CS 677: Parallel Programming for Many-core Processors
Lecture 1

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Objectives

- Learn how to program massively parallel processors and achieve
  - High performance
  - Functionality and maintainability
  - Scalability across future generations
- Acquire technical knowledge required to achieve the above goals
  - Principles and patterns of parallel programming
  - Processor architecture features and constraints
  - Programming API, tools and techniques

Important Points

- This is an elective course. You chose to be here.
- Expect to work and to be challenged.
- If your programming background is weak, you will probably suffer.

- This course will evolve to follow the rapid pace of progress in GPU programming. It is bound to always be a little behind…

Important Points II

- At any point ask me WHY?
- You can ask me anything about the course in class, during a break, in my office, by email.
  – If you think a homework is taking too long or is wrong.
  – If you can't decide on a project.

Logistics

- Class webpage:
  http://mordohai.github.io/classes/cs677_s21.html
- Office hours: Mondays 5-6pm and by email
- Evaluation:
  - Homework assignments (40%)
  - Quizzes (20%)
  - Final project (40%)

Project

- Pick topic BEFORE middle of the semester
- I will suggest ideas and datasets, if you can’t decide
- Deliverables:
  - Project proposal (Week 8)
  - Status report (Week 12)
  - Presentation in class (Week 14)
  - Final report (around 8 pages, day of final)

Project Examples

- k-means
- Perceptron
- Boosting
  - General
  - Face detector (group of 2)
- Mean Shift
- Normal estimation for 3D point clouds

More Ideas

- Look for parallelizable problems in:
  - Image processing
  - Cryptanalysis
  - Graphics
    - GPU Gems
  - Nearest neighbor search

Version	Time Elapsed*	Step Speedup	Cumulative Speedup
C# CPU Version w/ GUI and CPU-only solver	~900 seconds	n/a	n/a
C CPU Version Command-line only CPU solver	236.65 seconds	Reference	Reference
Kernel1 Working solver on GPU	16.07 seconds	14.73x	14.73x
Kernel3 Added reduction kernel	9.18 seconds	1.75x	25.78x
Kernel4 Changed data structure to array instead of AoS	8.47 seconds	1.08x	27.94x
Kernel5 Simple caching w/ shared memory	7.25 seconds	1.17x	32.64x

GPU: Shared Memory
512 Zombies
Average FPS: 45.9

Even More…

- Particle simulations
- Financial analysis
- MCMC
- Games/puzzles

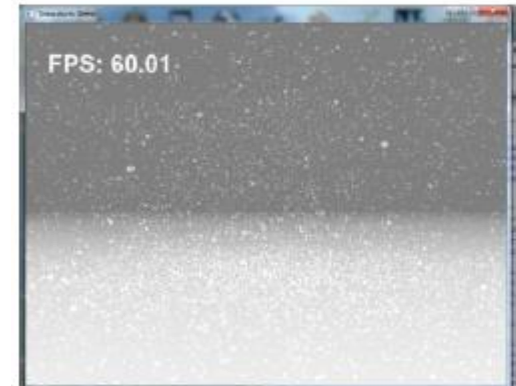
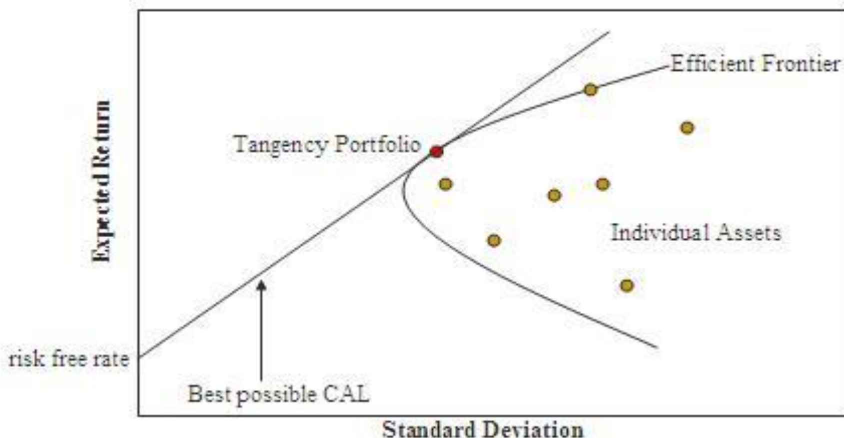


Figure 3: Snowfall

Figure 4: Interactive Snow



Resources

- Textbook
  - Kirk & Hwu. Programming Massively Parallel Processors: A Hands-on Approach. Third Edition, December 2016
  - Slides and more
    - Textbook companion site https://booksite.elsevier.com/9780128119860/
    - Companion site of second edition http://booksite.elsevier.com/9780124159921/

Online Resources

- NVIDIA. The NVIDIA CUDA Programming Guide.
  - http://docs.nvidia.com/cuda/pdf/CUDA_C_Programming_Guide.pdf
- NVIDIA. CUDA Reference Manual.
- CUDA Toolkit
  - ~~http://developer.nvidia.com/object/cuda_3_2_downloads.html~~
  - ~~http://developer.nvidia.com/cuda-toolkit-41~~
  - …
  - https://developer.nvidia.com/cuda-downloads
- POLL

Lecture Overview

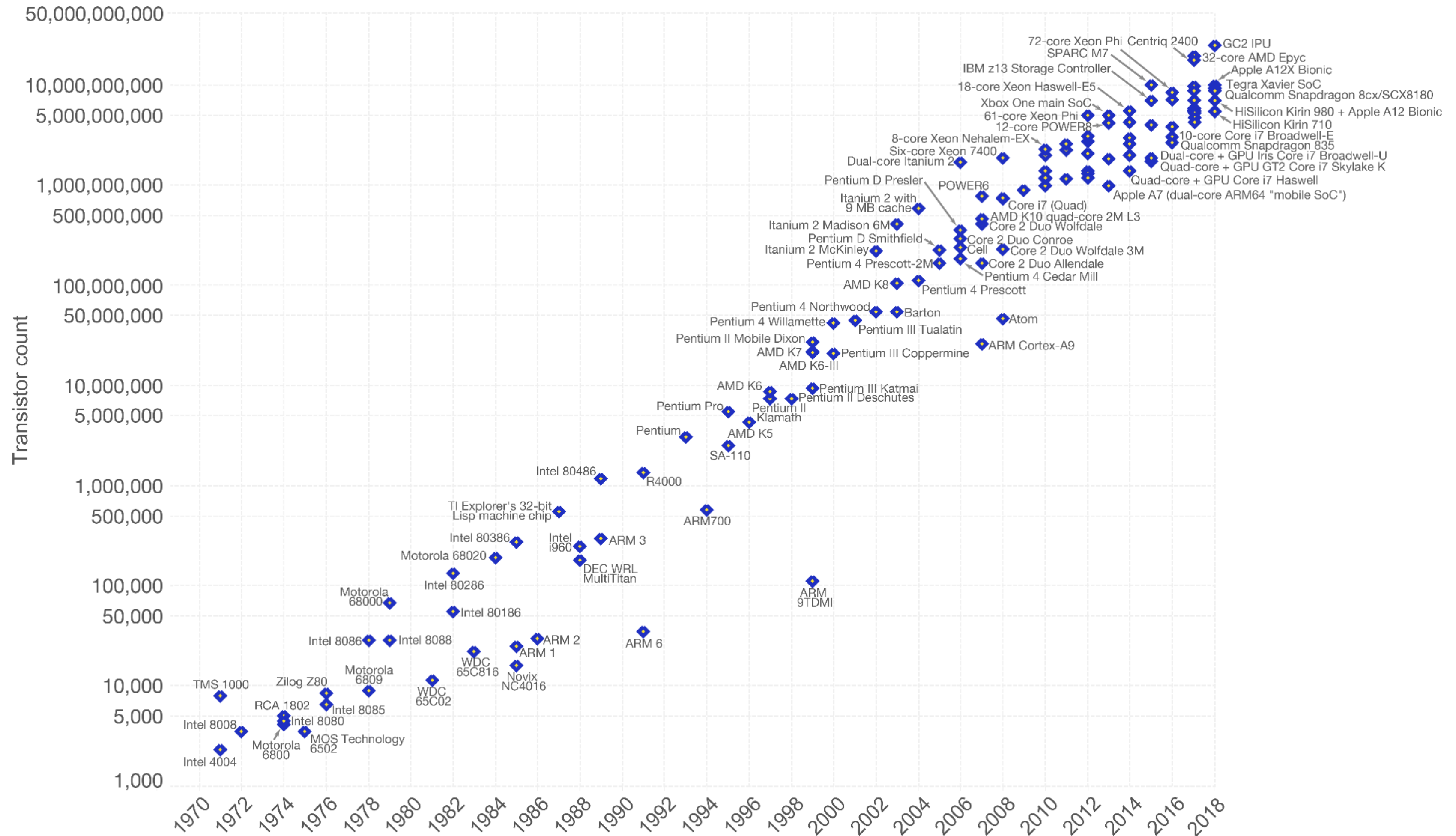
- Scaling up computational power
- GPUs
- Introduction to CUDA
- CUDA programming model

Moore’s Law (paraphrased)

“The number of transistors on an integrated circuit doubles every two years.”

– Gordon E. Moore

Moore’s Law (Visualized)



Serial Performance Scaling is Over

- Cannot continue to scale processor frequencies
  - no 10 GHz chips
- Cannot continue to increase power consumption
  - cannot melt chip
- Can continue to increase transistor density
  - as per Moore's Law

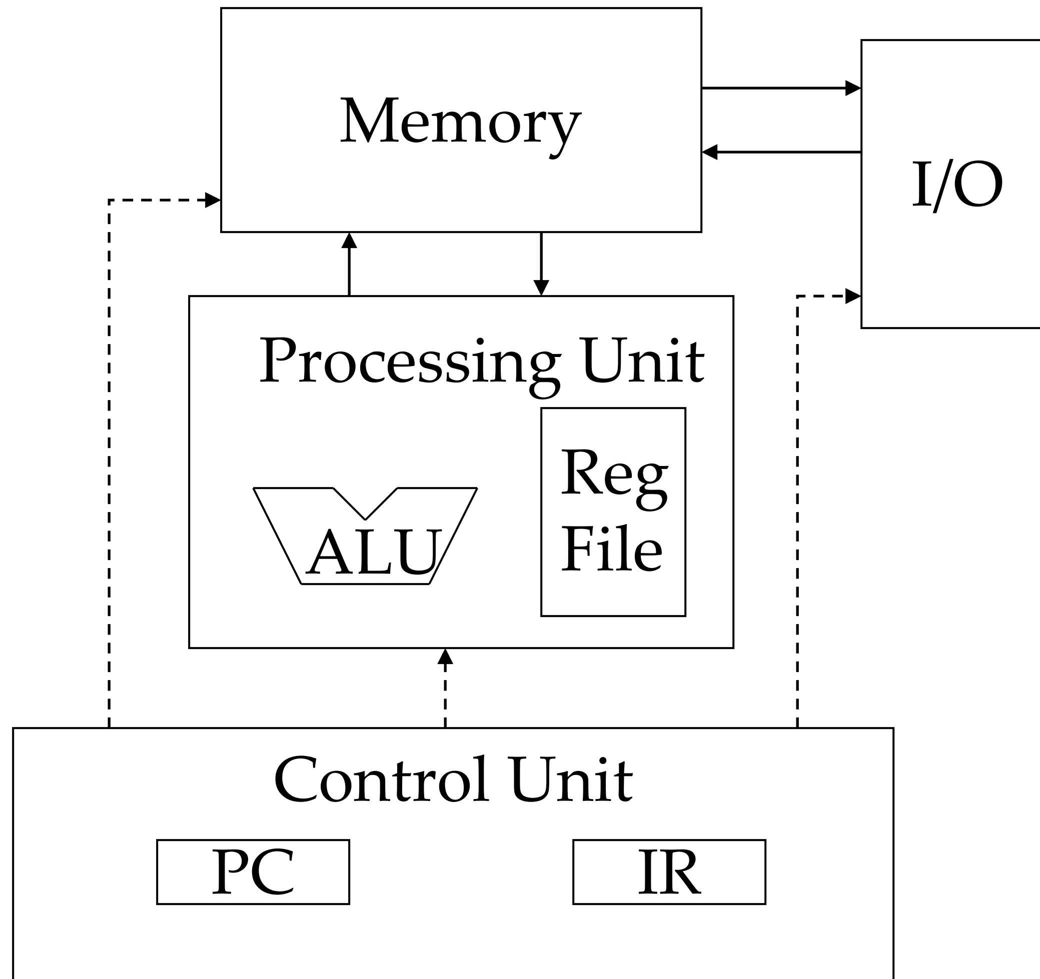
How to Use Transistors?

- Instruction-level parallelism
  - out-of-order execution, speculation, …
  - vanishing opportunities in power-constrained world
- Data-level parallelism
  - vector units, SIMD execution, …
  - increasing … SSE, AVX, Cell SPE, Clearspeed, GPU
- Thread-level parallelism
  - increasing … multithreading, multicore, manycore
  - Intel Core2, AMD Phenom, Sun Niagara, STI Cell, NVIDIA Fermi, …

The "New" Moore's Law

- Computers no longer get faster, just wider
- You *must* re-think your algorithms to be parallel !
- Data-parallel computing is most scalable solution
  - Otherwise: refactor code for ~~2 cores~~ ~~4 cores~~ ~~8 cores~~ 16 cores…
  - You will always have more data than cores – build the computation around the data

The von Neumann Model



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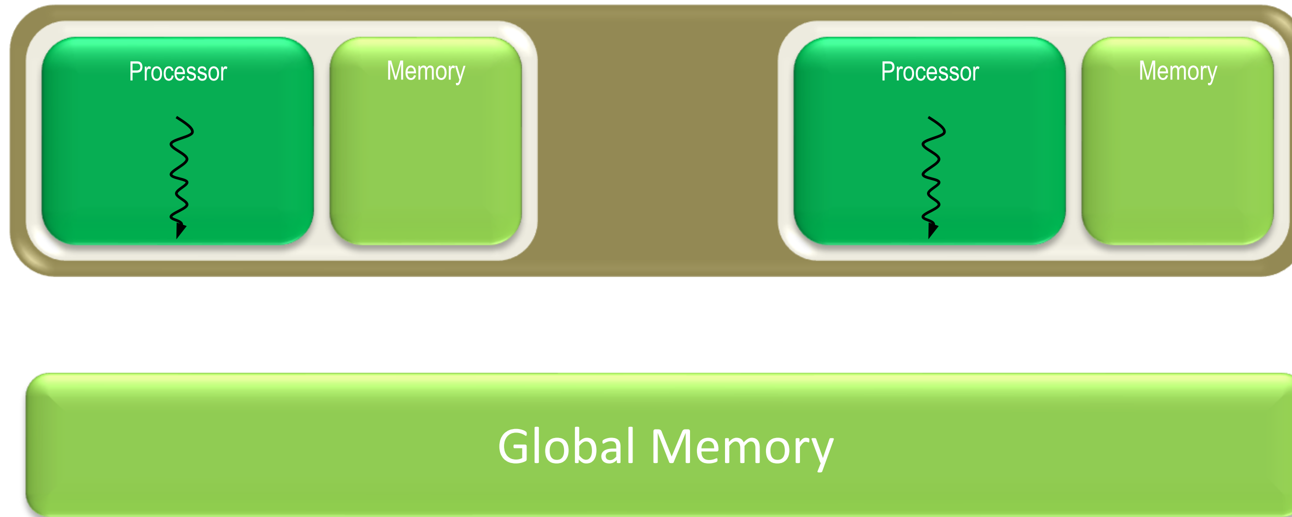
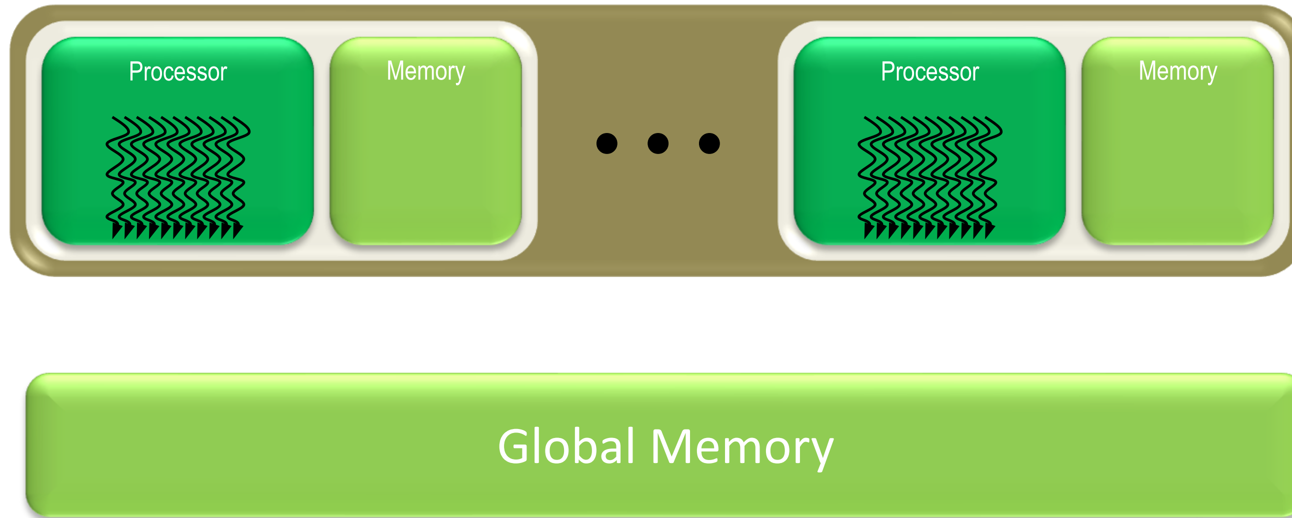
Generic Multicore Chip



