Brook for GPUs: Stream Computing on Graphics Hardware

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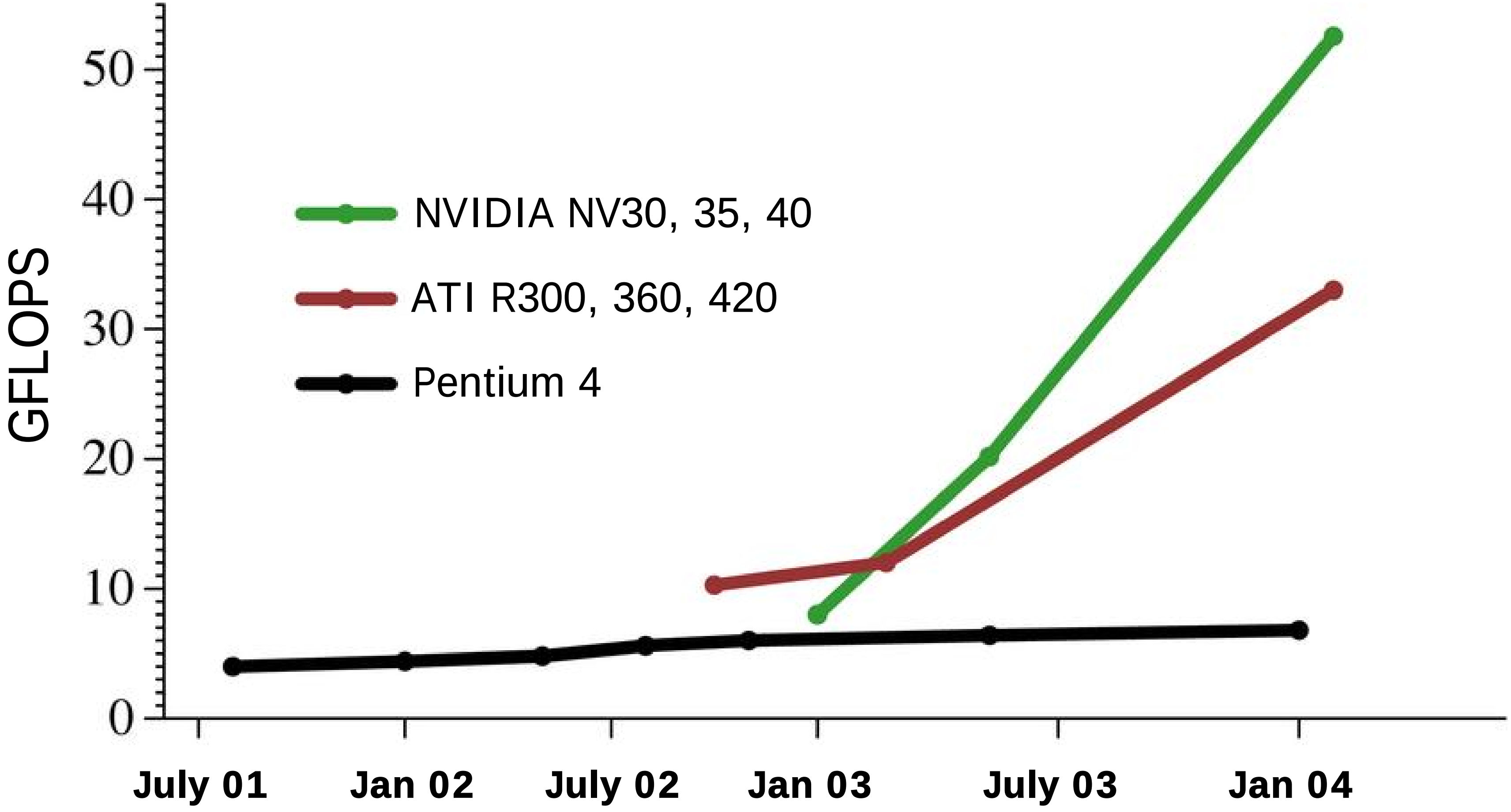
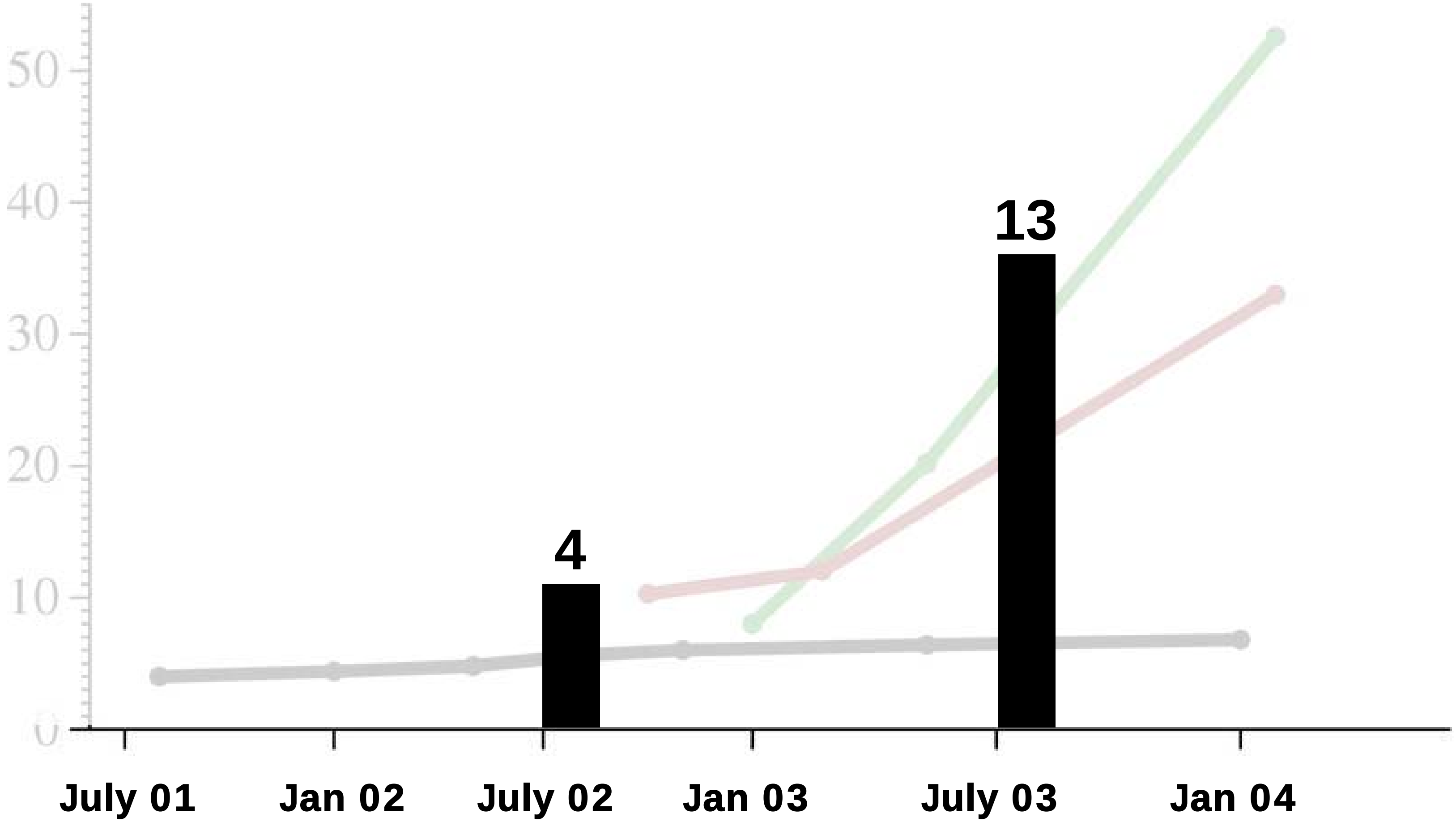
recent trends

