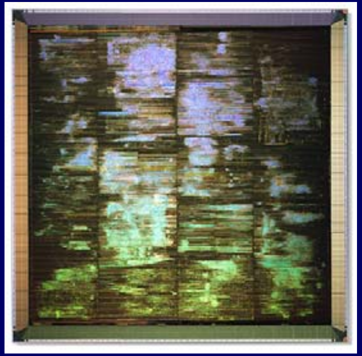
Data Parallel Computing on Graphics Hardware

Ian Buck
Stanford University

Brook
General purpose *Streaming* language

- DARPA Polymorphous Computing Architectures
  - Stanford - Smart Memories
  - UT Austin - TRIPS Processor
  - MIT - RAW Processor
- Stanford Streaming Supercomputer
- Brook: general purpose *streaming* language
  - Language developed at Stanford
  - Compiler in development by **Reservoir Labs**
- **Study of GPUs as Streaming processor**

Why graphics hardware



GeForce FX

Raw Performance:

Pentium 4 SSE **Theoretical***

3GHz * 4 wide * .5 inst / cycle = **6 GFLOPS**

GeForce FX 5900 (NV35) Fragment Shader **Obtained**:

MULR R0, R0, R0: **20 GFLOPS**

Equivalent to a 10 GHz P4

And getting faster: 3x improvement over NV30 (6 months)

2002 R&D Costs:

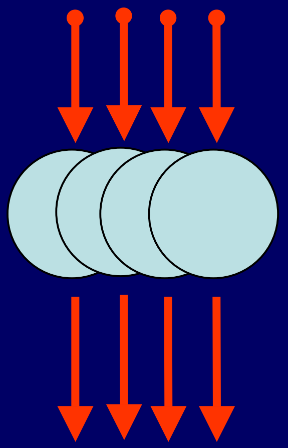
Intel: $4 Billion

NVIDIA: $150 Million

*from Intel P4 Optimization Manual

GPU: Data Parallel

– Each fragment shaded independently
  - No dependencies between fragments
    - – Temporary registers are zeroed
    - – No static variables
    - – No Read-Modify-Write textures
  - Multiple “pixel pipes”



– **Data Parallelism**
  - Support ALU heavy architectures
  - Hide Memory Latency

[Torborg and Kajiya 96, Anderson et al. 97, Igehy et al. 98]

Arithmetic Intensity

Lots of ops per word transferred

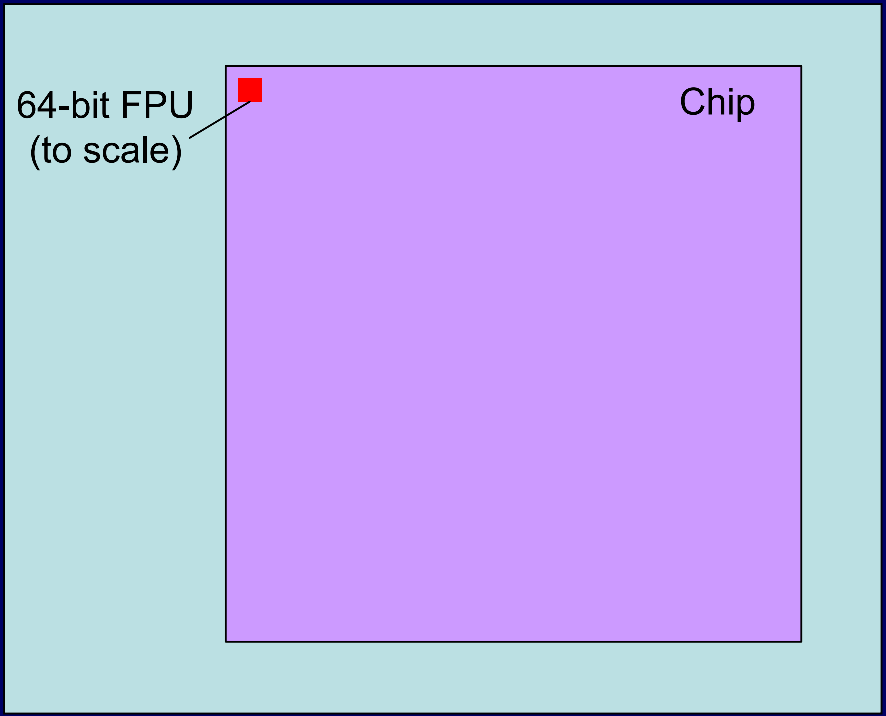
Graphics pipeline

– Vertex
  - BW: 1 triangle = 32 bytes;
  - OP: 100-500 f32-ops / triangle
– Rasterization
  - Create 16-32 fragments per triangle
– Fragment
  - BW: 1 fragment = 10 bytes
  - OP: 300-1000 i8-ops/fragment

