

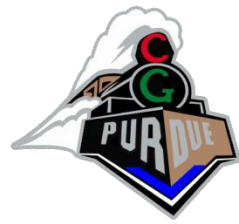
The Way of the GPU

(based on GPGPU SIGGRAPH Course)

CS334
Fall 2026

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Purdue University

(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

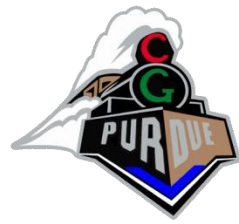
Projection

Transform into 2D camera coordinate system

Scan Conversion

Draw pixels (incl. texturing, hidden surface...)

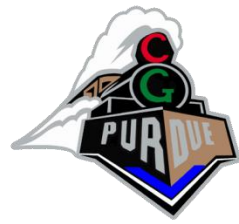
Image



Today, we have GPUs...



(GPU = graphical processing unit)



Some history and context...

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



Motivation: Computational Power

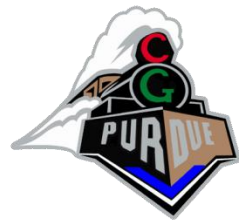
- *Why are GPUs fast?*
 - Arithmetic intensity: the specialized nature of GPUs makes it easier to use additional transistors for computation not cache
 - Economics: multi-billion dollar video game market is a pressure cooker that drives innovation

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!

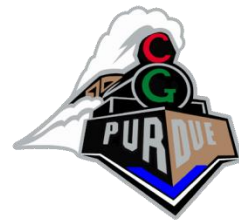
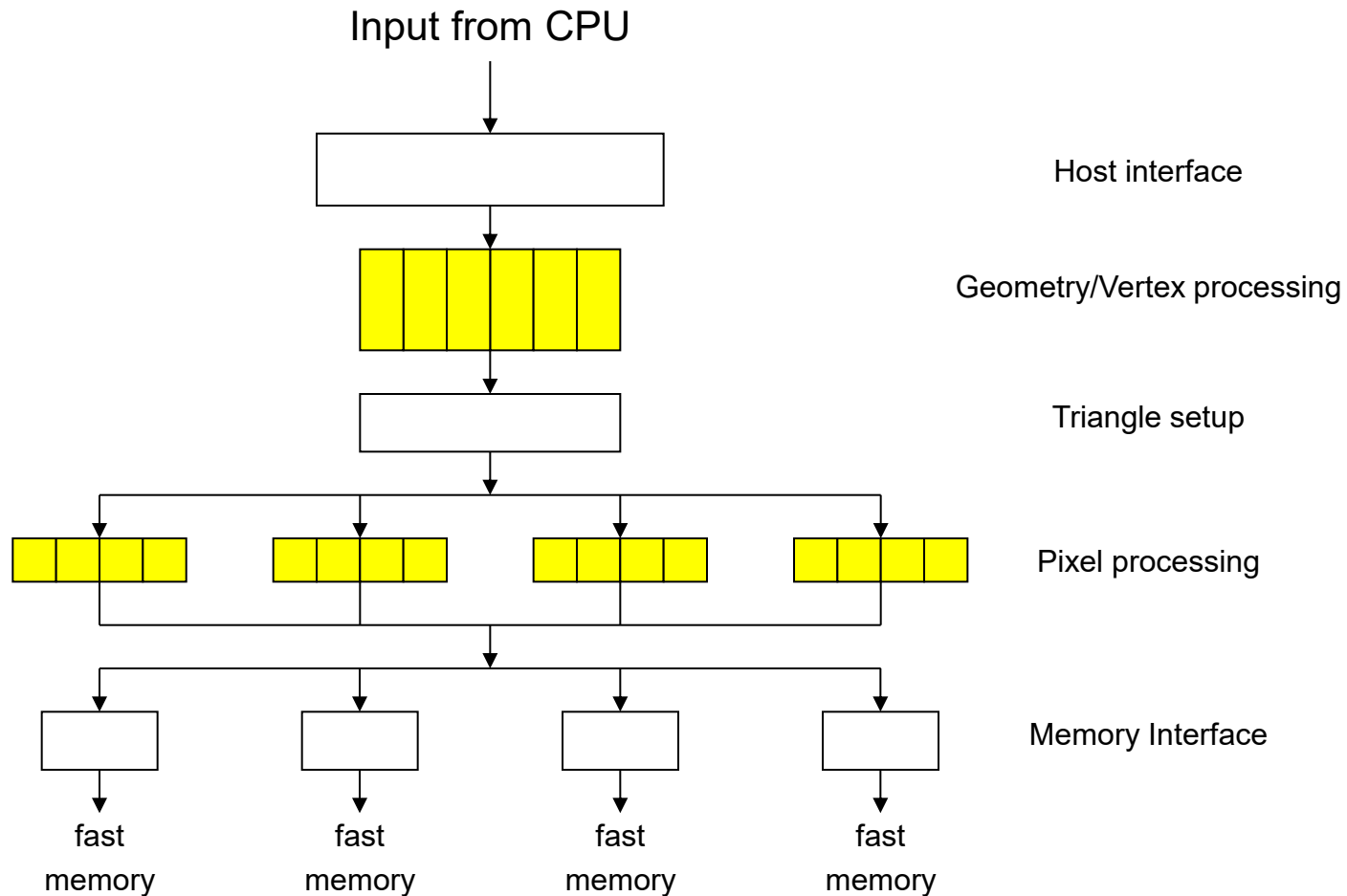
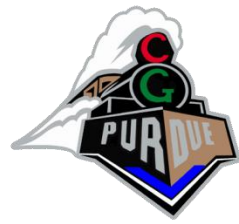


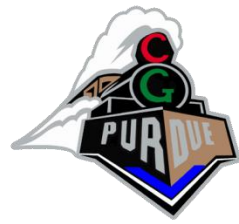
Diagram of a Modern GPU





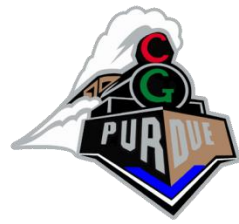
nVIDIA GPU

- **GTX 5090 (2026)**
 - 21,760 (CUDA) cores @ 2GHz (i.e., mini processors)
 - 1,792 GB/sec (memory bandwidth)
 - 32-80 GB video memory
 - 7680x4320 pixels
 - 575W power
 - 91C max GPU temp
 - **\$2000**
- e.g.: in research, we use machines with 10,000 GPUs
 - That means **200,000,000 (two hundred million)** mini processors!!!!



