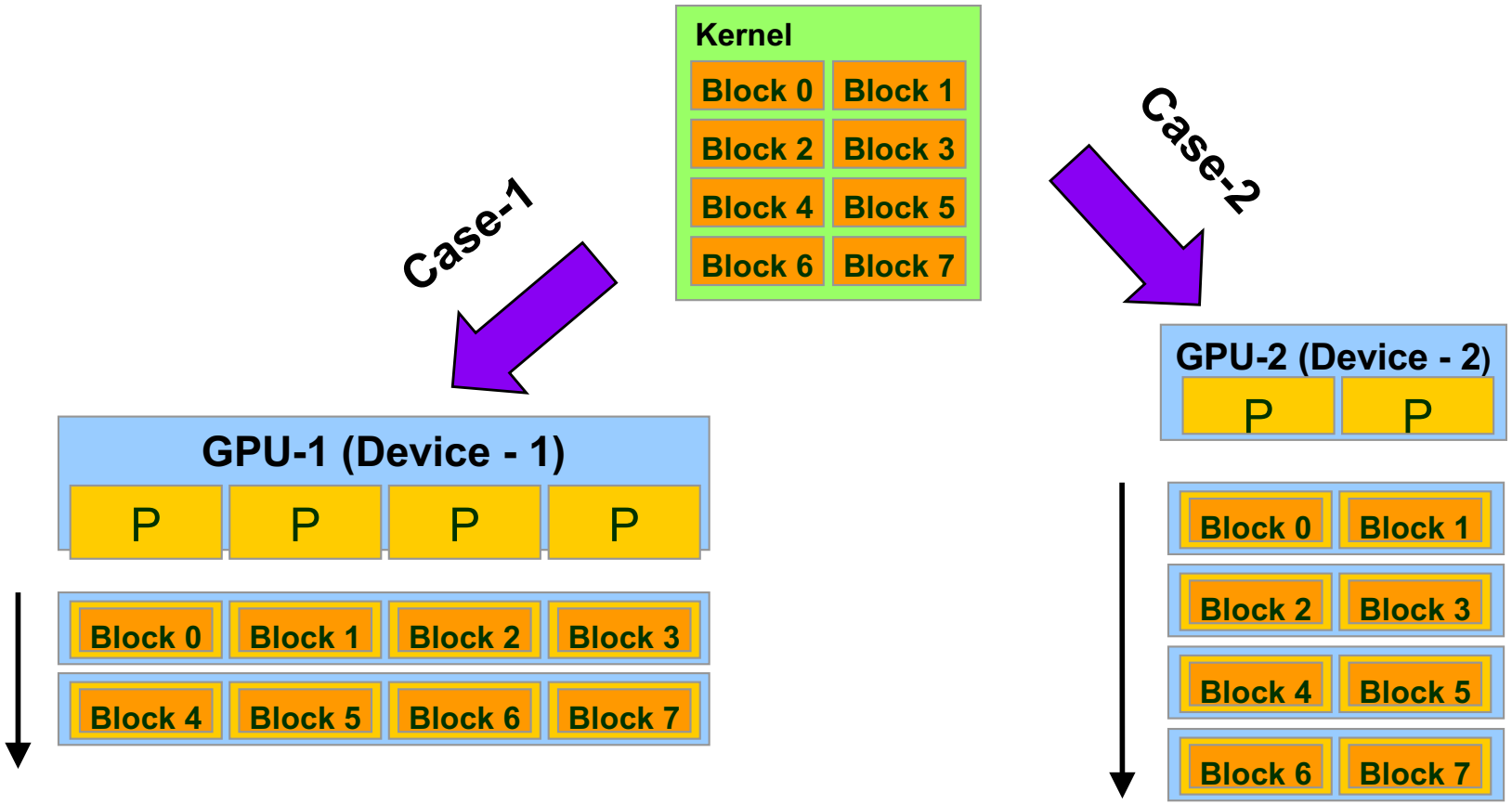
```
__global__ void saxpy(int n, float a, float *x, float *y) {
    int i = blockIdx.x*blockDim.x + threadIdx.x;
    if(i<n) y[i]=a*x[i]+y[i];
}
```

Runs on GPU

```
int main() {

    // omitted: allocate and initialize memory

   int nblocks = (n + 255) / 256;

   cudaMalloc((void**) &d_x, n);
   cudaMalloc((void**) &d_y, n);
   cudaMemcpy(d_x,h_x,n*sizeof(float),cudaMemcpyHostToDevice);
   cudaMemcpy(d_y,h_y,n*sizeof(float),cudaMemcpyHostToDevice);
   saxpy<<<nblocks, 256>>>(n, 2.0, d_x, d_y);
   cudaMemcpy(h_y,d_y,n*sizeof(float),cudaMemcpyDeviceToHost);

    // omitted: using result
}
```