Courtesy of Pat Hanrahan

Arithmetic Intensity

- Compute-to-Bandwidth ratio
- High Arithmetic Intensity desirable
  - App limited by ALU performance, not off-chip bandwidth
  - More chip real estate for ALUs, not caches



Courtesy of Bill Dally

Brook
General purpose *Streaming* language

Stream Programming Model

- Enforce Data Parallel computing
- Encourage Arithmetic Intensity
- Provide fundamental ops for stream computing

Brook
General purpose *Streaming* language

- Demonstrate GPU streaming coprocessor
  - Make programming GPUs easier
    - Hide texture/pbuffer data management
    - Hide graphics based constructs in CG/HLSL
    - Hide rendering passes
  - Highlight GPU areas for improvement
    - Features required general purpose stream computing

Streams & Kernels

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

Brook

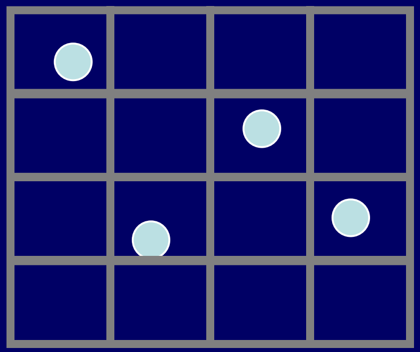
- C with Streams
  - API for managing streams
  - Language additions for kernels

- Stream Create/Store

```
stream s = CreateStream (float, n, ptr);
StoreStream (s, ptr);
```

Brook

- Kernel Functions
  - Pos update in velocity field
  - Map a function to a set



```
kernel void updatepos (stream float3 pos,
                       float3 vel[100][100][100],
                       float timestep,
                       out stream float newpos) {
  newpos = pos + vel[pos.x][pos.y][pos.z]*timestep;
}

s_pos = CreateStream(float3, n, pos);
s_vel = CreateStream(float3, n, vel);
updatepos (s_pos, s_vel, timestep, s_pos);
```

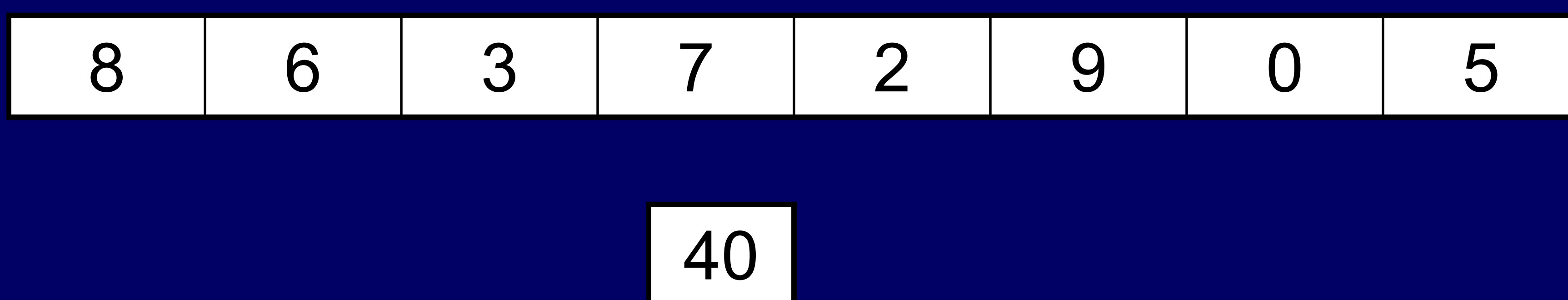
Fundamental Ops

- Associative Reductions

  `KernelReduce(func, s, &val)`

  – Produce a single value from a stream

  – Examples: Compute Max or Sum



Fundamental Ops

- Associative Reductions

  `KernelReduce(func, s, &val)`

  – Produce a single value from a stream
  – Examples: Compute Max or Sum
- Gather: `p = a[i]`
  – Indirect Read
  – Permitted inside kernels
- Scatter: `a[i] = p`
  – Indirect Write