- Handful of processors each supporting ~1 hardware thread
- On-chip memory near processors (cache, RAM, or both)
- Shared global memory space (external DRAM)

Generic Manycore Chip



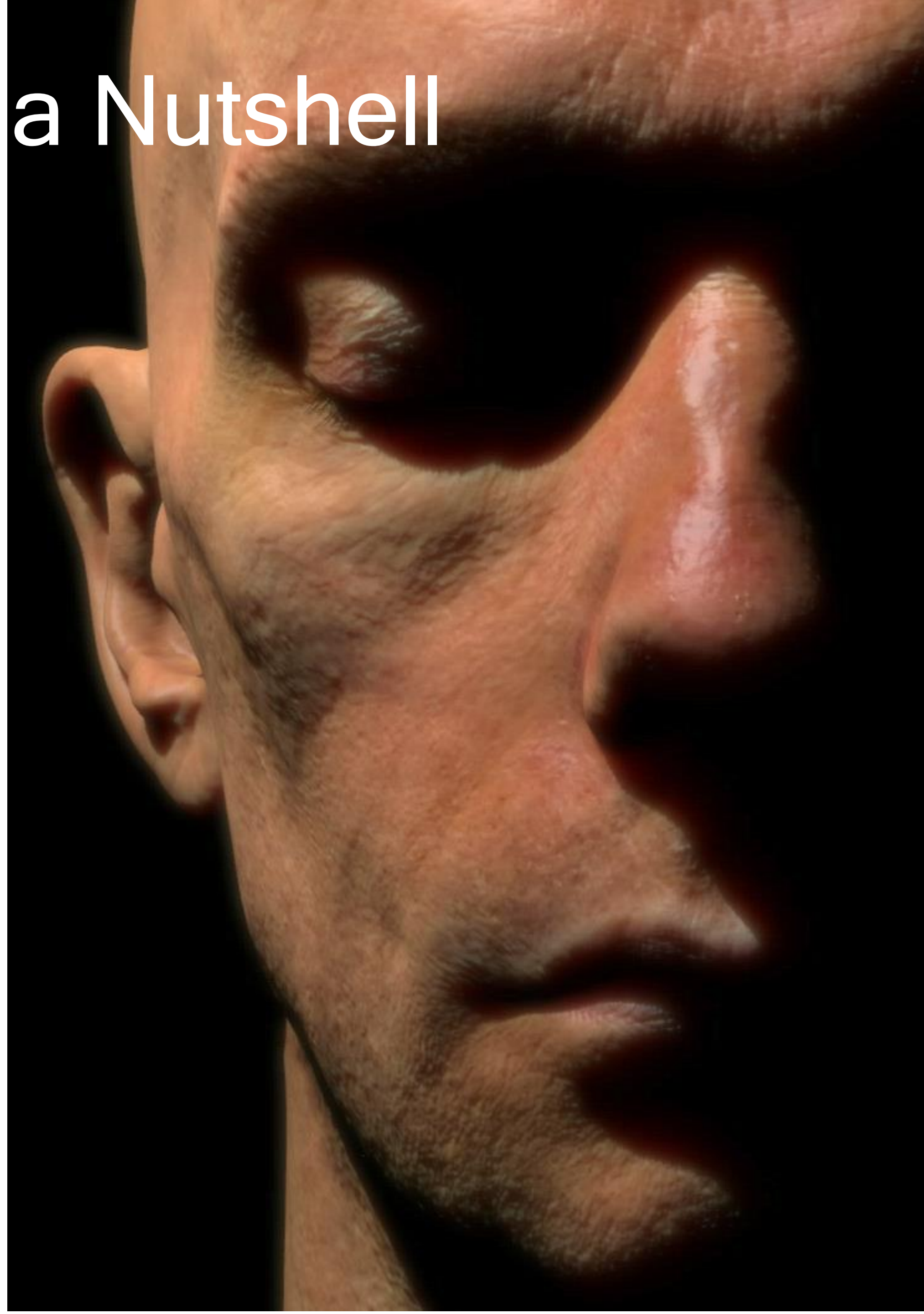
- Many processors each supporting many hardware threads
- On-chip memory near processors (cache, RAM, or both)
- Shared global memory space (external DRAM)

Enter the GPU

- Massive economies of scale
- Massively parallel

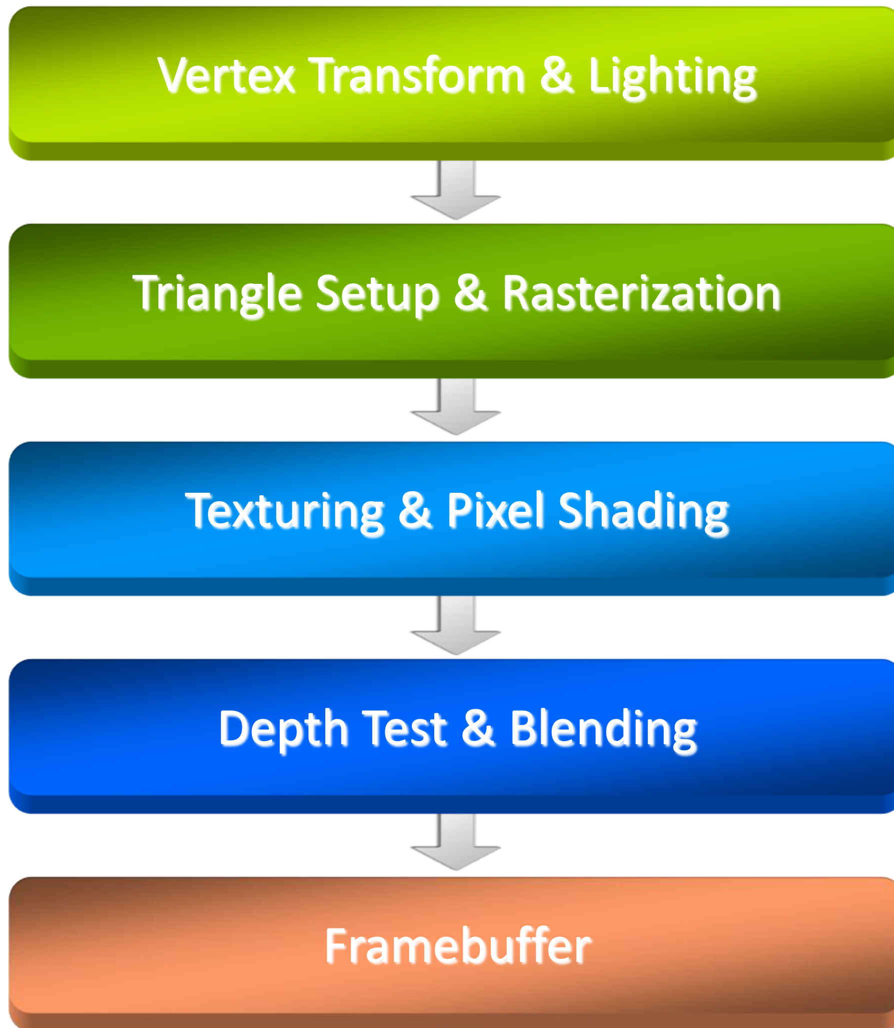
Graphics in a Nutshell

- Make great images
  - intricate shapes
  - complex optical effects
  - seamless motion
- Make them fast
  - invent clever techniques
  - use every trick imaginable
  - build monster hardware

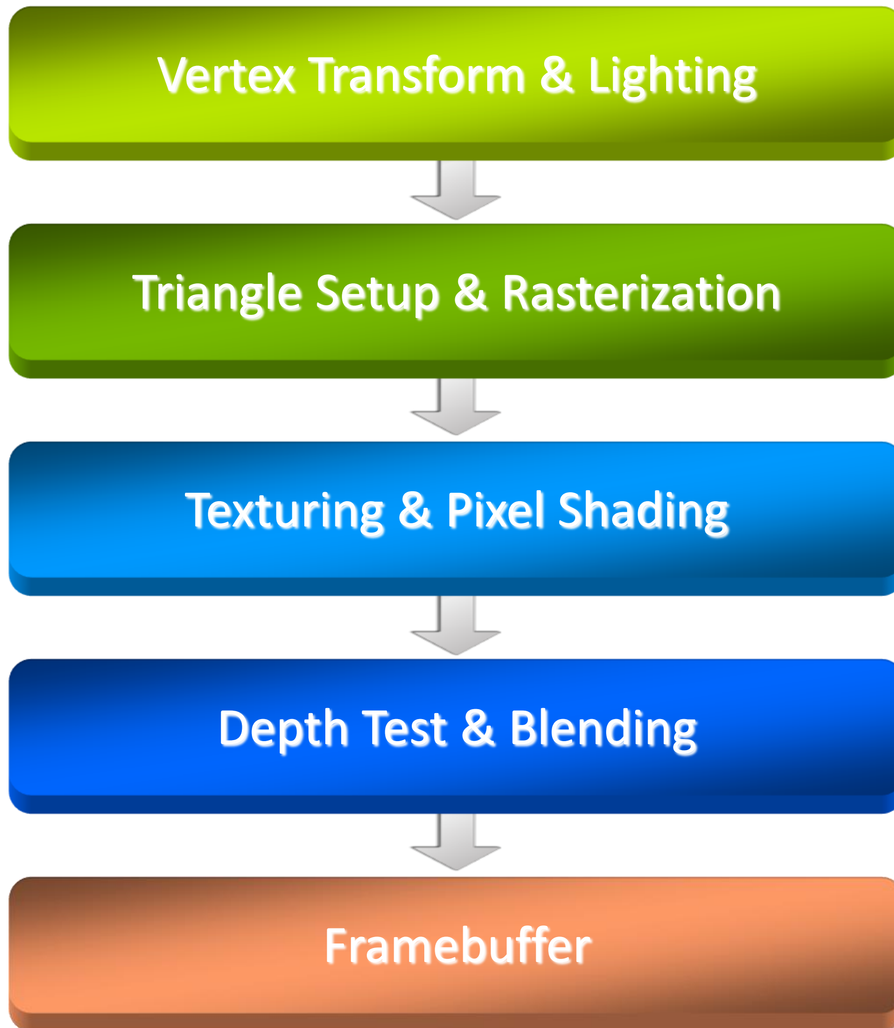


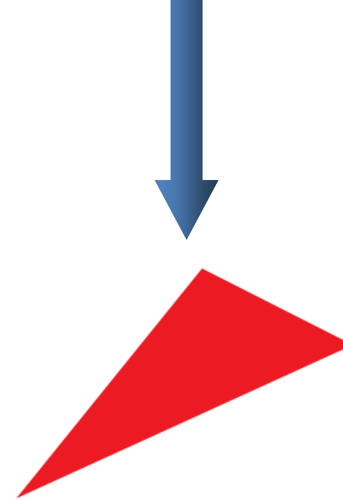
Eugene d'Eon, David Luebke, Eric Enderton
In *Proc. EGSR 2007* and *GPU Gems 3*

