The Way of the GPU

(based on GPGPU SIGGRAPH Course)

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(this is really from 20 years ago…)

Computer Graphics Pipeline

Geometry

Modeling Transformation	Transform into 3D *world* coordinate system
Lighting	Simulate illumination and reflectance
Viewing Transformation	Transform into 3D *camera* coordinate system
Clipping	Clip primitives outside camera’s view
Projection	Transform into 2D camera coordinate system
Scan Conversion	Draw pixels (incl. texturing, hidden surface…)

Image

Today, we have GPUs…

(GPU = graphical processing unit)

Some history and context…

- 1980s
- 1990s and programming shading
- 2000s and PCs
- GPUs…

Motivation: Computational Power

- *Why are GPUs fast?*
  - Arithmetic intensity: the specialized nature of GPUs makes it easier to use additional transistors for computation not cache
  - Economics: multi-billion dollar video game market is a pressure cooker that drives innovation

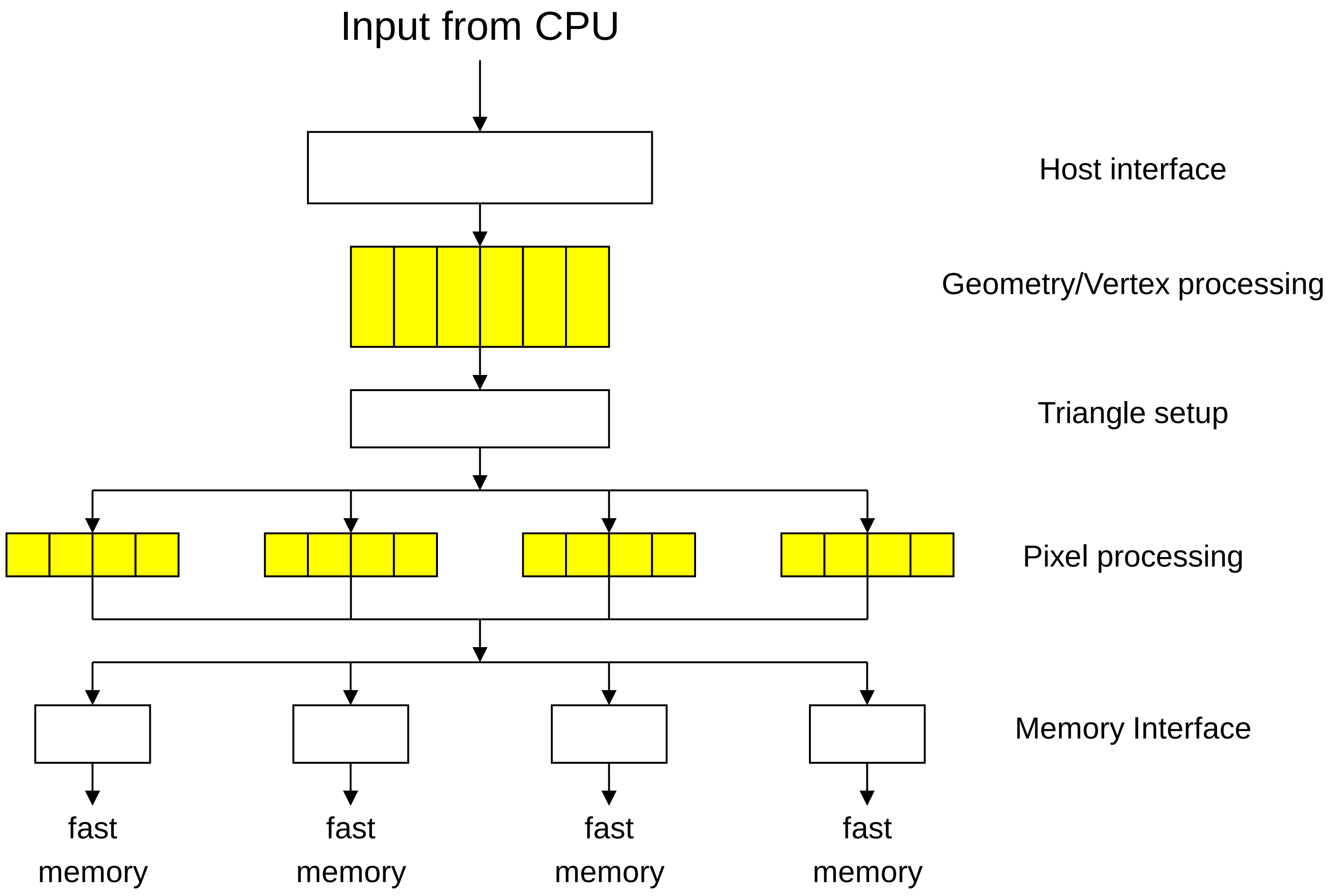
Motivation: Flexible and Precise

- *Modern GPUs are deeply programmable*
  - Programmable pixel, vertex, video engines
  - Solidifying high-level language support
- *Modern GPUs support high precision*
  - 32 bit floating point throughout the pipeline
  - High enough for many (not all) applications

The Problem: Difficult To Use

- GPUs designed for & driven by video games
  - Programming model unusual
  - Programming idioms tied to computer graphics
  - Programming environment tightly constrained
- Underlying architectures are:
  - Inherently parallel
  - Rapidly evolving (even in basic feature set!)
  - Largely secret
- Can’t simply “port” CPU code!

