General Purpose Computation on Graphics Processors (GPGPU)

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A little about me

- http://graphics.stanford.edu/~mhouston
- Education:
  - UC San Diego, Computer Science BS
  - Stanford University, Computer Science MS
  - Currently a PhD candidate at Stanford University
- Research
  - Parallel Rendering
  - High performance computing
  - Computation on graphics processors (GPGPU)

What can you do on GPUs other than graphics?

- Large matrix/vector operations (BLAS)
- Protein Folding (Molecular Dynamics)
- FFT (SETI, signal processing)
- Ray Tracing
- Physics Simulation [cloth, fluid, collision]
- Sequence Matching (Hidden Markov Models)
- Speech Recognition (Hidden Markov Models, Neural nets)
- Databases
- Sort/Search
- Medical Imaging (image segmentation, processing)
- And many, many more…

http://www.gpgpu.org

Why use GPUs?

- COTS
  - In every machine
- Performance
  - Intel 3.0 GHz Pentium 4
    - 12 GFLOPs peak (MAD)
    - 5.96 GB/s to main memory
  - ATI Radeon X1800XT
    - 120 GFLOPs peak (fragment engine)
    - 42 GB/s to video memory

Task vs. Data parallelism

- Task parallel
  - Independent processes with little communication
  - Easy to use
    - “Free” on modern operating systems with SMP
- Data parallel
  - Lots of data on which the same computation is being executed
  - No dependencies between data elements in each step in the computation
  - Can saturate many ALUs
  - But often requires redesign of traditional algorithms

CPU vs. GPU

- CPU
  - Really fast caches (great for data reuse)
  - Fine branching granularity
  - Lots of different processes/threads
  - High performance on a single thread of execution
- GPU
  - Lots of math units
  - Fast access to onboard memory
  - Run a program on each fragment/vertex
  - High throughput on parallel tasks

- CPUs are great for ***task*** parallelism
- GPUs are great for ***data*** parallelism

The Importance of Data Parallelism for GPUs

- GPUs are designed for highly parallel tasks like rendering
- GPUs process *independent* vertices and fragments
  - Temporary registers are zeroed
  - No shared or static data
  - No read-modify-write buffers
  - In short, no communication between vertices or fragments
- Data-parallel processing
  - GPU architectures are ALU-heavy
    - Multiple vertex & pixel pipelines
    - Lots of compute power
  - GPU memory systems are designed to ***stream*** data
    - Linear access patterns can be prefetched
    - Hide memory latency

Courtesy GPGPU.org

GPGPU Terminology

Arithmetic Intensity

- Arithmetic intensity
  - Math operations per word transferred
  - Computation / bandwidth
- Ideal apps to target GPGPU have:
  - Large data sets
  - High parallelism
  - Minimal dependencies between data elements
  - High arithmetic intensity
  - Lots of work to do without CPU intervention

Courtesy GPGPU.org

Data Streams & Kernels

- Streams
  - Collection of records requiring similar computation
    - Vertex positions, Voxels, FEM cells, etc.
  - Provide data parallelism
- Kernels
  - Functions applied to each element in stream
    - transforms, PDE, …
  - No dependencies between stream elements
    - Encourage high Arithmetic Intensity

Courtesy GPGPU.org

Scatter vs. Gather

- Gather
  - Indirect read from memory (x = a[i])
  - Naturally maps to a texture fetch
  - Used to access data structures and data streams
- Scatter
  - Indirect write to memory (a[i] = x)
  - Difficult to emulate:
    - Render to vertex array
    - Sorting buffer
  - Needed for building many data structures
  - Usually done on the CPU

Mapping algorithms to the GPU

Mapping CPU algorithms to the GPU

- Basics
  - Stream/Arrays -> Textures
  - Parallel loops -> Quads
  - Loop body -> vertex + fragment program
  - Output arrays -> render targets
  - Memory read -> texture fetch
  - Memory write -> framebuffer write
- Controlling the parallel loop
  - Rasterization = Kernel Invocation
  - Texture Coordinates = Computational Domain
  - Vertex Coordinates = Computational Range

