Stream Programming Environments

Pat Hanrahan
Computer Science & Electrical Engineering
Stanford University

GP^2 Workshop
August 7-8, 2004

Acknowledgements

- Bill Dally
- Eric Darve
- Vijay Pande
- Bill Mark
- John Owens
- Kurt Akeley
- Mark Horowitz
- Ian Buck
- Mattan Erez
- Kayvon Fatahalian
- Tim Foley
- Daniel Horn
- Michael Houston
- Jeremy Sugarman

Funding: DARPA, DOE, ATI, IBM, NVIDIA, SONY

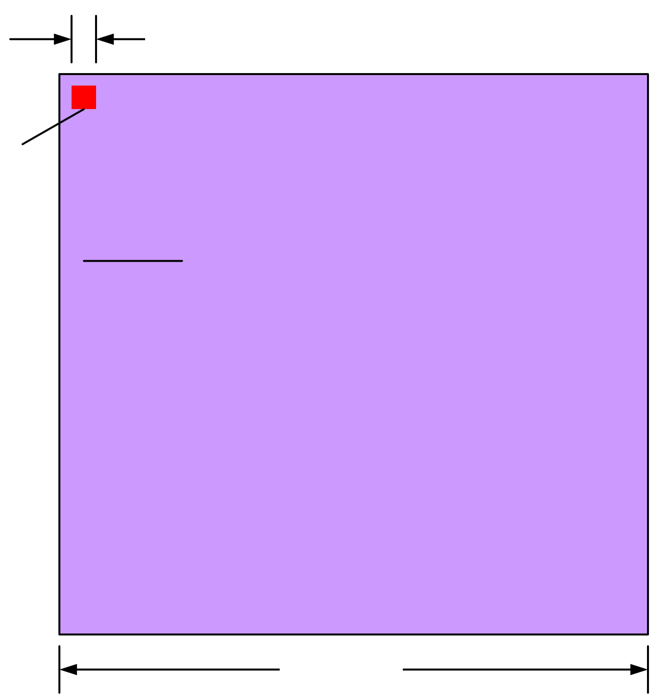
Motivation

- Cinematic games and media drive GPU market
- Current GPU faster than CPU (at graphics)
- Gap between the GPU and the CPU increasing
- Why? Data parallelism; efficient communication
- Programmable GPUs ≈ Stream processors
- Many applications map to stream processing
- Therefore, a $50 high-performance parallel-computer is shipping with every PC
- Revolutionize computing

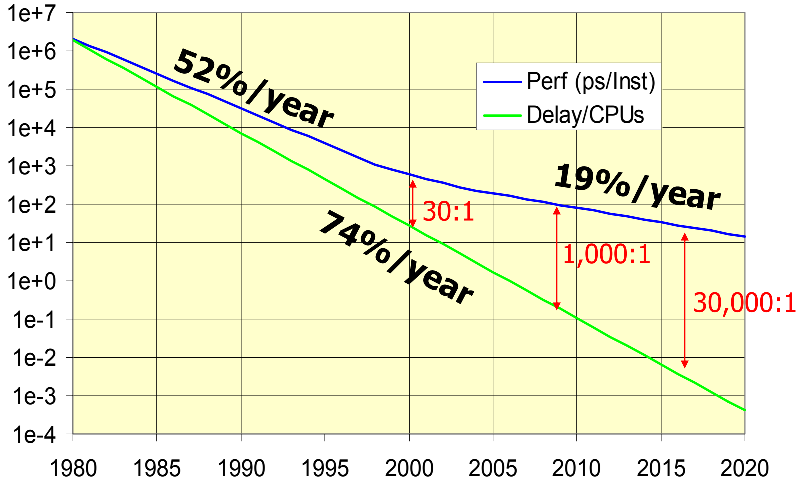
Overview

- Technology trends
- Stream programming abstraction
- Brook for GPUs
- Applications

VLSI for Programmers :-)

