CS 193G

Lecture 1: Introduction to Massively Parallel Computing

Course Goals

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

People

- Lecturers
  - Jared Hoberock: jaredhoberock at gmail.com
  - David Tarjan: tar.cs193g at gmail.com
  - Office hours: 3:00-4:00 PM, Tu Th, Gates 195
- Course TA
  - Niels Joubert: njoubert at cs.stanford.edu
- Guest lecturers
  - Domain experts

Web Resources

- Website:
    - http://stanford-cs193g-sp2010.googlecode.com
    - Lecture slides/recordings
    - Documentation, software resources
    - Note: while we'll make an effort to post announcements on the web, we can't guarantee it, and won't make allowances for people who miss things in class
- Mailing list
    - Channel for electronic announcements
    - Forum for Q&A – Lecturers and assistants read the board, and your classmates often have answers
- Axess for Grades

Grading

- This is a lab oriented course!
- Machine problems: 50%
  - Correctness: ~40%
  - Performance: ~35%
  - Report: ~25%
- Project: 50%
  - Technical pitch: 25%
  - Project Presentation: 25%
  - Demo: 50%

Bonus Days

- Every student is allocated two bonus days
  - No-questions asked one-day extension that can be used on any MP
  - Use both on the same thing if you want
  - Weekends/holidays don’t count for the number of days of extension (Friday-Monday is just one day extension)
- Intended to cover illnesses, interview visits, just needing more time, etc.
- Late penalty is 10% of the possible credit/day, again counting only weekdays

Academic Honesty

- You are allowed and encouraged to discuss assignments with other students in the class. Getting verbal advice/help from people who've already taken the course is also fine.
- Any reference to assignments from previous terms or web postings is unacceptable
- Any copying of non-trivial code is unacceptable
  - Non-trivial = more than a line or so
  - Includes reading someone else's code and then going off to write your own.

Course Equipment

- Your own PCs with a CUDA-enabled GPU
- NVIDIA GeForce GTX 260 boards
  - Lab facilities: Pups cluster, Gates B21
  - Nodes 2, 8, 11, 12, & 13
  - New Fermi Architecture GPUs?
    - As they become available

Text & Notes

- Course text:
  - Kirk & Hwu. *Programming Massively Parallel Processors: A Hands-on Approach*. 2010.
- References:
  - NVIDIA. *The NVIDIA CUDA Programming Guide*. 2010.
  - NVIDIA. CUDA Reference Manual. 2010.
- Lectures will be posted on the class website.

Schedule

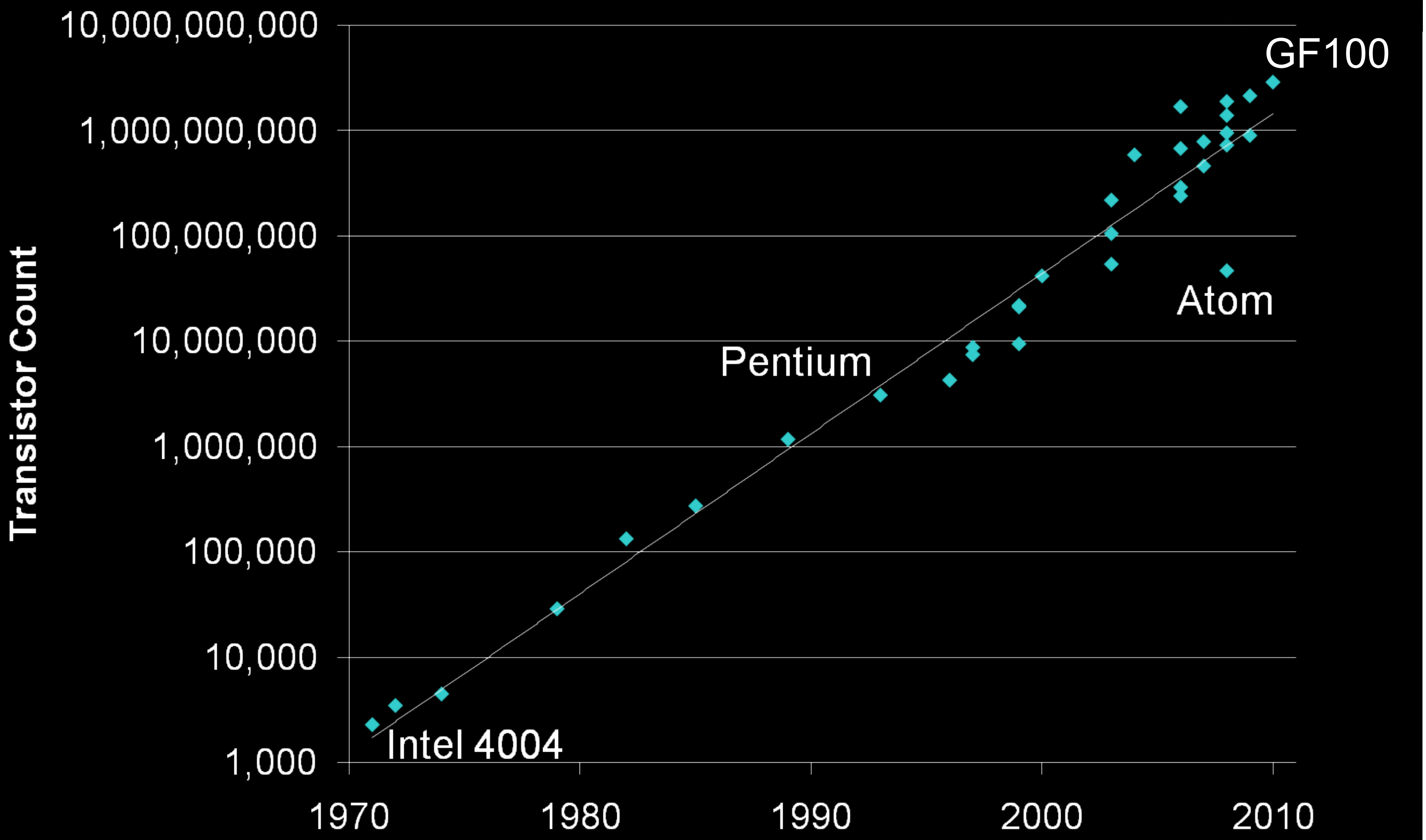
- Week 1:
  - Tu: Introduction
  - Th: CUDA Intro
  - MP 0: Hello, World!
  - MP 1: Parallel For
- Week 2
  - Tu: Threads & Atomics
  - Th: Memory Model
  - MP 2: Atomics
- Week 3
  - Tu: Performance
  - Th: Parallel Programming
  - MP 3: Communication
- Week 4
  - Tu: Project Proposals
  - Th: Parallel Patterns
  - MP 4: Productivity
- Week 5
  - Tu: Productivity
  - Th: Sparse Matrix Vector
- Week 6
  - Tu: PDE Solvers Case Study
  - Th: Fermi
- Week 7
  - Tu: Ray Tracing Case Study
  - Th: Future of Throughput
- Week 8
  - Tu: AI Case Study
  - Th: Advanced Optimization
- Week 9
  - Tu: TBD
  - Th: Project Presentations
- Week 10
  - Tu: Project Presentations