multiplies per second

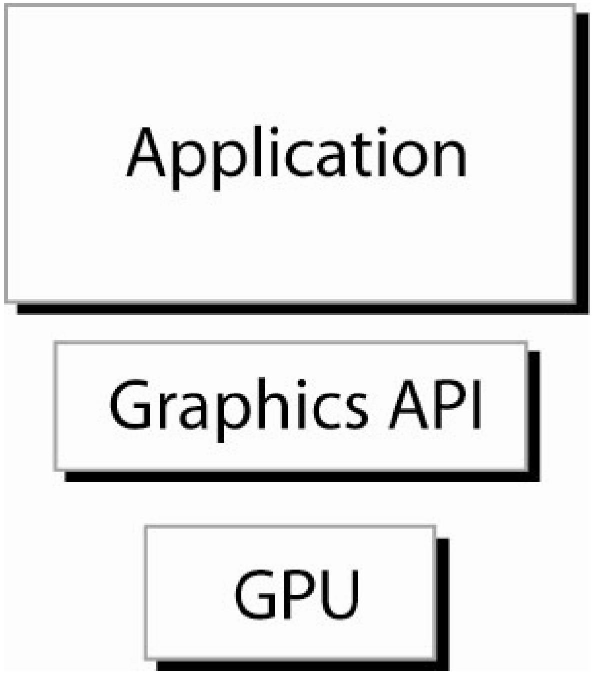


recent trends

GPU-based SIGGRAPH/Graphics Hardware papers



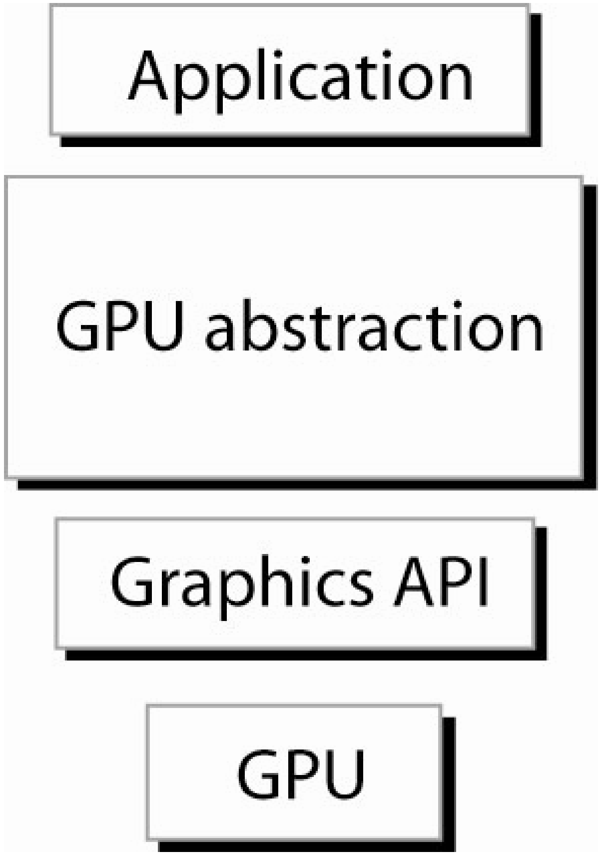
domain specific solutions



map directly to graphics primitives

requires extensive knowledge of GPU programming

building an abstraction



general GPU computing question

- can we simplify GPU programming?
- what is the correct abstraction for GPU-based computing?
- what is the scope of problems that can be implemented efficiently on the GPU?

