CS 380 - GPU and GPGPU Programming
Lecture 18: Stream Computing and GPGPU

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Reading Assignment #11 (until Nov 15)

Read (required):

- Programming Massively Parallel Processors book, 3rd edition

  Chapter 5 (Performance Considerations) [was Chap. 6 in 2nd ed.]

- Read

  https://en.wikipedia.org/wiki/Stream_processing

Read (optional):

- Linear algebra operators for GPU implementation of numerical algorithms, Krueger and Westermann, SIGGRAPH 2003

  https://dl.acm.org/doi/10.1145/882262.882363

- A Survey of General-Purpose Computation on Graphics Hardware (2007)

  https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1467-8659.2007.01012.x

Quiz #2: Nov 10

Organization

- First 30 min of lecture
- No material (book, notes, ...) allowed

Content of questions

- Lectures (both actual lectures and slides)
- Reading assigments
- Programming assignments (algorithms, methods)
- Solve short practical examples

Stream Computing and GPGPU

Types of Parallelism

Bit-Level Parallelism (70s and 80s)

- Doubling the word size 4, 8, 16, 32-bit (64-bit ~2003)

Instruction-Level Parallelism (mid 80s-90s)

IF	ID	EX	MEM	WB				
	IF	ID	EX	MEM	WB			
		IF	ID	EX	MEM	WB		
			IF	ID	EX	MEM	WB	
				IF	ID	EX	MEM	WB

- Instructions are split into stages → multi stage pipeline
- Superscalar execution, …

Data Parallelism

- Multiple processors execute the same instructions on different parts of the data

Task Parallelism

- Multiple processors execute instructions independently

From GPU to GPGPU

1990s Fixed function graphics-pipeline used for more general computations in academia (e.g., rasterization, z-buffer)

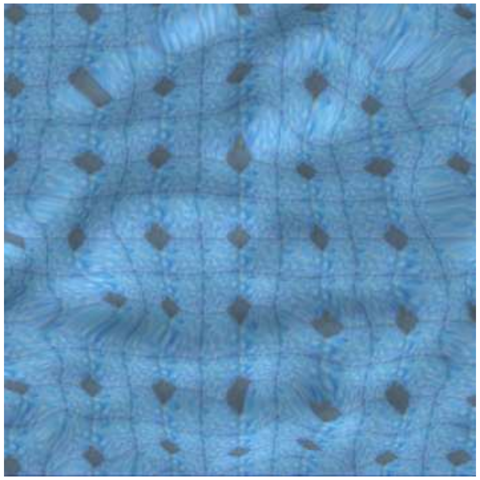
2001 Shaders changed the API to access graphics cards

2004 Brook for GPUs changed the terminology

Since then:

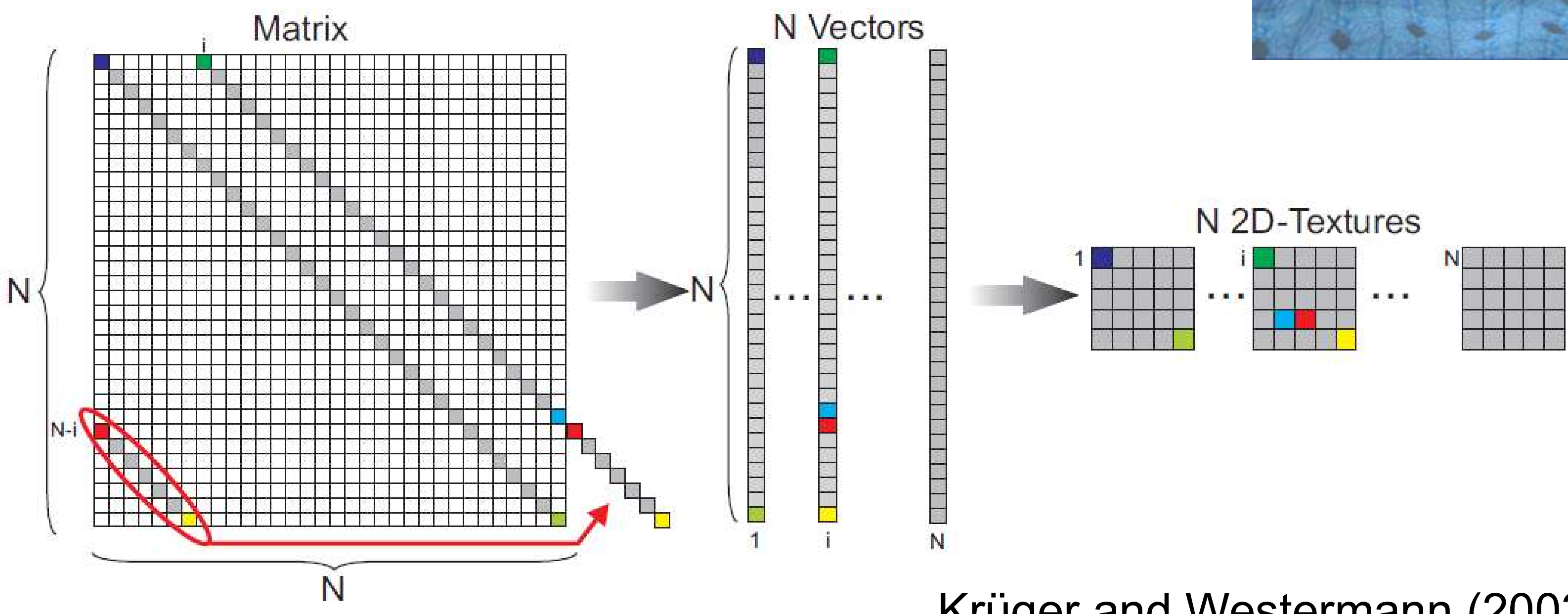
- ATI’s Stream SDK (originally based on Brook)
- NVIDIA’s CUDA (started by Brook developers)
- OpenCL (platform independent)
- GLSL Compute Shaders (platform independent)
- Vulkan Compute Shaders (platform independent)
- DirectX 12 Compute Shaders

Early GPGPU: Linear Algebra Operators



Vector and matrix representation and operators

- Early approach based on graphics primitives
- Now CUDA makes this much easier
- Linear systems solvers



Krüger and Westermann (2003)

Stream Programming Abstraction

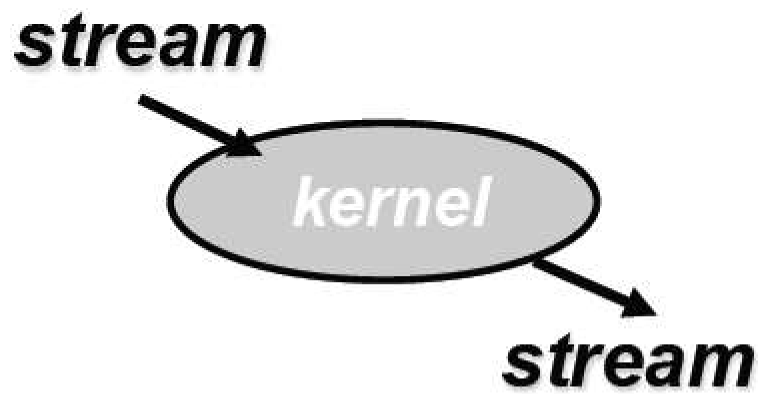
Goal: SW programming model that matches data parallelism

Streams

- Collection of data records
- All data is expressed in streams

Kernels

- Inputs/outputs are streams
- Perform computation on streams
  (each data record is processes independently)
- Can be chained together



Courtesy John Owens

Why Streams?

