Enhancing Computer Graphics Effects by Writing Shaders

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How Many Computers do you see in this Photo? One?

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No, There Are *Two* Computers Here

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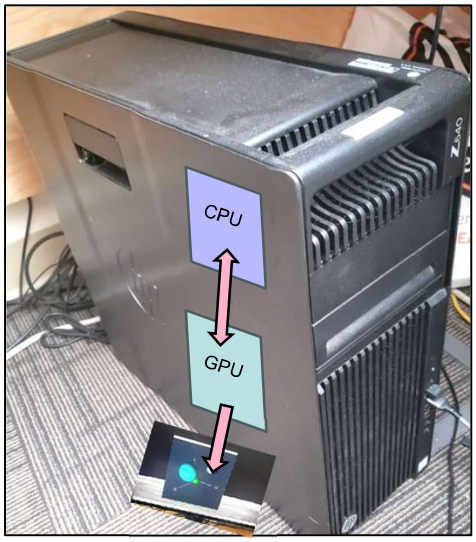
Buried within a single chassis, we are tempted to think there is just one computer here.



But there are really *two* computers here, a CPU and a GPU. So far, you have been "programming" the GPU by telling OpenGL how to do it for us. This is about to change!

No, There Are *Two* Computers Here

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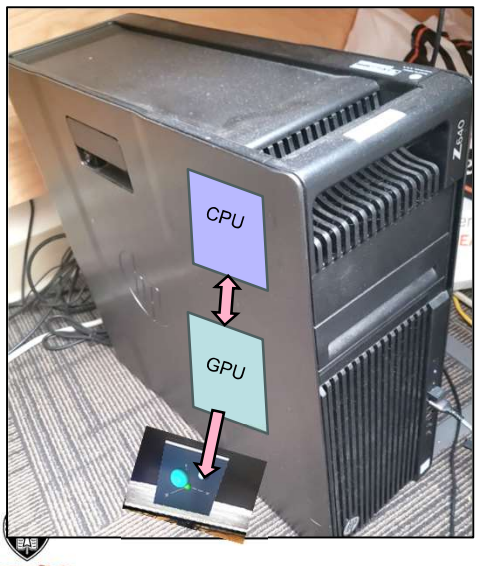
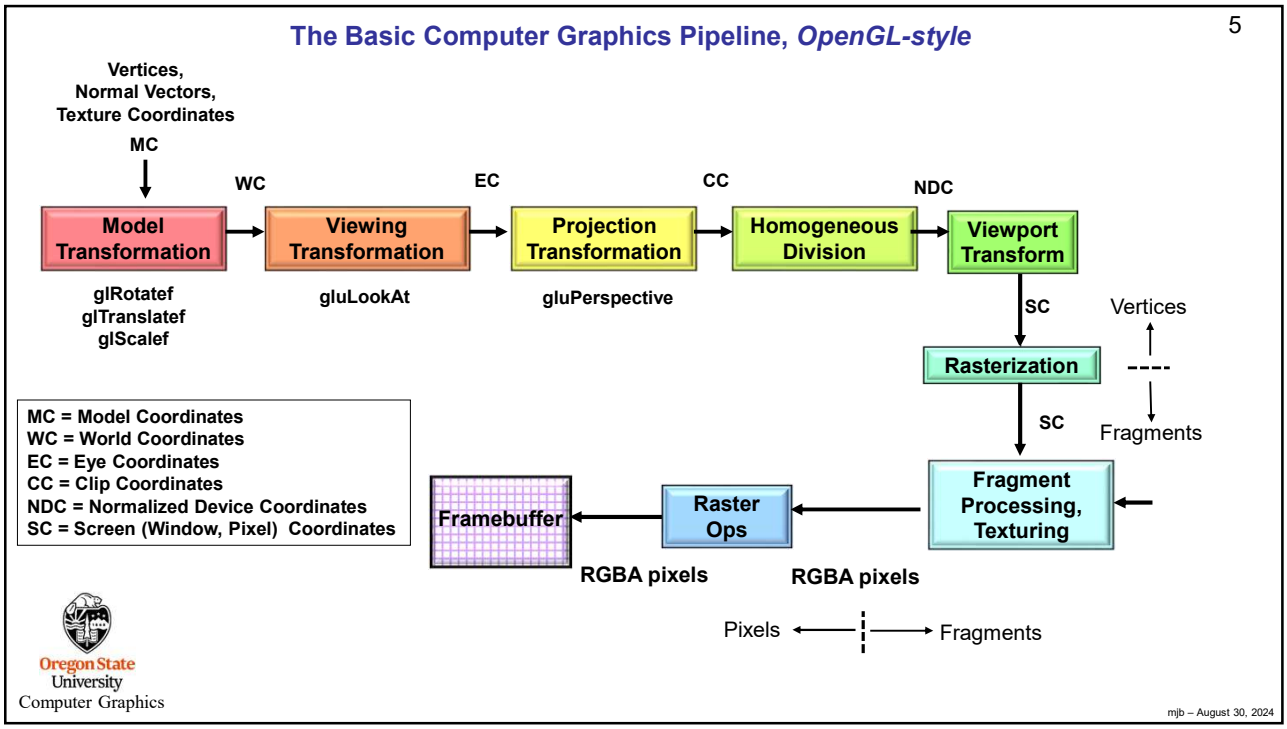


We are now going to get into a way-cool part of this class where you get to program the GPU yourself. This is called ***Shaders***.

Let's think about it. If you set out to program an external computer, here is what you would need:

1. **A programming language**
2. **A compiler for that language to create an executable**
3. **A way to see the compiler's error messages**
4. **A way to download the executable onto the external computer**
5. **A way to run that executable on the external computer**
6. **A way to get information into the executable**

This sounds like a lot, but it won't turn out to be that big a deal. Trust me!


The Basic Computer Graphics Pipeline, OpenGL-style
5
Vertices,
Normal Vectors,
Texture Coordinates
MC
WC
EC
CC
NDC
Model Transformation
Viewing Transformation
Projection Transformation
Homogeneous Division
Viewport Transform
glRotatef
glTranslatef
glScalef
gluLookAt
gluPerspective
SC
Vertices
Rasterization
Fragments
SC
MC = Model Coordinates
WC = World Coordinates
EC = Eye Coordinates
CC = Clip Coordinates
NDC = Normalized Device Coordinates
SC = Screen (Window, Pixel) Coordinates
Framebuffer
Raster Ops
Fragment Processing, Texturing
RGBA pixels
RGBA pixels
Pixels
Fragments
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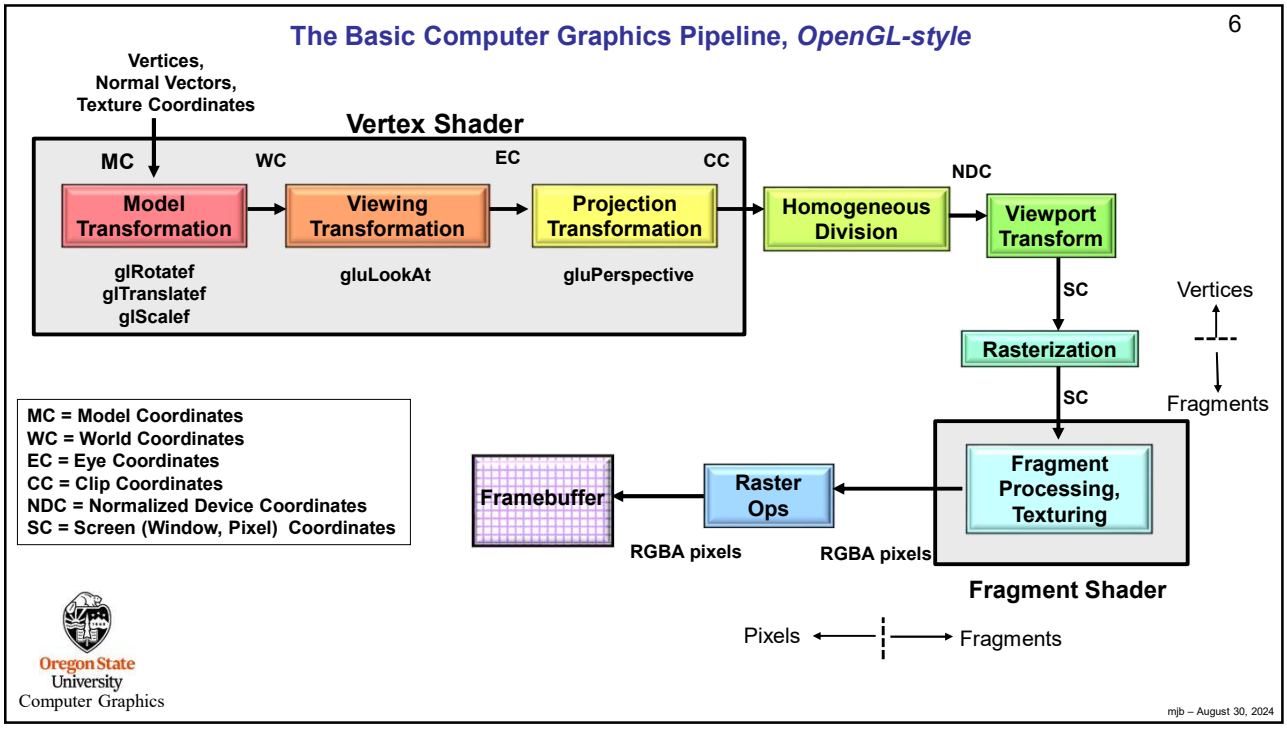
5


The Basic Computer Graphics Pipeline, OpenGL-style
6
Vertices,
Normal Vectors,
Texture Coordinates
Vertex Shader
MC
WC
EC
CC
NDC
Model Transformation
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Fragments
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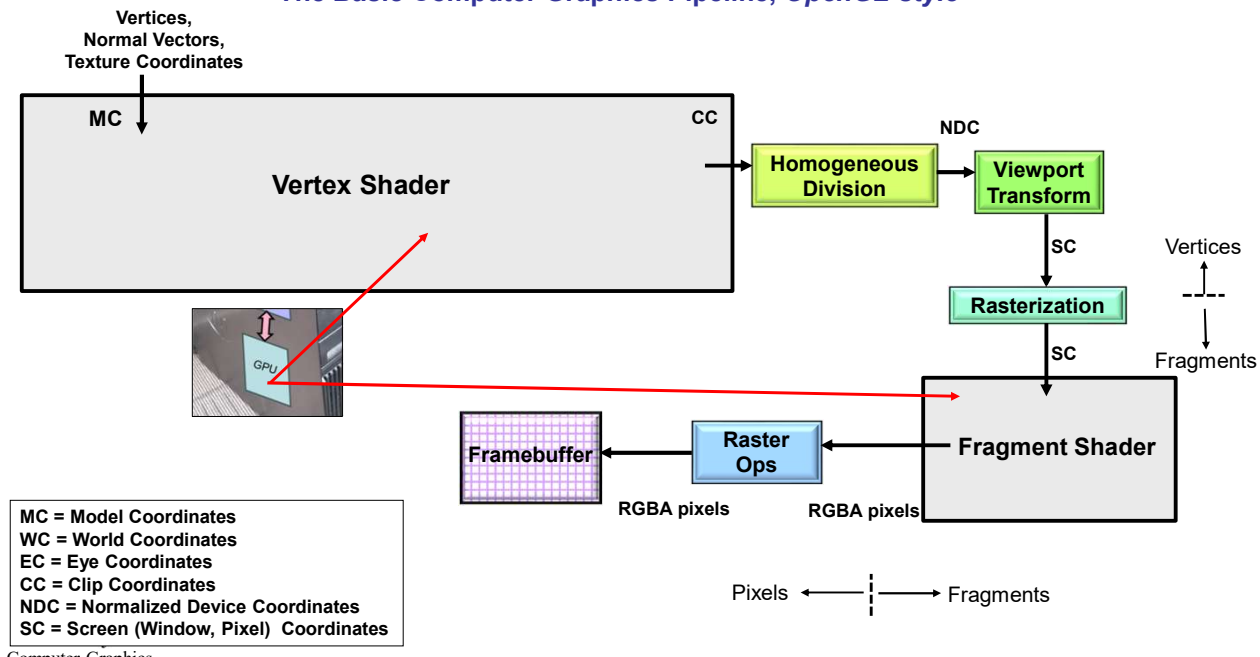
The Basic Computer Graphics Pipeline, *OpenGL-style*