Courtesy GPGPU.org

Computational Resources

- Programmable parallel processors
  - Vertex & Fragment pipelines
- Rasterizer
  - Mostly useful for interpolating values (texture coordinates) and per-vertex constants
- Texture unit
  - Read-only memory interface
- Render to texture
  - Write-only memory interface

Courtesy GPGPU.org

Vertex Processors

- Fully programmable (SIMD / MIMD)
- Processes 4-vectors (RGBA / XYZW)
- Capable of scatter but not gather
  - Can change the location of current vertex
  - Cannot read info from other vertices
  - Can only read a small constant memory
- Vertex Texture Fetch
  - Random access memory for vertices
  - Limited gather capabilities
    - Can fetch from texture
    - Cannot fetch from current vertex stream

Courtesy GPGPU.org

Fragment Processors

- Fully programmable (SIMD)
- Processes 4-component vectors (RGBA / XYZW)
- Random access memory read (textures)
- Generally capable of gather but not scatter
  - Indirect memory read (texture fetch), but no indirect memory write
  - Output address fixed to a specific pixel
- Typically more useful than vertex processor
  - More fragment pipelines than vertex pipelines
  - Direct output (fragment processor is at end of pipeline)
  - Better memory read performance

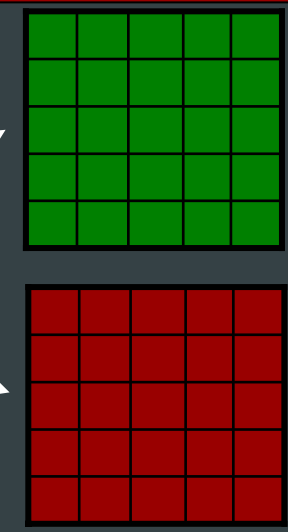
- For GPGPU, we mainly concentrate on using the fragment processors
  - Most of the flops
  - Highest memory bandwidth

Courtesy GPGPU.org

GPGPU example – Adding Vectors

- Place arrays into 2D textures
- Convert loop body into a shader
- Loop body = Render a quad
  - Needs to cover all the pixels in the output
  - 1:1 mapping between pixels and texels
- Readback framebuffer into result array