- Exposing parallelism
  - Data parallelism
  - Task parallelism

```
for(i = 0; i<size; i++)
{
    a[i] = 2*b[i];
}
```

```
for(each a, b)
{
    a = 2*b;
}
```

```
for(i = 0; i<size; i++)
{
    a[i] = a[i+1]*2;
}
```

```
for(each a)
{
    ???
}
```

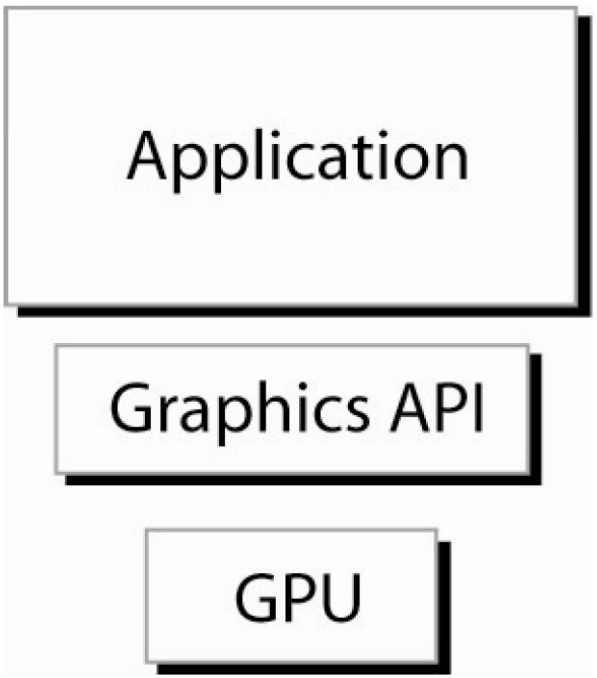
- Multiple stream elements can be processed in parallel
- Multiple tasks can be processed in parallel
- Predictable memory access pattern
- Optimize for throughput of all elements, not latency of one
- Processing many elements at once allows latency hiding

Brook for GPUs: Stream Computing on Graphics Hardware

Ian Buck, Tim Foley, Daniel Horn, Jeremy Sugerman, Kayvon Fatahalian, Mike Houston, and Pat Hanrahan

Computer Science Department
Stanford University

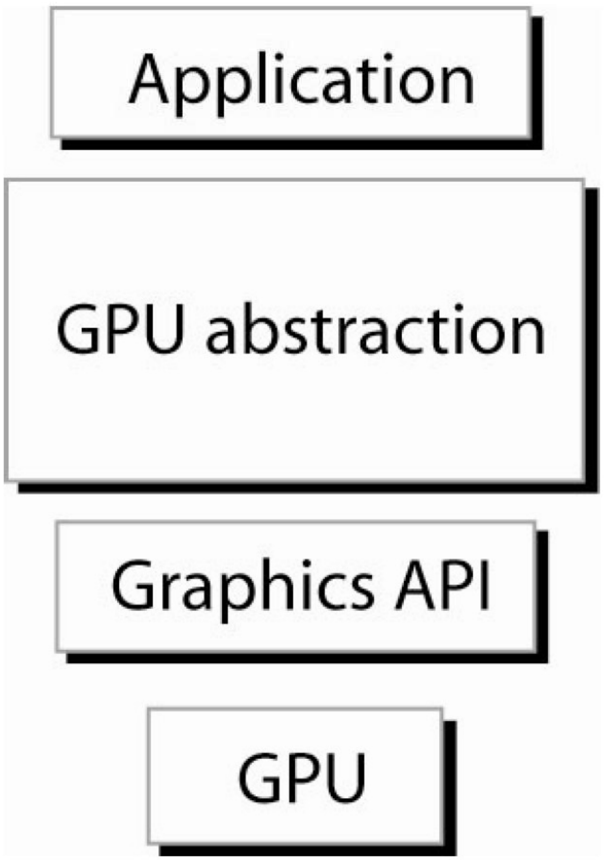
domain specific solutions



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?