Diagram of a Modern GPU



nVIDIA GPU

- **GTX 3090 Founder's Edition**
  - 10496 (CUDA) cores @ 1.7GHz (i.e., mini processors)
  - 936 GB/sec (memory bandwidth)
  - 36 TFLOPS (shader)
  - 24 GB video memory
  - 7680x4320 pixels
  - 350W power
  - 91C max GPU temp
  - **$1500-$3000**

nVIDIA GPU

- **GeForce 256 (from 1999)**
  - 120 MHz
  - 4.8 GB/sec (memory bandwidth)
  - 32 MB memory
  - **$100**

Before…

- SGI InfiniteReality (inside Onyx) (1995)
  - 2-4 raster boards (i.e., boards used in parallel)
  - 0.8 GB/sec (memory bandwidth)
  - 0.000640 TFLOPS
  - 2560x2048 pixels
  - ?? power
  - ?? max GPU temp
  - **$390,000**

Before

- SGI Personal IRIS 4D (1985)
  - 0.000000940 TFLOPS
  - **$68000**

Before

- **IBM PC 5150 (~1985)**
  - 0.000004.77 GHz
  - 16-640 KB
  - ~200W power

Modern GPU has more ALU's

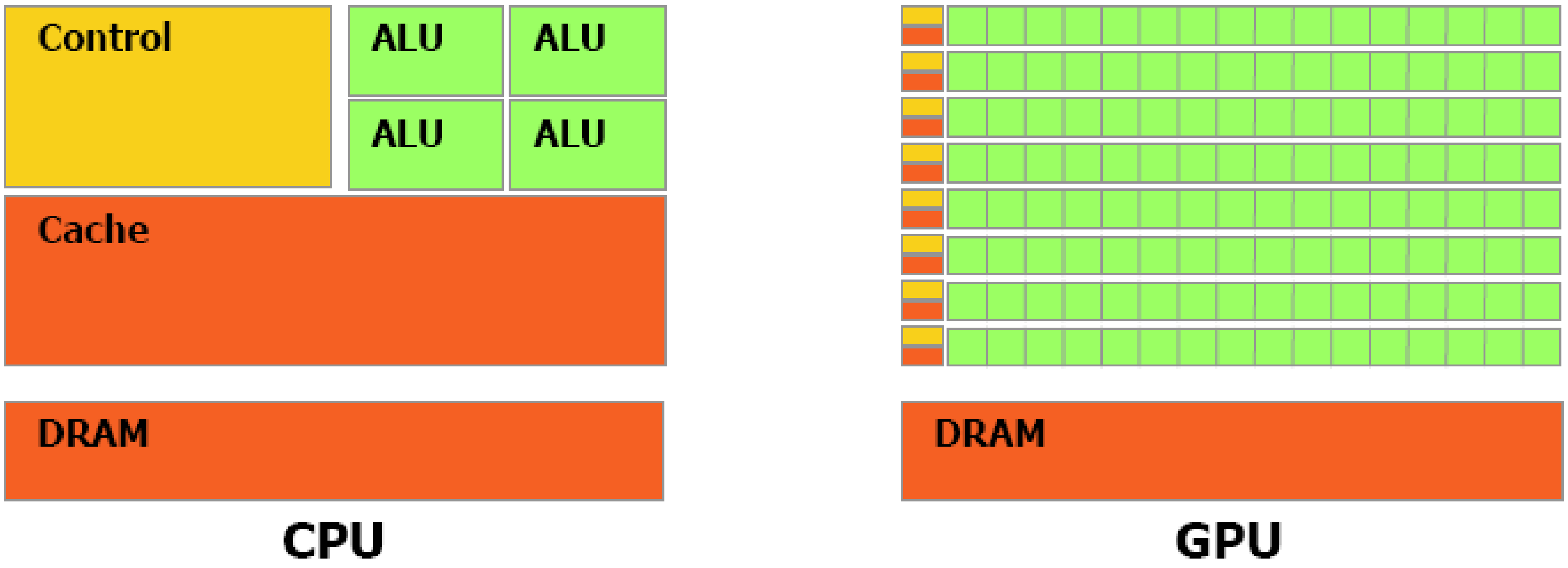
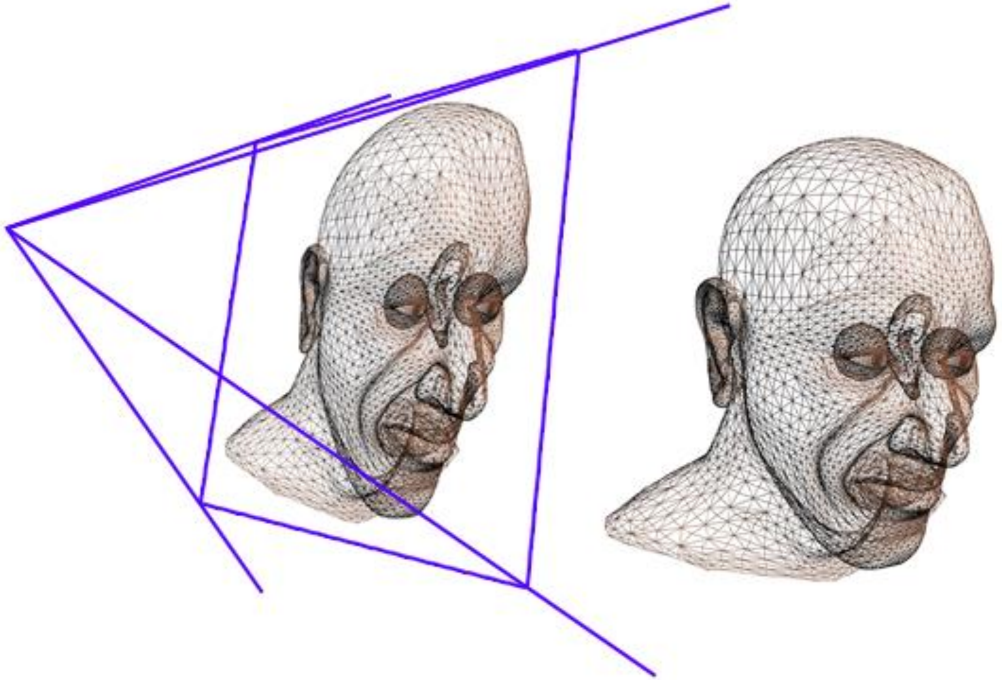