  `ScatterOp(s_index, s_data, s_dst, SCATTEROP_ASSIGN)`

  – Last write wins rule

GatherOp & ScatterOp

Indirect read/write with atomic operation

- GatherOp: `p = a[i]++`

```
GatherOp(s_index, s_data, s_src, GATHEROP_INC)
```

- ScatterOp: `a[i] += p`

```
ScatterOp(s_index, s_data, s_dst, SCATTEROP_ADD)
```

- Important for building and updating data structures for data parallel computing

Brook

- C with streams
  - kernel functions
  - `CreateStream, StoreStream`
  - `KernelReduce`
  - `GatherOp, ScatterOp`

Implementation

- Streams
  - Stored in 2D fp textures / pbuffers
  - Managed by runtime
- Kernels
  - Compiled to fragment programs
  - Executed by rendering quad

Implementation

- Compiler: brcc

foo.br

foo.cg

foo.fp

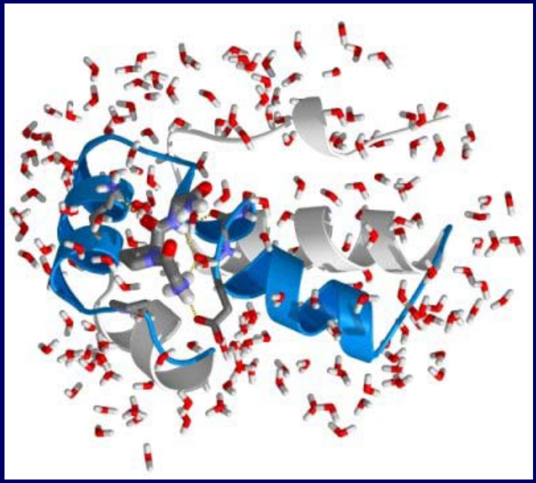
foo.c

- Source to Source compiler
  - Generate CG code
    - Convert array lookups to texture fetches
    - Perform stream/texture lookups
    - Texture address calculation
  - Generate C Stub file
    - Fragment Program Loader
    - Render code

Gromacs

Molecular Dynamics Simulator

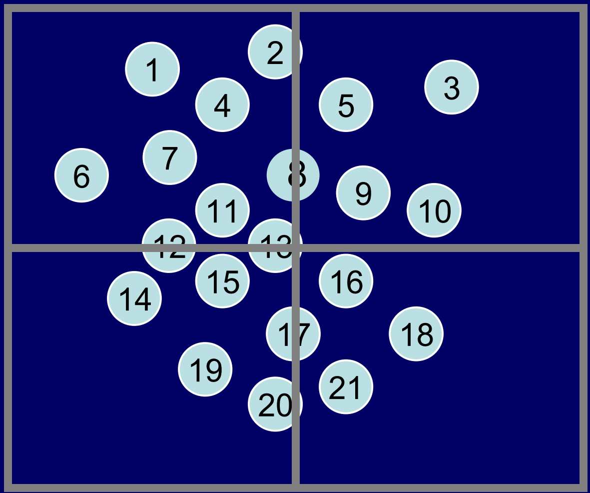
Eric Lindhal, Erik Darve, Yanan Zhao



Force Function (~90% compute time):

$$F_i\left(\mathbf{r}_{ij}\right) = \left(\frac{1}{4\pi\epsilon_0}\frac{q_i q_j}{\epsilon_r r_{ij}^2} + 12\frac{C_{12}}{r_{ij}^{12}} - 6\frac{C_6}{r_{ij}^6}\right)\frac{\mathbf{r}_{ij}}{r_{ij}}$$

Acceleration Structure:

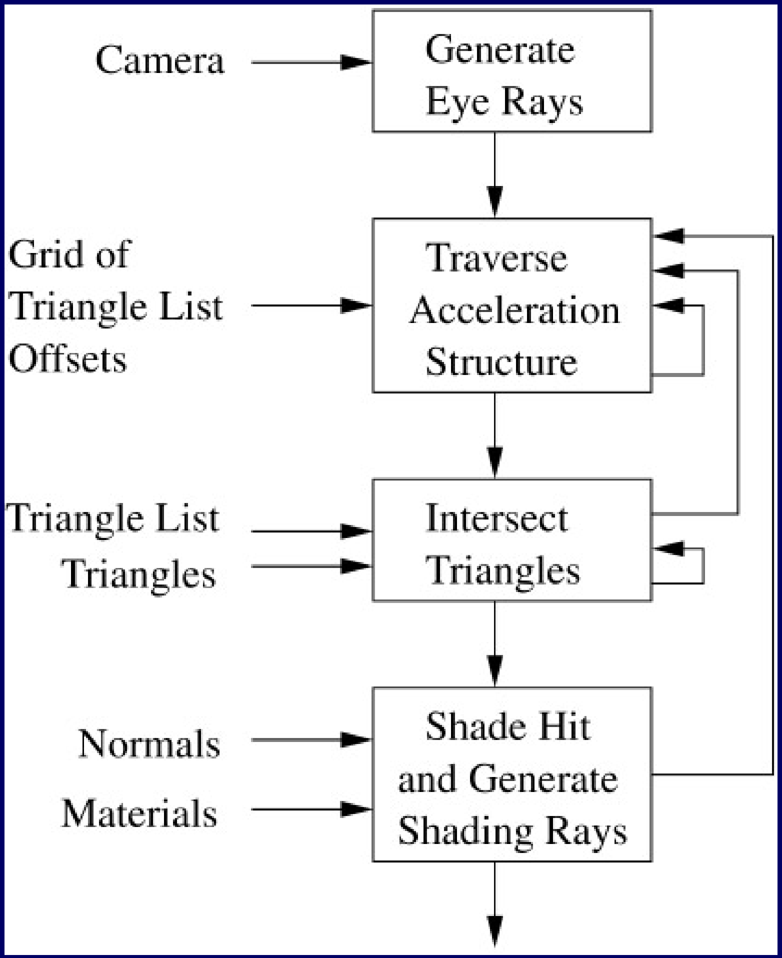


Energy Function:

$$V_{nb} = \sum_{i,j}\left[\frac{1}{4\pi\epsilon_0}\frac{q_i\, q_j}{r_{ij}} + \left(\frac{C_{12}}{r_{ij}^{12}} - \frac{C_6}{r_{ij}^6}\right)\right]$$

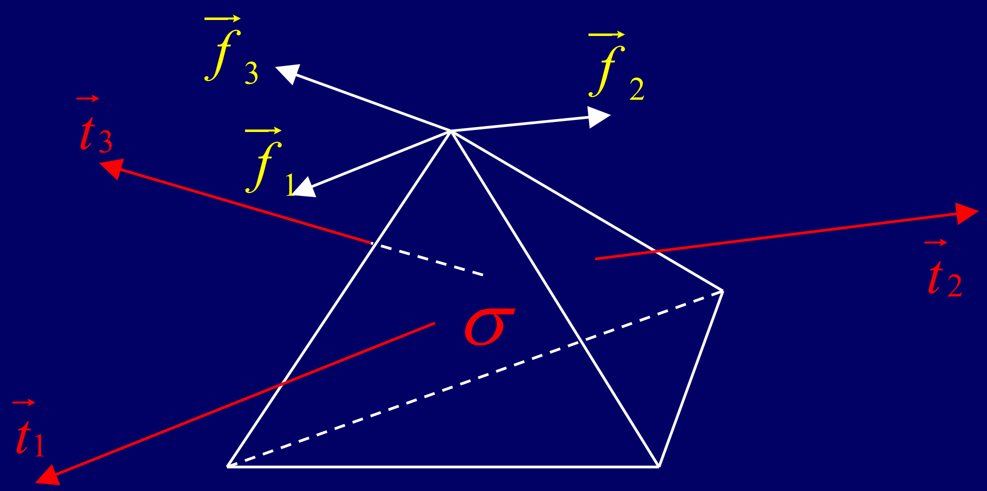
Ray Tracing

Tim Purcell, Bill Mark, Pat Hanrahan



Finite Volume Methods

Joseph Teran, Victor Ng-Thow-Hing, Ronald Fedkiw



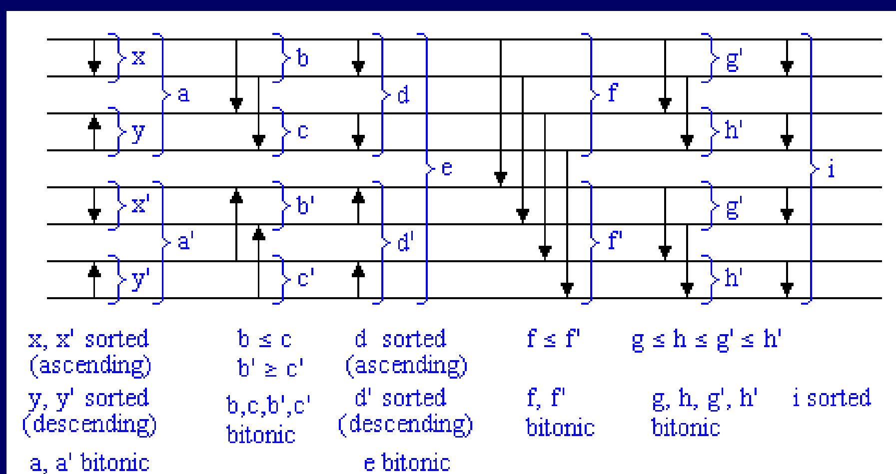
$$\sigma = p\mathbf{I} + 2\left\{\left(W_1 + I_1 W_2\right)\mathbf{B} - W_2\mathbf{B}^2\right\} + W_4 a \otimes a$$