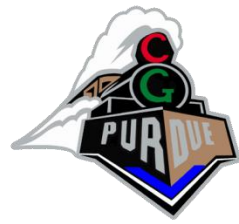
nVIDIA GPU

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



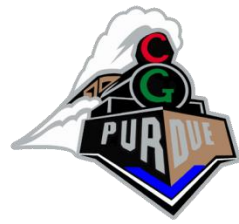
Before...

- 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**



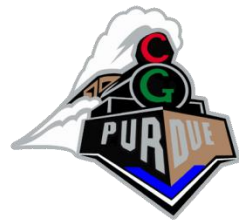
Before

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

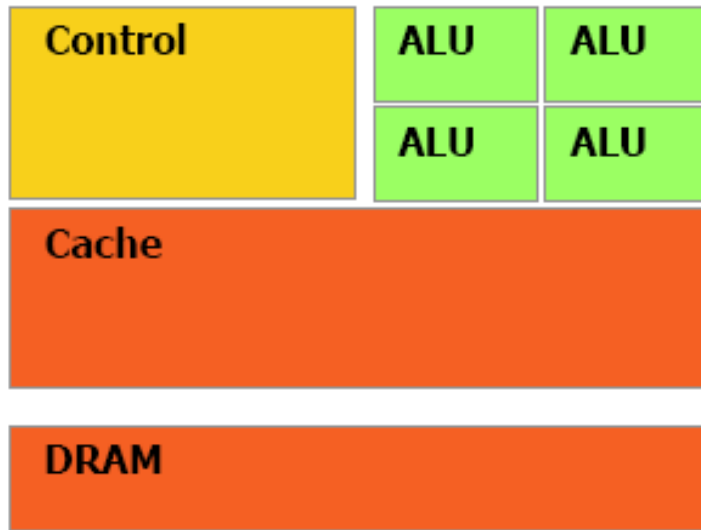


Before

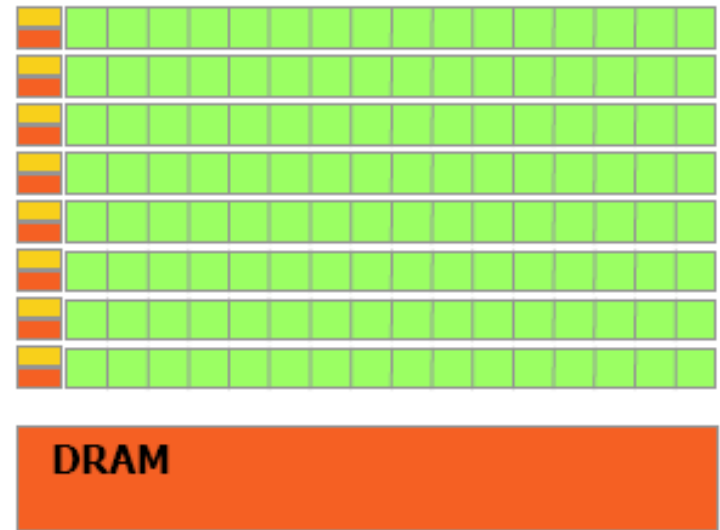
- **IBM PC 5150 (~1985)**
 - 0.000004.77 GHz
 - 16-640 KB
 - ~200W power



