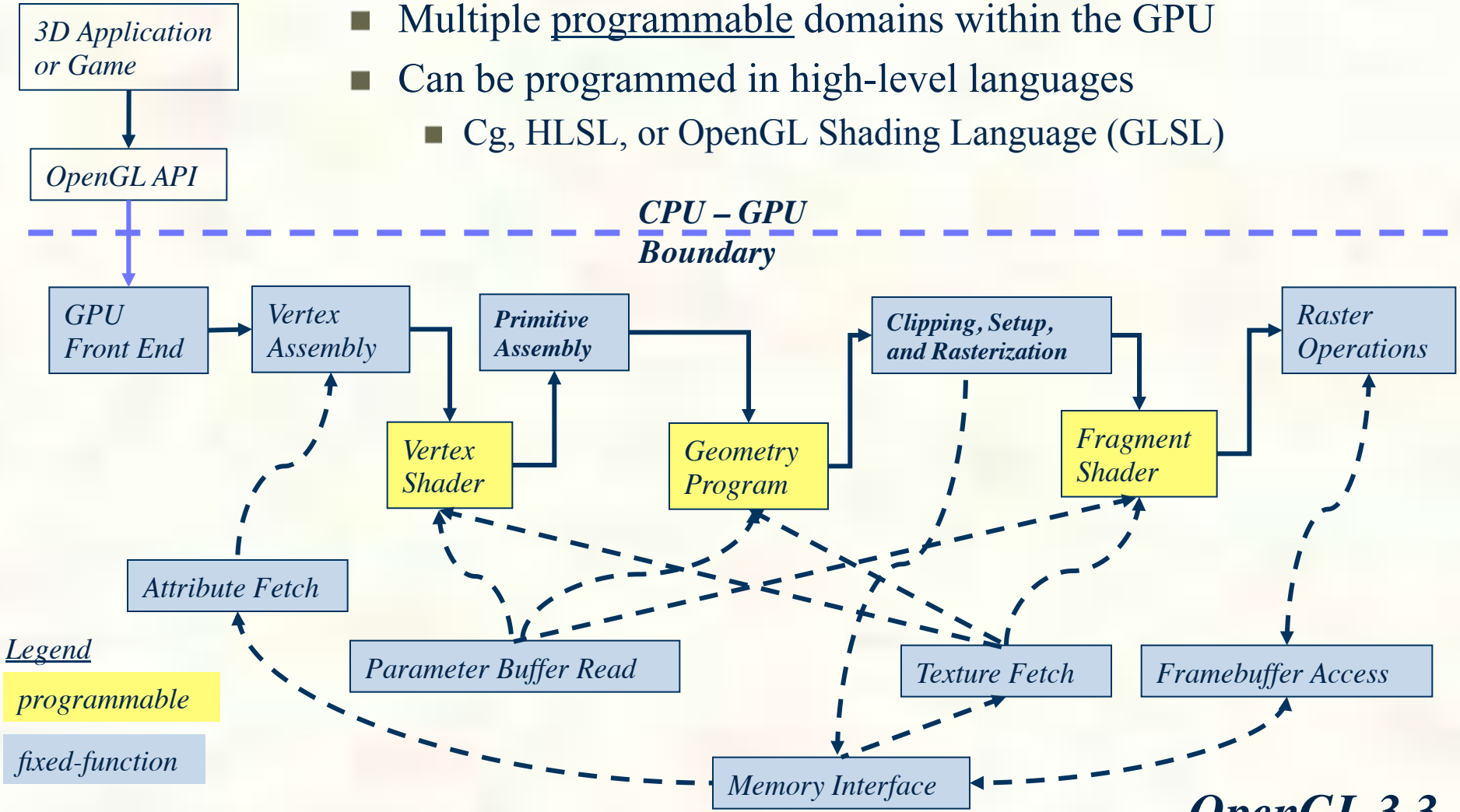
Programmable Shading

Lighting, Texturing, Shading

- Discussed
  - Transformation, Texturing, and Lighting
- What if…
  - We could write a program that controls these
- What if…
  - These programs could execute in dedicated hardware
- What if…
  - We could write these programs in a high-level language
- That's what shaders are about!

Programming Shaders **inside** GPU

- Multiple programmable domains within the GPU
- Can be programmed in high-level languages
  - Cg, HLSL, or OpenGL Shading Language (GLSL)



OpenGL 3.3

Example Simple GLSL Shaders

- Vertex Shader
  - Operates on each vertex of geometric primitives

```
void main(void)
{
  gl_FrontColor = gl_Color;
  gl_Position =
ftransform();
}
```

  - Passes through per-vertex color
  - Transforms the vertex to match fixed-function processing

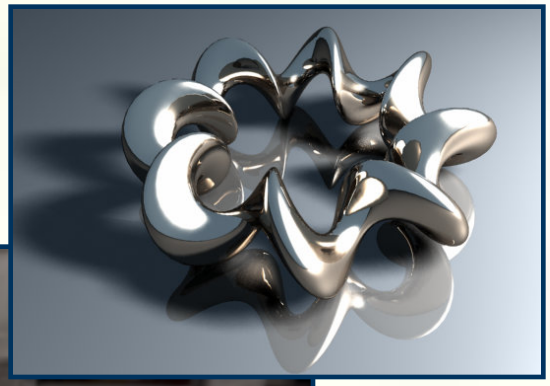
- Fragment Shader
  - Operates on each fragment (think pixel)

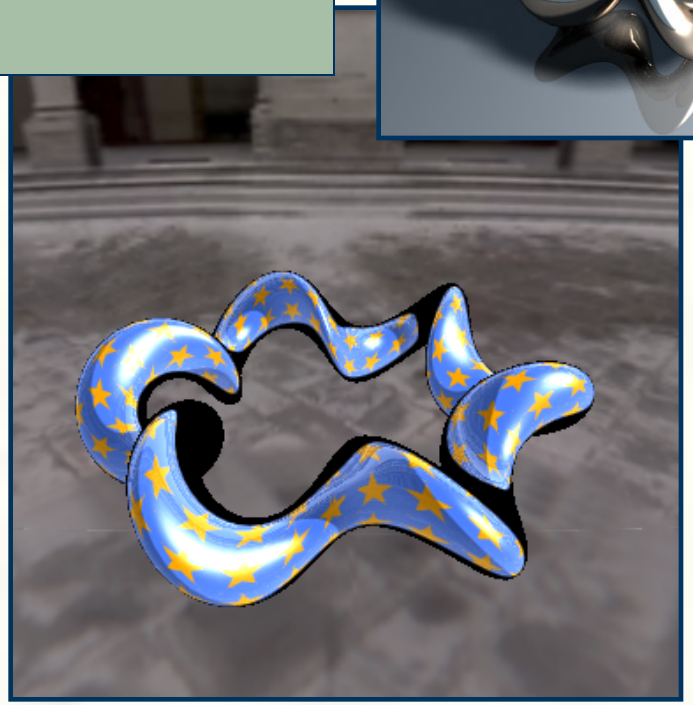
```
void main(void)
{
  gl_FragColor =
gl_Color;
}
```

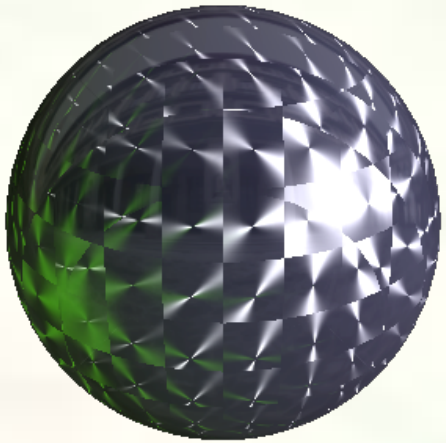
  - Outputs the fragment's interpolated color to the framebuffer

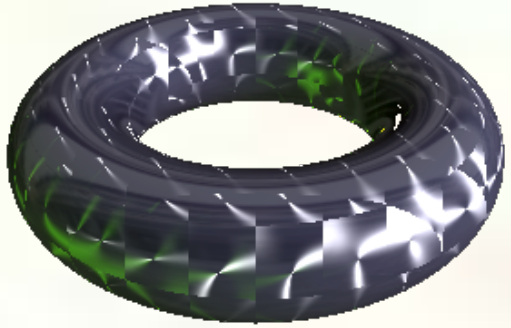
Shaders are way more interesting than these minimal examples

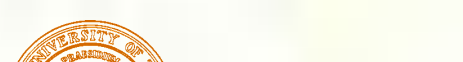
Examples of Complex Shaders







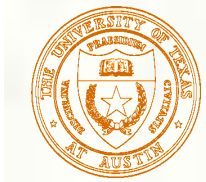




Building Up Shaders

Diffuse *Decal* *Specular* *Gloss*

Result



Shade Trees

- Lucasfilms [Cook ’84] proposes using a tree structure to represent shading expressions
  - Proposed a specialized language to represent shading expressions

