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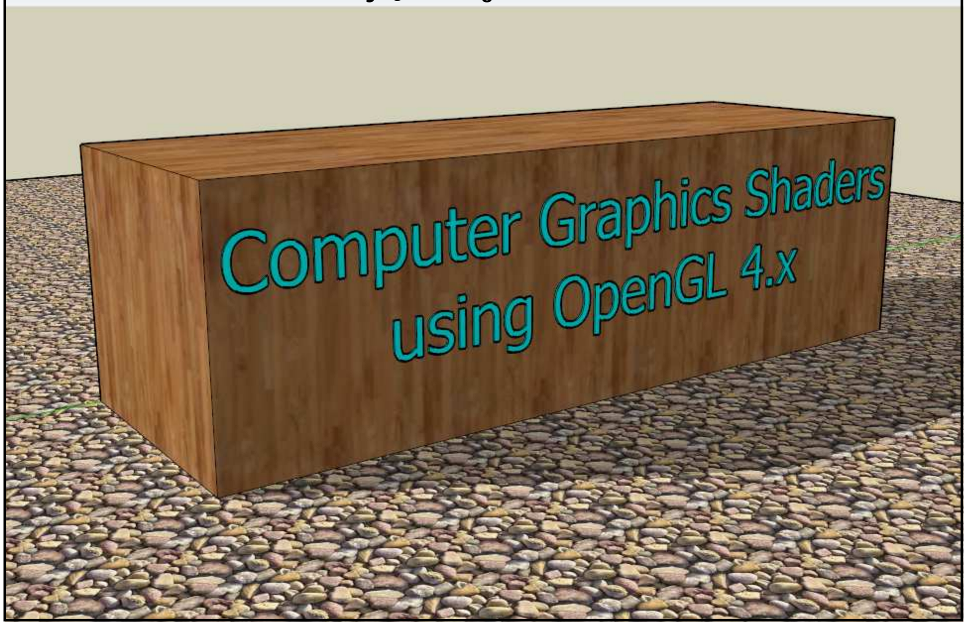


Mike Bailey

- **Professor of Computer Science, Oregon State University**
- **Has worked at Sandia Labs, Purdue University, Megatek, San Diego Supercomputer Center (UC San Diego), and OSU**
- **Has taught over 4,600 students in his classes**
- **mjb@cs.oregonstate.edu**

Schedule

0:00	Welcome and Overview
0:05	Review of the Graphics Pipeline
0:15	Basic Shader Concepts
0:30	Transformations
0:45	Introduction to GLSL
1:00	GLSL Variables
1:15	*glman*
1:30	Vertex Shaders
1:45	Break
2:00	Fragment Shaders
2:15	Image Manipulation
2:30	Textures
2:45	Noise
3:00	Geometry and Tessellation Shaders
3:30	Questions and Answers / Discussion

Two Windows Program Executables and Lots of Shader Files

Many of you have them on the *glman* CD

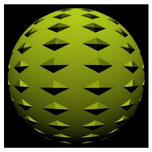
For those who don't, you can get a .zip file of everything by going to:

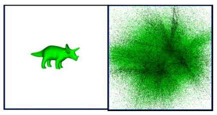
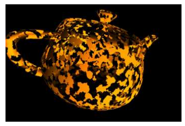
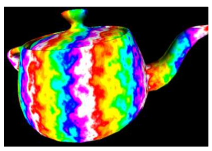
http://cs.oregonstate.edu/~mjb/glman

and following the link that says "SIGGRAPH 2012 Attendees"

Feel free to unload them now on your laptop (all in the same folder) and follow along with the examples.

Why Do We Care About Graphics Shaders?



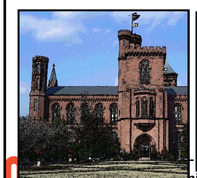
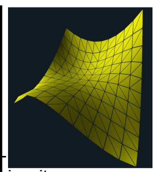
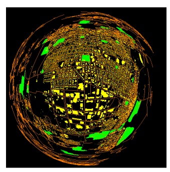
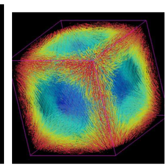
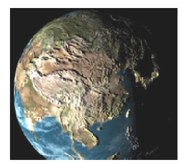

1. You can get effects that are difficult or impossible to get any other way

2. You can get innovative data displays

3. You get a much better understanding of the graphics pipeline

4. The fixed-function pipeline was deprecated in OpenGL Desktop starting with OpenGL 3.0

5. The fixed-function pipeline has completely gone away in OpenGL ES 2.0

Start with Some Terminology

Fragment – a “pixel-to-be”: all of the information about that pixel is available, but the pixel’s color has not yet been determined

Fragment Processor – the part of the graphics pipeline that takes all of the information about a fragment and determines what color to paint there

Fragment Shader – the code you can write to determine the color to paint at a particular fragment

Geometry Shader – the code that you can write to convert or expand one form of geometry into another

GLSL – the OpenGL Shading Language

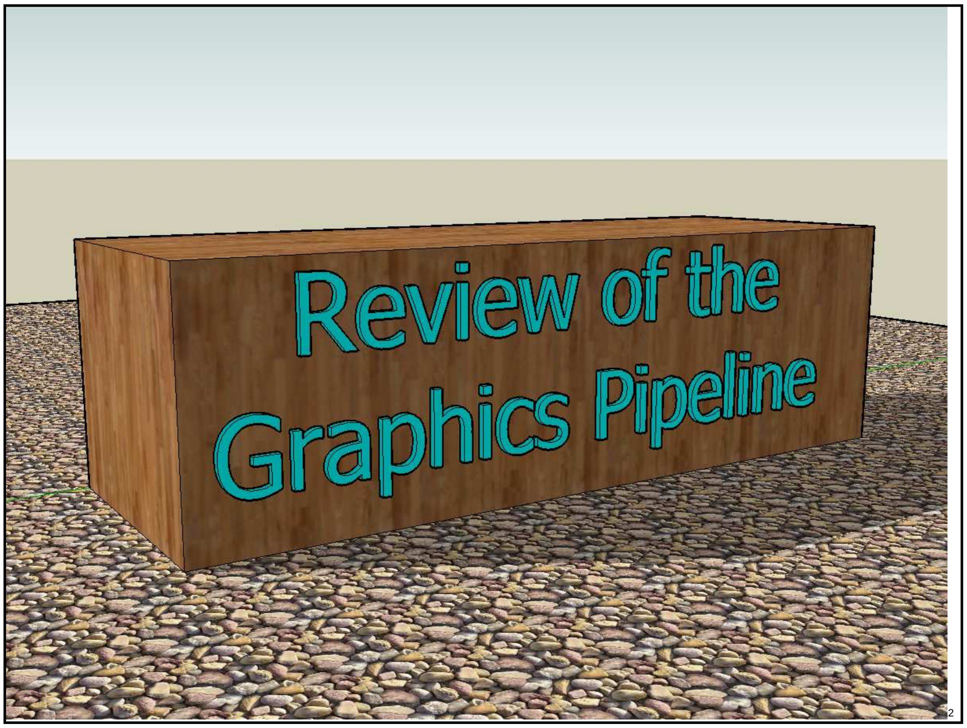
OpenGL – a multi-vendor, multi-platform, multi-operating system graphics API

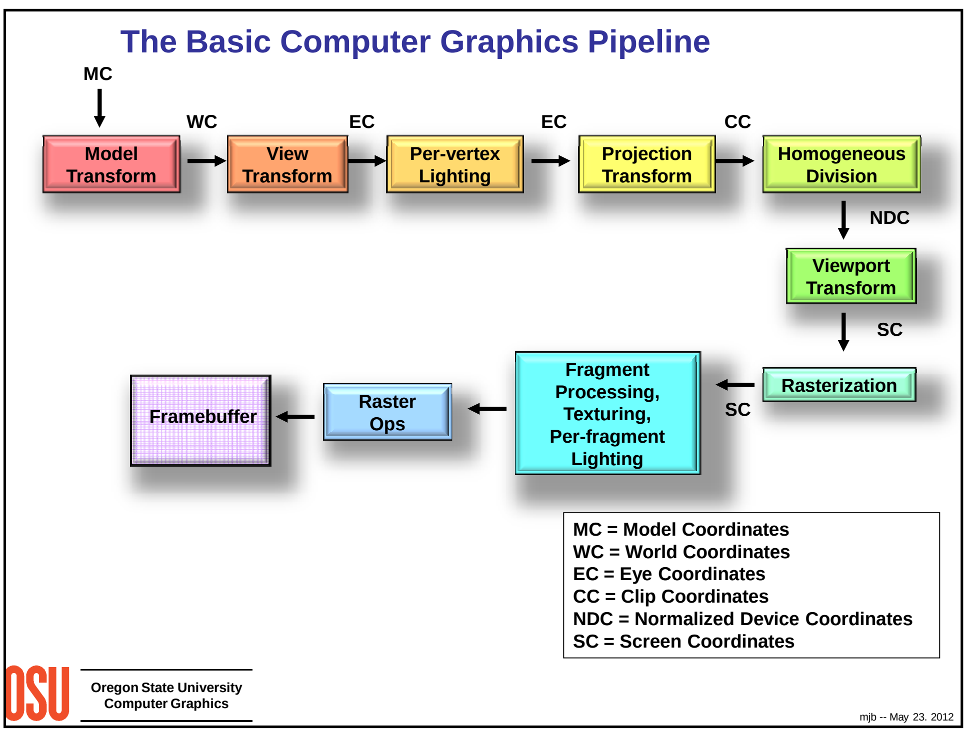
Tessellation Shader – the code that you can write to adaptively convert coarse geometry into much finer geometry

Texture – an image (read or computed) to be attached to a piece of geometry

Vertex Processor – the part of the graphics pipeline that handles vertices, from model coordinates to clipped screen space coordinates

Vertex Shader – the code that you can write to perform the transformations of the vertices and set auxiliary values


Review of the
Graphics Pipeline
2


The Basic Computer Graphics Pipeline
MC
WC
EC
EC
CC
Model Transform
View Transform
Per-vertex Lighting
Projection Transform
Homogeneous Division
NDC
Viewport Transform
SC
Rasterization
SC
Fragment Processing, Texturing, Per-fragment Lighting
Raster Ops
Framebuffer
MC = Model Coordinates
WC = World Coordinates
EC = Eye Coordinates
CC = Clip Coordinates
NDC = Normalized Device Coordinates
SC = Screen Coordinates
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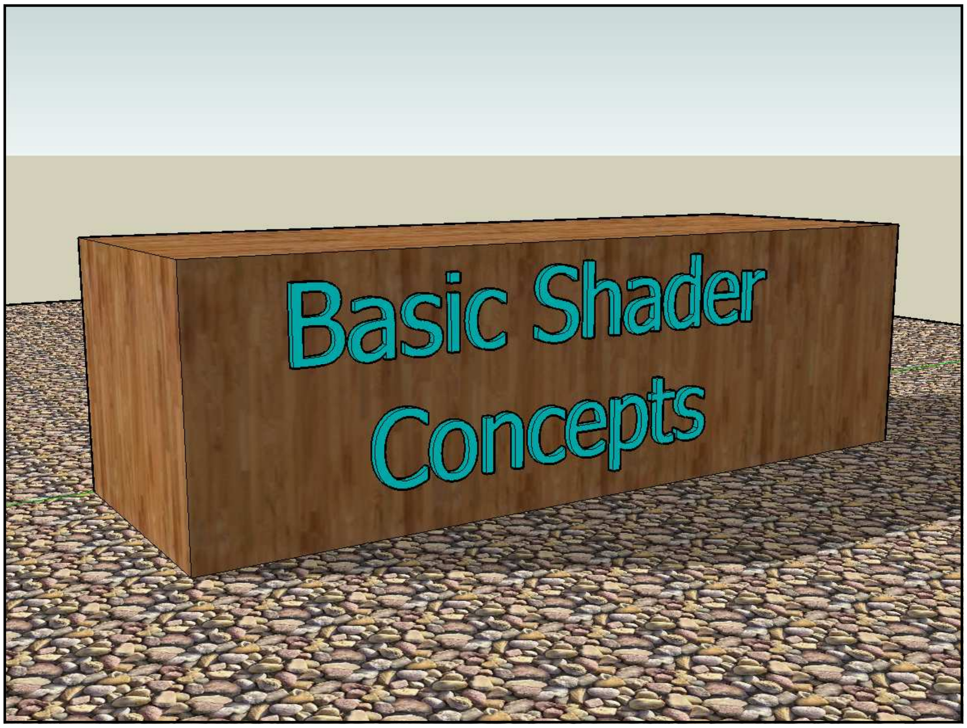
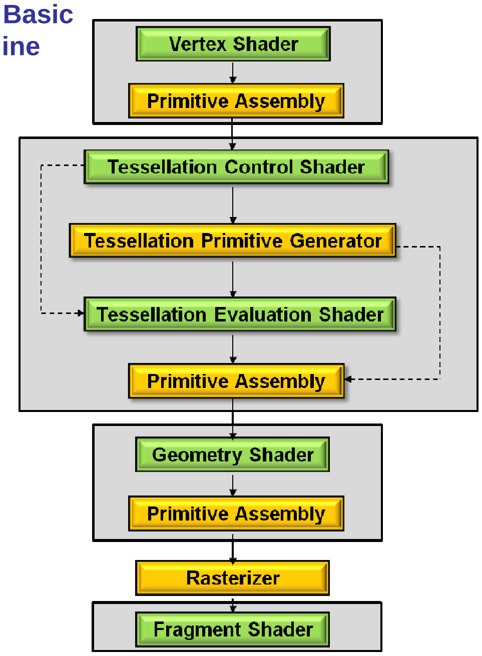


The Shaders' View of the Basic Computer Graphics Pipeline

• In general, you want to have a vertex and fragment shader as a minimum.

• A missing stage is OK. The output from one stage becomes the input of the next stage that is there.

• The last stage before the fragment shader feeds its output variables into the **rasterizer**. The interpolated values then go to the fragment shaders



= Fixed Function

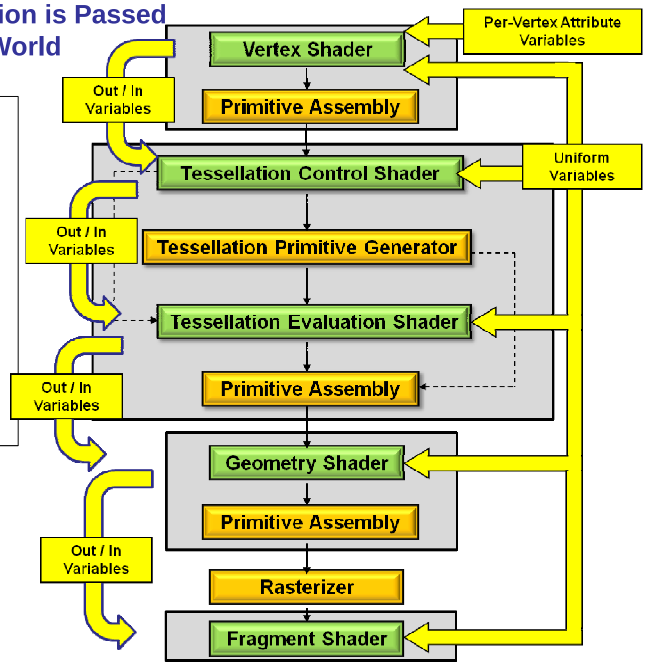
= Programmable

Here's How Information is Passed Around the Shader World

Attribute Variables are passed per-vertex from the application into the vertex shader.

Uniform Variables are passed per-primitive from the application into all shaders. To each shader, they look like read-only global variables.

Out and In Variables are used to pass information from one stage to the next



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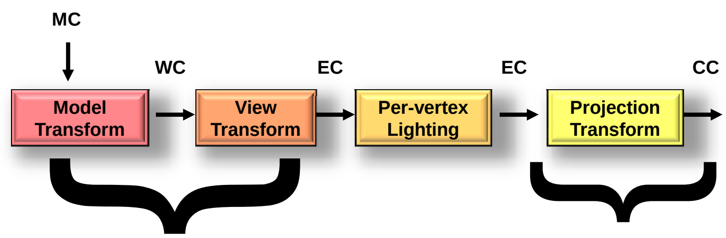
Standard OpenGL gives you Access to Two Transformations



These two are lumped together into a single matrix called the *ModelView Matrix*.

In GLSL, this is called **gl_ModelViewMatrix**

This one is called the *Projection Matrix*.

In GLSL, this is called **gl_ProjectionMatrix**

GLSL also provides you with these two multiplied together.

This is called **gl_ModelViewProjectionMatrix**

MC = Model Coordinates
WC = World Coordinates
EC = Eye Coordinates
CC = Clip Coordinates

Producing Transformed Coordinates and Normals

```
vec4 ModelCoords = gl_Vertex ;

vec4 EyeCoords = gl_ModelViewMatrix * gl_Vertex ;

vec4 ClipCoords = gl_ModelViewProjectionMatrix * gl_Vertex ;
```

GLSL also gives you the matrix to transform normal vectors. It performs the same operations on normal vectors as the ModelView matrix does on vertices.

In GLSL, this is called **gl_NormalMatrix**

It is actually the transpose of the inverse of the ModelView matrix. (Trust us on this…)

```
vec3 TransfNorm = gl_NormalMatrix * gl_Normal ;
```

GLSL Deprecation

Variables like **gl_Vertex** and **gl_ModelViewMatrix** have been built-in to the GLSL language.

However, starting with Desktop OpenGL 3.0, they have been deprecated in favor of you defining your own variables and passing them in from the application yourself. The built-ins still work, but be prepared for them to go away some day. Also, OpenGL ES has already completely *eliminated* the built-ins.

What to do?

In these notes, we have chosen to pretend that we have created variables in an application and have passed them in. So, the previous lines of code would be changed to look like:

```
vec4 ModelCoords = gl_Vertex ;
vec4 ModelCoords = aVertex ;

vec4 EyeCoords = gl_ModelViewMatrix * gl_Vertex ;
vec4 EyeCoords = uModelViewMatrix * aVertex ;

vec4 ClipCoords = gl_ModelViewProjectionMatrix * gl_Vertex ;
vec4 ClipCoords = uModelViewProjectionMatrix * aVertex ;

vec3 TransfNorm = gl_NormalMatrix * gl_Normal ;
vec3 TransfNorm = uNormalMatrix * aNormal ;
```

Why do some of our variables begin with 'a'? Why do some begin with 'u'?

Our Own Variable Naming Convention

With *7* different places GLSL variables can be written, we have decided to adopt a naming convention to help us recognize what variables came from what sources:

Beginning letter(s)	Means that the variable …
a	Is a per-vertex attribute from the application
u	Is a uniform variable from the application
v	Came from the vertex shader
tc	Came from the tessellation control shader
te	Came from the tessellation evaluation shader
g	Came from the geometry shader
f	Came from the fragment shader

This isn't part of "official" OpenGL – it is *our* way of handling the confusion

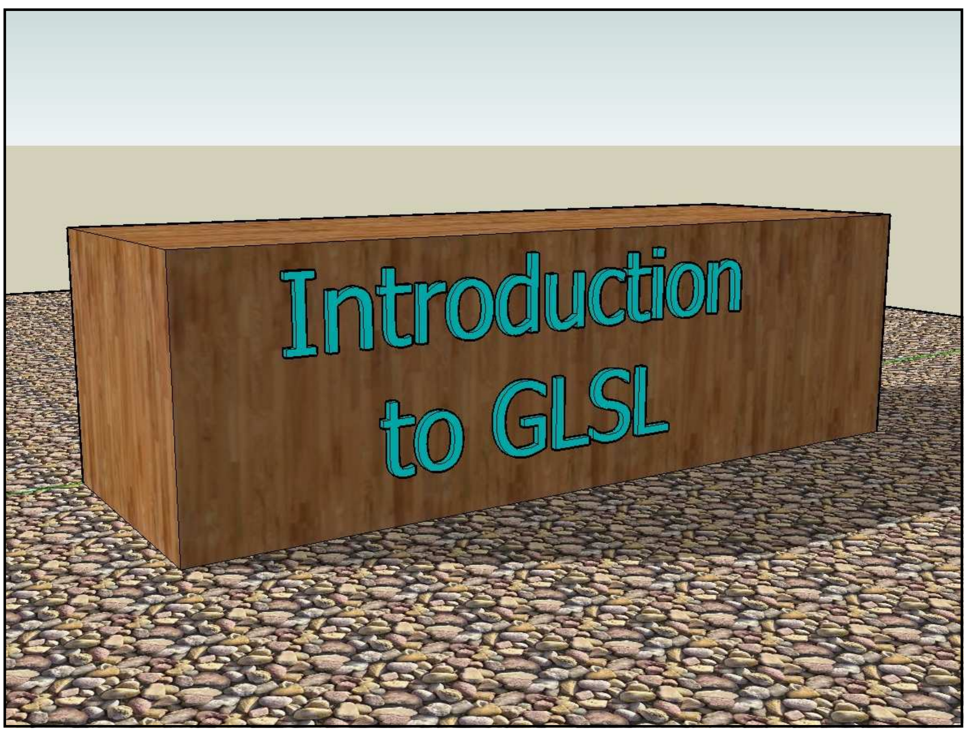
Handling the Transition Now

This is how we equivalence our new names to the deprecated (but still working) ones:

File *gstap.h*

```
// uniform variables:

#define uModelViewMatrix                 gl_ModelViewMatrix
#define uProjectionMatrix                gl_ProjectionMatrix
#define uModelViewProjectionMatrix       gl_ModelViewProjectionMatrix
#define uNormalMatrix                    gl_NormalMatrix
#define uModelViewMatrixInverse          gl_ModelViewMatrixInverse

// attribute variables:

#define aColor                           gl_Color
#define aNormal                          gl_Normal
#define aVertex                          gl_Vertex
#define aTexCoord0                       gl_MultiTexCoord0
#define aTexCoord1                       gl_MultiTexCoord1
#define aTexCoord2                       gl_MultiTexCoord2
#define aTexCoord3                       gl_MultiTexCoord3
#define aTexCoord4                       gl_MultiTexCoord4
#define aTexCoord5                       gl_MultiTexCoord5
#define aTexCoord6                       gl_MultiTexCoord6
#define aTexCoord7                       gl_MultiTexCoord7
```

This isn't part of "official" OpenGL – it is *our* way of handling the transition



GLSL Shaders Look Like C
With Extensions for Graphics:

- Types include int, ivec2, ivec3, ivec4
- Types include float, vec2, vec3, vec4
- Types include mat2, mat3, mat4
- Types include bool, bvec2, bvec3, bvec4
- Types include sampler to access textures
- Vector components are accessed with [index] or with the name sets: .rgba, .xyzw, or.stpq
- Vector components can be "swizzled" (c1.rgba = c2.abgr)
- *discard* operator used in fragment shaders to discard fragments
- Type qualifiers: out, in, const, uniform, flat, noperspective
- Procedure type qualifiers: in, out, inout