Modern GPU has more ALU's

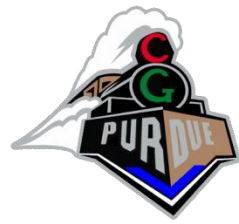


CPU



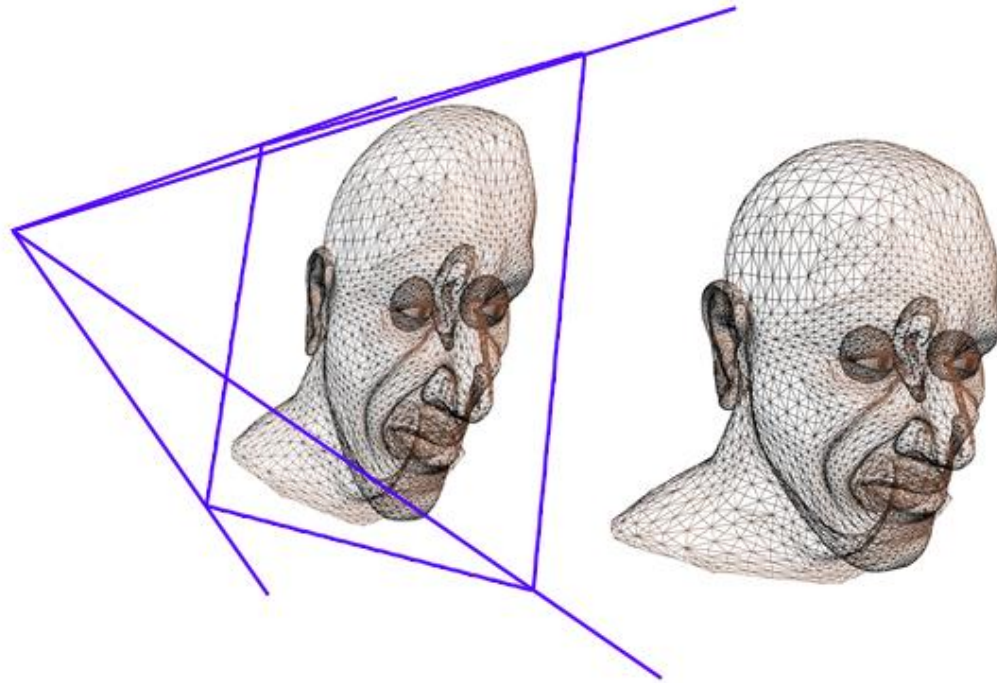
GPU

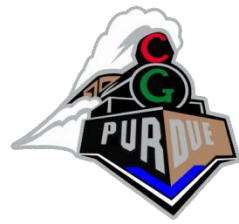
Figure 1-2. The GPU Devotes More Transistors to Data Processing



GPU Pipeline: Transform

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

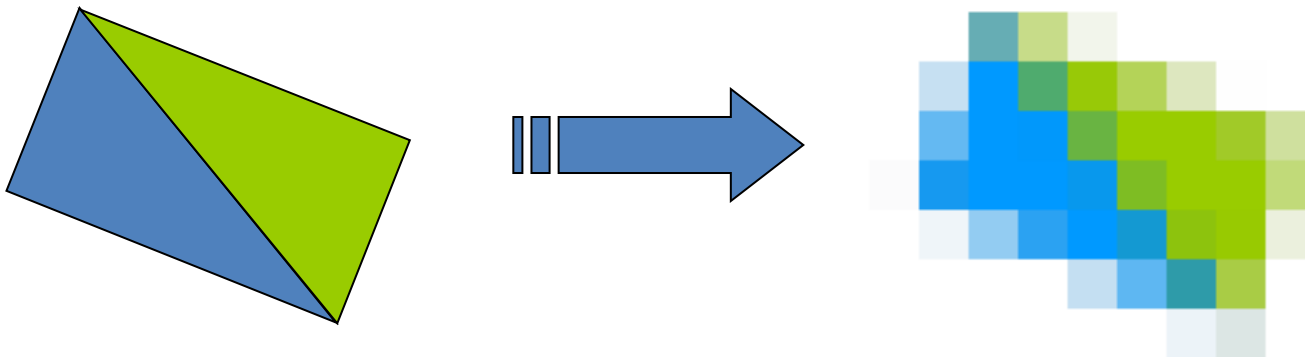


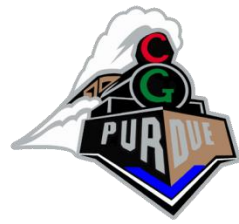


GPU Pipeline: Rasterize

(typically not programmable)

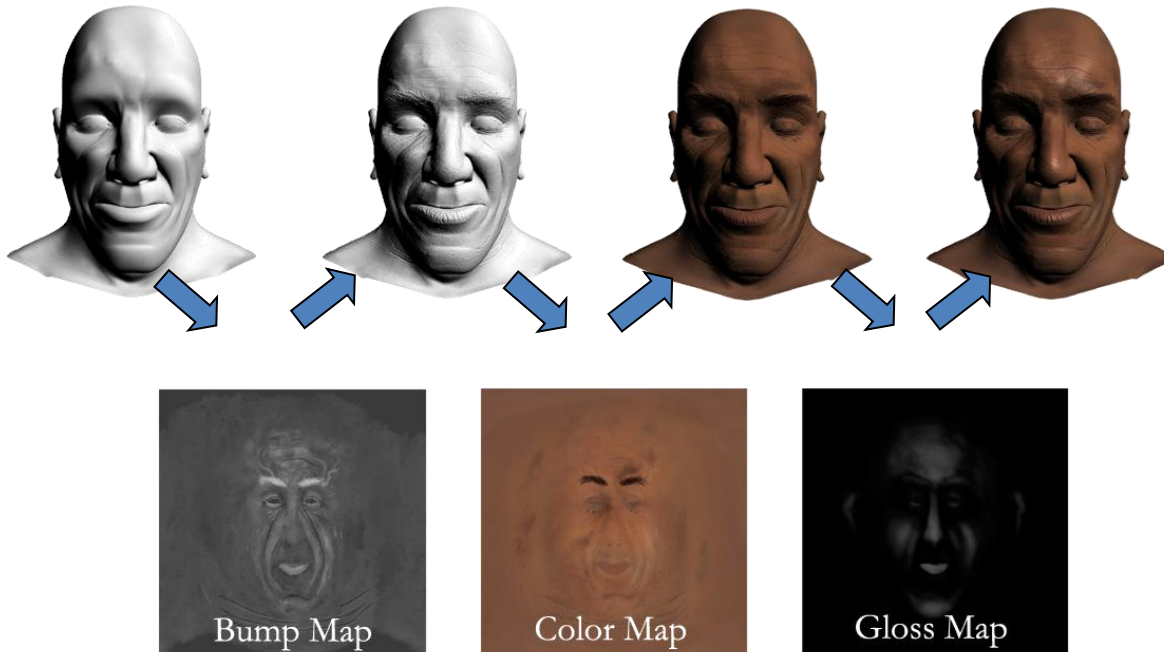
- Rasterizer
 - Convert geometric rep. (vertex) to image rep. (fragment)
 - Fragment = image fragment
 - Pixel + associated data: color, depth, stencil, etc.
 - Interpolate per-vertex quantities across pixels