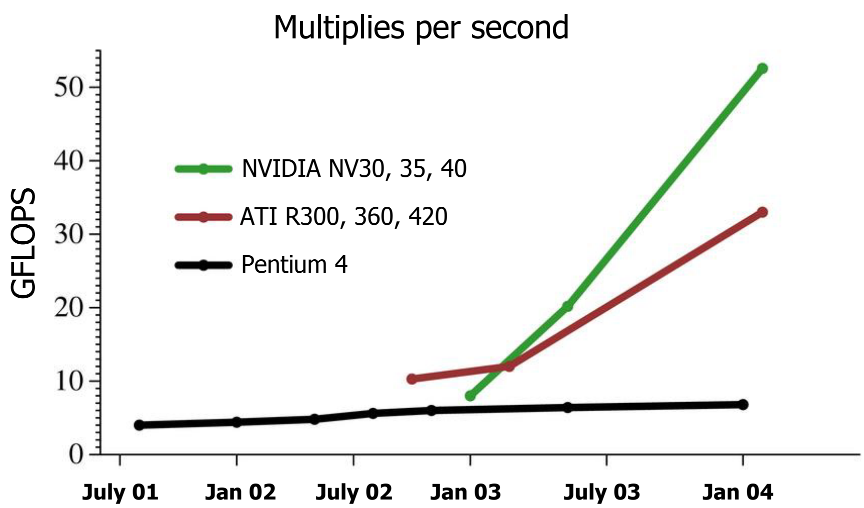


The Capability Gap



Graph courtesy of Bill Dally

Recent Performance Trends



Programming Environments[1999]?

RenderMan

Real-Time Shading Language (RTSL)

Rendering

RenderMan++

Programming Environments[2004]?

RenderMan

Real-Time Shading Language (RTSL)

Simulation

Brook (Stream)

Stream Abstraction

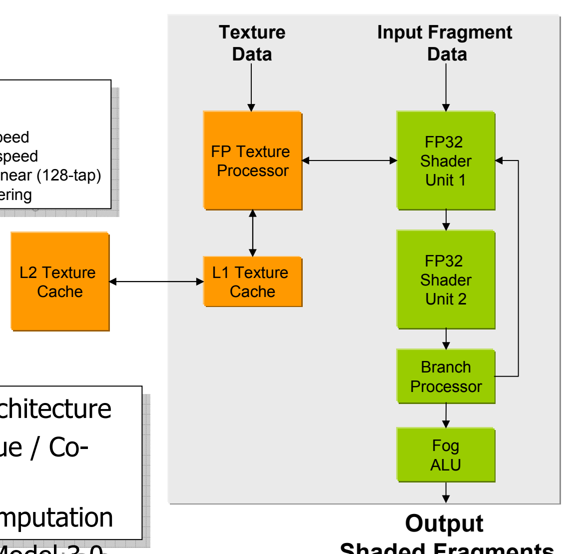
Streams – Old/Hot Idea in CS

- <stream.h>
- OpenGL/GLS/Chromium
- Data visualization systems (vtk, avs, dx)
- Signal processing (signal flow graphs)
- Functional programming
- Streaming data bases
- Sensor nets

Minimize State!

Fragment Processor

Texture Filter
Bi / Tri / Aniso
1 texture @ full speed
4-tap filter @ full speed
16:1 Aniso w/ Trilinear (128-tap)
FP16 Texture Filtering

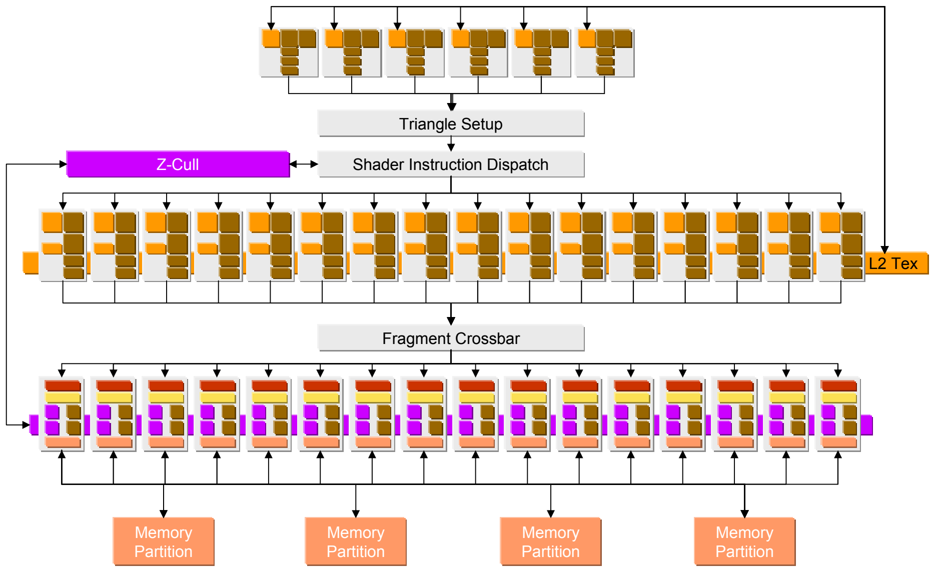


Shader Unit 1
4 FP Ops / pixel
Dual/Co-Issue
Texture Address Calc
Free fp16 normalize
+ mini ALU