Moore’s Law (paraphrased)

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

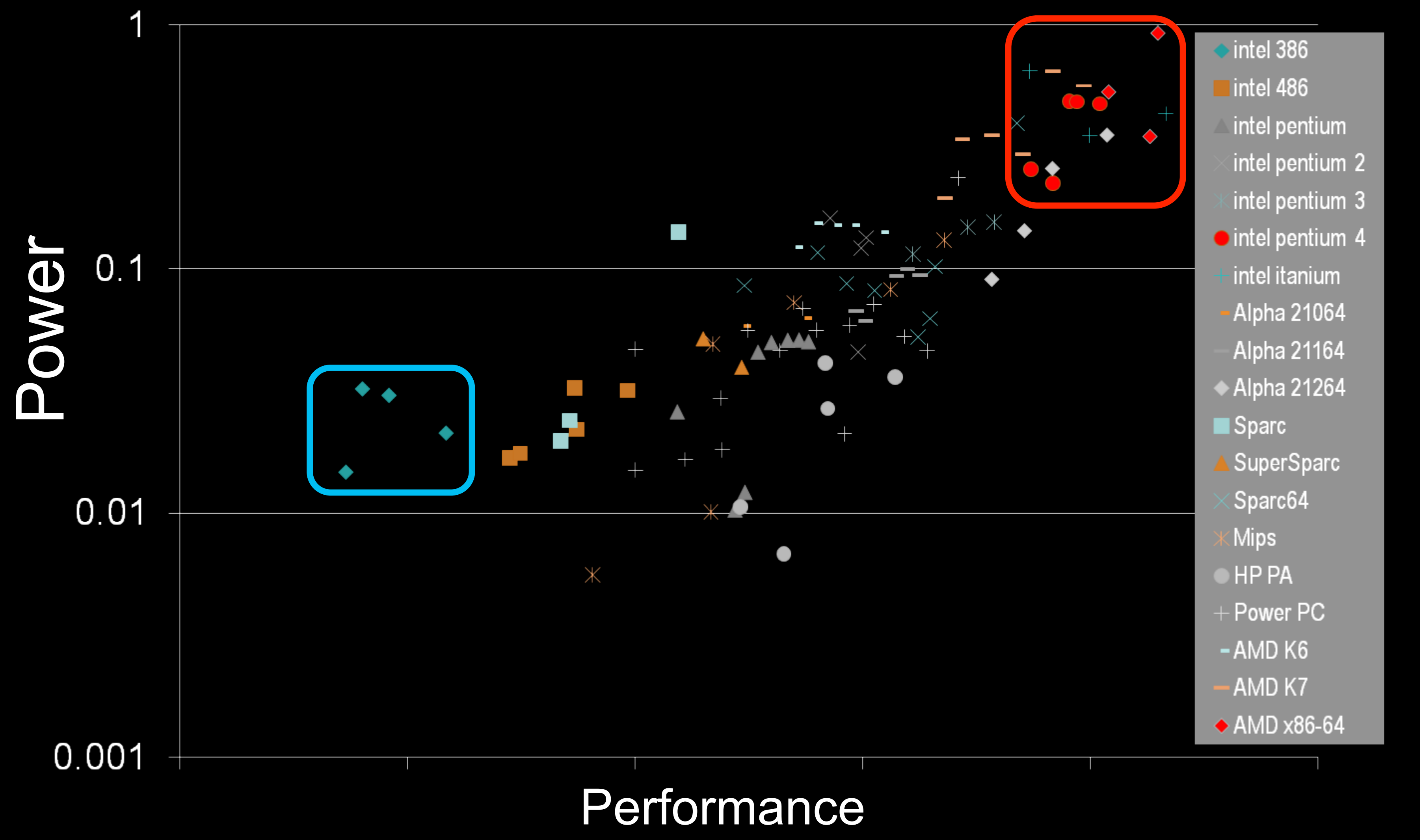
– Gordon E. Moore

Moore's Law (Visualized)



Data credit: Wikipedia

Buying Performance with Power



(courtesy Mark Horowitz and Kevin Skadron)

Serial Performance Scaling is Over

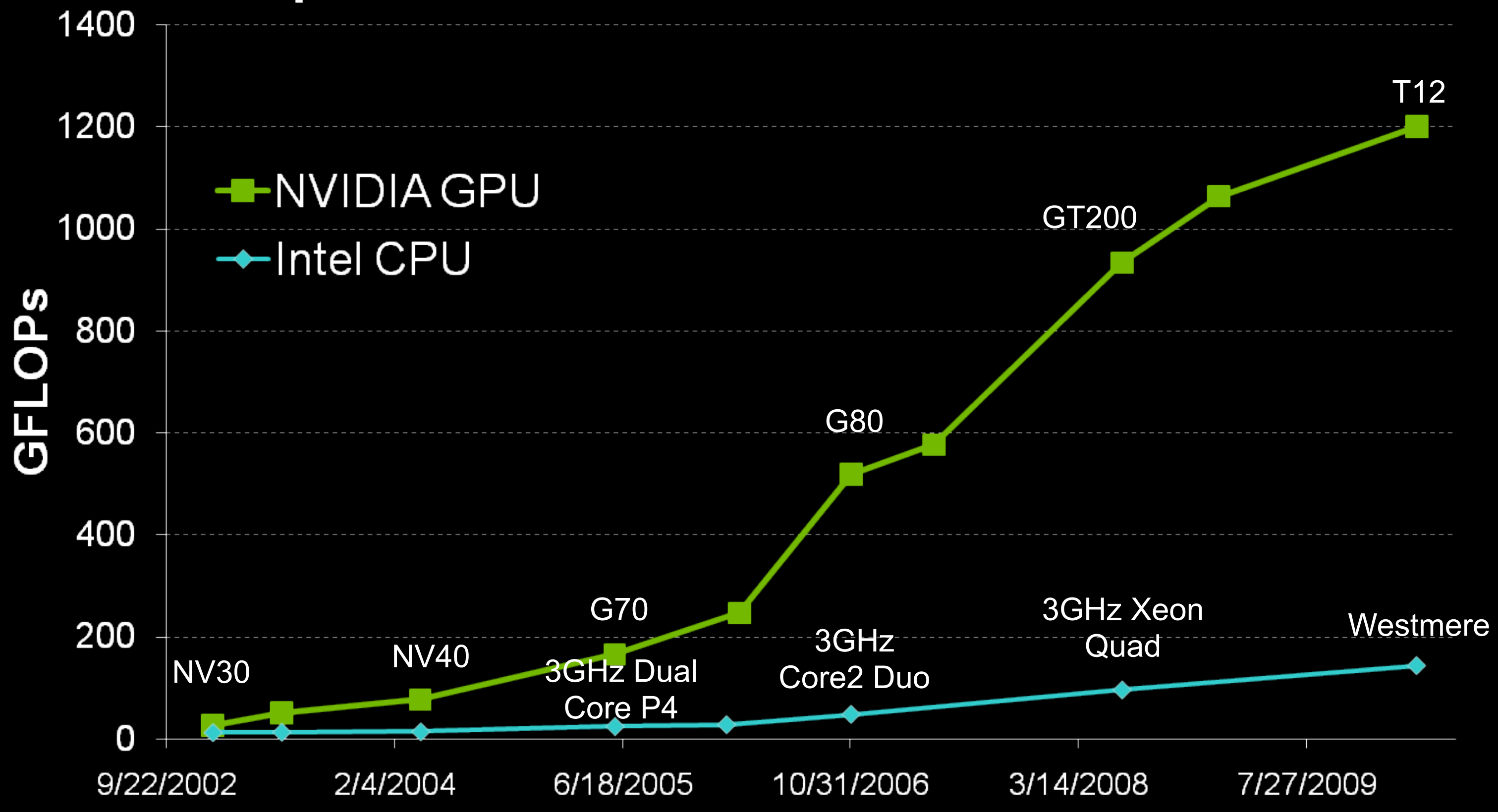
- Cannot continue to scale processor frequencies
  - no 10 GHz chips
- Cannot continue to increase power consumption
  - can’t melt chip
- Can continue to increase transistor density
  - as per Moore’s Law