Figure 1-2. The GPU Devotes More Transistors to Data Processing

GPU Pipeline: Transform

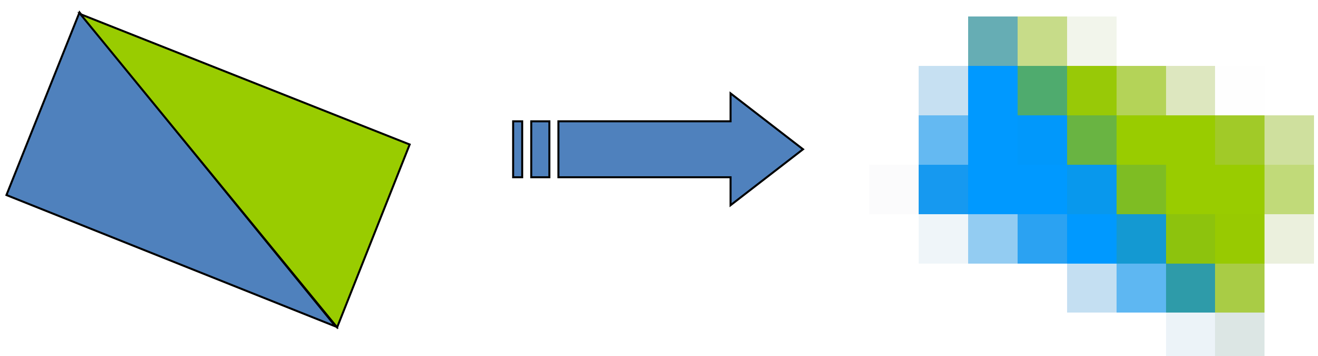
- Vertex/Geometry processor (multiple in parallel)
  - Transform from "world space" to "image space"
  - Compute per-primitive and per-vertex lighting



GPU Pipeline: Rasterize

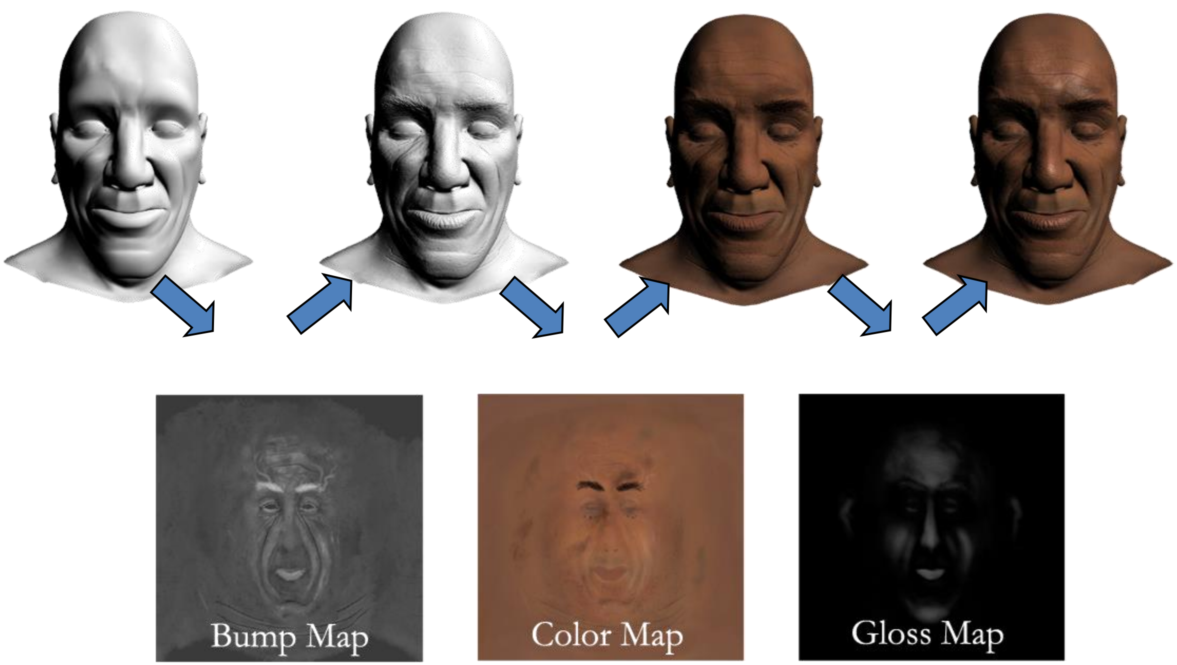
(typically not programmable)

- Rasterizer
  - Convert geometric rep. (vertex) to image rep. (fragment)
    - Fragment = image fragment
      - Pixel + associated data: color, depth, stencil, etc.
  - Interpolate per-vertex quantities across pixels



GPU Pipeline: Shade

- Fragment processors (multiple in parallel)
  - Compute a color for each pixel
  - Optionally read colors from textures (images)



GPU Programming Languages

- Many options!
  - A while ago: "Renderman"
  - cG (from NVIDIA)
  - GLSL (GL shading Language)
  - CUDA (more general that graphics)...
- Lets focus first on the concept, later on the language specifics...