contributions

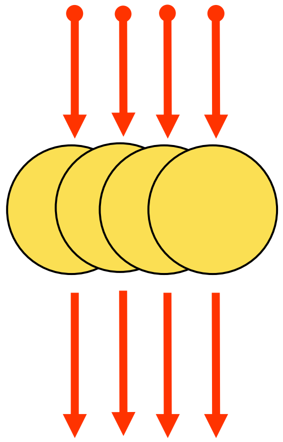
- Brook stream programming environment for GPU-based computing
  - language, compiler, and runtime system
- virtualizing or extending GPU resources
- analysis of when GPUs outperform CPUs

GPU programming model

each fragment shaded independently

– no dependencies between fragments
  - temporary registers are zeroed
  - no static variables
  - no read-modify-write textures

– multiple “pixel pipes”

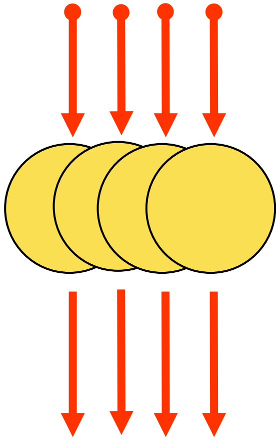


GPU = data parallel

each fragment shaded independently

– no dependencies between fragments
  - temporary registers are zeroed
  - no static variables
  - no read-modify-write textures

– multiple “pixel pipes”



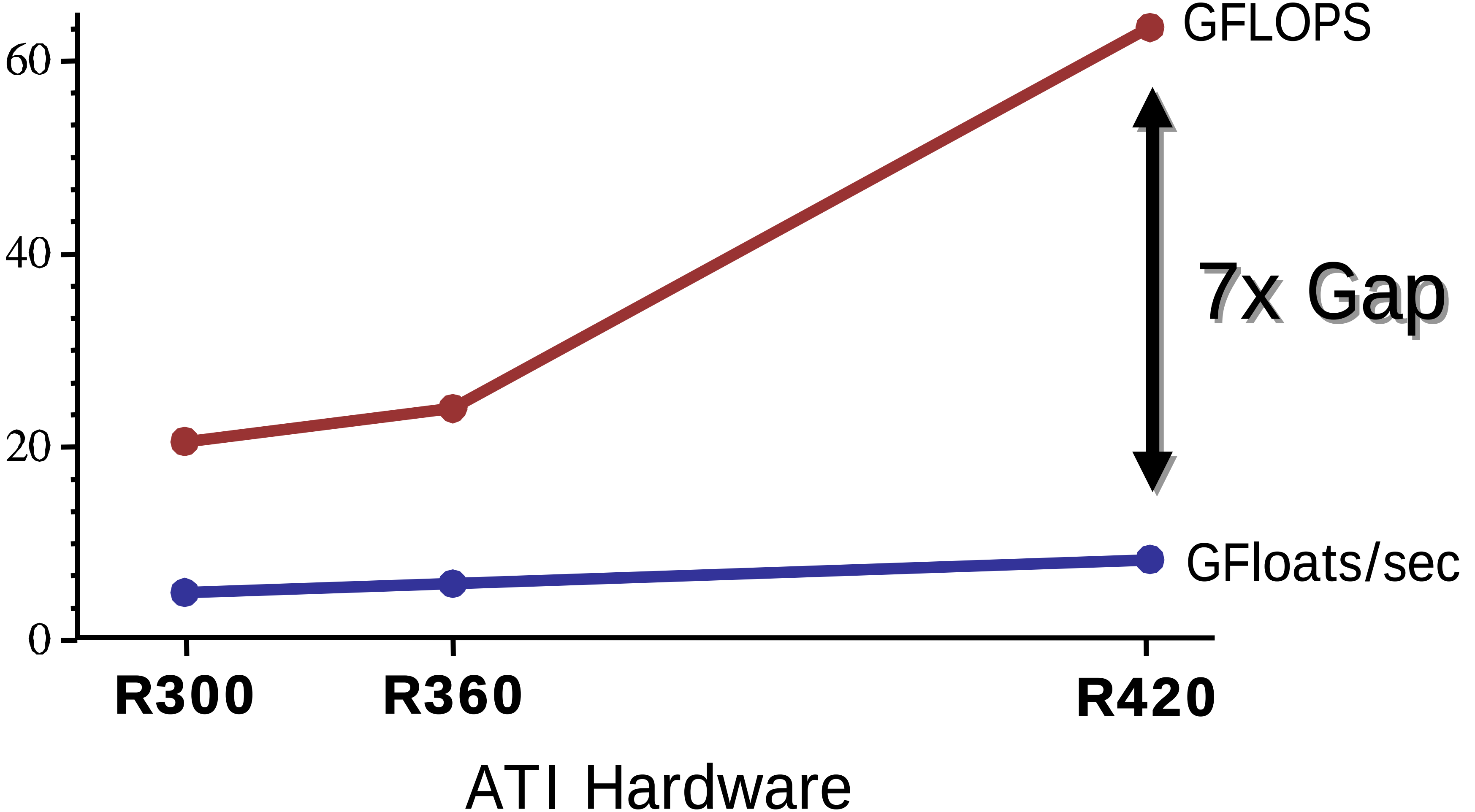
data parallelism

– support ALU heavy architectures

– hide memory latency

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

compute vs. bandwidth



compute vs. bandwidth

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

Brook language

stream programming model

- enforce data parallel computing
  - streams
- encourage arithmetic intensity
  - kernels