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, …

Why Massively Parallel Processing?

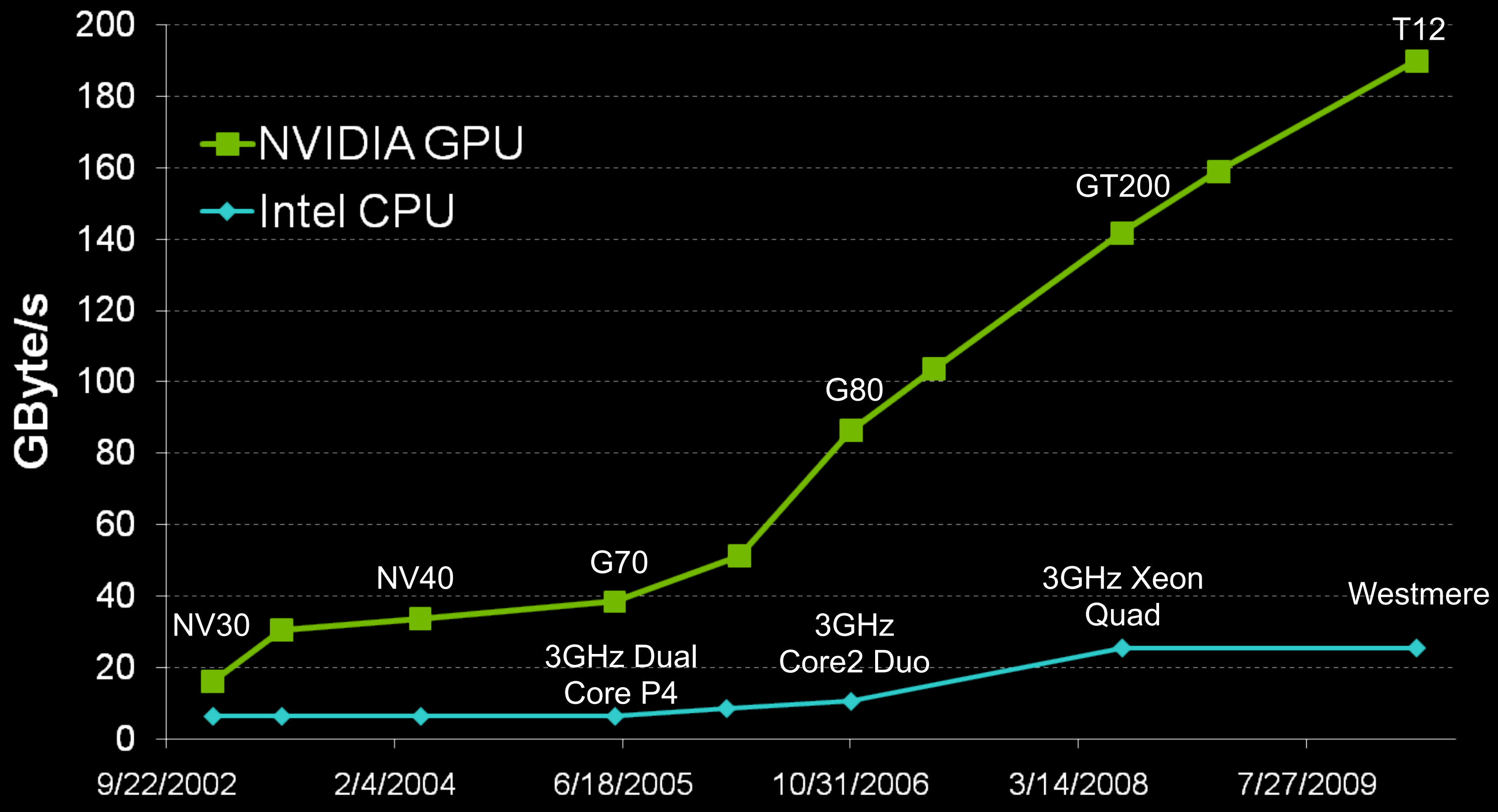
- A quiet revolution and potential build-up
  - Computation: TFLOPs vs. 100 GFLOPs



  - GPU in every PC – massive volume & potential impact

Why Massively Parallel Processing?