Shader Unit 2
4 FP Ops / pixel
Dual/Co-Issue
+ mini ALU

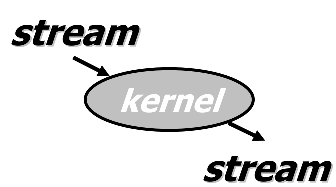
- SIMD Architecture
- Dual Issue / Co-Issue
- FP32 Computation
- Shader Model 3.0

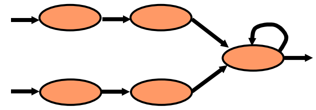
GeForce 6800 Series 3D Pipeline



Stream Programming Abstraction

- Streams
  - Collection of data records
- Kernels
  - Inputs/outputs are streams
  - Perform computation
  - Can be chained together





Why Architects like Streams?

- Parallelism
  - Data parallelism
  - Pipeline (task) parallelism
- Communication
  - Producer-consumer locality
  - Predictable memory access pattern
  - No read-write hazards; simple coherence
  - Hide latency of random memory accesses
  - High arithmetic intensity

A lot like vector machines …

Arithmetic Intensity

Arithmetic Intensity =
Compute-to-bandwidth ratio

Graphics pipeline

- Vextex
  BW: 1 vertex = 32 bytes;
  OP: 100-500 f32-ops / vertex
- Fragment
  BW: 1 fragment = 10 bytes
  OP: 300-1000 i8-ops/fragment

Measured Arithmetic Intensity

Microbenchmarks

	GFLOPS	Cache BW	Seq BW
NV 5900 Ultra	40.0	11.4	4.1
NV 6800 Ultra	53.4	20.6	8.4
ATI 9800 XT	26.1	12.2	7.3
ATI X800 XT PE*	63.7	28.4	15.6

Bandwidth measured in GB/sec.

* ATI X800 XT PE is a prerelease board: 500Mhz core / 500Mhz clock

GPUBench: Evaluating GPU performance for numerical and scientific applications, K. Fatahalian, I. Buck, M. Houston, P. Hanrahan, GP^2 2004

CPU vs GPU

- Intel 3 Ghz Pentium 4
  - 12 GFLOPS peak performance (via SSE2)
  - 6 GB/sec peak memory bandwidth
  - 44 GB/sec peak bw from 8K L1 data cache
- NVIDIA GeForce 6800
  - 45 GFLOPS peak performance
  - 36 GB/sec peak memory bandwidth
  - 21 GB/sec peak bw from ?K L1 data cache

Approach I

Map application to graphics primitives

- Graphics library-based programming models
  - Cg/HLSL
  - OpenGL Shading Language
  - Sh [McCool et al. 2004]

Approach II

Map application to parallel computer

- Stream languages
  - AWK, Ptolemy, …
  - StreaMIT, StreamC/KernelC, …
- Data parallel programming
  - APL, SETL, S, Fortran90, …
  - C* (lisp*), NESL, …
- Communicating sequential processes (CSP)
  - Threads: Occam, UPC
  - Message passing: MPI

Stream Programming Environment

- Collections stored in memory
  - Multidimensional arrays (stencils)
  - Graphs and meshes (topology)
- Data parallel operators
  - Application: map
  - Reductions: scan, reduce (fold)
  - Communication: send, sort, gather, scatter
  - Filter (|O|<|I|) and generate (|O|>|I|)

Brook

Ian Buck, Ph. D. Thesis, Stanford

Brook for GPUs: Stream computing on graphics hardware,
I. Buck, T. Foley, D. Horn, J. Sugarman, K. Fatahalian,
M. Houston, P. Hanrahan, SIGGRAPH 2004

Brook Language

```
kernel void foo (
        float a<>, float b<>,
        out float result<> )
{
        result = a + b;
}

float a<100>;
float b<100>;
float c<100>;
foo(a,b,c);
```

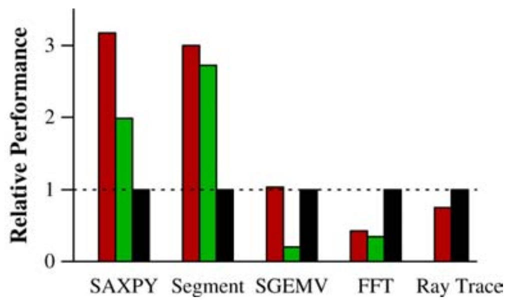
```
for (i=0; i<100; i++)
     c[i] = a[i]+b[i];
```