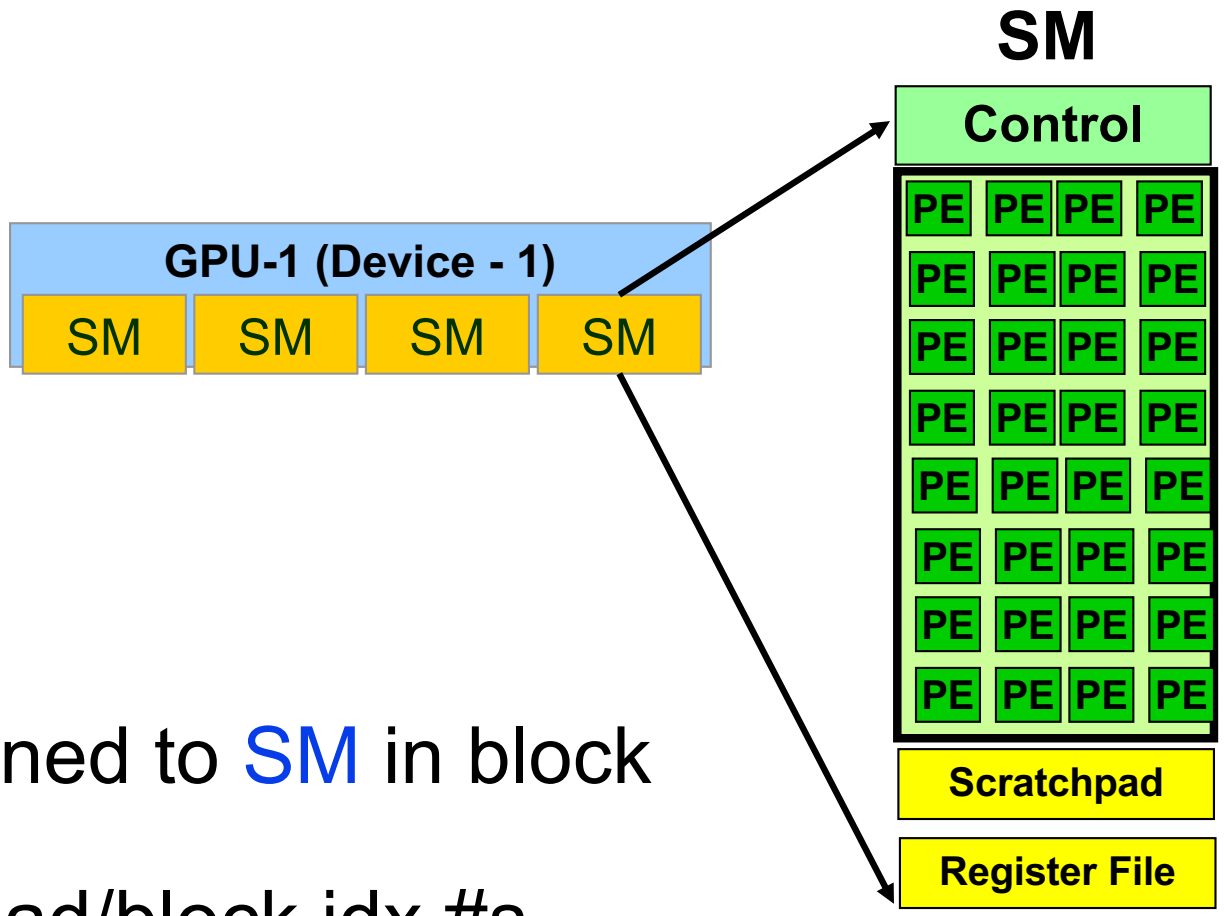
Code to Hardware Mapping

Code to Hardware Mapping: Transparent Scalability



- Each block can execute in any order relative to others.
- GPU Hardware is free to assign blocks to any processor at any time
  - A kernel scales to any number of parallel processors.

Streaming Multi-Processor (SM)