- A quiet revolution and potential build-up
  - Bandwidth: ~10x

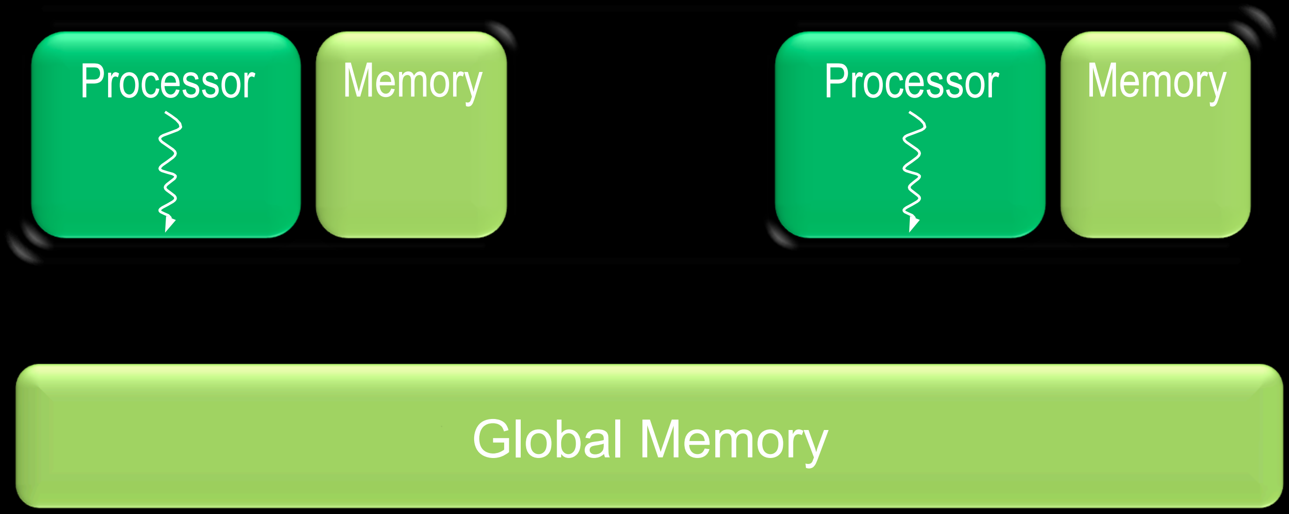


  - GPU in every PC – massive volume & potential impact

The “New” Moore’s Law

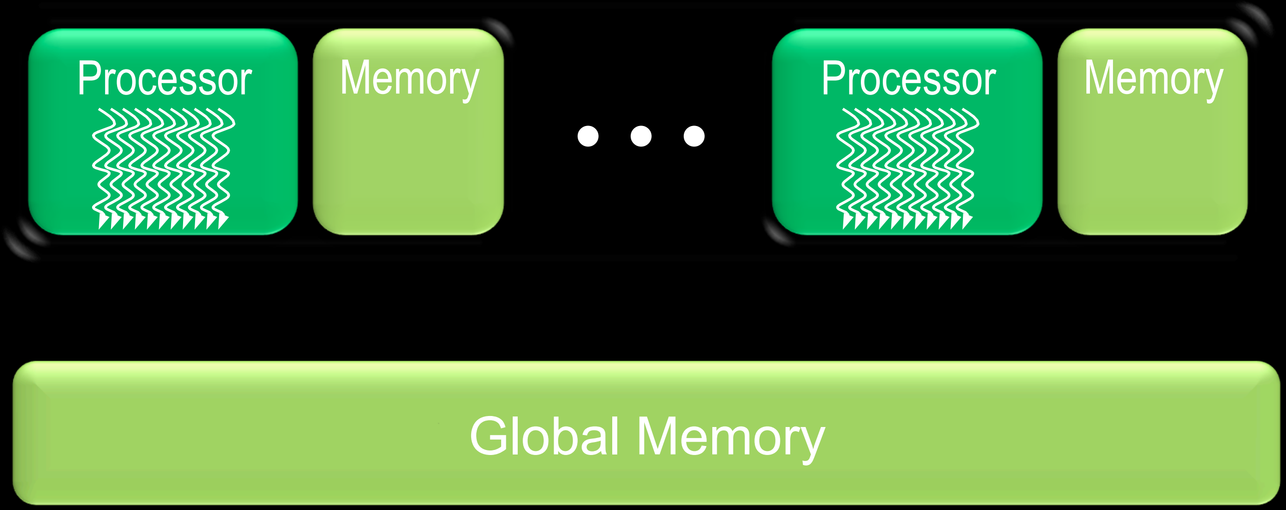
- **Computers no longer get faster, just wider**
- **You *must* re-think your algorithms to be parallel !**
- **Data-parallel computing is most scalable solution**
  - **Otherwise: refactor code for ~~2 cores~~** ~~4 cores~~ ~~8 cores~~ 16 cores…
  - **You will always have more data than cores – build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

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)

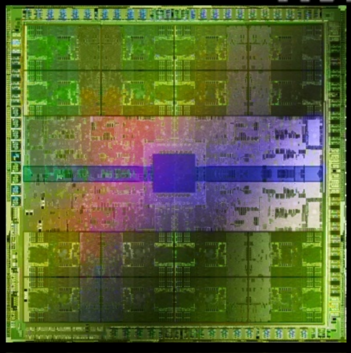
Enter the GPU

- Massive economies of scale

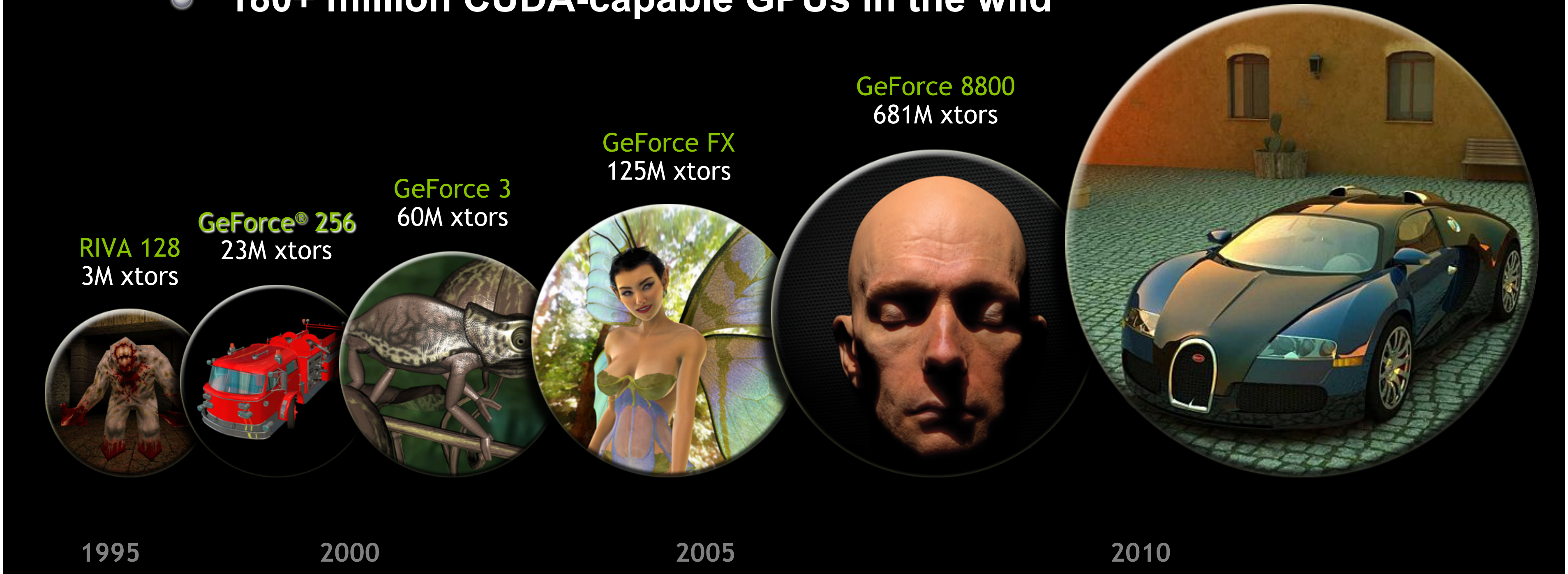
- Massively parallel

GPU Evolution

- High throughput computation
  - GeForce GTX 280: 933 GFLOP/s
- High bandwidth memory
  - GeForce GTX 280: 140 GB/s
- High availability to all
  - 180+ million CUDA-capable GPUs in the wild



“Fermi”
3B xtors



Lessons from Graphics Pipeline

- Throughput is paramount
  - must paint every pixel within frame time
  - scalability
- Create, run, & retire lots of threads very rapidly
  - measured 14.8 Gthread/s on `increment()` kernel
- Use multithreading to hide latency
  - 1 stalled thread is OK if 100 are ready to run

Why is this different from a CPU?