Goals

- Develop version of PCA Brook for GPUs
  - Programmer need not know GL
- Versions
  - New ATI (420) and NVIDIA (NV40) hardware
  - Linux and Windows
  - DX and OpenGL
- Release as open source [V1.0 Dec 2003]
  - http://brook.sourceforge.net
  - http://sourceforge.net/projects/brook
  - over 6,300 downloads in 8 months

Brook Performance

First Generation GPUs



Floating precisions different
- ATI – 24-bit
- NV – ~IEEE 32-bit
- Intel – IEEE 32-bit

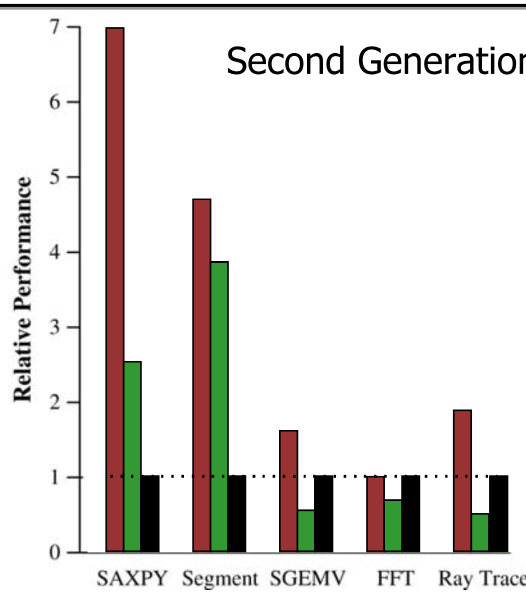
compared against:
- Intel Math Library
- Atlas Math Library
- Cached blocked segmentation
- FFTW
- SSE-opt Ray Triangle code

ATI Radeon 9800 XT

NVIDIA GeForceFX

Brook Performance

Second Generation GPUs



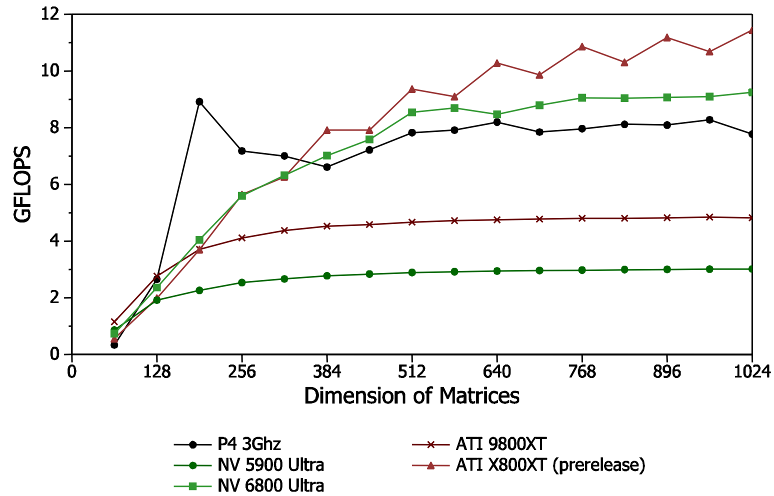
Floating precisions different
- ATI – 24-bit
- NV – ~IEEE 32-bit
- Intel – IEEE 32-bit

compared against:
- Intel Math Library
- Atlas Math Library
- Cached blocked segmentation
- FFTW
- SSE-opt Ray Triangle code

ATI Radeon X800 XT

NVIDIA GeForce 6800

Dense Matrix-Matrix Multiplication



Dense Matrix-Matrix Multiplication

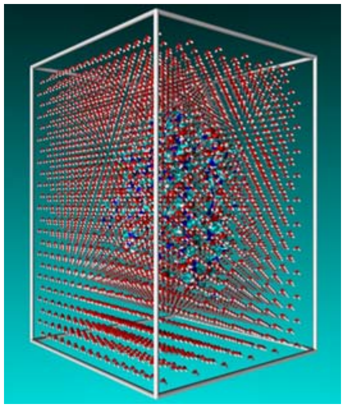
	Time (s)	GFLOPS	Compute Efficiency	BW (GB/sec)	BW Efficiency
NV 5900 Ultra	0.713	3.01	**7.5%**	9.07	**79.6%**
NV 6800 Ultra	0.232	9.25	**17.3%**	18.78	**90.9%**
ATI 9800 XT	0.445	4.83	**18.5%**	12.06	**98.9%**
ATI X800 XT*	0.188	11.40	**17.9%**	27.50	**96.8%**
P4 ATLAS	0.289	7.78	**64.8%**	27.68	**61.9%**