7



Our Shaders' View of the Basic Computer Graphics Pipeline

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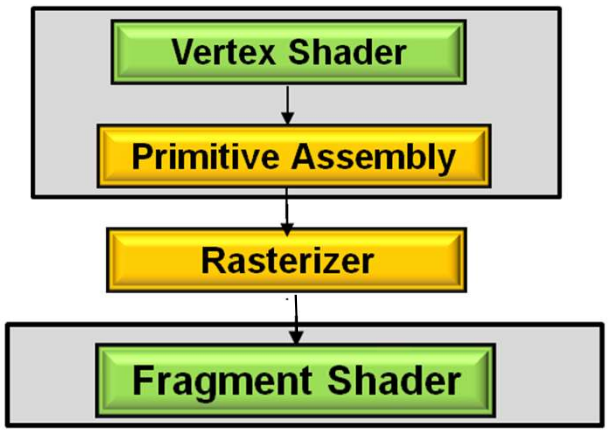
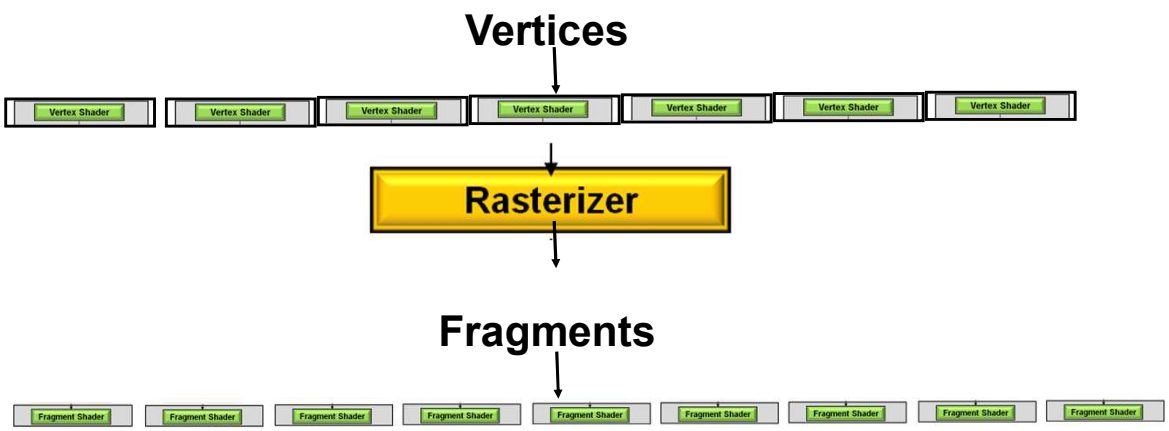
= Fixed Function (non-you-programmable)

= You-Programmable



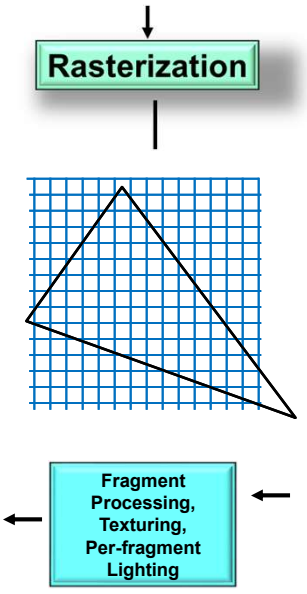
There are actually four more GLSL shader types we won't be covering here. In CS 457/557, we will cover all of them.

We Like to Draw the Diagram with One Vertex Shader and One Fragment Shader, but CG Hardware Achieves Much of its Speed by Handling Hundreds or Thousands of Vertices and Fragments at the Same Time



We talk more about the specifics of GPU parallelism in CS 475/575.

A Reminder of what a Rasterizer does



There is a piece of hardware called the **Rasterizer**. Its job is to interpolate a line or polygon, defined by vertices, into a collection of **fragments**. Think of it as filling in squares on graph paper.

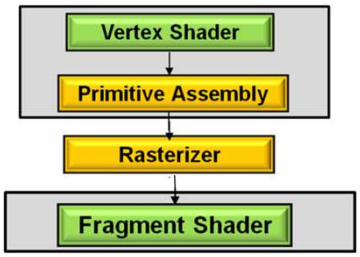
Rasterizers interpolate built-in variables, such as the (x,y) position where the pixel will live and the pixel's z-coordinate. They also interpolate the normal vector (nx,ny,nz) and the texture coordinates (s,t). They can also interpolate user-defined variables as well.

A fragment is a "pixel-to-be". In computer graphics, "pixel" is defined as having its full RGBA already computed and is headed to be stored in the framebuffer. A fragment does not yet have a computed RGBA, but all of the information needed to compute the RGBA is available.

A fragment is turned into an RGBA pixel by the **fragment processing** operation.

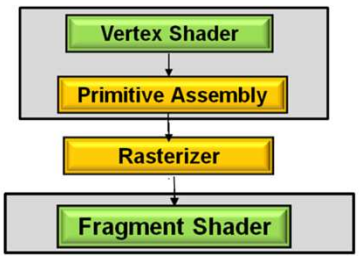
A GLSL Vertex Shader Takes Over These Operations:

- Vertex transformations
- Normal Vector transformations
- Computing per-vertex lighting (although, if you are using shaders anyway, per-fragment lighting looks better)
- Taking per-vertex texture coordinates (s,t) and interpolating them through the rasterizer into the fragment shader



A GLSL Fragment Shader Takes Over These Operations:

- Color computation
- Texture lookup
- Blending colors with textures (like GL_REPLACE and GL_MODULATE used to do)
- Discarding fragments



1. We Need a Programming Language

OpenGL developed a shader language called **GLSL: GL Shader Language.**

GLSL is very C-ish, so it should look familiar.

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GLSL has Many C-Familiar Data Types, plus Extensions for Graphics:

- Types include int, ivec2, ivec3, ivec4
- Types include float, vec2, vec3, vec4
- Types include bool, bvec2, bvec3, bvec4

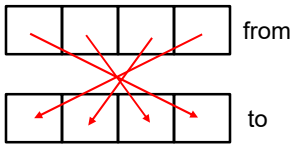
} Computer Graphics uses values in groups of 2, 3, and 4

- Vector components are accessed with .rgba, .xyzw, or.stpq
- Types include mat4

} Computer Graphics uses 4x4 matrices to transform 3D vertices

- Types include sampler1D, sampler2D, sampler3D to access textures
- You can use parallel SIMD operations (doesn't necessarily get implemented in hardware):

```
vec4 a = vec4( 1., 2., 3., 4. );
vec4 b = vec4( 5., 6., 7., 8. );
. . .
vec4 c = a + b;
```



- Vector components can be "swizzled" (to.abgr = from.rgba)
- Type qualifiers: const, uniform, in, out
- Variables can have "layout qualifiers" to describe how data is stored
- The *discard* operator is used in fragment shaders to get rid of the current fragment

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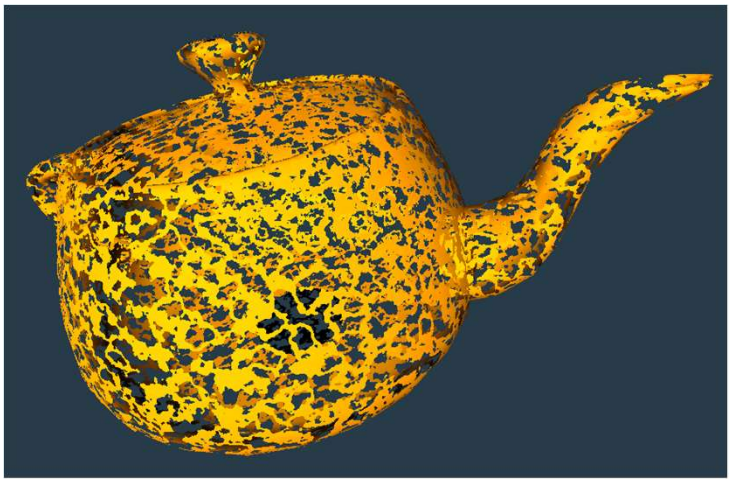
The *discard* Operator Halts Production of the Current Fragment

```
if( random_number < 0.5 )
        discard;
```



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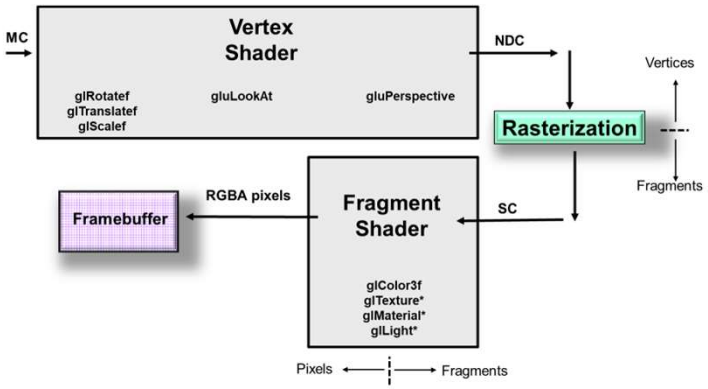
GLSL also has Some Different Variable Types to Pass Information Around

uniform These are "global" values, assigned into your GLSL program from your C++ program and left alone for a group of primitives. They are read-only accessible from all of your shaders. **They cannot be written to from a shader.**

out / in These are passed ***out*** from the vertex shader stage, interpolated in the rasterizer, and passed ***in*** to the fragment shader stage.



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GLSL has Some *Built-in* Vertex Shader Variables :

Input built-ins:

- vec4 gl_Vertex
- vec3 gl_Normal
- vec4 gl_Color
- vec4 gl_MultiTexCoord0
- mat4 gl_ModelViewMatrix
- mat4 gl_ProjectionMatrix
- mat4 gl_ModelViewProjectionMatrix (= gl_ModelViewMatrix * gl_ProjectionMatrix)
- mat3 gl_NormalMatrix (this is the transpose of the inverse of the MV matrix)

Output built-in:

- vec4 gl_Position

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Note: while this all still works, OpenGL now prefers that you pass in all the above input variables as user-defined *in* variables. We can talk about this later. For now, we are going to use the most straightforward approach possible.

GLSL has Some *Built-in* Fragment Shader Variables :

Output built-in:

- vec4 gl_FragColor = the RGBA being sent to the framebuffer

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Note: while this all still works, OpenGL now prefers that you pass the RGBA out as a user-defined *out* variable. We can talk about this later. For now, we are going to use the most straightforward approach possible.

We haven't forgotten about this.
If you set out to program an external computer, here is what you would need:

1. A programming language

   GLSL

2. A compiler for that language to create an executable

   The GLSL compiler is pre-built into the OpenGL driver. You've already got it.

3. A way to see the compiler's error messages
4. A way to download the executable onto the external computer
5. A way to run that executable on the external computer
6. A way to get information into the executable

We will give you a C++ class to take care of all of this. This is coming up soon.

.
But, first, let's take a look at what vertex and fragment shader code looks like.

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My Own Variable Naming Convention

With 7 different places that GLSL variables can be created from, I decided to adopt a naming convention to help me recognize what program-defined variables came from what sources:

Beginning letter(s)	Means that the variable …
a	Is a per-vertex in (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" GLSL – it is just *my* way of handling the chaos

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The Minimal Vertex and Fragment Shader

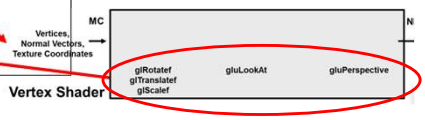
A Vertex Shader is automatically called once per vertex:

```
#version 330 compatibility

void
main( )
{
        gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

vec4 gl_Vertex
vec3 gl_Normal
vec4 gl_Color
vec4 gl_MultiTexCoord0
mat4 gl_ModelViewMatrix
mat4 gl_ProjectionMatrix
mat4 gl_ModelViewProjectionMatrix (= gl_ModelViewMatrix * gl_ProjectionMatrix)
mat3 gl_NormalMatrix (this is the transpose of the inverse of the MV matrix)

vec4 gl_Position



Rasterizer

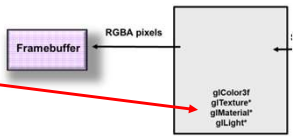
A Fragment Shader is automatically called once per fragment:

```
#version 330 compatibility

void
main( )
{
        gl_FragColor = vec4( .5, 1., 0.,  1. );
}
```

This code assigns a fixed color (r=0.5, g=1., b=0.) and alpha (=1.) to each fragment drawn

vec4 gl_FragColor



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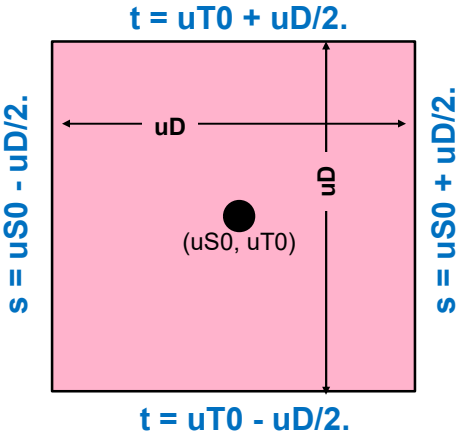
Not terribly useful yet …

A Little More Interesting, I: What if we Want to Color in a Pattern?

This pattern example is defined by three uniform variables: uS0, uT0, and uD, all in texture coordinates (0.-1.). **(uS0,uT0)** are the center of the pattern. **uD** is the length of each edge of the pattern. The s and t boundaries of the pattern are like this:



- uS0, uT0 are the center of the pattern in (0.-1.) texture coordinates
- uD is the size of the pattern in (0.-1.) texture coordinates

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A Little More Interesting, II:
Getting the Texture Coordinates from the Vertex Shader to the Fragment Shader

The vertex shader needs to pass the texture coordinates to the rasterizer so that each fragment shader gets it:

A Vertex Shader is automatically called once per vertex:

```
#version 330 compatibility

out  vec2  vST;

void
main( )
{
        vST = gl_MultiTexCoord0.st;          // a vertex's (s,t) texture coordinates

        gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

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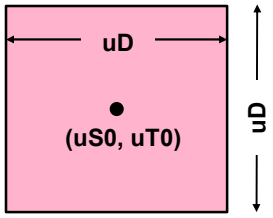
The texture coordinates need to come from the *vertex shader* because they were assigned to each *vertex* to begin with

A Little More Interesting, III:
Drawing a Pattern with the Fragment Shader

The fragment shader answers the question: *"Am I (the current fragment) inside the pattern or outside it?"*