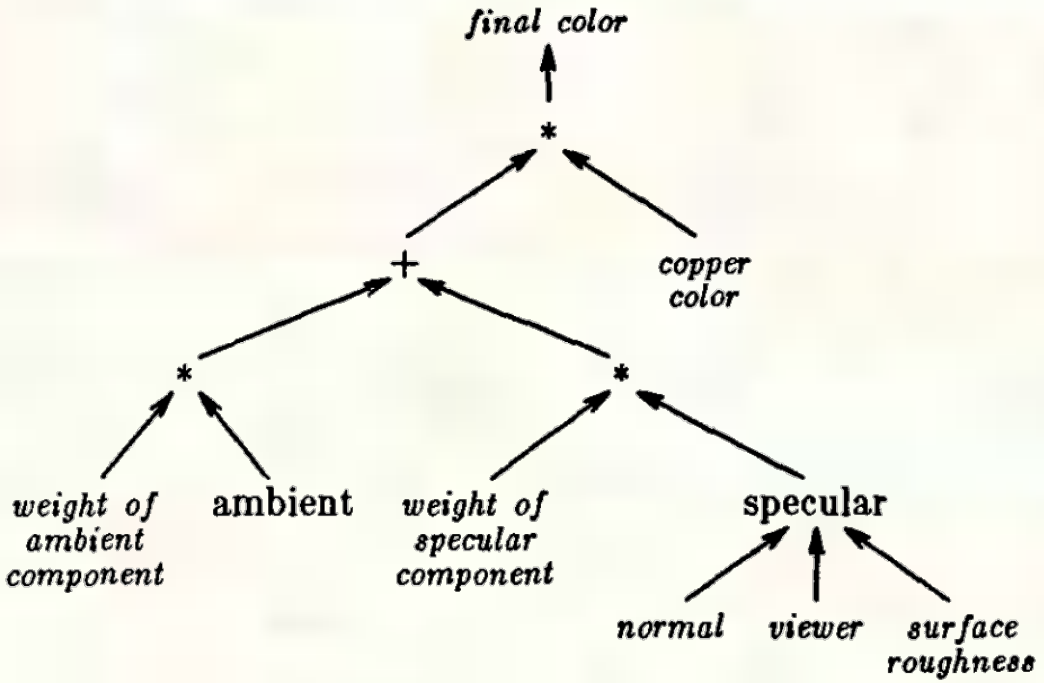


Figure 1a. Shade tree for copper.

Pioneering Shading Language

- RenderMan Shading Language
  - Developed by Pixar
    - Academy Award winning!
  - For production rendering of animated films
    - Still in use
  - Intended for CPU-based rendering system
    - Not oriented for graphics hardware
    - Assumes a micro-polygon style renderer

PIXAR's RenderMan

OpenGL Shading Language

- Known as GLSL
  - Part of core OpenGL 2.0 and beyond
- Uses a C-like language
  - Authoring of vertex and fragment shaders
    - Later added geometry shaders (GL 3.0) and tessellation shaders (GL 4.0)

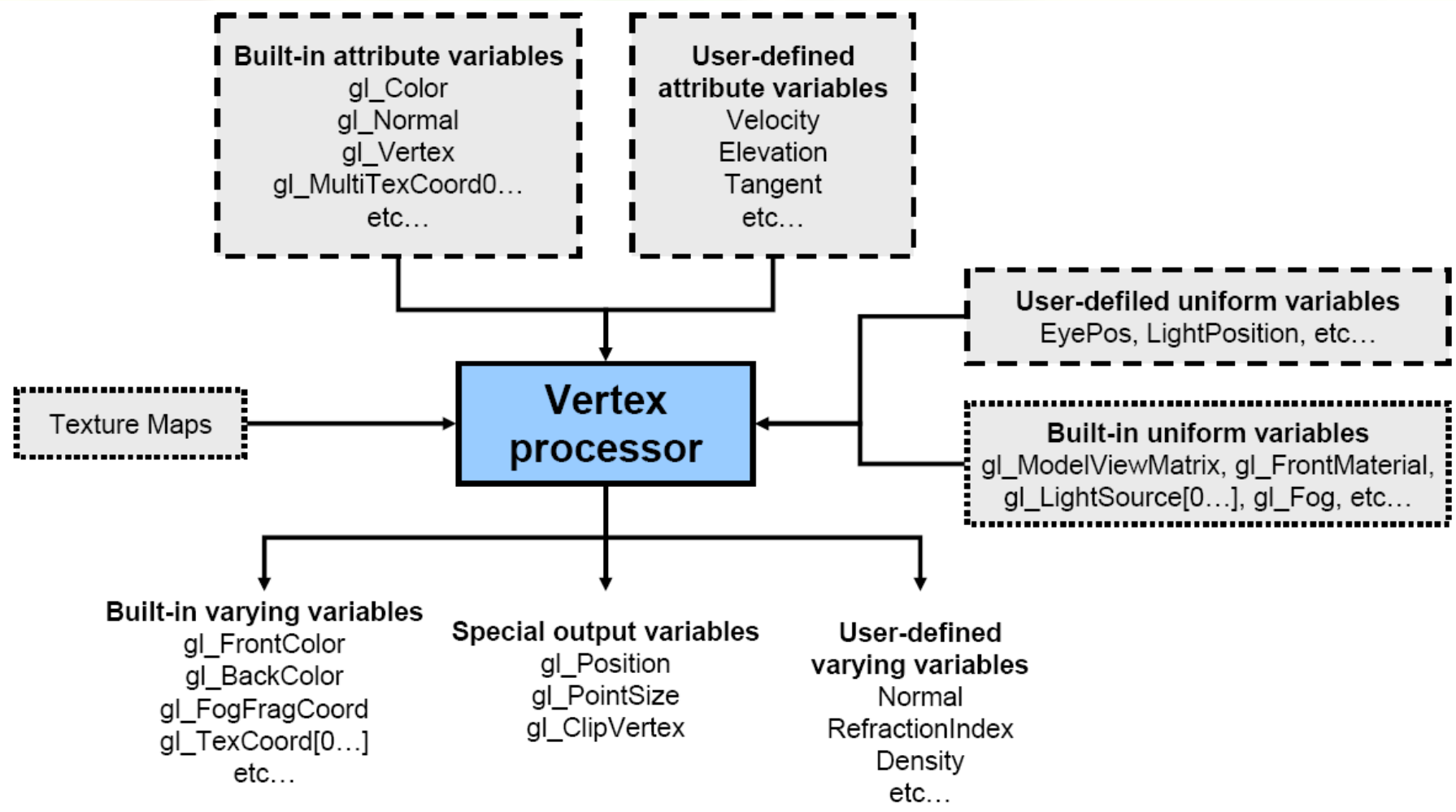
OpenGL Versions, Extensions

- OpenGL is constantly evolving
  - New core version updates:
    - 1.0, 1.1, 1.2,… 2.0, 2.1,… 3.0, … 4.2
    - Updates happening every year now!
  - OpenGL also supports extensions
- Using new versions and extensions
  - Possible using "GetProcAddress" API to ask driver for entry-point for new commands
    - Avoids probably with static OpenGL library linking
  - Particularly a problem on Windows
    - Because Microsoft has not updated OpenGL since 1.1!
      - Benign neglect sometimes better than other alternative ☺
  - Still Linux and Mac support a "GetProcAddress" mechanism too
- **Solution:** OpenGL Extension Wrangler Library (GLEW)
  - Regularly updated to support all available OpenGL extensions and versions
  - Linking with GLEW keeps you from dealing with "GetProcAddress" hassles
- Details
  - Link with –lGLEW
  - Call glewInit() right after creating an OpenGL context
  - Call OpenGL new version and extension routines
  - That's basically it
- Open source
  - http://glew.sourceforge.net/