The Graphics Pipeline

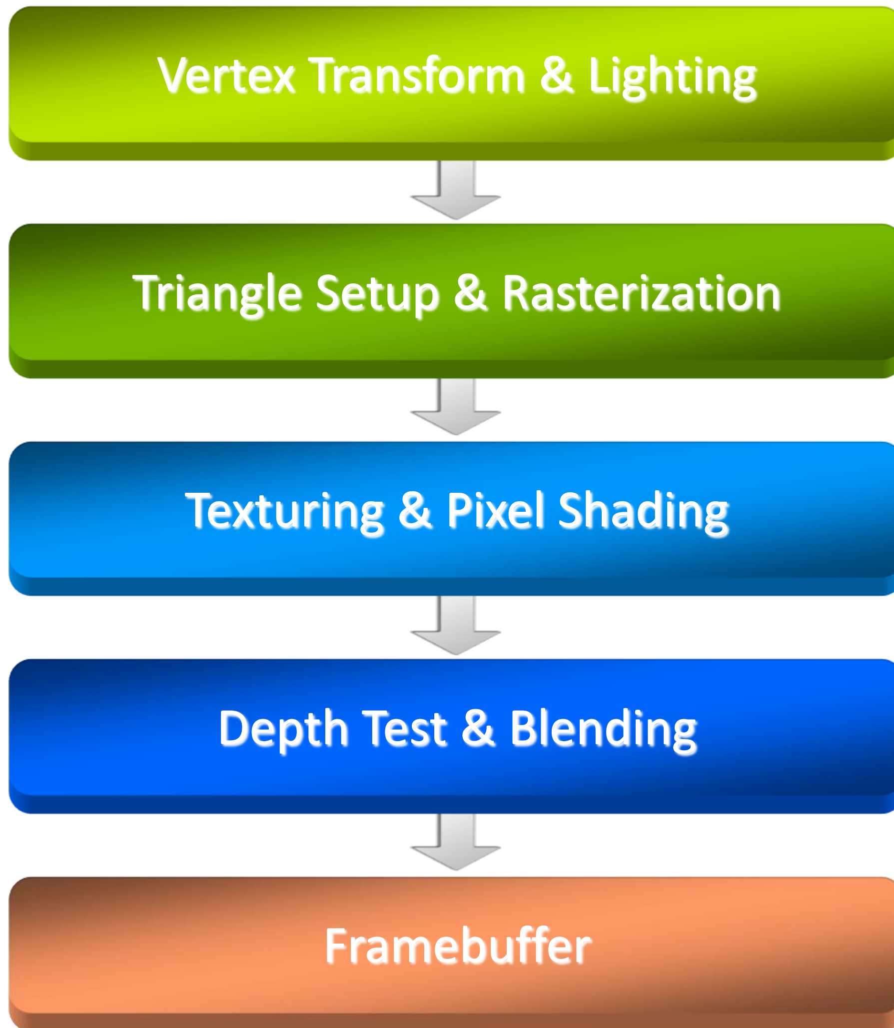


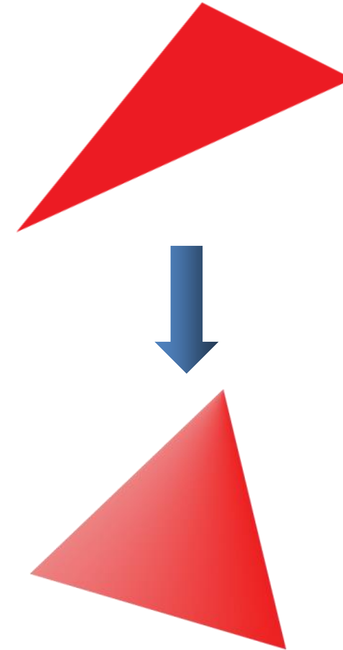
The Graphics Pipeline





The Graphics Pipeline





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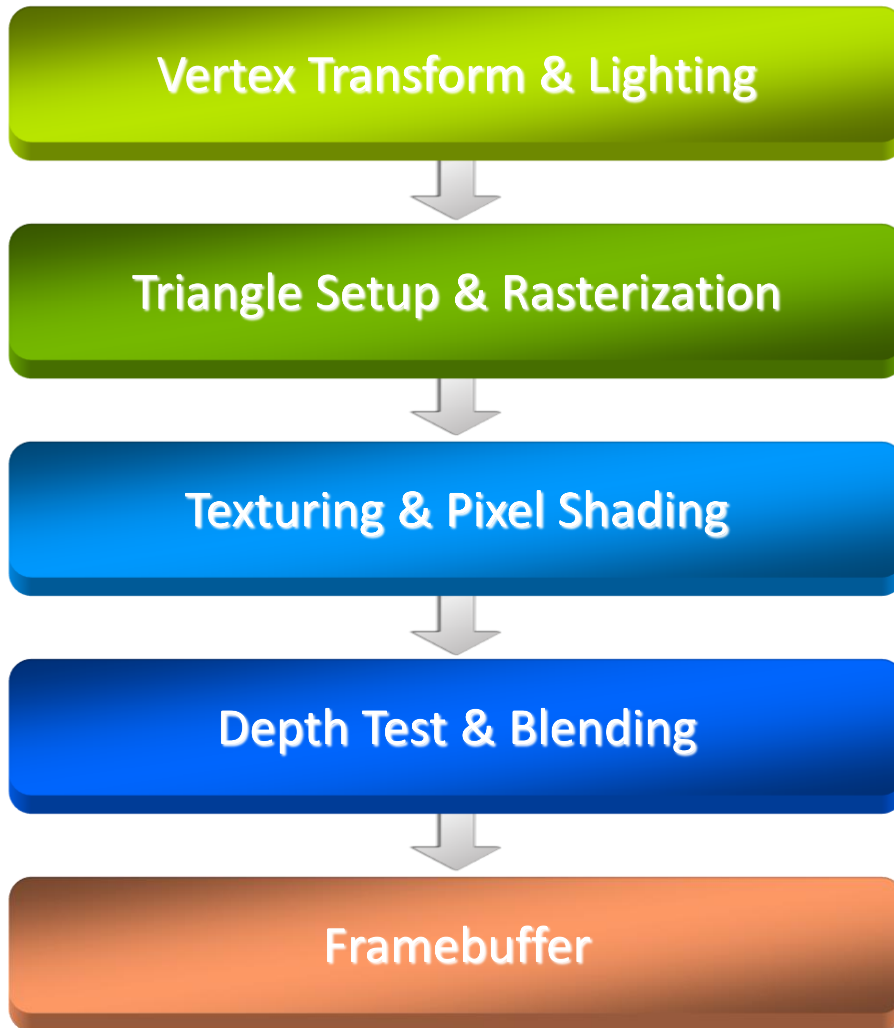
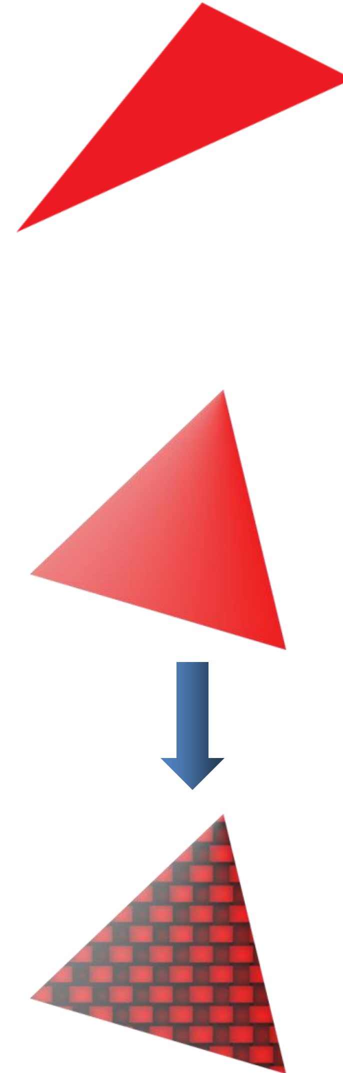
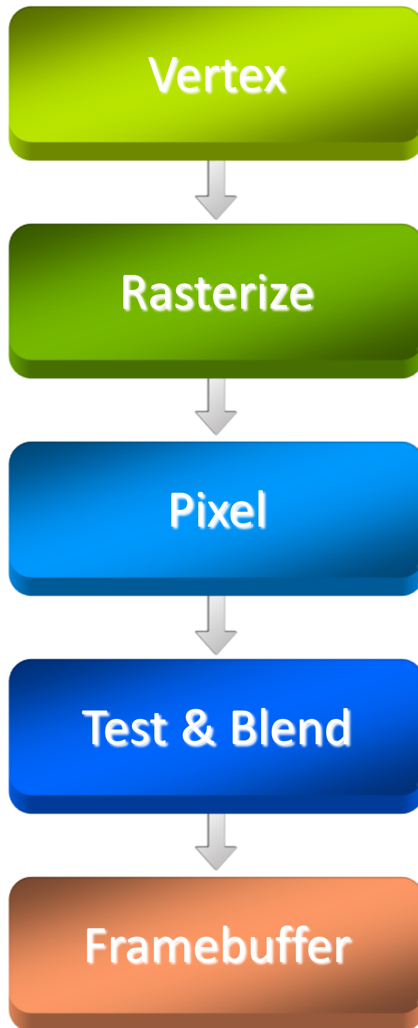


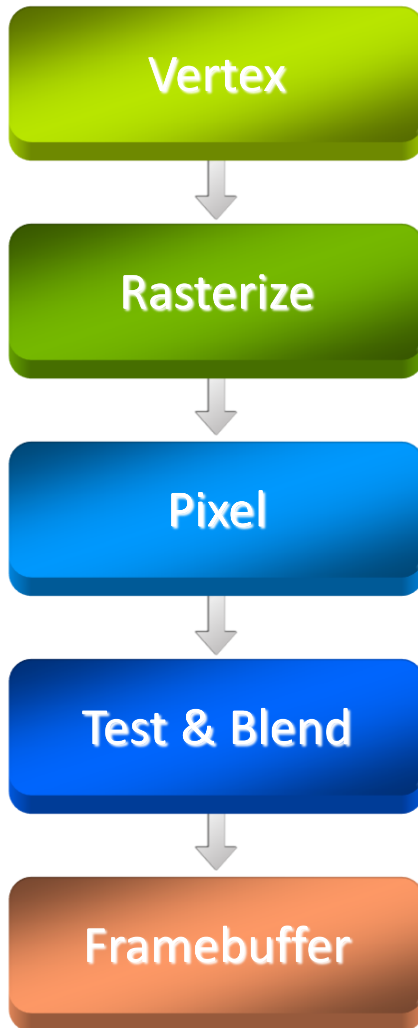


The Graphics Pipeline



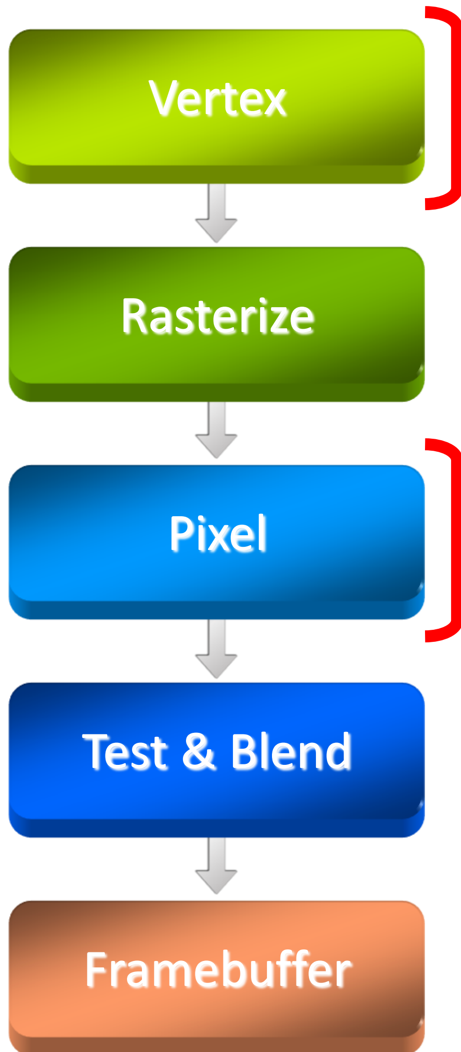
- Key abstraction of real-time graphics
- Hardware used to look like this
- One chip/board per stage
- Fixed data flow through pipeline

The Graphics Pipeline



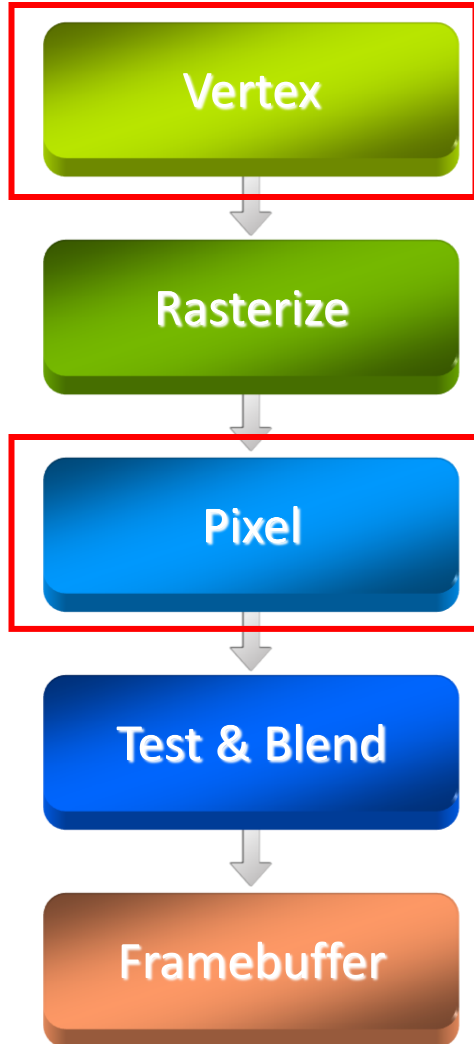
- Everything had fixed function, with a certain number of modes
- Number of modes for each stage grew over time
- Hard to optimize HW
- Developers always wanted more flexibility

The Graphics Pipeline



- Remains a key abstraction
- Hardware used to look like this
- Vertex & pixel processing became programmable, new stages added
- GPU architecture increasingly centers around shader execution

The Graphics Pipeline

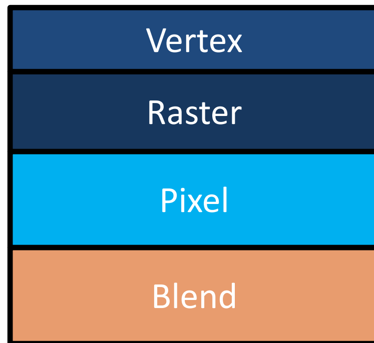


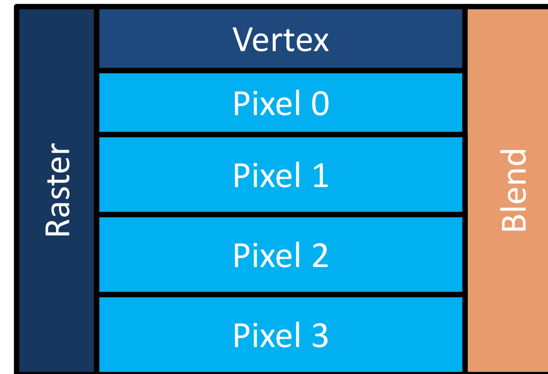
- Exposing an (at first limited) instruction set for some stages
- Limited instructions & instruction types and no control flow at first
- Expanded to full Instruction Set Architecture

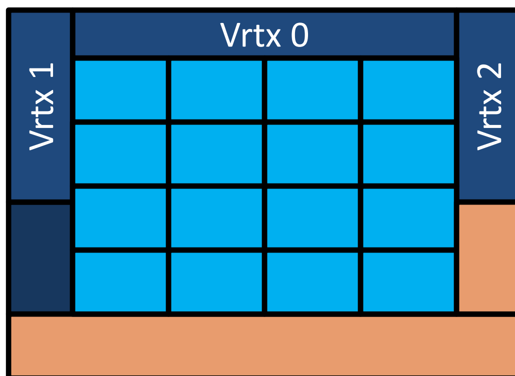
Why GPUs scale so nicely

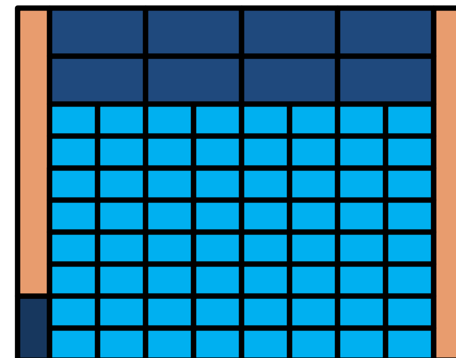
- Workload and Programming Model provide lots of parallelism
- Applications provide large groups of vertices at once
  - Vertices can be processed in parallel
  - Apply same transform to all vertices
- Triangles contain many pixels
  - Pixels from a triangle can be processed in parallel
  - Apply same shader to all pixels
- Very efficient hardware to hide serialization bottlenecks