design goals

- general purpose computing
  - GPU = general streaming-coprocessor
- GPU-based computing for the masses
  - no graphics experience required
  - eliminating annoying GPU limitations
- performance
- platform independent
  - ATI & NVIDIA
  - DirectX & OpenGL
  - Windows & Linux

Other languages

- Cg / HLSL / OpenGL Shading Language
  - + C-like language for expressing shader computation
  - – graphics execution model
  - – requires graphics API for data management and shader execution
- Sh [McCool et al. '04]
  - + functional approach for specifying shaders
  - • evolved from a shading language
- Connection Machine C*
- StreamIt, StreamC & KernelC, Ptolemy

Brook language

C with streams

- streams
  - collection of records requiring similar computation
    - particle positions, voxels, FEM cell, ...

```
Ray r<200>;
float3 velocityfield<100,100,100>;
```

  - data parallelism
    - provides data to operate on in parallel

kernels

- kernels
  - functions applied to streams
    - similar to for_all construct
    - no dependencies between stream elements

```
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];
```

kernels

- kernels arguments
  - input/output streams

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

kernels

- kernels arguments
  - input/output streams
  - gather streams

```
kernel void foo (..., float array[] ) {
      a = array[i];
}
```

kernels

- kernels arguments
  - input/output streams
  - gather streams
  - iterator streams

```
kernel void foo (..., iter float n<> ) {
      a = n + b;
}
```

kernels

- kernels arguments
  - input/output streams
  - gather streams
  - iterator streams
  - constant parameters

```
kernel void foo (..., float c ) {
      a = c + b;
}
```

kernels

why not allow direct array operators?

A + B * C

– arithmetic intensity
  - temporaries kept local to computation

– explicit communication
  - kernel arguments

Ray-triangle intersection

```
kernel void
krnIntersectTriangle(Ray ray<>, Triangle tris[],
                     RayState oldraystate<>,
                     GridTrilist trilist[],
                     out Hit candidatehit<>) {
  float idx, det, inv_det;
  float3 edge1, edge2, pvec, tvec, qvec;
  if(oldraystate.state.y > 0) {
    idx = trilist[oldraystate.state.w].trinum;
    edge1 = tris[idx].v1 - tris[idx].v0;
    edge2 = tris[idx].v2 - tris[idx].v0;
    pvec = cross(ray.d, edge2);
    det = dot(edge1, pvec);
    inv_det = 1.0f/det;
    tvec = ray.o - tris[idx].v0;
    candidatehit.data.y = dot( tvec, pvec );
    qvec = cross( tvec, edge1 );
    candidatehit.data.z = dot( ray.d, qvec );
    candidatehit.data.x = dot( edge2, qvec );
    candidatehit.data.xyz *= inv_det;
    candidatehit.data.w = idx;
  } else {
    candidatehit.data = float4(0,0,0,-1);
  }
}
```

reductions

- reductions
  - compute single value from a stream

```
reduce void sum (float a<>,
                 reduce float r<>)
  r += a;
}
```

reductions

- reductions
  - compute single value from a stream

```
reduce void sum (float a<>,
                 reduce float r<>)
  r += a;
}
```

```
float a<100>;
float r;

sum(a,r);
```

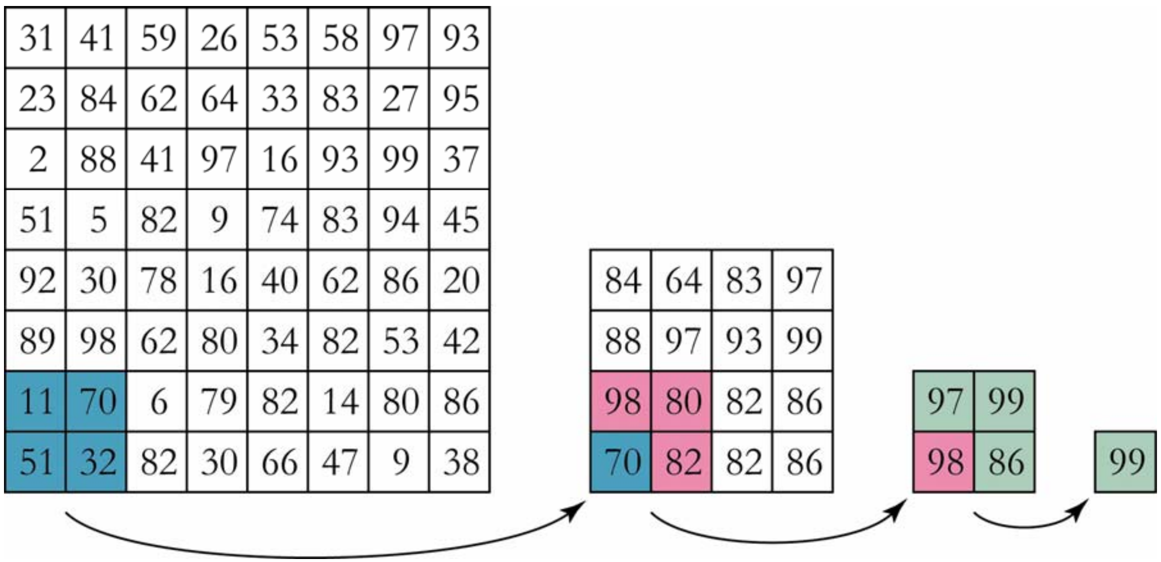
```
r = a[0];
for (int i=1; i<100; i++)
  r += a[i];
```