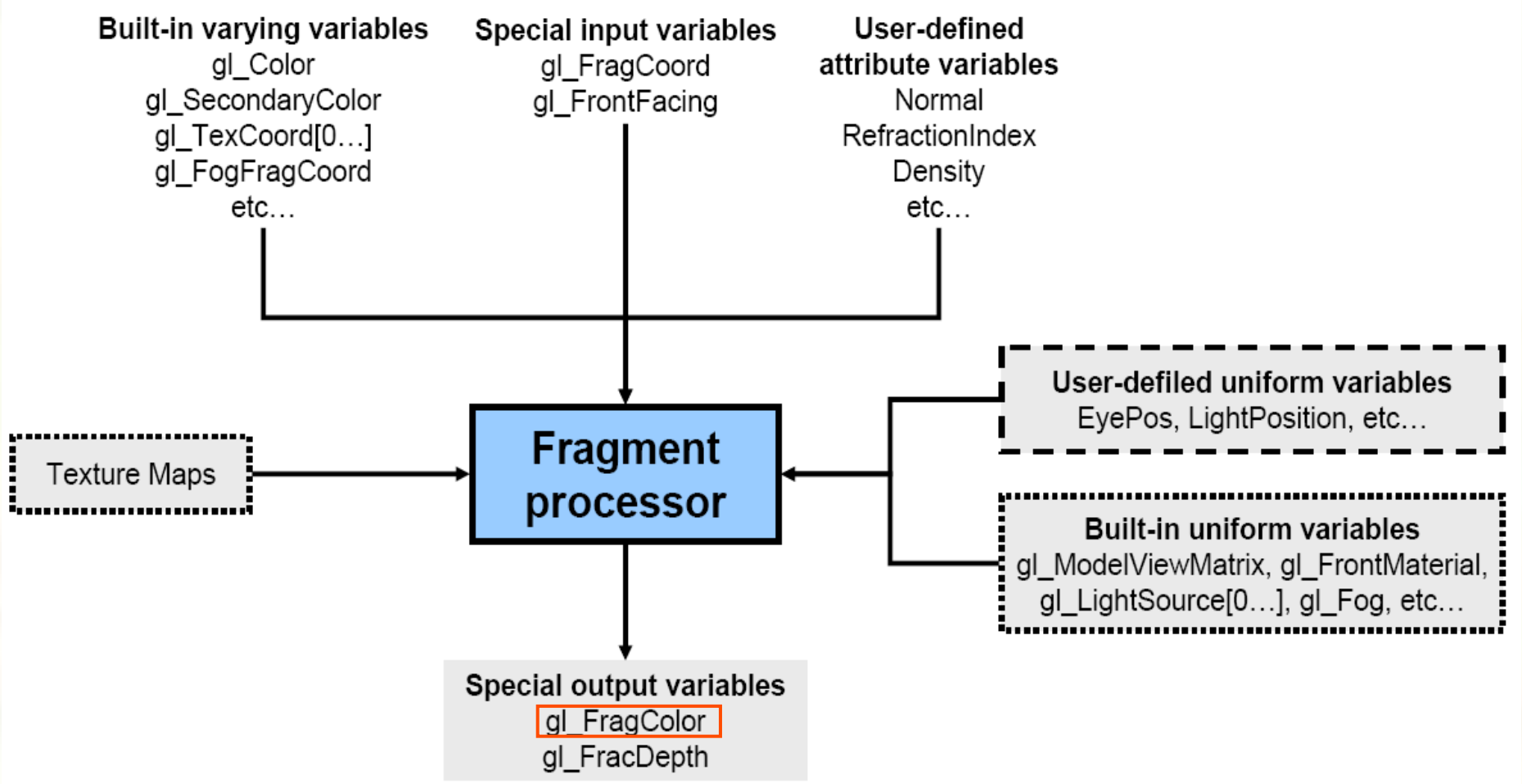
GLSL Language Overview

- C-like
  - C-style syntax and control flow
- Adds graphics features
  - First-class vertex and matrix data types
  - Texture samplers
  - Graphics-oriented standard library
    - Including built-in OpenGL state variables
  - Uniform and varying parameters, interpolation qualifiers
- Various modern language features
  - bool, // comments, limited overloaded functions
  - in/out/inout function parameters
- Minus features of C not suited for GPUs
  - Pointers, unions, multi-dimensional arrays
  - goto, string literals, standard C library stuff like printf and malloc

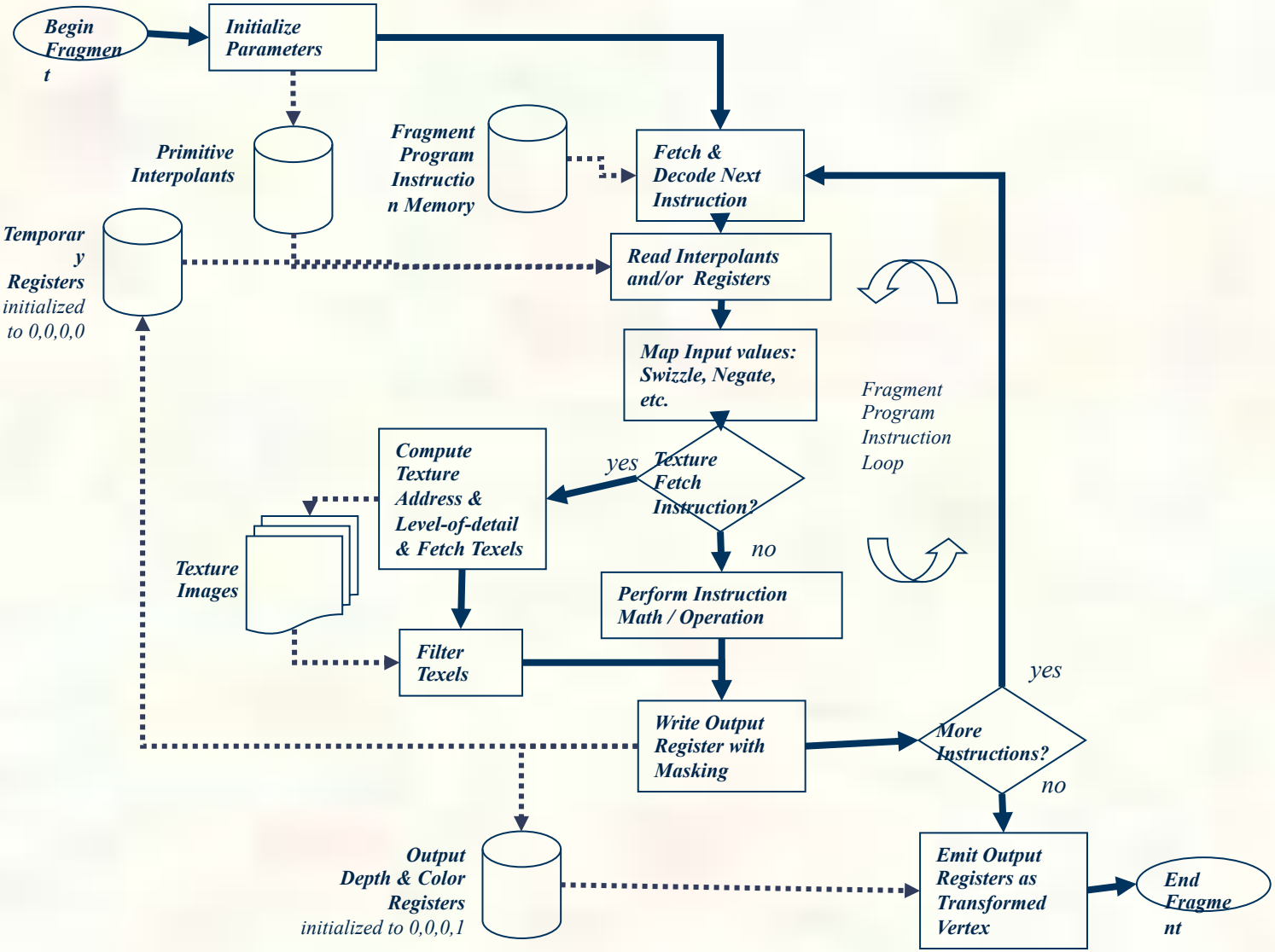
Vertex Shader Inputs & Outputs



Fragment Shader Ins & Outs

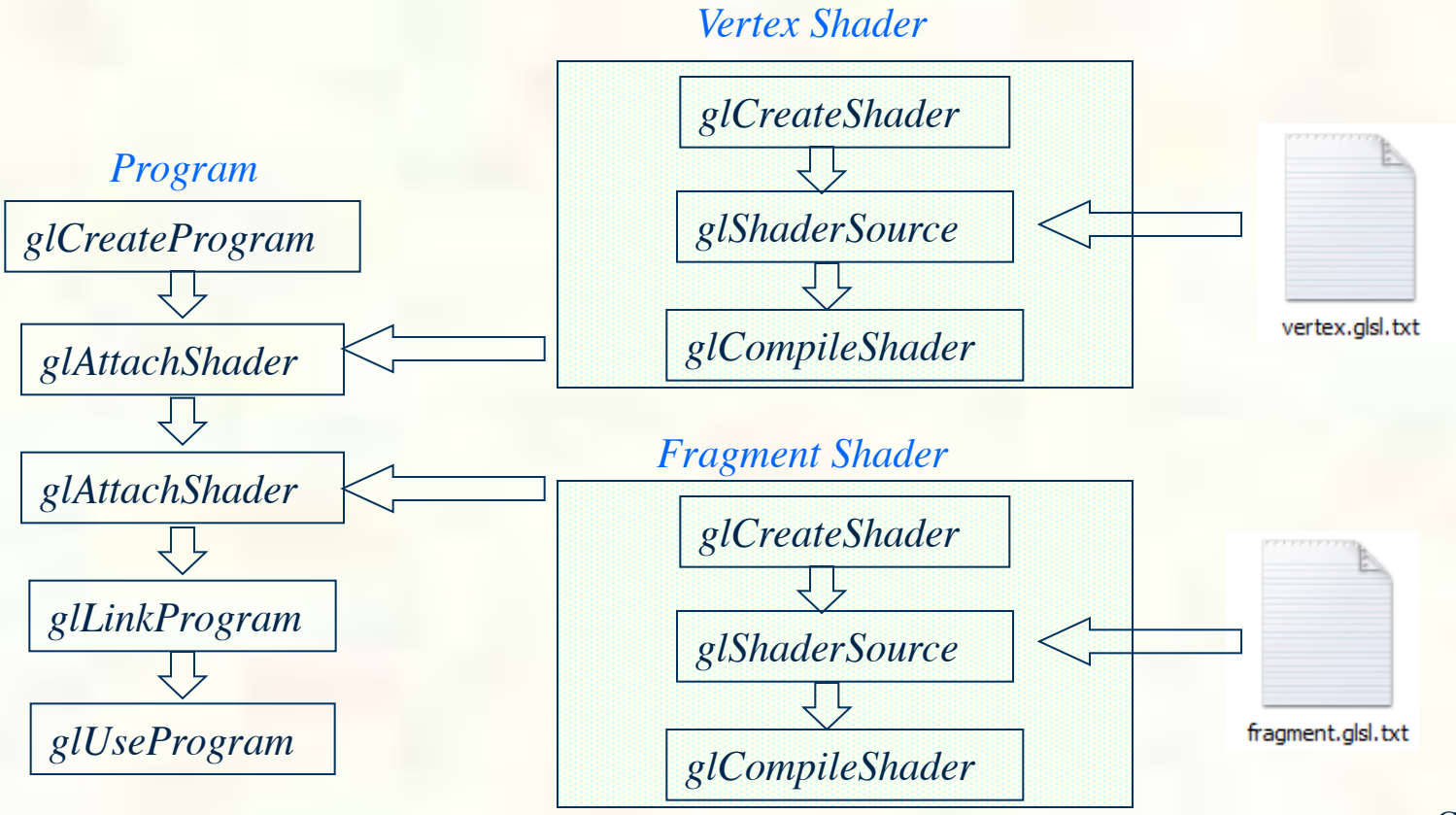


OpenGL Fragment Program Flowchart



Creating GLSL Programs

- Create & compile vertex & fragment shader
- Attach shaders & link program



GLSL Implementation

- GLSL is built into OpenGL drivers
  - Means your graphics driver contains an optimizing compiler for a high-level language
    - Targeting a complex, dedicate processor
    - What could possibly go wrong?
      - Well, you might want to test your shaders on hardware from different vendors (hint, careful about Intel Integrated Graphics)
      - But fairly mature at this point, assuming good drivers
- GLSL shaders compiled to hardware-dependent shader micro-code
  - Details all hidden from the OpenGL application programmer
  - Provides very little visibility into compiled result
    - NVIDIA's Cg Toolkit contains compiler for Cg and GLSL code that can show you an assembly level view of your program
      - Use –oglsl option to accept GLSL language into cgc compiler
- Shaders execution in *Single Program, Multiple Data* (SPMD) model
  - Means (in latest GPUs) that each shader instance can branch differently
    - More powerful than *Single Instruction, Multiple Data* (SIMD) model

Vector Data Types

- Vector data types built into language
  - First class
  - Supports swizzling, masking, and operators
    - Swizzling/mask example: foo.zyx = foo.xxy
    - Operators like +, -, *, and / do component-wise operations
      - Also supports vector-with-scalar operations
  - Type names
    - **Floating-point vectors:** vec2, vec3, vec4
    - **Integer vectors:** ivec2, ivec3, ivec4
    - **Double-precision vectors:** dvec2, dvec3, dvec4
- Lots of standard library support
  - dot, length, normalize, reflect, etc.
  - sin, cos, rsqrt, etc.