With Moore's Law…



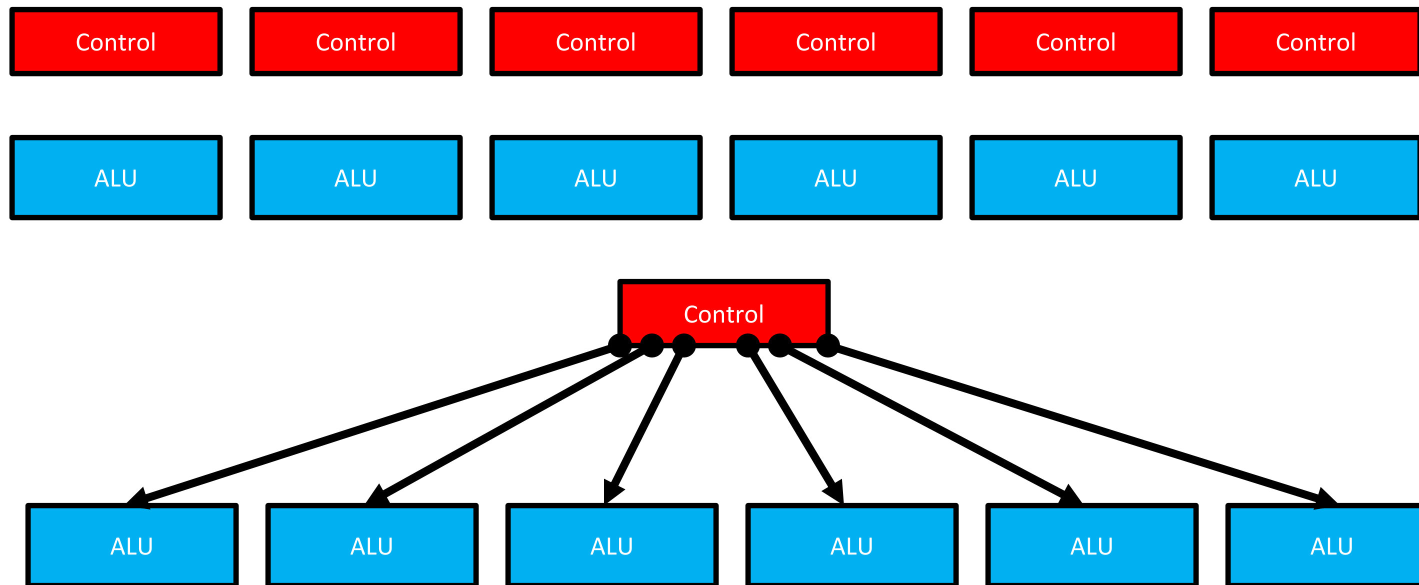






More Efficiency

- Note that we do the same thing for lots of pixels/vertices



- A warp = 32 threads launched together
- Usually, execute together as well

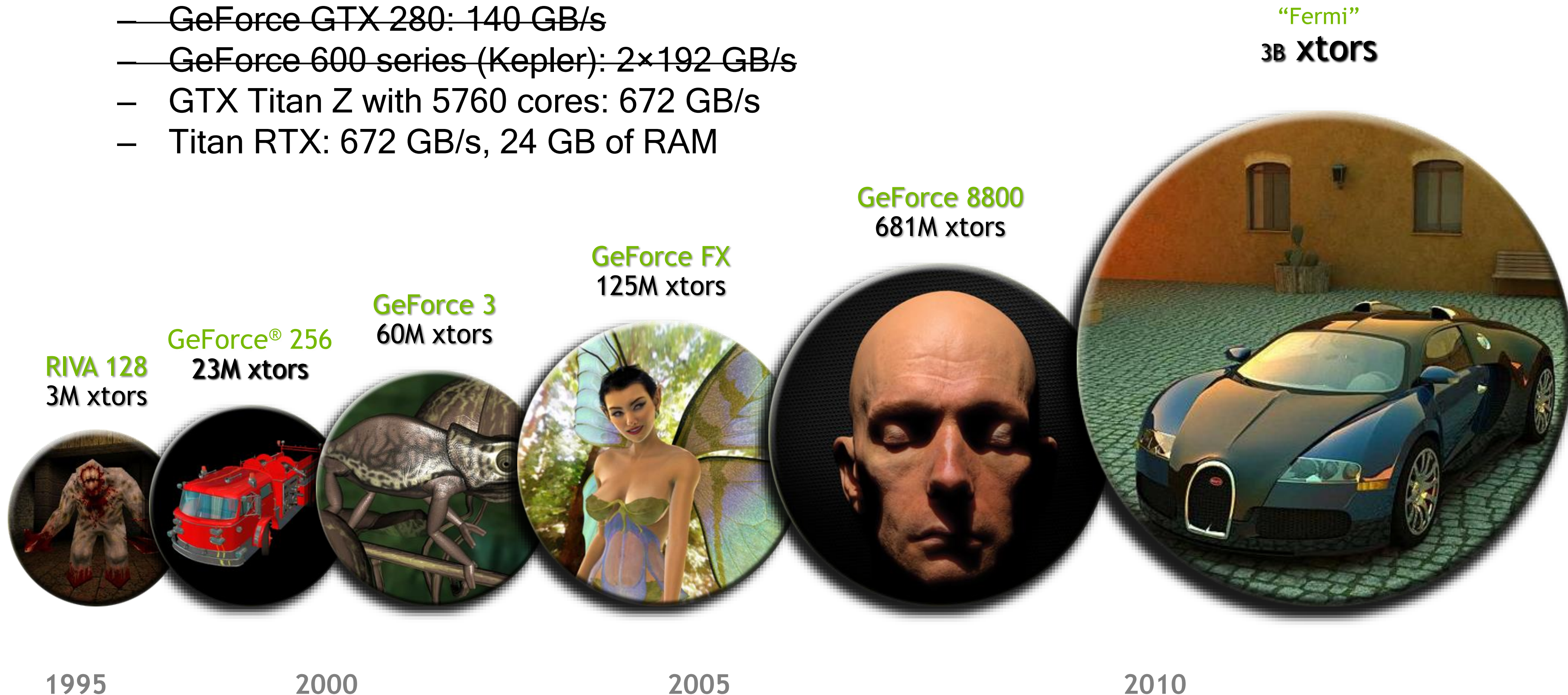
Early GPGPU

- All this performance attracted developers
- To use GPUs, they re-expressed their algorithms as graphics computations
- Very tedious, limited usability
- Still had some very nice results

- This was the lead up to CUDA

GPU Evolution

- High throughput computation
  - ~~GeForce GTX 280: 933 GFLOPS~~
  - ~~GeForce 600 series (Kepler): 2×2811 GFLOPS~~
  - GTX Titan Z with 5760 cores: 8000 GFLOPS
  - Titan RTX, 4608 cores, 576 Turing Tensor Cores, 72 RT cores: 130 TFLOPS
- High bandwidth
  - ~~GeForce GTX 280: 140 GB/s~~
  - ~~GeForce 600 series (Kepler): 2×192 GB/s~~
  - GTX Titan Z with 5760 cores: 672 GB/s
  - Titan RTX: 672 GB/s, 24 GB of RAM



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- High bandwidth
  - ~~GeForce~~
  - ~~GeForce~~
  - GTX Tita
  - Titan RT

RIVA 128
3M xtors

GeForce® 2
23M xtors

1995 2000 2005 2010

Lessons from Graphics Pipeline

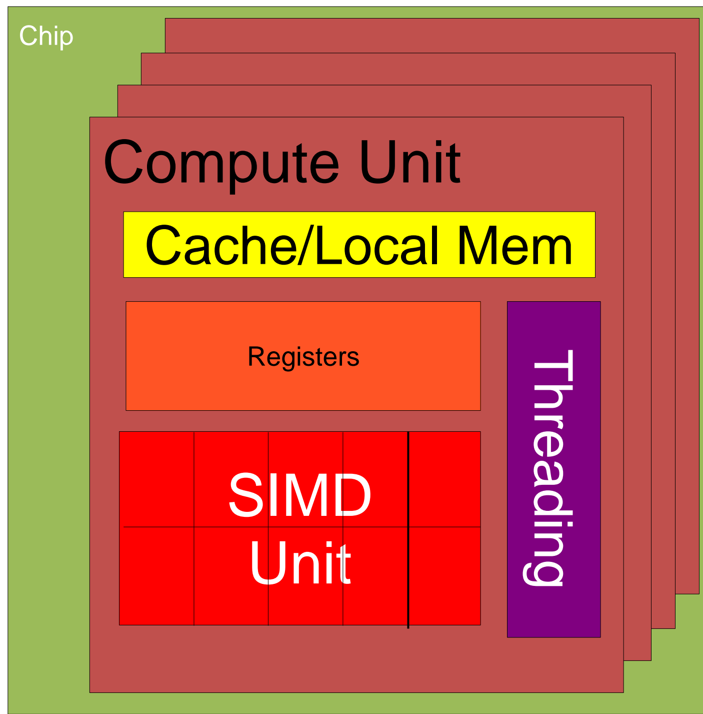
- Throughput is paramount
  - must paint every pixel within frame time
  - scalability
  - video games have strict time requirements: bare minimum: 2 Mpixels * 60 fps * 2 = 240 Mthread/s
- Create, run, & retire lots of threads very rapidly
  - measured 14.8 Gthread/s on `increment()` kernel (2010)
- Use multithreading to hide latency
  - 1 stalled thread is OK if 100 are ready to run

Why is this different from a CPU?

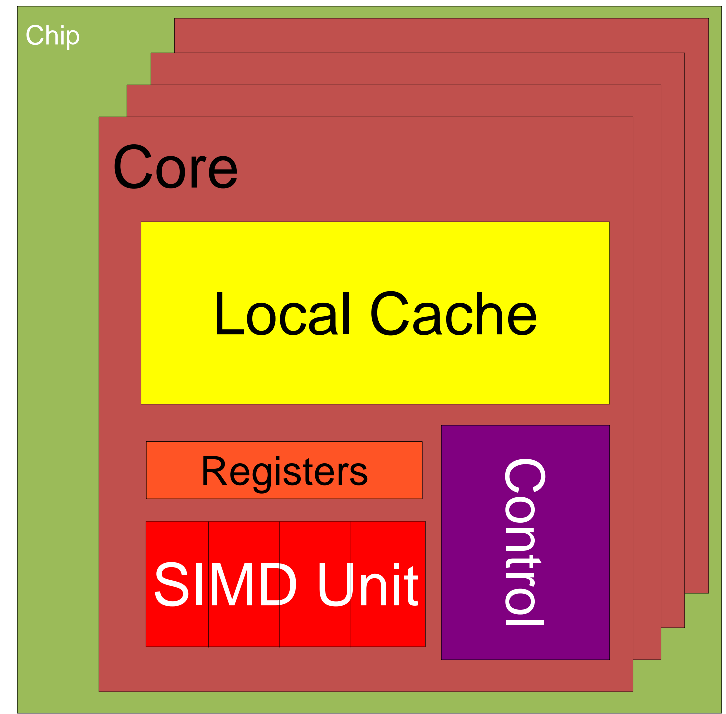
- Different goals produce different designs
  - GPU assumes workload is highly parallel
  - CPU must be good at everything, parallel or not
- CPU: minimize latency experienced by 1 thread
  - big on-chip caches
  - sophisticated control logic
- GPU: maximize throughput of all threads
  - # threads in flight limited by resources => lots of resources (registers, bandwidth, etc.)
  - multithreading can hide latency => skip the big caches
  - share control logic across many threads

Design Philosophies

GPU
Throughput Oriented Cores



CPU
Latency Oriented Cores



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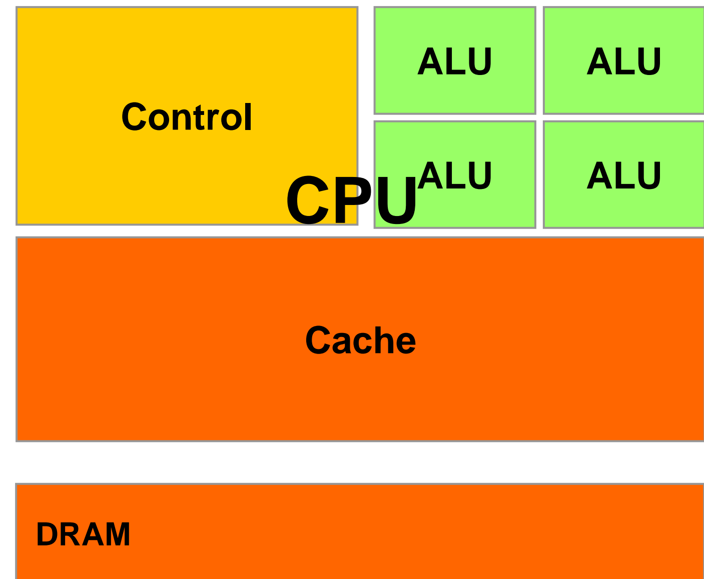
CPUs: Latency Oriented Design

- Large caches
  - Convert long latency memory accesses to short latency cache accesses
- Sophisticated control
  - Branch prediction for reduced branch latency
  - Data forwarding for reduced data latency
- Powerful ALU
  - Reduced operation latency



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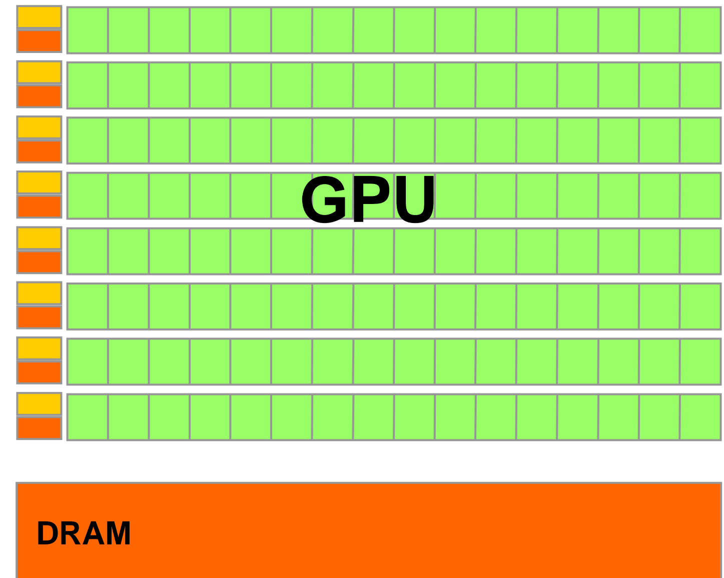
GPUs: Throughput Oriented Design

- Small caches
  - To boost memory throughput
- Simple control
  - No branch prediction
  - No data forwarding
- Energy efficient ALUs
  - Many, long latency but heavily pipelined for high throughput
- Require massive number of threads to tolerate latencies



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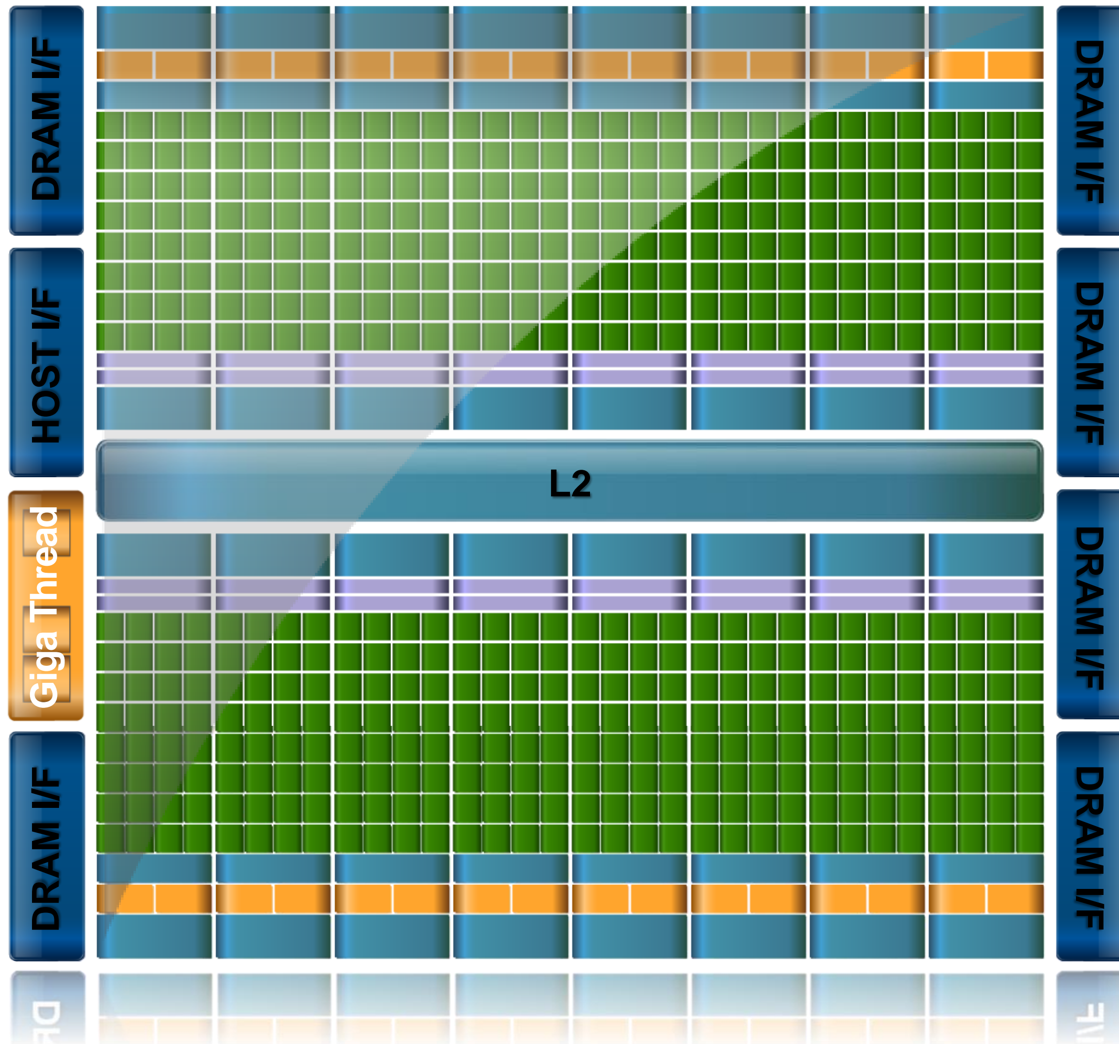
SMs and SPs