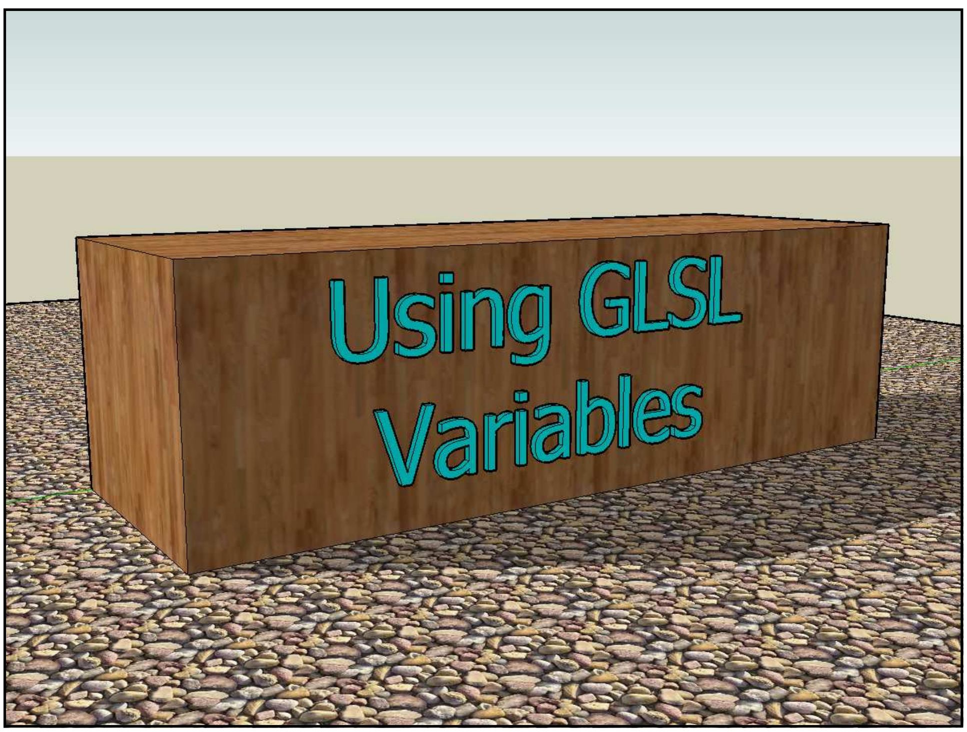
GLSL Shaders Are Missing Some C-isms:

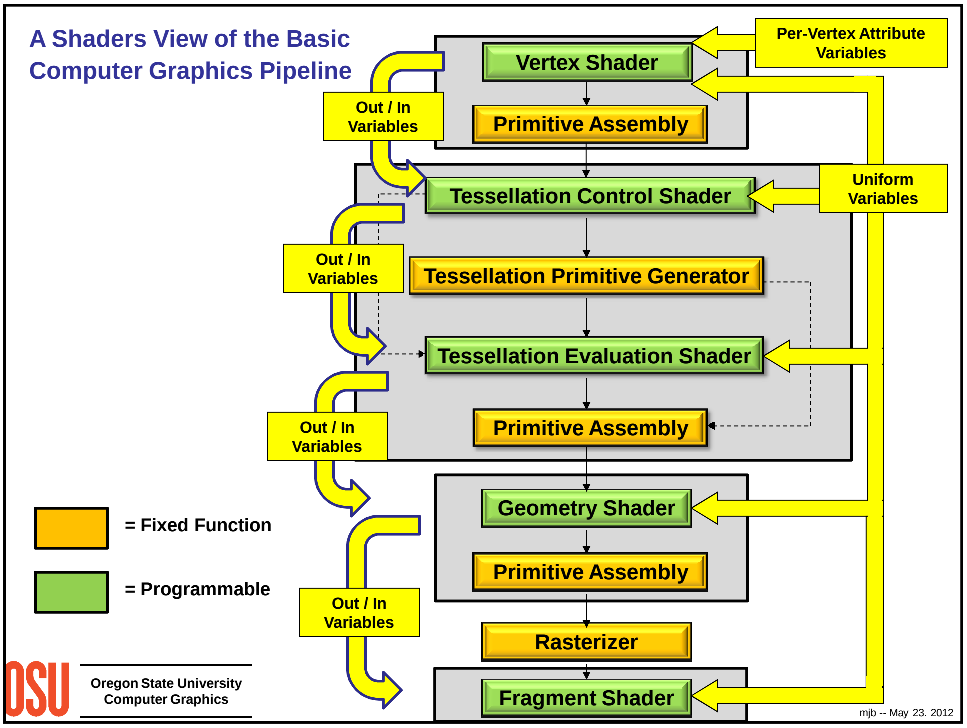
- No type casts (use constructors instead)
- No automatic promotion
- No pointers
- No strings
- No enums

Here’s What a GLSL Vertex Shader Looks Like

```
out  vec4  vColor;
out  float  vX, vY, vZ;
out  float  vLightIntensity;

const vec3 LIGHTPOS = vec3( 0., 0., 10. );

void
main( )
{
		vec3 TransNorm = normalize( uNormalMatrix * aNormal );
		vec3 ECposition = ( uModelViewMatrix * aVertex ).xyz;
		vLightIntensity  = dot( normalize( LIGHTPOS – ECposition ), TransNorm );
		vColor = aColor;
		vec3 MCposition = aVertex.xyz;

		vX = MCposition.x;
		vY = MCposition.y;
		vZ = MCposition.z;

		gl_Position = uModelViewProjectionMatrix * aVertex;
}
```

Don’t worry about the details right now, just take comfort in the fact that it is C-like and that there appears to be a lot of support routines for you to use




A Shaders View of the Basic Computer Graphics Pipeline
Per-Vertex Attribute Variables
Vertex Shader
Out / In Variables
Primitive Assembly
Uniform Variables
Tessellation Control Shader
Out / In Variables
Tessellation Primitive Generator
Tessellation Evaluation Shader
Out / In Variables
Primitive Assembly
Geometry Shader
= Fixed Function
= Programmable
Primitive Assembly
Out / In Variables
Rasterizer
Fragment Shader
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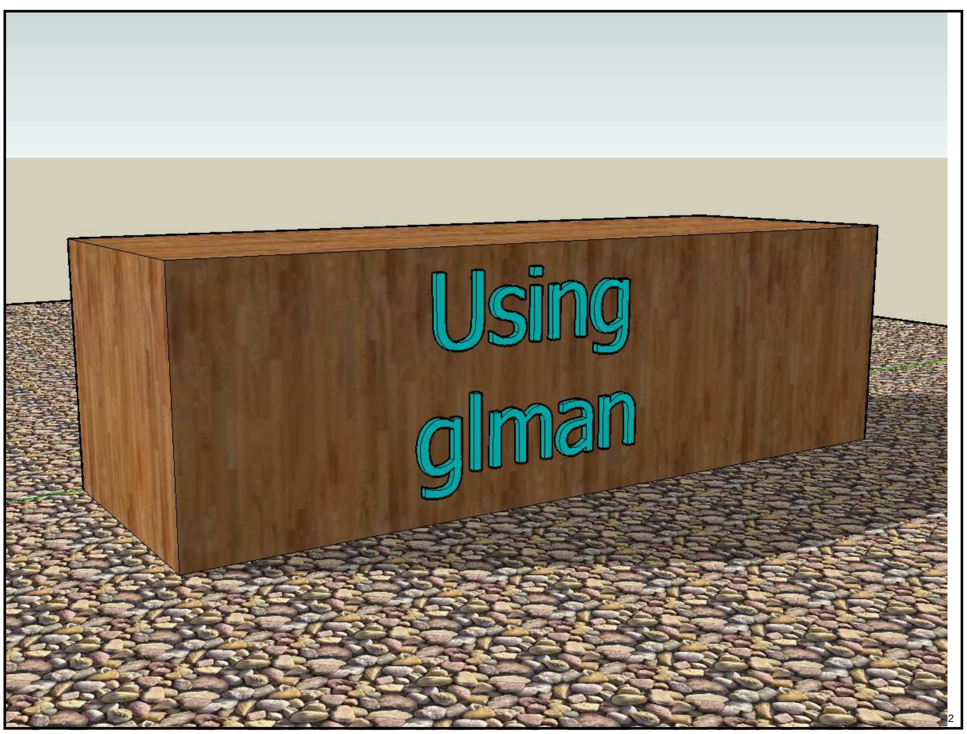
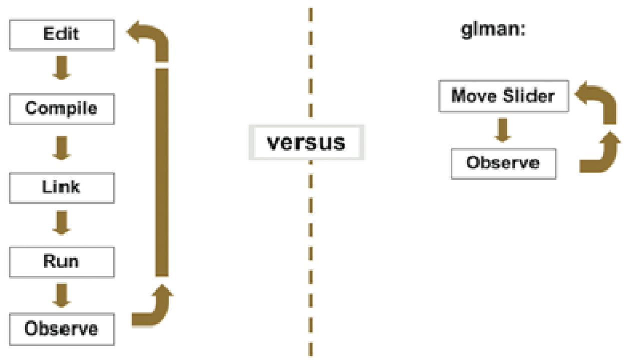

Using
glman

Why use glman?



Writing a program

Using glman

glman User Interface

Load or re-load a **.glib** file

Edit a specific type of file

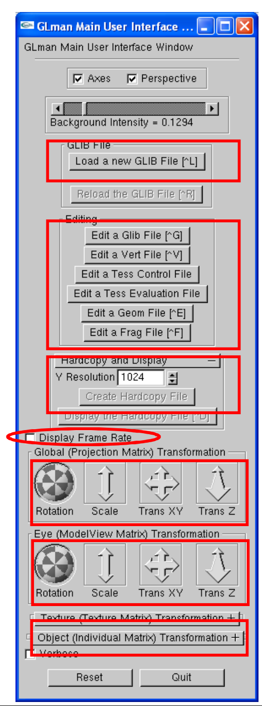
Dump an arbitrary-resolution BMP file

Display the speed of the display (fps)

Transformations in the projection matrix

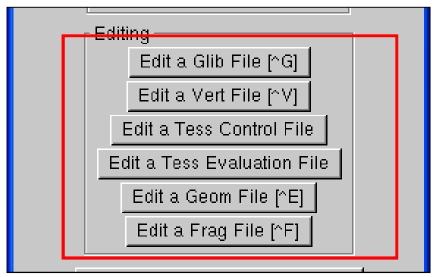
Transformations in the modelview matrix

Allow picking and transformation of individual objects



glman is looking for up to *6* different files

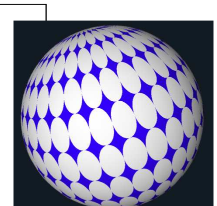
- A **.glib** file that acts as a scene description script
- A **.vert** file that contains the vertex shader
- A **.frag** file that contains the fragment shader
- Optional **.tcs** and **.tes** files that contain the tessellation control shader and the tessellation evaluation shader.
- An optional **.geom** file that contains the geometry shader

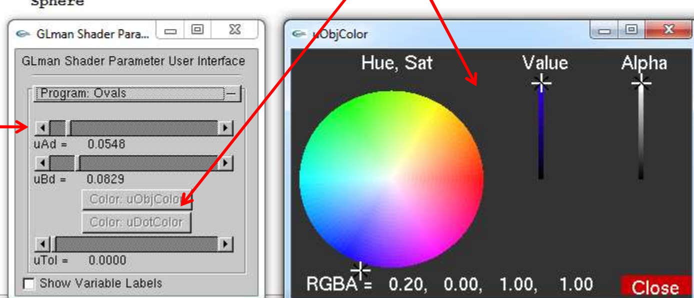


Sample .glib file and the User Interface it creates

```
##OpenGL GLIB
Perspective 70
LookAt  0 0 3    0 0 0    0 1 0

Gstap

Vertex   ovals.vert
Fragment ovals.frag
Program  Ovals                                          \
             uAd <.01 .05 .5>  uBd <.01 .05 .5>         \
             uObjColor { .2 0. 1. }                     \
             uDotColor { 1. 1. 1. }                     \
             uTol <0. 0. 1.>

Sphere
```

Equivalence our names to deprecated names





.glib Range Variables

• Scalar variables are just listed as numbers.

Array variables are enclosed in square brackets, as [ ].

• Range variables are enclosed in angle brackets, as < >. These are scalar variables, and *glman* automatically generates a slider in the Uniform Variable user interface for each range variable so that you can then change this value as *glman* executes. The three values in the brackets are : <min current max>, e.g., <0. 5. 10.>. *glman* will look into your shader program's symbol table to decide if this range variable should be a *float* an *int,* or a *bool*, and will create a slider of the appropriate type.

• Color variables are enclosed in curly brackets, as { }. Color variables may be either RGB or RGBA, as:

{*red green blue*}

or

{*red green blue alpha*}

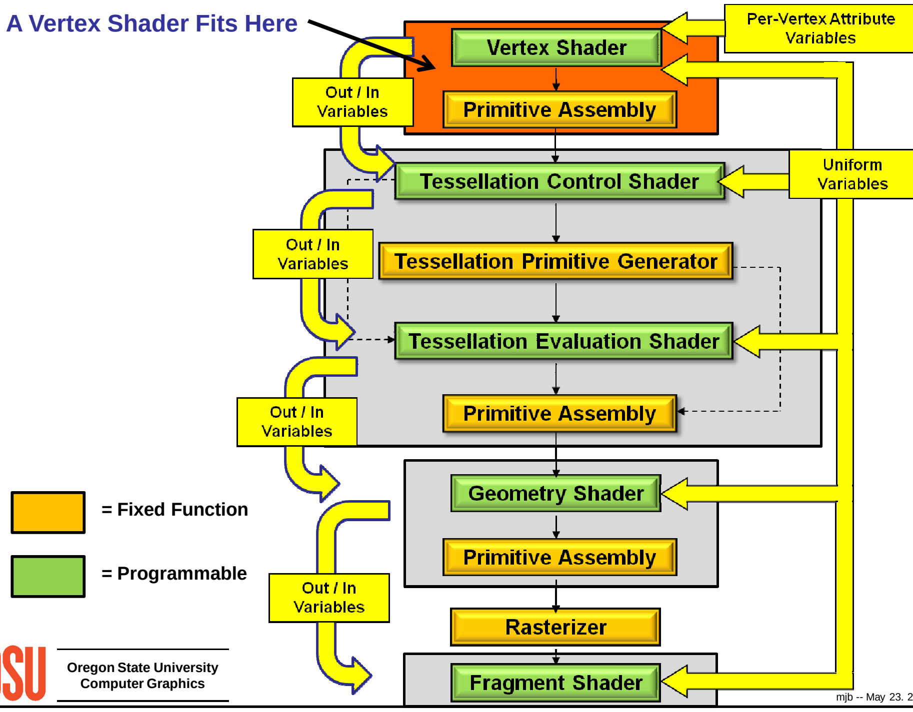
This will generate a button in the UI panel that, when clicked, brings up a color selector window. The color selector allows you to change the value of this color variable as *glman* executes.

• A Boolean variable is available to select or de-select options in your shader. The glman user interface will automatically create a checkbox in the user interface window. In the GLIB file, a Boolean variable has a name and then the word true or the word false inside parenthesis, e.g., "(true)". This is the initial setting of the checkbox.

• Multiple vertex-geometry-fragment-program combinations are allowed in the same GLIB file. If there is more than one combination, then they will appear as separate rollout panels in the user interface. The first program rollout will be open, and all the others will be closed. Open the ones you need when you need them.

2012

A Vertex Shader Fits Here



What does a Vertex Shader Do?

The basic function of a vertex shader is to take the vertex coordinates and other per-vertex information as supplied by the application, and perform whatever arithmetic is required.

At the same time, the vertex shader can perform various analyses based on those vertex coordinates and other data and prepare variable values for later on in the graphics process.

A GLSL Vertex Shader Replaces These Operations:

- Vertex transformations
- Normal transformations
- Normal normalization
- Handling of per-vertex lighting
- Handling of per-vertex colors
- Handling of texture coordinates

A GLSL Vertex Shader Does Not Replace These Operations:

- Frustum clipping
- Homogeneous division
- Viewport mapping
- Backface culling
- Polygon mode
- Polygon offset

Built-in Vertex Shader Variables You Will Use *a Lot*:

vec4 aVertex

vec3 aNormal

vec4 aColor

vec4 aTexCoord*i* (i=0, 1, 2, …)

mat4 uModelViewMatrix

mat4 uProjectionMatrix

mat4 uModelViewProjectionMatrix

mat4 uNormalMatrix

Note: these are *our* names for these variables. The application would either need to pass them into the shaders under these names, or you would need to #define them to their (deprecated) built-in equivalents.

```
// uniform variables:

#define uModelViewMatrix              gl_ModelViewMatrix
#define uProjectionMatrix             gl_ProjectionMatrix
#define uModelViewProjectionMatrix    gl_ModelViewProjectionMatrix
#define uNormalMatrix                 gl_NormalMatrix
#define uModelViewMatrixInverse       gl_ModelViewMatrixInverse

// attribute variables:

#define aColor                        gl_Color
#define aNormal                       gl_Normal
#define aVertex                       gl_Vertex
#define aTexCoord0                    gl_MultiTexCoord0
#define aTexCoord1                    gl_MultiTexCoord1
#define aTexCoord2                    gl_MultiTexCoord2
#define aTexCoord3                    gl_MultiTexCoord3
#define aTexCoord4                    gl_MultiTexCoord4
#define aTexCoord5                    gl_MultiTexCoord5
#define aTexCoord6                    gl_MultiTexCoord6
#define aTexCoord7                    gl_MultiTexCoord7
```

Sample Vertex Shader: Stripes in Model and Eye Coordinates

stripes.glib

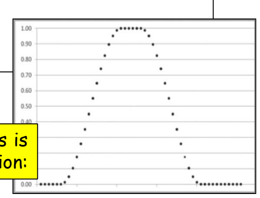
```
uniform bool  uUseEyeCoords;
out vec4      vColor;
out float     vX, vY, vZ;
out float     vLightIntensity;

const vec3 LIGHTPOS = vec3( 0., 0., 10. );

void
main( )
{
        vec3 transNorm = normalize( uNormalMatrix * aNormal );
        vec3 ECposition = ( uModelViewMatrix * aVertex ).xyz;
        vLightIntensity  = dot(normalize( LIGHTPOS - ECposition), transNorm );
        vLightIntensity = abs( vLightIntensity );
        vColor = aColor;
        vec3 MCposition = aVertex.xyz;
        if( uUseEyeCoords )
        {
                vX = ECposition.x;
                vY = ECposition.y;
                vZ = ECposition.z;
        }
        else
        {
                vX = MCposition.x;
                vY = MCposition.y;
                vZ = MCposition.z;
        }
        gl_Position = uModelViewProjectionMatrix * aVertex;
}
```

This is a good example of why we adopted a consistent naming convention !

The Fragment Shader then sets the color based on the X value.

Sample Fragment Shader: Stripes in Model and Eye Coordinates

```
in vec4       vColor;
in float      vX, vY, vZ;
in float      vLightIntensity;

out vec4      fFragColor;

uniform float  uA;
uniform float  uP;
uniform float  uTol;

const vec3 WHITE = vec3( 1., 1., 1. );

void
main( )
{
      float f = fract( uA*vX );
      float t = smoothstep( 0.5-uP-uTol, 0.5-uP+uTol, f )  -  smoothstep( 0.5+uP-uTol, 0.5+uP+uTol, f );

      vec3 color = mix( WHITE, vColor.rgb, t );
      fFragColor= vec4( vLightIntensity*color, 1. );
}
```



This combination of smoothstep( ) functions is known as a "smoothpulse" function:

Sample Vertex Shader:
Stripes in Model and Eye Coordinates

They might (momentarily) look the same, but they don't act the same !

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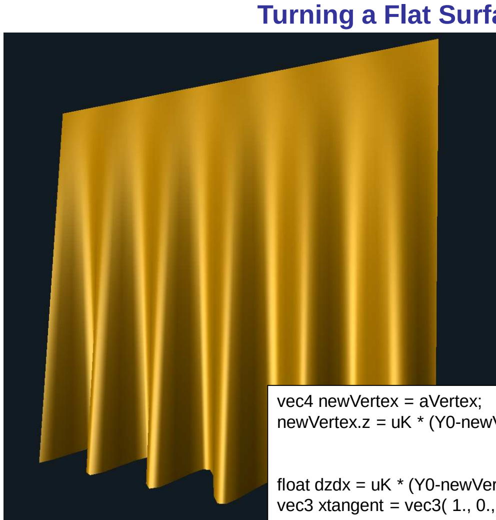
Sample Vertex Shader:
Turning a Flat Surface into Pleats



Producing a new vertex coordinate

Producing a new surface normal

```
vec4 newVertex = aVertex;
newVertex.z = uK * (Y0-newVertex.y) * sin( 2.*PI*newVertex.x/uP );

float dzdx = uK * (Y0-newVertex.y) * (2.*PI/uP) * cos( 2.*PI*newVertex.x/uP );
vec3 xtangent = vec3( 1., 0., dzdx );

float dzdy = -uK * sin( 2.*PI*newVertex.x/uP );
vec3 ytangent = vec3( 0., 1., dzdy );

vec3 newNormal = normalize(  cross( xtangent, ytangent )  );

gl_Position = uModelViewProjectionMatrix * newVertex;
```

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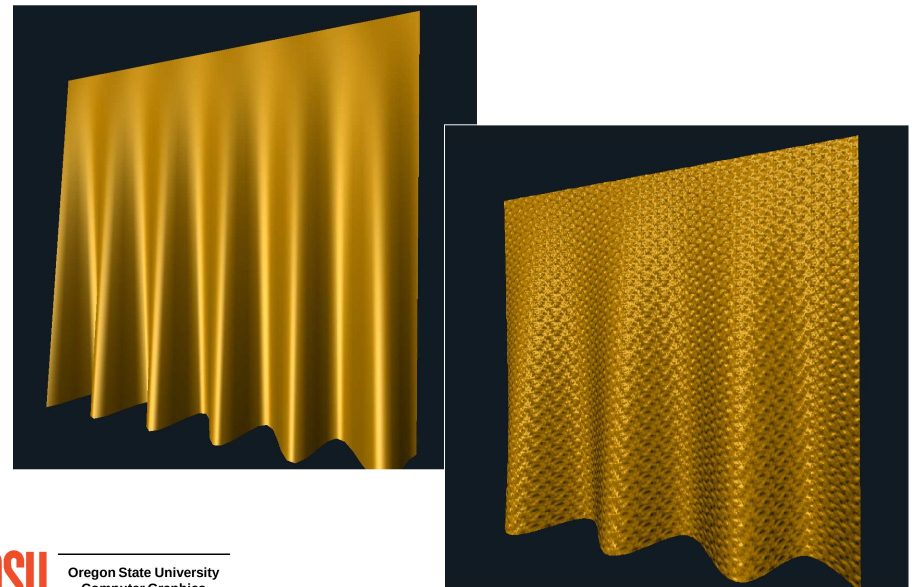
A Gimmick:
Adding Noise in the Fragment Shader