GLSL Demo

- http://glslsandbox.com/

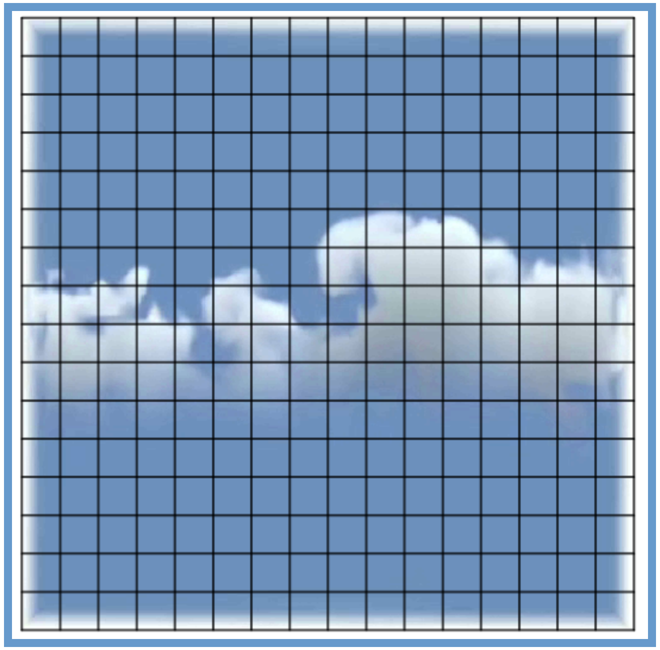
(backup:
https://www.youtube.com/watch?v=9ETfgTD6L2I
https://www.youtube.com/watch?v=8gHx7nMCVp4
https://www.youtube.com/watch?v=t2yPfenzkII
https://www.youtube.com/watch?v=M_FsjL9j0HY)

Mapping Parallel Computational Concepts to GPUs

- GPUs are designed for graphics
  - Highly parallel tasks
- GPUs process *independent* vertices & fragments
  - Temporary registers are zeroed
  - No shared or static data
  - No read-modify-write buffers
- Data-parallel processing
  - GPUs architecture is ALU-heavy
    - Multiple vertex & pixel pipelines, multiple ALUs per pipe
  - Hide memory latency (with more computation)

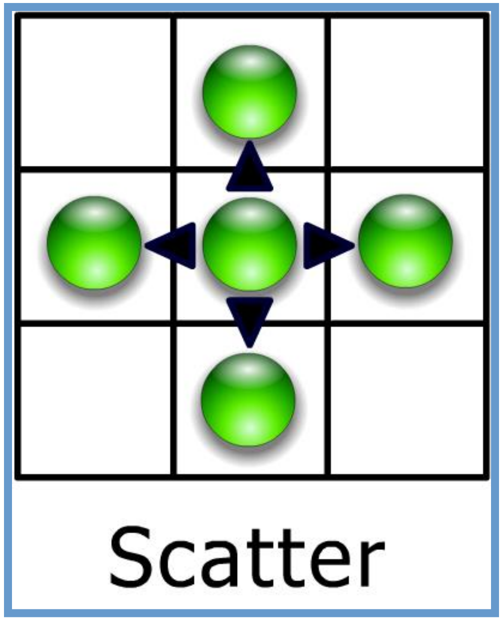
Example: Simulation Grid

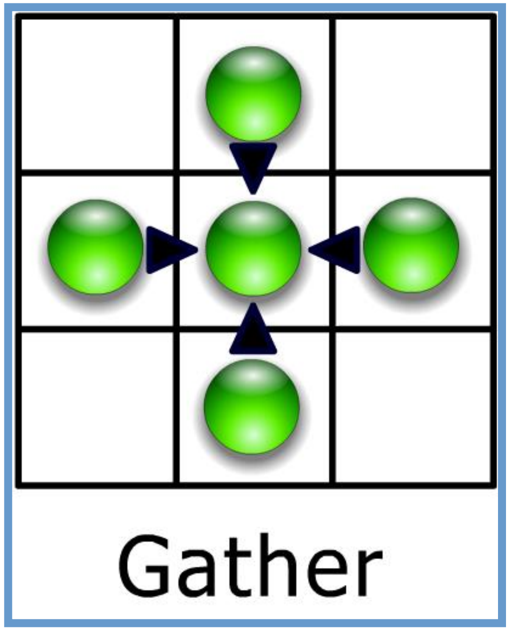
- Common GPGPU computation style
  - Textures represent computational grids = streams
- Many computations map to grids
  - Matrix algebra
  - Image & Volume processing
  - Physically-based simulation
  - Global Illumination
    - ray tracing, photon mapping, radiosity
- Non-grid streams can be mapped to grids



e.g.: Scatter vs. Gather

- Grid communication
  - Grid cells share information





Vertex Processor

- 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
- Latest GPUs: Vertex Texture Fetch
  - Random access memory for vertices
  - ≈Gather (But not from the vertex stream itself)