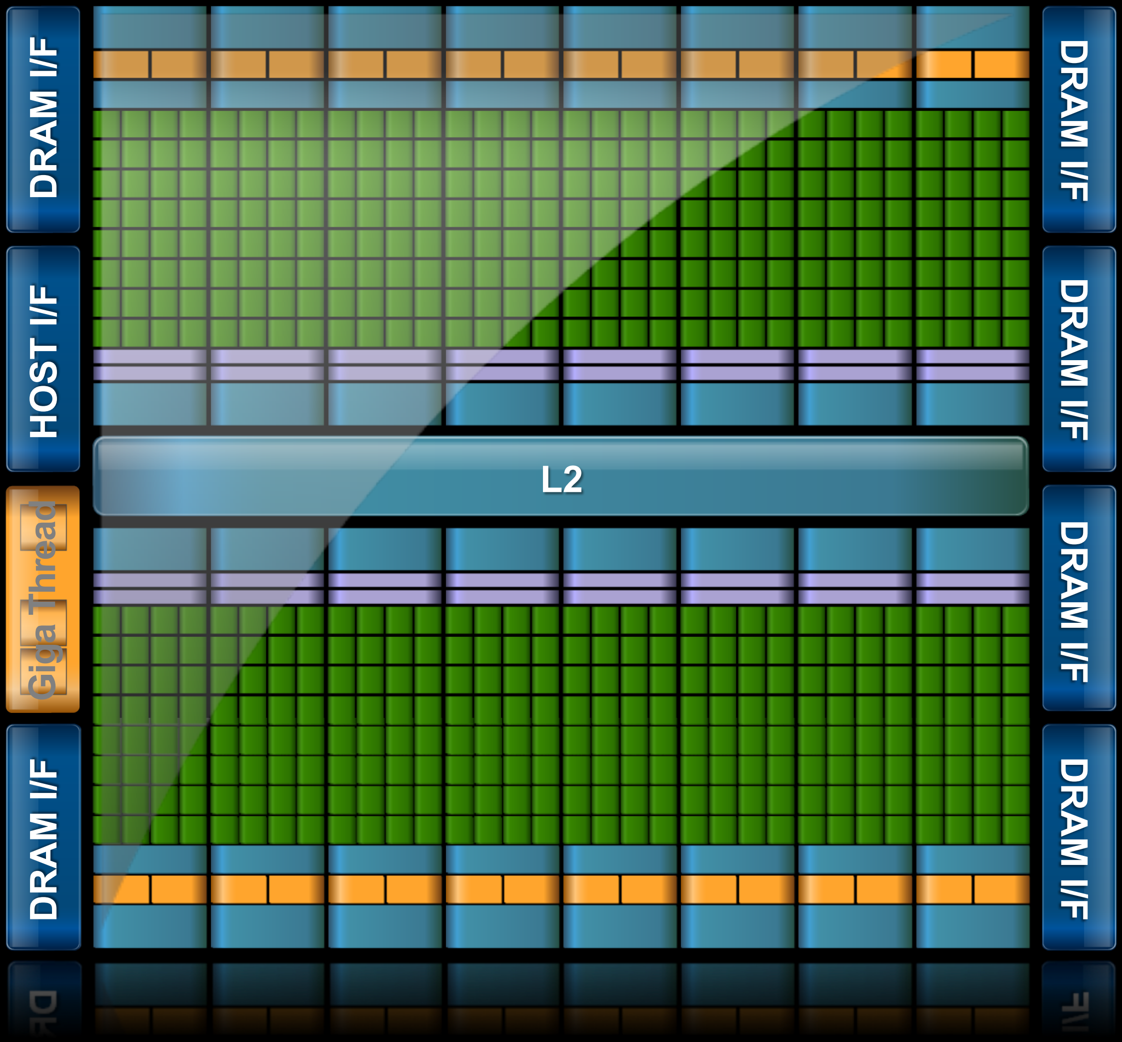
- Different goals produce different designs
  - GPU assumes work load is highly parallel
  - CPU must be good at everything, parallel or not

- 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

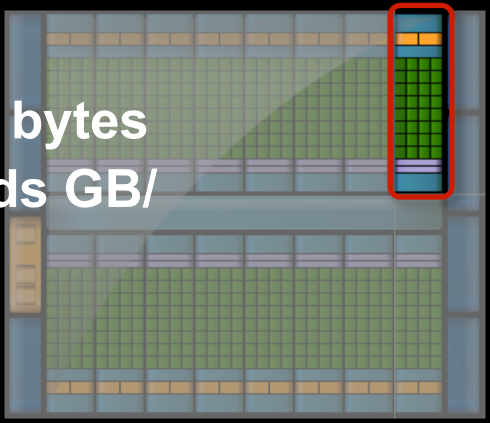
NVIDIA GPU Architecture

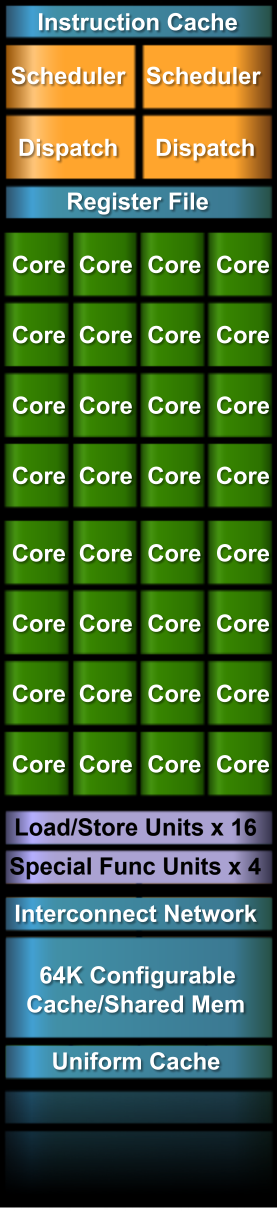
Fermi GF100



SM Multiprocessor

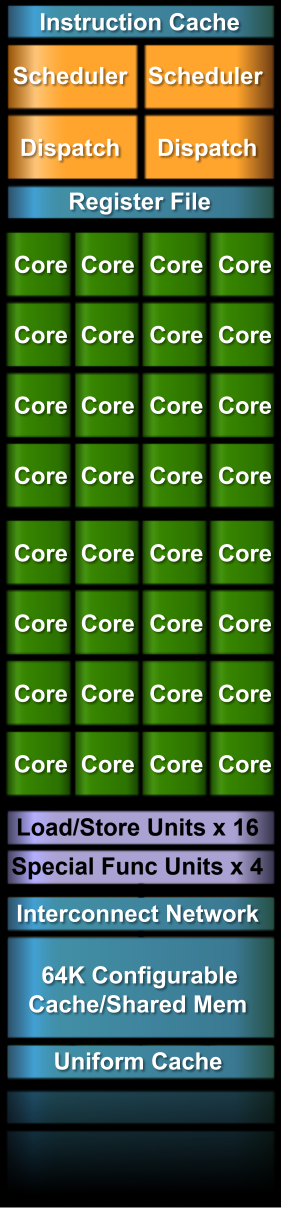
- 32 CUDA Cores per SM (512 total)
- 8x peak FP64 performance
  - 50% of peak FP32 performance
- Direct load/store to memory
  - Usual linear sequence of bytes
  - High bandwidth (Hundreds GB/sec)
- 64KB of fast, on-chip RAM
  - Software or hardware-managed
  - Shared amongst CUDA cores
  - Enables thread communication