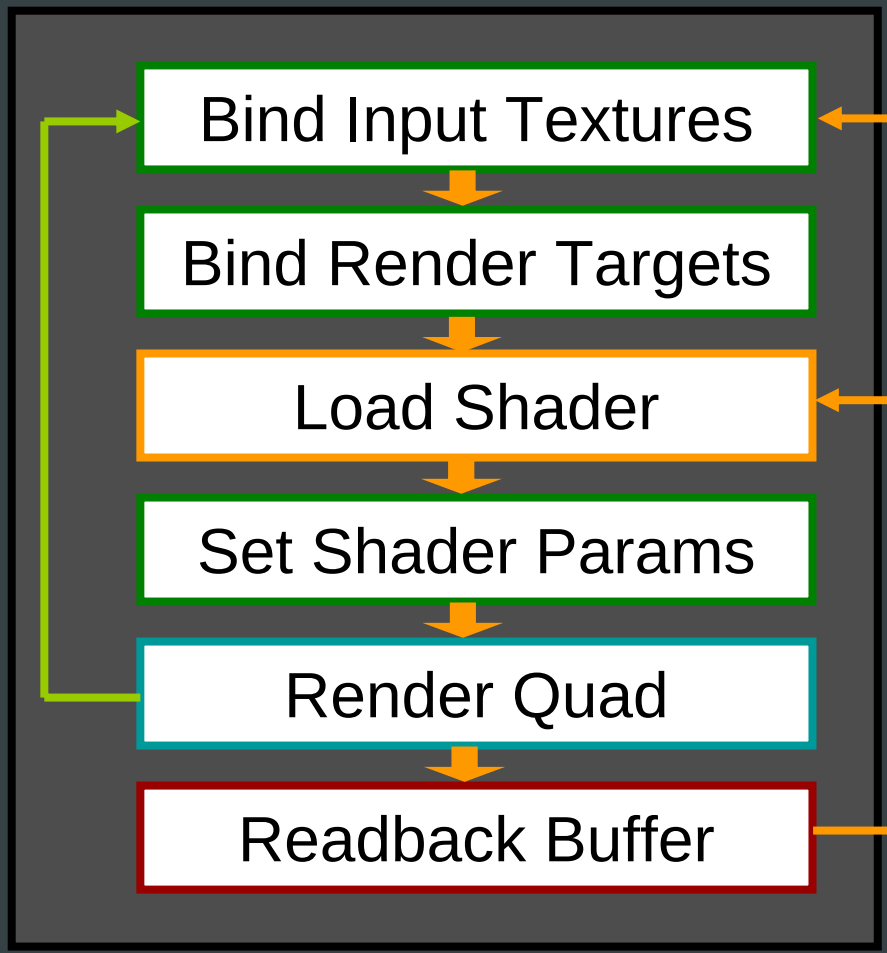
0	1	2	3	4
5	6	7	8	9
10	11	12	13	14
15	16	17	18	19
20	21	22	23	24



```
float a[5*5];
float b[5*5];
float c[5*5];
//initialize vector a
//initialize vector b
for(int i=0; i<5*5; i++)
{
    c[i] = a[i] + b[i];
}
```

```
!!ARBfp1.0
TEMP R0;
TEMP R1;
TEX R0, fragment.position, texture[0], 2D;
TEX R1, fragment.position, texture[1], 2D;
ADD R0, R0, R1;
MOV fragment.color, R0;
```

How this basically works – Adding vectors



Vector A , Vector B

```
!!ARBfp1.0
TEMP R0;
TEMP R1;
TEX R0, fragment.position, texture[0], 2D;
TEX R1, fragment.position, texture[1], 2D;
ADD R0, R0, R1;
MOV fragment.color, R0;
```

Vector C

C = A+B

Rolling your own GPGPU apps

- Lots of information on GPGPU.org
- For those with a strong graphics background:
  - Do all the graphics setup yourself
  - Write your kernels:
    - Use high level languages
      - Cg, HLSL, ASHLI
    - Or, direct assembly
      - ARB_fragment_program, ps20, ps2a, ps2b, ps30
- High level languages and systems to make GPGPU easier
  - Brook (http://graphics.stanford.edu/projects/brookgpu/)
  - Sh (http://libsh.org)

BrookGPU

- History
  - Developed at Stanford University
  - Goal: allow non-graphics users to use GPUs for computation
  - Lots of GPGPU apps written in Brook
- Design
  - C based language with streaming extensions
  - Compiles kernels to DX9 and OpenGL shading models
  - Runtimes (DX9/OpenGL) handle all graphics commands
- Performance
  - 80-90% of hand tuned GPU application in many cases

GPGPU and the ATI X1800

GPGPU on the ATI X1800

- IEEE 32-bit floating point
  - Simplifies precision issues in applications
- Long programs
  - We can now handle larger applications
  - 512 static instructions
  - Effectively unlimited dynamic instructions
- Branching and Looping
  - No performance cliffs for dynamic branching and looping
  - Fine branch granularity: ~16 fragments
- Faster upload/download
  - 50-100% increase in PCIe bandwidth over last generation

GPGPU on the ATI X1800, cont.

- Advanced memory controller
  - Latency hiding for streaming reads and writes to memory
    - With enough math ops you can hide all memory access!
  - Large bandwidth improvement over previous generation
- Scatter support (a[i] = x)
  - Arbitrary number of float outputs from fragment processors
  - Uncached reads and writes for register spilling
- F-Buffer
  - Support for linearizing datasets
  - Store temporaries “in flight”

GPGPU on the ATI X1800, cont.