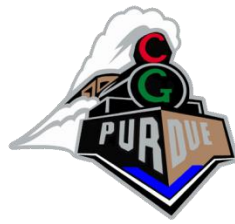


GPU Pipeline: Shade

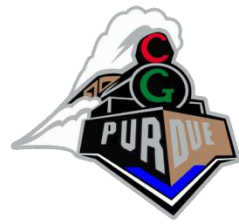
- Fragment processors (multiple in parallel)
 - Compute a color for each pixel
 - Optionally read colors from textures (images)



GPU Programming Languages



- Many options!
 - A while ago: “Renderman”
 - cG (from NVIDIA)
 - GLSL (GL shading Language)
 - CUDA (more general than 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>

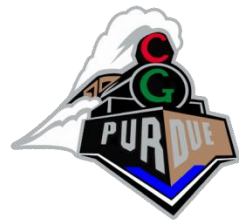
<https://www.youtube.com/watch?v=t2yPfenzkII>

https://www.youtube.com/watch?v=M_FsjL9j0HY)

Mapping Parallel Computational Concepts to GPUs

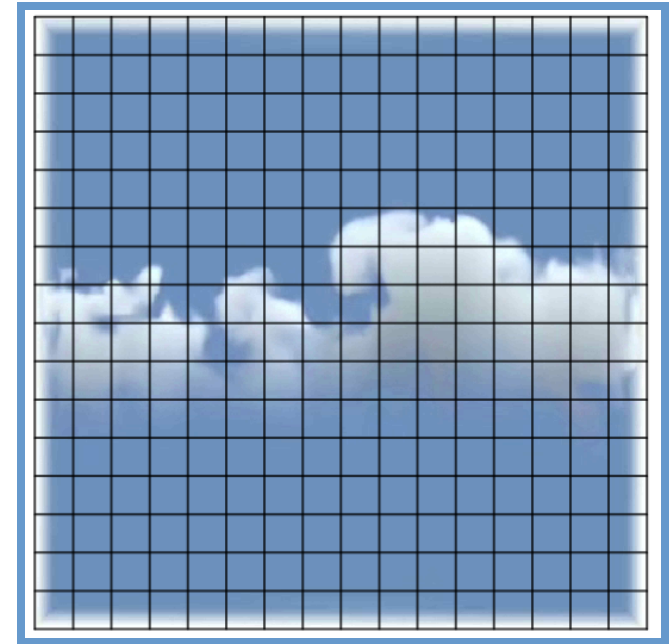


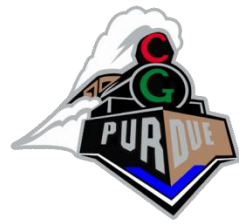
- GPUs are designed for graphics
 - Highly parallel tasks
- GPUs process *independent* vertices & fragments
 - Temporary registers are zeroed
 - No shared or static data
 - No read-modify-write buffers
- Data-parallel processing
 - GPUs architecture is ALU-heavy
 - Multiple vertex & pixel pipelines,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



Example: Simulation Grid

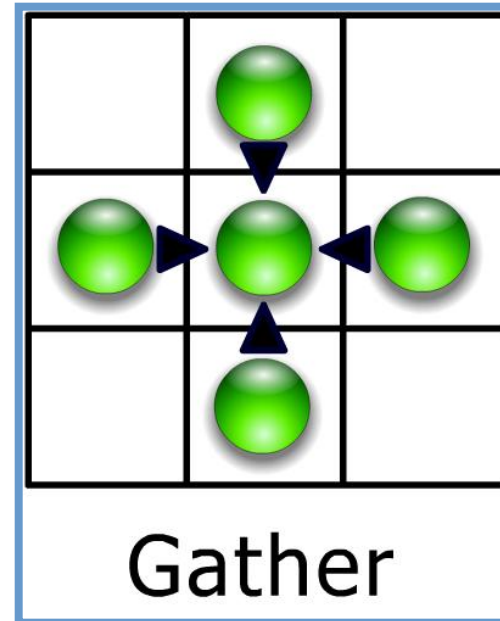
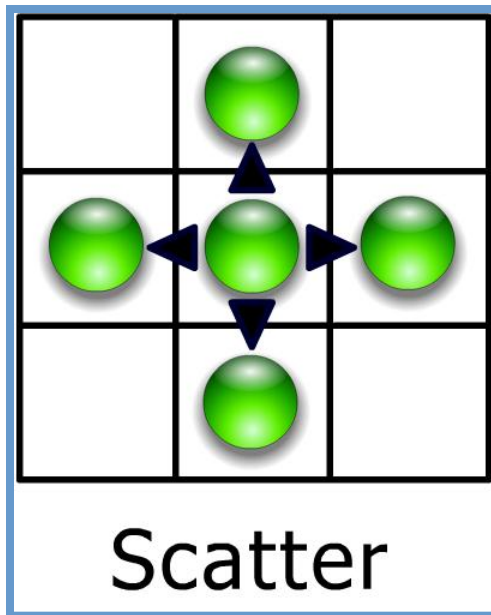
- Common GPGPU computation style
 - Textures represent computational grids = streams
- Many computations map to grids
 - Matrix algebra
 - Image & Volume processing
 - Physically-based simulation
 - Global Illumination
 - ray tracing, photon mapping, radiosity
- Non-grid streams can be mapped to grids

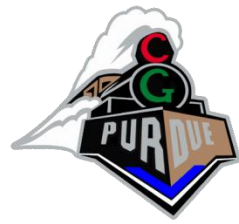




e.g.: Scatter vs. Gather

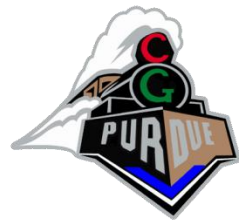
- Grid communication
 - Grid cells share information