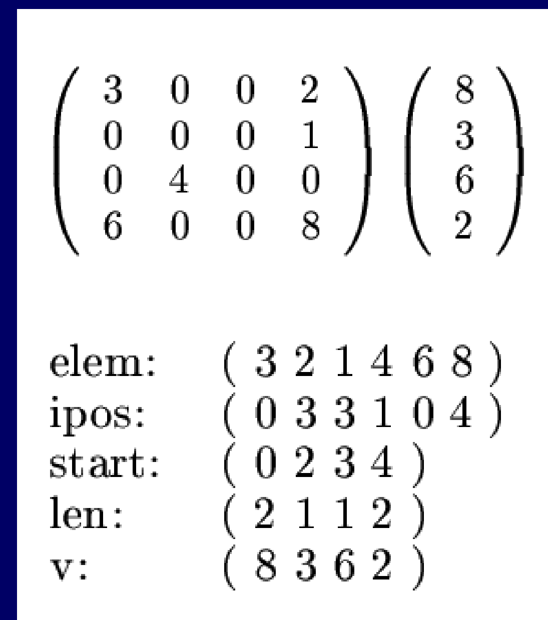
$W_i = \partial W / \partial I_i$

Applications

Sparse Matrix Multiply

Batcher Bitonic Sort

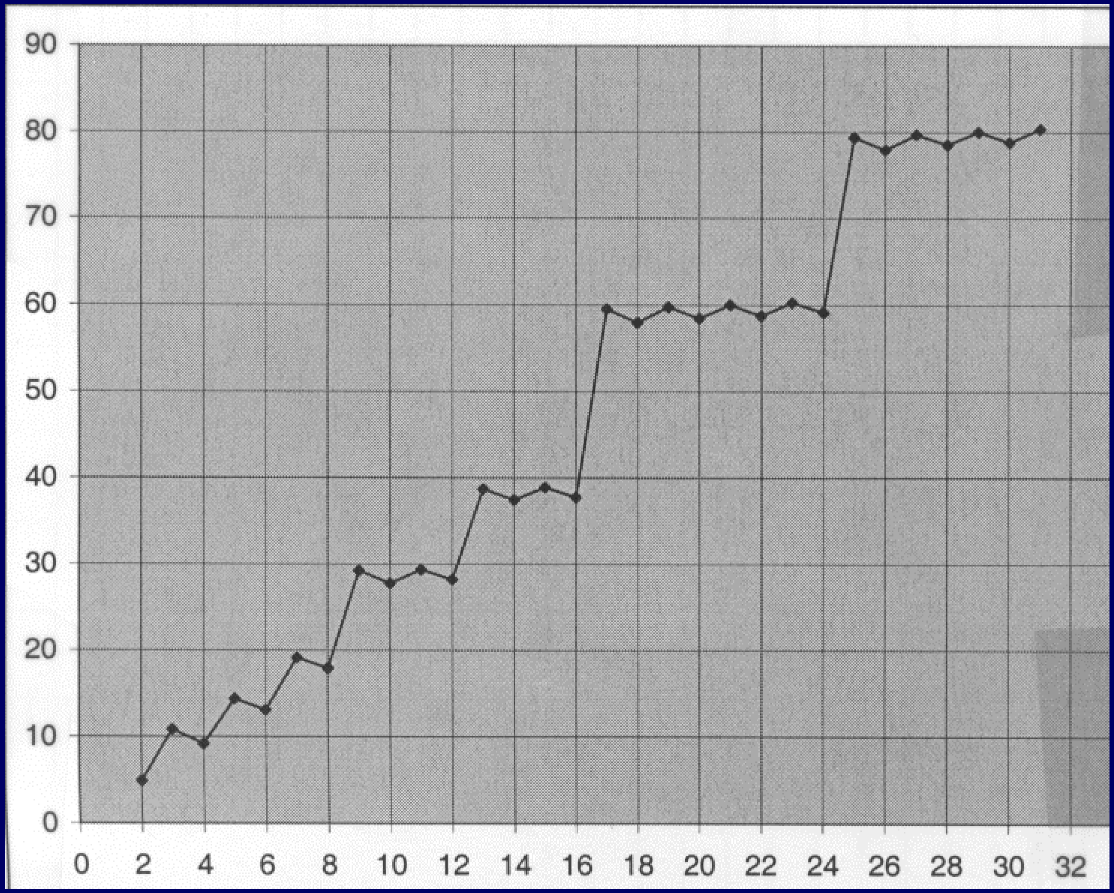




Summary

- GPUs are faster than CPUs
  – and getting faster
- Why?
  – Data Parallelism
  – Arithmetic Intensity
- What is the right programming model?
  – Stream Computing
  – Brook for GPUs

GPU Gotchas



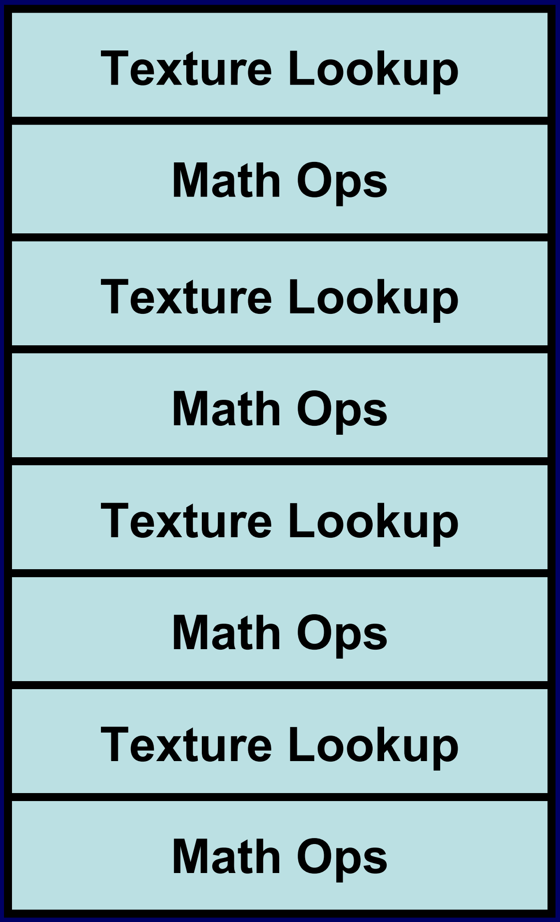
Time

Registers Used

NVIDIA NV3x: Register usage vs. GFLOPS

GPU Gotchas

- ATI Radeon 9800 Pro
- Limited dependent texture lookup
- 96 instructions
- 24-bit floating point



Summary

"All processors aspire to be general-purpose"

– Tim van Hook, Keynote, Graphics Hardware 2001

GPU Issues

- Missing Integer & Bit Ops
- Texture Memory Addressing
  - Address conversion burns 3 instr. per array lookup
  - Need large flat texture addressing
- Readback still slow
- CGC Performance
  - Hand code performance critical code
- No native reduction support

GPU Issues

- No native Scatter Support
  - – Cannot do p[i] = a (indirect write)
  - – Requires CPU readback.
  - – Needs:
    - Dependent Texture **Write**
    - Set x,y inside fragment program
- No programmable blend
  - – GatherOp / ScatterOp

GPU Issues

- Limited Output
  - Fragment program can only output single 4-component float or 4x4 component float (ATI)
  - Prevents multiple kernel outputs and large data types.

Implementation

- Reduction
  – O(lg(n)) Passes
- Gather
  – Dependent texture read
- Scatter
  – Vertex shader (slow)
- GatherOp / ScatterOp
  – Vertex shader with CPU sort (slow)

Acknowledgments

- NVIDIA Fellowship program
- DARPA PCA
- Pat Hanrahan, Bill Dally, Mattan Erez, Tim Purcell, Bill Mark, Eric Lindahl, Erik Darve, Yanan Zhao

Status

- Compiler/Runtime work complete
- Applications in progress
- Release open source in fall
- Other streaming architectures
  - Stanford Streaming Supercomputer
  - PCA Architectures (DARPA)