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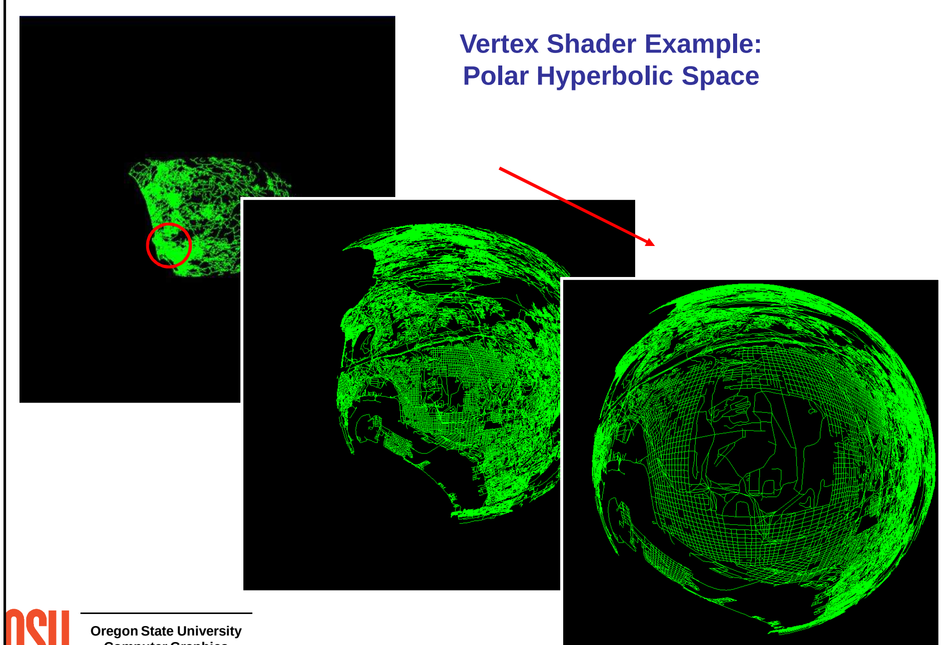

Vertex Shader Example:
Polar Hyperbolic Space

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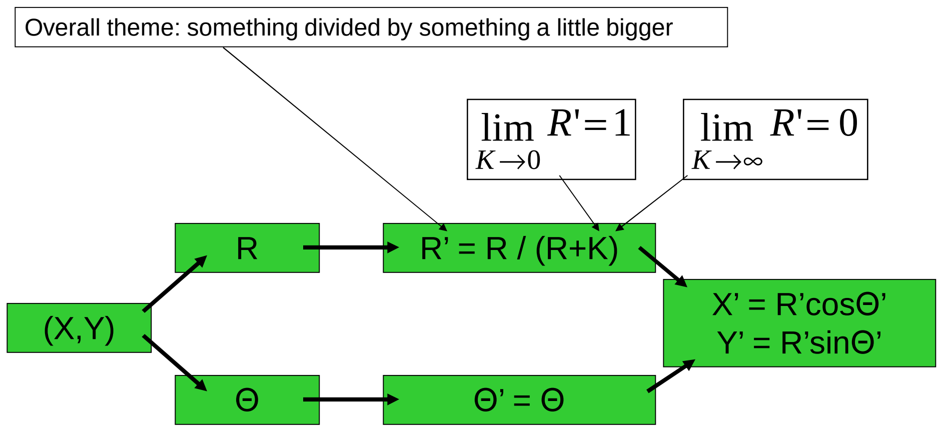
Polar Hyperbolic Equations



Polar Hyperbolic Equations

$$R = \sqrt{X^2 + Y^2}$$

$$\Theta = \tan^{-1}\left(\frac{Y}{X}\right)$$

$$R' = \frac{R}{R + K}$$

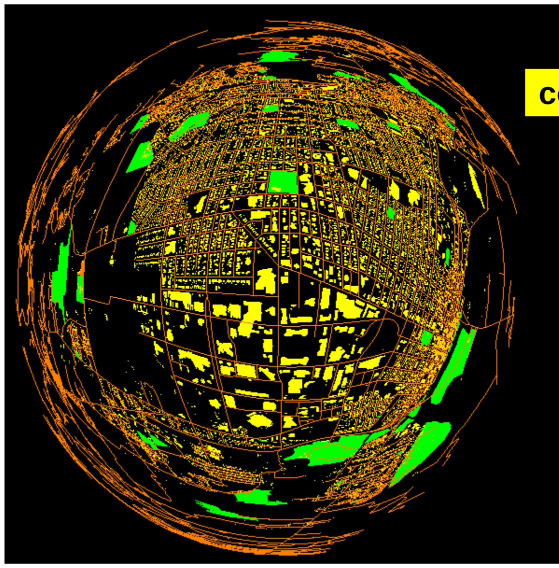
Coordinates moved to outer edge when K = 0

Coordinates moved to center when K = ∞

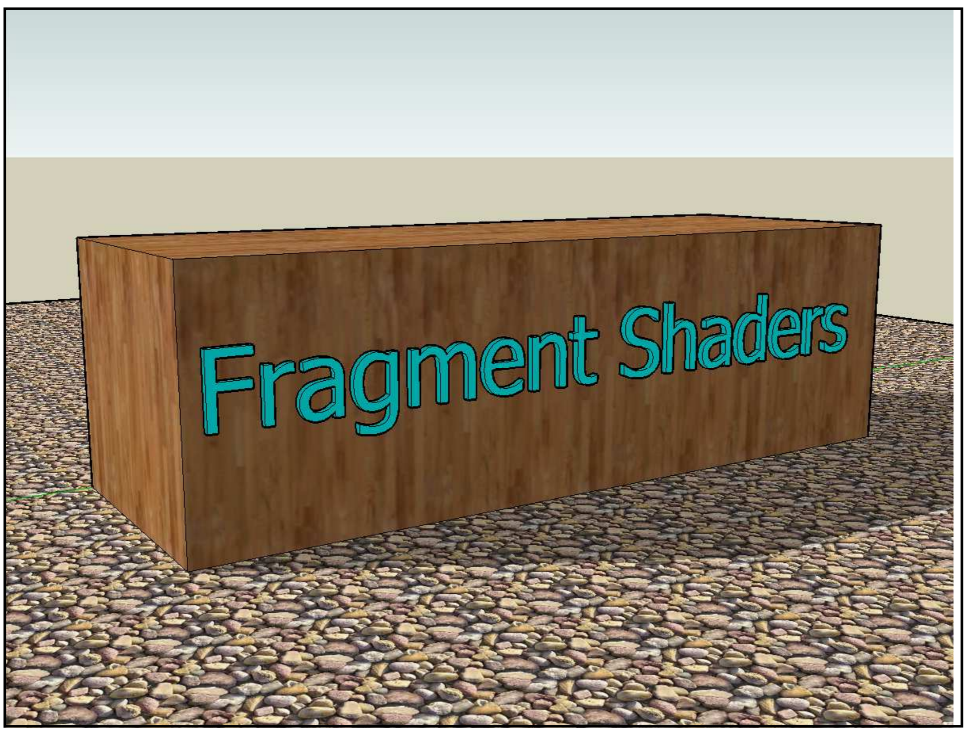
$$X' = R'\cos\Theta = \frac{R}{R+K} \times \frac{X}{R} = \frac{X}{R+K}$$

$$Y' = R'\cos\Theta = \frac{R}{R+K} \times \frac{Y}{R} = \frac{Y}{R+K}$$

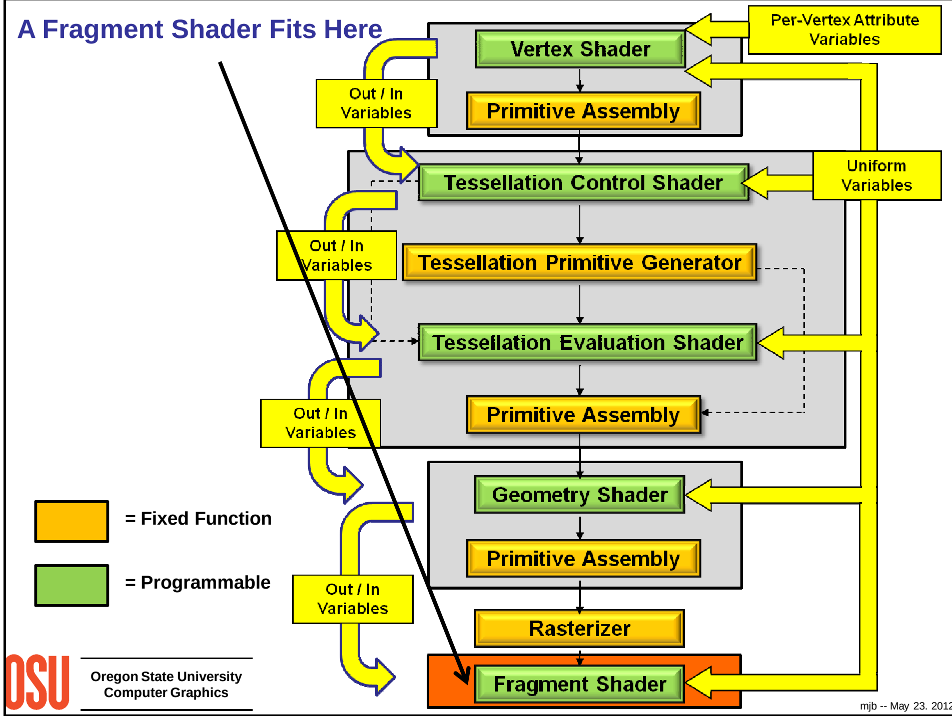
A Good Way to Look at Detailed City Streets, Buildings, Parks



corvallis.glib



A Fragment Shader Fits Here

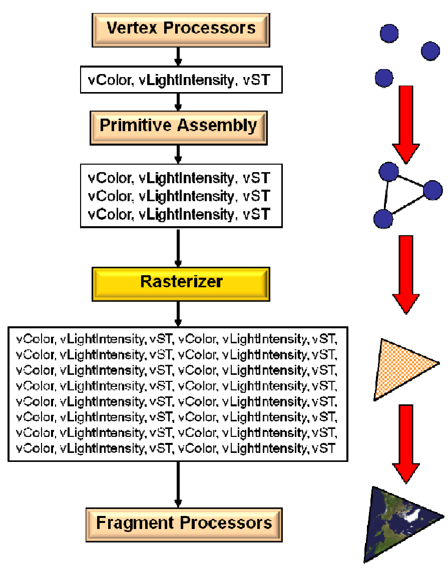


What does a Fragment Shader Do?

The fragment shader starts with the output of the rasterizer. This figure illustrates the rasterizer process, showing how the distinct vertices of a primitive are processed to create the fragments that make up the primitive.

The interpolated quantities, the textures, and the uniform variables are then used to compute the final color of each fragment.

This diagram shows the vertex shaders feeding the rasterizer, but they could also be fed from a geometry or a tessellation shader.



A GLSL Fragment Shader Replaces These Operations:

- Color computation
- Texturing
- Handling of per-pixel lighting
- Fog
- Blending
- Discarding fragments

A GLSL Fragment Shader Does Not Replace These Operations:

- Stencil test
- Z-buffer test
- Stippling

The Fragment Shader Variable You Will Use *a Lot*:

```
out vec4 fFragColor;
```

You can call this whatever you want. This name is our standard.

Simple Fragment Shader: Setting the Color

```
in  float           vLightIntensity;

uniform  vec4       uColor;

out  vec4           fFragColor;

void main(  )
{
        fFragColor= vec4( vLightIntensity * uColor.rgb, 1. );
}
```

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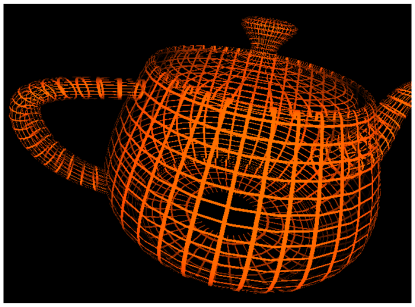
Fragment Shader: Discarding Fragments

```
uniform vec4 uColor;
uniform float  uDensity;
uniform float  uFrequency;

in float  vLightIntensity;
in vec2 vST;

out vec4 fFragColor;

void main( )
{
    vec2 stf = vST * uFrequency;

    if( all( fract( stf ) >= uDensity )  )
        discard;

    fFragColor = vec4( vLightIntensity * uColor.rgb, 1. );
}
```



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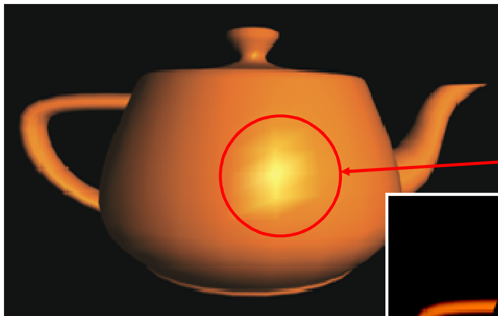
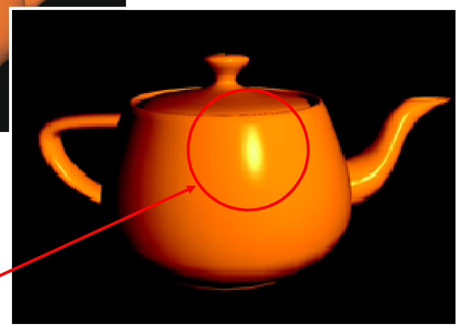
Per-vertex vs. Per-fragment Lighting

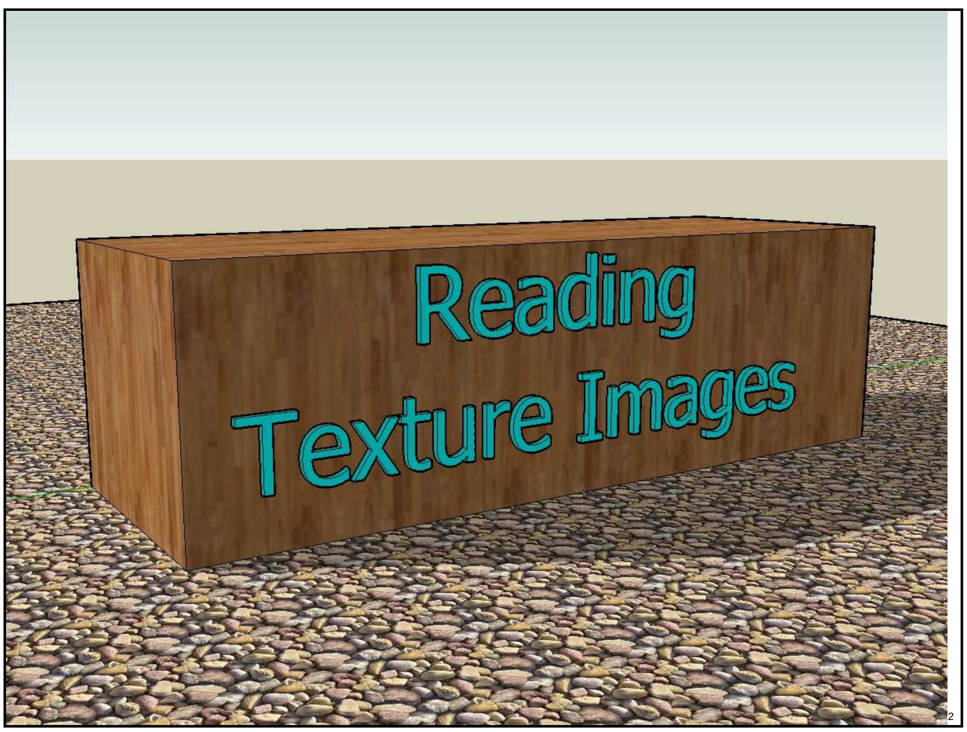
lighting.glib



In per-vertex lighting, the normal at each vertex is turned into a lighted intensity. That intensity is then interpolated throughout the polygon. This gives splotchy polygon artifacts like this.



In per-fragment lighting, the normal is interpolated throughout the polygon and turned into a lighted intensity at each fragment. This gives smoother results, like this.



Some of theTexture-reading Functions

`vec4 texture( sampler1D sampler, float coord )`
`vec4 texture( sampler2D sampler, vec2 coord )`
`vec4 texture( sampler3D sampler, vec3 coord )`
	Use the texture coordinate `coord` to do a texture lookup in the n-D texture currently bound to `sampler`.

`vec4 texture( samplerCube sampler, vec3 coord )`	Use the texture coordinate `coord` to do a texture lookup in the cube map texture currently bound to `sampler`. The direction of coord is used to select in which face to do a two-dimensional texture lookup.

You usually call these routines from a fragment shader (that's why we're covering it here), but in fact you can read textures into any other shader as well.

Texture-reading Example

glib file

```
##OpenGL GLIB

Gstap

Texture2D  texture.bmp

Vertex      texture.vert
Fragment  texture.frag
Program   Texture  uTexUnit  7

Teapot
```

vert file

```
out vec2 vST;

void
main( )
{
	vST = aTexCoord0.st;
	gl_Position = uModelViewProjectionMatrix * aVertex;
}
```

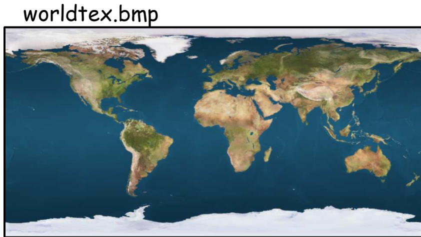
frag file

```
uniform  sampler2D      uTexUnit;
in  vec2                vST;
out  vec4               fFragColor;

void
main( )
{
	vec3 rgb = texture( uTexUnit, vST ).rgb;
	fFragColor = vec4( rgb, 1. );
}
```

Texture Example

worldtex.bmp

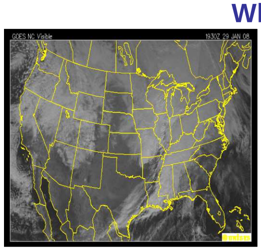


+

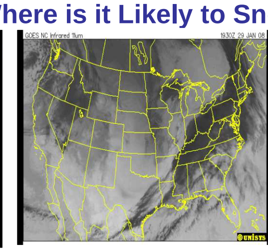
=

world.glib

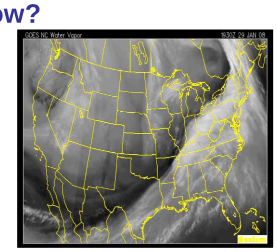
Using Textures as Data: Where is it Likely to Snow?



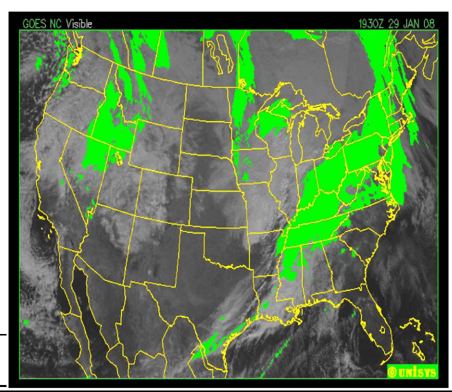
Visible



Infrared



Water vapor



Using Textures as Data

glib file

```
##OpenGL GLIB

Texture2D  5  goes.visible.bmp
Texture2D  6  goes.infrared.bmp
Texture2D  7  goes.watervapor.bmp

Gstap

Vertex      multiband.vert
Fragment multiband.frag
Program  MultiBand                                                              \
            uVisibleUnit 5       uInfraRedUnit 6         uWaterVaporUnit 7         \
            uVisible <0. 1. 1.>  uInfraRed <0. 0. 1.>  uWaterVapor <0. 0. 1.>      \
            uVisibleThreshold <0. 1. 1.>                                           \
            uInfraRedThreshold <0. 0. 1.>                                          \
            uWaterVaporThreshold <0. 0. 1.>                                        \
            uBrightness <0. 1. 3.>

QuadXY
```

vert file

```
out  vec2  vST;
void main(  )
{
      vST= aTexCoord0.st;
      gl_Position = uModelViewProjectionMatrix * aVertex;
}
```


Using Textures as Data

frag file, I

```
uniform sampler2D       uVisibleUnit;
uniform sampler2D       uInfraRedUnit;
uniform sampler2D       uWaterVaporUnit;
uniform float           uVisible;
uniform float           uInfraRed;
uniform float           uWaterVapor;
uniform float           uVisibleThreshold;
uniform float           uInfraRedThreshold;
uniform float           uWaterVaporThreshold;
uniform float           uBrightness;

in  vec2  vST;

out  vec4 fFragColor;

void
main(  )
{
      vec3 visibleColor    = texture( uVisibleUnit, vST ).rgb;
      vec3 infraredColor   = texture( uInfraRedUnit, vST).rgb;
      infraredColor = vec3(1.,1.,1.) - infraredColor;
      vec3 watervaporColor = texture( uWaterVaporUnit, vST ).rgb;

      vec3 rgb;
```

Using a Texture as Data

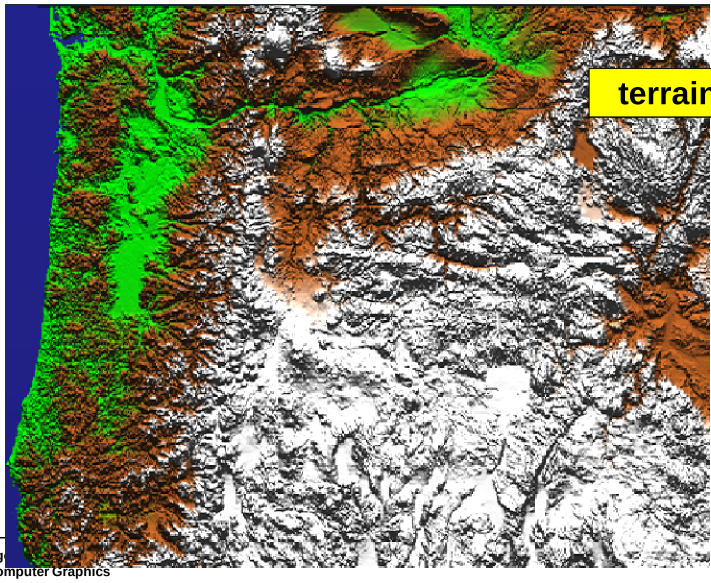
frag file, II

```
        if( visibleColor.r - visibleColor.g  > .25   &&   visibleColor.r - visibleColor.b > .25 )
        {
             rgb = vec3( 1., 1., 0. );       // state outlines become yellow
        }
        else
        {
            rgb = uVisible*visibleColor  +  uInfraRed*infraredColor  +  uWaterVapor*watervaporColor;
            rgb /= 3.;
            vec3 coefs = vec3( 0.296, 0.240, 0.464 );
            float visibleInten = dot(coefs,visibleColor);
            float infraredInten = dot(coefs,infraredColor);
            float watervaporInten = dot(coefs,watervaporColor);
            if( visibleInten > uVisibleThreshold  &&  infraredInten < uInfraRedThreshold  &&  watervaporInten > uWaterVaporThreshold )
            {
                rgb = vec3( 0., 1., 0. );
            }
            else
            {
                rgb *= uBrightness;
                rgb  = clamp( rgb, 0., 1. );
            }
        }

        fFragColor = vec4( rgb, 1. );
}
```