A Fragment Shader is automatically called once per fragment:

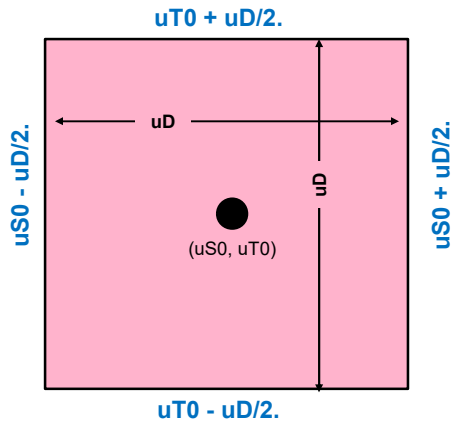
```
#version 330 compatibility
uniform float uS0, uT0, uD;  // from your program
in vec2 vST;                 // from the vertex shader, interpolated through the rasterizer

void
main( )
{
        float s = vST.s;                // the s coordinate of where this fragment is
        float t = vST.t;                // the t coordinate of where this fragment is
        vec3 myColor = vec3( 1., 0.5, 0. );                // default color

        if(     uS0 - uD/2. <= s  &&  s <= uS0 + uD/2.  &&
                uT0 - uD/2. <= t  &&  t <= uT0 + uD/2.  )
        {
                myColor = vec3( 1., 0., 0. );  // new pattern color
        }

        . . .
        gl_FragColor = << myColor with lighting applied >>
}
```



A Little More Interesting, IV: Drawing a Pattern with the Fragment Shader

The fragment shader answers the question: *"Am I (the current fragment) inside the pattern or outside it?"*

```
if( uS0 - uD/2. <= s  &&  s <= uS0 + uD/2.  &&  uT0 - uD/2. <=  t  &&  t <= uT0 + uD/2. )
{
        myColor = vec3( 1., 0., 0. );          // change the pattern color if inside the pattern boundaries
}
```



All 4 of these must be true to conclude this fragment is inside the pattern!

- uS0, uT0 are the center of the pattern in (0.-1.) texture coordinates
- uD is the size of the pattern in (0.-1.) texture coordinates

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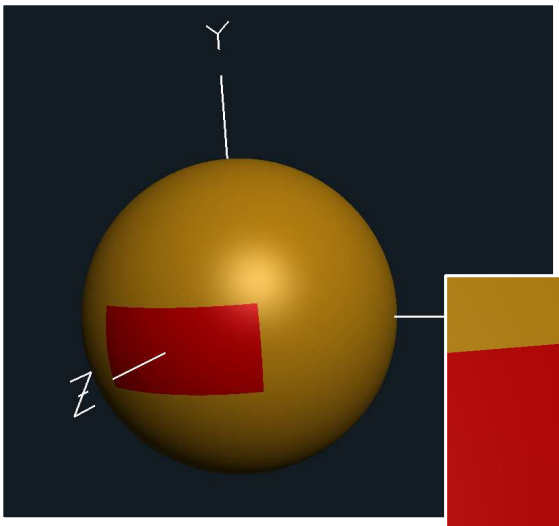
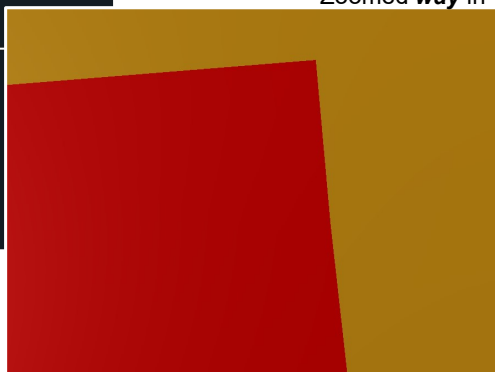
Drawing a Pattern on an Object



Here's the cool part: It doesn't matter (up to the limits of 32-bit floating-point precision) how far you zoom in. You still get a crisp edge. This is an advantage of procedural (equation-based) textures, as opposed to image-based textures.

Zoomed ***way*** in



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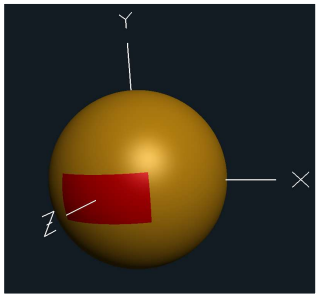
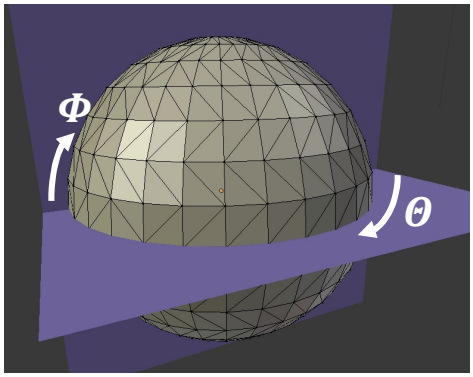
If the Equation Defines a *Square*, Why Does the Pattern Look Like a *Rectangle*?



$$s = \frac{\Theta - (-\pi)}{2\pi} \qquad t = \frac{\Phi - (-\frac{\pi}{2})}{\pi}$$



It's because, ***in a sphere***, the s coordinate encompasses twice as much angle (-180° → +180°) as the t coordinate does (-90° → +90°). So the same amount of "s" produces twice the distance as the same amount of "t". If you care, you can fix it like this:

```
float s = vST.s;
float t = vST.t;
s = 2.*s;
```

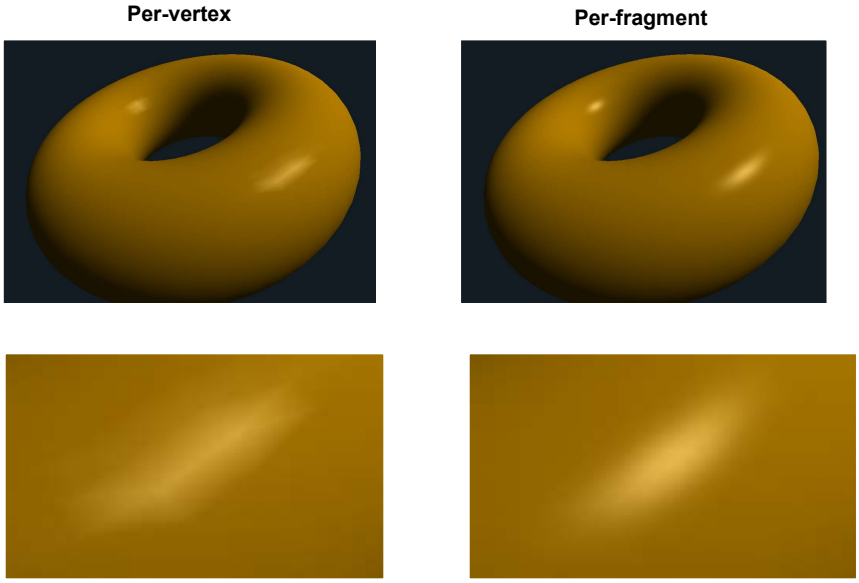

Per-Vertex Lighting vs. Per-Fragment Lighting

In **per-vertex lighting**, like we have done so far, we apply the lighting equation to the parameters at the vertices and then interpolate the color intensities in the rasterizer. This is what is built-in to standard OpenGL.

In **per-fragment lighting**, we will interpolate the parameters through the rasterizer first and then apply the lighting equation in the fragment shader. To do this, requires shaders.

Lighting Type	Vertex Shader	Rasterizer	Fragment Shader
Per-vertex	Apply lighting model to produce color intensities	Interpolate color intensities	Color the fragments
Per-fragment	Send parameters to rasterizer	Interpolate the parameters	Apply lighting model to color the fragments

Per-Vertex Lighting vs. Per-Fragment Lighting



Applying Per-Fragment Lighting, I

Vertex shader:

```
#version 330 compatibility
out vec2  vST;                  // texture coords
out  vec3  vN;                  // normal vector
out  vec3  vL;                  // vector from point to light
out  vec3  vE;                  // vector from point to eye

const vec3 LIGHTPOSITION = vec3(  5., 5., 0. );

void
main( )
{
        vST = gl_MultiTexCoord0.st;
        vec4 ECposition = gl_ModelViewMatrix * gl_Vertex;       // eye coordinate position
        vN = normalize( gl_NormalMatrix * gl_Normal );          // normal vector
        vL = LIGHTPOSITION - ECposition.xyz;                    // vector from the point to the light position
        vE = vec3( 0., 0., 0. ) - ECposition.xyz;               // vector from the point to the eye position
        gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Applying Per-Fragment Lighting, II

Fragment shader:

```
#version 330 compatibility
uniform float   uKa, uKd, uKs;                  // coefficients of each type of lighting
uniform float   uShininess;                     // specular exponent
in vec2   vST;                                  // texture cords
in  vec3  vN;                                                   // normal vector
in  vec3  vL;                                   // vector from point to light
in  vec3  vE;                                   // vector from point to eye
void main( )
{
        vec3 Normal = normalize(vN);
        vec3 Light     = normalize(vL);
        vec3 Eye       = normalize(vE);

        vec3 myColor =          vec3( 1.0, 0.5, 0.0 );          // default color
        vec3 mySpecularColor = vec3( 1.0, 1.0, 1.0 );           // specular highlight color

        << possibly change myColor >>

        vec3 ambient = uKa * myColor;
        float d = 0.;
        float s = 0.
        if( dot(Normal,Light) > 0. )                    // only do specular if the light can see the point
        {
                d = dot(Normal,Light);
                vec3 ref = normalize(  reflect( -Light, Normal )  );                    // reflection vector
                s = pow( max( dot(Eye,ref),0. ), uShininess );
        }
        vec3 diffuse    = uKd * d * myColor;
        vec3 specular = uKs * s * mySpecularColor;
        gl_FragColor = vec4( ambient + diffuse + specular,  1. );
}
```

Here's where we figure out what color this fragment will be, like before

Here's where we apply lighting to that color

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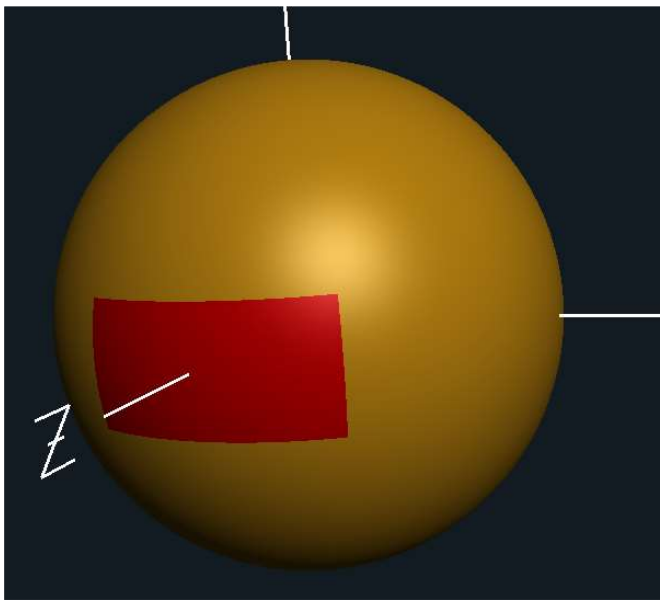
Applying Per-Fragment Lighting, III



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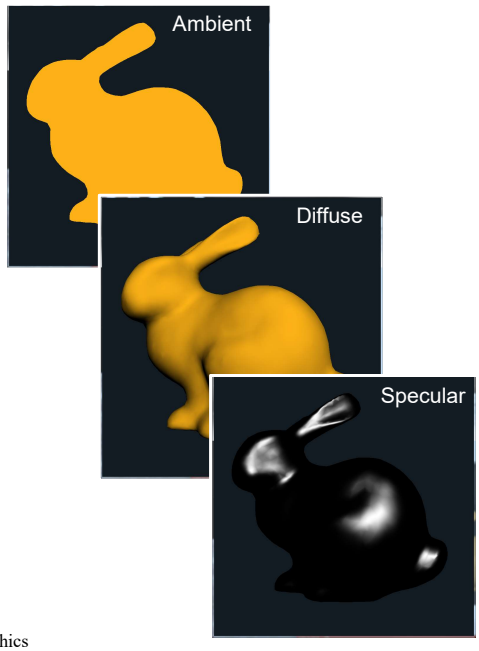
Per-fragment Lighting is Good, Even Without a Pattern!



Setting up a Shader via the OpenGL API is somewhat Involved: Here is our C++ Class to Simplify the Shader Setup for You

First, follow these steps:

1. You will see two files that are already in your Sample folder: **glslprogram.h** and **glslprogram.cpp**
2. In your sample.cpp file, un-comment the line:
   #include "glslprogram.cpp"

These two files have been reduced to have just the shader features you need for Project #6.

If you are not working on Project #6, but are working on something bigger, I have more complete versions of glslprogram.h and glslprogram.cpp – just ask me.

Setting up a Shader via the OpenGL API is somewhat Involved: Here is our C++ Class to Simplify the Shader Setup for You

Put these in with the Global Variables:

```
GLSLProgram   Pattern;          // your VS+FS shader program name
float         Time;
#define MS_IN_THE_ANIMATION_CYCLE      10000
```

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Setting up a Shader via the OpenGL API is somewhat Involved: Here is our C++ Class to Simplify the Shader Setup for You

Do this in Animate( ) like you've always done:

```
void
Animate( )
{
        int ms = glutGet( GLUT_ELAPSED_TIME );                  // milliseconds
        ms  %=  MS_IN_THE_ANIMATION_CYCLE;


        Time = (float)ms  /  (float)MS_IN_THE_ANIMATION_CYCLE;       // [ 0., 1. )
}
```

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Setting up a Shader via the OpenGL API is somewhat Involved: Here is our C++ Class to Simplify the Shader Setup for You

Do this in InitGraphics( ) somewhere after where the window has been created and GLEW has been setup:

```
Pattern.Init( );
bool valid = Pattern.Create( "pattern.vert",  "pattern.frag" );

if( ! valid )
{
        fprintf( stderr, "Yuch!  The shader did not compile.\n" );

}
else
{
        fprintf( stderr, "Woo-Hoo!  The shader compiled.\n" );
}
```

In C/C++, the exclamation point (!) is pronounced "not".

2. A compiler for that language to create an executable
3. A way to see the compiler's error messages
4. A way to download the executable onto the external computer

This attempts to load, compile, and link the shader program. If something goes wrong, Pattern.Create( ) prints error messages into the console window and returns a value of ***valid=false***.

We cover the full GLSL API in CS 457/557

Setting up a Shader via the OpenGL API is somewhat Involved: Here is our C++ Class to Simplify the Shader Setup for You

Do this in Display( ):

```
float s0 = some function of Time
float t0  = some function of Time
float d   = some function of Time
        . . .
Pattern.Use( );          // turns the shader program on
                         // no more fixed-function – the shader Pattern now handles everything
                         // but the shader program just sits there idling until you draw something

Pattern.SetUniformVariable( "uS0", s0);
Pattern.SetUniformVariable( "uT0", t0 );
Pattern.SetUniformVariable( "uD",    d);

glCallList( SphereList );  // now the shader program has vertices and fragments to work on

Pattern.UnUse( );        // go back to fixed-function OpenGL
```

5. A way to run that executable on the external computer

6. A way to get information into the executable

Setting Up Texturing with Shaders

Graphics chips have functionality on them called ***Texture Units***. Each Texture Unit is identified by an integer number, typically 0-15, but oftentimes more.

To tell a shader how to get to a specific texture image, assign that texture into a specific **Texture Unit number** and then tell your shader what Texture Unit number to use. Your C/C++ code will look like this:

```
glActiveTexture( GL_TEXTURE5 );              // use texture unit 5
glBindTexture( GL_TEXTURE_2D, TexName );
```

The file gl.h has these lines:

```
#define GL_TEXTURE0                0x84C0
#define GL_TEXTURE1                0x84C1
#define GL_TEXTURE2                0x84C2
#define GL_TEXTURE3                0x84C3
#define GL_TEXTURE4                0x84C4
#define GL_TEXTURE5                0x84C5
#define GL_TEXTURE6                0x84C6
#define GL_TEXTURE7                0x84C7
#define GL_TEXTURE8                0x84C8
. . .
```

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The Whole Process Looks Like This, I:


```
// globals:

unsigned char * Texture;
GLuint          TexName;
GLSLProgram     Pattern;

. . .
// In InitGraphics( ):

glGenTextures( 1, &TexName );
int nums, numt;
Texture = BmpToTexture( "filename.bmp", &nums, &numt );
glBindTexture( GL_TEXTURE_2D, TexName );
glTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT );
glTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT );
glTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
glTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );
glTexImage2D(   GL_TEXTURE_2D, 0, 3, nums, numt, 0, 3, GL_RGB, GL_UNSIGNED_BYTE, Texture );

Pattern.Init( );
bool valid = Pattern.Create( "pattern.vert", "pattern.frag" );
If( !valid )
{
        . . .
}
```

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The Whole Process Looks Like This, II:

This is the hardware Texture Unit Number. You can choose anything in the range 0-15.

```
. . .
// In Display( ):

Pattern.Use( );
glActiveTexture( GL_TEXTURE5 )              // your C++ program specifies that you want the texture to live on texture unit 5
glBindTexture( GL_TEXTURE_2D, TexName );
Pattern.SetUniformVariable( "uTexUnit", 5 );   // tell your shader program to find the texture on texture unit 5
      << draw something >>
Pattern.UnUse( );
```

2D Texturing within the Shaders

Vertex shader:

```
#version 330 compatibility
out  vec2  vST;

void
main( )
{
        vST = gl_MultiTexCoord0.st;
        gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

***texture( )* is a built-in texture map lookup function – it returns a vec4 (RGBA)**

Rasterizer

Fragment shader:

```
#version 330 compatibility
in  vec2  vST;
uniform sampler2D uTexUnit;

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

Pattern.SetUniformVariable("uTexUnit", 5);

Convert the vec4 rgba from the texture( ) call to just the vec3 rgb that we need

2D Texturing within the Shaders

What if You Want to Use Two Textures in a Shader?


```
// In Display( ):

Pattern.Use( );
glActiveTexture( GL_TEXTURE5 );
glBindTexture( GL_TEXTURE_2D, TexName0 );

glActiveTexture( GL_TEXTURE6 );
glBindTexture( GL_TEXTURE_2D, TexName1 );

Pattern.SetUniformVariable( "uTexUnit0", 5 );
Pattern.SetUniformVariable( "uTexUnit1", 6 );

glCallList( … );

Pattern.UnUse( );
```

Fragment shader:

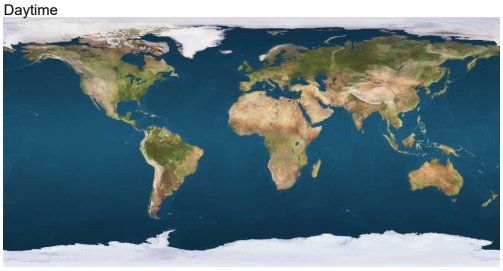
```
#version 330 compatibility
in  vec2  vST;
uniform sampler2D  uTexUnit0;
uniform sampler2D  uTexUnit1;

void
main( )
{
        vec3 newcolor0 = texture( uTexUnit0, vST ).rgb;
        vec3 newcolor1 = texture( uTexUnit1, vST ).rgb;
        gl_FragColor = …
}
```

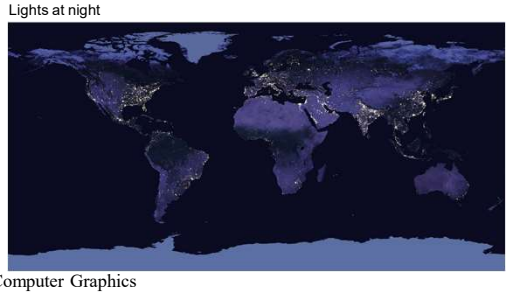
Why Would You Want to Use More Than One Texture in a Shader?

Once the RGBs have been read from a texture, they are just numbers. You can do any arithmetic you want with the texture RGBs, other colors, lighting, etc. Here is an example of blending two textures at once:

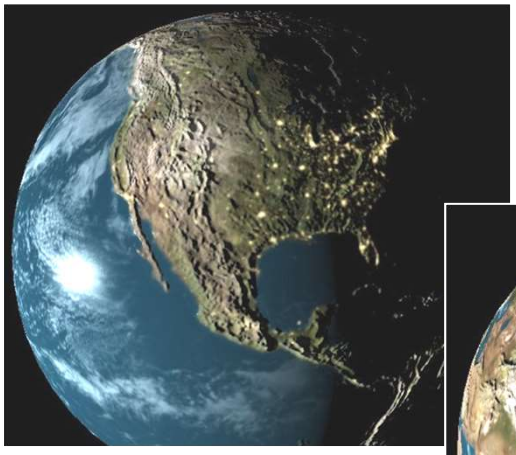
Daytime



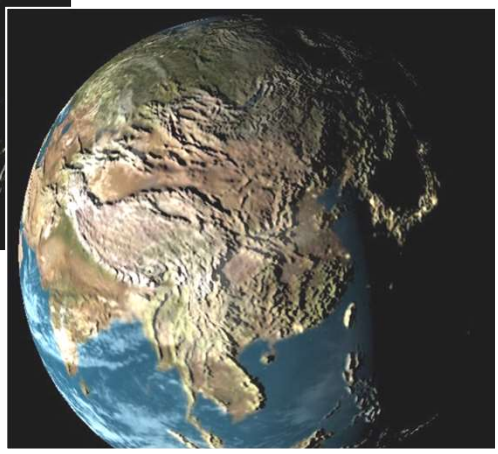
Lights at night



Why Would You Want to Use More Than One Texture in a Shader?



Textures used here:
- Day
- Night
- Heights (bump-mapping)
- Clouds
- Specular highlights



Visualization by Nick Gebbie

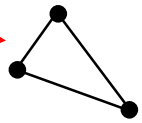
Something Goofy: Turning XYZs into RGBs in Model Coordinates

Vertex shader:

```
#version 330 compatibility
out  vec3  vColor;

void
main( )
{
        vec4 pos = gl_Vertex;
        vColor = pos.xyz;              // set rgb from xyz!
        gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

per-vertex



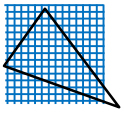
Rasterizer

Fragment shader:

```
#version 330 compatibility
in  vec3  vColor;

void
main( )
{
        gl_FragColor = vec4( vColor,  1. );
}
```

per-fragment



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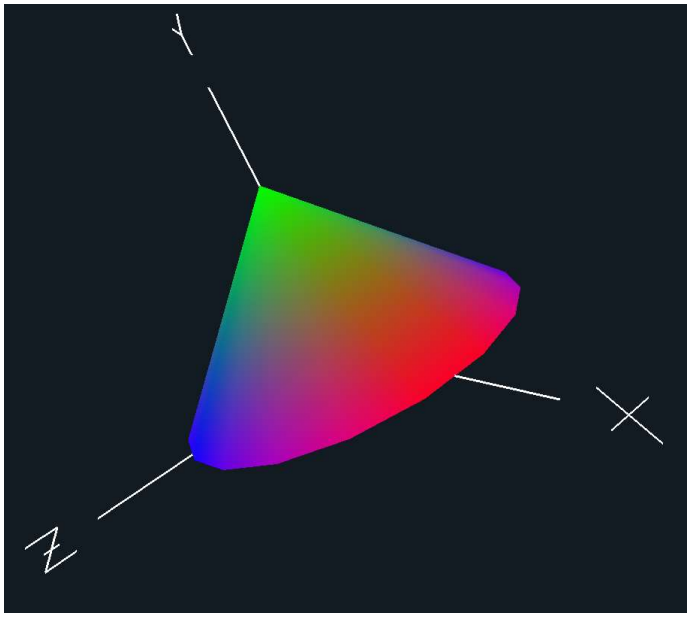
Setting rgb from the Untransformed xyz, I

vColor = gl_Vertex.xyz;



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Turning XYZs into RGBs in Eye (World) Coordinates

Vertex shader:

```
#version 330 compatibility
out  vec3  vColor;

void
main( )
{
        vec4 pos = gl_ModelViewMatrix * gl_Vertex;
        vColor = pos.xyz;                    // set rgb from xyz!
        gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

```
#version 330 compatibility
out  vec3  vColor;

void
main( )
{
        vec4 pos = gl_Vertex;
        vColor = pos.xyz;                    // set rgb from xyz!
        gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Rasterizer

Fragment shader:

```
#version 330 compatibility
in  vec3  vColor;

void
main( )
{
        gl_FragColor = vec4( vColor,  1. );
}
```

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What's Different About These Two?