Vector Details

- Swizzle forms
  - .x, .y, .z, .w
  - .r, .g, .b, .a
  - .s, .t, .p, .q
- Create with C++ style constructors
  - **Example:** vec3 foo = foo(1.0, 2.0, 3.0)
  - Aggregate initializiers aren't allowed
    - So cannot say: vec3 foo = { 1, 2, 3 }

Matrix Data Types

- Matrix data types also built into language
  - **Floating-point matrices:** mat2, mat3, mat4
    - Also mat2x2, mat3x3, mat4x4
  - **Non-square matrices**: mat4x2, etc.
- Operator overloading
  - * does matrix-by-vector and matrix-by-matrix multiplication
- Matrices are stored column-major
  - Defying the convention of C/C++ 2D arrays
- Use matrix constructors
  - **Example:** mat2x2 foo = mat2x2(1.0, 2.0, 3.0, 4.0)
- Access matrix elements via swizzles and/or indexing
  - **Example:** foo[0].y or foo[0][1]

Samplers

- Samplers = opaque objects
  - Provides access textures and fetching texels
  - Type names:
    - **Basic:** sampler1D, sampler2D, sample3D
    - **Cube maps:** samplerCube
    - **Shadow maps:** sampler2DShadow, etc.
    - **Rectangle:** sampler2DRect, etc.
    - **Array textures:** sampler2DArray, etc.
- Standard library routines
  - texture2D, textureCube, texture3D, etc.
  - Returns a 4-component vector, typically a color

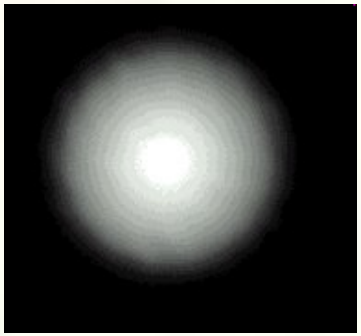
Type Qualifiers

- Shaders are expected to source inputs and write outputs
  - Type qualifiers identify these special variables
  - Vertex input qualifier: attribute
  - Vertex-fragment interface qualifier: varying
    - Also interpolation modifiers: centroid, flat, noperspective
  - Shader parameters initialized by driver: uniform
- Newer usage is in for attribute; out for vertex shader varying; in for fragment shader varying
  - One problem with GLSL is deprecation
  - GLSL designers don't respect compatibility
    - Hard to write a single shader that works on multiple GLSL versions

Other Details

- C preprocessor functionality available
- Has its own extension and version mechanism
  - #version
  - #extension
    - require, enable, warn, disable
- Type qualifiers for controlling precision
  - lowp, mediump, highp—mainly for embedded GPUs
- Entry function must be named main

Consider a Light Map Shader

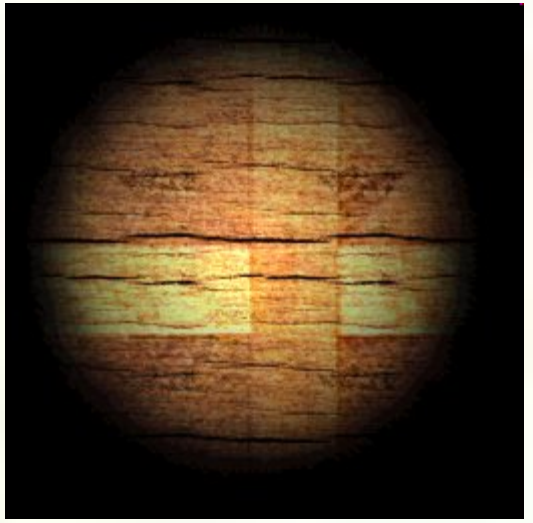


Precomputed light

x

Surface color

$=$



"lit" surface

Images from: http://zanir.wz.cz/?p=56&lang=en

- Multiply two textures component-wise

Light Map - Fixed Function OpenGL

- *Application code making OpenGL calls*

```
GLuint lightMap;
GLuint surfaceMap;

glActiveTexture(GL_TEXTURE0);
glEnable(GL_TEXTURE_2D);
glBindTexture(GL_TEXTURE_2D, lightMap);
glTexEnvi(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE);

glActiveTexture(GL_TEXTURE1);
glEnable(GL_TEXTURE_2D);
glBindTexture(GL_TEXTURE_2D, surfaceMap);
glTexEnvf(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE);

glDrawArrays(...);
```

Light Map - Fixed Function OpenGL

- *Application code making OpenGL calls*

```
GLuint lightMap;
GLuint surfaceMap;

glActiveTexture(GL_TEXTURE0);
glEnable(GL_TEXTURE_2D);
glBindTexture(GL_TEXTURE_2D, lightMap);
glTexEnvi(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE);

glActiveTexture(GL_TEXTURE1);
glEnable(GL_TEXTURE_2D);
glBindTexture(GL_TEXTURE_2D, surfaceMap);
glTexEnvf(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE);

glDrawArrays(...);
```

Tell fixed function we are using texture mapping

Tell fixed function how to combine textures

Light Map Shader in GLSL

- Write a fragment shader in GLSL

```
#version 330

uniform sampler2D lightMap;
uniform sampler2D surfaceMap;

in vec2 fs_TxCoord;
out vec3 out_Color;

void main(void)
{
    float intensity = texture2D(lightMap, fs_TxCoord).r;
    vec3 color = texture2D(surfaceMap, fs_TxCoord).rgb;
    out_Color = intensity * color;
}
```

Light Map Shader in GLSL

- Write a fragment shader in GLSL

```
#version 330

uniform sampler2D lightMap;
uniform sampler2D surfaceMap;

in vec2 fs_TxCoord;
out vec3 out_Color;

void main(void)
{
    float intensity = texture2D(lightMap, fs_TxCoord).r;
    vec3 color = texture2D(surfaceMap, fs_TxCoord).rgb;
    out_Color = intensity * color;
}
```

GLSL version 3.3

Textures (input)

Per-fragment input

shader output

one channel intensity

three channel color

modulate

Switching to GLSL Shaders

- *Recall the fixed function light map in C/C++*
  - *What code can be eliminated?*

```
GLuint lightMap;
GLuint surfaceMap;

glActiveTexture(GL_TEXTURE0);
glEnable(GL_TEXTURE_2D);
glBindTexture(GL_TEXTURE_2D, lightMap);
glTexEnvi(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE);

glActiveTexture(GL_TEXTURE1);
glEnable(GL_TEXTURE_2D);
glBindTexture(GL_TEXTURE_2D, surfaceMap);
glTexEnvf(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE);

glDrawArrays(...);
```