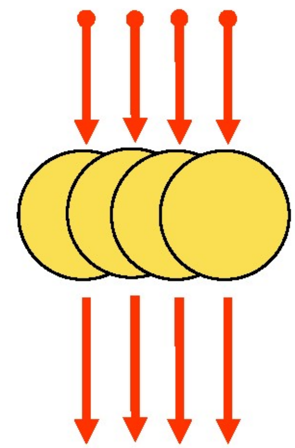
contributions

- 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

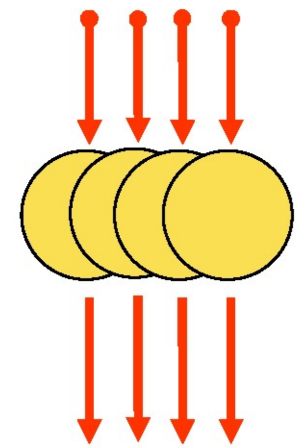
- no dependencies between fragments
  - temporary registers are zeroed
  - no static variables
  - no read-modify-write textures
- multiple “pixel pipes”



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]

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

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

```
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;
}
```

Brook language

kernels

- 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 ) * inv_det;
    qvec = cross( tvec, edge1 );
    candidatehit.data.z = dot( ray.d, qvec ) * inv_det;
    candidatehit.data.x = dot( edge2, qvec ) * 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);
```

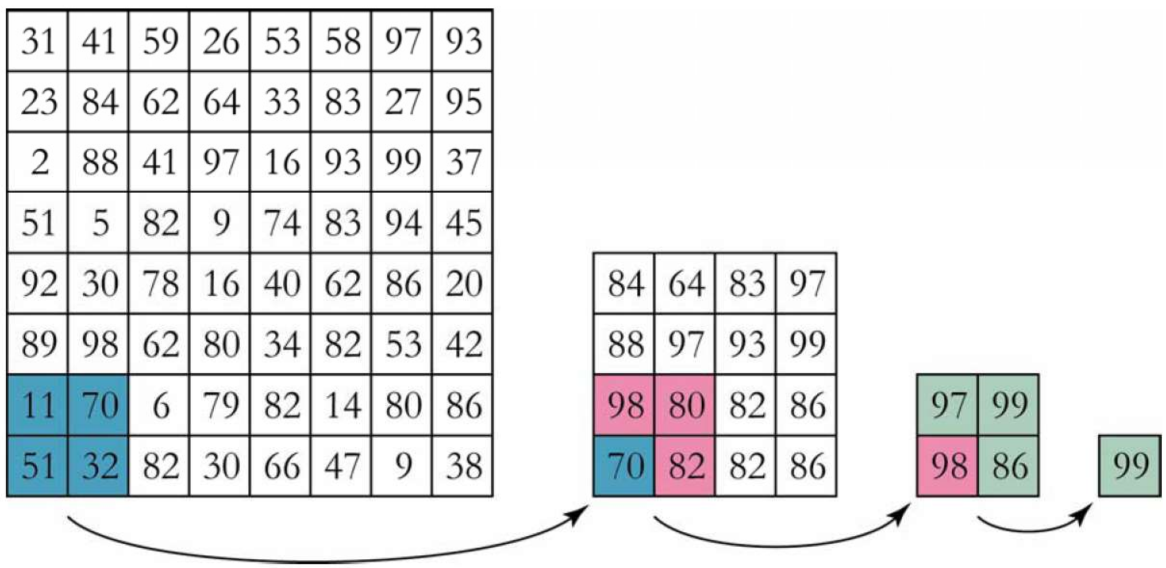
```
r = a[0];
for (int i=1; i<100; i++)
  r += a[i];
```

reductions

- reductions
  - associative operations only

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

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



reductions

- multi-dimension reductions
  - stream “shape” differences resolved by reduce function

Brook language

reductions

- multi-dimension reductions
  - stream “shape” differences resolved by reduce function

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


float a<20>;
float r<5>;

sum(a,r);
```

reductions

- multi-dimension reductions
  - stream "shape" differences resolved by reduce function