reductions

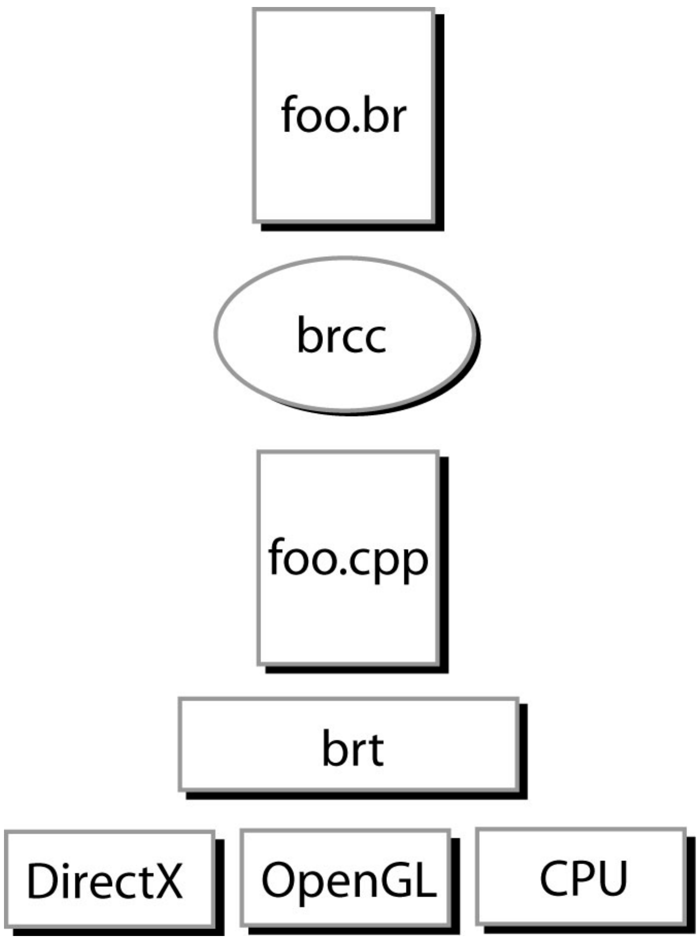
- reductions
  - associative operations only

    (a+b)+c = a+(b+c)

    - sum, multiply, max, min, OR, AND, XOR
    - matrix multiply
  - permits parallel execution



system outline



brcc

source to source compiler

- generate CG & HLSL code
- CGC and FXC for shader assembly
- virtualization

brt

Brook run-time library

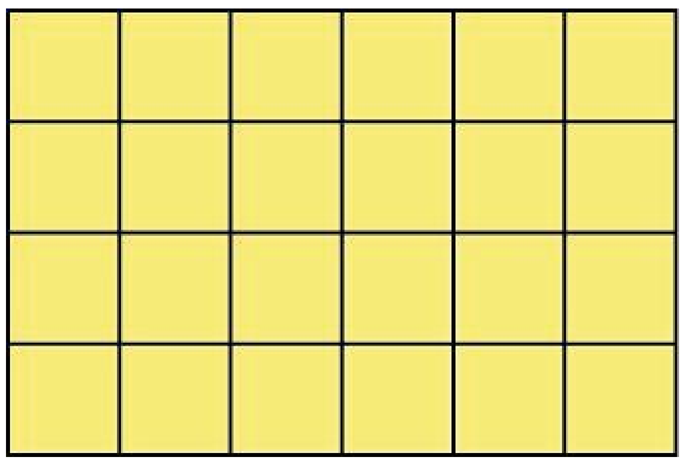
- stream texture management
- kernel shader execution

eliminating GPU limitations

treating texture as memory

- limited texture size and dimension
- compiler inserts address translation code

```
float matrix<8096,10,30,5>;
```



eliminating GPU limitations

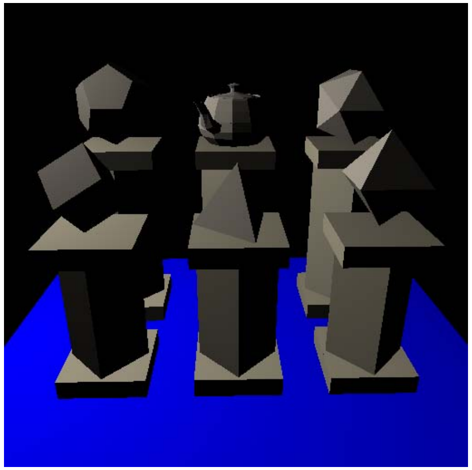
extending kernel outputs

- duplicate kernels, let **cgc** or **fxc** do dead code elimination
- better solution:

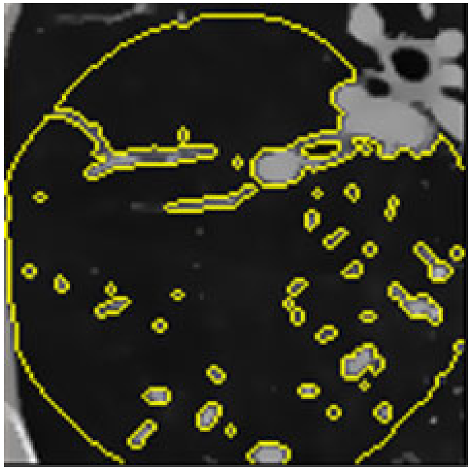
"Efficient Partitioning of Fragment Shaders for Multiple-Output Hardware”
Tim Foley, Mike Houston, and Pat Hanrahan

"Mio: Fast Multipass Partitioning via Priority-Based Instruction Scheduling"
Andrew T. Riffel, Aaron E. Lefohn, Kiril Vidimce, Mark Leone, and John D. Owens

applications

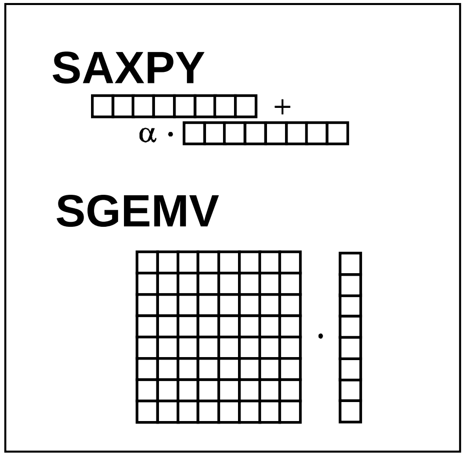


ray-tracer



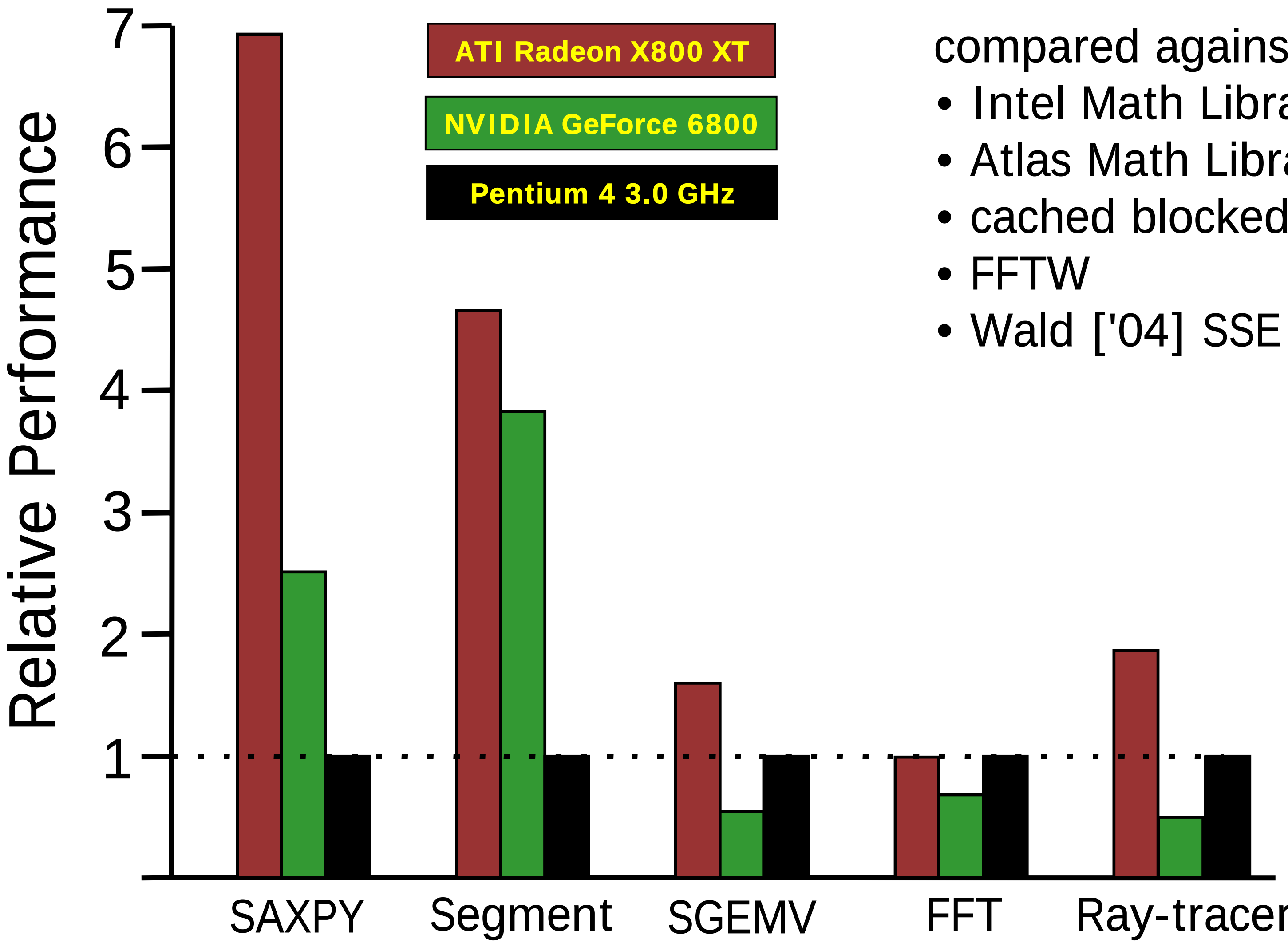
segmentation

fft edge detect