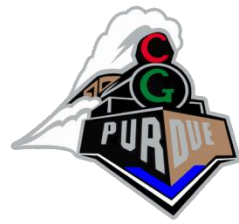
Vertex Processor

- 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
 - $\approx$ Gather (But not from the vertex stream itself)



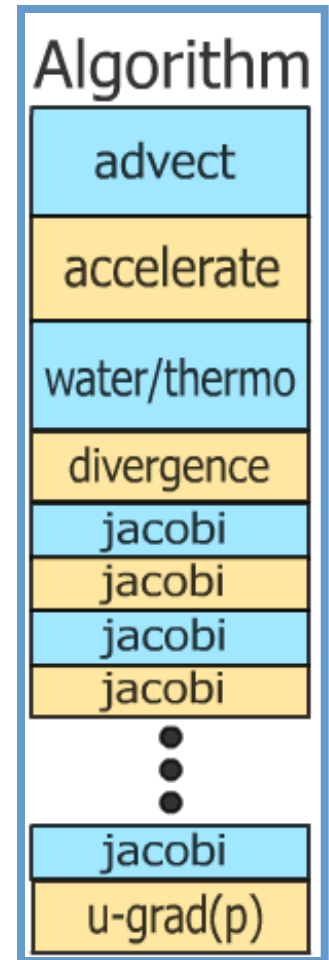
Fragment Processor

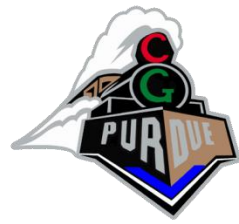
- Fully programmable (SIMD)
- Processes 4-component vectors (RGBA / XYZW)
- Random access memory read (textures)
- Capable of **gather** but not scatter
 - RAM read (texture fetch), but no RAM write
 - Output address fixed to a specific pixel
- Typically more useful than vertex processor
 - More fragment pipelines than vertex pipelines
 - Direct output (fragment processor is at end of pipeline)



GPU Simulation Overview

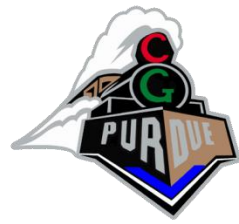
- A Simulation:
 - Its algorithm steps are fragment programs
 - Called Computational *kernels*
 - Current state is stored in textures
 - Feedback via “render to texture”
- Question:
 - How do we invoke computation?





Invoking Computation

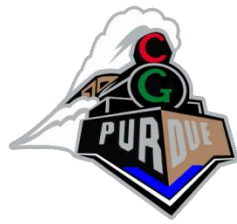
- Must invoke computation at each pixel
 - Just draw geometry!
 - Most common GPGPU invocation is a full-screen quad
- Other Useful Analogies
 - Rasterization = Kernel Invocation
 - Texture Coordinates = Computational Domain
 - Vertex Coordinates = Computational Range