Key Architectural Ideas

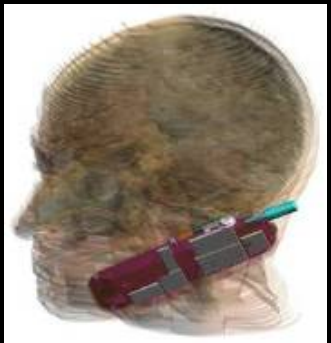
- **SIMT** (Single Instruction Multiple Thread) **execution**
  - **threads run in groups of 32 called warps**
  - **threads in a warp share instruction unit (IU)**
  - **HW automatically handles divergence**
- **Hardware multithreading**
  - **HW resource allocation & thread scheduling**
  - **HW relies 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**



Enter CUDA

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

Motivation



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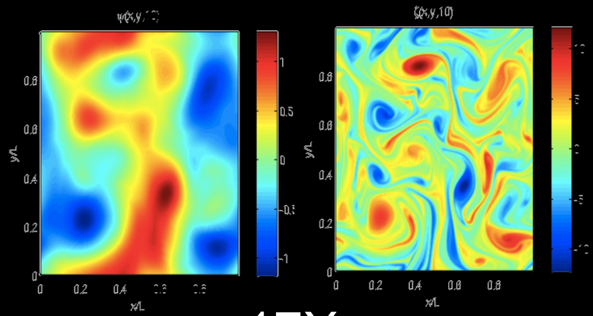
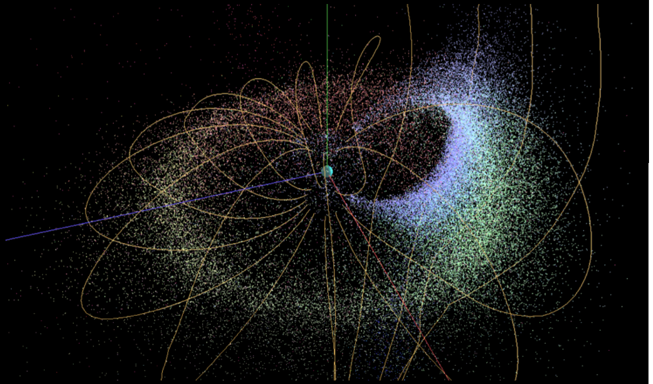
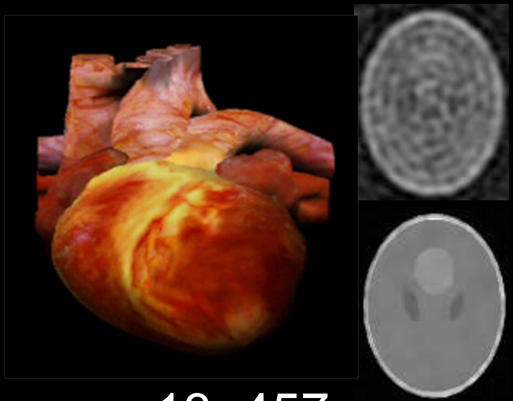


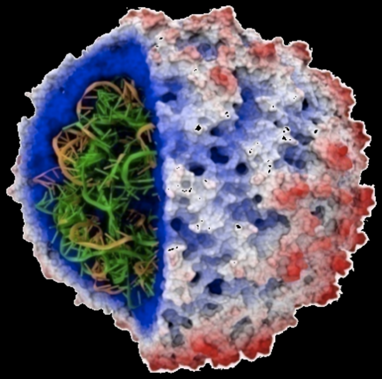
17X



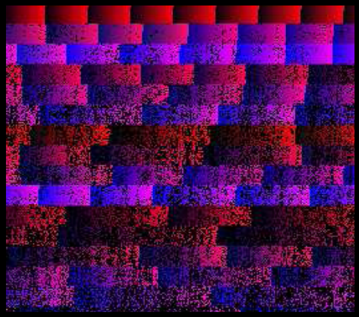
100X



13–457x



110-240X



35X

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

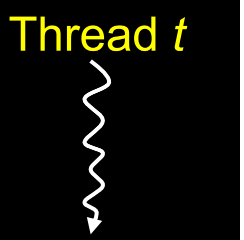
- Scale to 100s of cores & 10,000s of parallel threads
  - GPU threads are lightweight — create / switch is free
  - GPU needs 1000s of threads for full utilization

Key Parallel Abstractions in CUDA

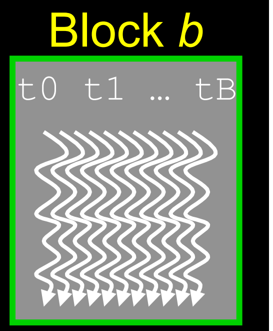
- Hierarchy of concurrent threads
- Lightweight synchronization primitives
- Shared memory model for cooperating threads

Hierarchy of concurrent threads

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

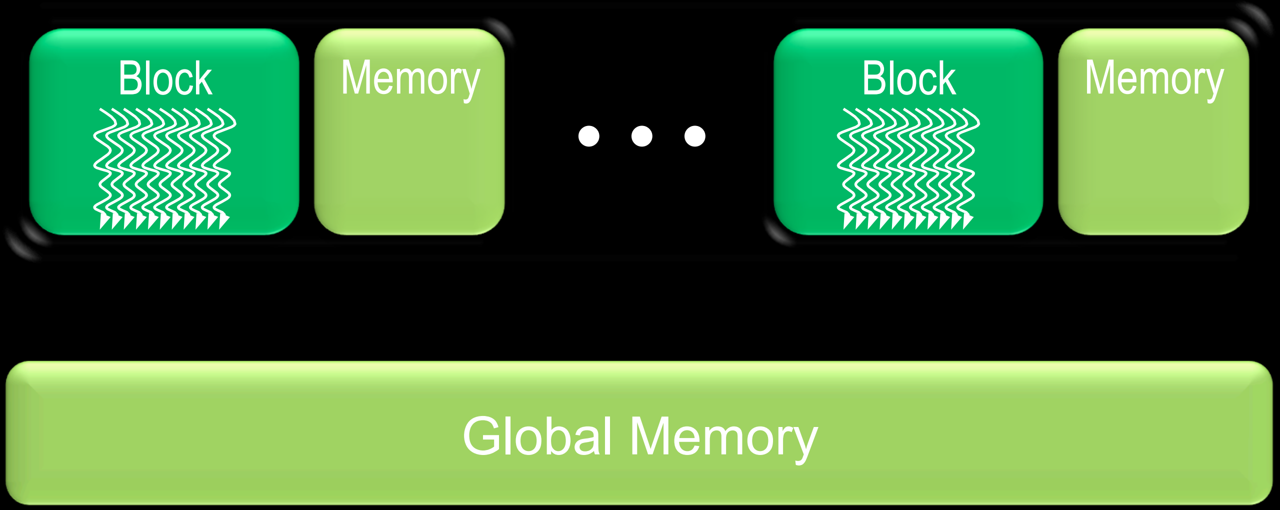


- Threads are grouped into **thread blocks**
  - threads in the same block can cooperate