linear algebra

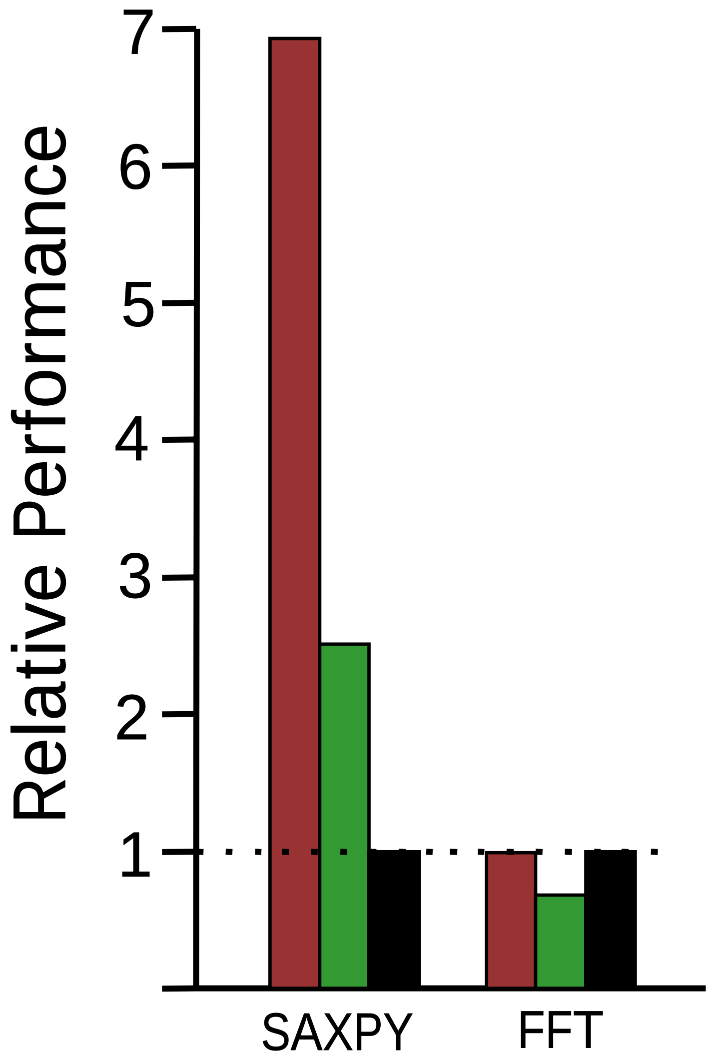
evaluation



compared against:

- Intel Math Library
- Atlas Math Library
- cached blocked segmentation
- FFTW
- Wald ['04] SSE Ray-Triangle

evaluation



GPU wins when...

- limited data reuse
  - ✓ SAXPY
  - ✗ FFT

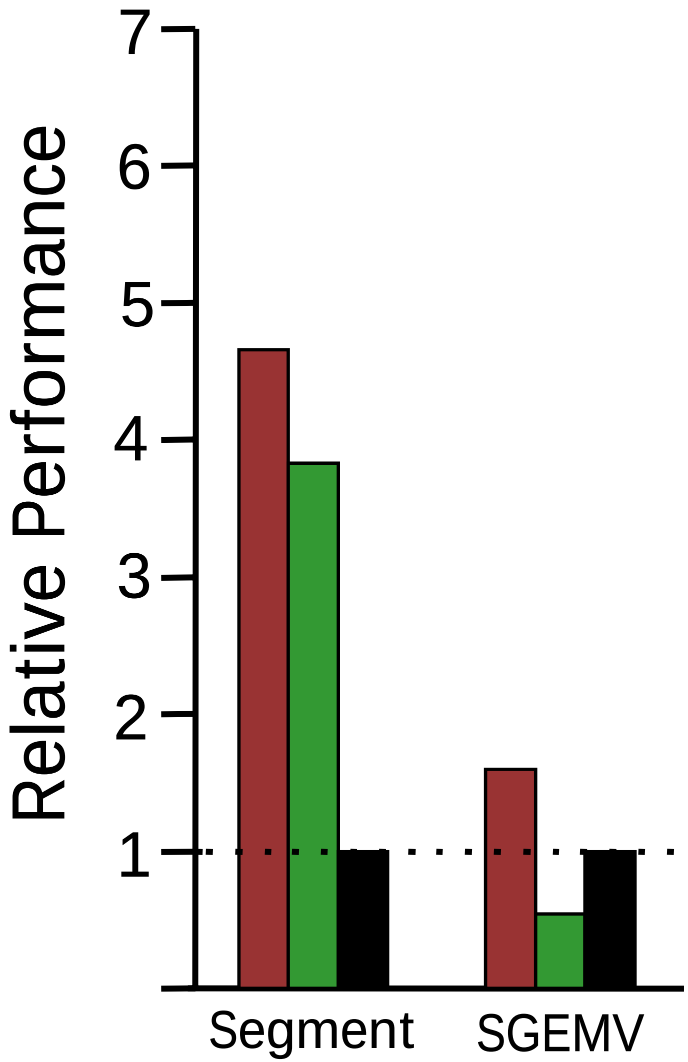
Pentium 4 3.0 GHz

44 GB/sec peak cache bandwidth

NVIDIA GeForce 6800 Ultra

36 GB/sec peak memory bandwidth

evaluation



GPU wins when...