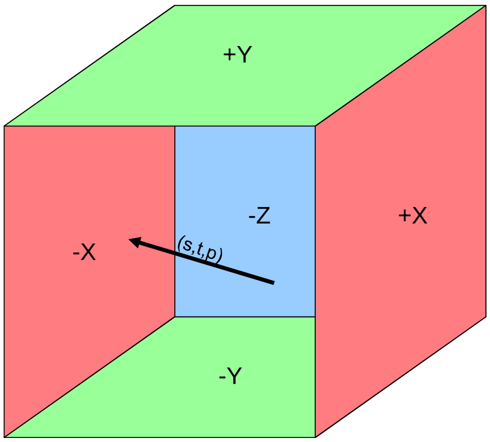

Bonus Demo

Bump-Mapping a Terrain Surface by Storing Heights in a Texture



terrain.glib

Cube Map Texture Lookup: Simulating a Surrounding 3D Environment



- Let L be the texture coordinate of (s, t, and p) with the largest magnitude
- L determines which of the 6 2D texture “walls” is being hit by the vector (-X in this case)
- The texture coordinates in that texture are the remaining two texture coordinates divided by L: (a/L,b/L)

```
vec3 ReflectVector = reflect( vec3 eyeDir, vec3 normal );

vec3 RefractVector = refract( vec3 eyeDir, vec3 normal, float Eta );
```


Cube Map of Nvidia’s Lobby

http://www.codemonsters.de/home/content.php?show=cubemaps

Using the Cube Map for Reflection

reflect.glib

Using the Cube Map for Reflection

```
out vec3 vReflectVector;

void main( )
{
        vec3 ECposition = vec3( uModelViewMatrix * aVertex );
        vec3 eyeDir = ECposition – vec3(0.,0.,0.);            // vector from eye to pt
        vec3 normal = normalize( uNormalMatrix * aNormal );
        vReflectVector = reflect( eyeDir, normal );
        gl_Position = uModelViewProjectionMatrix * aVertex;
}
```

```
in vec3   vReflectVector;
out vec4 fFragColor;
uniform samplerCube uReflectUnit;

void main( )
{
        vec4 newcolor = textureCube( uReflectUnit, vReflectVector );
        fFragColor = newcolor;
}
```

Using the Cube Map for Refraction

refract.glib

Using the Cube Map for Refraction

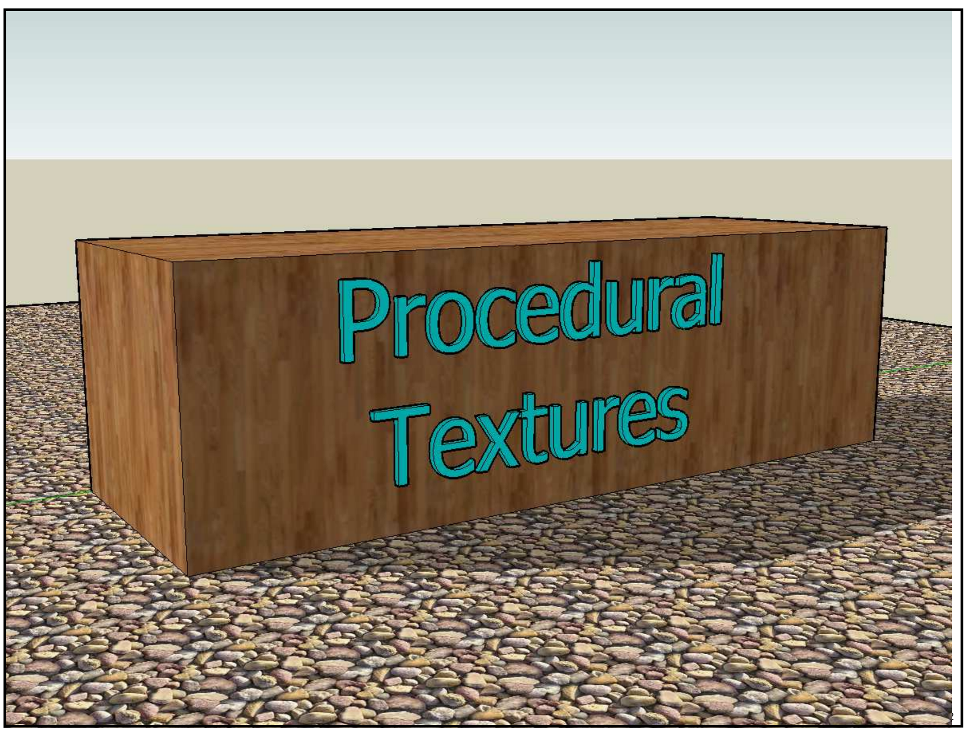
```
out vec3 vRefractVector;
out vec3 vReflectVector;
uniform float uEta;

void main( )
{
        vec3 ECposition = vec3( uModelViewMatrix * aVertex );
        vec3 eyeDir = normalize( ECposition ) – vec3(0.,0.,0.);        // vector from eye to pt
        vec3 normal = normalize( uNormalMatrix * aNormal );
        vRefractVector = refract( eyeDir, normal, uEta );
        vReflectVector = reflect(  eyeDir, normal );
        gl_Position = uModelViewProjectionMatrix * aVertex;
}
```

```
in vec3 vReflectVector;
in vec3 vRefractVector;
out vec4 fFragColor;
uniform float uMix;
uniform samplerCube uReflectUnit;
uniform samplerCube uRefractUnit;
const vec4 WHITE = vec4( 1.,1.,1.,1. );

void main( )
{
        vec4 refractcolor = textureCube( uRefractUnit, vRefractVector );
        vec4 reflectcolor = textureCube( uReflectUnit,  vReflectVector );
        refractcolor = mix( refractcolor, WHITE, .3 );
        fFragColor = mix( refractcolor, reflectcolor, uMix );
}
```

A Comparison of Reflection and Refraction



What if you want multi-colored stripes?

rainbow.glib

Tol = 0.

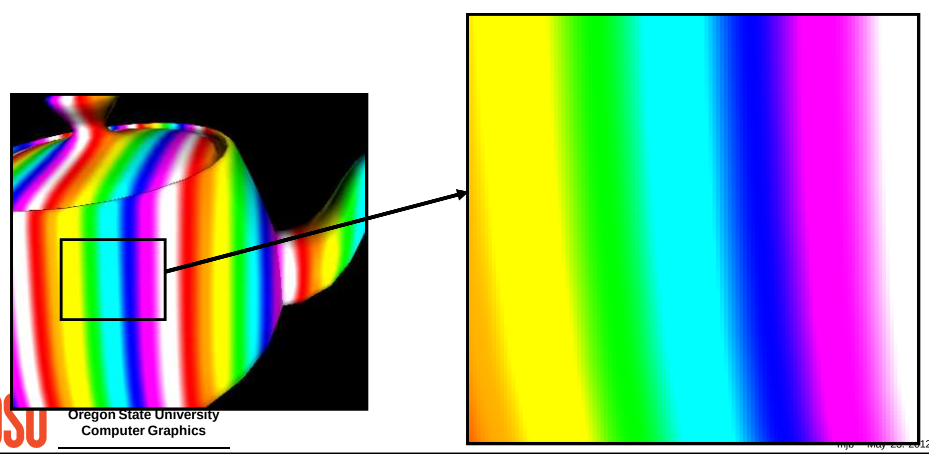
And, what if you want the stripes to smoothly blend into each other?

Tol > 0.

What if you want multi-colored stripes?

This is a good example of a *Procedural Texture*. It is like a texture that is read from a file, but instead is computed as the display is being created.

Procedural Textures are very popular because (1) you can do some amazing things with them, and (2) they don't "run out of texels" like a fixed-size texture would.



Here's how to do the Colored Stripes

frag file, I

```
in  vec3   vMCposition;
in  float    vLightIntensity;
out  vec4  fFragColor;

uniform float  uA;
uniform float  uTol;

const  vec4  RED          = vec4( 1., 0., 0., 1. );
const  vec4 ORANGE    = vec4( 1., .5, 0., 1. );
const  vec4 YELLOW     = vec4( 1., 1., 0., 1. );
const  vec4 GREEN       = vec4( 0., 1., 0., 1. );
const  vec4 CYAN         = vec4( 0., 1., 1., 1. );
const  vec4 BLUE         = vec4( 0., 0., 1., 1. );
const  vec4 MAGENTA  = vec4( 1., 0., 1., 1. );
const  vec4 WHITE       = vec4( 1., 1., 1., 1. );

const float ONE16           = 1./16.;
const float THREE16       = 3./16.;
const float FIVE16           = 5./16.;
const float SEVEN16       = 7./16.;
const float NINE16           = 9./16.;
const float ELEVEN16      = 11./16.;
const float THIRTEEN16  = 13./16.;
const float FIFTEEN16     = 15./16.;
```


frag file, II

```
void
main( )
{
	float X = vMCposition.x;
	float Y = vMCposition.y;
	float f = fract(  uA*X );
	float t = smoothstep( ONE16 - uTol, ONE16 + uTol, f );
	fFragColor = vLightIntensity * mix( WHITE, RED, t );

	if( f >= THREE16 - Tol )
	{
		t = smoothstep( THREE16 - uTol, THREE16 + uTol, f );
		fFragColor = vLightIntensity * mix( RED, ORANGE, t );
	}
	if( f >= FIVE16 - Tol )
	{
		t = smoothstep( FIVE16 - uTol, FIVE16 + uTol, f );
		fFragColor = vLightIntensity * mix( ORANGE, YELLOW, t );
	}


	. . .
}
```

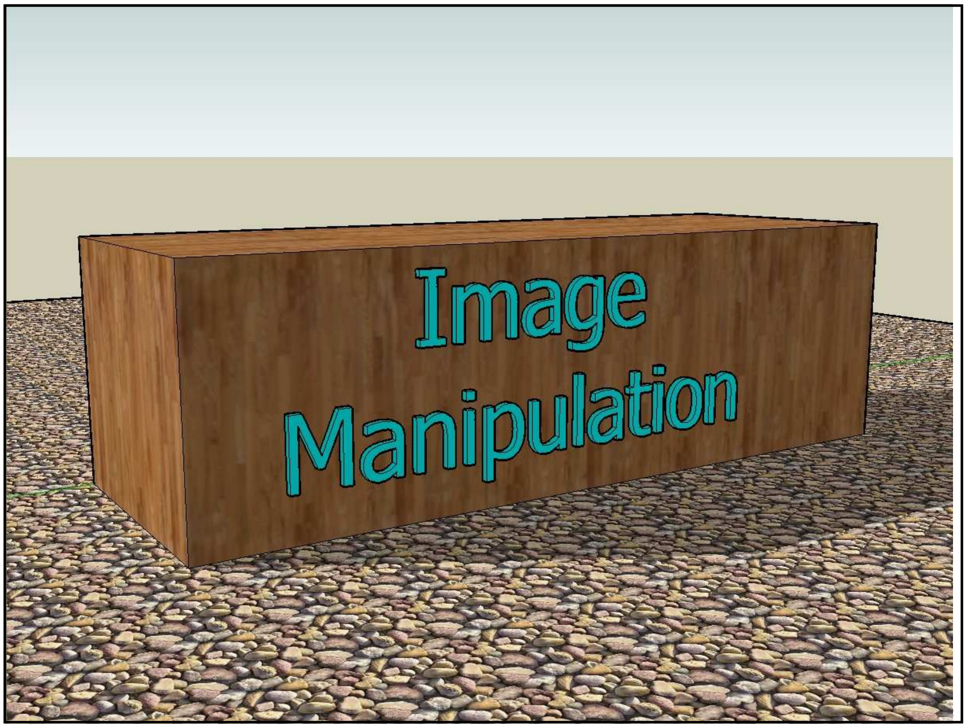
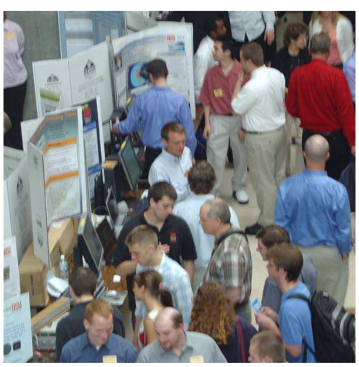


Image Negative

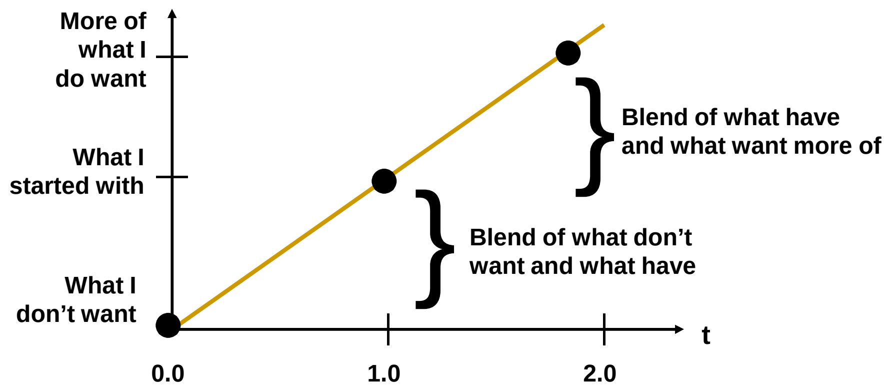
image.glib



```
in vec2 vST;
out vec4 fFragColor;
uniform sampler2D uImageUnit;
uniform float uT;

void main( )
{
      vec2 st = vST;
      vec3 irgb = texture( uImageUnit,  st ).rgb;
      vec3 neg = vec3( 1.,1.,1. ) – irgb;
      fFragColor = vec4( mix( irgb, neg, uT ), 1. );
}
```

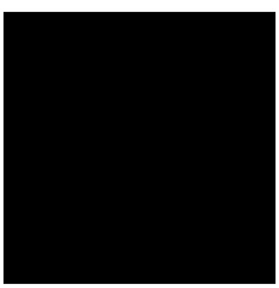
Image Un-Masking:
Sometimes it's easier to ask for what you *don't* want than asking for what you *do* want !



$$I_{out} = (1.-t)*I_{dontwant} + t*I_{in}$$

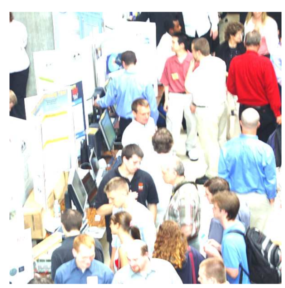
Brightness

$$I_{dontwant} = vec3(0., 0., 0.);$$



T = 0.

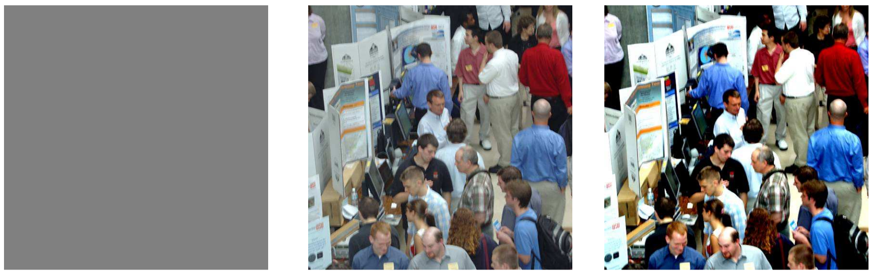
T = 1.



T = 2.

Contrast

$I_{dontwant}$ = vec3(0.5, 0.5, 0.5);



T = 0. T = 1. T = 2.

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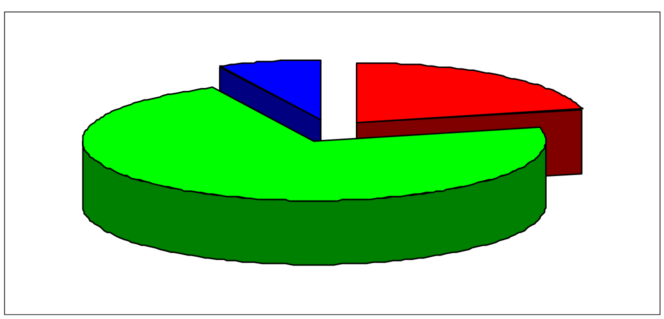
HDTV Luminance Standard

Luminance = 0.2125*Red + 0.7154*Green + 0.0721*Blue



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Saturation

$I_{dontwant}$ = vec3(luminance, luminance, luminance);

T = 0.

T = 1.

T = 3.

Blur

Blur Convolution:

$$B = \frac{1.}{16.}\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

Sharpening

Blur Convolution:

$$B = \frac{1.}{16.}\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

$$I_{dontwant} = I_{blur}$$

Sharpening

T = 0.

T = 1.

T = 2.

Sharpening

frag file

```
in vec2 vST;
out vec4 fFragColor;
uniform sampler2D uImageUnit, uBeforeUnit, uAfterUnit;
uniform float uT;

void main( )
{
        ivec2 res = textureSize( uImageUnit, 0 );
        vec2 st = vST;

        vec2 stp0 = vec2(1./float(res.s),  0.              );
        vec2 st0p = vec2(0.             ,  1./float(res.s));
        vec2 stpp = vec2(1./float(res.s),  1./float(res.t));
        vec2 stpm = vec2(1./float(res.s), -1./float(res.t));
        vec3 i00   = texture( uImageUnit, st ).rgb;
        vec3 im1m1 = texture( uImageUnit, st-stpp ).rgb;
        vec3 ip1p1 = texture( uImageUnit, st+stpp ).rgb;
        vec3 im1p1 = texture( uImageUnit, st-stpm ).rgb;
        vec3 ip1m1 = texture( uImageUnit, st+stpm ).rgb;
        vec3 im10  = texture( uImageUnit, st-stp0 ).rgb;
        vec3 ip10  = texture( uImageUnit, st+stp0 ).rgb;
        vec3 i0m1  = texture( uImageUnit, st-st0p ).rgb;
        vec3 i0p1  = texture( uImageUnit, st+st0p ).rgb;
        vec3 target = vec3(0.,0.,0.);
        target += 1.*(im1m1+ip1m1+ip1p1+im1p1);
        target += 2.*(im10+ip10+i0m1+i0p1);
        target += 4.*(i00);
        target /= 16.;
        fFragColor = vec4( mix( target, irgb, uT ), 1. );
}
```

Get size of the texture in pixels → `ivec2 res = textureSize( uImageUnit, 0 );`

Edge Detection

Horizontal and Vertical Sobel Convolutions:

$$H = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix} \qquad V = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}$$

$$S = \sqrt{H^2 + V^2} \qquad \Theta = \text{atan2}(V, H)$$

Edge Detection

```
vec2 stp0 = vec2(1./float(res.s),  0.             );
vec2 st0p = vec2(0.             ,  1./float(res.s));
vec2 stpp = vec2(1./float(res.s),  1./float(res.t));
vec2 stpm = vec2(1./float(res.s), -1./float(res.t));

float i00   = dot( texture( uImageUnit, st ).rgb,      vec3(0.2125,0.7154,0.0721) );
float im1m1 = dot( texture( uImageUnit, st-stpp ).rgb, vec3(0.2125,0.7154,0.0721) );
float ip1p1 = dot( texture( uImageUnit, st+stpp ).rgb, vec3(0.2125,0.7154,0.0721) );
float im1p1 = dot( texture( uImageUnit, st-stpm ).rgb, vec3(0.2125,0.7154,0.0721) );
float ip1m1 = dot( texture( uImageUnit, st+stpm ).rgb, vec3(0.2125,0.7154,0.0721) );
float im10  = dot( texture( uImageUnit, st-stp0 ).rgb, vec3(0.2125,0.7154,0.0721) );
float ip10  = dot( texture( ImageUnit,  st+stp0 ).rgb, vec3(0.2125,0.7154,0.0721) );
float i0m1  = dot( texture( uImageUnit, st-st0p ).rgb, vec3(0.2125,0.7154,0.0721) );
float i0p1  = dot( texture( uImageUnit, st+st0p ).rgb, vec3(0.2125,0.7154,0.0721) );
float h = -1.*im1p1 - 2.*i0p1 - 1.*ip1p1  +  1.*im1m1 + 2.*i0m1 + 1.*ip1m1;
float v = -1.*im1m1 - 2.*im10 - 1.*im1p1  +  1.*ip1m1 + 2.*ip10 + 1.*ip1p1;

float mag = sqrt( h*h + v*v );
vec3 target = vec3( mag,mag,mag );
color = vec4( mix( irgb, target, uT ), 1. );
```


Edge Detection

edge.glib

T = 0.

T = 0.5

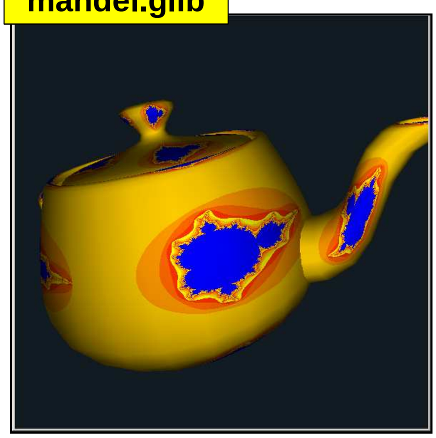
T = 1.