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


float a<20>;
float r<5>;

sum(a,r);
```

```
for (int i=0; i<5; i++)
  r[i] = a[i*4];
  for (int j=1; j<4; j++)
    r[i] += a[i*4 + j];
```

reductions

- multi-dimension reductions
  - stream "shape" differences resolved by reduce function

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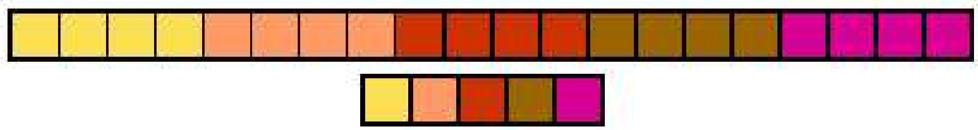

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```

stream repeat & stride

- kernel arguments of different shape
  - resolved by repeat and stride

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  - resolved by repeat and stride

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kernel void foo (float a<>, float b<>,
                 out float result<>);

float a<20>;
float b<5>;
float c<10>;

foo(a,b,c);
```

stream repeat & stride

- kernel arguments of different shape
  - resolved by repeat and stride

```
kernel void foo (float a<>, float b<>,
                 out float result<>);

float a<20>;
float b<5>;
float c<10>;

foo(a,b,c);
```

```
foo(a[0],  b[0], c[0])
foo(a[2],  b[0], c[1])
foo(a[4],  b[1], c[2])
foo(a[6],  b[1], c[3])
foo(a[8],  b[2], c[4])
foo(a[10], b[2], c[5])
foo(a[12], b[3], c[6])
foo(a[14], b[3], c[7])
foo(a[16], b[4], c[8])
foo(a[18], b[4], c[9])
```

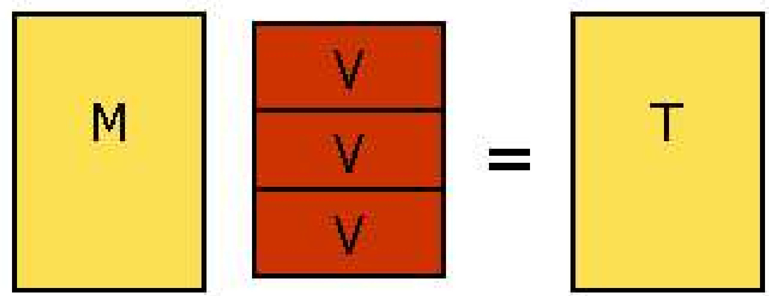
matrix vector multiply

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

reduce void sum (float a<>,
                 reduce float result<>) {
   result += a;
}


float matrix<20,10>;
float vector<1, 10>;
float tempmv<20,10>;
float result<20, 1>;