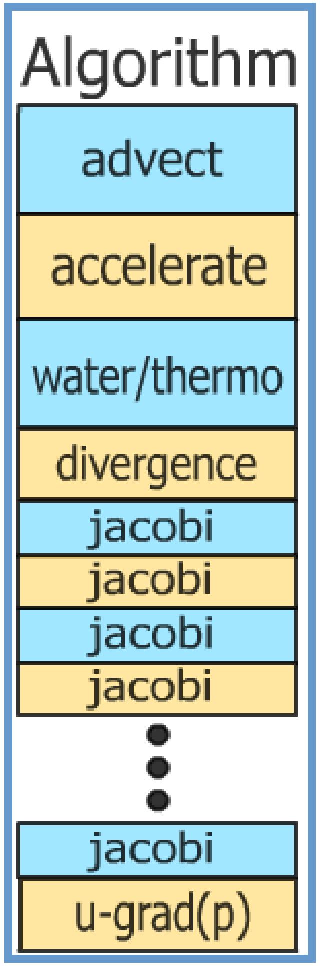
Fragment Processor

- Fully programmable (SIMD)
- Processes 4-component vectors (RGBA / XYZW)
- Random access memory read (textures)
- Capable of gather but not scatter
  - RAM read (texture fetch), but no RAM 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)

GPU Simulation Overview

- A Simulation:
  - Its algorithm steps are fragment programs
    - Called Computational *kernels*
  - Current state is stored in textures
  - Feedback via "render to texture"

- Question:
  - How do we invoke computation?



Invoking Computation

- Must invoke computation at each pixel
  - Just draw geometry!
  - Most common GPGPU invocation is a full-screen quad
- Other Useful Analogies
  - Rasterization = Kernel Invocation
  - Texture Coordinates = Computational Domain
  - Vertex Coordinates = Computational Range

Typical “Grid” Computation

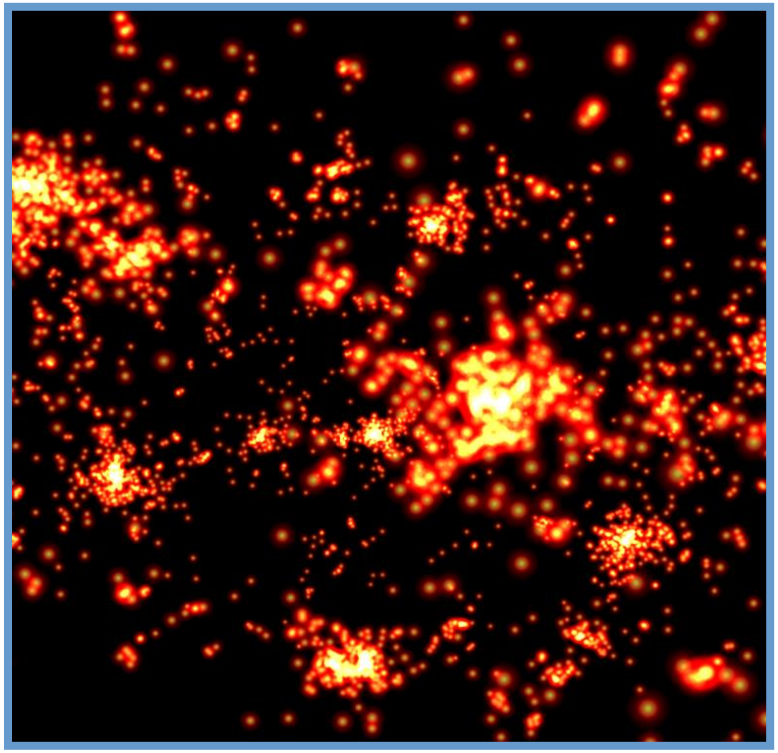
- Initialize “view” (so that pixels:texels::1:1)

```
glMatrixMode(GL_MODELVIEW);
glLoadIdentity();
glMatrixMode(GL_PROJECTION);
glLoadIdentity();
glOrtho(0, 1, 0, 1, 0, 1);
glViewport(0, 0, outTexResX, outTexResY);
```

- For each algorithm step:
  - Activate render-to-texture
  - Setup input textures, fragment program
  - Draw a full-screen quad (1x1)