Set the color from the ***untransformed (MC)*** **xyz**

```
#version 330 compatibility
out  vec3  vColor;

void
main( )
{
        vec4 pos = gl_Vertex;
        vColor = pos.xyz;                    // set rgb from xyz!
        gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Set the color from the ***transformed (WC/EC)*** **xyz**:

```
#version 330 compatibility
out  vec3  vColor;

void
main( )
{
        vec4 pos = gl_ModelViewMatrix * gl_Vertex;
        vColor = pos.xyz;                    // set rgb from xyz!
        gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

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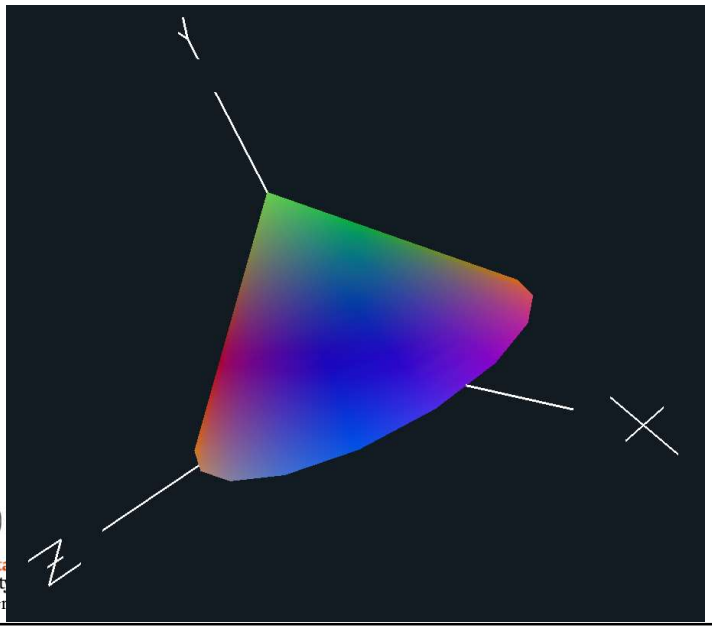
Setting rgb from the Transformed xyz, II

vColor = (gl_ModelViewMatrix * gl_Vertex).xyz;

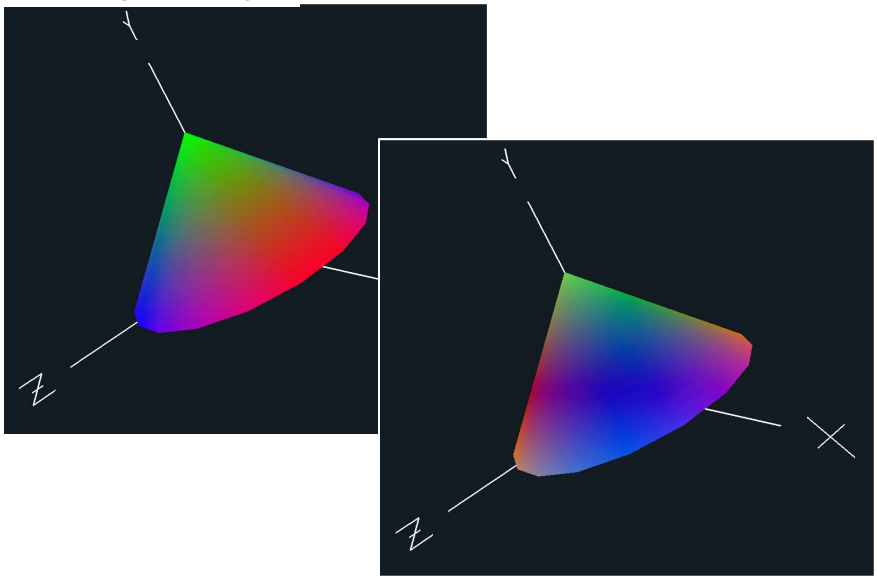


Note: the phrase ".xyz" and the phrase ".rgb" mean exactly the same thing: "give me the first 3 numbers from this vec variable".

What you can't do is mix them, such as ".xgz"

Setting rgb From xyz

vColor = gl_Vertex.xyz;



vColor = (gl_ModelViewMatrix * gl_Vertex).xyz;

Hints on Running Shaders on Your Own System

- You need a graphics system that is OpenGL 2.0 or later. Basically, if you got your graphics system in the last 5 years, you should be OK, unless it came from Apple. In that case, who knows how much OpenGL support it has? (The most recent OpenGL level is 4.6)
- Update your graphics driver to the most recent version!
- Do the GLEW setup if you are on Windows. It looks like this in the sample code:

```
GLenum err = glewInit( );
if( err != GLEW_OK )
{
	fprintf( stderr, "glewInit Error\n" );
}
else
	fprintf( stderr, "GLEW initialized OK\n" );
```

  This must come ***after you've created a graphics window***. (It is this way in the sample code, but I'm saying this because I know some of you go in and "simplify" my sample code by deleting everything you don't think you need.)

- You use the GLSL C++ class you've been given ***only after a window has been created and GLEW has been setup***. Only then can you initialize your shader program:

```
Pattern.Init( );
bool valid = Pattern.Create( "pattern.vert", "pattern.frag" );
```


A Common Error to Look Out For

Here is a piece of code:


```
#version 330 compatibility
out  vec3  vColor;

void
main( )
{
	vec4 pos = gl_Vertex;
	vec3 vColor = pos.xyz;		// set rgb from xyz!
	gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

It looks like our example from earlier in these notes. It compiles OK. It should work, right?

Wrong! By re-declaring vColor in "vec3 vColor = pos.xyz", you are making a *local version* of vColor and writing pos.xyz into that local version, not the out variable! The out version of vColor is never getting written to, and so the vColor in the fragment shader will have no sensible value.

Don't ever re-declare in, out, or uniform variables!

Trust me, you will do this sometime. It's an easy mistake to make mindlessly. I do it every so often myself.

Differences if You are on a Mac

Unfortunately, Apple froze their GLSL support at version 1.20 – here is how to adapt to that:

- Your shader version number should be 120 (at the top of the .vert and .frag files):
  `#version 120 compatibility`
- Instead of the keywords **in** and **out**, use ***varying***
- Your OpenGL includes will need to look like this:
  #include <OpenGL/gl.h>
  #include <OpenGL/glu.h>
- You don't need to do anything with GLEW
- Your compile sequence will look like this:
  g++ -framework OpenGL -framework GLUT sample.cpp -o sample -Wno-deprecated

Guide to Where to Put Pieces of Your Shader Code, I

1. Declare the GLSLProgram above the main program (i.e., as a global):

```
GLSLProgram   Pattern;
```

2. At the end of InitGraphics( ), create the shader program and setup your shaders:

```
Pattern.Init( );
bool valid = Pattern.Create( "pattern.vert", "pattern.frag" );
if( ! valid ) { . . . }
```

3. Turn on the shader program in Display( ), set shader uniform variables, draw the objects, then turn off the shader program:

```
Pattern.Use( );

Pattern.SetUniformVariable( ...

glCallList( SphereList(  );

Pattern.UnUse( );                // return to the fixed function pipeline
```

4. When you run your program, be sure to check the console window for shader compilation errors!

Guide to Where to Put Pieces of Your Shader Code, II

Tips on drawing the object:

- If you want to key off of s and t coordinates in your shaders, the object must *have* s and t coordinates (vt) assigned to its vertices – *not all OBJ files do*!
- If you want to use surface normals in your shaders, the object must *have* surface normals (vn) assigned to its vertices – *not all OBJ files do*!
- Be sure you explicitly assign *all* of your uniform variables – no error messages occur if you forget to do this – it just quietly screws up.
- The glutSolidTeapot( ) has been textured in patches, like a quilt – cute, but weird
- The **OsuSphere( )** function from the texturing project will give you a very good sphere. Use it, not the GLUT sphere.

OpenGL Picking

Mike Bailey

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What is OpenGL Picking?

In 3D applications, it is useful for the user to point to something and have the program figure out what is being pointed to. This is called ***picking***.

You can imagine how you could do this in *software*. You would do all of the transformations yourself and figure out where each object ends up being drawn on the screen and then check its closeness to the cursor. The good news is that this can be done. The bad news is that none of us wants to do it, and it would be painfully slow if we did. Mercifully, OpenGL allows the hardware to help us out. The strategy is straightforward:

1. **Tell the hardware that we are in picking ("selection") mode.**
2. **Ask the hardware to pretend it is drawing the scene. Go through all the motions, just don't actually color any pixels.**
3. **As part of "drawing" the scene, we occasionally give the hardware "names" for the objects we are drawing.**
4. **Whenever the hardware finds that it would have colored a pixel within a certain tolerance of the cursor, it returns to us the object "name" that it is currently holding. This tells you what set of drawn objects must have passed near the cursor.**
5. **Tell the hardware that we are back in drawing ("render") mode.**

The Setup

Let's look at all the **steps** in detail. The first step is to setup some things in the #defines. This typically includes a picking tolerance (in pixels) and how large to make the array that the hardware will use to record the names that it finds upon a successful pick:

```
// picking tolerance in pixels:

#define PICK_TOL                10.

// how big to make the pick buffer:

#define PICK_BUFFER_SIZE        4096
```

Next, declare the picking buffer and a way to keep track of the rendering mode in the global variables:

```
unsigned int    PickBuffer[ PICK_BUFFER_SIZE ];    // picking buffer
int             RenderMode = GL_RENDER;            // GL_RENDER or GL_SELECT
```

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In InitGraphics( )

In InitGraphics( ), tell the hardware what picking array to use and how big it is. You *must* do this *after* you create the window:

```
// open the window and set its title:

glutInitWindowSize( INIT_WINDOW_SIZE, INIT_WINDOW_SIZE );
glutInitWindowPosition( 0, 0 );
MainWindow = glutCreateWindow( WINDOWTITLE );
glutSetWindowTitle( WINDOWTITLE );

    . . .

// setup the picking buffer:

glSelectBuffer( PICK_BUFFER_SIZE, PickBuffer );
```

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Assigning the Pick "Names" (numbers)

Now comes the part that requires you to plan some strategy: assigning pick names. The names are really unsigned 32-bit integer numbers that get passed down to the hardware during display. The hardware will tell you what name(s) it is holding at the moment a pick occurs. Thus, use enough unique names to establish the identity of the individual objects. For example:

```
glLoadName( 0 );
glutWireSphere( 1.0, 15, 15 );

glLoadName( 1 );
glutWireCube( 1.5 );

glLoadName( 2 );
glutWireCone( 1.0, 1.5, 20, 20 );

glLoadName( 3 );
glutWireTorus( 0.5, 0.75, 20, 20 );
```

would work nicely to distinguish four shapes. Note that you can have as many graphics objects after a call to glLoadName( ) as you'd like. A pick on *any* of those objects, though, will return the same name. You won't know which one caused the pick.

Pick Names Cannot be Loaded Inside glBegin-glEnd

One thing to be aware of, however, is that a call to glLoadName( ) cannot be embedded inside a glBegin( ) - glEnd( ) pair. Thus, if you are displaying a collection of triangles, you ***cannot*** say:

```
glBegin( GL_TRIANGLES );
for( int i = 0; i < NTRIS; i++ )
{
        glLoadName( i );
        glVertex3f( Tris[i].x0, Tris[i],y0, Tris[i].z0 );
        glVertex3f( Tris[i].x1, Tris[i],y1, Tris[i].z1 );
        glVertex3f( Tris[i].x2, Tris[i],y2, Tris[i].z2 );
}
glEnd( );
```

Instead, you ***must*** say:

```
for( int i = 0; i < NTRIS; i++ )
{
        glLoadName( i );
        glBegin( GL_TRIANGLES );
                glVertex3f( Tris[i].x0, Tris[i],y0, Tris[i].z0 );
                glVertex3f( Tris[i].x1, Tris[i],y1, Tris[i].z1 );
                glVertex3f( Tris[i].x2, Tris[i],y2, Tris[i].z2 );
        glEnd( );
}
```

A Better Idea

But this is inefficient. So, only do this when you are in selection mode, like this:

```
if( RenderMode == GL_RENDER )
{
	glBegin( GL_TRIANGLES );
	for( int i = 0; i < NTRIS; i++ )
	{
		glVertex3f( Tris[i].x0, Tris[i],y0, Tris[i].z0 );
		glVertex3f( Tris[i].x1, Tris[i],y1, Tris[i].z1 );
		glVertex3f( Tris[i].x2, Tris[i],y2, Tris[i].z2 );
	}
	glEnd( );
}
else
{
	for( int i = 0; i < NTRIS; i++ )
	{
		glLoadName( i );
		glBegin( GL_TRIANGLES );
			glVertex3f( Tris[i].x0, Tris[i],y0, Tris[i].z0 );
			glVertex3f( Tris[i].x1, Tris[i],y1, Tris[i].z1 );
			glVertex3f( Tris[i].x2, Tris[i],y2, Tris[i].z2 );
		glEnd( );
	}
}
```

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An Even Better Idea

Or, better yet, put each in its own display list:

```
if( RenderMode == GL_RENDER )
{
	glCallList( RenderDisplayList );
}
else
{
	glCallList( PickDisplayList );
}
```

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The Pick Names Can Be Hierarchical

The pick names can be more sophisticated than just a single name. The name-holding place in the hardware is actually a *stack*, so multiple names can be pushed onto the stack. This is useful for hierarchical situations such as:

```
glLoadName( JAGUAR );
glPushName( BODY );
        glCallList( JagBodyList );
glPopName( );

glPushName( FRONT_LEFT_TIRE );
        glPushMatrix( );
                glTranslatef( ??, ??, ?? );
                glCallList( TireList );
        glPopMatrix( );
glPopName( );

glPushName( FRONT_RIGHT_TIRE );
        • • •

glLoadName( PRIUS );
glPushName( BODY );
        glCallList( PriusBodyList );
        • • •
```

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so that by looking at the 2 pick names that are returned, you know which car *and* what part of that car was picked.

In MouseButton( )


