

# 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



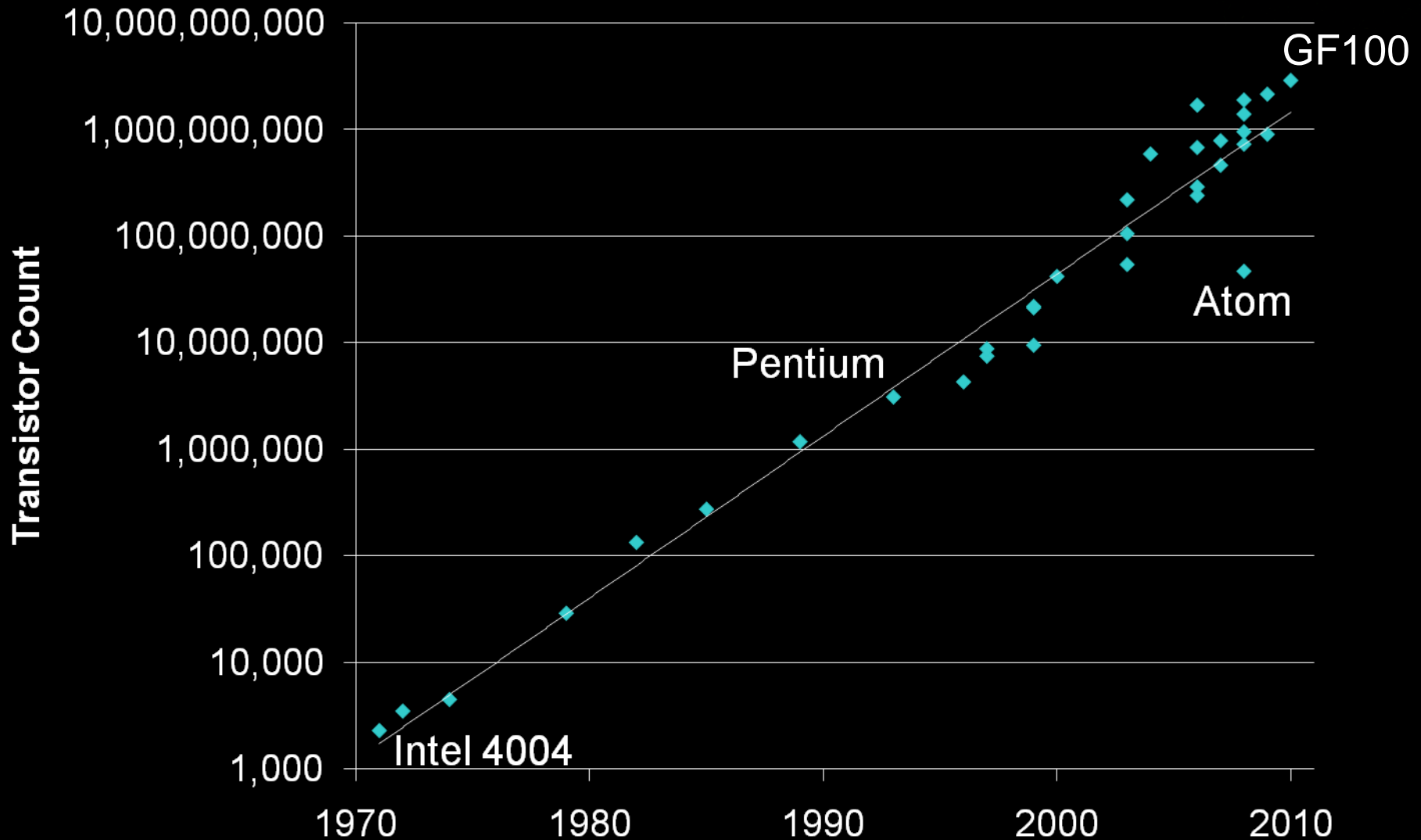
- **Week 1:**
  - Tu: Introduction
  - Th: CUDA Intro
  - MP 0: Hello, World!
  - MP 1: Parallel For
- **Week 2**
  - Tu: Threads & Atomics
  - Th: Memory Model
  - MP 2: Atomics
- **Week 3**
  - Tu: Performance
  - Th: Parallel Programming
  - MP 3: Communication
- **Week 4**
  - Tu: Project Proposals
  - 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)