Bonus Demo

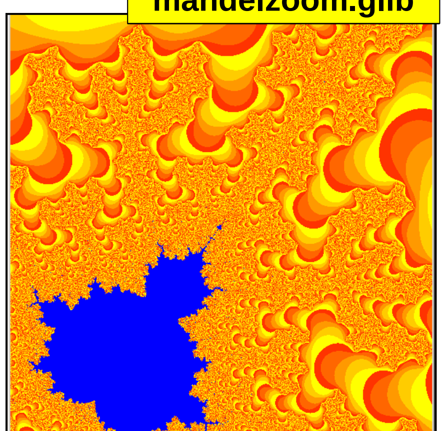
imageripple.glib

Bonus Demos

mandel.glib

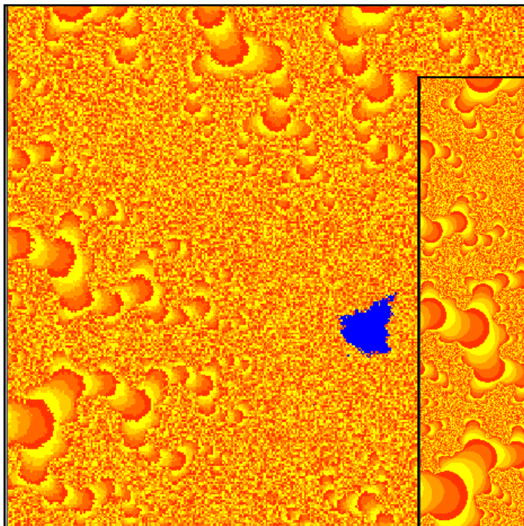


mandelzoom.glib

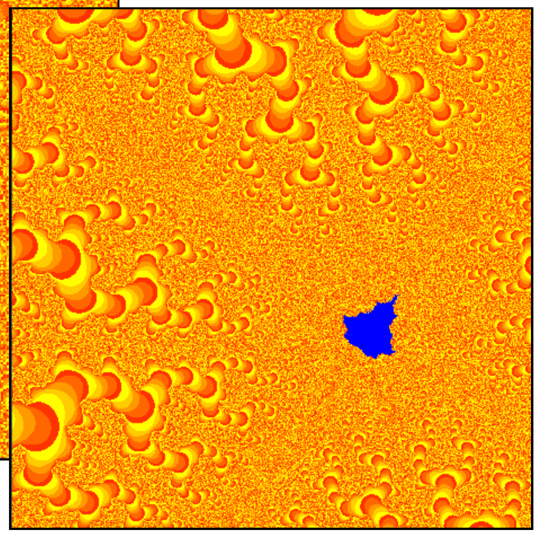


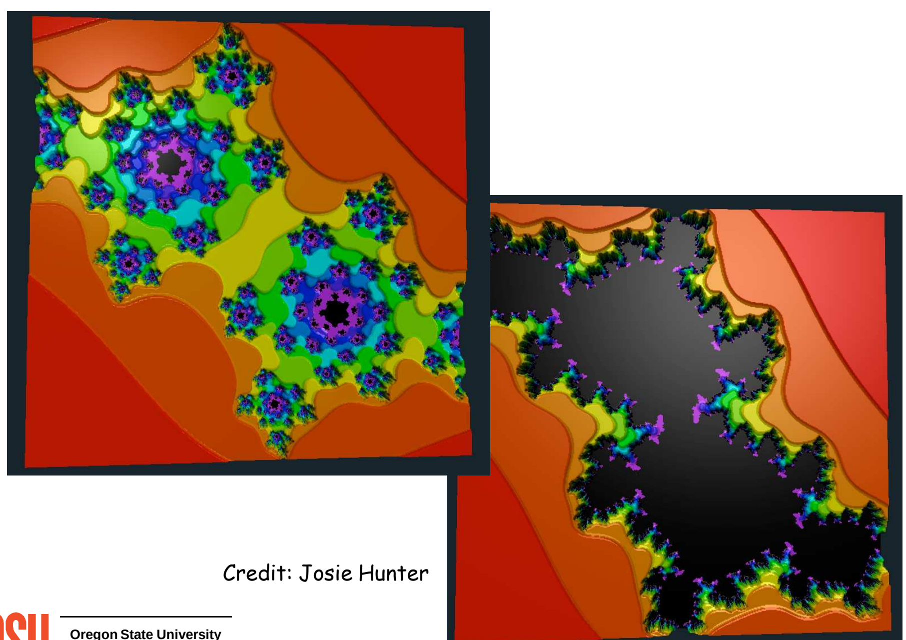
Using Double Precision in a Shader

float

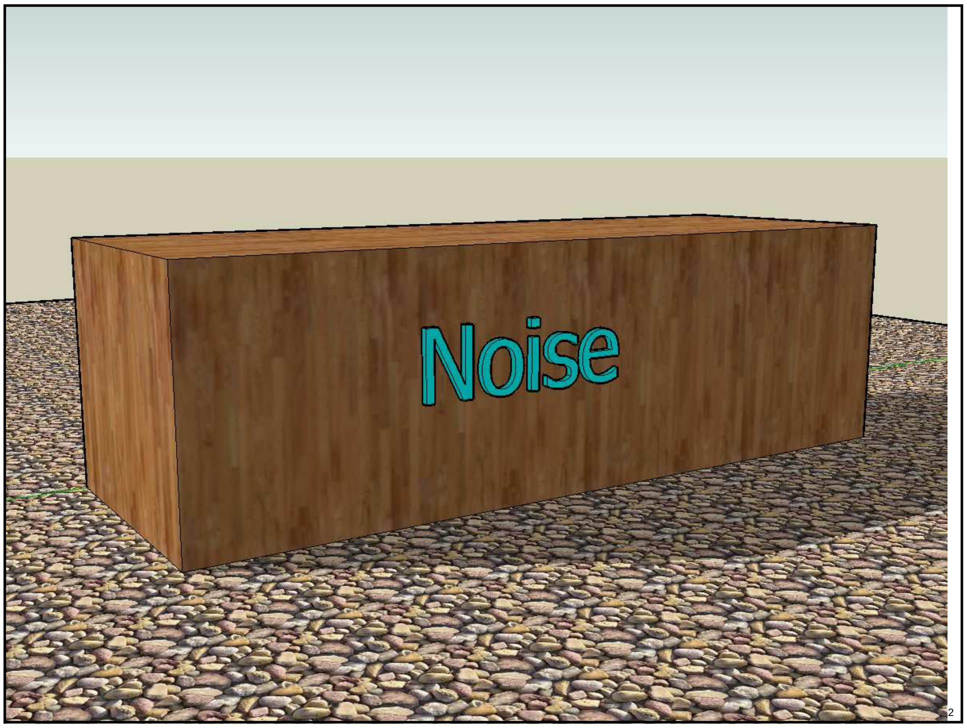


double





Credit: Josie Hunter

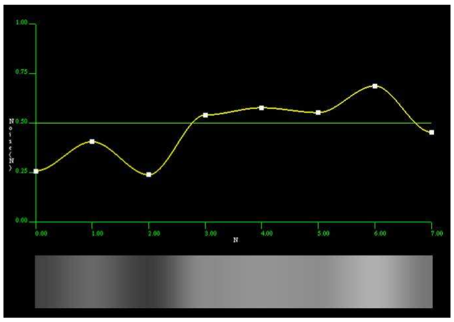


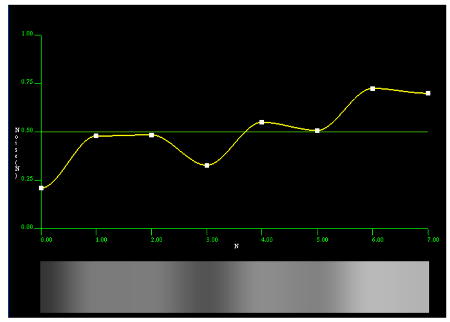
Noise:

- Is a function of input value(s)
- Ranges from -1. to +1. or from 0. to 1.
- Looks random, but really isn't
- Has continuity
- Is repeatable
- Has statistical properties that are translational and rotational invariant

Positional Noise:
Two sets of random numbers

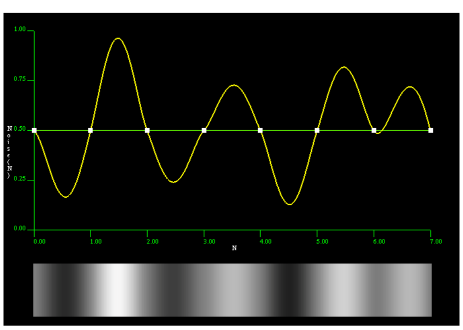
noisegraph.exe

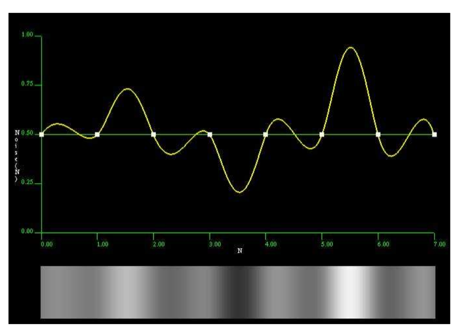




Gradient Noise:
Two sets of random numbers

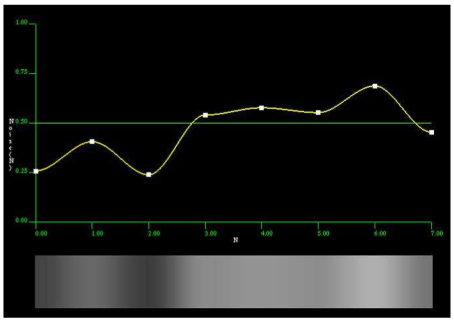
noisegraph.exe

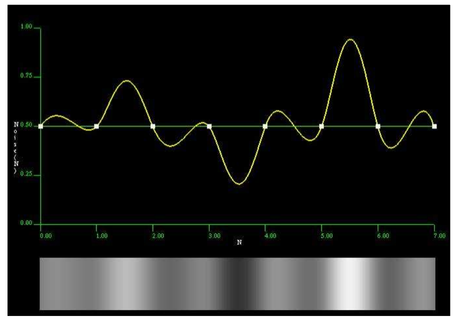




Positional vs. Gradient Noise: Gradient has more variation

noisegraph.exe





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Coefficients for Noise

$$N(t) = C_{N0}N_0 + C_{N1}N_1 + C_{G0}G_0 + C_{G1}G_1$$

Noise values (N_0, N_1) **Gradients** (G_0, G_1)

$$C_{N0} = 1 - 3t^2 + 2t^3$$

$$C_{N1} = 3t^2 - 2t^3 = 1 - C_{N0}$$

$$C_{G0} = t - 2t^2 + t^3$$

$$C_{G1} = -t^2 + t^3$$

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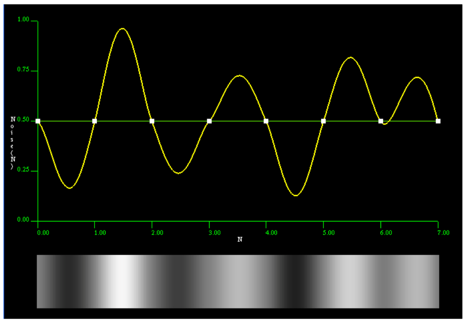
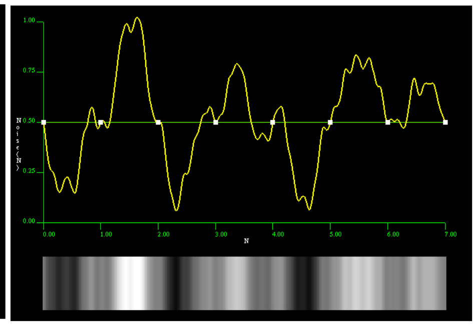
Noise Octaves

Idea: Add multiple noise waves, each one twice the frequency and half the amplitude of the previous one

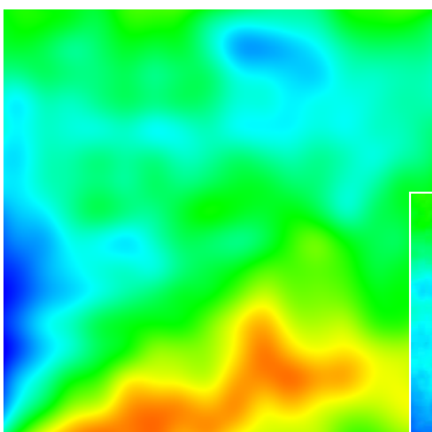


1 Octave



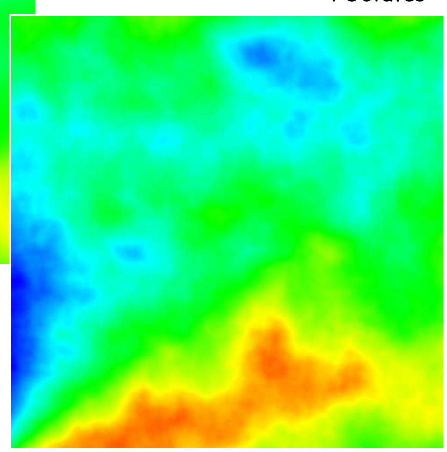
4 Octaves

Image Representation of 2D Noise

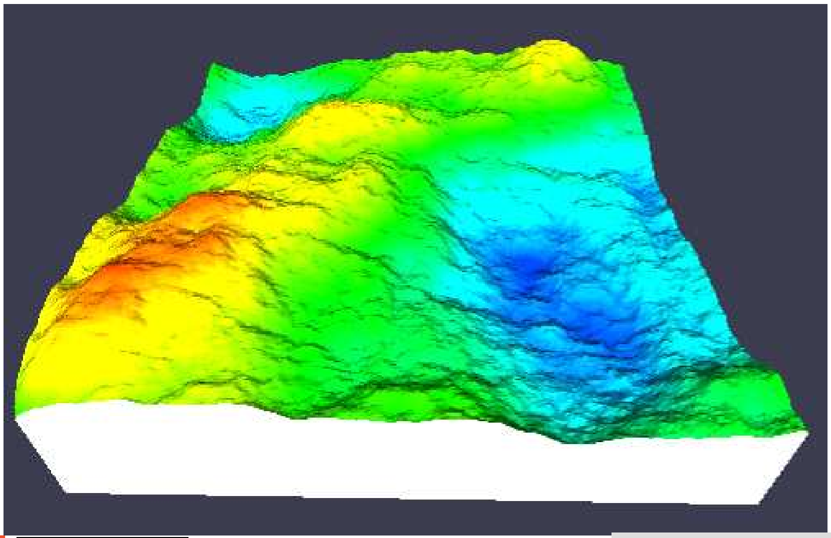


1 Octave

4 Octaves



Surface Representation of 2D Noise



4 Octaves

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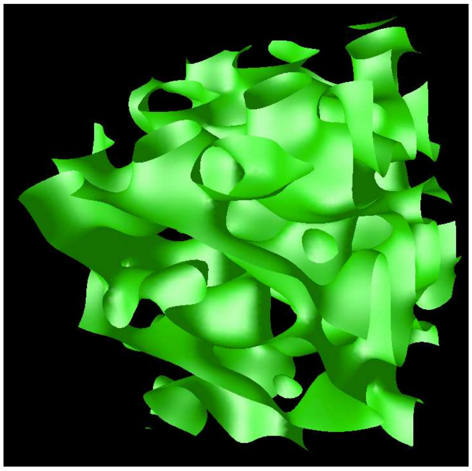
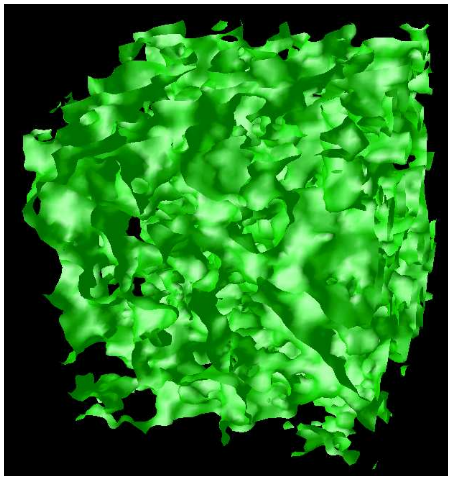
3D Isosurfaces of 3D Noise

S* = Mid-value



1 Octave



4 Octaves

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Built-In GLSL Noise Functions

`float noise1( genType x )`	Returns a 1D noise value based on the input value *x*. At this time, this function is not available in GLSL.
`vec2 noise2( genType x )`	Returns a 2D noise value based on the input value *x*. At this time, this function is not available in GLSL.
`vec3 noise3( genType x )`	Returns a 3D noise value based on the input value *x*.
`vec4 noise4( genType x )`	Returns a 4D noise value based on the input value *x*.

Note: as of this writing, these functions don't work on all graphics systems!

To compensate, *glman* has a built-in noise texture.

glman has a built-in 3D Noise Texture

glman automatically creates a 3D noise texture and places it into Texture Unit 3.

Your vertex, geometry, or fragment shader can get at it through the pre-created uniform variable called ***Noise3***.

You can reference it in your shader as:

```
uniform sampler3D Noise3;
. . .
vec3 stp = ...
vec4 nv = texture( Noise3, stp );
```

glman has a built-in 3D Noise Texture

The noise texture is a vec4 whose components have separate meanings.
The [0] component is the low frequency noise.
The [1] component is twice the frequency and half the amplitude of the [0] component, and so on for the [2] and [3] components.

Each component is centered around a value of .5, so that if you want a plus-or-minus effect, subtract .5 from each component. To get a nice four-octave noise value between 0 and 1 (useful for noisy mixing), add up all four components, subtract 1 and divide the result by 2, as shown in the following table and GLSL code:.

Component	Term	Term Range
0	nv.r	0.5 ± .5000
1	nv.g	0.5 ± .2500
2	nv.b	0.5 ± .1250
3	nv.a	0.5 ± .0675
	sum	**2.0 ± ~ 1.0**
	sum - 1	**1.0 ± ~ 1.0**
	(sum - 1) / 2	**0.5 ± ~ 0.5**

```
float sum = nv.r + nv.g + nv.b + nv.a;        // range is 1. -> 3.
      sum = ( sum - 1. ) / 2.;               // range is now 0. -> 1.
```


How to Apply Noise

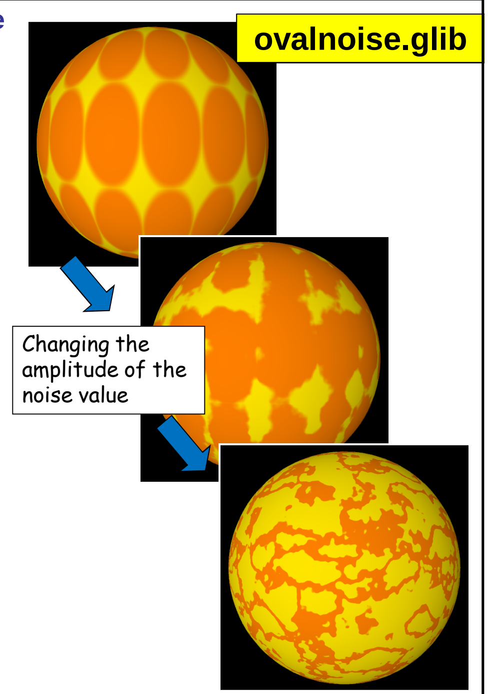
1. Have an equation to describe color assignment

2. Have actual coordinates at a pixel

Coordinates could be in (s,t) or in (x,y,z)

3. Add Noise to the actual coordinates to produce new coordinates

4. Use the new coordinates in the old equation to assign a color at that pixel



frag file, I

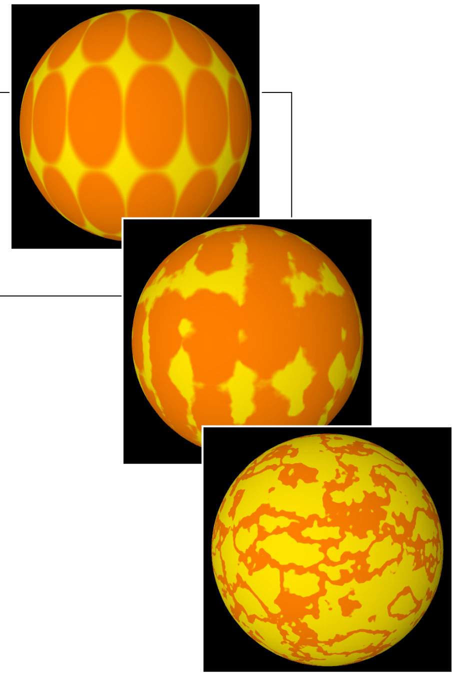
```
in vec3 vMCposition;              // model coord position from the vertex shader
in float  vLightIntensity;        // light intensity from the vertex shader
in vec2 vST;                      // texture coords from the vertex shader

out vec4 fFragColor;

uniform float uAd;
uniform float uBd;
uniform float uNoiseAmp;
uniform float uNoiseFreq;
uniform float uAlpha;
uniform float uTol;
uniform float uBlend;
uniform sampler3D Noise3;

const vec3 ORANGE = vec3( 1., .5, 0. );
const vec3 YELLOW = vec3( 1., .9, 0.);
```


frag file, II

```
void
main(  )
{
        vec4  noisevec  = texture( Noise3, uNoiseFreq*vMCposition );
        float n = noisevec.r + noisevec.g + noisevec.b + noisevec.a;        // 1. -> 3.
         n = ( n - 2. );                        // -1. -> 1.
         n *= uNoiseAmp;

        vec2 st = vST;
        st.s *= 2.;

        float Ar = uAd / 2.;
        float Br = uBd / 2.;

        int numinu = int( st.s / uAd );
        int numinv = int( st.t / uBd );

        vec3 theColor = YELLOW;

        st.s -= float(numinu) * uAd;
        st.t -= float(numinv) * uBd;
        vec3 upvp =  vec3( st, 0. );
        vec3 cntr =  vec3( Ar, Br, 0. );
        vec3 delta = upvp - cntr;
        float oldrad = length( delta );
        float newrad = oldrad + n;
```

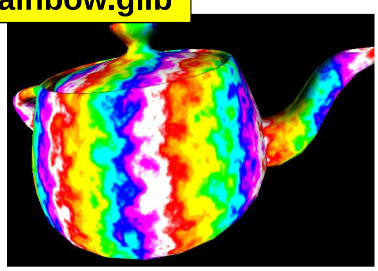
frag file, III

```
        delta = delta * newrad / oldrad;
        float du = delta.x/Ar;
        float dv = delta.y/Br;
        float d = du*du + dv*dv;

        float t = smoothstep( 1.-uTol, 1.+uTol, d );
        theColor = mix( ORANGE, YELLOW, t );

        fFragColor = vec4( vLightIntensity*theColor, 1. );
}
```