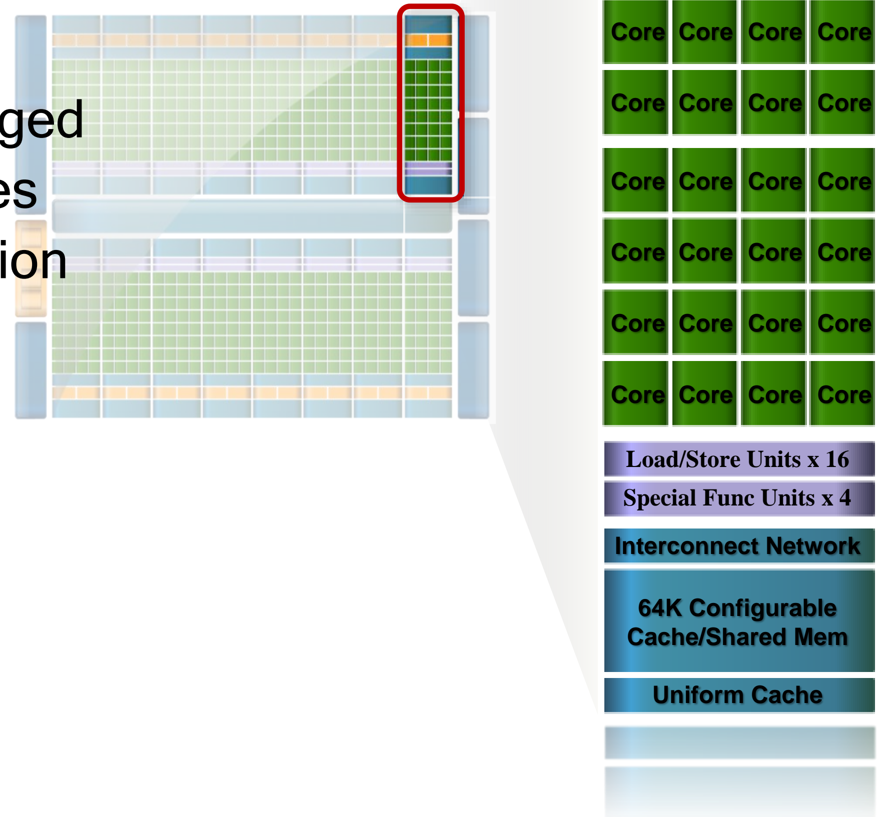
- SM: Streaming Multiprocessor
- SP: Streaming Processor (core)

NVIDIA GPU Architecture



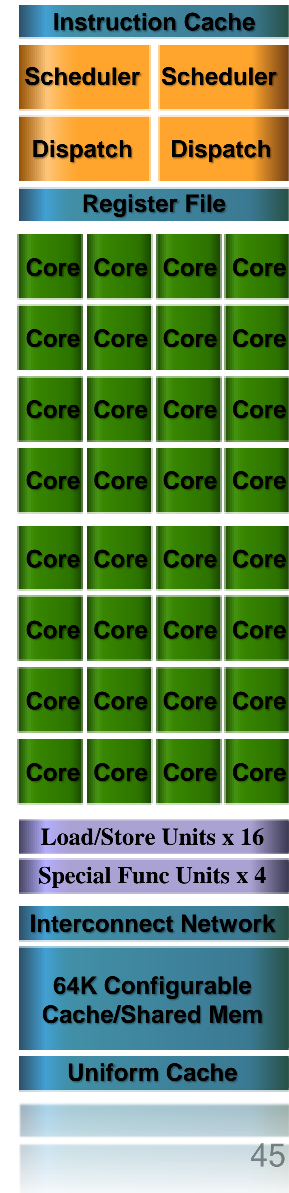
SM Multiprocessor

- 32 CUDA Cores per SM (512 total)
- Direct load/store to memory
  - High bandwidth (Hundreds GB/sec)
- 64KB of fast, on-chip RAM
  - Software or hardware-managed
  - Shared amongst CUDA cores
  - Enables thread communication

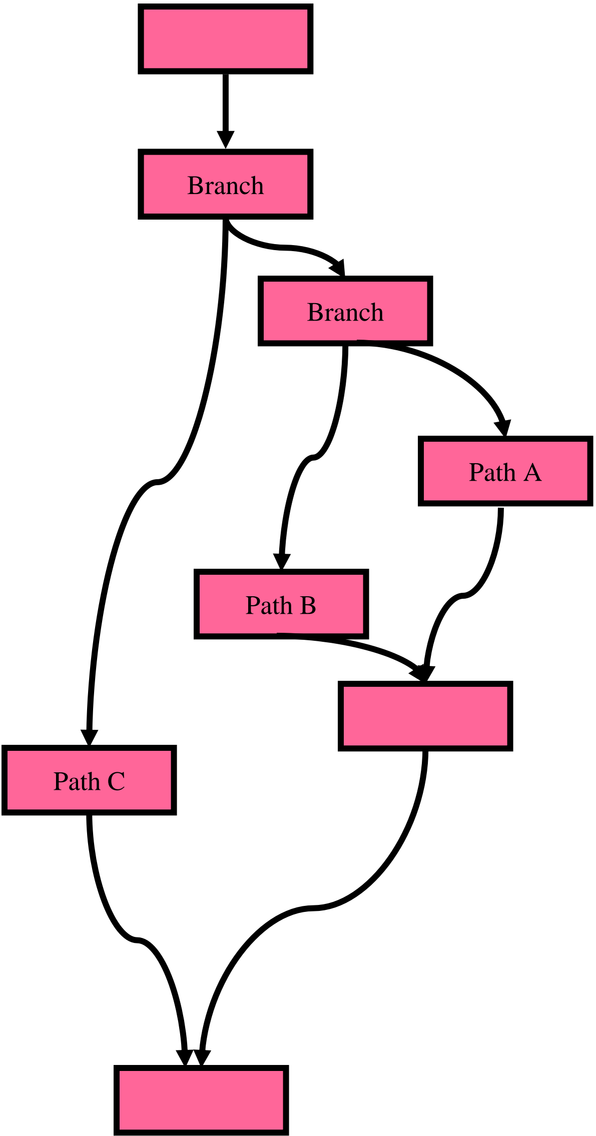


Key Architectural Ideas

- SIMT (Single Instruction Multiple Thread) execution
  - threads run in groups of 32 called warps
  - threads in a warp share instruction unit (IU)
  - HW automatically handles divergence
- Hardware multithreading
  - HW resource allocation & thread scheduling
  - HW relies on threads to hide latency
- Threads have all resources needed to run
  - any warp not waiting for something can run
  - context switching is (basically) free



Control Flow Divergence



Enter CUDA

- Scalable parallel programming model
- Minimal extensions to familiar C/C++ environment
- Heterogeneous serial-parallel computing

CUDA: Scalable parallel programming

- Augment C/C++ with minimalist abstractions
  - let programmers focus on parallel algorithms
  - *not* mechanics of a parallel programming language

- Provide straightforward mapping onto hardware
  - good fit to GPU architecture
  - maps well to multi-core CPUs too

- Scale to 100s of cores & 10,000s of parallel threads
  - GPU threads are lightweight – create / switch is free
  - GPU needs 1000s of threads for full utilization

Key Parallel Abstractions in CUDA

- Hierarchy of concurrent threads

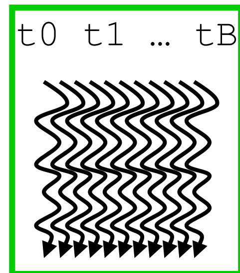
- Lightweight synchronization primitives

- Shared memory model for cooperating threads

Hierarchy of concurrent threads

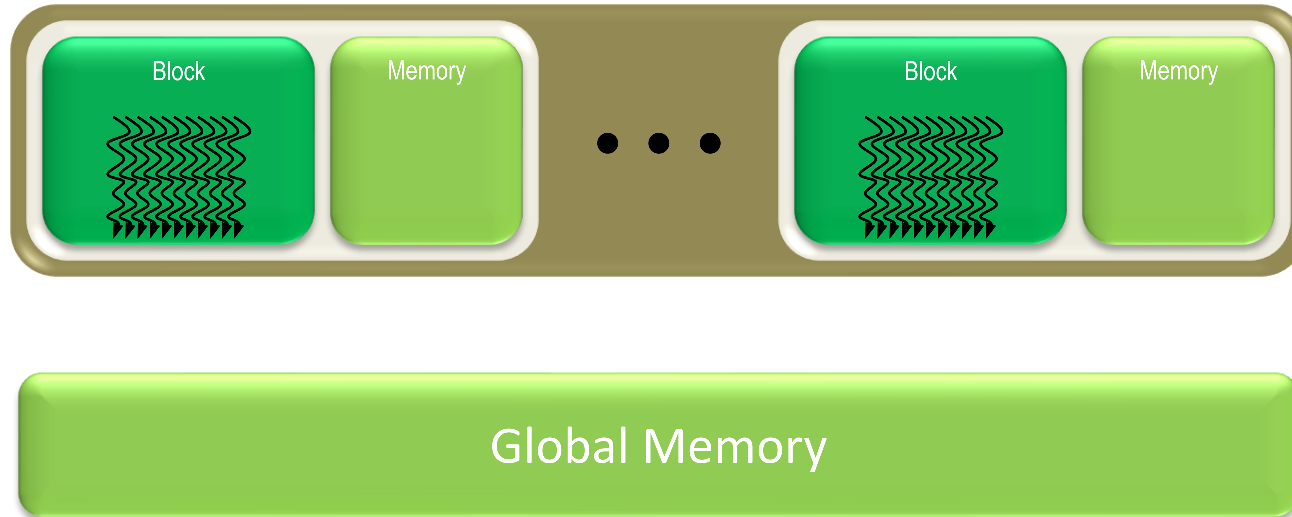
- Parallel kernels composed of many threads
  - all threads execute the same sequential program

- Threads are grouped into thread blocks
  - threads in the same block can cooperate



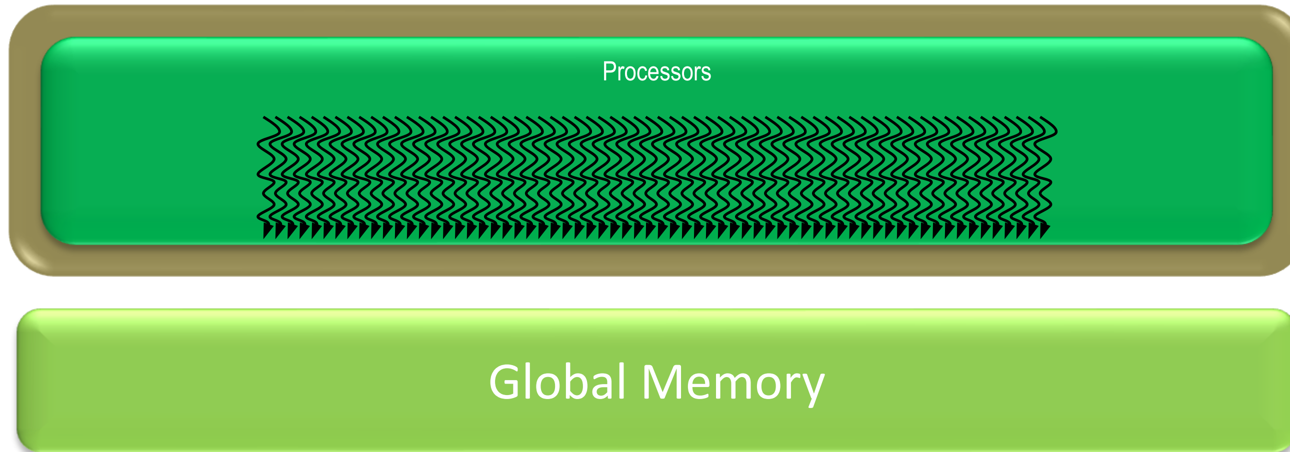
- Threads/blocks have unique IDs

CUDA Model of Parallelism



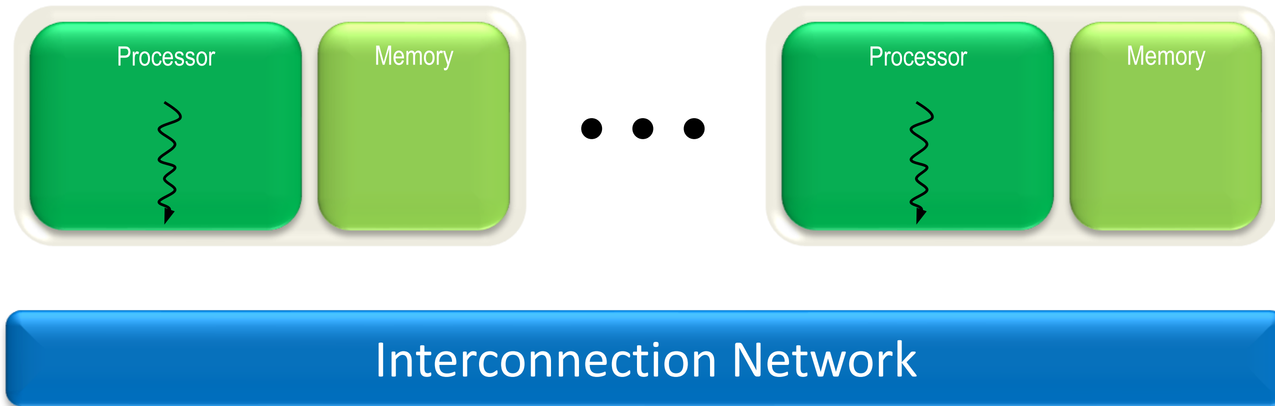
- CUDA virtualizes the physical hardware
  - a thread is a virtualized scalar processor (registers, PC, state)
  - a block is a virtualized multiprocessor (threads, shared memory)
- Scheduled onto physical hardware without pre-emption
  - threads/blocks launch & run to completion
  - blocks should be independent