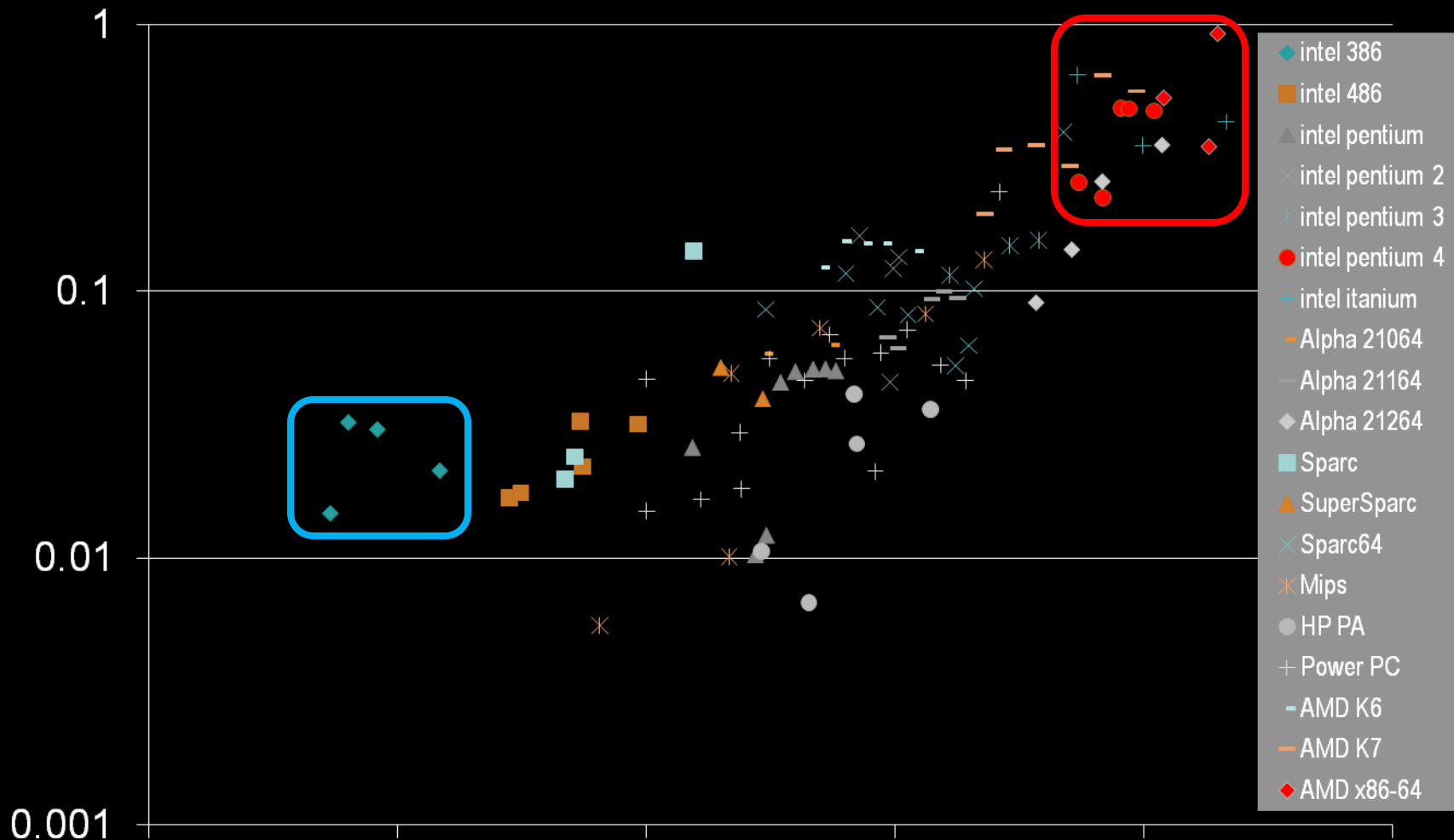


**“The number of transistors on an integrated circuit doubles every two years.”**  
**– Gordon E. Moore**

# Moore's Law (Visualized)



# Buying Performance with Power



# 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?



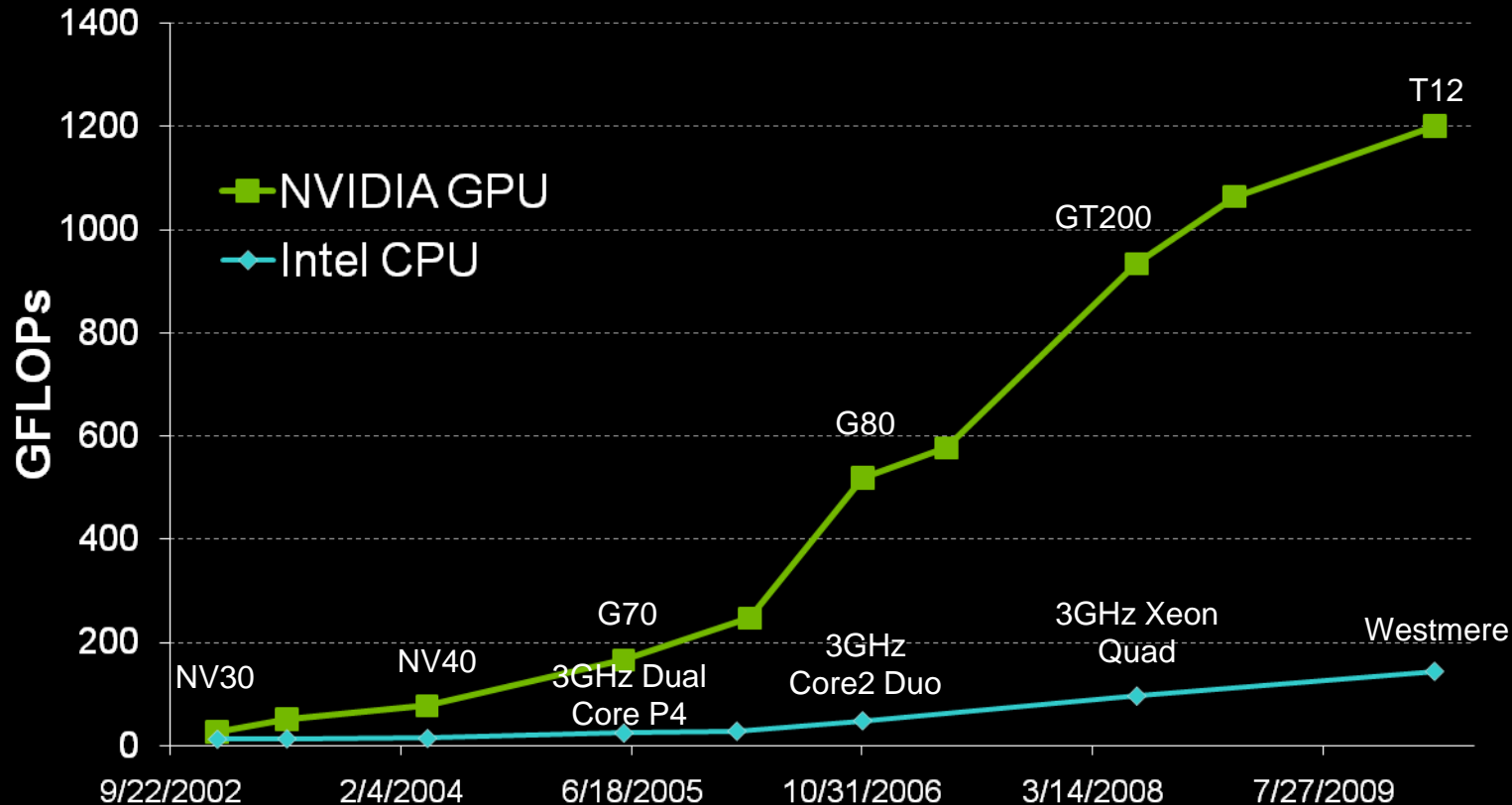
- **Instruction-level parallelism**
  - out-of-order execution, speculation, ...
  - **vanishing opportunities** in power-constrained world
- **Data-level parallelism**
  - vector units, SIMD execution, ...
  - **increasing** ... SSE, AVX, Cell SPE, Clearspeed, GPU
- **Thread-level parallelism**
  - **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**