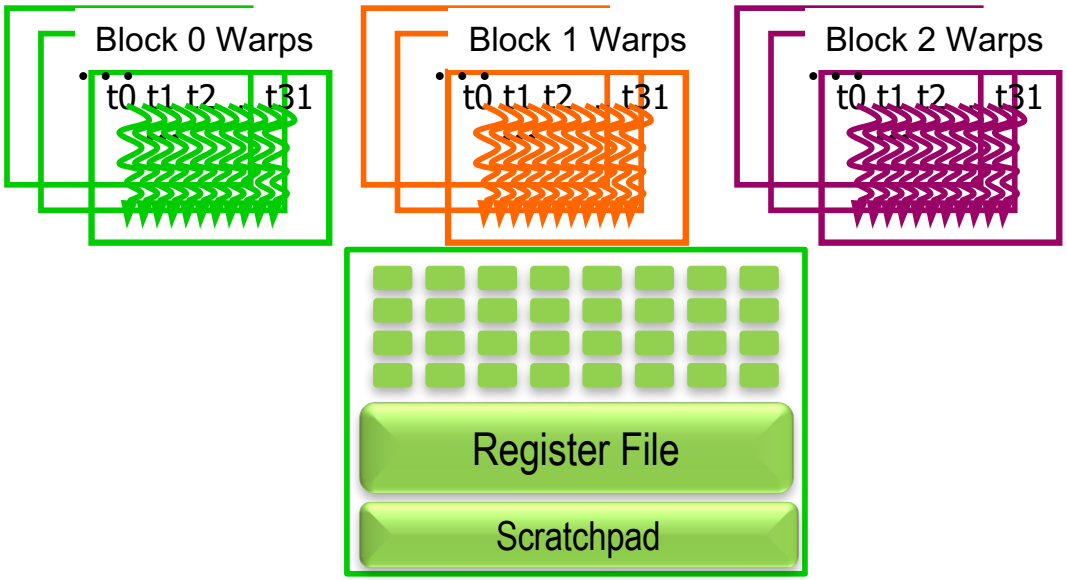
- Threads are assigned to SM in block granularity
- SM maintains thread/block idx #s
- SM manages/schedules thread execution
- Multiple blocks can be allocated to the SM
  - Based on the amount of resources (shared memory, register file etc.)

GPU Execution Model

- Blocks assigned to each SM are scheduled on the associated SIMD hardware (i.e., on the Processing Elements (PEs)).
- SM bundles threads (from various blocks) into warps (wavefronts) and runs them in lockstep on across PEs.
- An NVIDIA warp groups 32 consecutive threads together (AMD wave-fronts group 64 threads together)
- Warps are:
  - Scheduling units in SM
  - Scheduled in multiplexed and pipelined manner on the SM

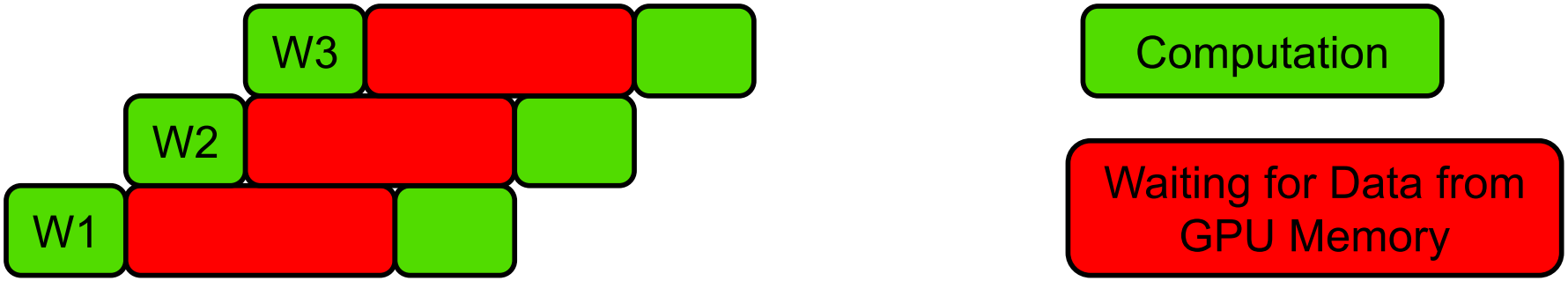
Warp Example

- If 3 blocks are assigned to an SM and each block has 256 threads, how many warps are there in an SM?
  - Each Block is divided into 256/32 = 8 Warps
  - There are 8 * 3 = 24 Warps



Tolerating Long Latencies

- Execution in an SM



GPU attempts to hide long memory latency with computation from other warps

How SMs are able to context switch between warps so quickly?

Summary

- Spawns more threads than GPU can run (some may wait)
- Organize threads into “blocks” (up to 1024 threads per block)
- Motivation: Write parallel software once and run on future hardware
- Warps associated with blocks can help in tolerating long latencies.
- GPUs support large register files (for fast context switching) and high bandwidth memories (for providing data to large number of concurrent threads)

Reading Material

- D. Kirk and W. Hwu, "Programming Massively Parallel Processors – A Hands-on Approach, 3rd Edition"
- *Patterson and Hennesy, Computer Organization and Design, 5th Edition, Appendix C-2 on GPUs*
- More background material: Jog et al., OWL: Cooperative Thread Array Aware Scheduling Techniques for Improving GPGPU performance, ASPLOS'13
- *Nvidia CUDA C Programming Guide*
  - *https://docs.nvidia.com/cuda/cuda-c-programming-guide/*