NOT: Flat Multiprocessor



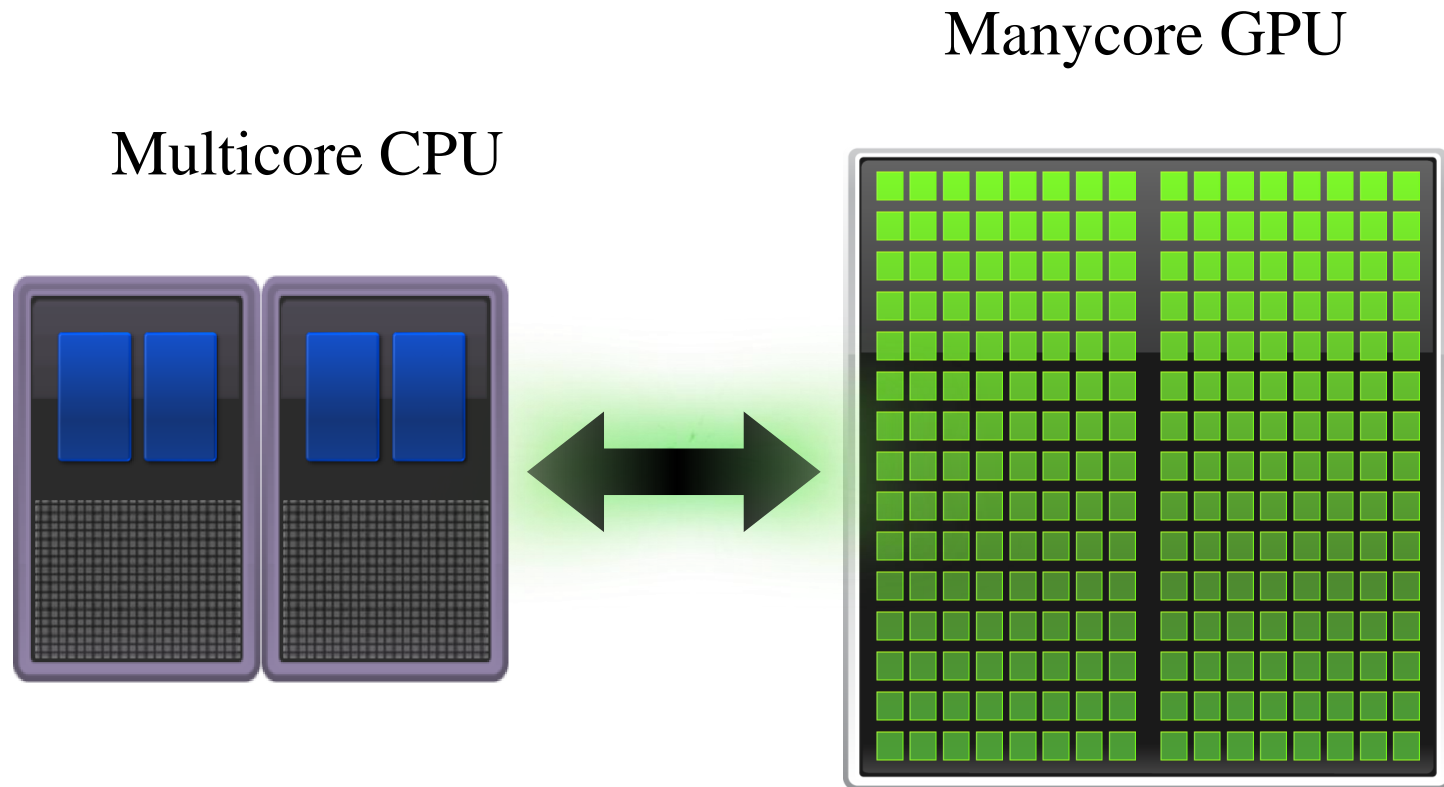
- Global synchronization isn't cheap
- Global memory access times are expensive

NOT: Distributed Processors



- Distributed computing is a different setting
- cf. BSP (Bulk Synchronous Parallel) model, MPI

Heterogeneous Computing



CUDA Programming Model

Overview

- CUDA programming model – basic concepts and data types
- CUDA application programming interface - basic
- Simple examples to illustrate basic concepts and functionalities
- Performance features will be covered later

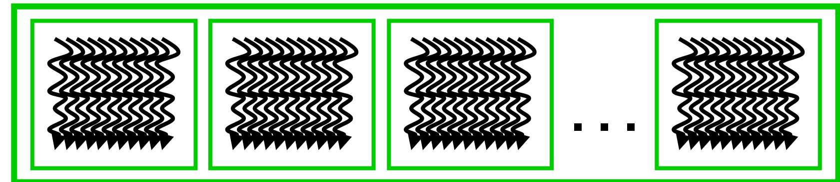
CUDA - C

- Integrated host+device app C program
  - Serial or modestly parallel parts in **host** C code
  - Highly parallel parts in **device** SPMD kernel C code

Serial Code (host)

Parallel Kernel (device)

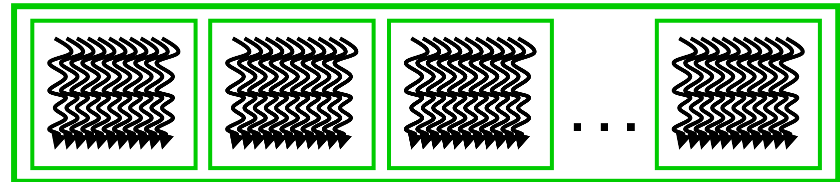
KernelA<<< nBlk, nTid >>>(args);



Serial Code (host)

Parallel Kernel (device)

KernelB<<< nBlk, nTid >>>(args);



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CUDA Devices and Threads

- A compute device
  - Is a coprocessor to the CPU or host
  - Has its own DRAM (device memory)
  - Runs many threads in parallel
  - Is typically a GPU but can also be another type of parallel processing device
- Data-parallel portions of an application are expressed as device kernels which run on many threads
- Differences between GPU and CPU threads
  - GPU threads are extremely lightweight
    - Very little creation overhead
  - GPU needs 1000s of threads for full efficiency
    - Multi-core CPU needs only a few

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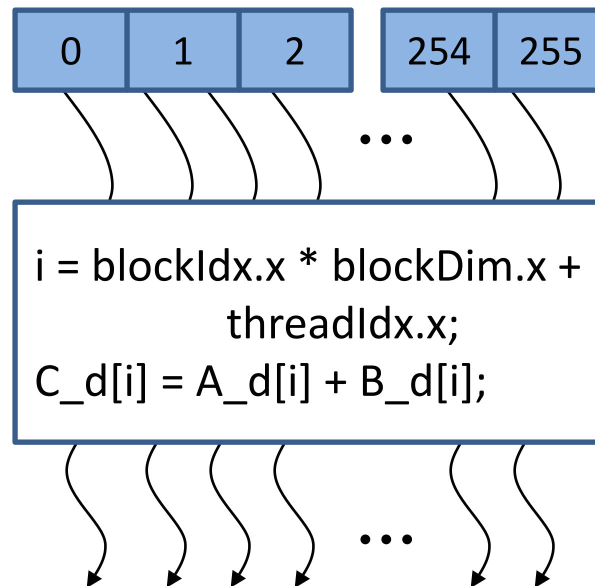
Arrays of Parallel Threads

- A CUDA kernel is executed by a grid (array) of threads
  - All threads run the same code
  - Each thread has an ID that it uses to compute memory addresses and make control decisions



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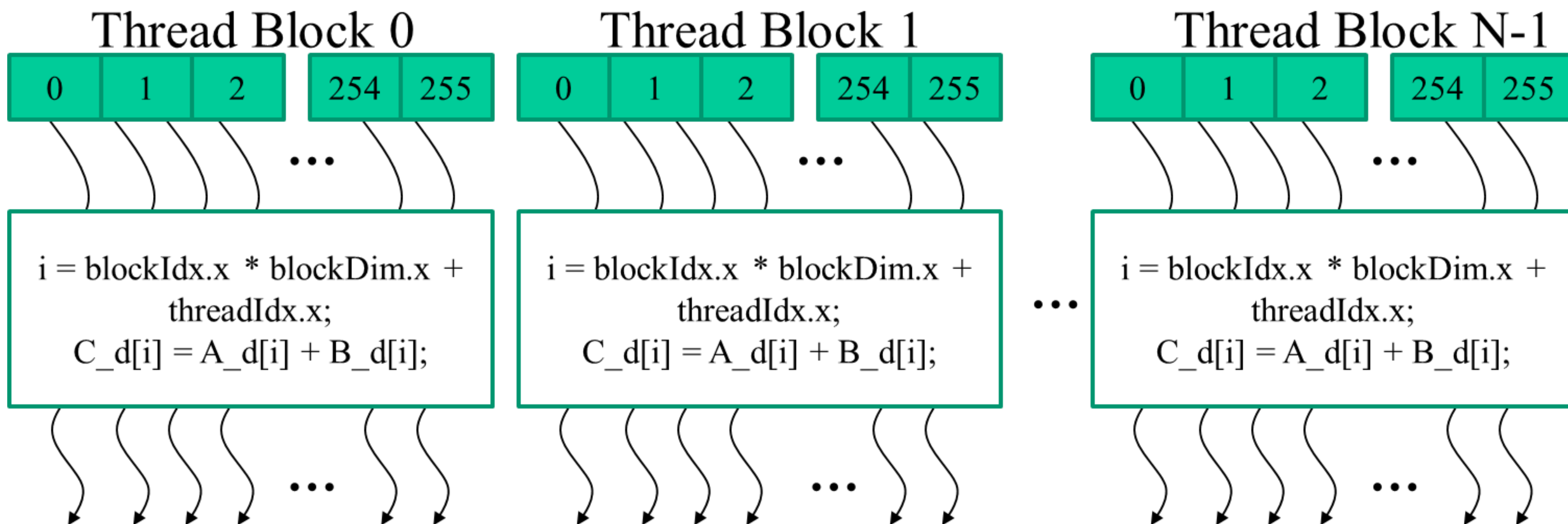
Thread Blocks: Scalable Cooperation

- Divide monolithic thread array into multiple blocks
  - Threads within a block cooperate via **shared memory, atomic operations** and **barrier synchronization**
  - Threads in different blocks cannot cooperate



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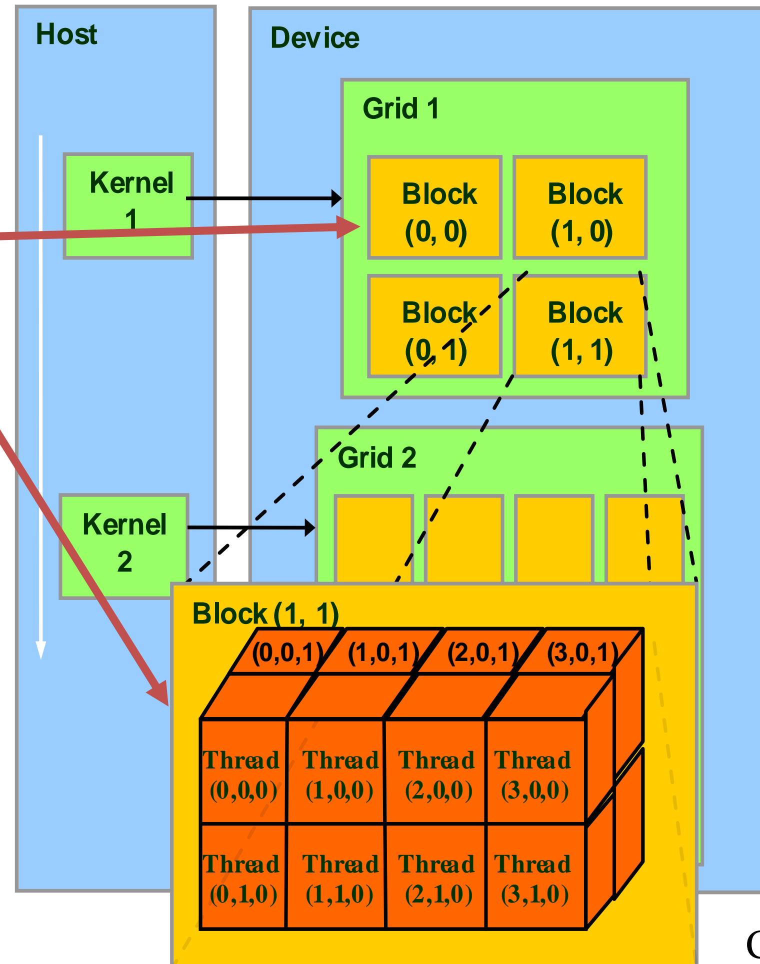
Block IDs and Thread IDs

- Each thread uses IDs to decide what data to work on
  - Block ID: 1D or 2D
  - Thread ID: 1D, 2D, or 3D
- Simplifies memory addressing when processing multidimensional data
  - Image processing
  - Solving PDEs on volumes
  - …



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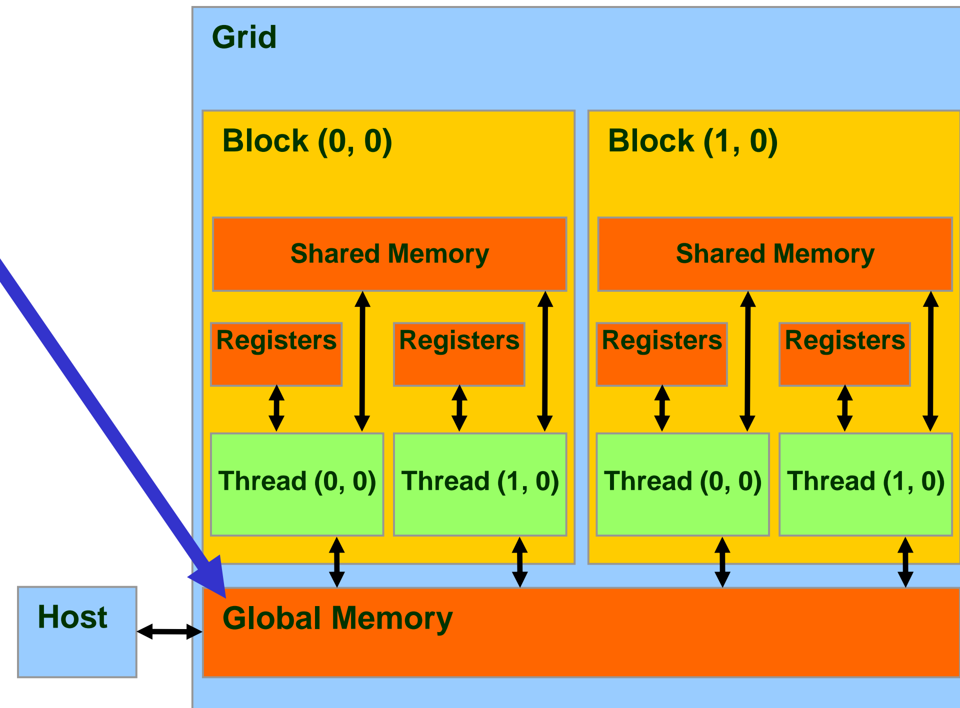
CUDA Memory Model Overview

- Global memory
  - Main means of communicating R/W Data between host and device
  - Contents visible to all threads
  - Long latency access
- We will focus on global memory for now
  - Constant and texture memory will come later



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CUDA API Highlights: Easy and Lightweight

- The API is an extension to the ANSI C programming language
  → Low learning curve

- The hardware is designed to enable lightweight runtime and driver
  → High performance