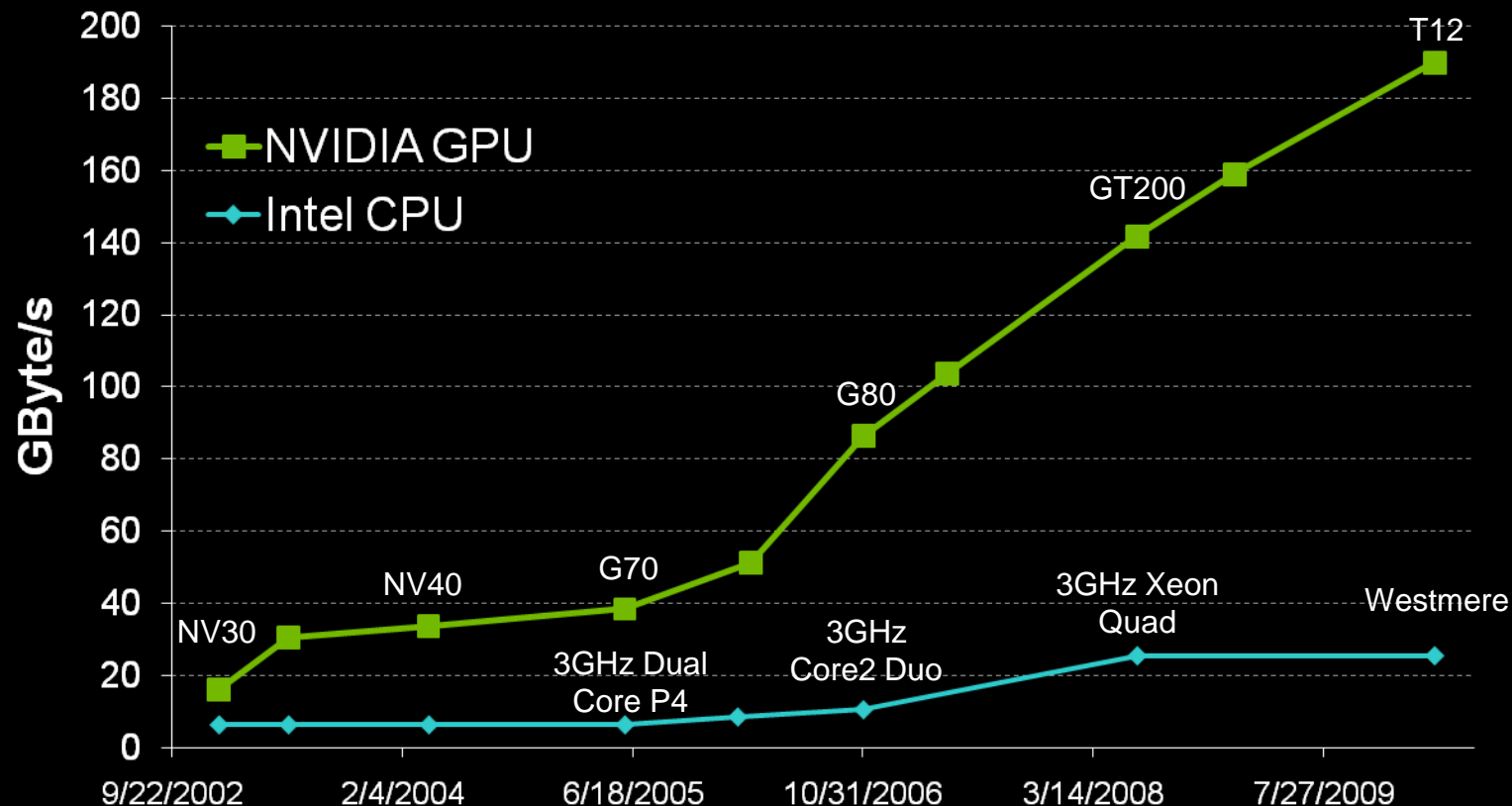


# Why Massively Parallel Processing?



## ● A quiet revolution and potential build-up

### ● Bandwidth: ~10x



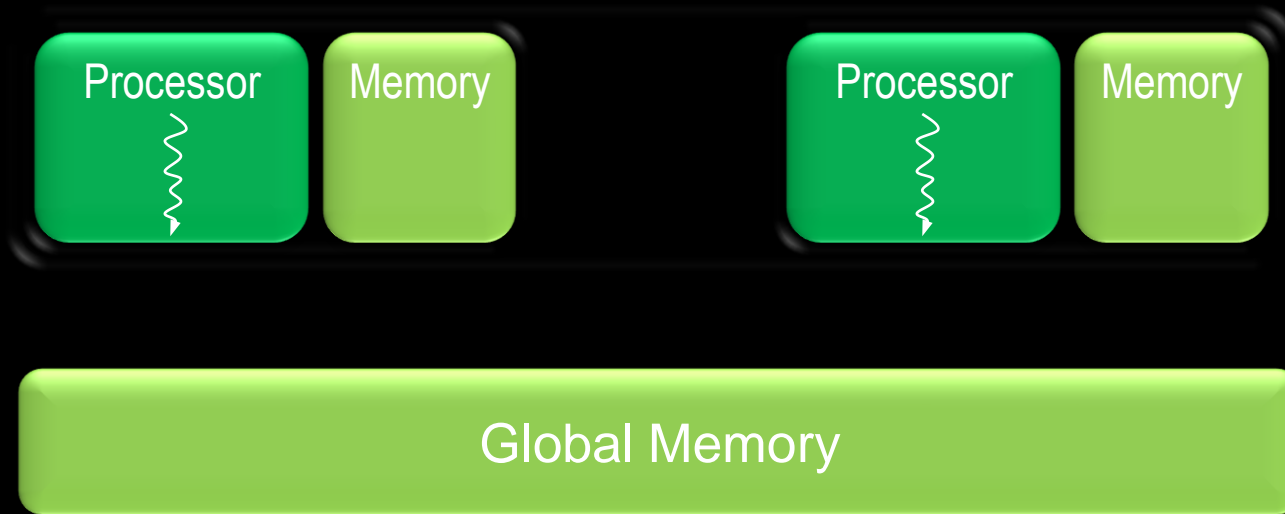
### ● GPU in every PC – massive volume & potential impact

# The “New” Moore’s Law



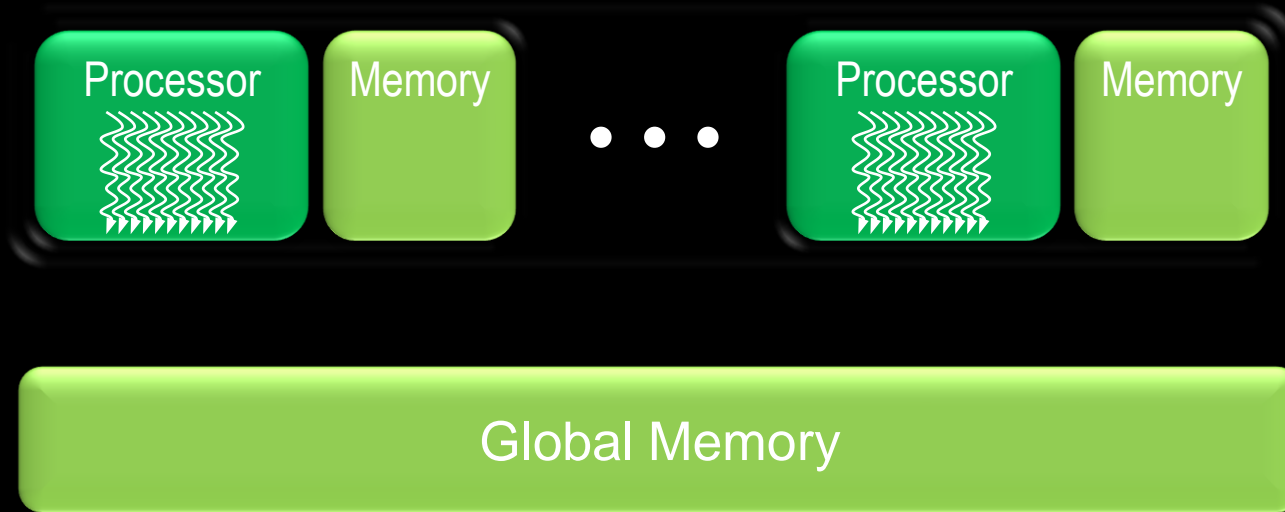
- Computers no longer get faster, just wider
- You *must* re-think your algorithms to be parallel !
- Data-parallel computing is most scalable solution
  - Otherwise: refactor code for ~~2 cores~~ ~~4 cores~~ ~~8 cores~~ 16 cores...
  - You will always have more data than cores – build the computation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



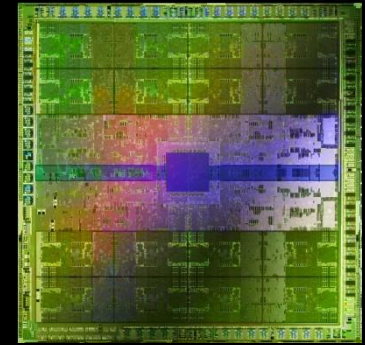
- **Massive economies of scale**
- **Massively parallel**