- Flexibility
  - Unlimited texture reads
  - Unlimited dependent texture reads
  - 32 hardware registers per fragment
- 512MB memory support
  - Larger datasets without going to system memory

Performance basics for GPGPU – X1800XT (from GPUBench)

- Compute
  - 83 GFLOPs (MAD)
- Memory
  - 42 GB/s cache bandwidth
  - 21 GB/s streaming bandwidth
  - 4 cycle latency for a float4 fetch (cache hit)
  - 8 cycle latency for a float4 fetch (streaming)
- Branch granularity – 16 fragments
- Offload to GPU
  - Download (GPU -> CPU): 900 MB/s
  - Upload (CPU -> GPU): 1.4 GB/s

http://graphics.stanford.edu/projects/gpubench

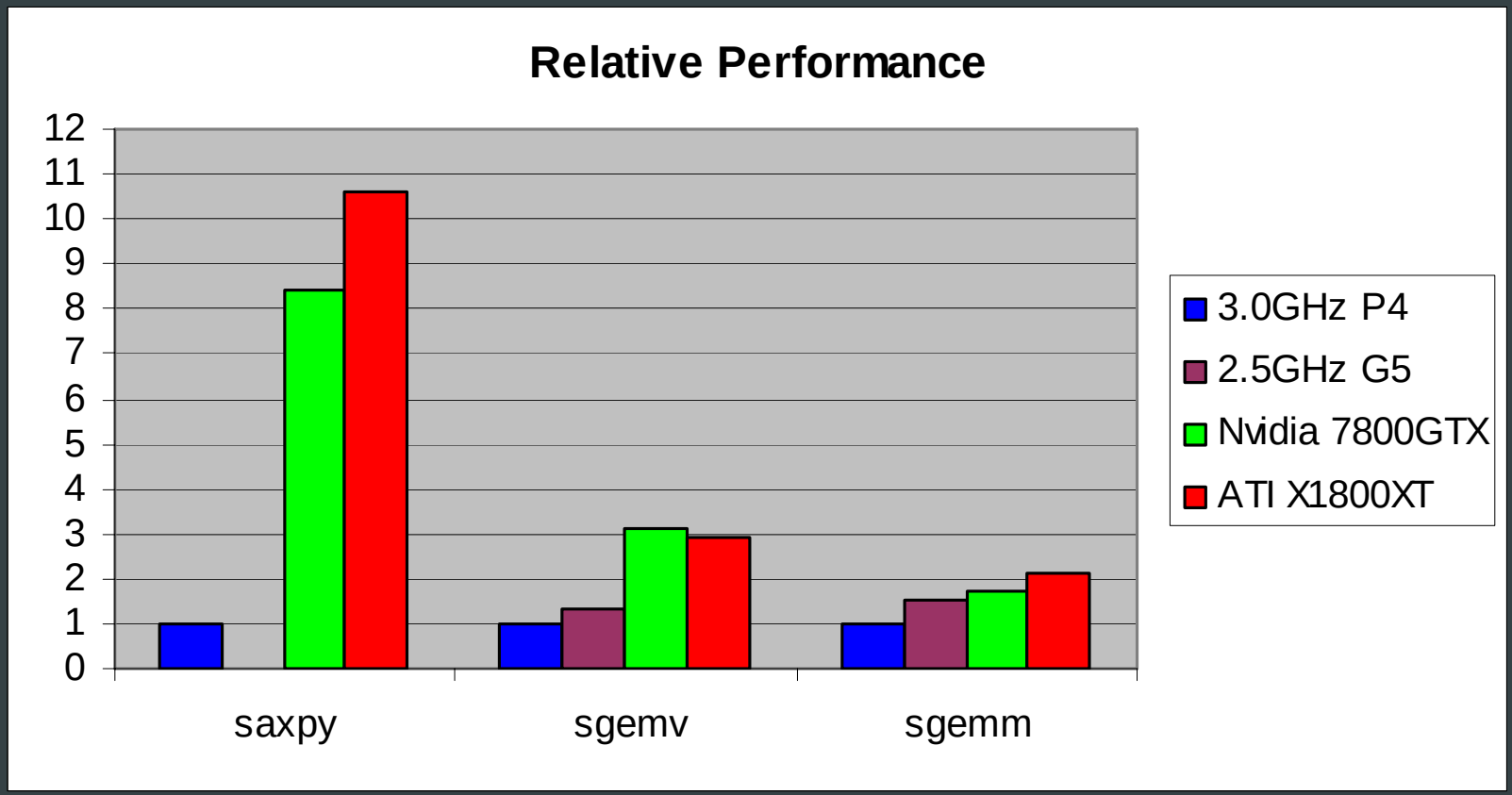
A few examples on the ATI X1800XT

BLAS

- Basic Linear Algebra Subprograms
  - High performance computing
    - The basis for LINPACK benchmarks
    - Heavily used in simulation
  - Ubiquitous in many math packages
    - MatLab™
    - LAPACK
- BLAS 1: scalar, vector, vector/vector operations
- BLAS 2: matrix-vector operations
- BLAS 3: matrix-matrix operations

BLAS GPU Performance

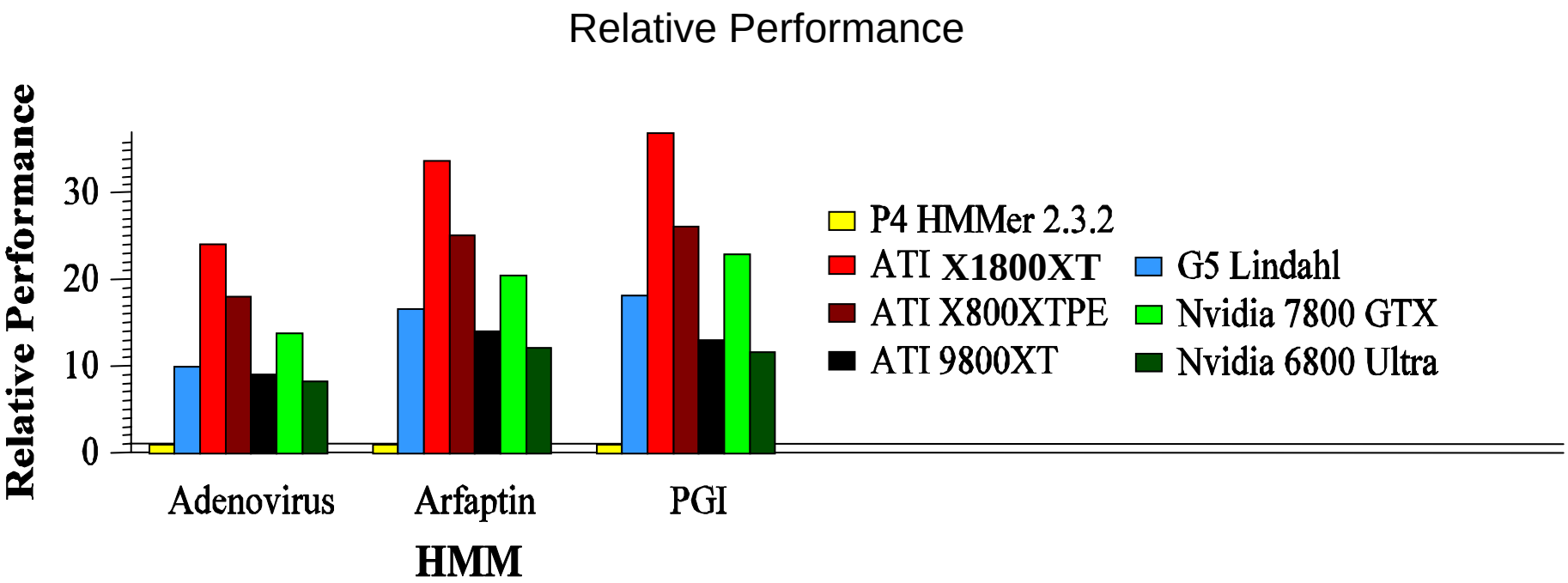
- saxpy (BLAS1) – single precision vector-scalar product
- sgemv (BLAS2) – single precision matrix-vector product
- sgemm (BLAS3) – single precision matrix-matrix product