Example: N-Body Simulation

- Brute force ☹
- N = 8192 bodies
- N^2 gravity computations



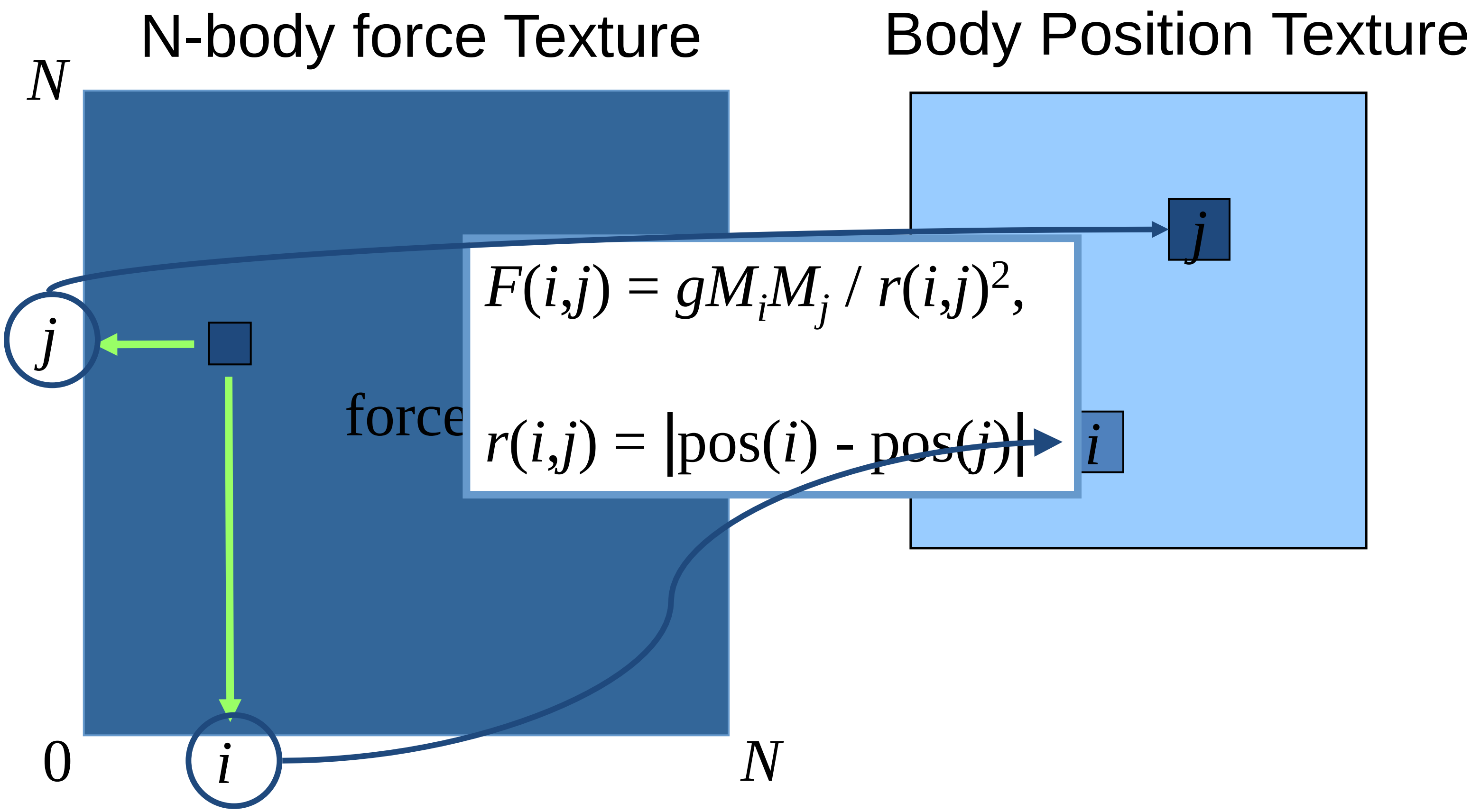
- 64M force comps. / frame
- ~25 flops per force
- 10.5 fps

- 17+ GFLOPs sustained in this example

Computing Gravitational Forces

- Each body attracts all other bodies
  - *N* bodies, so N^2 forces
- Draw into an *N*x*N* buffer
  - Pixel (*i*,*j*) computes force between bodies *i* and *j*
  - Very simple fragment program
    - More than N=2048 bodies is tricky
    - Why?

Computing Gravitational Forces



$$F(i,j) = gM_iM_j / r(i,j)^2,$$

$$r(i,j) = |pos(i) - pos(j)|$$

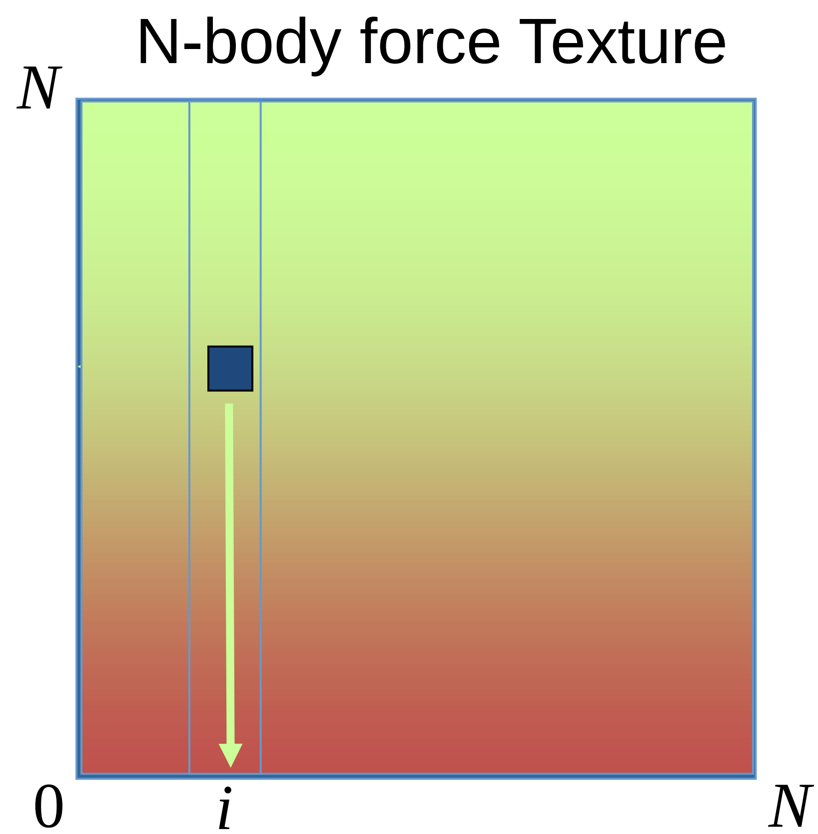
Force is proportional to the inverse square of the distance between bodies