# 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



RIVA 128  
3M xtors



GeForce® 256  
23M xtors



GeForce 3  
60M xtors



GeForce FX  
125M xtors



GeForce 8800  
681M xtors



1995

2000

2005

2010

# 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?



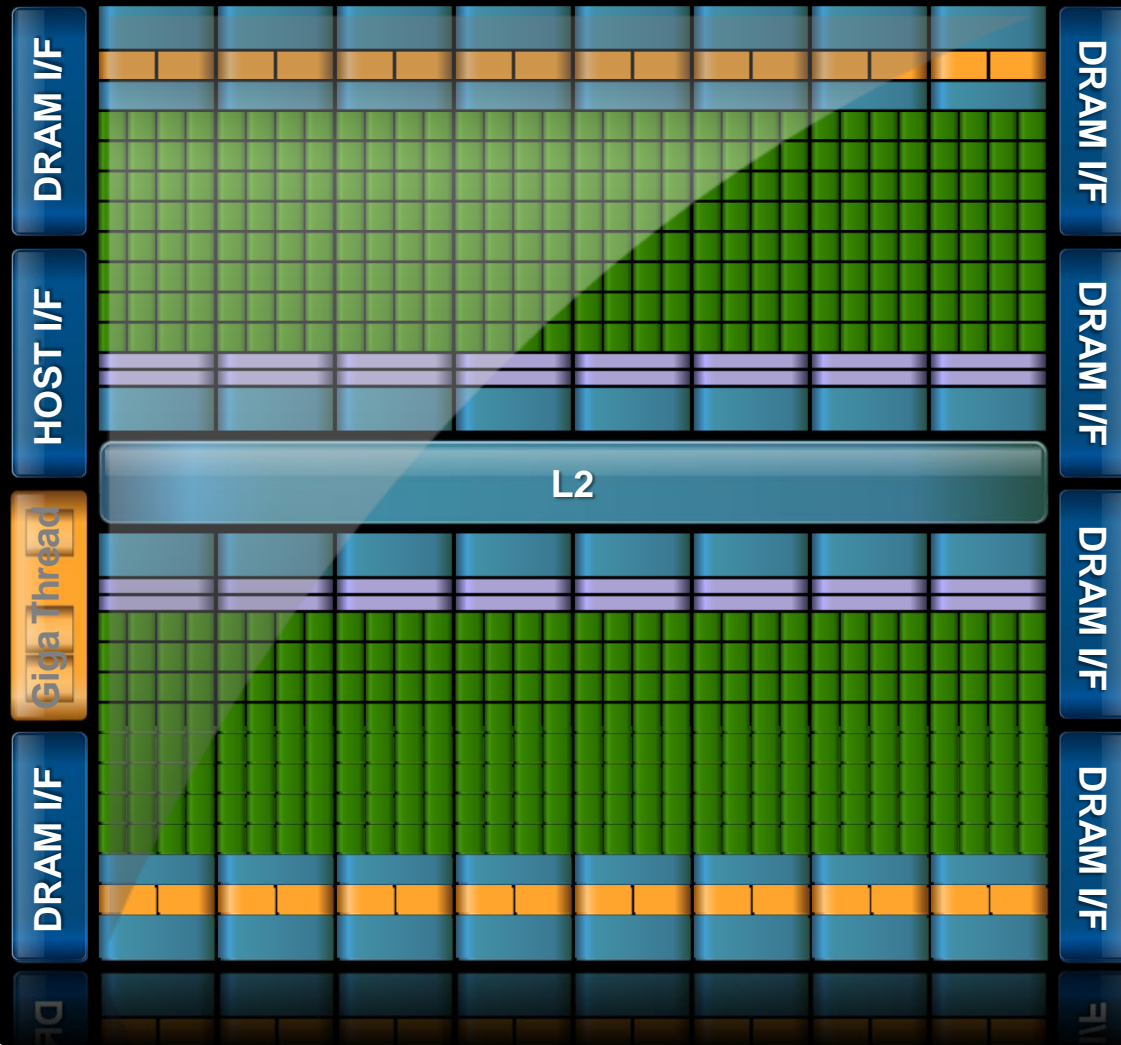
- Different goals produce different designs
  - GPU assumes work load is highly parallel
  - CPU must be good at everything, parallel or not
- CPU: **minimize latency** experienced by 1 thread
  - big on-chip caches
  - sophisticated control logic
- GPU: **maximize throughput** of all threads
  - # threads 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



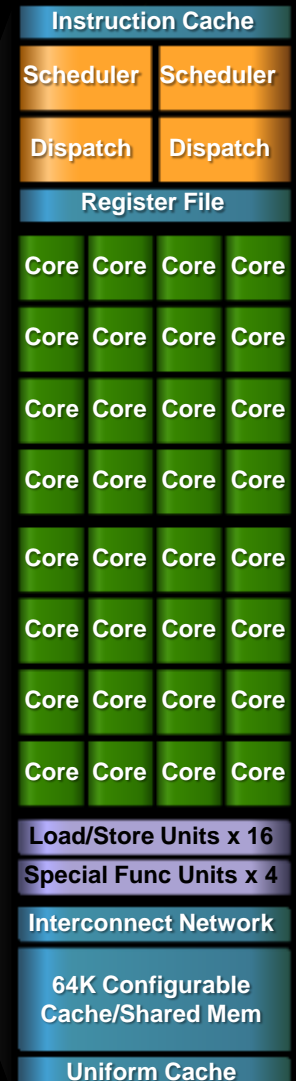
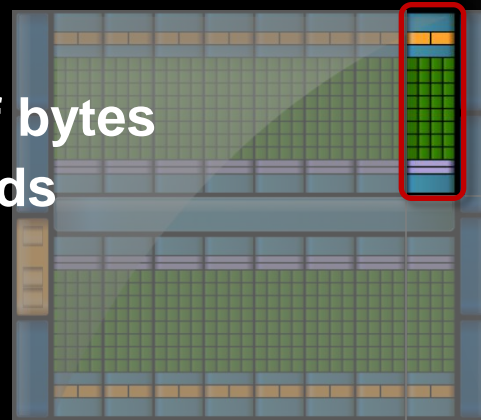
## Fermi GF100