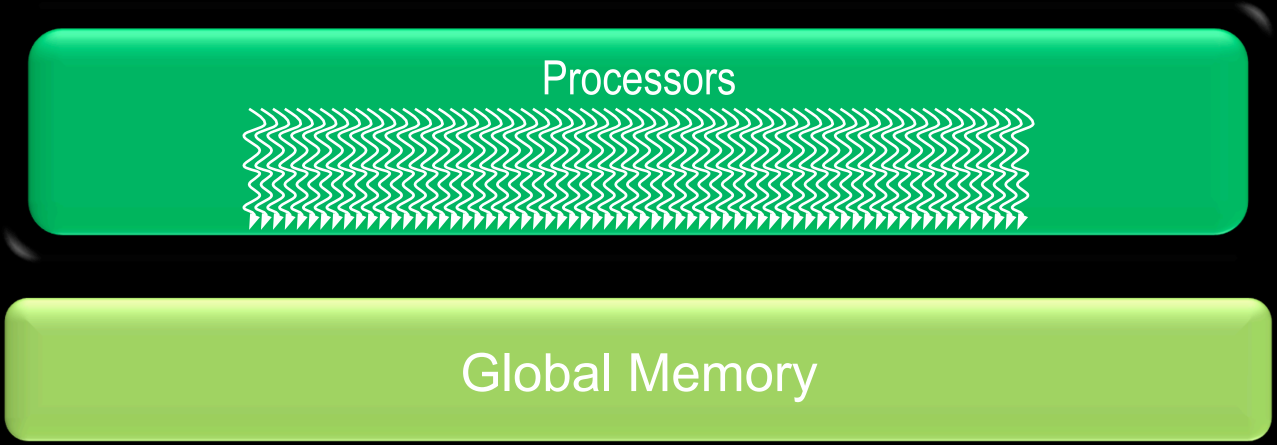
- Threads/blocks have unique IDs

CUDA Model of Parallelism



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

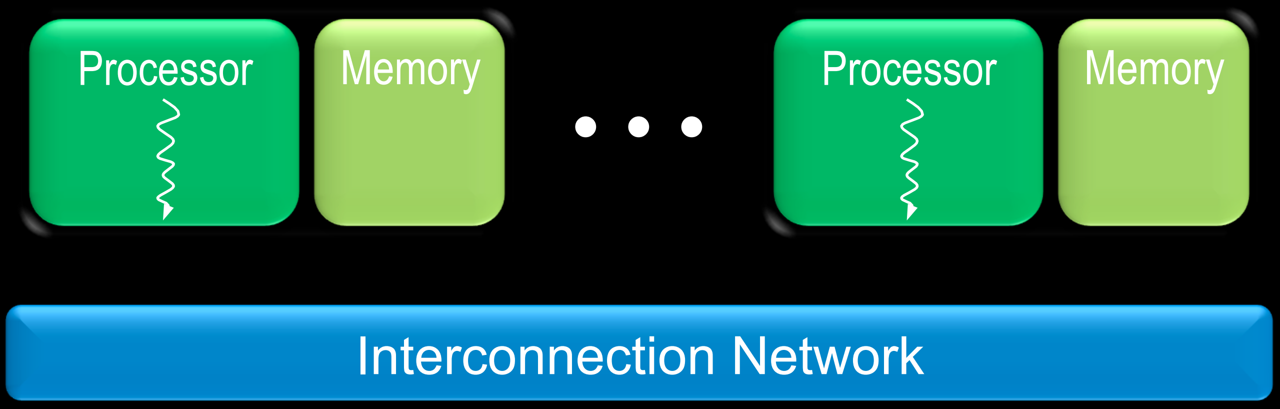
NOT: Flat Multiprocessor



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

- cf. PRAM (Parallel Random Access Machine) model

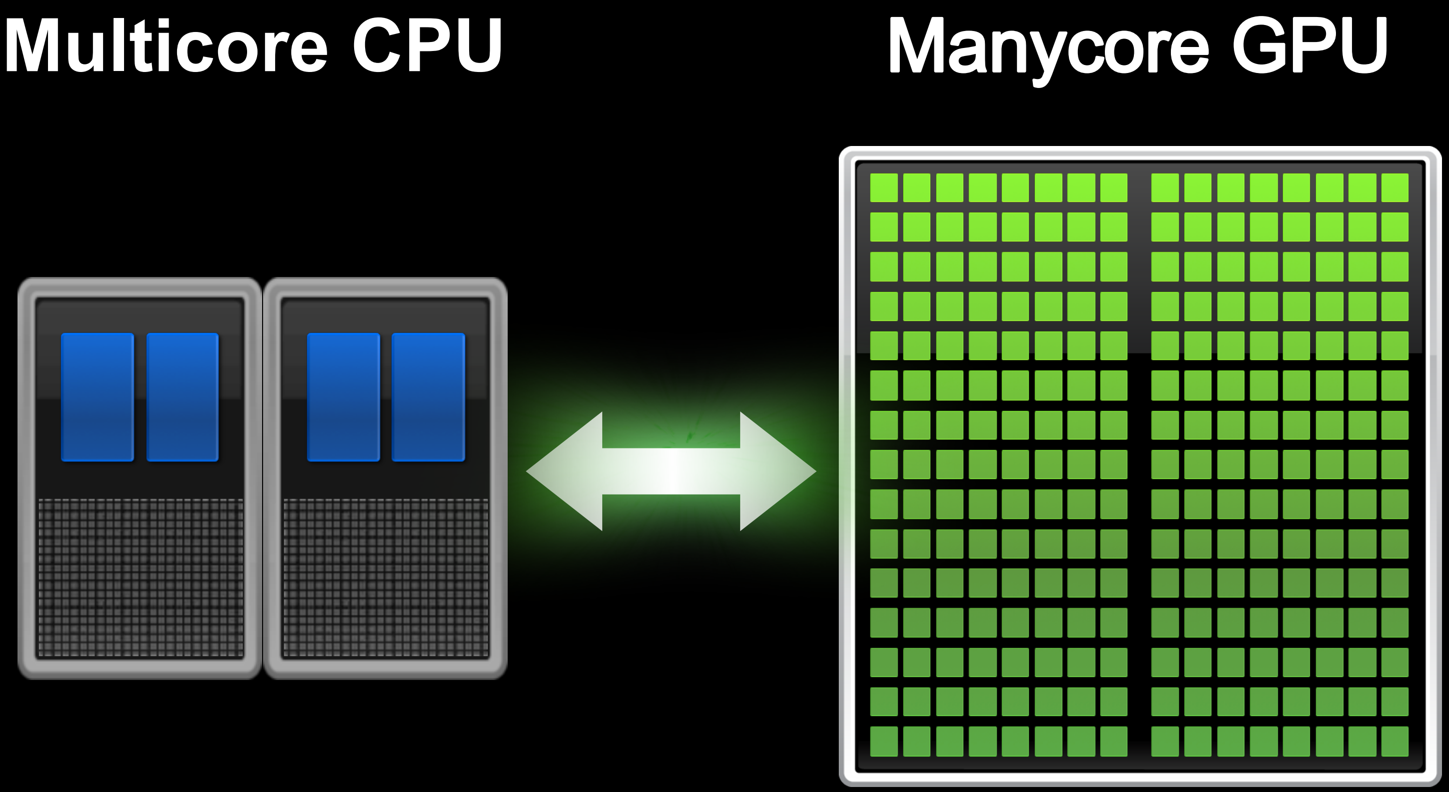
NOT: Distributed Processors



- Distributed computing is a different setting

- cf. BSP (Bulk Synchronous Parallel) model, MPI

Heterogeneous Computing



Multicore CPU

Manycore GPU

C for CUDA

- Philosophy: provide minimal set of extensions necessary to expose power

- Function qualifiers:

```
__global__ void my_kernel() { }
__device__ float my_device_func() { }
```