mul(matrix,vector,tempmv);
sum(tempmv,result);
```



Brook language

matrix vector multiply

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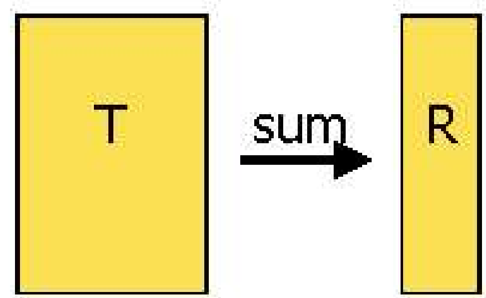
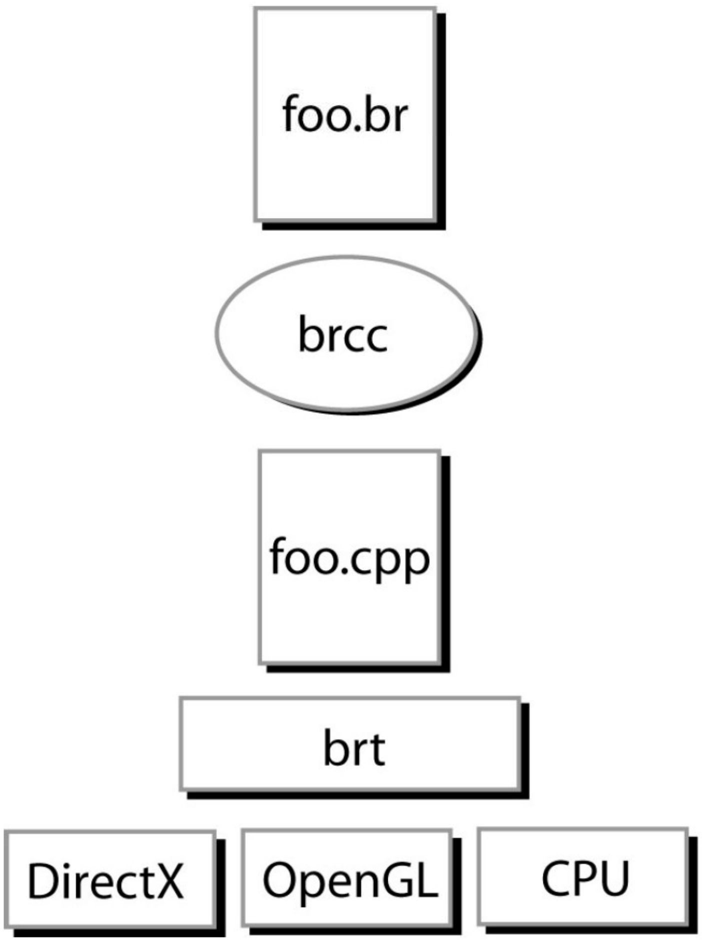


system outline



brcc

source to source compiler

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

brt

Brook run-time library

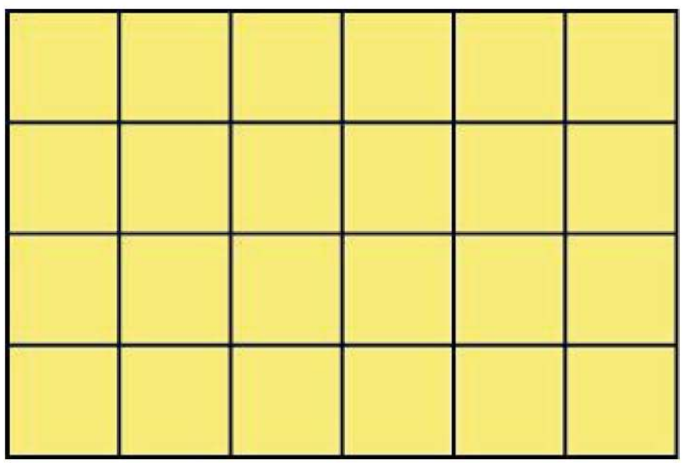
- stream texture management
- kernel shader execution

eliminating GPU limitations

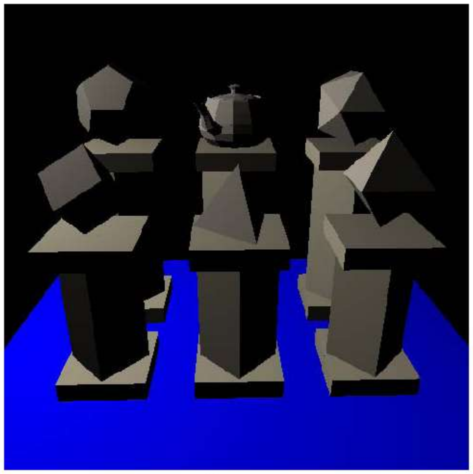