Switching to GLSL Shaders

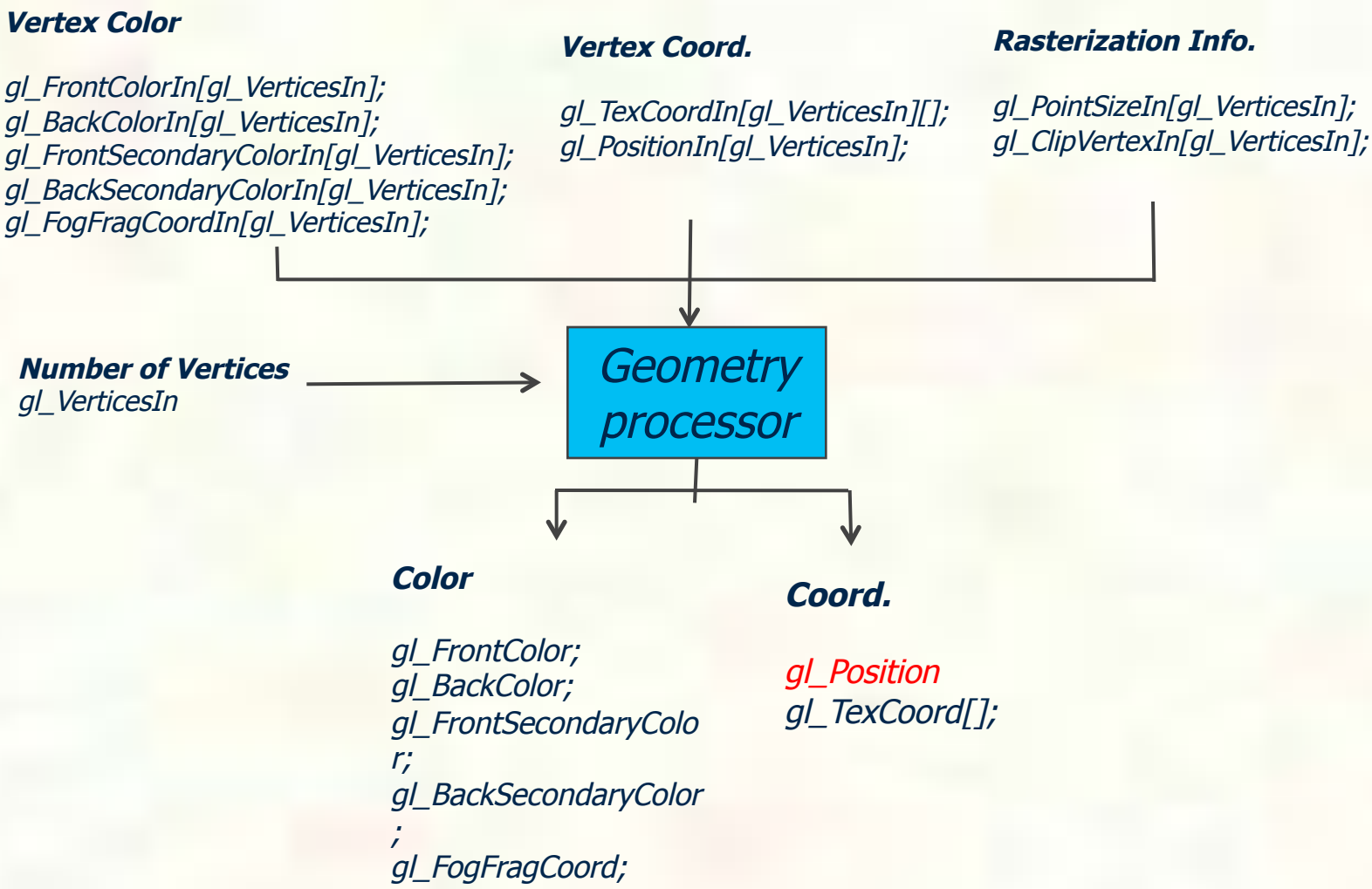
- *Added code to use GLSL shaders*

```
GLuint lightMap;
GLuint surfaceMap;
GLuint program;

glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE_2D, lightMap);

glActiveTexture(GL_TEXTURE1);
glBindTexture(GL_TEXTURE_2D, surfaceMap);

glUseProgram(program);
glDrawArray(...);
```

Careful: What's not shown

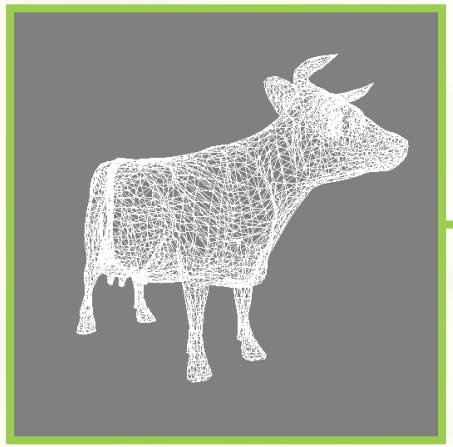
- This example cuts a number of corners
- The example leaves out code for
  - Initializing and loading the image data for the two textures
  - The vertex shader that outputs the varying fs_TxCoord texture coordinate set
  - GLSL shader compilation and linking code to create the program object
  - Setting the sampler units of lightMap and surfaceMap to point at texture units 1 and 2
    - Use glUniform1i for this