# SM Multiprocessor



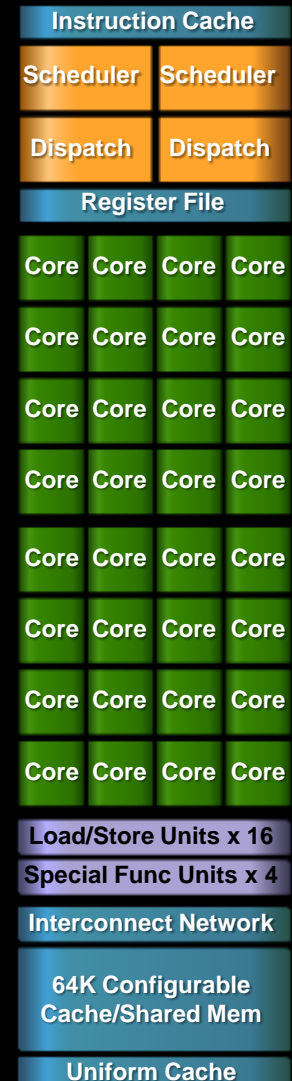
- 32 CUDA Cores per SM (512 total)
- 8x peak FP64 performance
  - 50% of peak FP32 performance
- Direct load/store to memory
  - Usual linear sequence of bytes
  - High bandwidth (Hundreds GB/sec)
- 64KB of fast, on-chip RAM
  - Software or hardware-managed
  - Shared amongst CUDA cores
  - Enables thread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



# Key Architectural Ideas



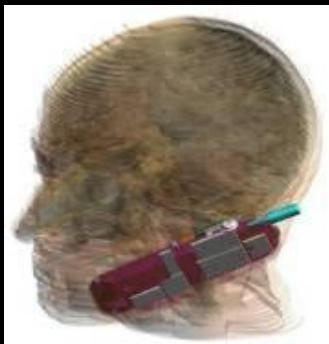
- **SIMT** (Single Instruction Multiple Thread) **execution**
  - threads run in groups of 32 called **warps**
  - threads in a warp share instruction unit (IU)
  - HW automatically handles divergence
- **Hardware multithreading**
  - HW resource allocation & thread scheduling
  - HW relies on threads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



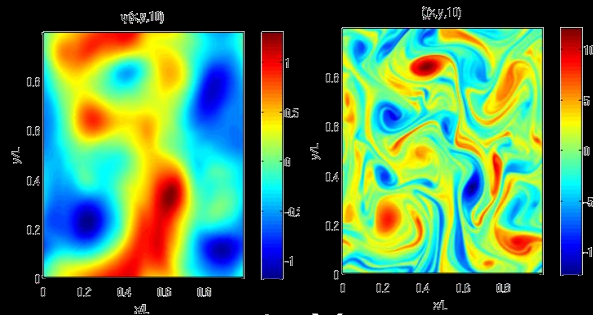
# Enter CUDA



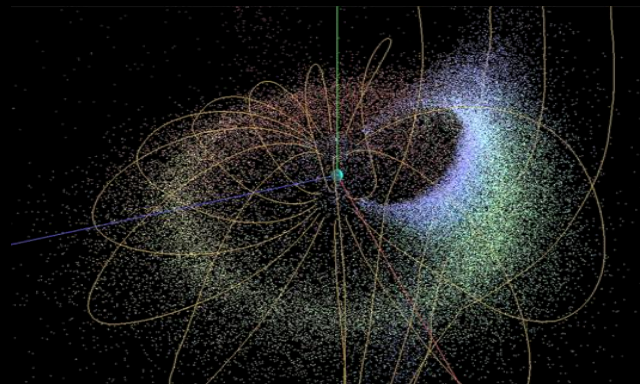
- **Scalable parallel programming model**
- **Minimal extensions to familiar C/C++ environment**
- **Heterogeneous serial-parallel computing**



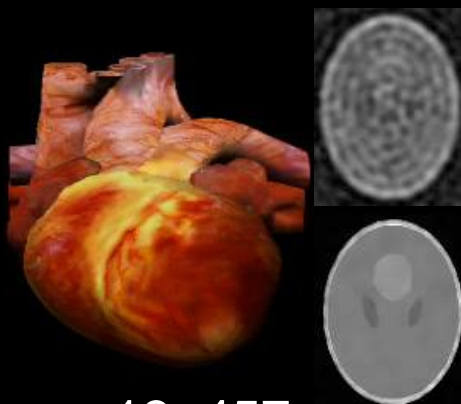
45X



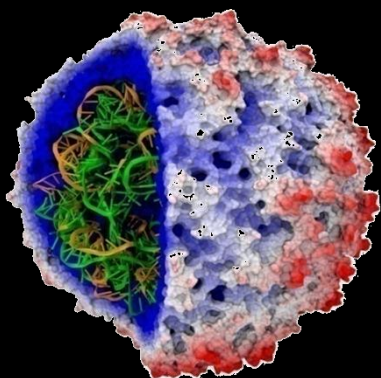
17X



100X

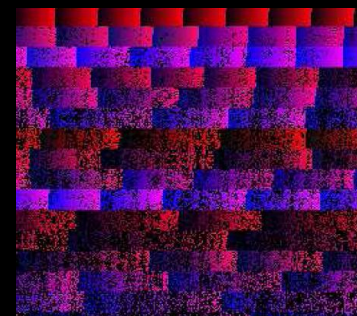


13–457x



110-240X

Motivation



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

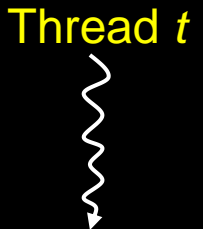


- **Hierarchy of concurrent threads**
- **Lightweight synchronization primitives**
- **Shared memory model for cooperating threads**