treating texture as memory

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

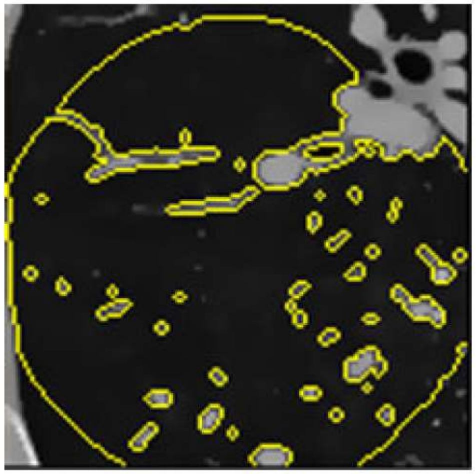
```
float matrix<8096,10,30,5>;
```



applications

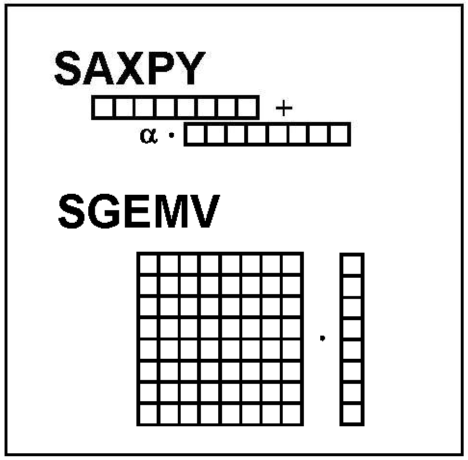


ray-tracer



segmentation

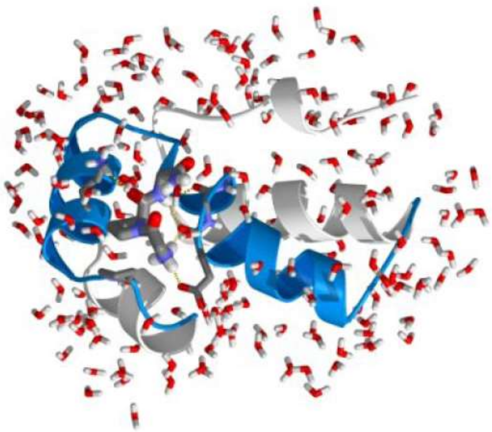
fft edge detect



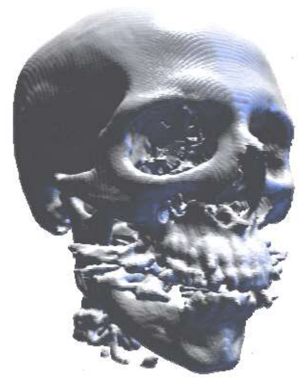
linear algebra

summary

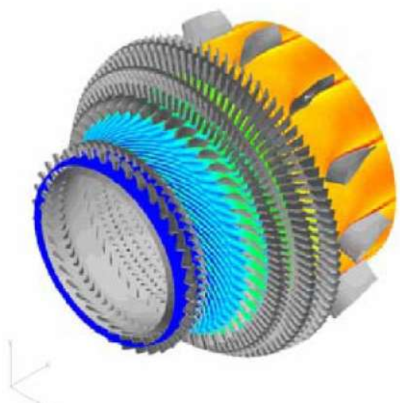
GPU-based computing for the masses



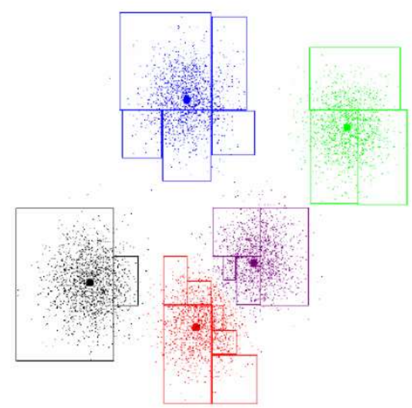
bioinfomatics



rendering