Typical “Grid” Computation

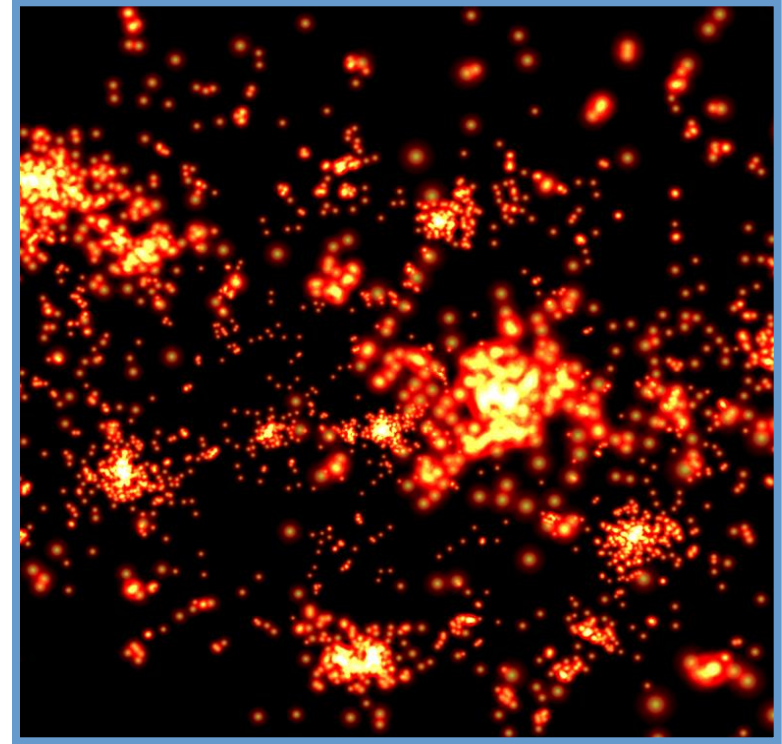
- Initialize “view” (so that pixels:texels::1:1)

```
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)

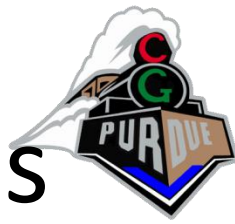


Example: N-Body Simulation

- 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



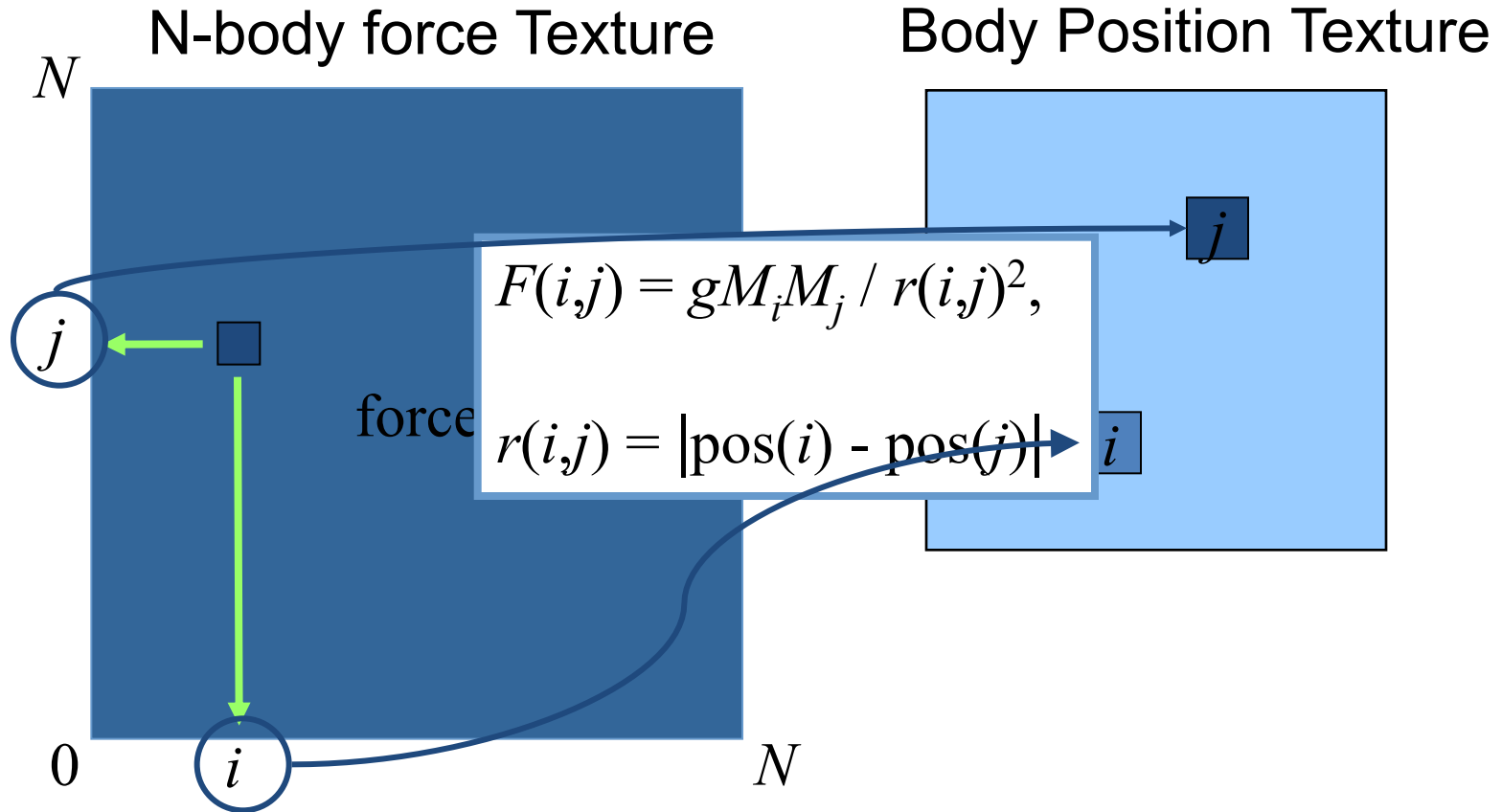
Computing Gravitational Forces



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

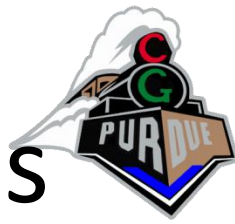


Computing Gravitational Forces

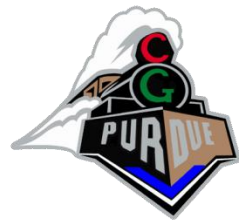


**Force is proportional to the inverse square
of the distance between bodies**

Computing Gravitational Forces

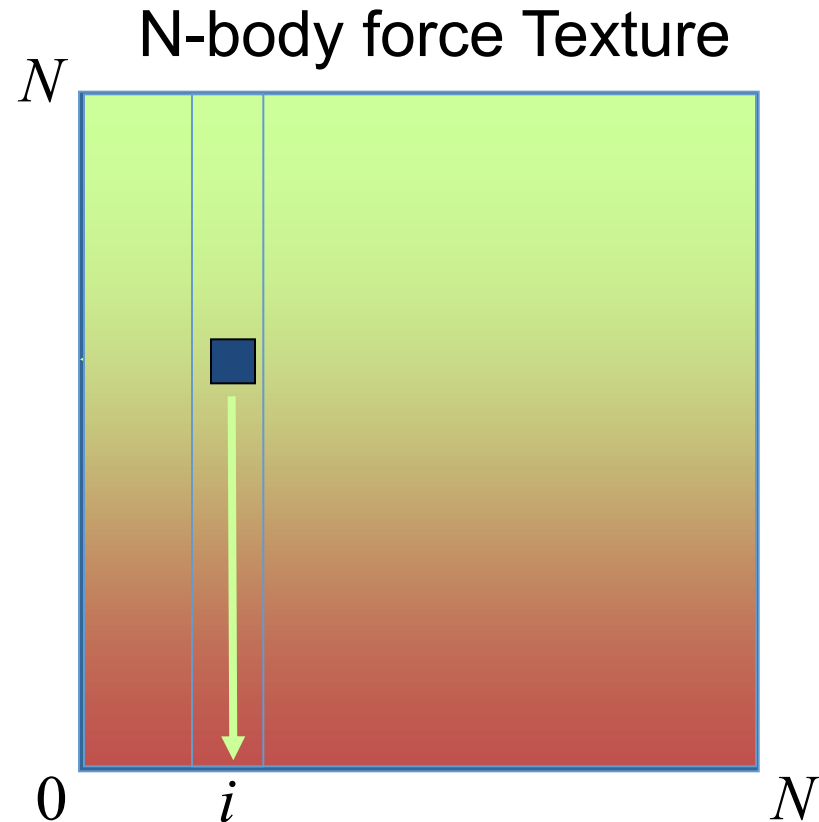