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Extended C

- Declspecs
  - global, device, shared, local, constant
- Keywords
  - threadIdx, blockIdx
- Intrinsics
  - __syncthreads
- Runtime API
  - Memory, symbol, execution management
- Function launch

```
__device__ float filter[N];

__global__ void convolve (float *image)  {

__shared__ float region[M];
  ...

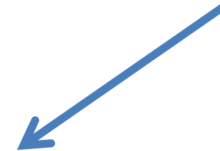
  region[threadIdx] = image[i];

  __syncthreads()
  ...

  image[j] = result;
}

// Allocate GPU memory
void *myimage; cudaMalloc(myimage, bytes)

// 100 blocks, 10 threads per block
convolve<<<100, 10>>> (myimage);
```



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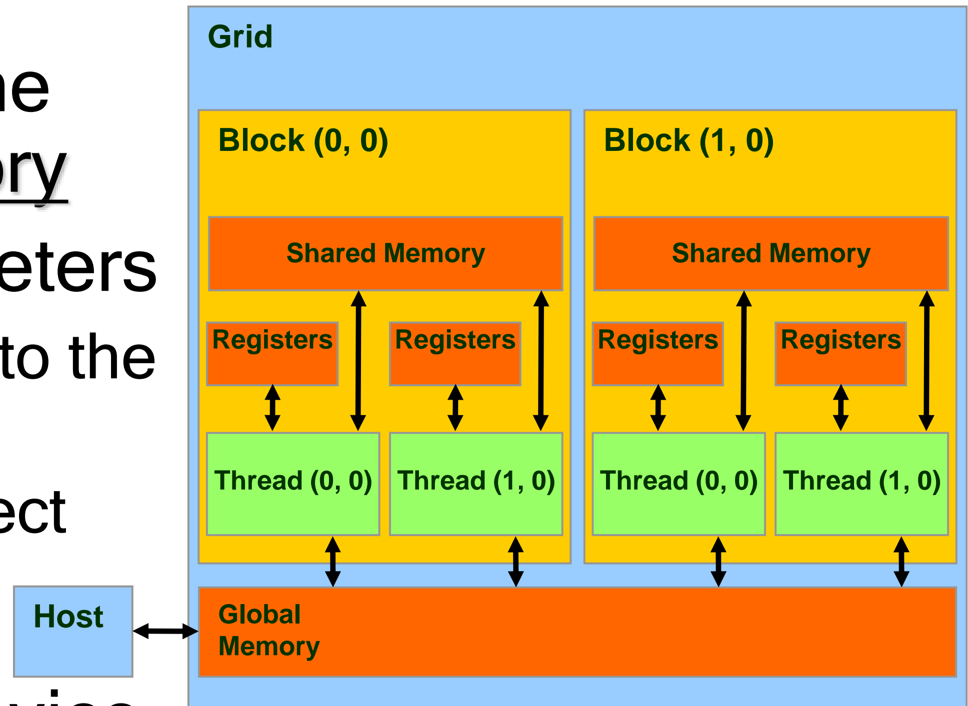
CUDA Device Memory Allocation

- cudaMalloc()
  - Allocates object in the device Global Memory
  - Requires two parameters
    - **Address of a pointer** to the allocated object
    - **Size of** allocated object
- cudaFree()
  - Frees object from device Global Memory
    - Pointer to freed object



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CUDA Device Memory Allocation (cont.)

- Code example:
  - Allocate a 64 * 64 single precision float array
  - Attach the allocated storage to Md
  - “d” is often used to indicate a device data structure

```
int TILE_WIDTH = 64;
float* Md;
int size = TILE_WIDTH * TILE_WIDTH * sizeof(float);

cudaMalloc((void**)&Md, size);
cudaFree(Md);
```

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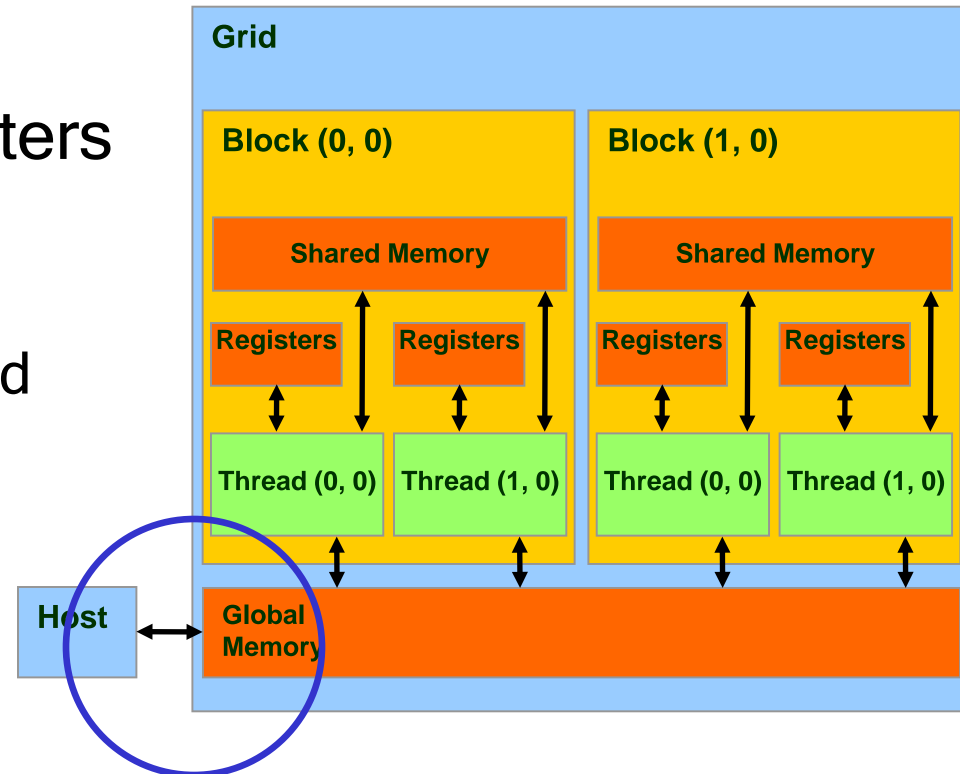
CUDA Host-Device Data Transfer

- cudaMemcpy()
  - memory data transfer
  - Requires four parameters
    - Pointer to destination
    - Pointer to source
    - Number of bytes copied
    - Type of transfer
      - Host to Host
      - Host to Device
      - Device to Host
      - Device to Device
- Asynchronous transfer



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CUDA Host-Device Data Transfer (cont.)

- Code example:
  - Transfer a 64 * 64 single precision float array
  - M is in host memory and Md is in device memory
  - cudaMemcpyHostToDevice and cudaMemcpyDeviceToHost are symbolic constants

```
cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);

cudaMemcpy(M, Md, size, cudaMemcpyDeviceToHost);
```

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CUDA Keywords

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CUDA Function Declarations

	Executed on the:	Only callable from the:
`__device__ float DeviceFunc()`	device	device
`__global__ void KernelFunc()`	device	host
`__host__ float HostFunc()`	host	host

- `__global__` defines a kernel function
  - Must return `void`
- `__device__` and `__host__` can be used together (function compiled twice)

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CUDA Function Declarations (cont.)

- `__device__` functions cannot have their address taken
- For functions executed on the device:
  - ~~No recursion~~
    - Recursion supported since CUDA Toolkit 3.1
  - No static variable declarations inside the function
  - ~~No variable number of arguments~~

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Calling a Kernel Function - Thread Creation

- A kernel function must be called with an execution configuration:

```
__global__ void KernelFunc(...);
dim3   DimGrid(100, 50);     // 5000 thread blocks
dim3   DimBlock(4, 8, 8);    // 256 threads per block
size_t SharedMemBytes = 64; // 64 bytes of shared
   memory
KernelFunc<<< DimGrid, DimBlock, SharedMemBytes,
   stream >>>(...);
```

- Any call to a kernel function is asynchronous, explicit synch needed for blocking

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Example: `vector_addition`

Device Code

```
// compute vector sum c = a + b
// each thread performs one pair-wise addition
__global__ void vector_add(float* A, float* B, float* C)
{
    int i = threadIdx.x + blockDim.x * blockIdx.x;
    C[i] = A[i] + B[i];
}

int main()
{
    // initialization code
    ...
    // Launch N/256 blocks of 256 threads each
    vector_add<<< N/256, 256>>>(d_A, d_B, d_C);
}
```

Example: `vector_addition`

Device Code

```
// compute vector sum c = a + b
// each thread performs one pair-wise addition
__global__ void vector_add(float* A, float* B, float* C)
{
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    C[i] = A[i] + B[i];
}

int main()
{
    // initialization code
    ...
    // Launch N/256 blocks of 256 threads each
    vector_add<<< N/256, 256>>>(d_A, d_B, d_C);
}
```

Example: `vector_addition`

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    C[i] = A[i] + B[i];
}

int main()
{
    // initialization code
    ...
    // launch N/256 blocks of 256 threads each
    vector_add<<< N/256, 256>>>(d_A, d_B, d_C);
}
```

Host Code

Example: Initialization code for `vector_addition`

```
// allocate and initialize host (CPU) memory
float *h_A = …,    *h_B = …;

// allocate device (GPU) memory
float *d_A, *d_B, *d_C;
cudaMalloc( (void**) &d_A, N * sizeof(float));
cudaMalloc( (void**) &d_B, N * sizeof(float));
cudaMalloc( (void**) &d_C, N * sizeof(float));

// copy host memory to device
cudaMemcpy( d_A, h_A, N * sizeof(float),
   cudaMemcpyHostToDevice) );
cudaMemcpy( d_B, h_B, N * sizeof(float),
   cudaMemcpyHostToDevice) );

// launch N/256 blocks of 256 threads each
vector_add<<<N/256, 256>>>(d_A, d_B, d_C);
```

Running Example: Matrix Multiplication

- A simple matrix multiplication example that illustrates the basic features of memory and thread management in CUDA programs
  - Leave shared memory usage until later
  - Local, register usage
  - Thread ID usage
  - Memory data transfer API between host and device
  - Assume square matrix for simplicity

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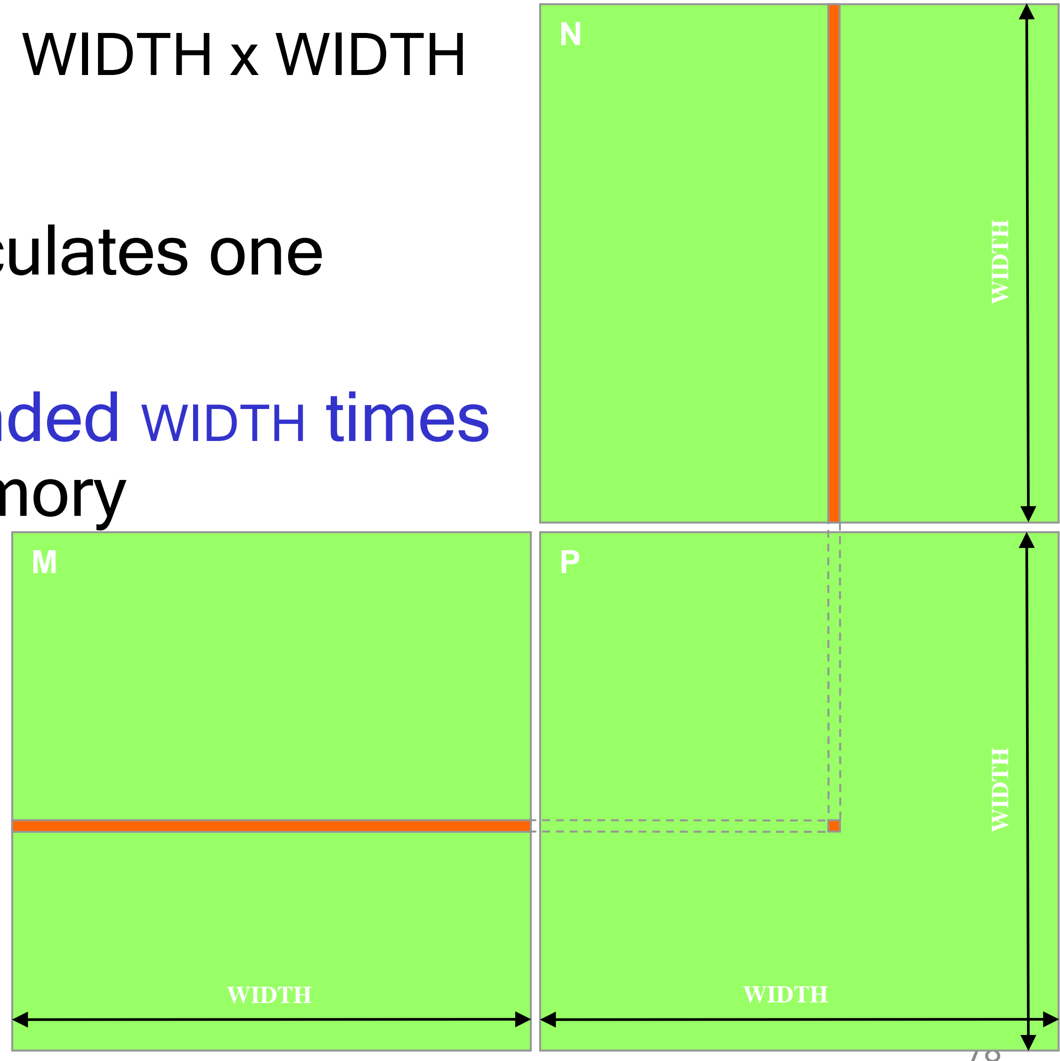
Programming Model: Square Matrix Multiplication Example

- P = M * N of size WIDTH x WIDTH
- Without tiling:
  - One thread calculates one element of P
  - M and N are loaded WIDTH times from global memory



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Memory Layout of a Matrix in C

$M_{0,0}$	$M_{1,0}$	$M_{2,0}$	$M_{3,0}$
$M_{0,1}$	$M_{1,1}$	$M_{2,1}$	$M_{3,1}$
$M_{0,2}$	$M_{1,2}$	$M_{2,2}$	$M_{3,2}$
$M_{0,3}$	$M_{1,3}$	$M_{2,3}$	$M_{3,3}$

M

$M_{0,0}$	$M_{1,0}$	$M_{2,0}$	$M_{3,0}$	$M_{0,1}$	$M_{1,1}$	$M_{2,1}$	$M_{3,1}$	$M_{0,2}$	$M_{1,2}$	$M_{2,2}$	$M_{3,2}$	$M_{0,3}$	$M_{1,3}$	$M_{2,3}$	$M_{3,3}$

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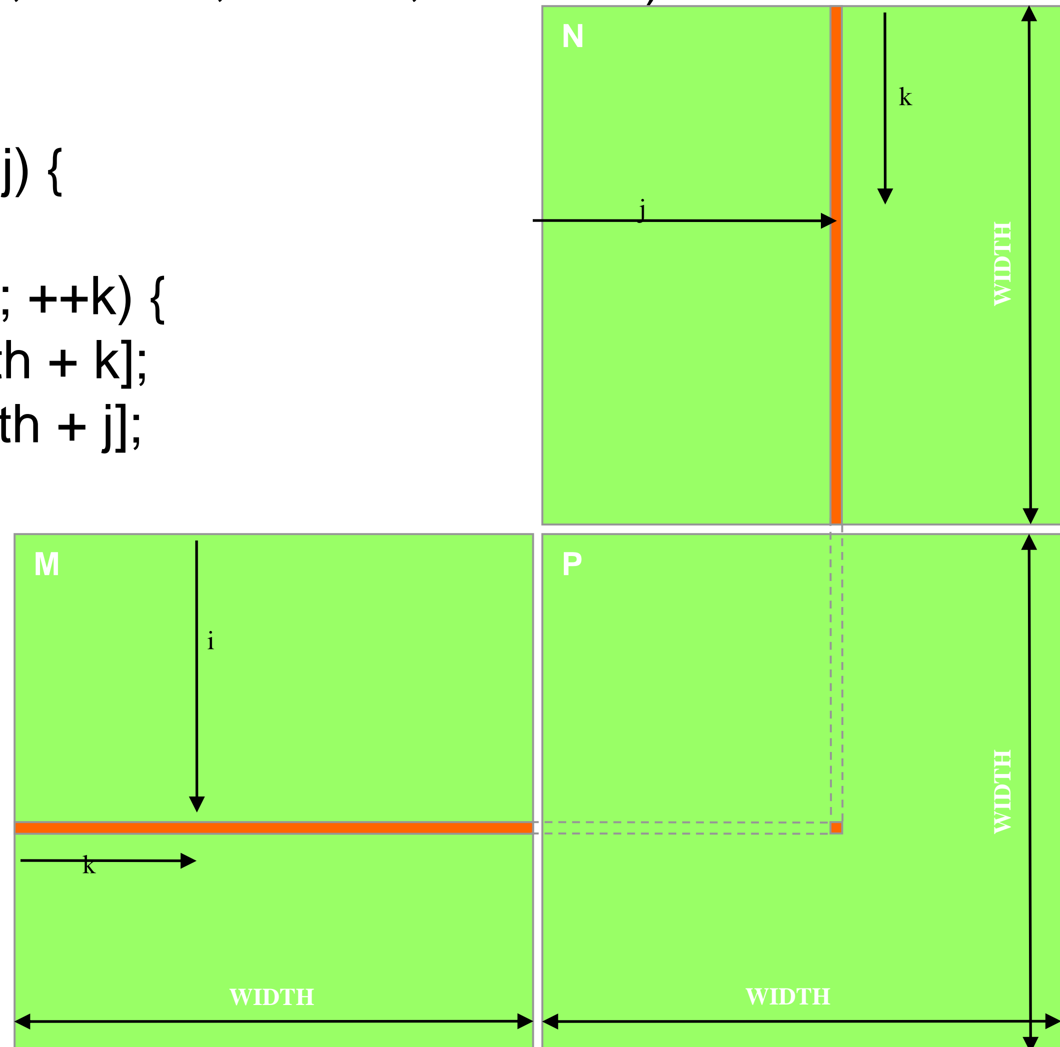
Matrix Multiplication
A Simple Host Version in C