Geometry Shaders



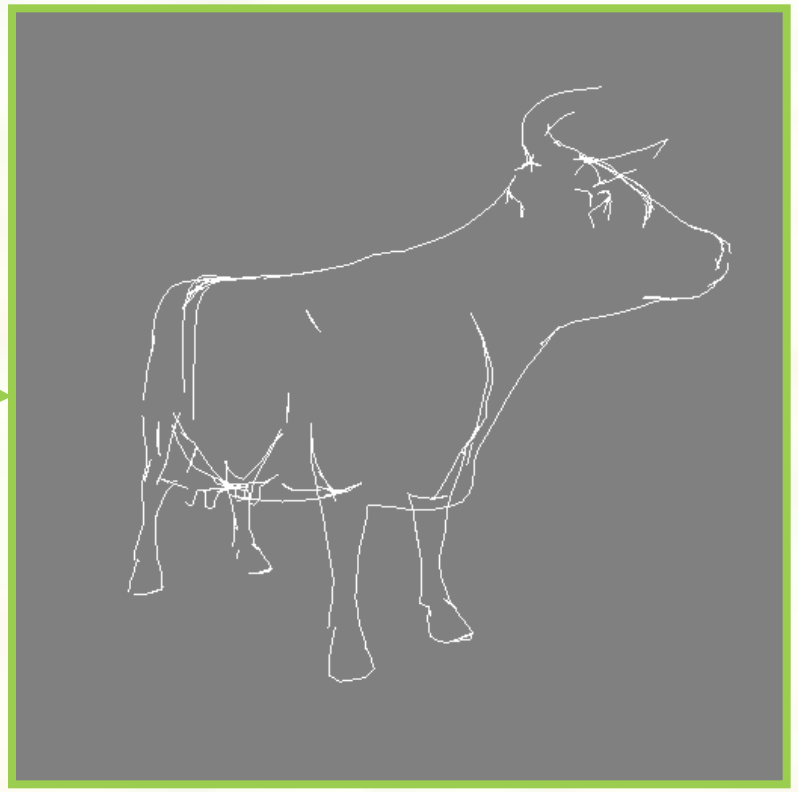
Silhouette Rendering

- *Uses geometry shader*



Complete mesh

silhouette edge detection geometry shader

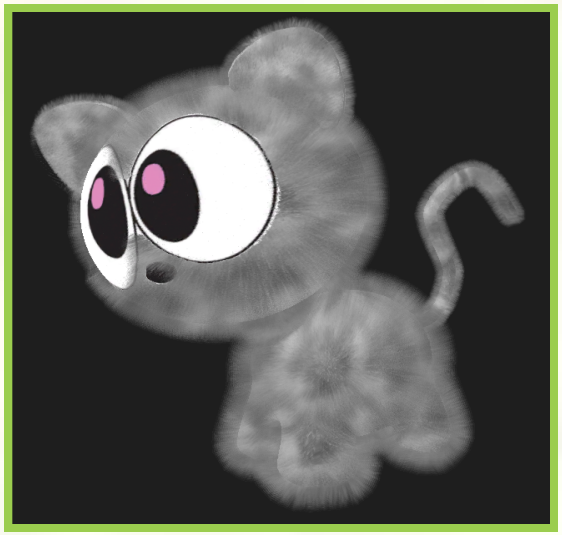


Silhouette edges

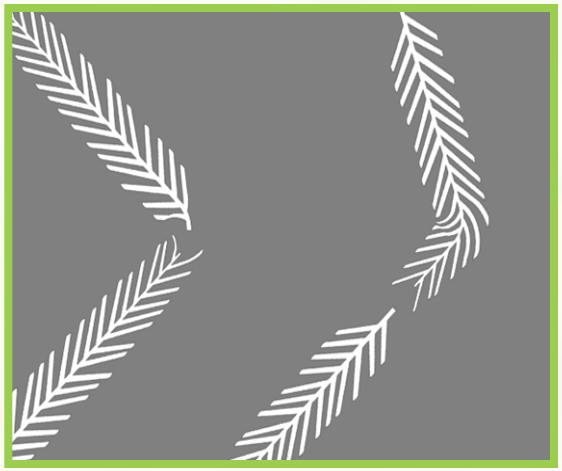
Useful for non-photorealistic rendering

Mimics artistic sketching

More Geometry Shader Examples



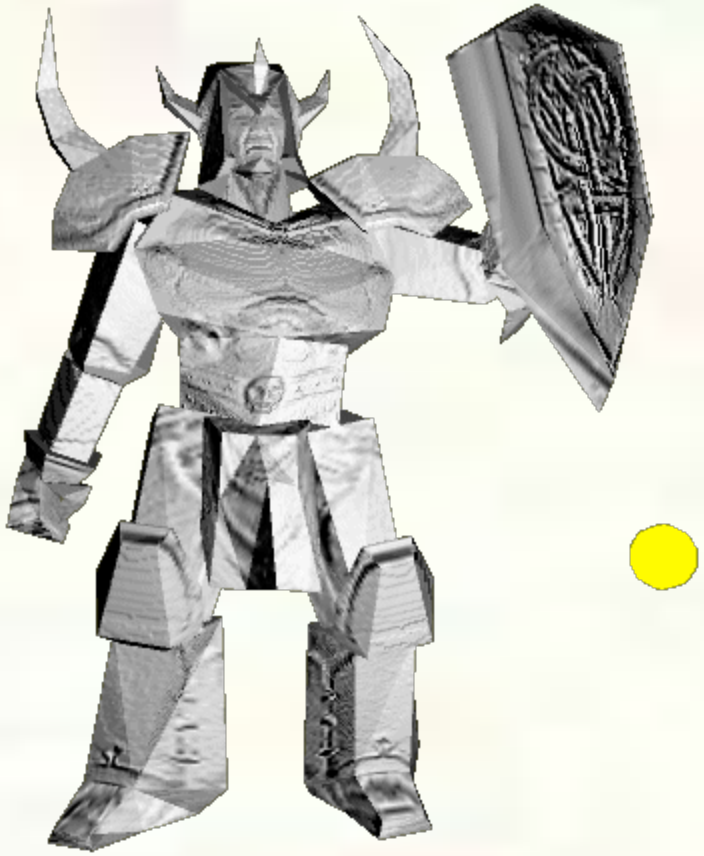
Generate shells for fur rendering



Generate fins for lines

Shimmering point sprites

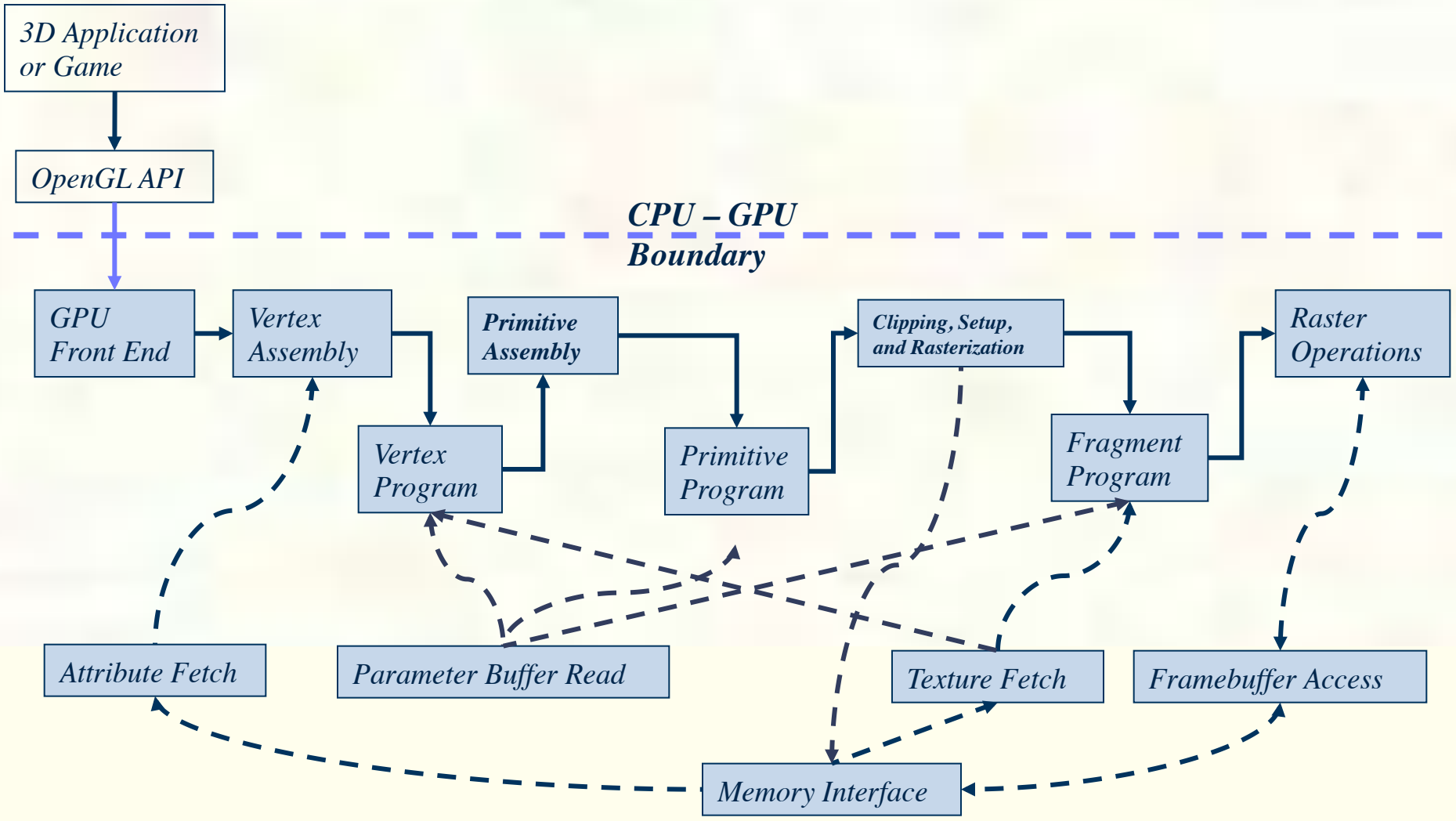
Geometry shader and per-vertex normals



Setup without per-vertex normals, relying on normalized gradients only; faceted look

Setup with per-vertex normals; smoother lighting appearance

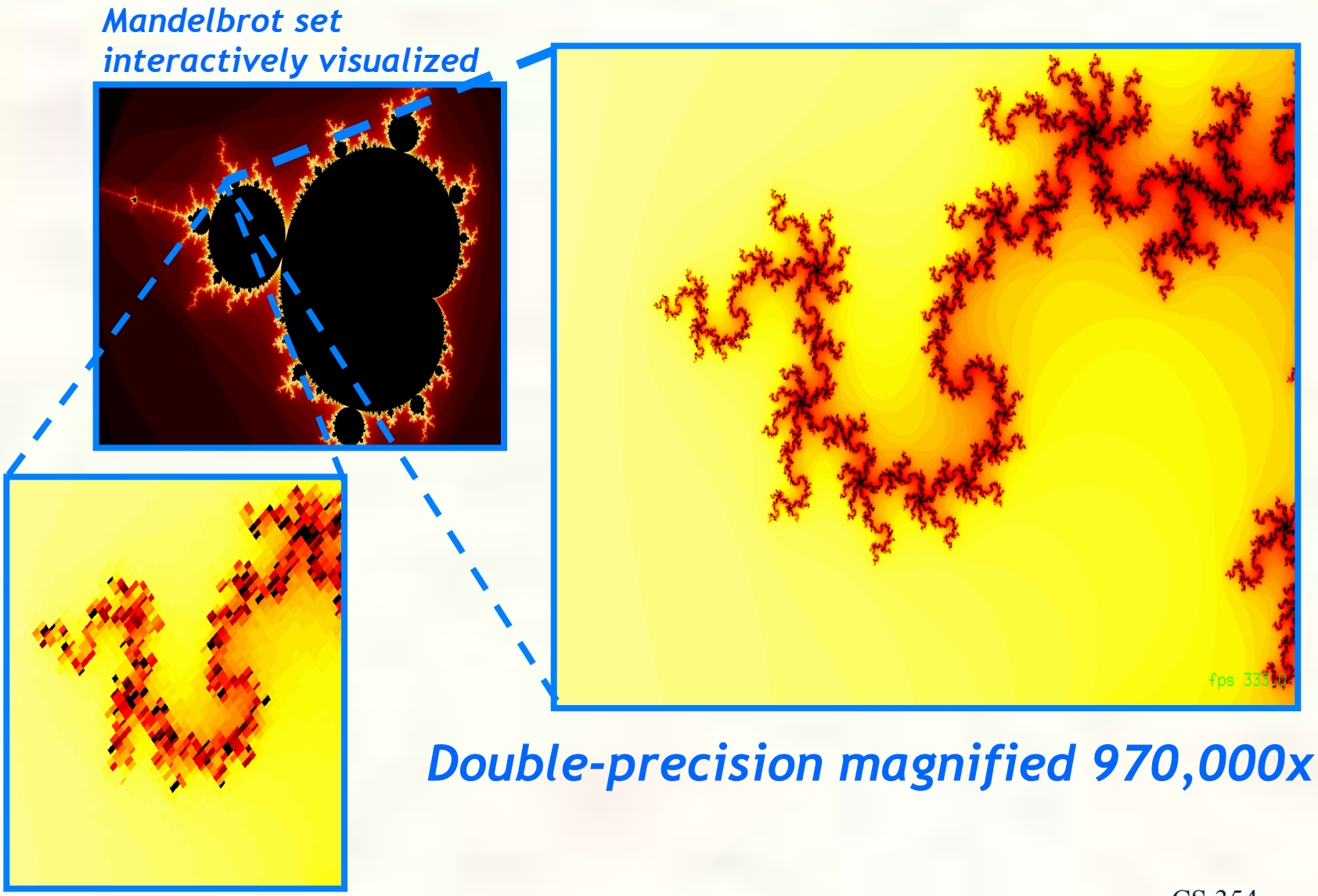
OpenGL 3.0 View of Hardware



OpenGL 4.0 Double-Precision

- Double-precision data types
  - Scalar double
  - Vector dvec4, etc
  - Matrix dmat3 (3x3), dmat4x2, etc.
  - Doubles can reside in buffer objects
- Double-precision operations
  - Multiply, add, multiply-add (MAD)
  - Relational operators, including vector comparisons
  - Absolute value
  - Minimum, maximum, clamping, etc.
  - Packing and unpacking
- No support for double-precision angle, trigonometric, or logarithmic functions

Double Precision in OpenGL Shaders



Mandelbrot Shaders Compared

Single-precision

mat2x3
vec2
vec3

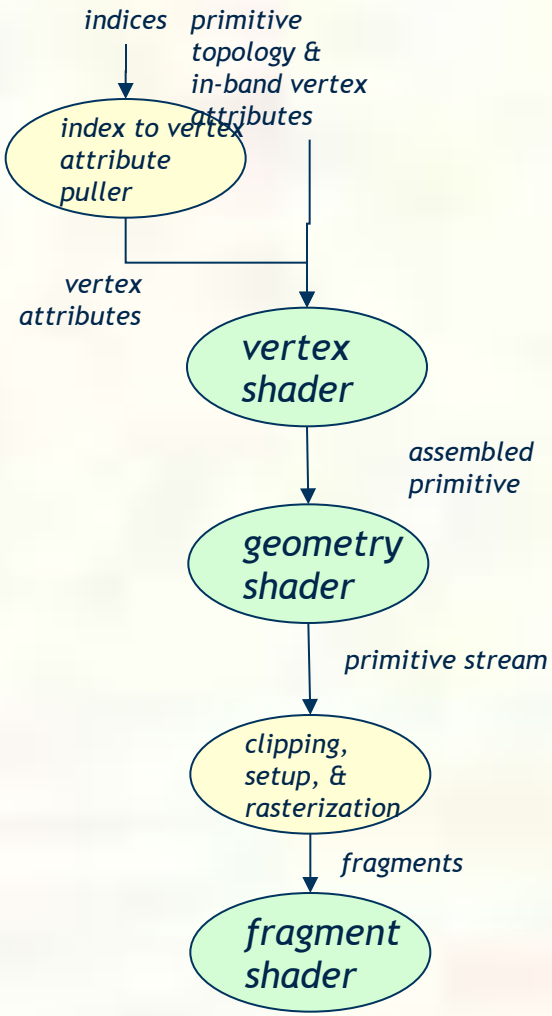
```
#version 400 compatibility

in vec2 position;
out vec4 color;

uniform float max_iterations;
uniform sampler1D lut;
uniform mat2x3 matrix;

float mandel(vec2 c)
{
    vec2 z = vec2(0.0);
    float iterations = 0.0;
    while(iterations < max_iterations)  {
        vec2 z2 = z*z;
        if (z2.x + z2.y > 4.0)
            break;
        z = vec2(z2.x - z2.y, 2.0 * z.x * z.y) + c;
        iterations++;
    }
    return iterations;
}

void main()
{
    vec2 pos = vec2(dot(matrix[0],vec3(position,1)),
                    dot(matrix[1],vec3(position,1)));

    float iterations = mandel(pos);

    // False-color pixel based on iteration
    // count in look-up table
    float s = iterations / max_iterations;
    color = texture(lut, s);
}
```