Noise Examples

rainbow.glib



More Interesting Stripe Blending

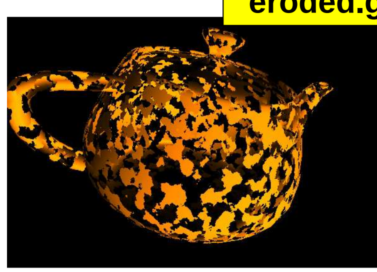
fire.glib

Fire Effect

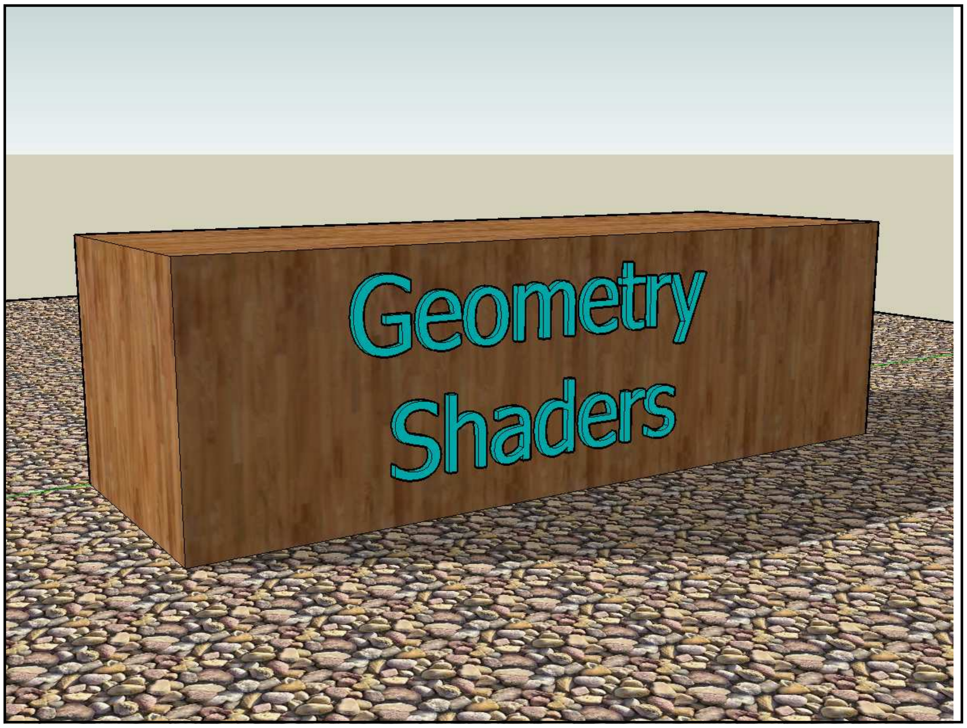
clouds.glib

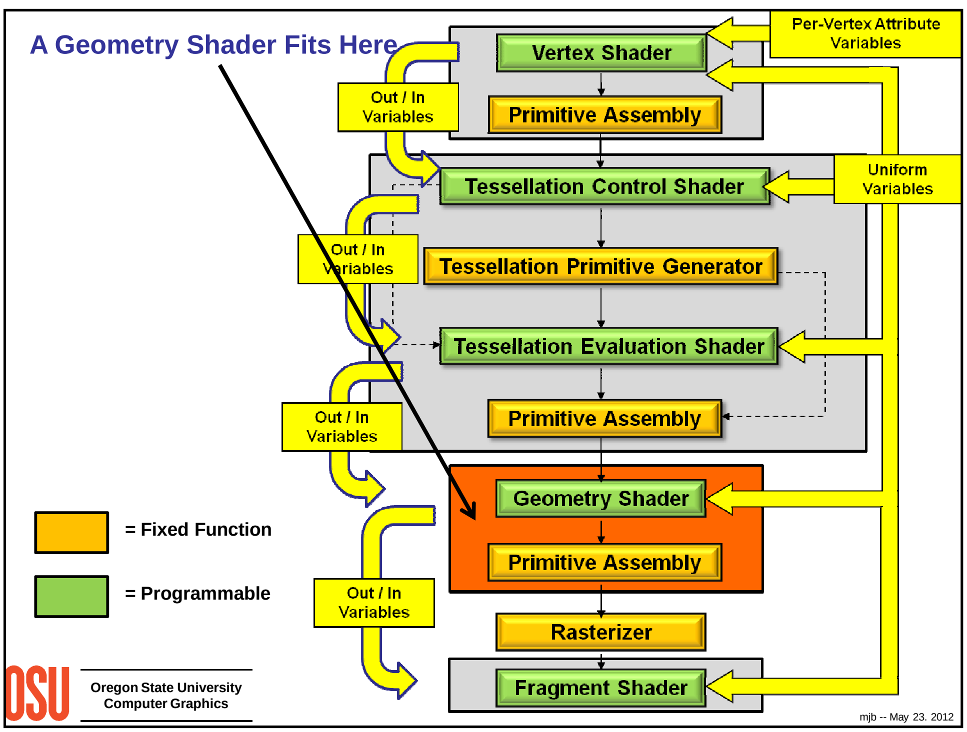
Cloud Effect

eroded.glib



Deciding when to Discard
for Erosion


Geometry
Shaders


A Geometry Shader Fits Here
Per-Vertex Attribute Variables
Vertex Shader
Out / In Variables
Primitive Assembly
Uniform Variables
Tessellation Control Shader
Out / In Variables
Tessellation Primitive Generator
Tessellation Evaluation Shader
Out / In Variables
Primitive Assembly
= Fixed Function
Geometry Shader
= Programmable
Primitive Assembly
Out / In Variables
Rasterizer
Fragment Shader
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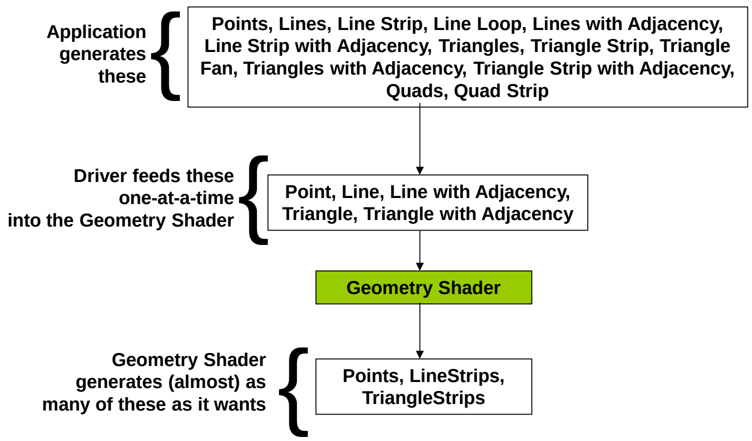
The Geometry Shader: What Does it Do?



There needn't be any correlation between Geometry Shader input type and Geometry Shader output type. Points can generate triangles, triangles can generate triangle strips, etc.

Additional Arguments are Available for glBegin( ) – glEnd( ):

GL_LINES_ADJACENCY

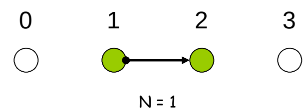
GL_LINE_STRIP_ADJACENCY

GL_TRIANGLES_ADJACENCY

GL_TRIANGLE_STRIP_ADJECENCY

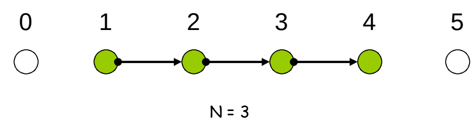
New Adjacency Primitives

Lines with Adjacency



4N vertices are given.
(where N is the number of line segments to draw).
A line segment is drawn between #1 and #2.
Vertices #0 and #3 are there to provide adjacency information.

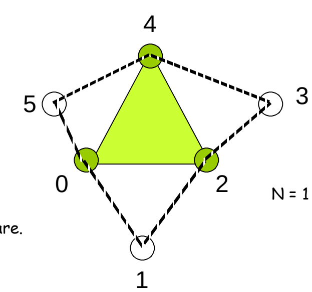
Line Strip with Adjacency



N+3 vertices are given
(where N is the number of line segments to draw).
A line segment is drawn between #1 and #2, #2 and #3, …, #N and #N+1.
Vertices #0 and #N+2 are there to provide adjacency information.

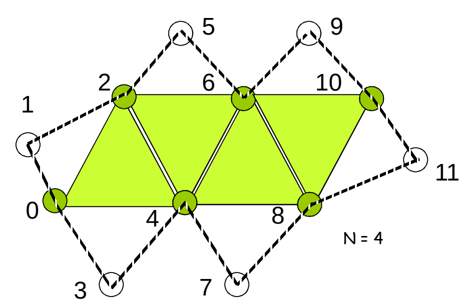
New Adjacency Primitives

Triangles with Adjacency



6N vertices are given
(where N is the number of triangles to draw).
Points 0, 2, and 4 define the triangle.
Points 1, 3, and 5 tell where adjacent triangles are.

Triangle Strip with Adjacency



4+2N vertices are given
(where N is the number of triangles to draw).
Points 0, 2, 4, 6, 8, 10, …define the triangles.
Points 1, 3, 5, 7, 9, 11, … tell where adjacent triangles are.

If a Vertex Shader writes variables as:		then the Geometry Shader will read them as:		and will write them as:
gl_Position	→	gl_PositionIn[■]	→	gl_Position
gl_PointSize	→	gl_PointSizeIn	→	gl_PointSize
vST	→	vST[■]	→	gST
vColor		vColor[■]		gColor
"out"		*"in"*		*"out"*

In the Geometry Shader, the dimensions indicated by ■ are given by the variable *gl_VerticesIn*, although you will already know this by the type of geometry you are inputting →

1	GL_POINTS
2	GL_LINES
4	GL_LINES_ADJACENCY_EXT
3	GL_TRIANGLES
6	GL_TRIANGLES_ADJACENCY_EXT

The Geometry Shader Can Assign These Variables:

- gl_Position
- User-defined

When the Geometry Shader calls

EmitVertex( )

this set of variables is copied to a slot in the shader's Primitive Assembly step

When the Geometry Shader calls

EndPrimitive( )

the vertices that have been saved in the Primitive Assembly step are then assembled, rasterized, etc.

Note: there is no "BeginPrimitive( )" routine. It is implied by (1) the start of the Geometry Shader, or (2) returning from the EndPrimitive( ) call.

Note: there is no need to call EndPrimitive( ) at the end of the Geometry Shader – it is implied.

Example: Expanding 4 Points into a Bezier Curve with a Variable Number of Line Segments

bezier.glib

```
Gstap

Vertex      bezier.vert
Geometry bezier.geom
Fragment bezier.frag
Program  Bezier  uNum <2 10 50>

LineWidth 3.
LinesAdjacency [0. 0. 0.]  [1. 1. 1.]  [2. 1. 2.]  [3. -1. 0.]
```

bezier.vert

```
void main( )
{
                gl_Position = uModelViewProjectionMatrix * aVertex;
}
```

bezier.frag

```
out vec4 fFragColor;

void main( )
{
   fFragColor = vec4( 0., 1., 0., 1. );
}
```


Example: Expanding 4 Points into a Bezier Curve with a Variable Number of Line Segments

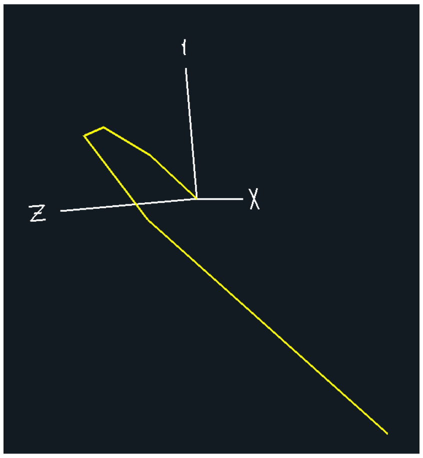
bezier.geom

```
#version 120
#extension GL_EXT_geometry_shader4: enable
layout( lines_adjacency )               in;
layout( lines, max_vertices=128 )  out;
uniform int uNum;
void main( )
{
            float dt = 1. / float(uNum);
            float t = 0.;
            for( int i = 0; i <= uNum; i++ )
            {
                        float omt = 1. - t;
                        float omt2 = omt * omt;
                        float omt3 = omt * omt2;
                        float t2 = t * t;
                        float t3 = t * t2;
                        vec4 xyzw =            omt3 * gl_PositionIn[0].xyzw  +
                                      3. * t * omt2 * gl_PositionIn[1].xyzw  +
                                      3. * t2 * omt * gl_PositionIn[2].xyzw  +
                                                 t3 * gl_PositionIn[3].xyzw;

                        gl_Position = xyzw;
                        EmitVertex()
                        t += dt;
            }
}
```

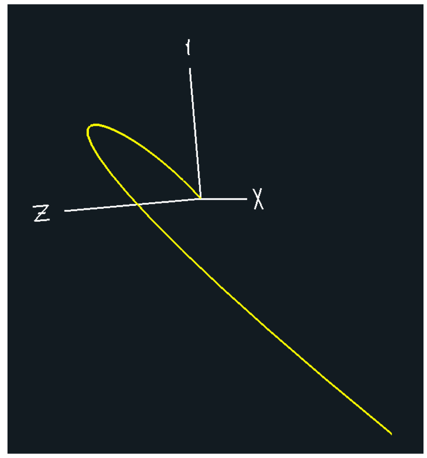
Used to declare the geometry shader's input and output topology

$$P(t) = (1-t)^3 P_0 + 3t(1-t)^2 P_1 + 3t^2(1-t) P_2 + t^3 P_3$$

Example: Expanding 4 Points into a Bezier Curve with a Variable Number of Line Segments

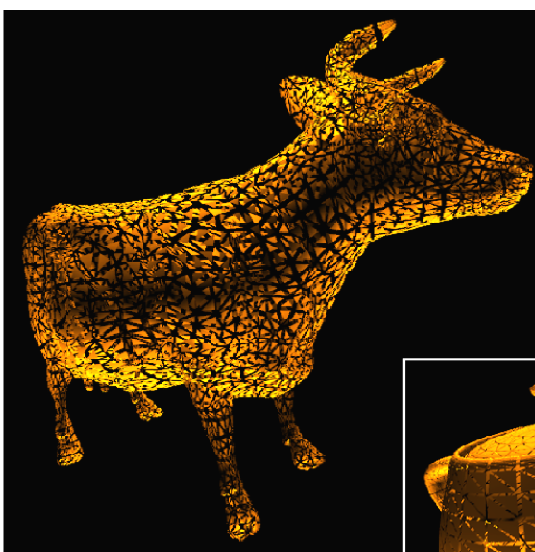


uNum = 5



uNum = 25

Example: Shrinking Triangles

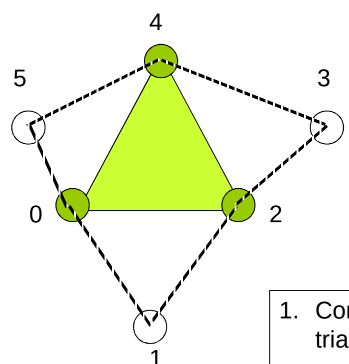


shrink.glib

shrink.geom

```
#version 120
#extension GL_EXT_geometry_shader4: enable
layout( triangles )                         in;
layout( triangle_strip, max_vertices=32 ) out;

uniform  float  uShrink;
in vec3          vNormal[  ];
out  float       gLightIntensity;

const  vec3  LIGHTPOS = vec3( 0., 10., 0. );
vec3 V[3];
vec3 CG;

void
ProduceVertex( int v )
{
      gLightIntensity  = dot( normalize( LIGHTPOS - V[v]), vNormal[v] );
      gLightIntensity = abs( gLightIntensity );

      gl_Position = uModelViewProjectionMatrix * vec4( CG + uShrink * ( V[v] - CG ), 1. );
      EmitVertex();
}

void
main( )
{
      V[0]  =   gl_PositionIn[0].xyz;
      V[1]  =   gl_PositionIn[1].xyz;
      V[2]  =   gl_PositionIn[2].xyz;
      CG = (  V[0] + V[1] + V[2]  ) / 3.;
      ProduceVertex( 0 );
      ProduceVertex( 1 );
      ProduceVertex( 2 );
}
```


Example: Silhouette Geometry Shader



1. Compute the normals of each of the four triangles
2. If there is a sign difference between the z component of the center triangle and the z component of an adjacent triangle, draw their common edge

Example: Silhouette Geometry Shader

silh.glib

```
Obj bunny.obj

Vertex        silh.vert
Geometry   silh.geom
Fragment   silh.frag
Program Silhouette  uColor { 0. 1. 0. }

ObjAdj   bunny.obj
```

This creates triangle-adjacency information when the file is read

Example: Silhouette Geometry Shader

silh.vert

```
void main( )
{
		gl_Position = uModelViewMatrix * aVertex;
}
```

silh.frag

```
uniform vec4 uColor;
out vec4        fFragColor;

void
main( )
{
		fFragColor = vec4( uColor.rgb, 1. );
}
```

Example: Silhouette Geometry Shader

silh.geom, I

```
#version 120
#extension GL_EXT_geometry_shader4: enable

layout( triangles_adjacency )            in;
layout( line_strip, max_vertices=32 )  out;

void
main( )
{
        vec3 V0 = gl_PositionIn[0].xyz;
        vec3 V1 = gl_PositionIn[1].xyz;
        vec3 V2 = gl_PositionIn[2].xyz;
        vec3 V3 = gl_PositionIn[3].xyz;
        vec3 V4 = gl_PositionIn[4].xyz;
        vec3 V5 = gl_PositionIn[5].xyz;

        vec3 N042 = cross( V4-V0, V2-V0 );
        vec3 N021 = cross( V2-V0, V1-V0 );
        vec3 N243 = cross( V4-V2, V3-V2 );
        vec3 N405 = cross( V0-V4, V5-V4 );
```

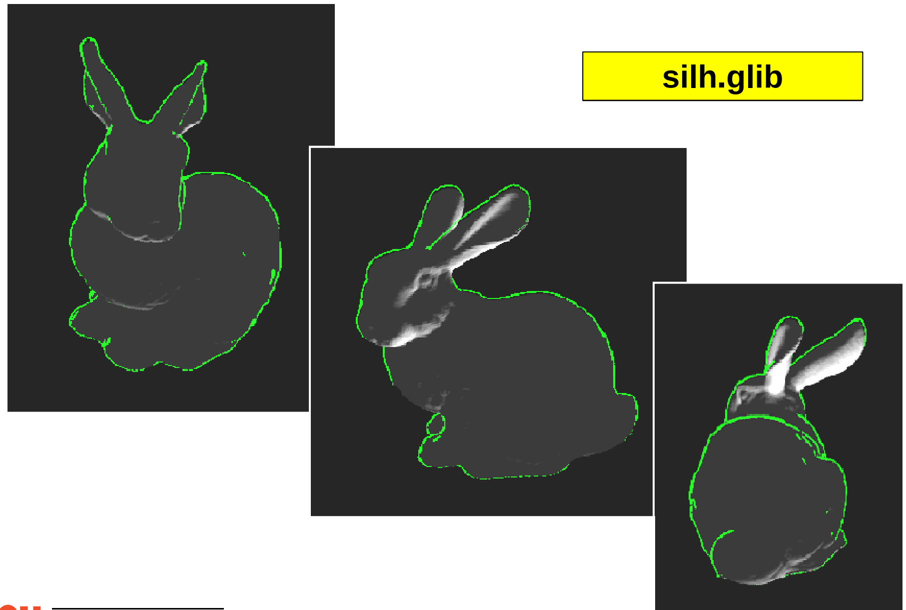

Example: Silhouette Geometry Shader

silh.geom, II

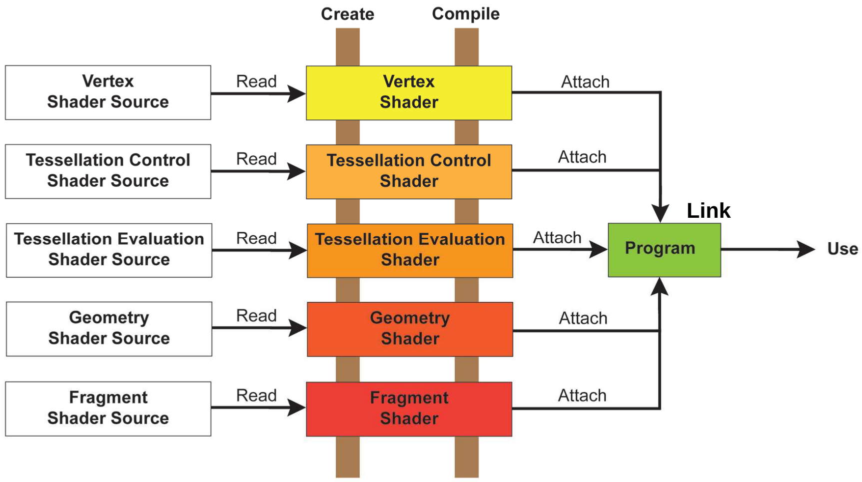
```
        if( N042.z * N021.z < 0. )
        {
                gl_Position = uProjectionMatrix * vec4( V0, 1. );
                EmitVertex( );
                gl_Position = uProjectionMatrix * vec4( V2, 1. );
                EmitVertex( );
                EndPrimitive( );
        }

        if( N042.z * N243.z < 0. )
        {
                gl_Position = uProjectionMatrix * vec4( V2, 1. );
                EmitVertex( );
                gl_Position = uProjectionMatrix * vec4( V4, 1. );
                EmitVertex( );
                EndPrimitive( );
        }

        if( N042.z * N405.z < 0. )
        {
                gl_Position = uProjectionMatrix * vec4( V4, 1. );
                EmitVertex();
                gl_Position = uProjectionMatrix * vec4( V0, 1. );
                EmitVertex( );
                EndPrimitive( );
        }
}
```

Example: Bunny Silhouettes

silh.glib



The GLSL Shader-creation Process



Initializing the GL Extension Wrangler (GLEW)

```
#include "glew.h"

. . .

GLenum err = glewInit( );
if( err != GLEW_OK )
{
        fprintf( stderr, "glewInit Error\n" );
        exit( 1 );
}

fprintf( stderr, "GLEW initialized OK\n" );
fprintf( stderr, "Status: Using GLEW %s\n", glewGetString(GLEW_VERSION) );
```

`http://glew.sourceforge.net`

Reading a Vertex, Tessellation, Geometry, or Fragment Shader source file into a character buffer

```
#include <stdio.h>

FILE *fp = fopen( filename, "r" );
if( fp == NULL )  { . . . }

fseek( fp, 0, SEEK_END );
int numBytes = ftell( fp );      // length of file

GLchar * buffer = new GLchar [numBytes+1];

rewind( fp );            // same as:  "fseek( in, 0, SEEK_SET )"
fread( buffer, 1, numBytes, fp );
fclose( fp );
buffer[numBytes] = '\0';     // the entire file is now in a byte string
```


Creating and Compiling a Vertex Shader from that character buffer (Tessellation, Geometry, and Fragment files work the same way)

```
int status;
int logLength;

GLuint  vertShader = glCreateShader( aVertex_SHADER );

glShaderSource( vertShader, 1, (const GLchar **)&buffer, NULL );
delete [  ] buffer;
glCompileShader( vertShader );
CheckGlErrors( "Vertex Shader 1" );

glGetShaderiv( vertShader, GL_COMPILE_STATUS, &status );
if( status == GL_FALSE )
{
      fprintf( stderr, "Vertex shader compilation failed.\n" );
      glGetShaderiv( vertShader, GL_INFO_LOG_LENGTH, &logLength );
      GLchar *  log = new GLchar [logLength];
      glGetShaderInfoLog( vertShader, logLength, NULL, log );
      fprintf( stderr, "\n%s\n", log );
      delete [  ] log;
      exit( 1 );
}
CheckGlErrors( "Vertex Shader 2" );
```

How does that array of strings thing work?

```
GLchar * ArrayOfStrings[3];
ArrayOfStrings[0] = "#define SMOOTH_SHADING";
ArrayofStrings[1] = " . . . a commonly-used procedure . . . ";
ArrayofStrings[2] = " . . . the real vertex shader code . .. ";
glShaderSource( vertShader, 3, ArrayofStrings, NULL );
```

These are two ways to provide a *single* character buffer:

```
GLchar *buffer[1];
buffer[0] = " . . . the entire shader code . . . ";
glShaderSource( vertShader, 1, buffer, NULL );
```

```
GLchar *buffer = " . . . the entire shader code . . . ";
glShaderSource( vertShader, 1, (const GLchar **)&buffer, NULL );
```


Why use an array of strings as the shader input, instead of just a single string?

- You can use the same shader source and insert the appropriate #defines at the beginning
- You can insert a common header file (≈ a .h file)
- You can simulate a #include to re-use common pieces of code

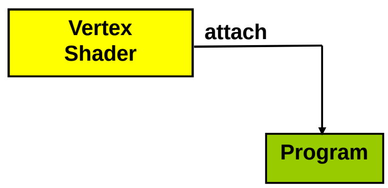
If-tests versus preprocessing

```
if( Mode == PerVertexShading )
{ . . . }
else if( Mode == PerFragmentShading )
{ . . . }
```

```
#ifdef PER_VERTEX_SHADING
{ . . . }
#endif

#ifdef PER_FRAGMENT_SHADING
{ . . . }
#endif
```

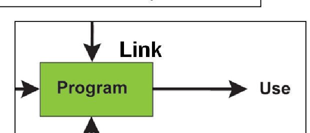
Creating the Program and Attaching the Shaders to It

```
GLuint  program = glCreateProgram( );

glAttachShader( program, vertShader );

glAttachShader( program, tessControlShader );

glAttachShader( program, tessEvaluationShader );

glAttachShader( program, geomShader );

glAttachShader( program, fragShader );
```



Linking the Program and Checking its Validity

```
glLinkProgram( program );
CheckGlErrors( "Shader Program 1" );
glGetProgramiv( program, GL_LINK_STATUS, &status );
if( status == GL_FALSE )
{
        fprintf( stderr, “Link failed.\n” );
        glGetProgramiv( program, GL_INFO_LOG_LENGTH, &logLength );
        log = new GLchar [logLength];
        glGetProgramInfoLog( program, logLength, NULL, log );
        fprintf( stderr, “\n%s\n”, log );
        delete [ ] log;
        exit( 1 );
}
CheckGlErrors( "Shader Program 2" );

glValidateProgram( program );
glGetProgramiv( program, GL_VALIDATE_STATUS, &status );
fprintf( stderr, “Program is %s.\n”, status == GL_TRUE ? “valid” : “invalid” );
```



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mjb -- May 23. 2012

Making the Program Active

```
glUseProgram( program );
```

This is now an "attribute", i.e., this shader combination is in effect until you change it

Making the Program Inactive (use the fixed function pipeline instead)

```
glUseProgram( 0 );
```


Passing in Uniform Variables

```
float lightLoc[3] = { 0., 100., 0. };

GLint location = glGetUniformLocation( program, "uLightLocation" );

if( location < 0 )
		fprintf( stderr, "Cannot find Uniform variable 'uLightLocation'\n" );
else
		glUniform3fv( location, 3, lightLoc );
```

In the shader, this would be declared as:

uniform vec3 uLightLocation;

Passing in Vertex Attribute Variables

```
Glint   location = glGetAttribLocation( program, "aArray" );

if( location < 0 )
 {
        fprintf( stderr, "Cannot find Attribute variable 'aArray'\n" );
 }
else
{
        glBegin( GL_TRIANGLES );
                glVertexAttrib2f( location, a0, b0 );
                glVertex3f( x0, y0, z0 );

                glVertexAttrib2f( location, a1, b1 );
                glVertex3f( x1, y1, z1 );

                glVertexAttrib2f( location, a2, b2 );
                glVertex3f( x2, y2, z2 );
        glEnd( );
}
```

We are using the deprecated glBegin-glVertex-glEnd process here for to keep this code concise and clear.