Computing Gravitational Forces

```
float4 force(float2 ij : WPOS,
       uniform sampler2D pos) : COLOR0
{
  // Pos texture is 2D, not 1D, so we need to
  // convert body index into 2D coords for pos tex
  float4 iCoords = getBodyCoords(ij);
  float4 iPosMass = texture2D(pos, iCoords.xy);
  float4 jPosMass = texture2D(pos, iCoords.zw);
  float3 dir = iPos.xyz - jPos.xyz;
  float r2 = dot(dir, dir);
  dir = normalize(dir);
  return dir * g * iPosMass.w * jPosMass.w / r2;
}
```

Computing Total Force

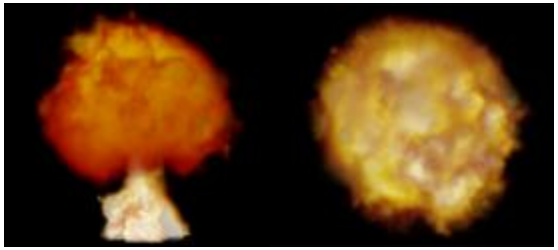
- Have: array of (i, j) forces
- Need: total force on each particle i
  - Sum of each column of the force array
- Can do all N columns in parallel



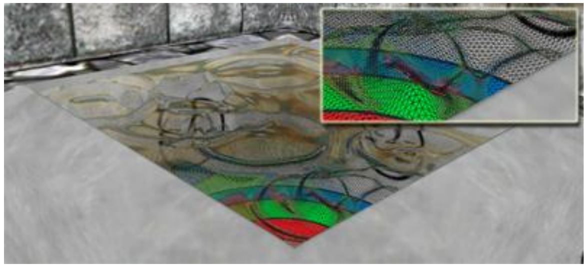
This is called a *Parallel Reduction*

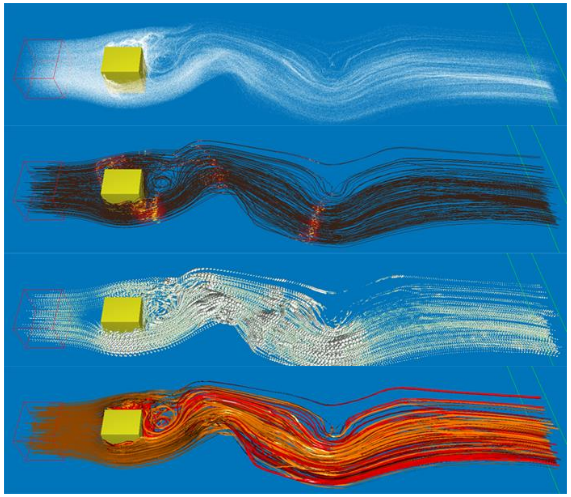
Geometry processing on GPUs

- so far: GPGPU limited to texture output



- new APIs allow geometry generation on GPU





Examples

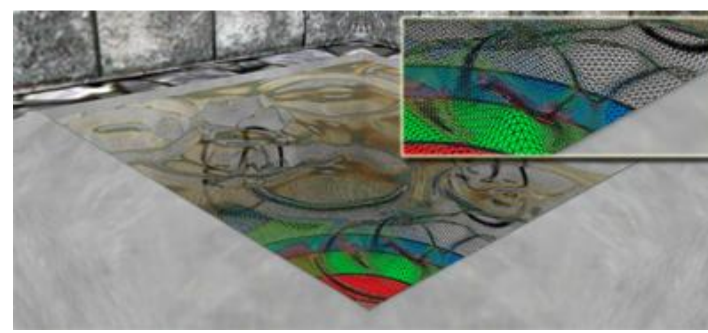
Fluid Simulation

Particles

3D Smoke & Fire

Water Simulation

Grid displacement



3D Water Surfaces

Examples

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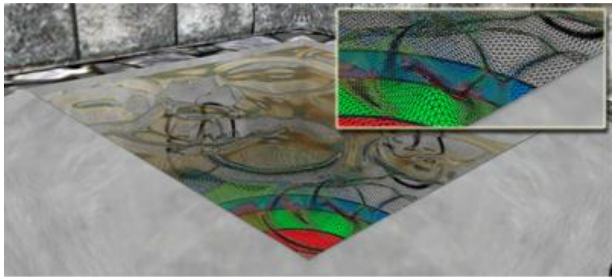
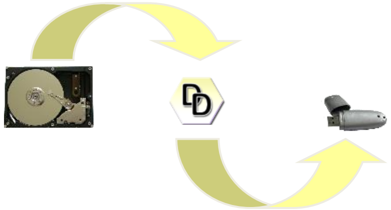