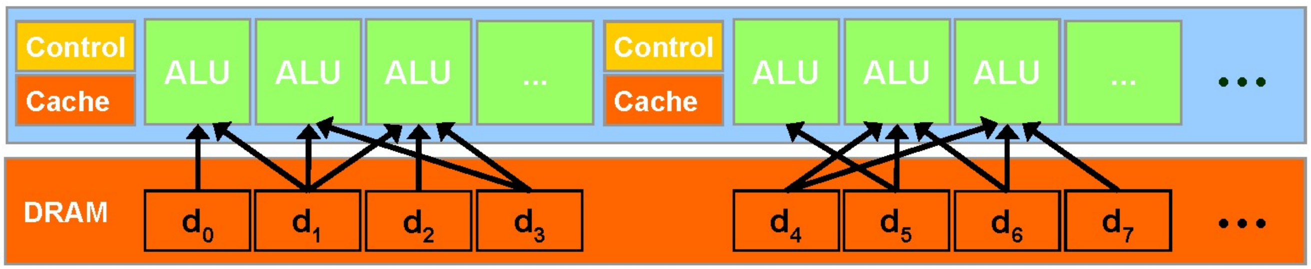
simulation



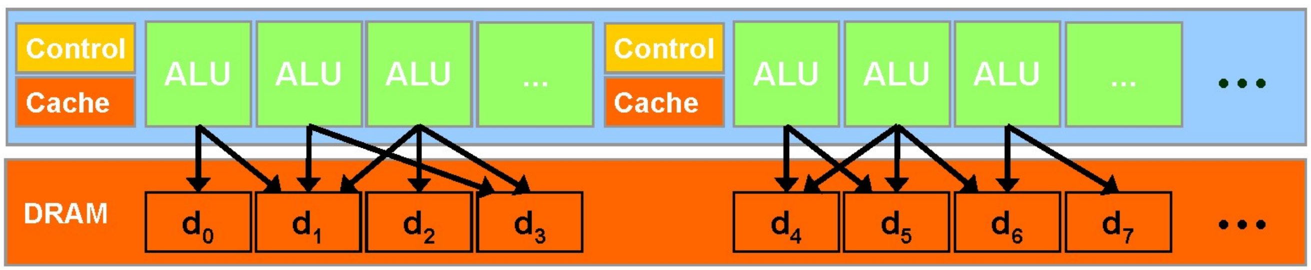
statistics

CUDA Highlights: Scatter

- **CUDA provides generic DRAM memory addressing**
  - Gather:



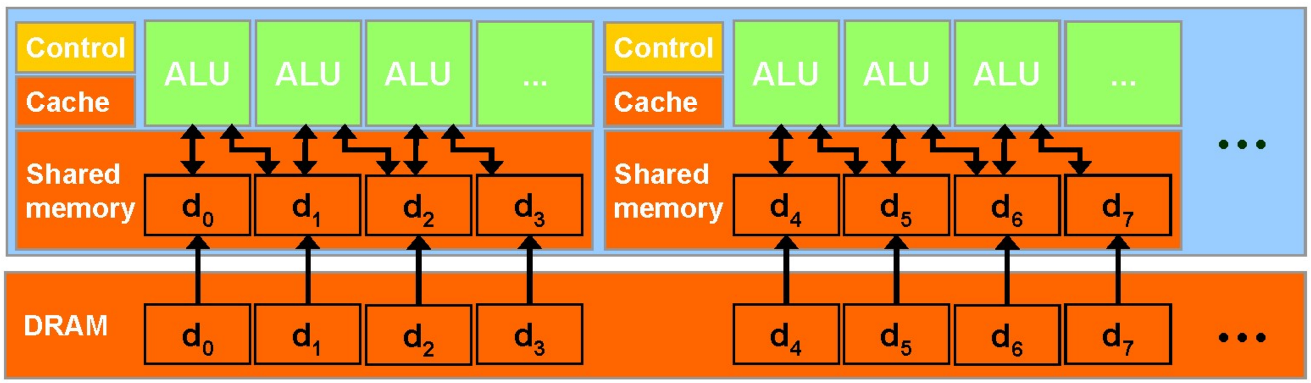
  - And scatter: no longer limited to write one pixel



→ **More programming flexibility**

CUDA Highlights: On-Chip Shared Memory

- **CUDA enables access to a parallel on-chip shared memory for efficient inter-thread data sharing**



Big memory bandwidth savings

Thank you.

- John Owens
- Ian Buck et al.
- AMD