```
float4 force(float2 ij : WPOS,  
            uniform sampler2D pos) : COLOR0  
{  
    // Pos texture is 2D, not 1D, so we need to  
    // convert body index into 2D coords for pos tex  
    float4 iCoords = getBodyCoords(ij);  
    float4 iPosMass = texture2D(pos, iCoords.xy);  
    float4 jPosMass = 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

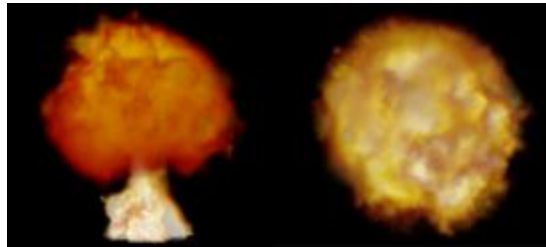


This is called a *Parallel Reduction*

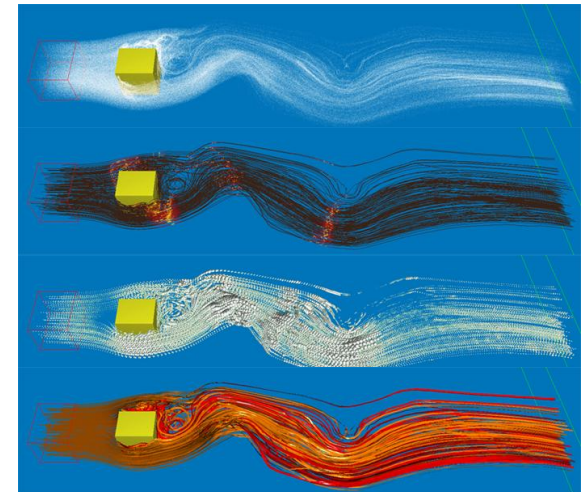
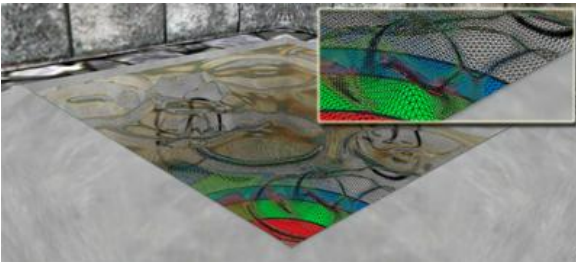
Geometry processing on GPUs