3D Water Surfaces



Point Compression

Point Decompression

Point Rendering

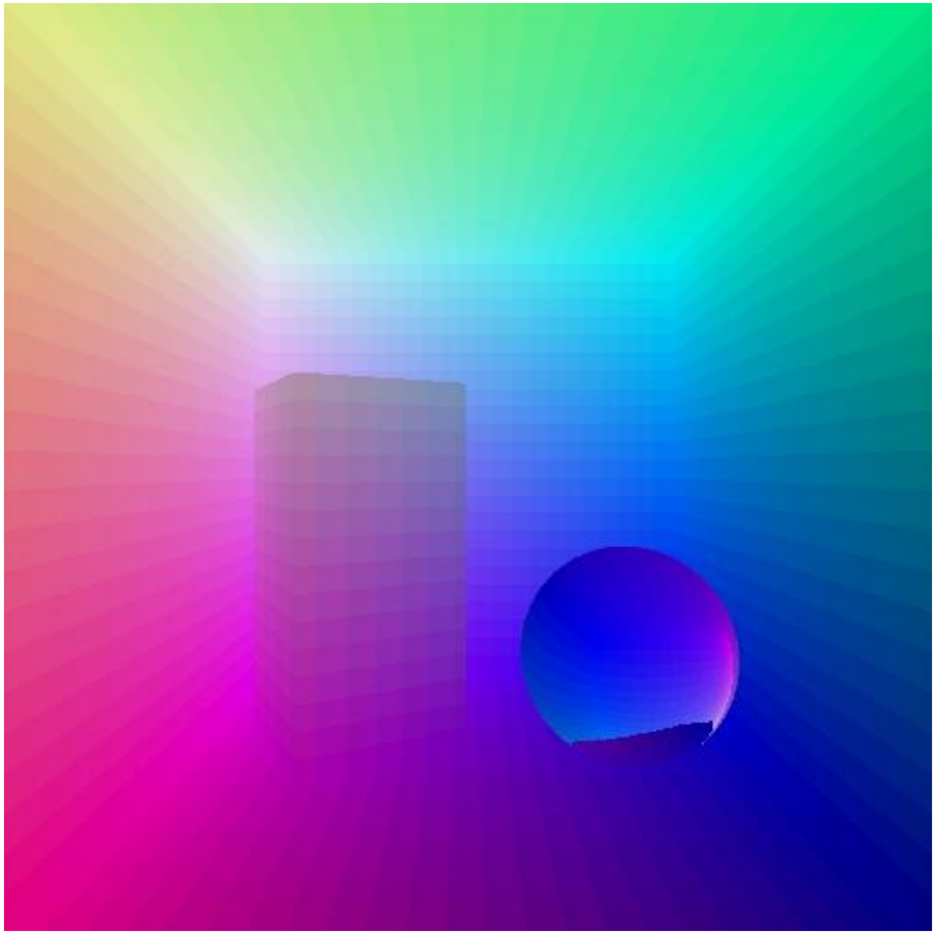
High Level Shading Languages

- Cg, HLSL, & OpenGL Shading Language
  - Cg:
    - http://www.nvidia.com/cg
  - HLSL:
    - http://msdn.microsoft.com/library/default.asp?url=/library/en-us/directx9_c/directx/graphics/reference/highlevellanguageshaders.asp
  - OpenGL Shading Language:
    - http://www.3dlabs.com/support/developer/ogl2/whitepapers/index.html

‘printf’ Debugging

- MOV suspect register to output
  - Comment out anything else writing to output
  - Scale and bias as needed
- Recompile
- Display/readback frame buffer
- Check values
- Repeat until error is (hopefully) found

‘printf’ Debugging Examples



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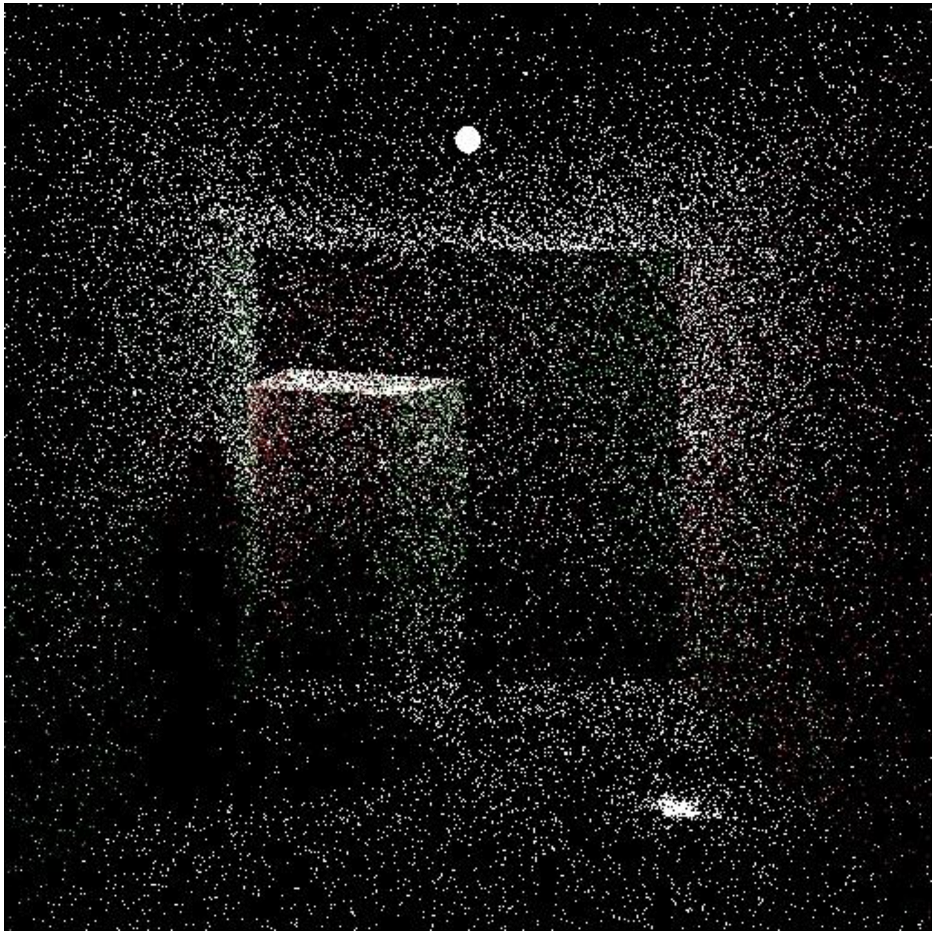

‘printf’ Debugging Examples