```
if( ( ActiveButton & LEFT )  &&  ( status == GLUT_DOWN ) )
{
        RenderMode = GL_SELECT;
        glRenderMode( GL_SELECT );
        Display( );
        RenderMode = GL_RENDER;
        NumHits = glRenderMode( GL_RENDER );
        int index = 0;
        for( int i = 0; i < NumHits; i++ )
        {
                unsigned nt numItems = PickBuffer[index++];
                unsigned int zmin  = PickBuffer[index++];
                unsigned int zmax  = PickBuffer[index++];
                for( int j = 0; j < numItems; j++ )
                {
                        unsigned int item = PickBuffer[index++];
                        << item is one of your pick names >>
                }
        }
        ActiveButton &= ~LEFT;
        glutSetWindow( GrWindow );
        glutPostRedisplay( );
}
if( NumHits == 0 )
{
        // didn't pick anything --
        // use the left mouse for rotation
        . . .           . . .
}
```

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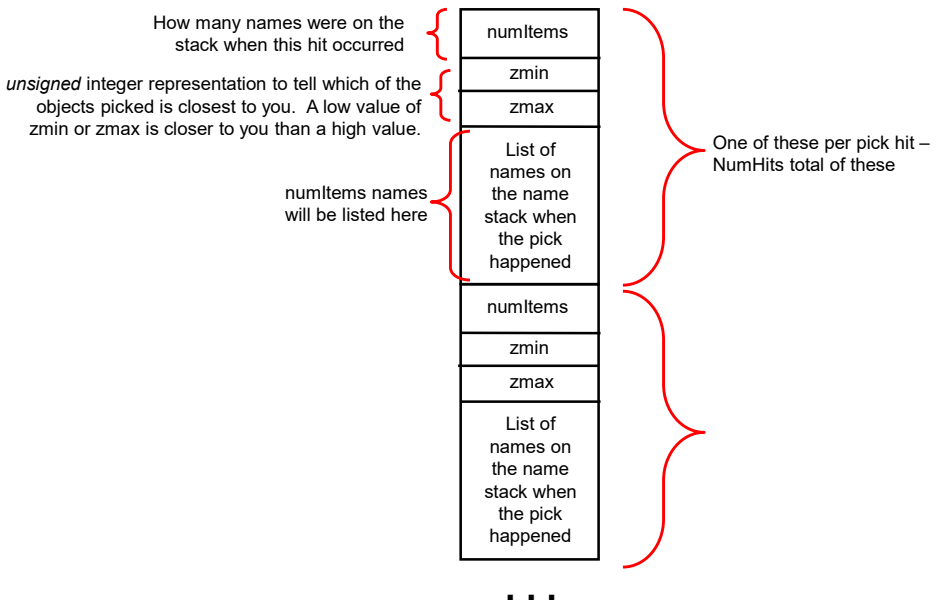
In MouseButton( ), Handling the Closest-Hit Option


```
int closestItem = -1;
int closestZ = 0xffffffff;

int index = 0;
for (int i = 0; i < NumHits; i++)
{
        unsigned int numItems = PickBuffer[index++];
        unsigned int zmin  = PickBuffer[index++];
        unsigned int zmax  = PickBuffer[index++];
        for( int j = 0; j < numItems; j++ )
        {
                int item = PickBuffer[index++];
                SomethingPicked = true;
                if (ClosestOnOff == OFF)
                {
                        Picked[item] = ! Picked[item];
                }
                else
                {
                        if (zmin < closestZ)
                        {
                                closestZ = zmin;
                                closestItem = item;
                        }
                }

        }
}
if (ClosestOnOff == ON && closestItem >= 0)
{
        Picked[closestItem] = ! Picked[closestItem];
        NumHits = 1;
}
```


What is Left in the Pick Buffer?



In Display( ), I


```
		. . .
int vx = glutGet( GLUT_WINDOW_WIDTH );
int vy = glutGet( GLUT_WINDOW_HEIGHT );
		. . .
glMatrixMode( GL_PROJECTION );
glLoadIdentity( );
if( RenderMode == GL_SELECT )
{
		int viewport[4];		// place to retrieve the viewport numbers
		glGetIntegerv( GL_VIEWPORT, viewport);
		gluPickMatrix( (double)Xmouse, (double)(vy - Ymouse), PICK_TOL, PICK_TOL, viewport );
}
<< the call to glOrtho( ) or gluPerspective( ) goes here >>

		. . .

// init the picking buffer:
if( RenderMode == GL_SELECT )
{
		glInitNames( );
		glPushName( 0xffffffff );		// something you will recognize
}

// draw the objects:
<< your graphics drawing and pick name calls go here >
```

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In Display( ), II


```
<< your graphics drawing and pick name calls go here >>

// possibly draw the axes:
if( AxesOnOff == ON  &&  RenderMode == GL_RENDER )
		glCallList( AxesList );		// don't draw in selection mode


// swap the double-buffered framebuffers:
if( RenderMode == GL_RENDER )
		glutSwapBuffers( );		// don't swap buffers in selection mode
```

Note:
1. When picking, don't draw the axes unless you want to be able to pick them
2. When picking, don't swap the double-buffers

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What is that gluPickMatrix( ) Call?

The only tricky thing is this part:

```
glGetIntegerv( GL_VIEWPORT, viewport);
gluPickMatrix( (double)Xmouse, (double)(vy - Ymouse), PICK_TOL, PICK_TOL, viewport );
```

This code looks at the location and size of your viewport, where the mouse is, and what picking tolerance you wanted and changes your projection matrix so that this pick box region occupies the full window. Thus, the hardware is going to check to see if *anything* gets through the clipping test and thus gets drawn. If it does, then a pick occurred.

Note that the gluPickMatrix( ) line is written *first* in the program's projection transformations because we want this transformation to happen *last* after all other projection transformations are done.

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Picking Tricks, I

1. Don't waste picking time looking at things you didn't want to pick anyway. For example, if the axes are not meant to *ever* be picked, do something like this:

```
if( AxesOnOff == ON  &&  RenderMode == GL_RENDER )
        glCallList( AxesList );
```

2. Don't try to pick raster characters. It doesn't work! I don't know if this is by design or by mistake, but allowing raster characters to be drawn *at all* during a Pick Display will cause the picking to think those characters were picked regardless of where you point the cursor. If you have to draw raster characters, do this:

```
if( RenderMode == GL_RENDER )
{
        glDisable( GL_DEPTH_TEST );
        glMatrixMode( GL_PROJECTION );
        glLoadIdentity( );
        gluOrtho2D( 0., 100.,     0., 100. );
        glMatrixMode( GL_MODELVIEW );
        glLoadIdentity( );
        glColor3f( 1., 1., 1. );
        sprintf( str, " NumHits = %d", NumHits );
        DoRasterString( 1., 1., 0., str );
}
```

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Picking Tricks, II

3. Recognizing that, since the user will never see what is being drawn during a Pick Display, you can draw your scene differently than what the user *thinks* he/she is seeing.

For example, a wireframe object normally cannot be picked in the empty space between the lines. But, if you draw a *solid* version of the same thing during the Pick Display, then it will look like a user's pick in the empty space will get the wireframe object, even though *you* know it shouldn't. So, in Display( ) you could say:

```
if( RenderMode == GL_SELECT )
        glCallList( SolidTorusList );
else
        glCallList( WireTorusList );
```

4. It is an interesting user interface-ism to experiment with the PICK_TOL value. Too small, and you have to be very exact to generate a hit. Too large, and you are likely to pick other things in addition to what you wanted to pick.

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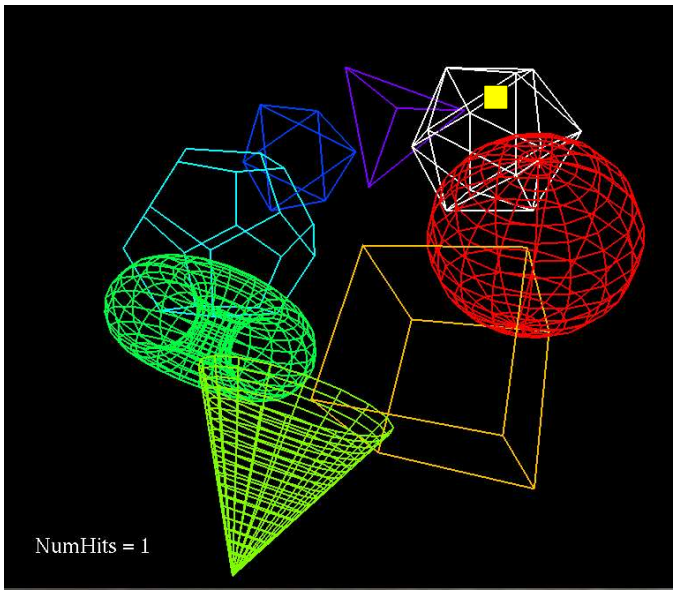
Examples, I

A pick occurred because an object's pixels went through the pickbox



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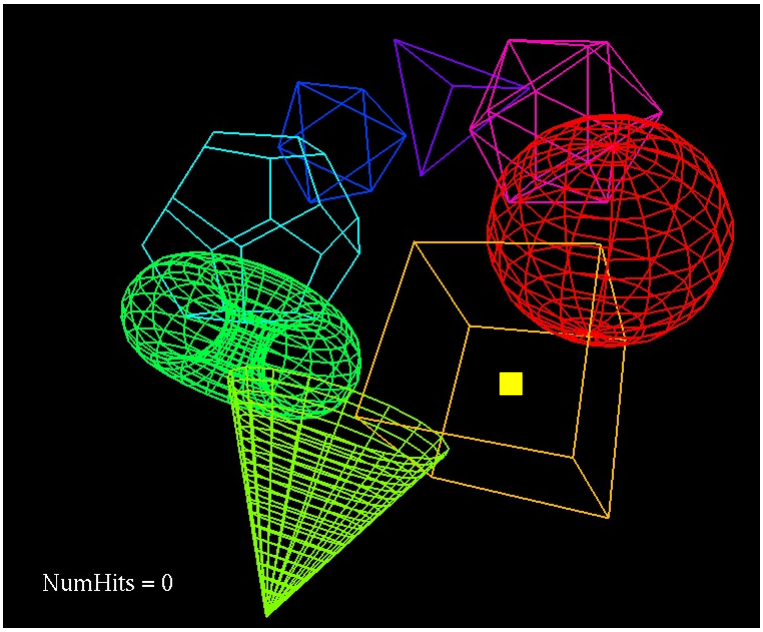
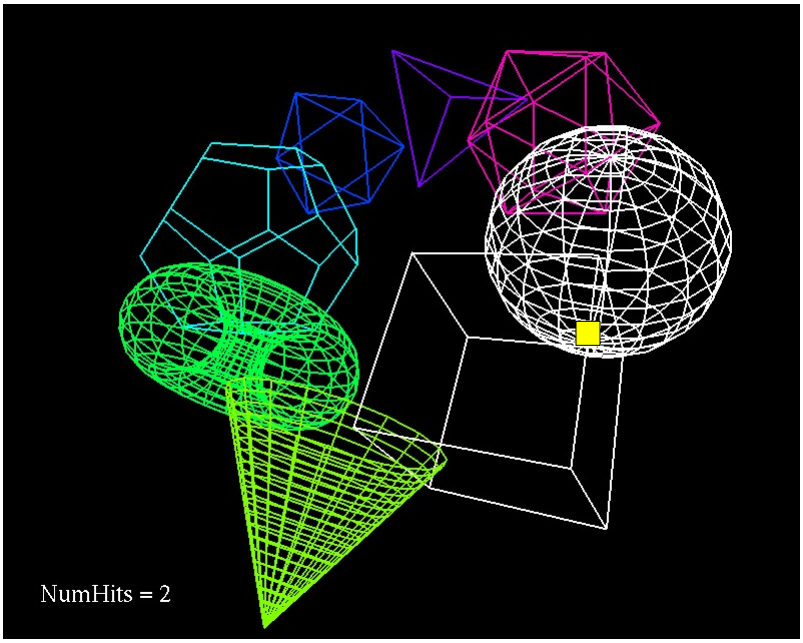
Examples, II

No pick occurred because no objects' pixels went through the pickbox

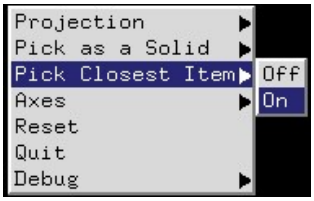


Examples, III

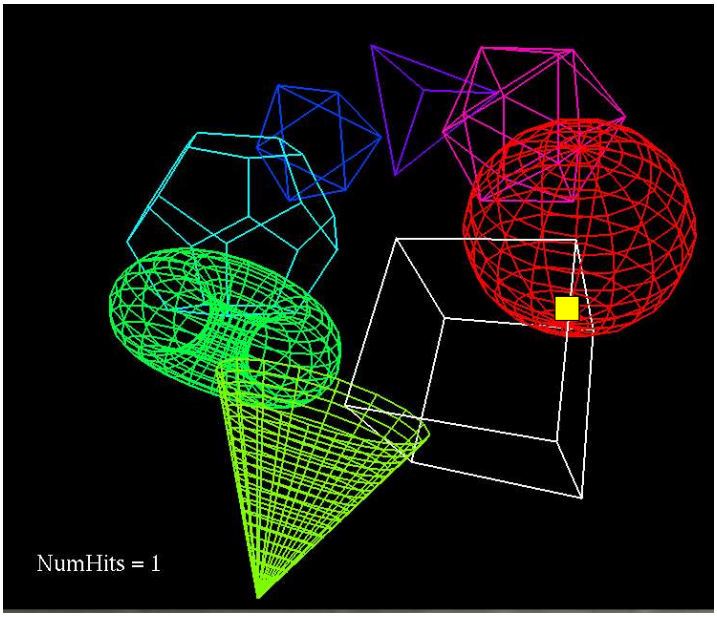
Two picks occurred because two object's pixels went through the pickbox



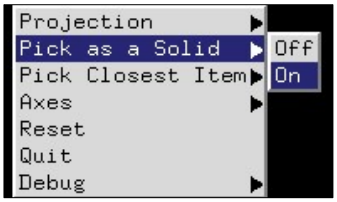
Examples, IV



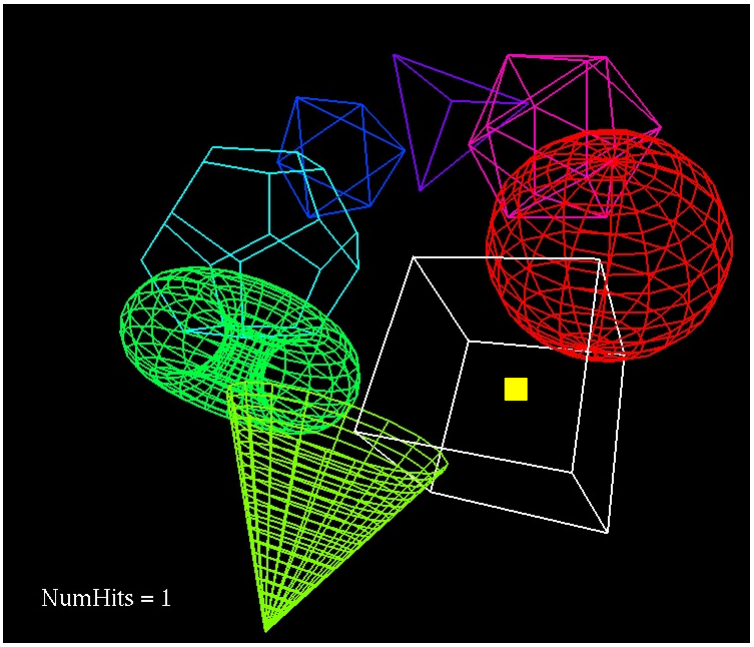
One pick occurred because it was selecting the closest object



Examples, V

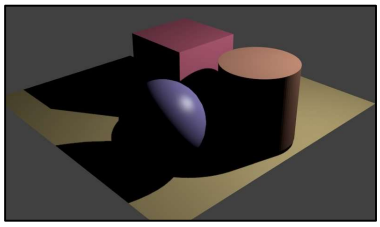


A pick occurred because an object's solid representation pixels went through the pickbox



1

Casting Shadows in OpenGL



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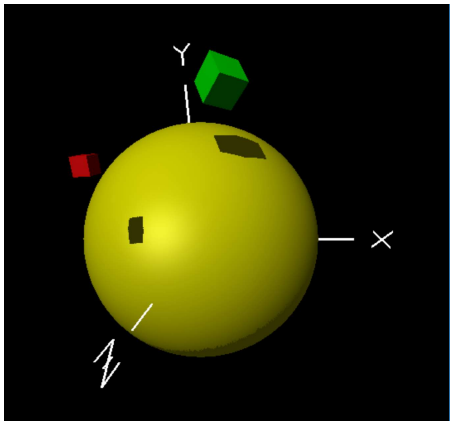
Mike Bailey
mjb@cs.oregonstate.edu



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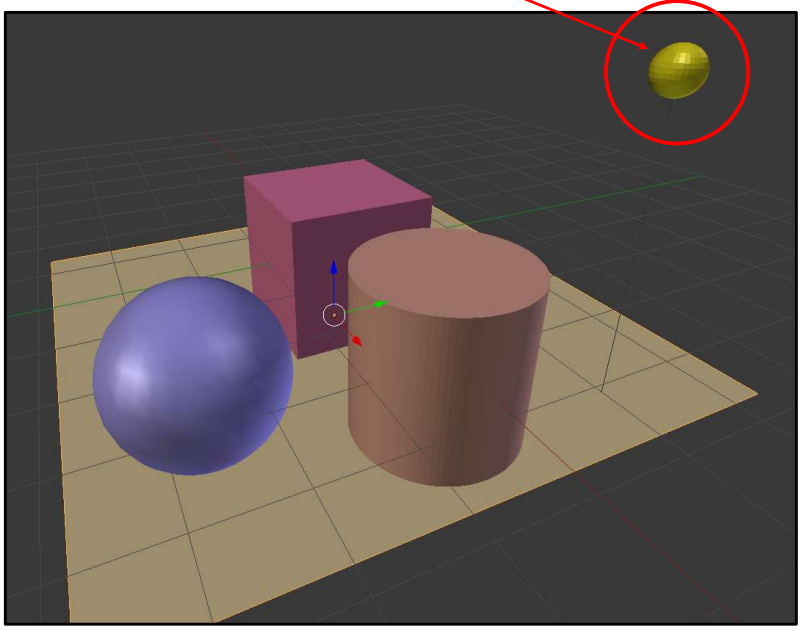
1

Identify the Light Source Casting the Shadow

2



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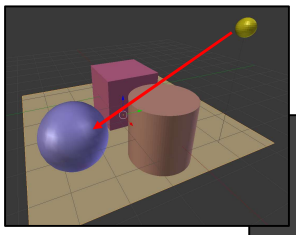
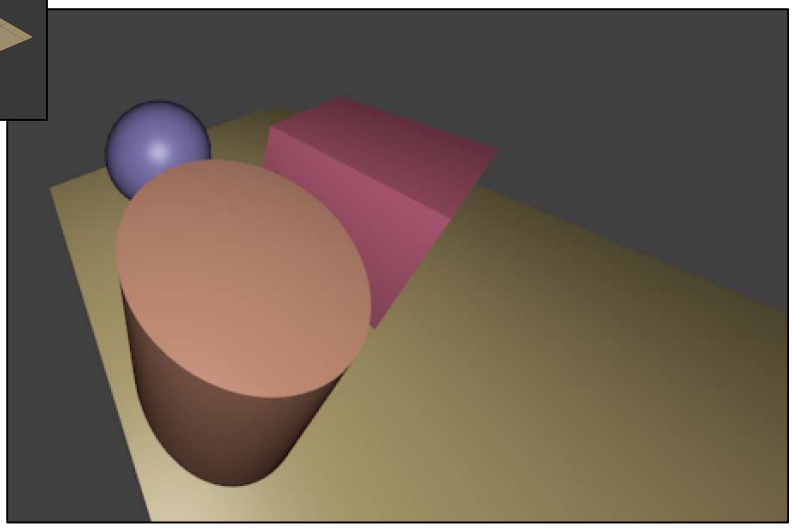
2

First, Render the Scene from the Point of View of that Light Source

3



1. Render a view from the light source – everything you cannot see must be in a shadow



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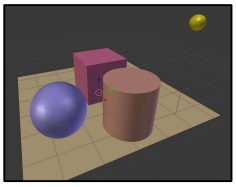
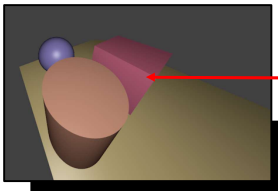
3

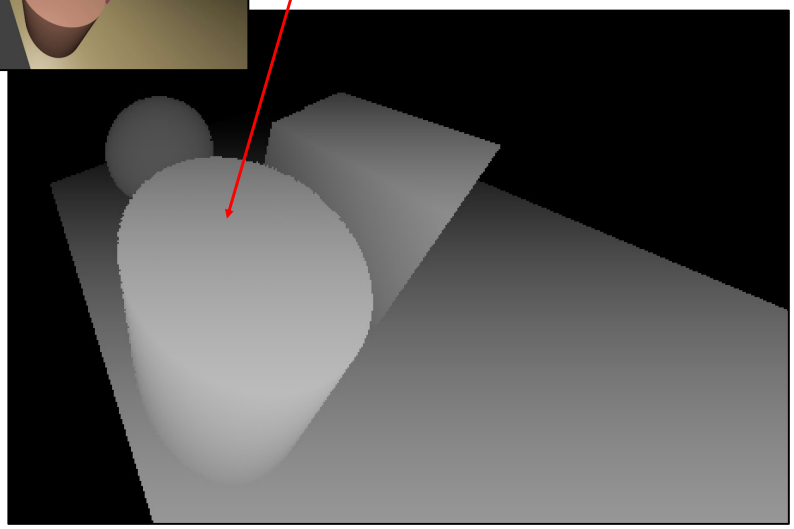
Second, use the Z-buffer as a Depth Shadow Map

4





2. Generate a depth view from the point of view of the light source (in OpenGL, this means extracting the z-buffer)



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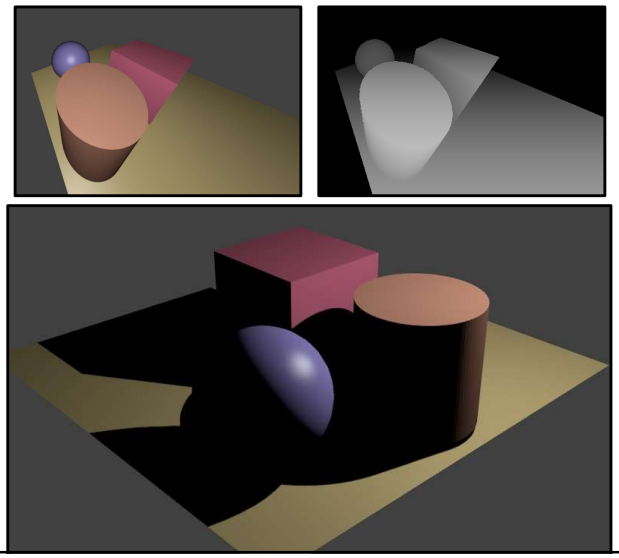
4

Third, Render the Scene as you Normally Would, but Consult the Depth Map to Decide where Lighting Can't Reach and Shouldn't Be Used

5

3. Put the eye back where it really belongs. Render that view. Every time you create a pixel in the scene, compare its 3D location against the depth map. If the light-position camera could not see it before, don't allow lighting to be applied to it now.



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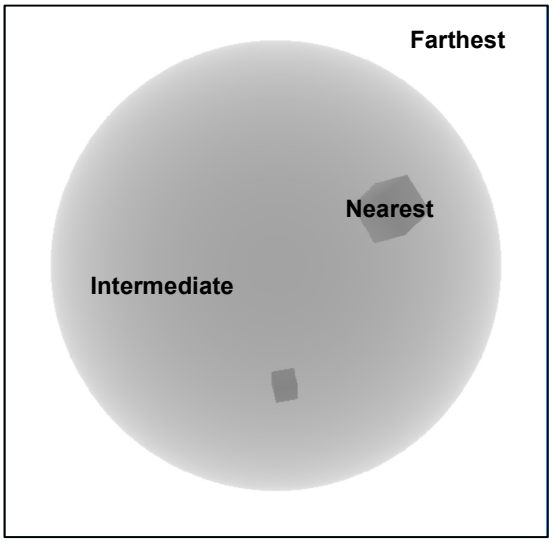
OpenGL Shadow Demo Program: The Depth (Z-buffer) Shadow Map

6

The depth shadow map is created from the point of view of the light source.

The rendering is done into an off-screen framebuffer and only renders the depth (z-buffer) , not any colors.

In this grayscale image, dark colors are nearest to the eye, light colors are farther away.



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OpenGL Demo Program: Creating the Off-screen Depth Shadow Map Framebuffer

7

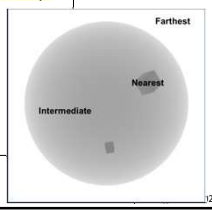
```
// create a framebuffer object and a depth texture object:
glGenFramebuffers(1, &DepthFramebuffer );
glGenTextures(       1, &DepthTexture );

//Create a texture that will be the framebuffer's depth buffer
glBindTexture(GL_TEXTURE_2D, DepthTexture );
glTexImage2D(GL_TEXTURE_2D, 0, GL_DEPTH_COMPONENT, SHADOW_WIDTH, SHADOW_HEIGHT,
                    0, GL_DEPTH_COMPONENT, GL_FLOAT, NULL);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_CLAMP_TO_EDGE);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_CLAMP_TO_EDGE);

// attach texture to framebuffer as depth buffer:
glBindFramebuffer(GL_FRAMEBUFFER, DepthFramebuffer);
glFramebufferTexture2D(GL_FRAMEBUFFER, GL_DEPTH_ATTACHMENT, GL_TEXTURE_2D, DepthTexture, 0);

// force opengl to accept a framebuffer that doesn't have a color buffer in it:
glDrawBuffer(GL_NONE);
glReadBuffer(GL_NONE);
glBindFramebuffer(GL_FRAMEBUFFER, 0);
```

In shadows.cpp:
InitGraphics( )



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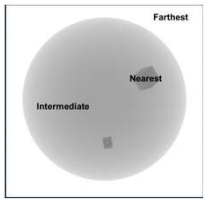
7

OpenGL Demo Program: Rendering into the Depth Shadow Map

8

```
//first pass, render from light's perspective, store depth of scene in texture
glBindFramebuffer(GL_FRAMEBUFFER, DepthFramebuffer);
glClear(GL_DEPTH_BUFFER_BIT);
glDrawBuffer(GL_NONE);
glReadBuffer(GL_NONE);
glEnable(GL_DEPTH_TEST);
glShadeModel(GL_FLAT);
glDisable(GL_NORMALIZE);

// these matrices are the equivalent of projection and view matrices
glm::mat4 lightProjection = glm::ortho(-10.0f, 10.0f, -10.0f, 10.0f, 1.f, 20.f);
glm::vec3 lightPos(LightX, LightY, LightZ);
glm::mat4 lightView = glm::lookAt(lightPos, glm::vec3(0., 0., 0.), glm::vec3(0., 1., 0.));

//this matrix is the transformation matrix that the vertex shader will use instead of glModelViewProjectionMatrix:
glm::mat4 lightSpaceMatrix = lightProjection * lightView;

glViewport(0, 0, SHADOW_WIDTH, SHADOW_HEIGHT);

GetDepth.Use( );
GetDepth.SetUniformVariable((char*)"uLightSpaceMatrix", lightSpaceMatrix);
glm::vec3 color = glm::vec3(0., 1., 1.);
GetDepth.SetUniformVariable((char*)"uColor", color);
DisplayOneScene(GetDepth);
GetDepth.UnUse( );
glBindFramebuffer(GL_FRAMEBUFFER, 0);
```

In shadows.cpp:
Display( ), l



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8

OpenGL Demo Program: Rendering using the Depth Shadow Map

9