Double-precision

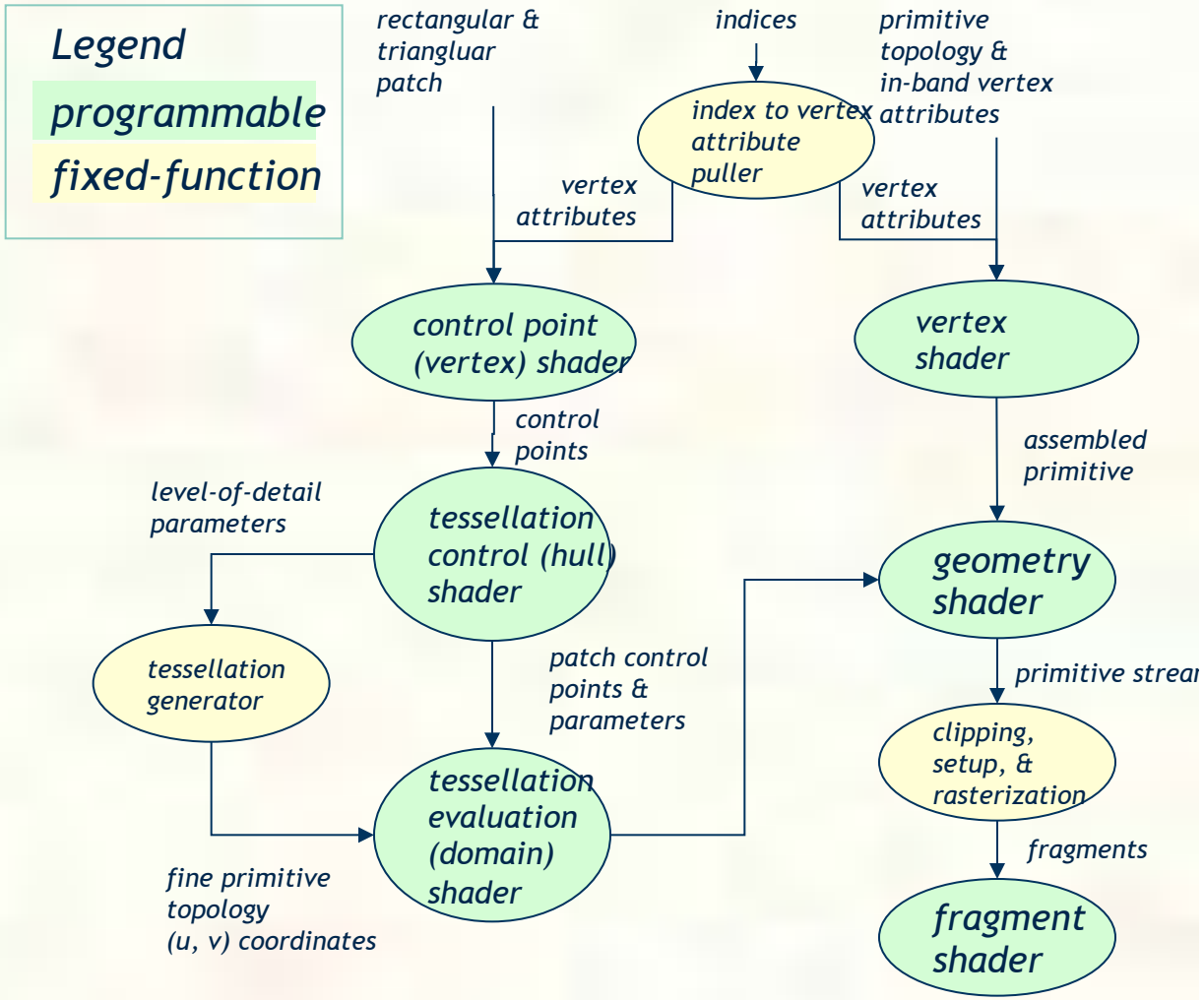
dmat2x3
dvec2
dvec3

```
#version 400 compatibility

in vec2 position;
out vec4 color;

uniform float max_iterations;
uniform sampler1D lut;
uniform dmat2x3 matrix;

float mandel(dvec2 c)
{
    dvec2 z = dvec2(0.0);
    float iterations = 0.0;
    while(iterations < max_iterations)  {
        dvec2 z2 = z*z;
        if (z2.x + z2.y > 4.0)
            break;
        z = dvec2(z2.x - z2.y, 2.0 * z.x * z.y) + c;
        iterations++;
    }
    return iterations;
}

void main()
{
    dvec2 pos = dvec2(dot(matrix[0],dvec3(position,1)),
                      dot(matrix[1],dvec3(position,1)));

    float iterations = mandel(pos);

    // False-color pixel based on iteration
    // count in look-up table
    float s = iterations / max_iterations;
    color = texture(lut, s);
}
```