```
// Matrix multiplication on the (CPU) host in double precision
void MatrixMulOnHost(float* M, float* N, float* P, int Width)
{
    for (int i = 0; i < Width; ++i)
        for (int j = 0; j < Width; ++j) {
            double sum = 0;
            for (int k = 0; k < Width; ++k) {
                double a = M[i * width + k];
                double b = N[k * width + j];
                sum += a * b;
            }
            P[i * Width + j] = sum;
        }
}
```



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Step 1: Input Matrix Data Transfer (Host-side Code)

```
void MatrixMulOnDevice(float* M, float* N, float* P, int Width)
{
   int size = Width * Width * sizeof(float);
    float *Md, *Nd, *Pd;
   …
1. // Allocate and Load M, N to device memory
    cudaMalloc(&Md, size);
    cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice);

     cudaMalloc(&Nd, size);
     cudaMemcpy(Nd, N, size, cudaMemcpyHostToDevice);

     // Allocate P on the device
    cudaMalloc(&Pd, size);
```

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Step 3: Output Matrix Data Transfer (Host-side Code)

2. // Kernel invocation code – to be shown later
   …

3. // Read P from the device
   cudaMemcpy(P, Pd, size, cudaMemcpyDeviceToHost);

   // Free device matrices
   cudaFree(Md); cudaFree(Nd); cudaFree (Pd);
   }

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Step 2: Kernel Function

```
// Matrix multiplication kernel – per thread code

__global__ void MatrixMulKernel(float* Md, float* Nd, float* Pd, int Width)
{

    // Pvalue is used to store the element of the matrix
    // that is computed by the thread
    float Pvalue = 0;
```

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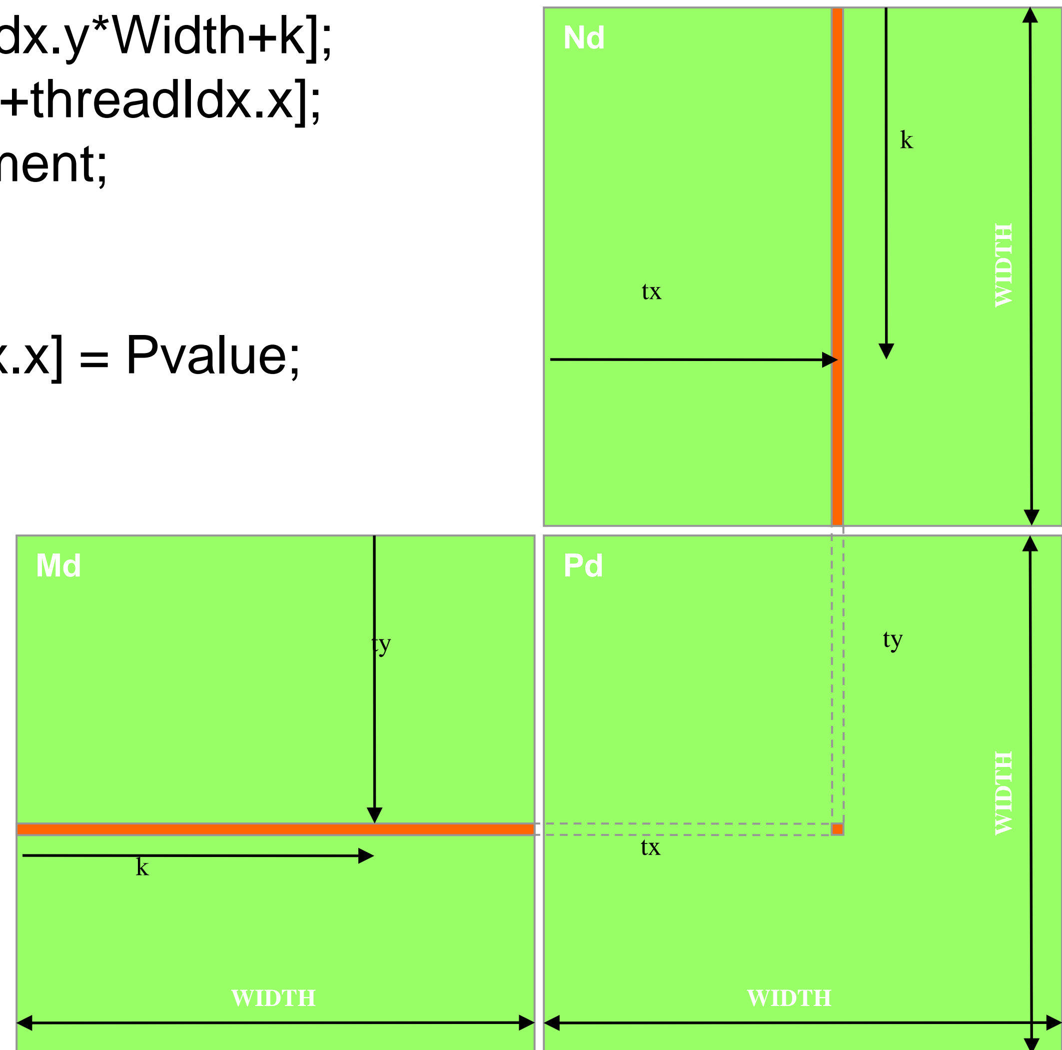
Step 2: Kernel Function (cont.)

```
for (int k = 0; k < Width; ++k) {
    float Melement = Md[threadIdx.y*Width+k];
    float Nelement = Nd[k*Width+threadIdx.x];
    Pvalue += Melement * Nelement;
 }

 Pd[threadIdx.y*Width+threadIdx.x] = Pvalue;
}
```



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Step 2: Kernel Invocation (Host-side Code)

```
// Setup the execution configuration
   dim3 dimGrid(1, 1);
  dim3 dimBlock(Width, Width);

// Launch the device computation threads!
MatrixMulKernel<<<dimGrid, dimBlock>>>(Md, Nd, Pd, Width);
```

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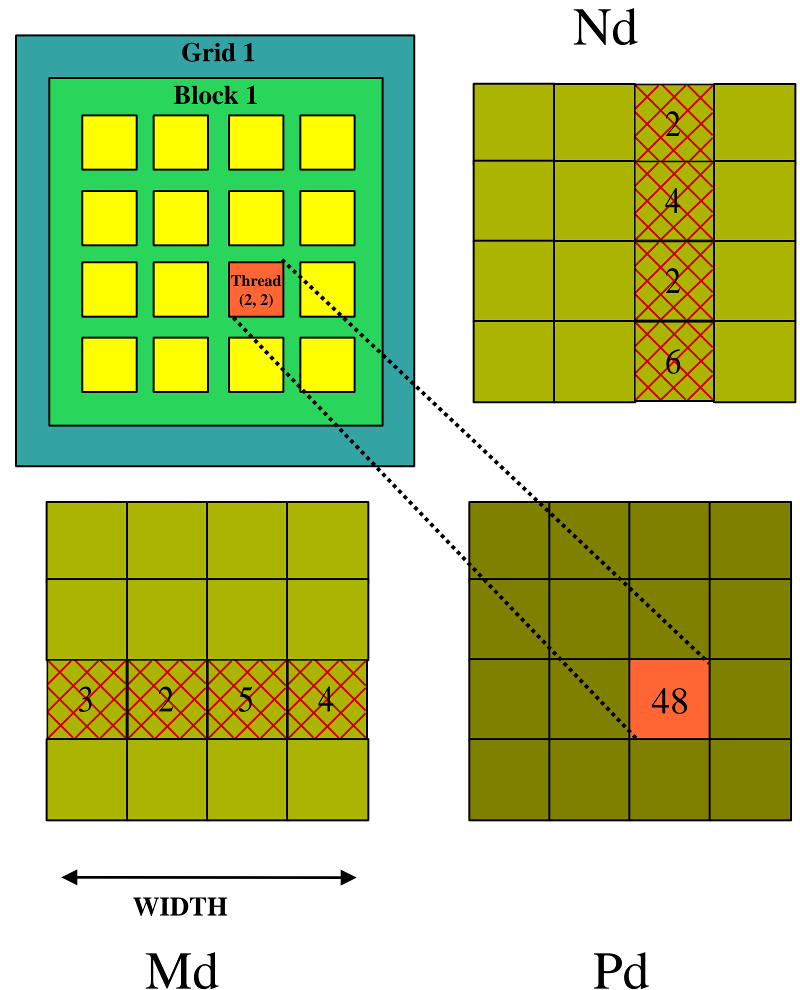
Only One Thread Block Used

- One Block of threads computes matrix Pd
  - Each thread computes one element of Pd
- Each thread
  - Loads a row of matrix Md
  - Loads a column of matrix Nd
  - Performs one multiply and addition for each pair of Md and Nd elements
  - Compute to off-chip memory access ratio close to 1:1 (not very high)
- Size of matrix limited by the number of threads allowed in a thread block



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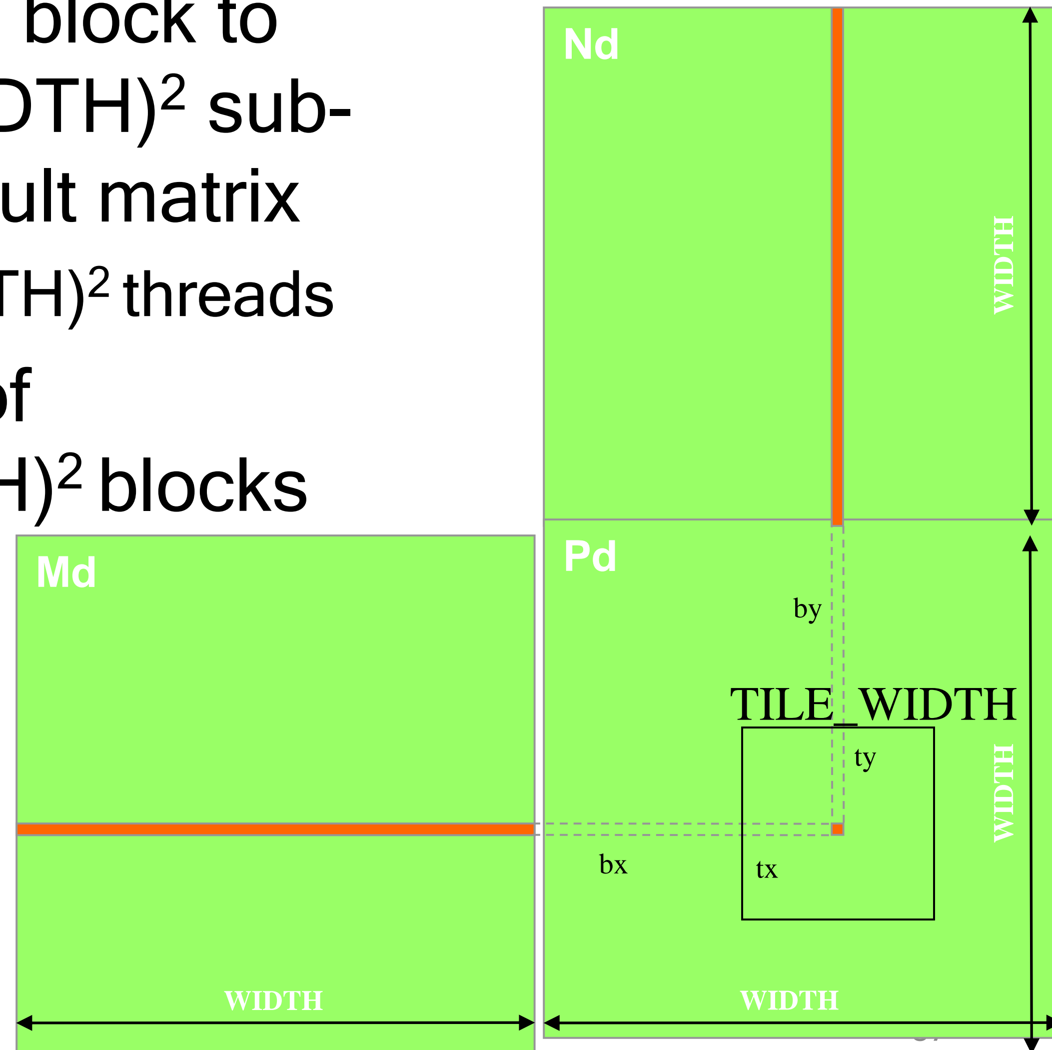
Handling Arbitrary Sized Square Matrices

- Have each 2D thread block to compute a $(TILE_WIDTH)^2$ sub-matrix (tile) of the result matrix
  - Each has $(TILE_WIDTH)^2$ threads
- Generate a 2D Grid of $(WIDTH/TILE_WIDTH)^2$ blocks

You still need to put a loop around the kernel call for cases where WIDTH/TILE_WIDTH is greater than max grid size (64K)!



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Compilation

- Any source file containing CUDA language extensions must be compiled with NVCC
- NVCC is a compiler driver
  - Works by invoking all the necessary tools and compilers like cudacc, g++, cl, ...
- NVCC outputs:
  - C code (host CPU Code)
    - Must then be compiled with the rest of the application using another tool
  - PTX (Parallel Thread eXecution)
    - Just-in-time compilation during loading

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Some Useful Information on Tools

- If you have access to a GPU locally, download CUDA Toolkit 11.2 https://developer.nvidia.com/cuda-downloads
- Else, instructions coming shortly…