- arithmetic intensity
  - ✓ Segment
    3.7 ops per word
  - ✗ SGEMV
    1/3 ops per word

outperforming the CPU

considering GPU transfer costs: T_r

- computational intensity: γ

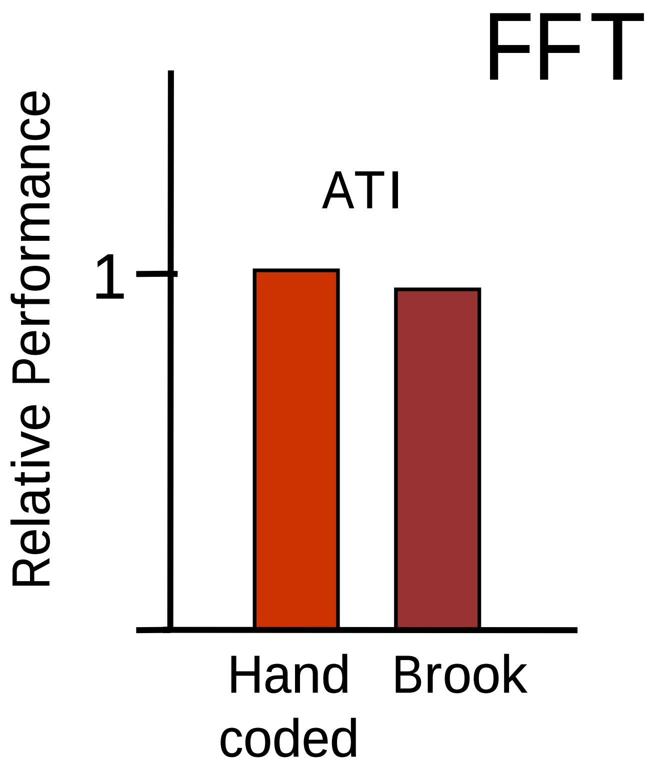
$$\gamma \equiv K_{gpu} / T_r$$

work per word transferred

considering CPU cost to issuing a kernel

efficiency

Brook version within 80% of hand-coded GPU version

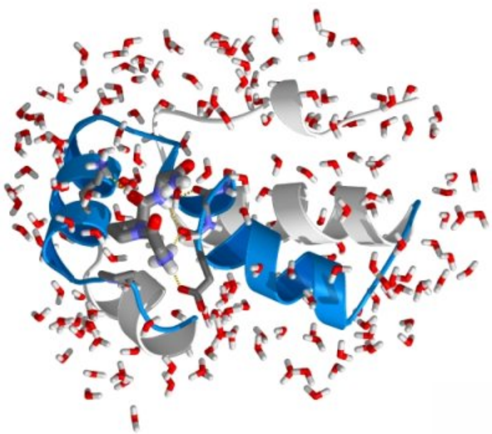


summary

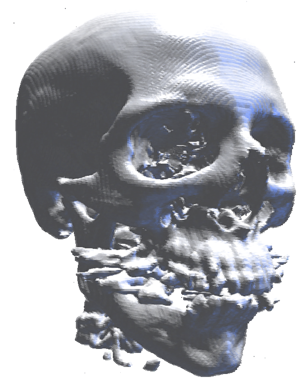
- GPUs are faster than CPUs
  - and getting faster
- why?
  - data parallelism
  - arithmetic intensity
- what is the right programming model?
  - Brook
  - stream computing

summary

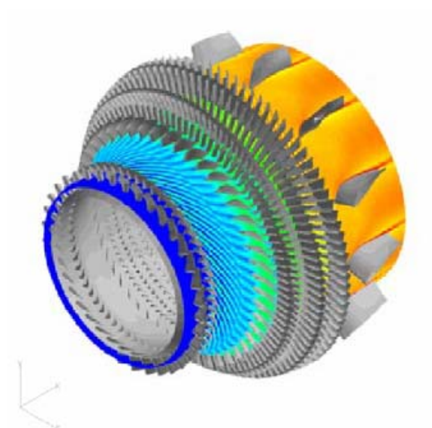
GPU-based computing for the masses



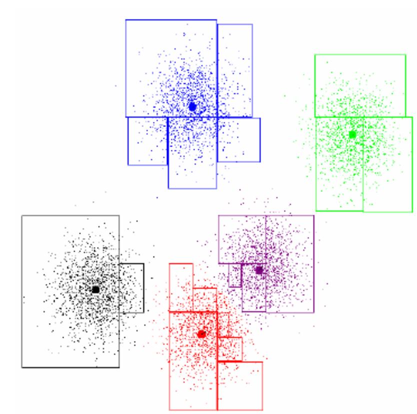
bioinfomatics



rendering



simulation



statistics

acknowledgements

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  - Rambus Stanford Graduate Fellowship
  - Stanford School of Engineering Fellowship

Brook for GPUs

- release v0.3 available on Sourceforge
- project page
  - http://graphics.stanford.edu/projects/brook
- source
  - http://www.sourceforge.net/projects/brook
- over 6K downloads!
- interested in collaborating?

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