- so far: GPGPU limited to texture output



- new APIs allow geometry generation on GPU



Examples



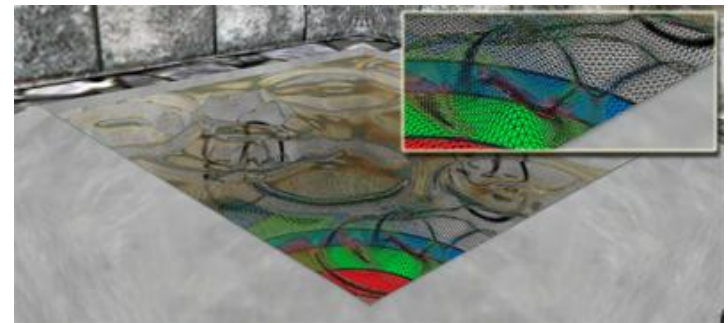
Fluid Simulation



3D Smoke & Fire



Water Simulation



3D Water Surfaces

Examples



Fluid Simulation



Particles



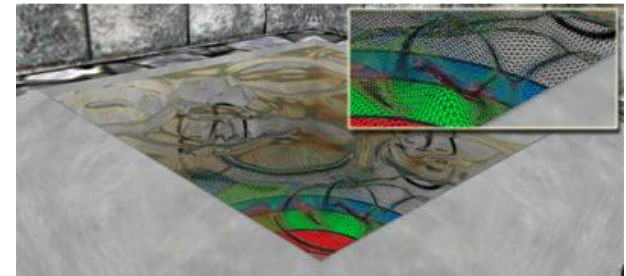
3D Smoke & Fire



Water Simulation



Grid displacement



3D Water Surfaces



Point Compression



Point Decompression

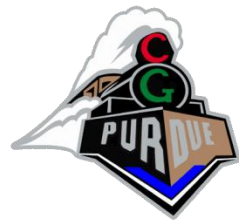


Point Rendering

High Level Shading Languages



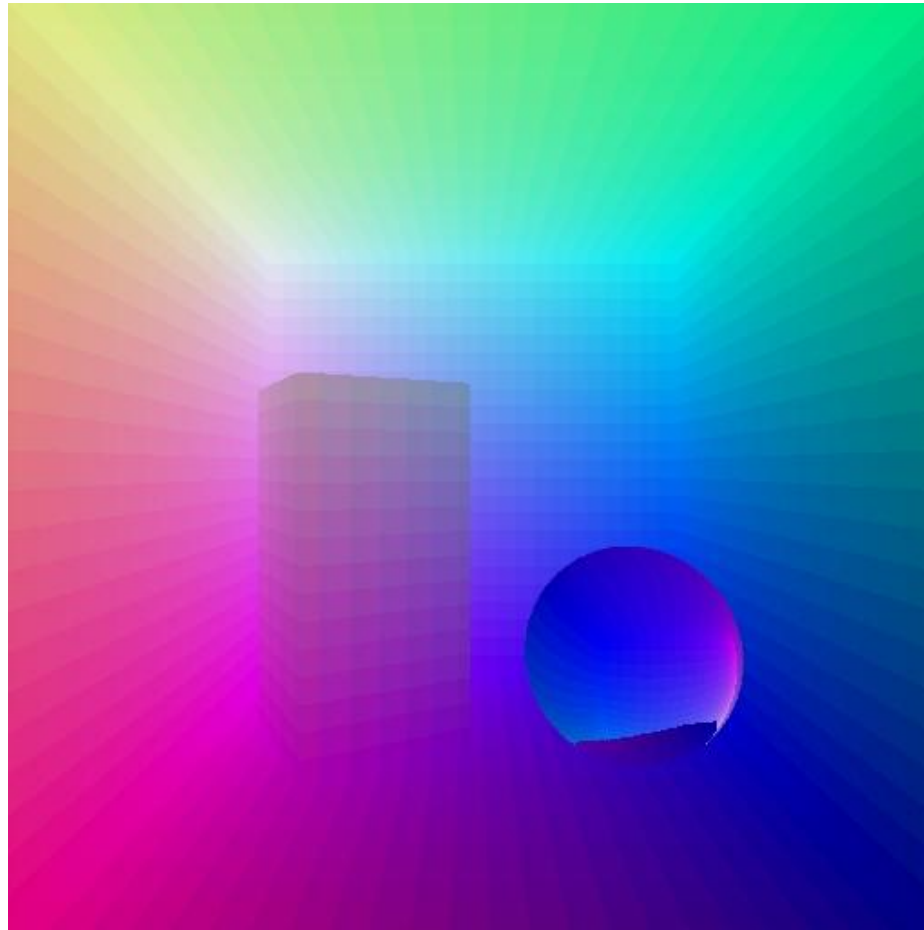
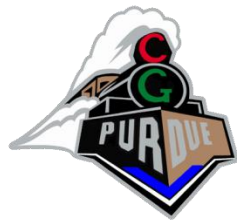
- Cg, HLSL, & OpenGL Shading Language
 - Cg:
 - <http://www.nvidia.com/cg>
 - HLSL:
 - http://msdn.microsoft.com/library/default.asp?url=/library/en-us/directx9_c/directx/graphics/reference/highlevellanguageshaders.asp
 - OpenGL Shading Language:
 - <http://www.3dlabs.com/support/developer/ogl2/whitepapers/index.html>



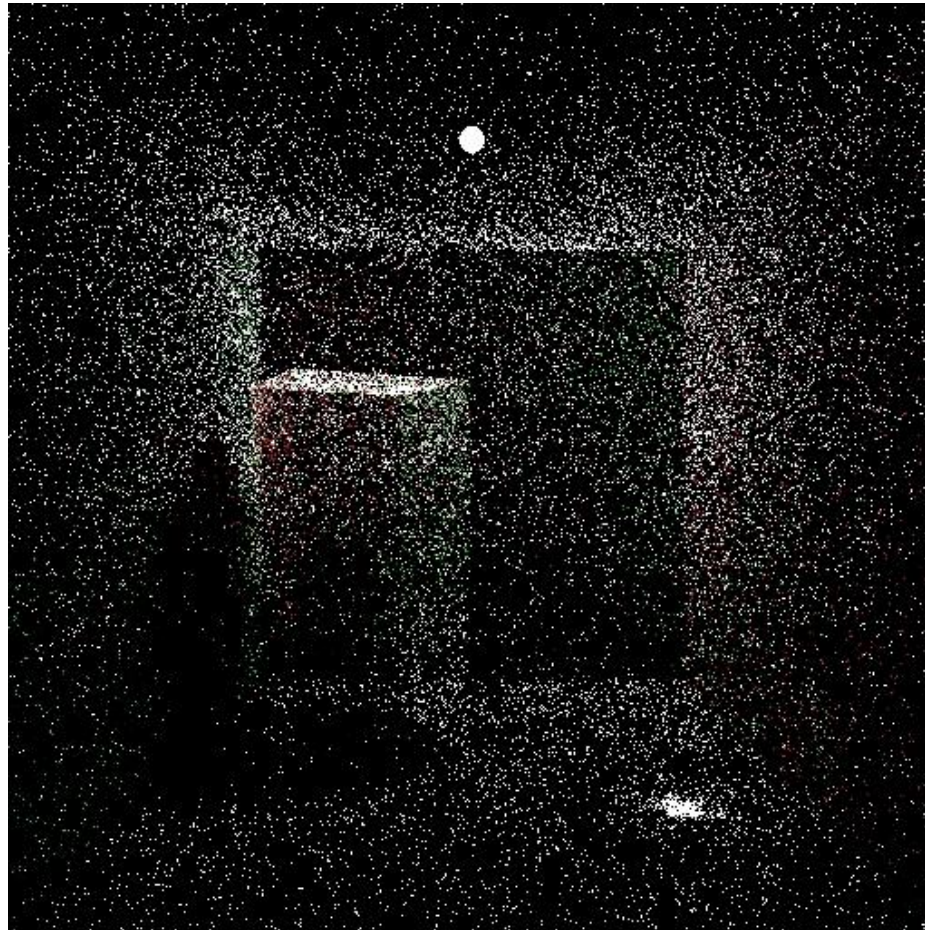
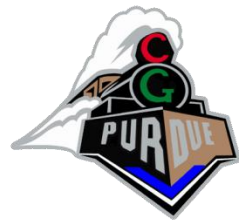
'printf' Debugging

- 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



'printf' Debugging Examples



'printf' Debugging Examples