Programmable Tessellation Data Flow

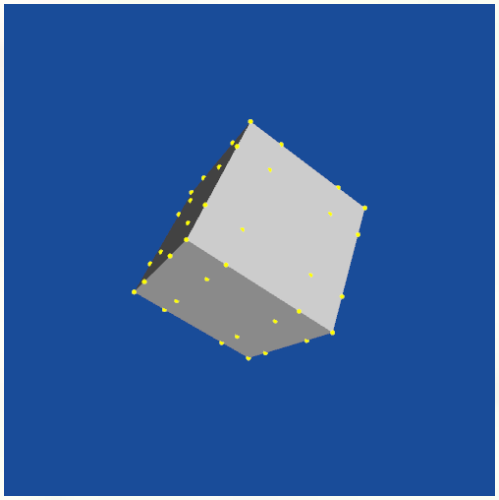


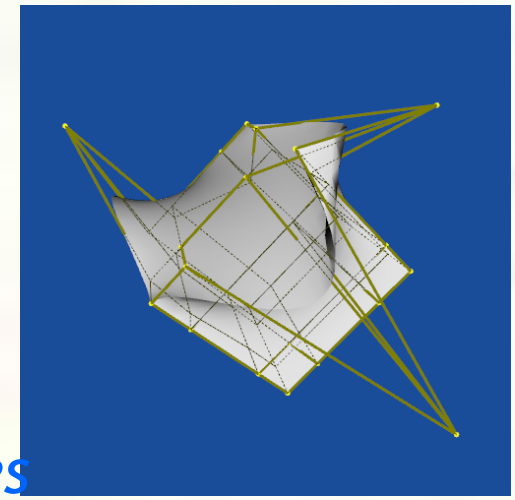
OpenGL 3.2



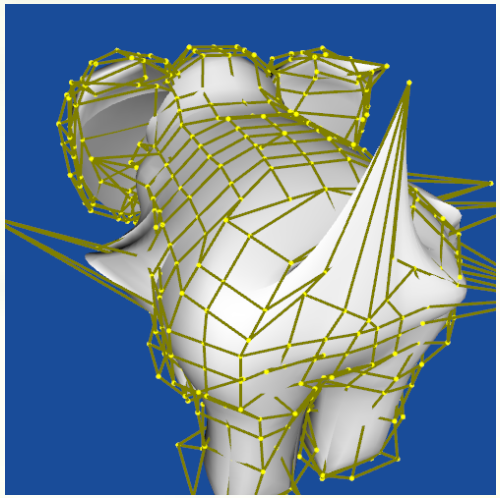
OpenGL 4.0 added tessellation shaders

Surfaces Determined by Control Points

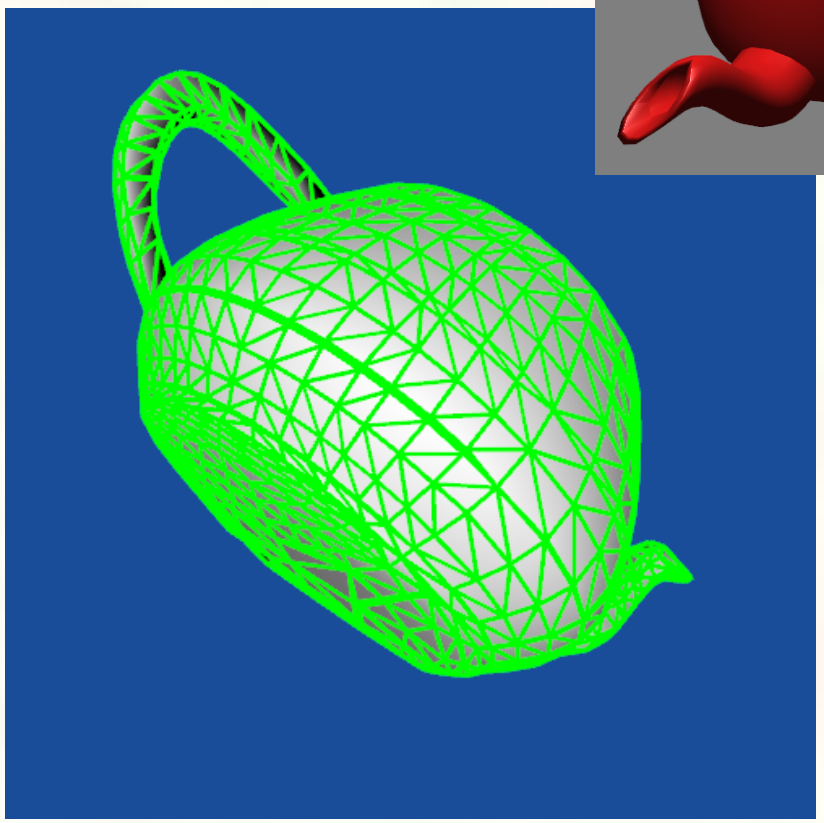


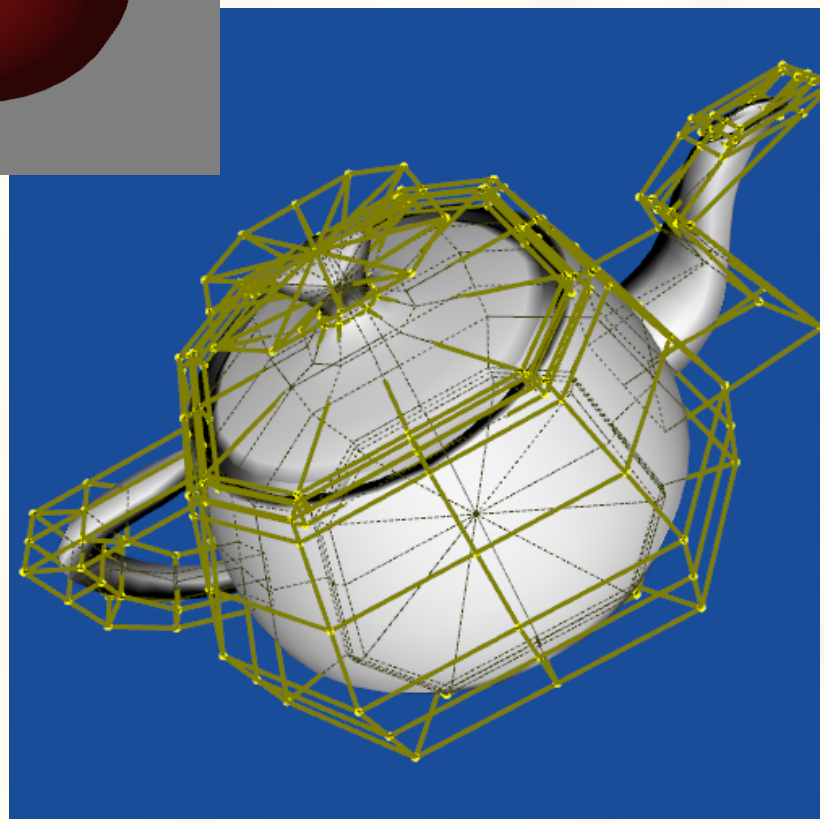


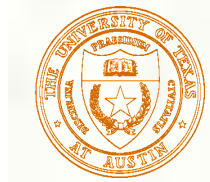
Moving control points displaces the evaluated surfaces



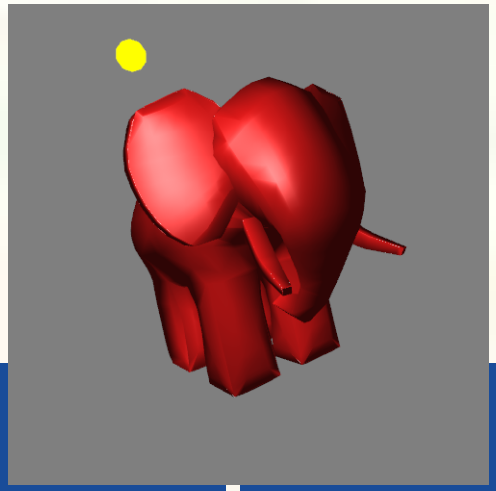
Utah Teapot: Bicubic Patch Mesh

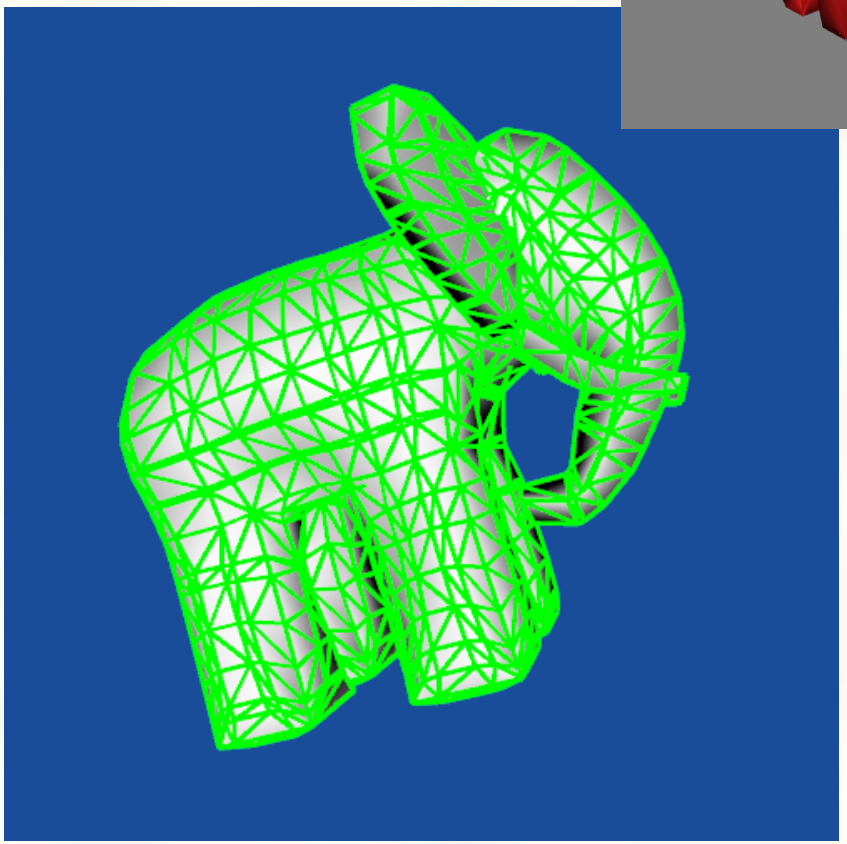


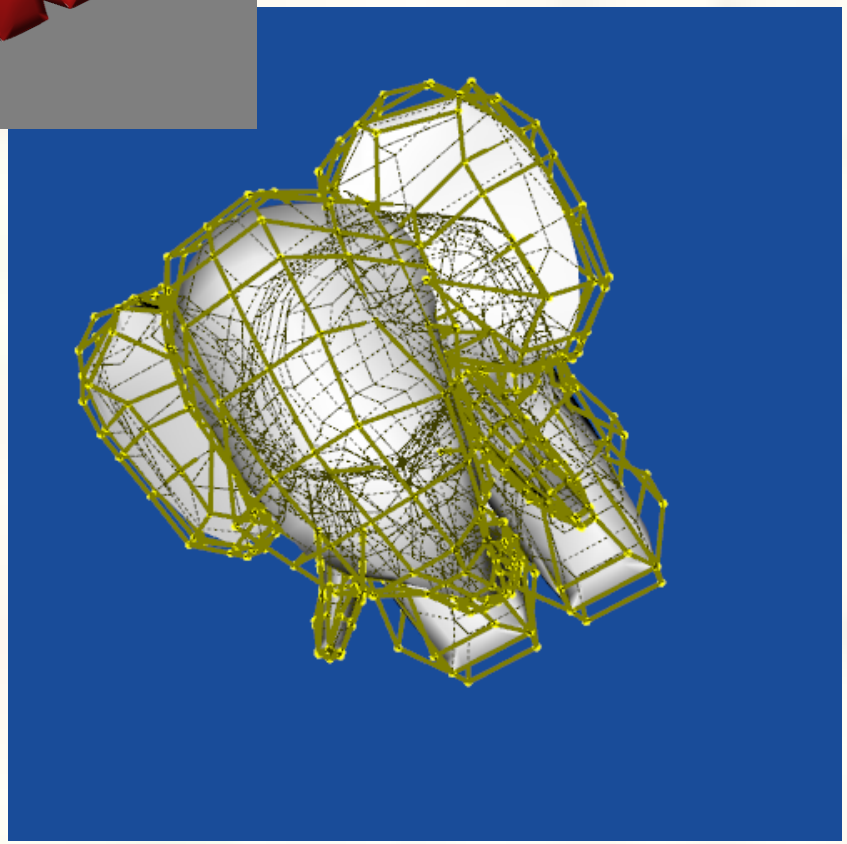




Ed Catmull's Gumbo







Take Away Information

- Shading gets complicated
  - High-level shading languages have completely obviated the need for the assembly level shading
  - GLSL is the OpenGL Shading Language
  - But Cg and HLSL are also widely used
- Multiple programmable domains in pipeline
  - Vertex and fragment domains
  - More recently: primitive (geometry) and tessellation
- You need to learn GLSL for current project
  - Read textbook and web tutorials