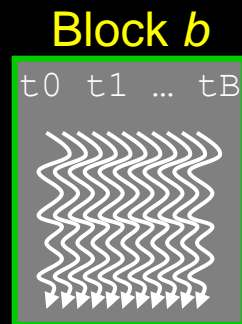
# Hierarchy of concurrent threads



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



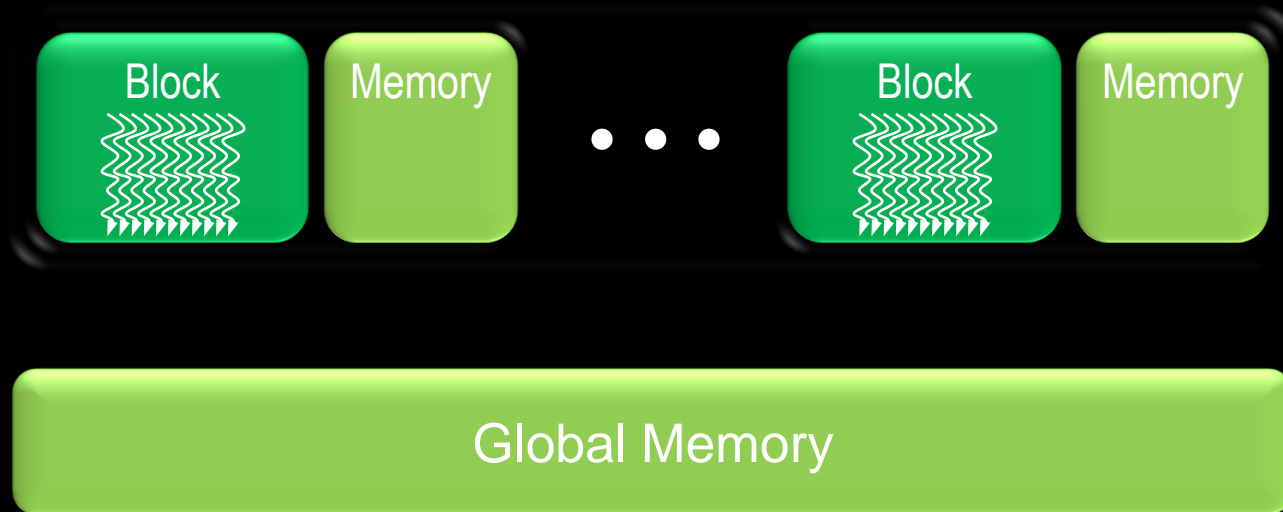
- Threads are grouped into **thread blocks**
  - threads in the same block can cooperate



- Threads/blocks have unique IDs

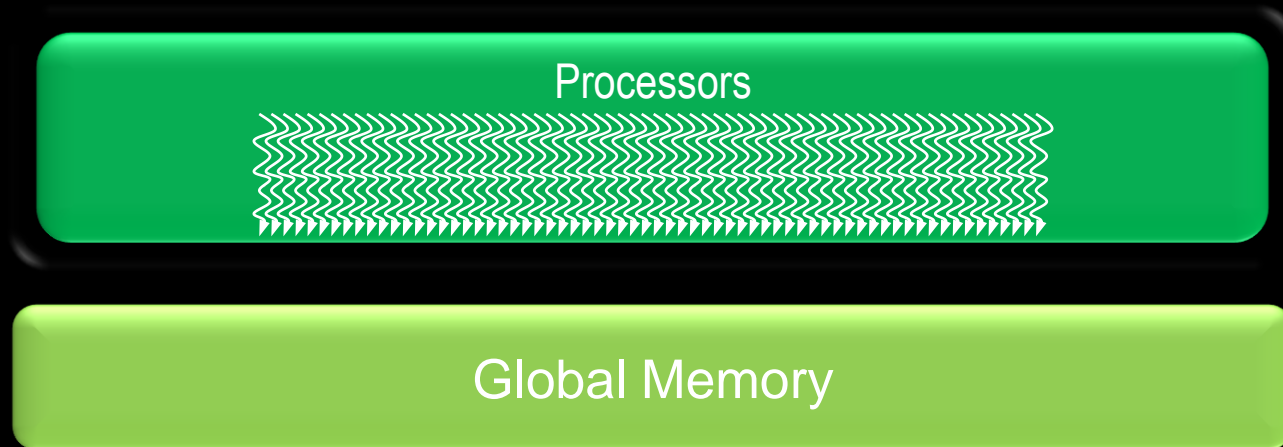


# CUDA Model of Parallelism



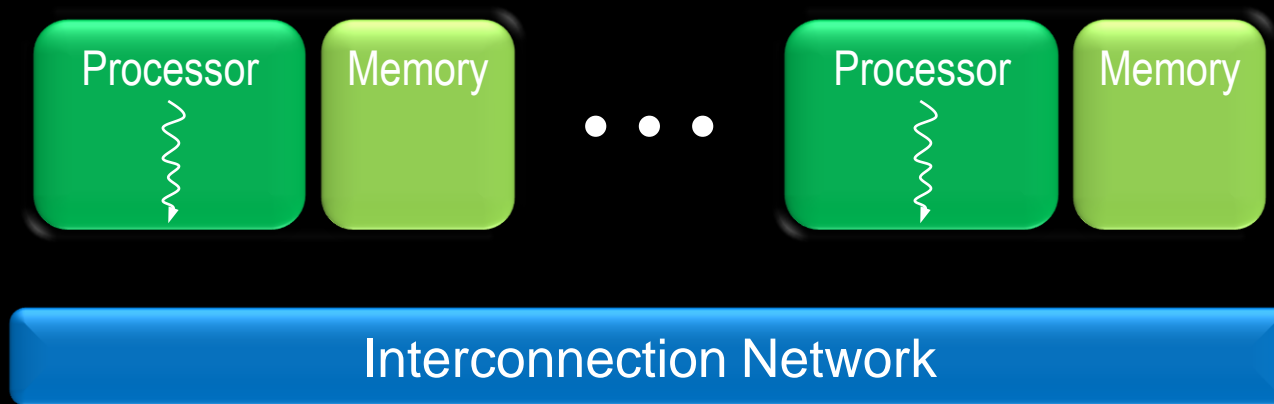
- **CUDA virtualizes the physical hardware**
  - thread is a virtualized scalar processor (registers, PC, state)
  - block is a virtualized multiprocessor (threads, shared mem.)
- **Scheduled onto physical hardware without pre-emption**
  - threads/blocks launch & run to completion
  - blocks should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