In the vertex shader, this would be declared as:

in vec2 aArray;

Checking for Errors

```
void
CheckGlErrors( const char* caller )
{
        unsigned int glerr = glGetError();
        if( glerr == GL_NO_ERROR )
                return;
        fprintf( stderr, "GL Error discovered from caller '%s': ", caller );
        switch( glerr )
        {
                case GL_INVALID_ENUM:
                        fprintf( stderr, "Invalid enum.\n" );
                        break;
                case GL_INVALID_VALUE:
                        fprintf( stderr, "Invalid value.\n" );
                        break;
                case GL_INVALID_OPERATION:
                        fprintf( stderr, "Invalid Operation.\n" );
                        break;
                case GL_STACK_OVERFLOW:
                        fprintf( stderr, "Stack overflow.\n" );
                        break;
                case GL_STACK_UNDERFLOW:
                        fprintf(stderr, "Stack underflow.\n" );
                        break;
                case GL_OUT_OF_MEMORY:
                        fprintf( stderr, "Out of memory.\n" );
                        break;
                case GL_INVALID_FRAMEBUFFER_OPERATION:
                        fprintf( stderr, ""Framebuffer object is not complete\n" );
                        break;
                default:
                        fprintf( stderr, "Unknown OpenGL error: %d (0x%0x)\n", glerr, glerr );
        }
```

This is not a bad idea to do all through your OpenGL programs, even without shaders!

Writing a C++ Class to Handle Everything is Fairly Straightforward

Setup:

```
int Polar;
float K;
GLSLProgram *Hyper = new GLSLProgram("hyper.vert", "hyper.geom", "hyper.frag" );
```

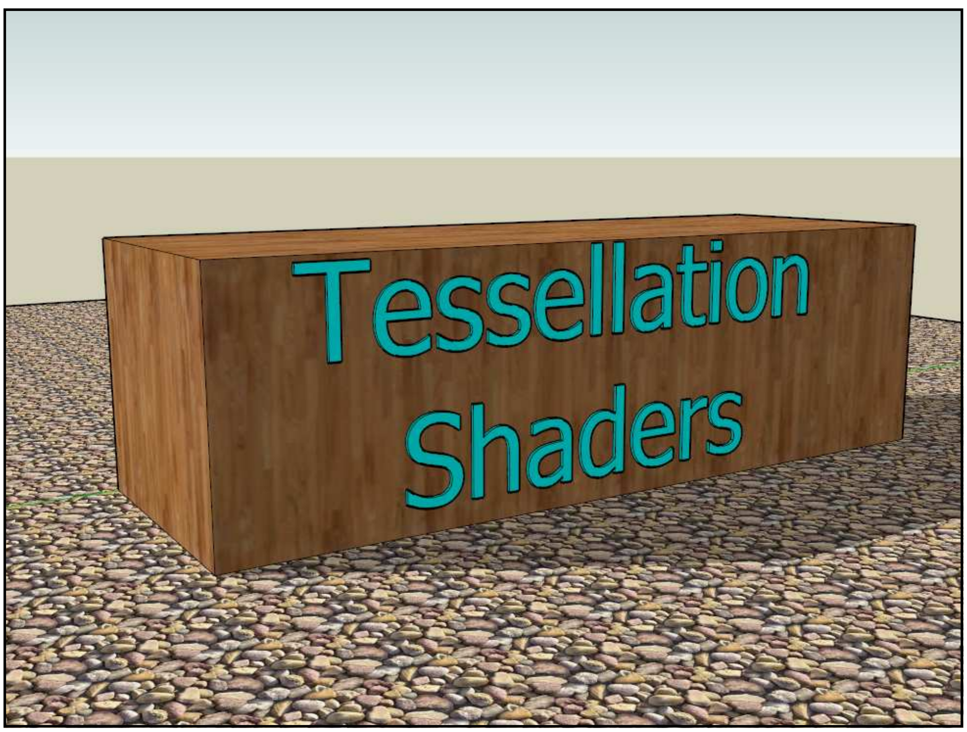
This loads, compiles, and links the shader.
It prints error messages and returns NULL if something failed.

Using the GPU program during display:

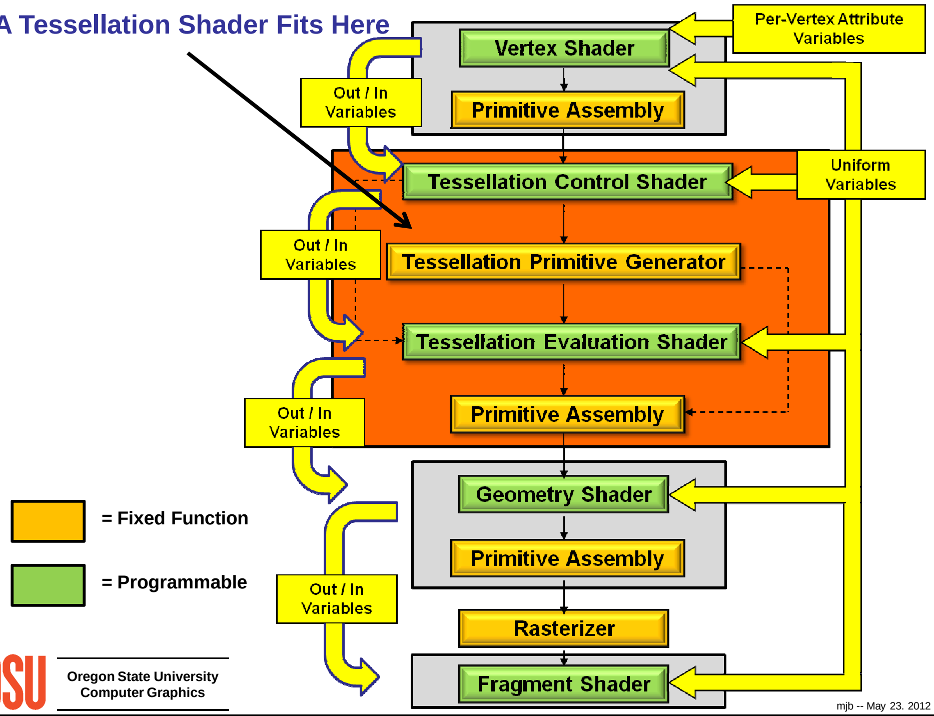
```
Hyper->Use( );
Hyper->SetUniform( "Polar", Polar );
Hyper->SetUniform( "K", K );
```

Reverting to the fixed-function pipeline during display:

```
Hyper->Use( 0 );
```

A Tessellation Shader Fits Here

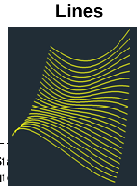


Why do we need a Tessellation step right in the pipeline?

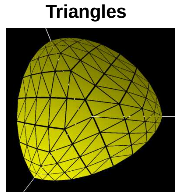
- You can perform adaptive subdivision based on a variety of criteria (size, curvature, screen extent, etc.)
- You can provide coarser models (≈ geometric compression)
- You can apply detailed displacement maps without supplying equally detailed geometry
- You can adapt visual quality to the required level of detail
- You can create smoother silhouettes
- You can perform skinning easier

What patterns can Tessellation shaders use?

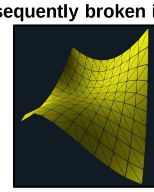
Lines



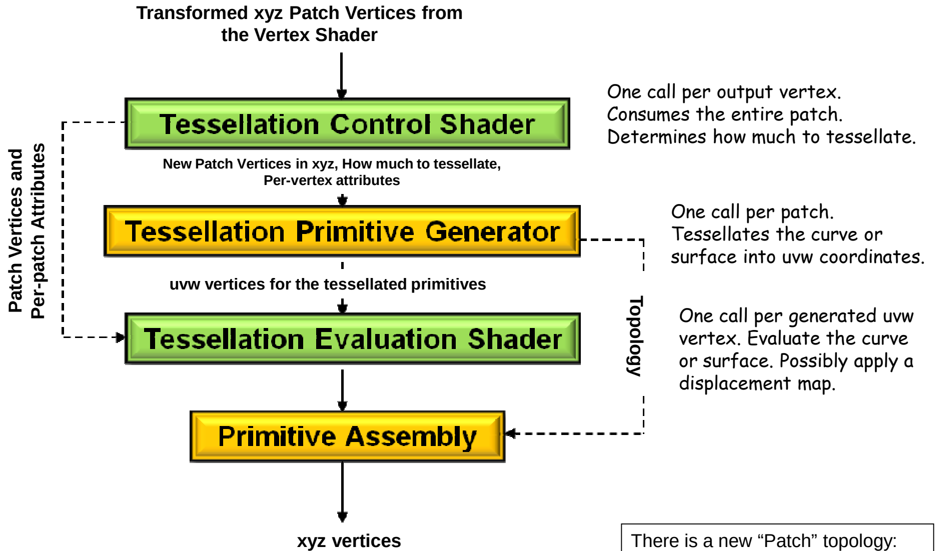
Triangles



Quads (subsequently broken into triangles)



Tessellation Shader Organization



There is a new "Patch" topology:
`glBegin( GL_PATCHES )`
There is no implied vertex order.

Tessellation Shader Organization

The **Tessellation Control Shader (TCS)** transforms the input coordinates to a regular surface representation. It also computes the required tessellation level based on distance to the eye, screen space spanning, hull curvature, or displacement roughness. There is one invocation per output vertex.

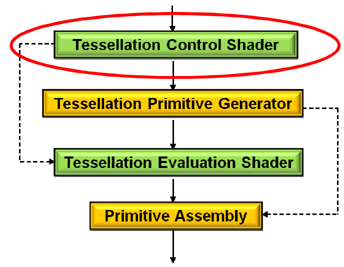
The Fixed-Function **Tessellation Primitive Generator (TPG)** generates semi-regular u-v-w coordinates. There is one invocation per patch.

The **Tessellation Evaluation Shader (TES)** evaluates the surface in *uvw* coordinates. It interpolates attributes and applies displacements. There is one invocation per generated vertex.

There is a new "Patch" primitive – it is the face and its neighborhood:
glBegin(GL_PATCHES)
There is no implied order – that is user-given.

TCS Outputs

gl_out[ ] is an array of structures containing:
gl_Position;
gl_PointSize;
gl_ClipDistance[ ];



All invocations of the TCS have read-only access to all the output information. **barrier( )** causes all instances of TCS's to wait here

layout(vertices = n) out; Used to specify the number of output vertices

gl_TessLevelOuter[4] is an array containing up to 4 edges of tessellation levels

gl_TessLevelInner[2] is an array containing up to 2 edges of tessellation levels

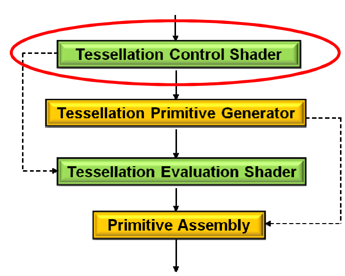
In the TCS

User-defined variables defined per-vertex are qualified as "out"

User-defined variables defined per-patch are qualified as "patch out"

Defining how many vertices this patch will output:

layout(vertices = 16) out;



Tessellation Primitive Generator

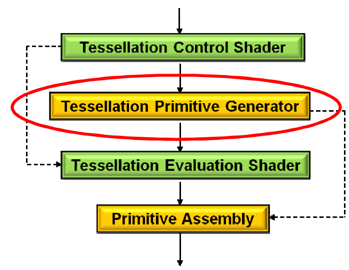
Is “fixed-function”, i.e., you can’t change its operation except by setting parameters

Consumes all vertices from the TCS and emits tessellated triangles, quads, or lines

Outputs positions as coordinates in barycentric (u,v,w)

All three coordinates (u,v,w) are used for triangles

Just (u,v) are used for quads and isolines

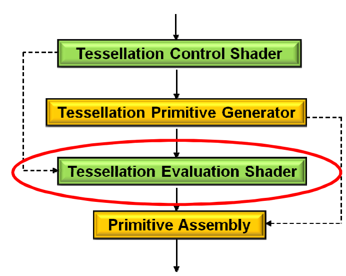


TES Inputs

Reads one vertex of 0 <= (u,v,w) <= 1 coordinates in variable *vec3 gl_TessCoord*

User-defined variables defined per-vertex are qualified as “out”
User-defined variables defined per-patch are qualified as “patch out”

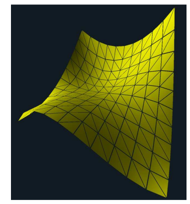
gl_in[ ] is an array of structures coming from the TCS containing:
gl_Position;
gl_PointSize;
gl_ClipDistance[ ];

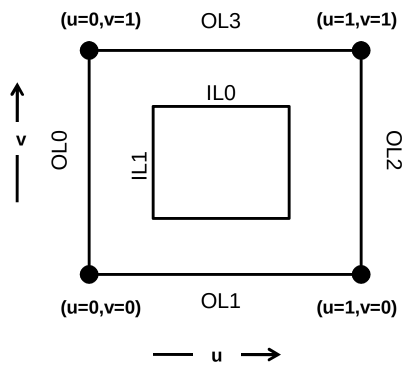


$$\text{layout(}\left\{\begin{array}{c}\text{triangles}\\ \text{quads}\\ \text{isolines}\end{array}\right\},\left\{\begin{array}{c}\text{equal\_spacing}\\ \text{fractional\_even\_spacing}\\ \text{fractional\_odd\_spacing}\end{array}\right\},\left\{\begin{array}{c}\text{ccw}\\ \text{cw}\end{array}\right\}\text{, point\_mode) in;}$$

TES Output Patterns

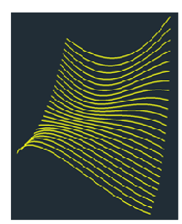
"quads"

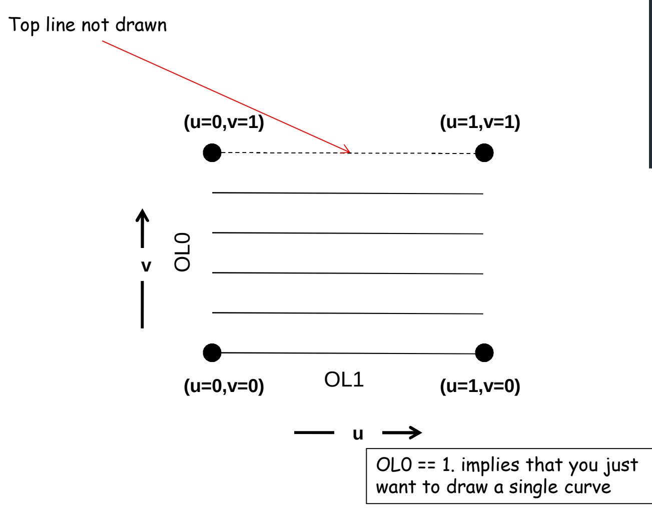




TES Output Patterns

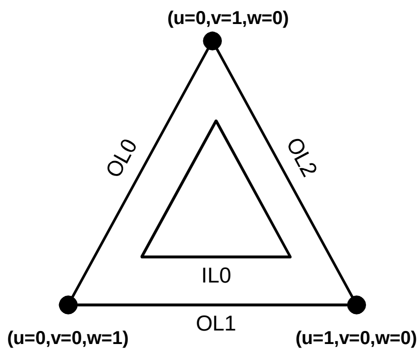
"isolines"

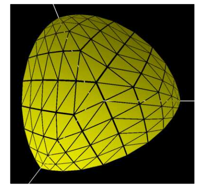


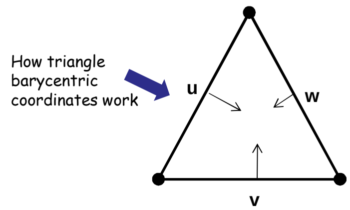


TES Output Patterns

"triangles"







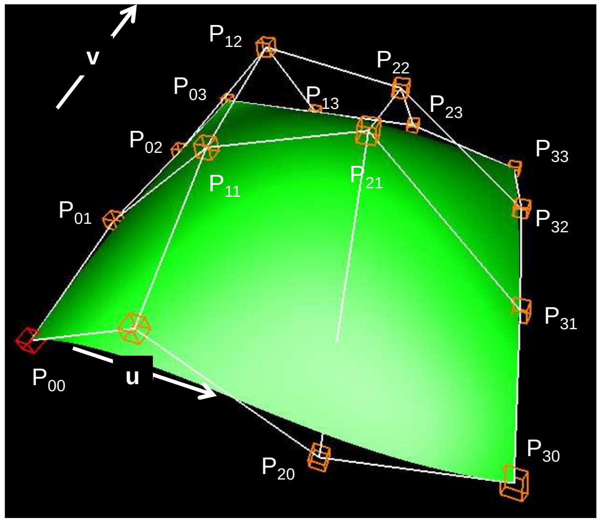
Examples

In these examples:

1. We are using *glman* to run them. The only necessary input files are the *glman* .glib file and the shader files. If you aren't using *glman*, you can easily also do this from a full OpenGL program.

2. All of the surface examples use the Geometry Shader *triangle-shrink* shader. This isn't necessary, but is instructional to really see how much and where the surfaces have been tessellated.

Example: A Bézier Surface



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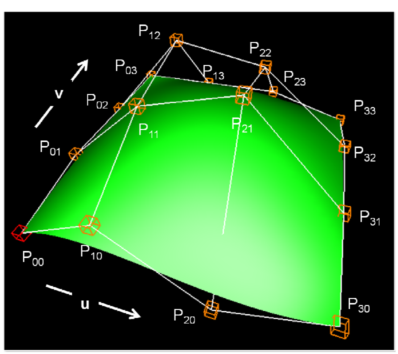
Bézier Surface Parametric Equations



$$P(u,v)=\begin{bmatrix}(1-u)^3 & 3u(1-u)^2 & 3u^2(1-u) & u^3\end{bmatrix}\begin{bmatrix}P_{00} & P_{01} & P_{02} & P_{03}\\ P_{10} & P_{11} & P_{12} & P_{13}\\ P_{20} & P_{21} & P_{22} & P_{23}\\ P_{30} & P_{31} & P_{32} & P_{33}\end{bmatrix}\begin{Bmatrix}(1-v)^3\\ 3v(1-v)^2\\ 3v^2(1-v)\\ v^3\end{Bmatrix}$$

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In the OpenGL Program

glPatchParameteri(GL_PATCH_VERTICES, 16);

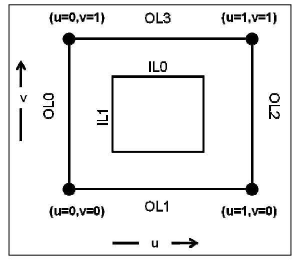
glBegin(GL_PATCHES);
glVertex3f(x_{00}, y_{00}, z_{00});
glVertex3f(x_{10}, y_{10}, z_{10});
glVertex3f(x_{20}, y_{20}, z_{20});
glVertex3f(x_{30}, y_{30}, z_{30});
glVertex3f(x_{01}, y_{01}, z_{01});
glVertex3f(x_{11}, y_{11}, z_{11});
glVertex3f(x_{21}, y_{21}, z_{21});
glVertex3f(x_{31}, y_{31}, z_{31});
glVertex3f(x_{02}, y_{02}, z_{02});
glVertex3f(x_{12}, y_{12}, z_{12});
glVertex3f(x_{22}, y_{22}, z_{22});
glVertex3f(x_{32}, y_{32}, z_{32});
glVertex3f(x_{03}, y_{03}, z_{03});
glVertex3f(x_{13}, y_{13}, z_{13});
glVertex3f(x_{23}, y_{23}, z_{23});
glVertex3f(x_{33}, y_{33}, z_{33});
glEnd( );

This order is unimportant. Pick a convention yourself and stick to it! GLSL doesn't care as long as you are consistent.