- Variable qualifiers:

```
__constant__ float my_constant_array[32];
__shared__   float my_shared_array[32];
```

- Execution configuration:

```
dim3 grid_dim(100, 50);  // 5000 thread blocks
dim3 block_dim(4, 8, 8); // 256 threads per block
my_kernel <<< grid_dim, block_dim >>> (...); // Launch kernel
```

- Built-in variables and functions valid in device code:

```
dim3 gridDim;   // Grid dimension
dim3 blockDim;  // Block dimension
dim3 blockIdx;  // Block index
dim3 threadIdx; // Thread index
void __syncthreads(); // Thread synchronization
```

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

Example: vector_addition

```
// 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];
}
```

Host Code

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

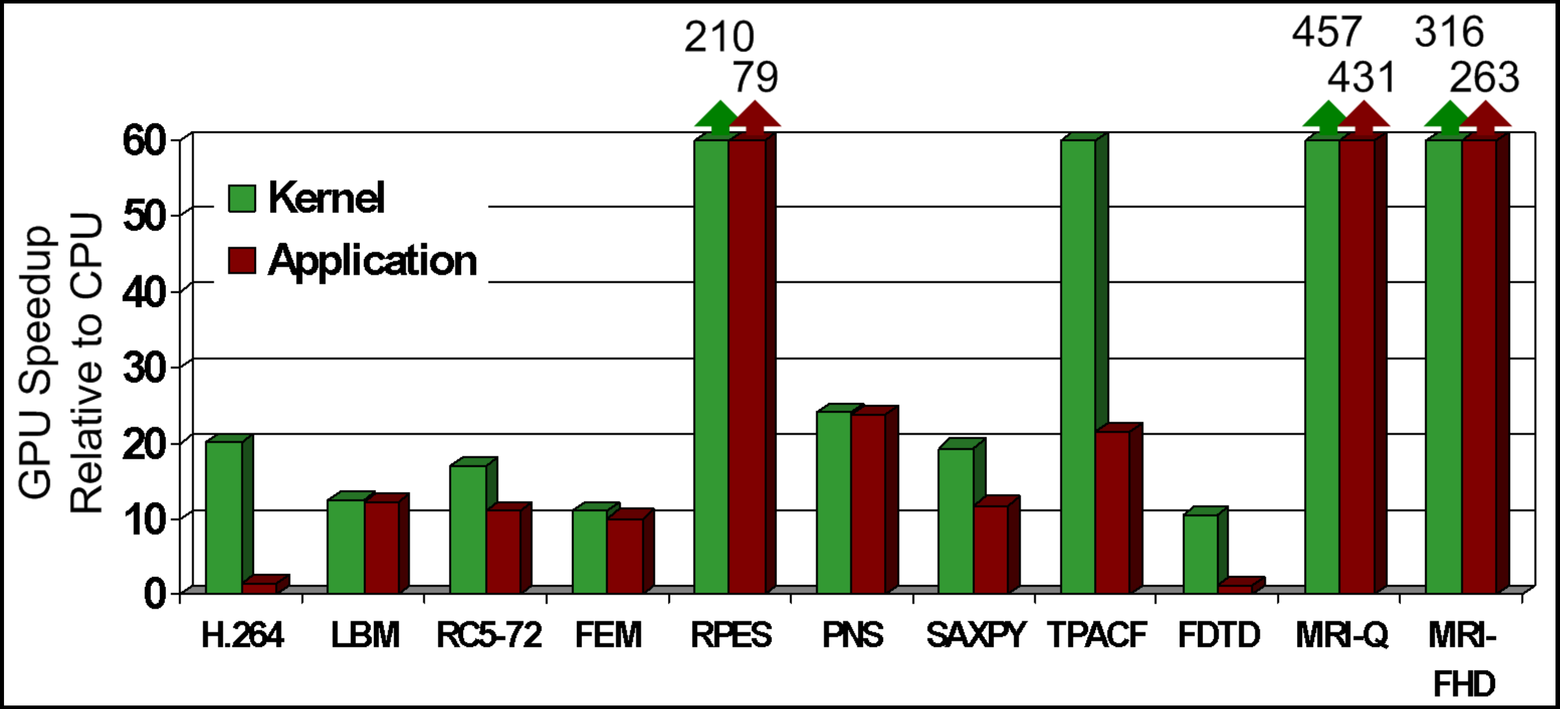
Example: Initialization code for vector_addition

```
// 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);
```

Previous Projects from UIUC ECE 498AL

Application	Description	Source	Kernel	% time
H.264	SPEC ‘06 version, change in guess vector	34,811	194	35%
LBM	SPEC ‘06 version, change to single precision and print fewer reports	1,481	285	>99%
RC5-72	Distributed.net RC5-72 challenge client code	1,979	218	>99%
FEM	Finite element modeling, simulation of 3D graded materials	1,874	146	99%
RPES	Rye Polynomial Equation Solver, quantum chem, 2-electron repulsion	1,104	281	99%
PNS	Petri Net simulation of a distributed system	322	160	>99%
SAXPY	Single-precision implementation of saxpy, used in Linpack’s Gaussian elim. routine	952	31	>99%
TPACF	Two Point Angular Correlation Function	536	98	96%
FDTD	Finite-Difference Time Domain analysis of 2D electromagnetic wave propagation	1,365	93	16%
MRI-Q	Computing a matrix Q, a scanner’s configuration in MRI reconstruction	490	33	>99%

Speedup of Applications



- GeForce 8800 GTX vs. 2.2GHz Opteron 248
- 10× speedup in a kernel is typical, as long as the kernel can occupy enough parallel threads
- 25× to 400× speedup if the function's data requirements and control flow suit the GPU and the application is optimized

Final Thoughts

- Parallel hardware is here to stay
- GPUs are massively parallel manycore processors
  - easily available and fully programmable
- Parallelism & scalability are crucial for success
- This presents many important research challenges
  - not to speak of the educational challenges

Machine Problem 0

- http://code.google.com/p/stanford-cs193g-sp2010/wiki/GettingStartedWithCUDA
- Work through tutorial codes
  - hello_world.cu
  - cuda_memory_model.cu
  - global_functions.cu
  - device_functions.cu
  - vector_addition.cu