HMMer – Protein sequence matching

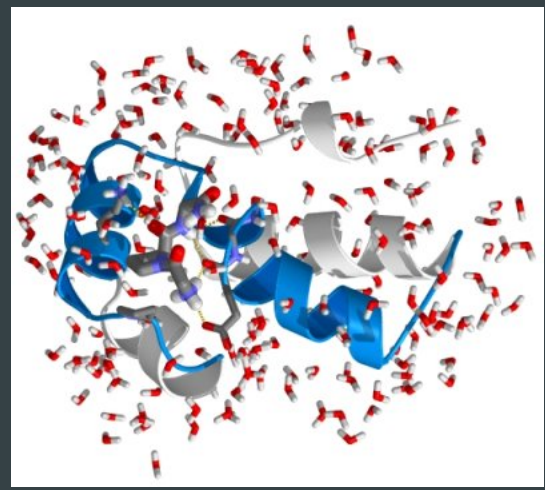
- Goal
  - Find matching patterns between protein sequences
  - Relationship between diseases and genetics
  - Genetic relationships between species
- Problem
  - HUGE databases to search against
  - Queries take lots of time to process
    - Researches start searches and go home for the night
- Core Algorithm (hmmsearch)
  - Viterbi algorithm
  - Compare a Hidden Markov Model against a large database of protein sequences
- Paper at IEEE Supercomputing 2005
  - http://graphics.stanford.edu/papers/clawhmmer/