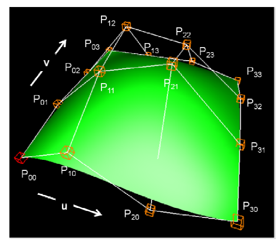
In the .glib File

```
##OpenGL GLIB
Perspective 70

GeometryInput     gl_triangles
GeometryOutput   gl_triangle_strip

Vertex            beziersurface.vert
Fragment          beziersurface.frag
TessControl       beziersurface.tcs
TessEvaluation beziersurface.tes
Geometry          beziersurface.geom
Program BezierSurface  uOuter02 <1 10 50>  uOuter13 <1 10 50>  uInner0 <1 10 50>  uInner1 <1 10 50>    \
                                uShrink <0. 1. 1.>                                                    \
                                u LightX <-10. 0. 10.>  u LightY <-10. 10. 10.>   uLightZ <-10. 10. 10. >

Color [1. 1. 0.]

NumPatchVertices 16

glBegin gl_patches
   glVertex 0. 2. 0.
   glVertex 1. 1. 0.
   glVertex 2. 1. 0.
   glVertex 3. 2. 0.

   glVertex 0. 1. 1.
   glVertex 1. -2. 1.
   glVertex 2. 1. 1.
   glVertex 3. 0. 1.

   glVertex 0. 0. 2.
   glVertex 1. 1. 2.
   glVertex 2. 0. 2.
   glVertex 3. -1. 2.

   glVertex 0. 0. 3.
   glVertex 1. 1. 3.
   glVertex 2. -1. 3.
   glVertex 3. -1. 3.
glEnd
```

In the TCS Shader

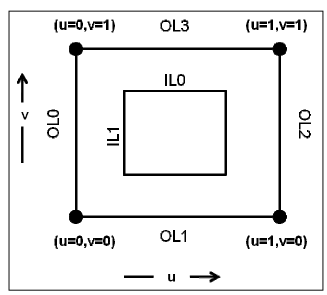


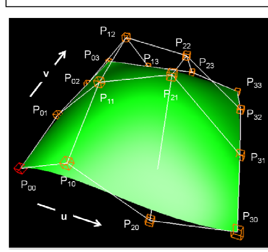

```
#version 400
#extension GL_ARB_tessellation_shader : enable

uniform float uOuter02, uOuter13, uInner0, uInner1;

layout( vertices = 16 )  out;

void main( )
{
        gl_out[ gl_InvocationID ].gl_Position = gl_in[ gl_InvocationID ].gl_Position;

        gl_TessLevelOuter[0] = gl_TessLevelOuter[2] = uOuter02;
        gl_TessLevelOuter[1] = gl_TesslevelOuter[3]  = uOuter13;
        gl_TessLevelInner[0]  = uInner0;
        gl_TessLevelInner[1]  = uInner1;
}
```



In the TES Shader

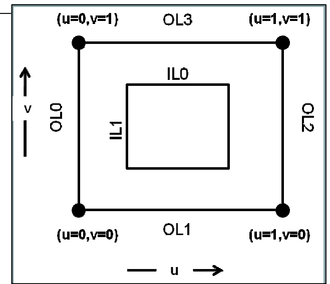
```
#version 400 compatibility
#extension GL_ARB_tessellation_shader : enable

layout( quads, equal_spacing, ccw)  in;

out vec3 teNormal;

void main(  )
{
        vec4 p00 = gl_in[ 0].gl_Position;
        vec4 p10 = gl_in[ 1].gl_Position;
        vec4 p20 = gl_in[ 2].gl_Position;
        vec4 p30 = gl_in[ 3].gl_Position;
        vec4 p01 = gl_in[ 4].gl_Position;
        vec4 p11 = gl_in[ 5].gl_Position;
        vec4 p21 = gl_in[ 6].gl_Position;
        vec4 p31 = gl_in[ 7].gl_Position;
        vec4 p02 = gl_in[ 8].gl_Position;
        vec4 p12 = gl_in[ 9].gl_Position;
        vec4 p22 = gl_in[10].gl_Position;
        vec4 p32 = gl_in[11].gl_Position;
        vec4 p03 = gl_in[12].gl_Position;
        vec4 p13 = gl_in[13].gl_Position;
        vec4 p23 = gl_in[14].gl_Position;
        vec4 p33 = gl_in[15].gl_Position;

        float u = gl_TessCoord.x;
        float v = gl_TessCoord.y;
```





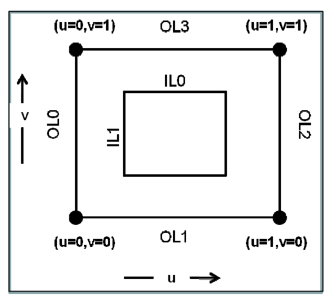
Assigning the intermediate pij's is here to make the code more readable. We assume that the compiler will optimize this away.

In the TES Shader – Computing the Position



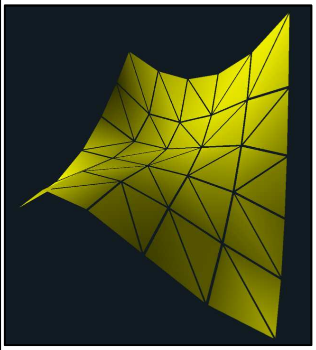

```
// the basis functions:

float bu0 = (1.-u) * (1.-u) * (1.-u);
float bu1 = 3. * u * (1.-u) * (1.-u);
float bu2 = 3. * u * u * (1.-u);
float bu3 = u * u * u;

float dbu0 = -3. * (1.-u) * (1.-u);
float dbu1 =  3. * (1.-u) * (1.-3.*u);
float dbu2 =  3. * u *      (2.-3.*u);
float dbu3 =  3. * u *      u;

float bv0 = (1.-v) * (1.-v) * (1.-v);
float bv1 = 3. * v * (1.-v) * (1.-v);
float bv2 = 3. * v * v * (1.-v);
float bv3 = v * v * v;

float dbv0 = -3. * (1.-v) * (1.-v);
float dbv1 =  3. * (1.-v) * (1.-3.*v);
float dbv2 =  3. * v *      (2.-3.*v);
float dbv3 =  3. * v *      v;

// finally, we get to compute something:

gl_Position =           bu0 * ( bv0*p00 + bv1*p01 + bv2*p02 + bv3*p03 )
                      + bu1 * ( bv0*p10 + bv1*p11 + bv2*p12 + bv3*p13 )
                      + bu2 * ( bv0*p20 + bv1*p21 + bv2*p22 + bv3*p23 )
                      + bu3 * ( bv0*p30 + bv1*p31 + bv2*p32 + bv3*p33 );
```


In the TES Shader – Computing the Normal



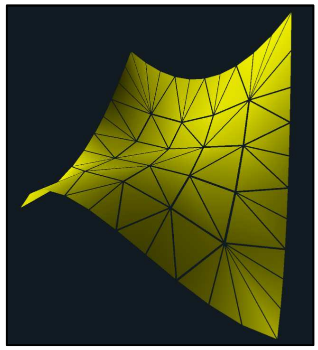

```
vec4 dpdu =              dbu0 * ( bv0*p00 + bv1*p01 + bv2*p02 + bv3*p03 )
                       + dbu1 * ( bv0*p10 + bv1*p11 + bv2*p12 + bv3*p13 )
                       + dbu2 * ( bv0*p20 + bv1*p21 + bv2*p22 + bv3*p23 )
                       + dbu3 * ( bv0*p30 + bv1*p31 + bv2*p32 + bv3*p33 );

vec4 dpdv =              bu0 * ( dbv0*p00 + dbv1*p01 + dbv2*p02 + dbv3*p03 )
                       + bu1 * ( dbv0*p10 + dbv1*p11 + dbv2*p12 + dbv3*p13 )
                       + bu2 * ( dbv0*p20 + dbv1*p21 + dbv2*p22 + dbv3*p23 )
                       + bu3 * ( dbv0*p30 + dbv1*p31 + dbv2*p32 + dbv3*p33 );

teNormal = normalize( cross( dpdu.xyz, dpdv.xyz ) );
}
```

Example: A Bézier Surface

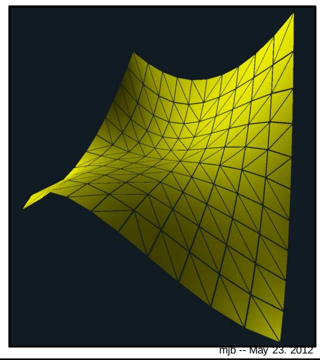


uOuter02 = uOuter13 = 5
uInner0 = uInner1 = 5

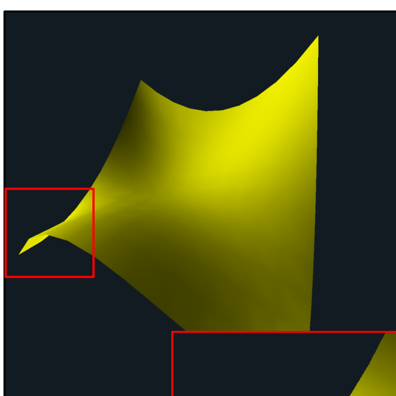
uOuter02 = uOuter13 = 10
uInner0 = uInner1 = 5

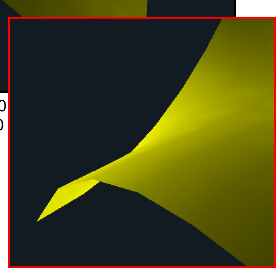


uOuter02 = uOuter13 = 10
uInner0 = uInner1 = 10

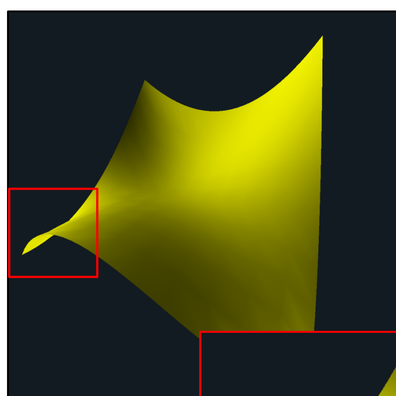


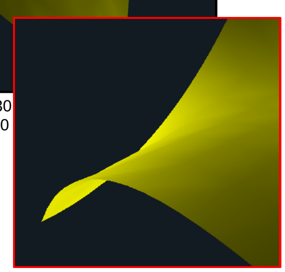
Tessellation Levels and Smooth Shading





uOuter02 = uOuter13 = 10
uInner0 = uInner1 = 10





uOuter02 = uOuter13 = 30
uInner0 = uInner1 = 10

Smoothing edge boundaries is one of the reasons that you can set Outer and Inner tessellation levels separately

Example: Whole-Sphere Subdivision

spheresubd.glib

```
##OpenGL GLIB

Vertex          spheresubd.vert
Fragment        spheresubd.frag
TessControl     spheresubd.tcs
TessEvaluation  spheresubd.tes
Geometry        spheresubd.geom
Program SphereSubd                                    \
                uDetail <1 30 200>                    \
                uScale <0.1 1. 10.>                   \
                uShrink <0. 1. 1.>                    \
                uFlat <false>                         \
                uColor {1. 1. 0. 0.}                  \
                uLightX <-10. 5. 10.>  uLightY <-10. 10. 10.>  uLightZ <-10. 10. 10.>

Color 1. 1. 0.

NumPatchVertices 1

glBegin gl_patches
                glVertex 0. 0. 0. .2
                glVertex 0. 1. 0. .3
                glVertex 0. 0. 1. .4
glEnd
```

Using the x, y, z, and w to specify the center and radius of the sphere

Example: Whole-Sphere Subdivision

spheresubd.vert

```
#version 400 compatibility

out vec3  vCenter;
out float   vRadius;

void main( )
{
                vCenter = aVertex.xyz;
                vRadius = aVertex.w;

                gl_Position = vec4( 0., 0., 0., 1. );
}
```

Using the x, y, z, and w to specify the center and radius of the sphere

Example: Whole-Sphere Subdivision

spheresubd.tcs

```
#version 400 compatibility
#extension GL_ARB_tessellation_shader : enable

in float   vRadius[ ];
in vec3  vCenter[ ];

patch out float   tcRadius;
patch out vec3  tcCenter;

uniform float uDetail;
uniform float uScale;

layout( vertices = 1 )  out;

void main( )
{
        gl_out[ gl_InvocationID ].gl_Position = gl_in[ 0 ].gl_Position;     // (0,0,0,1)

        tcCenter = vCenter[ 0 ];
        tcRadius = vRadius[ 0 ];

        gl_TessLevelOuter[0] = 2.;
        gl_TessLevelOuter[1] = uScale * tcRadius * uDetail;
        gl_TessLevelOuter[2] = 2.;
        gl_TessLevelOuter[3] = uScale * tcRadius * uDetail;
        gl_TessLevelInner[0]  = uScale * tcRadius * uDetail;
        gl_TessLevelInner[1]  = uScale * tcRadius * uDetail;
}
```

Using the scale and the radius to help set the tessellation detail

Outer[0] and Outer[2] are the number of divisions at the poles. Outer[1] and Outer[3] are the vertical seams. Inner[0] and Inner[1] are the inside sphere detail.

Example: Whole-Sphere Subdivision

spheresubd.tes

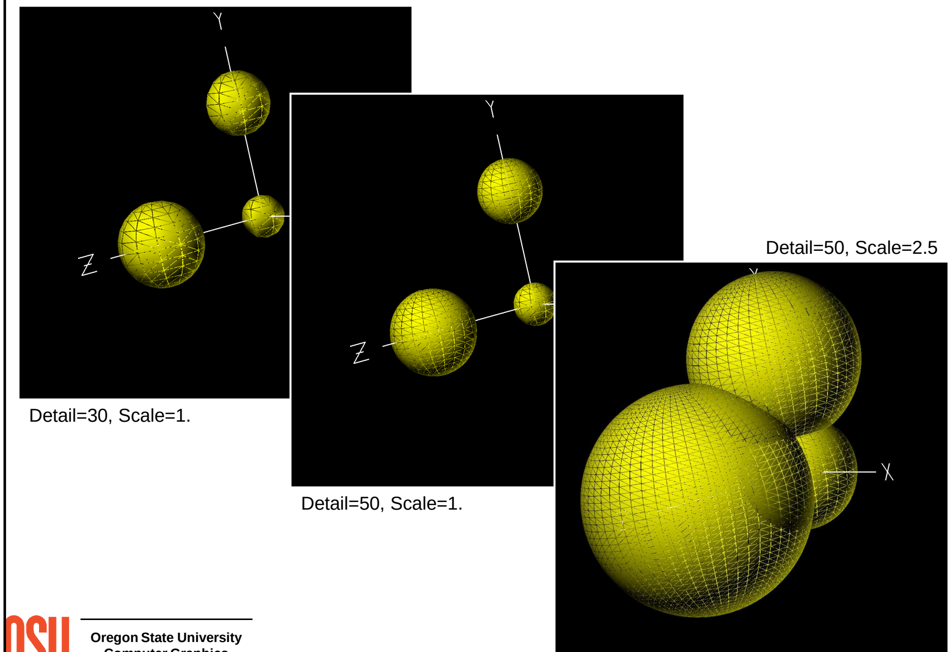
```
#version 400 compatibility
#extension GL_ARB_tessellation_shader : enable

uniform float uScale;

layout( quads, equal_spacing, ccw)  in;

patch in float   tcRadius;
patch in vec3  tcCenter;

out vec3 teNormal;

const float PI = 3.14159265;

void main( )
{
        vec3 p = gl_in[0].gl_Position.xyz;

        float u  = gl_TessCoord.x;
        float v  = gl_TessCoord.y;
        float w = gl_TessCoord.z;

        float phi    =       PI * ( u - .5 );
        float theta = 2. * PI * ( v - .5 );

        float cosphi = cos(phi);
        vec3 xyz = vec3( cosphi*cos(theta), sin(phi), cosphi*sin(theta) );
        teNormal = xyz;

        xyz *= ( uScale * tcRadius );
        xyz += tcCenter;

        gl_Position = uModelViewMatrix * vec4( xyz,1. );
}
```

$-\frac{\pi}{2} \le \phi \le +\frac{\pi}{2}$

$-\pi \le \theta \le +\pi$

Turning u and v into spherical coordinates

Example: Whole-Sphere Subdivision



Detail=30, Scale=1.

Detail=50, Scale=1.

Detail=50, Scale=2.5

Making the Whole-Sphere Subdivision Adapt to Screen Coverage

sphereadapt.tcs, I

```
#version 400 compatibility
#extension GL_ARB_tessellation_shader : enable

in float   vRadius[  ];
in vec3  vCenter[  ];

patch out float   tcRadius;
patch out vec3  tcCenter;

uniform float uDetail;

layout( vertices = 1 )  out;

void main( )
{
                gl_out[ gl_InvocationID ].gl_Position = gl_in[ 0 ].gl_Position;          // (0,0,0,1)

                tcCenter = vCenter[ 0 ];
                tcRadius = vRadius[ 0 ];

                vec4 mx = vec4( vCenter[0] - vec3( vRadius[0], 0., 0. ),  1. );
                vec4 px  = vec4( vCenter[0] + vec3( vRadius[0], 0., 0. ),  1. );
                vec4 my = vec4( vCenter[0] - vec3( 0., vRadius[0], 0. ),  1. );
                vec4 py  = vec4( vCenter[0] + vec3( 0., vRadius[0], 0. ),  1. );
                vec4 mz = vec4( vCenter[0] - vec3( 0., 0., vRadius[0] ),  1. );
                vec4 pz  = vec4( vCenter[0] + vec3( 0., 0., vRadius[0] ),  1. );
```

Extreme points of the sphere

Making the Whole-Sphere Subdivision Adapt to Screen Coverage

sphereadapt.tcs, II

```
        mx = uModelViewProjectionMatrix * mx;
        px  = uModelViewProjectionMatrix * px;
        my = uModelViewProjectionMatrix * my;
        py  = uModelViewProjectionMatrix * py;
        mz = uModelViewProjectionMatrix * mz;
        pz  = uModelViewProjectionMatrix * pz;

        mx.xy /= mx.w;
        px.xy  /= px.w;
        my.xy /= my.w;
        py.xy  /= py.w;
        mz.xy /= mz.w;
        pz.xy  /= pz.w;

        float dx = distance( mx.xy,  px.xy );
        float dy = distance( my.xy,  py.xy );
        float dz = distance( mz.xy,  pz.xy );
        float dmax = sqrt( dx*dx + dy*dy + dz*dz );

        gl_TessLevelOuter[0] = 2.;
        gl_TessLevelOuter[1] = dmax * uDetail;
        gl_TessLevelOuter[2] = 2.;
        gl_TessLevelOuter[3] = dmax * uDetail;
        gl_TessLevelInner[0]  = dmax * uDetail;
        gl_TessLevelInner[1]  = dmax * uDetail;
}
```

Extreme points of the sphere in Clip space

Extreme points of the sphere in NDC space

How large are the lines between the extreme points?

We no longer use uScale or tcRadius. But, we do use uDetail to provide a way to convert from NDC to Screen Space or to indicate the quality you'd like

(I.e., uDetail depends on how good you want the spheres to look and on how large the window is in pixels.)

Making the Whole-Sphere Subdivision Adapt to Screen Coverage

sphereadapt.tes

```
#version 400 compatibility
#extension GL_ARB_tessellation_shader : enable

layout( quads, equal_spacing, ccw)  in;

patch in float   tcRadius;
patch in vec3  tcCenter;

out vec3         teNormal;

const float PI = 3.14159265;

void main( )
{
        vec3 p = gl_in[0].gl_Position.xyz;

        float u = gl_TessCoord.x;
        float v = gl_TessCoord.y;
        float w = gl_TessCoord.z;

        float phi = PI * ( u - .5 );
        float theta = 2. * PI * ( v - .5 );

        float cosphi = cos(phi);
        vec3 xyz = vec3( cosphi*cos(theta), sin(phi), cosphi*sin(theta) );
        teNormal = xyz;

        xyz *= tcRadius;
        xyz += tcCenter;

        gl_Position = uModelViewMatrix * vec4( xyz,1. );
}
```

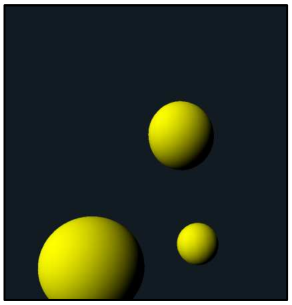
$-\frac{\pi}{2} \le \phi \le +\frac{\pi}{2}$

$-\pi \le \theta \le +\pi$

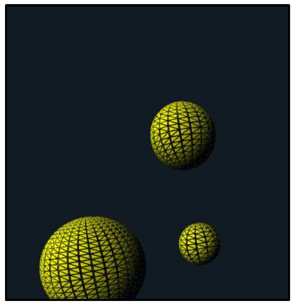
Spherical coordinates

No longer uses uScale

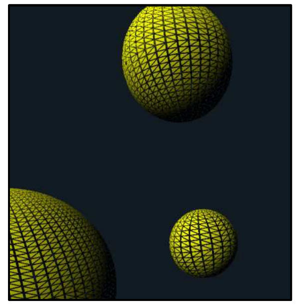
Making the Whole-Sphere Subdivision Adapt to Screen Coverage



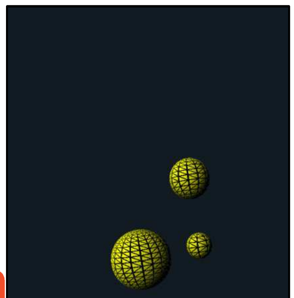
Original



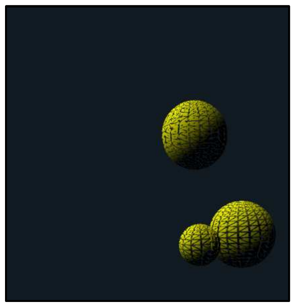
Triangles Shrunk



Zoomed In



Zoomed Out



Rotated

Notice that the number of triangles adapts to the screen coverage of each sphere, and that the size of the tessellated triangles stays about the same, regardless of radius or transformation

The Difference Between Tessellation Shaders and Geometry Shaders

By now, you are probably confused about when to use a Geometry Shader and when to use a Tessellation Shader. Both are capable of creating new geometry from existing geometry. See if this helps.

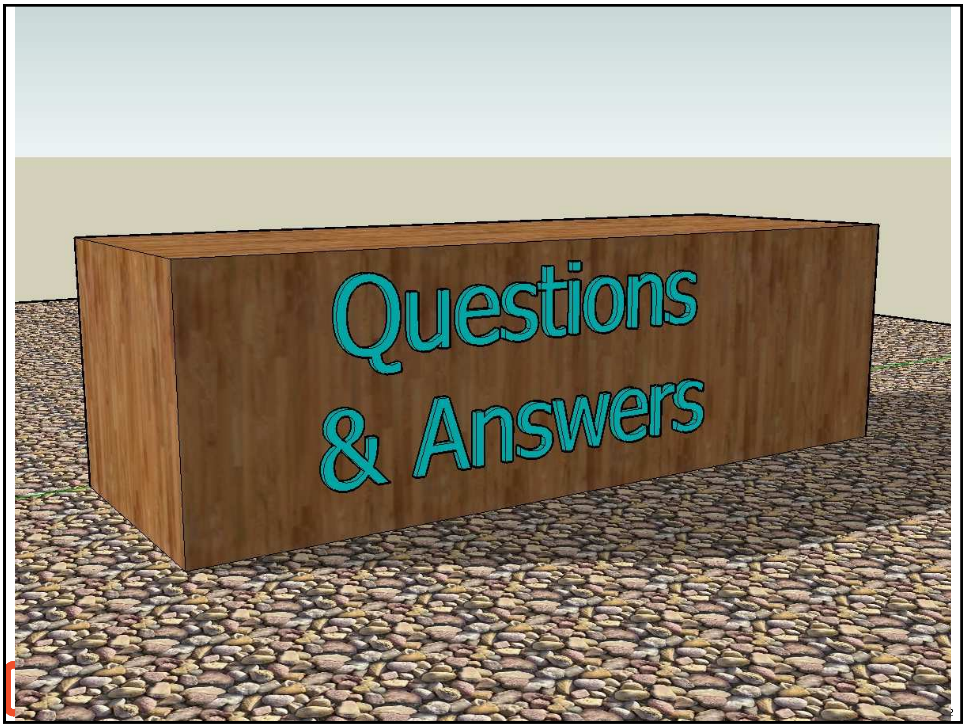
Use a **Geometry Shader** when:

1. You need to convert geometry topologies, such as the silhouette and hedgehog shaders (triangles→lines) or the explosion shader (triangles→points)

2. You need some sort of geometry processing to come after the Tessellation Shader (such as how the shrink shader was used here)

Use a **Tessellation Shader** when you need to generate many new vertices and one of the tessellation topologies will suit your needs.

Use a **Tessellation Shader** when you need more than 6 input vertices to define the surface being tessellated..



Two Windows Program Executables and Lots of Shader Files

Many of you have them on the *glman* CD

For those who don't, you can get a .zip file of everything by going to:

http://cs.oregonstate.edu/~mjb/glman

and following the link that says "SIGGRAPH 2012 Attendees"

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Oregon State University
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