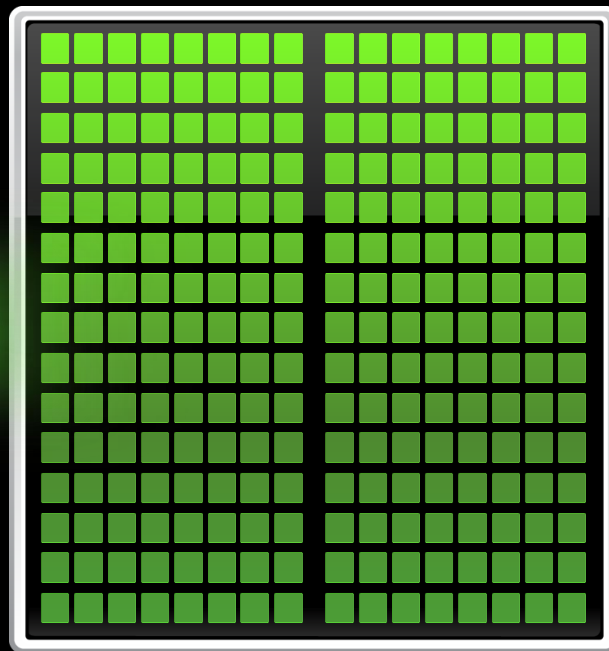
# Heterogeneous Computing



**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);
```

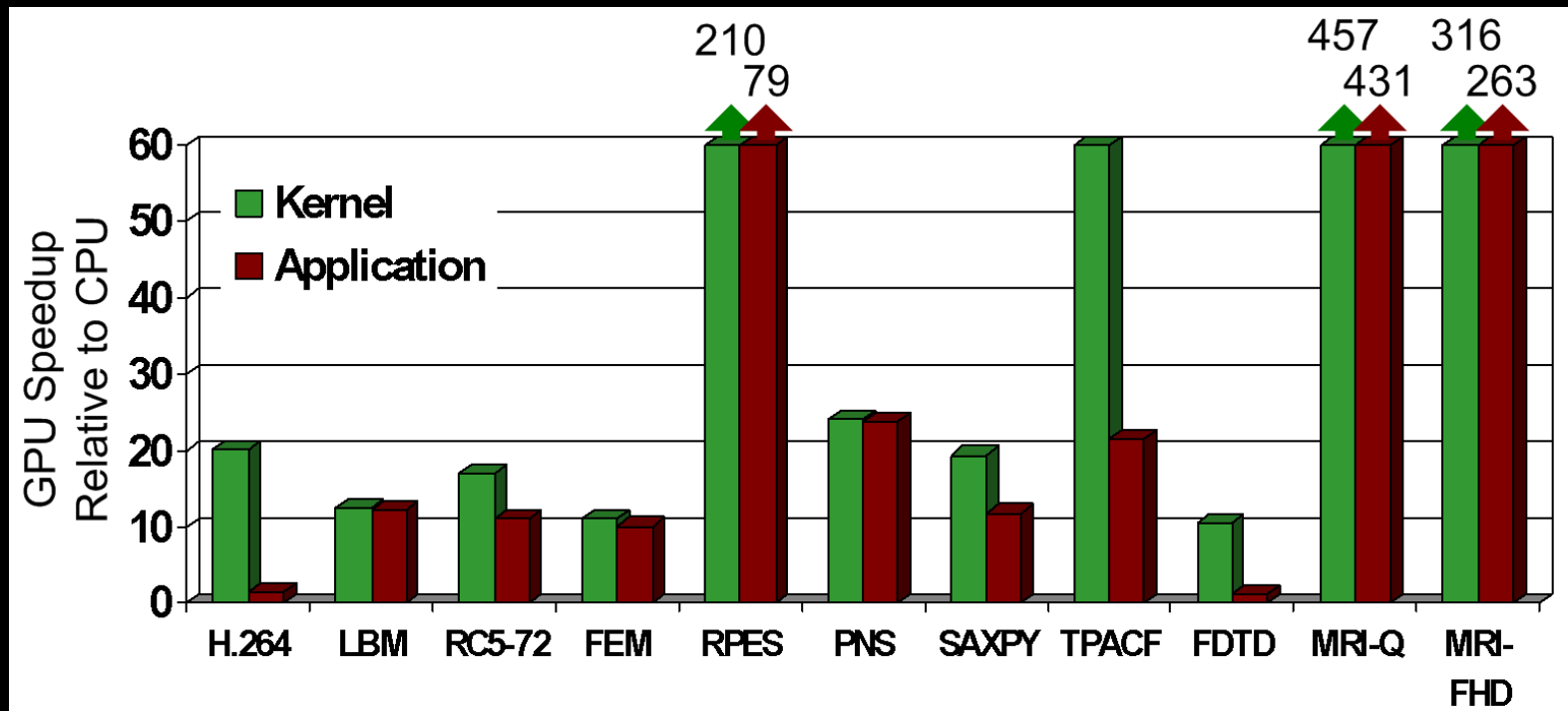


# Previous Projects from UIUC ECE 498AL



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/source/browse/#svn/trunk/tutorials>
- **Work through tutorial codes**
  - `hello_world.cu`
  - `cuda_memory_model.cu`
  - `global_functions.cu`
  - `device_functions.cu`
  - `vector_addition.cu`