HMMer – Performance

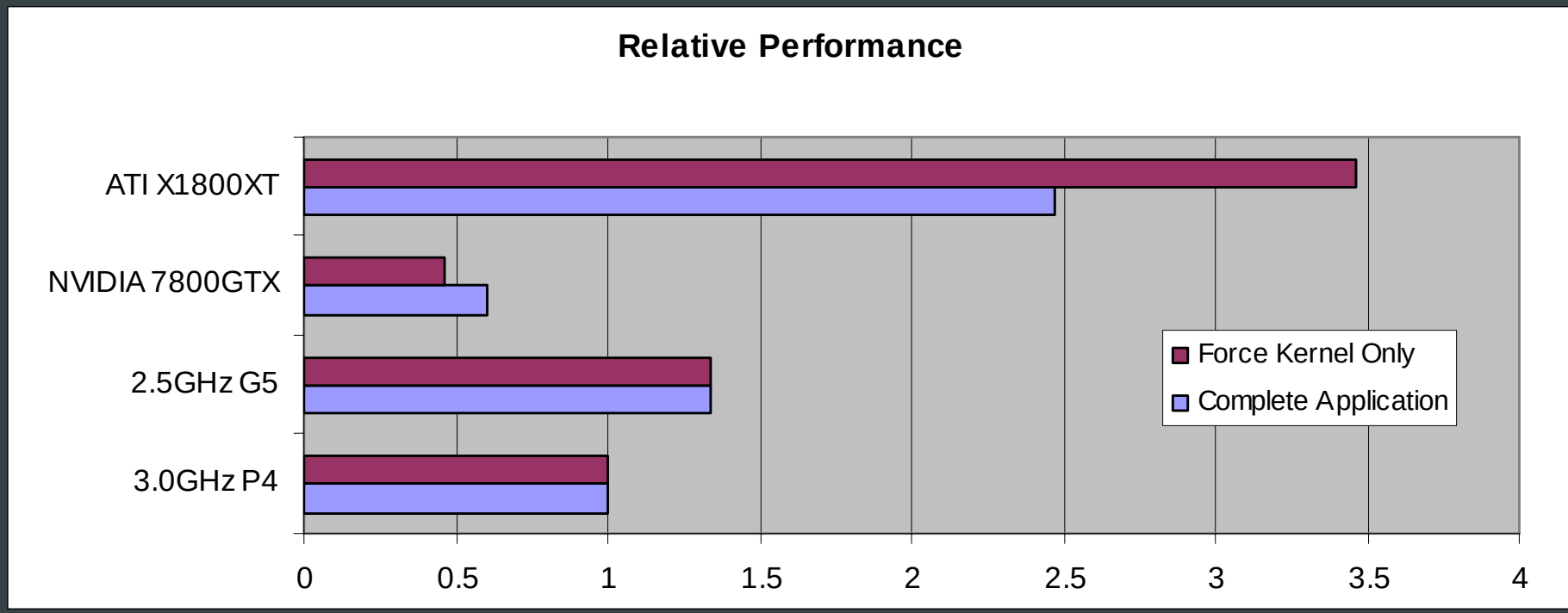


Protein Folding

- GROMACS provides *extremely high performance* compared to all other programs.
- Lot of algorithmic optimizations:
  - Own software routines to calculate the inverse square root.
  - Inner loops optimized to remove all conditionals.
  - Loops use SSE and 3DNow! multimedia instructions for x86 processors
  - For Power PC G4 and later processors: Altivec instructions provided
- Normally 3-10 times faster than any other program.
- Core algorithm in Folding@Home
- http://www.gromacs.org



GROMACS - Performance



GROMACS – GPU Implementation

- Written using Brook by non-graphics programmers
  - Offloads force calculation to GPU (~80% of CPU time)
  - Force calculation on X1800XT is ~3.5X a 3.0GHz P4
  - Overall speed up on X1800XT is ~2.5X a 3.0GHz P4
- Not yet optimized for X1800XT
  - Using ps2b kernels, i.e. no looping
  - Not making use of new scatter functionality
- The revenge of Ahmdal's law
  - Force calculation no longer bottleneck (38% of runtime)
  - Need to also accelerate data structure building (neighbor lists)
    - MUCH easier with scatter support
- This looks like a very promising application for GPUs
  - Combine CPU and GPU processing for a folding monster!

Making GPGPU easier

What GPGPU needs from vendors

- More information
  - Shader ISA
  - Latency information
  - GPGPU Programming guide (floating point)
    - How to order code for ALU efficiency
    - The “real” cost of all instructions
    - Expected latencies of different types of memory fetches
- Direct access to the hardware
  - GL/DX is not what we want to be using
    - We don’t need state tracking
    - Using graphics commands is odd for doing computation
    - The graphics abstractions aren’t useful for us
  - Better memory management
- Fast transfer to and from GPU
  - Non-blocking
- Consistent graphics drivers
  - Some optimizations for games hurt GPGPU performance

What GPGPU needs from the community

- Data Parallel programming languages
  - Lots of academic research
- “GCC” for GPUs
- Parallel data structures
- More applications
  - What will make the average user care about GPGPU?
  - What can we make data parallel and run fast?

Thanks

- The BrookGPU team – Ian Buck, Tim Foley, Jeremy Sugerman, Daniel Horn, Kayvon Fatahalian
- GROMACS – Vishal Vaidyanathan, Erich Elsen, Vijay Pande, Eric Darve
- HMMer – Daniel Horn, Eric Lindahl
- Pat Hanrahan
- Everyone at ATI Technologies

Questions?

- I'll also be around after the talk
- Email: mhouston@stanford.edu
- Web: http://graphics.stanford.edu/~mhouston

- For lots of great GPGPU information:
  - GPGPU.org (http://www.gpgpu.org)