- Matrix-matrix multiplication is bandwidth limited on GPU.
  - Memory blocking to increase cache utilization does not help
  - Architectural problem, not programming model problem

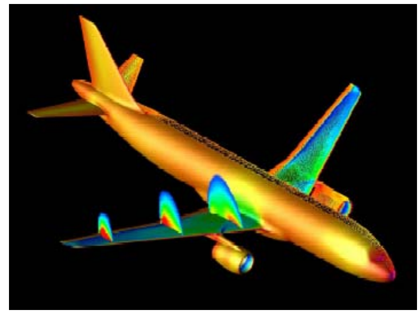
* ATI X800 XT PE is a prerelease board: 500Mhz core/500Mhz clock

Understanding the Efficiency of GPU Algorithms for Matrix-Matrix Multiplication, K. Fatahalian, J. Sugerman, P. Hanrahan, Graphics Hardware 2004

Beyond Graphics and Imaging …



Molecular Dynamics
Folding@Home



Fluid Flow

Accelerating molecular dynamics with GPUs, I. Buck, V. Rangasayee, E. Darve, V. Pande, P. Hanrahan GP^2 2004

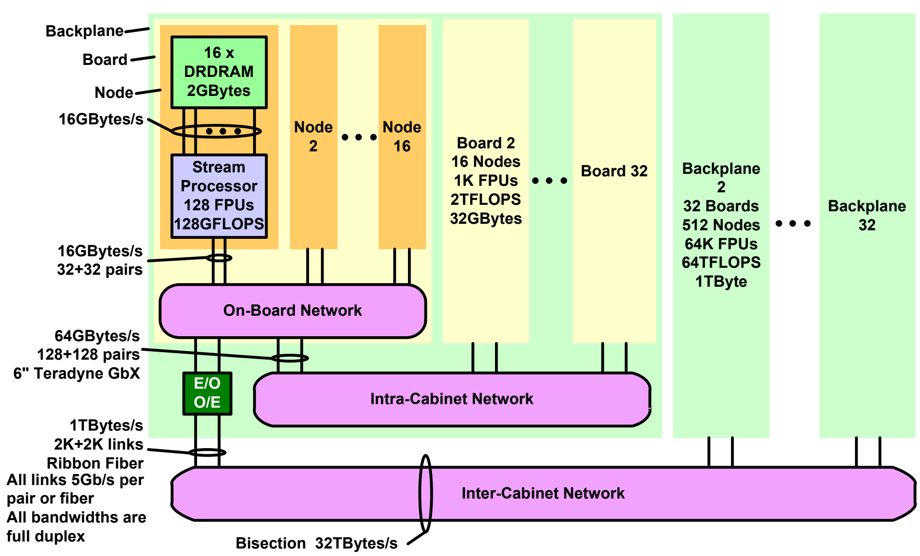
Applications

- Media: audio, images (vision), video, …
- Simulation
  - Monte Carlo
    - Ray tracing
  - Ordinary differential equations
    - N-body problems: molecular dynamics, astrophysics
    - Particle systems and rigid body dynamics
  - Partial differential equations
    - Explicit: elastic deformations
    - Implicit: cloth, fluid flow
- Machine learning and computational statistics?

16 Node GPU Cluster

- Compute
  - 32 2.4GHz P4 Xeons
  - 16GB DDR
  - 1.2TB disk
  - Intel E7505 chipset
- Network
  - Infiniband 4X interconnect
  - GigE
- Graphics
  - ATI Radeon 9800 Pro 256MB

Parallel computation on a cluster of GPUs, M. Houston, K. Fatahalian, J. Sugarman, I. Buck, P. Hanrahan GP^2 2004



Merrimac: Supercomputing with streams, M. Erez, J. Ahn, N. Jayasena, T. Knight, A. Das, F. Labonte, J. Gummaraju, W. Dally, P. Hanrahan, M. Rosenblum, GP^2 2004

Wrap-Up

Vision

- Cinematic games and media drive GPU market
- Current GPU faster than CPU (at graphics)
- Gap between the GPU and the CPU increasing
- Why? Data parallelism; efficient communication
- Programmable GPUs = Stream processors
- Many applications map to stream processing
- Therefore, a $50 high-performance parallel-computer is shipping with every PC
- Revolutionize computing

Opportunities

- Current hardware not optimal
  - Incredible opportunity for architectural innovation
- Current software environment immature
  - Incredible opportunity for reinventing parallel computing software

Questions?

Fly-fishing fly images from The English Fly Fishing Shop