```
RenderWithShadows.Use();
RenderWithShadows.SetUniformVariable((char*)"uShadowMap", 0 );
RenderWithShadows.SetUniformVariable((char*)"uLightX", LightX);
RenderWithShadows.SetUniformVariable((char*)"uLightY", LightY);
RenderWithShadows.SetUniformVariable((char*)"uLightZ", LightZ);
RenderWithShadows.SetUniformVariable((char*)"uLightSpaceMatrix", lightSpaceMatrix);

glm::vec3 eye = glm::vec3(0., 0., 8.);
glm::vec3 look = glm::vec3(0., 0., 0.);
glm::vec3 up = glm::vec3(0., 1., 0.);
glm::mat4 modelview = glm::lookAt(eye, look, up);

if (Scale < MINSCALE)            Scale = MINSCALE;
glm::vec3 scale = glm::vec3(Scale, Scale, Scale);
modelview = glm::scale(modelview, scale);
glm::vec3 xaxis = glm::vec3(1., 0., 0.);
glm::vec3 yaxis = glm::vec3(0., 1., 0.);
modelview = glm::rotate(modelview, glm::radians(Yrot), yaxis);
modelview = glm::rotate(modelview, glm::radians(Xrot), xaxis);
RenderWithShadows.SetUniformVariable((char*)"uModelView", modelview);

glm::mat4 proj = glm::perspective(glm::radians(75.f), 1.f, .1f, 100.f);
RenderWithShadows.SetUniformVariable((char*)"uProj", proj);
DisplayOneScene(RenderWithShadows);
RenderWithShadows.UnUse( );
```

In shadows.cpp:
Display( ), II

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9

OpenGL Shadows Demo Program Shaders: Rendering using the Depth Shadow Map

10

GetDepth.vert

```
#version 330 compatibility

uniform mat4 uLightSpaceMatrix;
uniform mat4 uAnim;

void
main()
{
    gl_Position = uLightSpaceMatrix * uAnim * gl_Vertex;
}
```

GetDepth.frag

```
#version 330 compatibility

uniform vec3 uColor;

void main()
{
    gl_FragColor = vec4(uColor, 1.);    // really doesn't matter...
}
```

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10

OpenGL Shadows Demo Program Shaders: Rendering using the Depth Shadow Map

RenderWithShadows.vert

```
#version 330 compatibility

uniform mat4  uLightSpaceMatrix;
uniform mat4  uAnim;
uniform mat4  uModelView;
uniform mat4  uProj;
uniform float   uLightX;
uniform float   uLightY;
uniform float   uLightZ;

out vec4 vFragPosLightSpace;
out vec3 vNs;
out vec3 vLs;
out vec3 vEs;

void
main()
{
        vec3 LightPosition = vec3(uLightX, uLightY, uLightZ);

        vec4 ECposition = uModelView * uAnim * gl_Vertex;
        vec3 tnorm = normalize( mat3(uAnim) * gl_Normal );
        vNs = tnorm;
        vLs = LightPosition      - ECposition.xyz;
        vEs = vec3( 0., 0., 0. ) - ECposition.xyz;

        vFragPosLightSpace = uLightSpaceMatrix       *   uAnim * gl_Vertex;
        gl_Position                = uProj * uModelView      * uAnim * gl_Vertex;
}
```


OpenGL Shadows Demo Program Shaders: Rendering using the Depth Shadow Map

RenderWithShadows.frag, I

```
#version 330 compatibility

uniform vec3        uColor;
uniform sampler2D uShadowMap;
uniform int           uShadowsOn;

in vec4 vFragPosLightSpace;
in vec3 vNs;
in vec3 vLs;
in vec3 vEs;

const float   BIAS =  0.01;
const vec3  SPECULAR_COLOR = vec3( 1., 1., 1. );
const float   SHININESS = 8.;

const float KA = 0.20;
const float KD = 0.60;
const float KS = (1.-KA-KD);

bool    IsInShadow(vec4 fragPosLightSpace)
{
   // have to manually do homogenous division to make light space position in range of -1 to 1:
   vec3 projection = fragPosLightSpace.xyz / fragPosLightSpace.w;
   //then make it from 0 to 1:
   projection = 0.5*projection + 0.5;

   //get closest depth from light's perspective
   float closestDepth = texture(uShadowMap, projection.xy).r;

   //get current depth:
   float currentDepth = projection.z;
   bool isInShadow = (currentDepth - BIAS) > closestDepth;
   return isInShadow;
}
```

OpenGL Shadows Demo Program Shaders: Rendering using the Depth Shadow Map

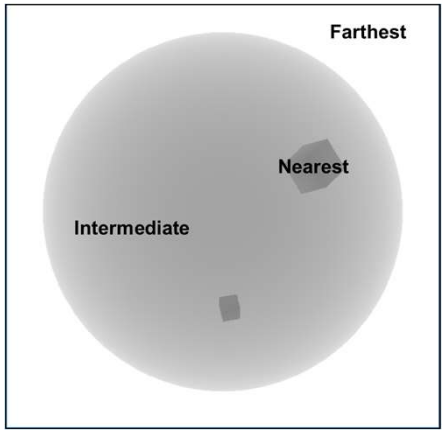
13

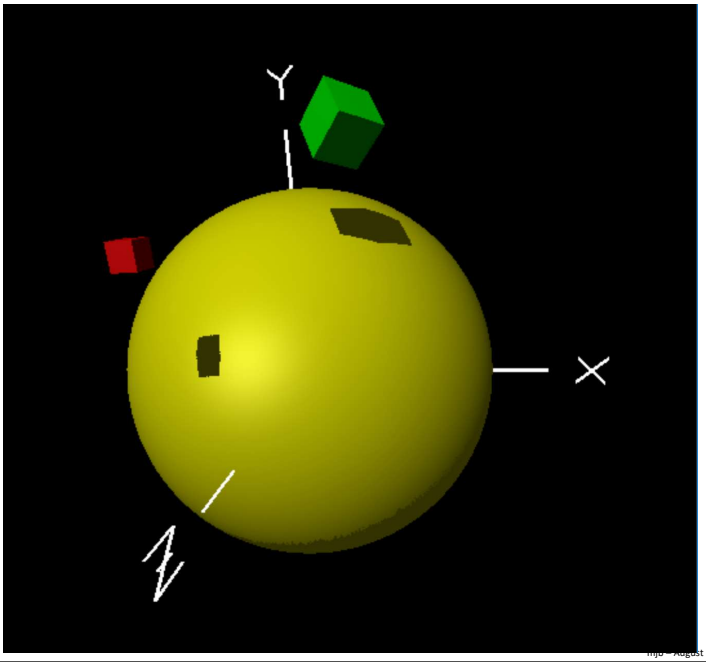
RenderWithShadows.frag, II

```
void    main( )
{
    vec3 normal  = normalize(vNs);
    vec3 light   = normalize(vLs);
    vec3 eye     = normalize(vEs);

    float d = 0.;
    float s = 0.;
    vec3 lighting = KA * uColor;

    bool isInShadow = IsInShadow(vFragPosLightSpace);
    if( uShadowsOn != 0 )
        isInShadow = false;     // if in ShadowOff mode, nothing should be cnsidered in a shadow
    if( ! isInShadow )
    {
        d = dot(normal,light);
        if(d > 0.)
        {
            vec3 diffuse = KD*d*uColor;
            lighting += diffuse;

            vec3 refl = normalize( reflect( -light, normal ) );
            float dd = dot(eye,refl);
            if( dd > 0. )
            {
                s = pow( dd, SHININESS );
                vec3 specular = KS*s*SPECULAR_COLOR;
                lighting += specular;
            }
        }
    }
    gl_FragColor = vec4( lighting, 1. );
}
```


OpenGL Shadows Demo Program: Rendering using the Depth Shadow Map

14

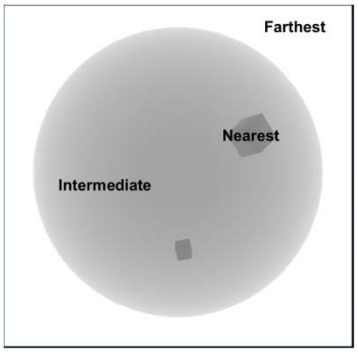




How Did the Demo Program Render that 2D Shadow Map?

In shadows.cpp

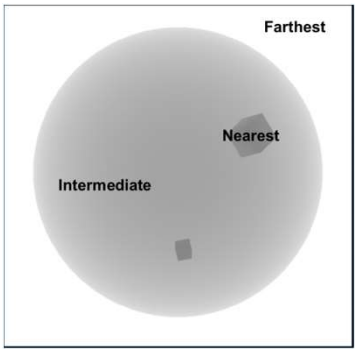
```
DisplayShadowMap.Use();
DisplayShadowMap.SetUniformVariable((char*)"uShadowMap", 0 );

glm::mat4 model = glm::mat4(1.f);
DisplayShadowMap.SetUniformVariable((char*)"uModel", model);

glm::vec3 eye = glm::vec3(0., 0., 1.);
glm::vec3 look = glm::vec3(0., 0., 0.);
glm::vec3 up = glm::vec3(0., 1., 0.);
glm::mat4 view = glm::lookAt(eye, look, up);
DisplayShadowMap.SetUniformVariable((char*)"uView", view);

glm::mat4 proj = glm::ortho(-0.6f, 0.6f,  -0.6f, 0.6f, .1f, 100.f);
DisplayShadowMap.SetUniformVariable((char*)"uProj", proj);

glBegin(GL_QUADS);
glTexCoord2f(0., 0.);
glVertex3f(-1., -1., 0.);
glTexCoord2f(1., 0.);
glVertex3f( 1., -1., 0.);
glTexCoord2f(1., 1.);
glVertex3f( 1.,  1., 0.);
glTexCoord2f(0., 1.);
glVertex3f(-1., 1., 0.);
glEnd();

DisplayShadowMap.UnUse( );
```



How Did the Demo Program Render the 2D Shadow Map?

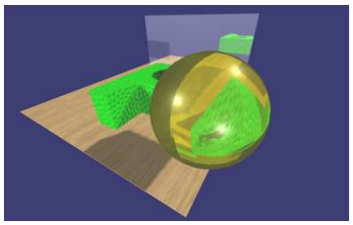
DisplayShadowMap.vert

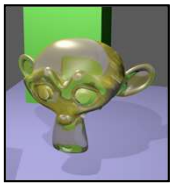
```
#version 330 compatibility

uniform mat4 uModel;
uniform mat4 uView;
uniform mat4 uProj;

out vec2 vST;

void
main()
{
	vST = gl_MultiTexCoord0.st;
	gl_Position = uProj * uView  * uModel * gl_Vertex;
}
```

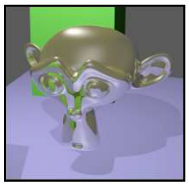


DisplayShadowMap.frag

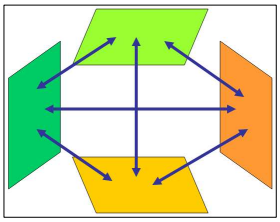
```
#version 330 compatibility

uniform sampler2D uShadowMap;

in vec2 vST;

void
main( )
{
	float gray = texture(uShadowMap, vST ).r;
	gl_FragColor = vec4( gray, gray, gray, 1. );
}
```







Rendering



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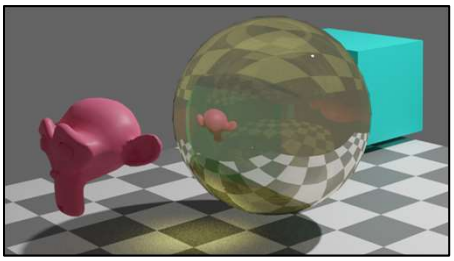
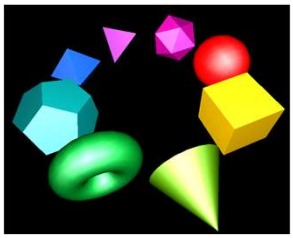
Mike Bailey
mjb@cs.oregonstate.edu



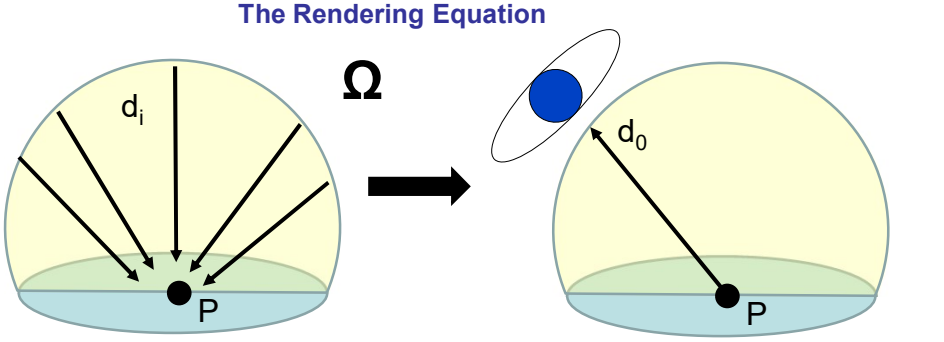


Rendering

Rendering is the process of creating an image of a geometric model.
There are questions you need to ask:

- For what purpose am I doing this?
- How realistic do I need this image to be?
- How much compute time do I have to create this image?
- Do I need to take lighting into account?
- Does the illumination need to be Global or will Local do?
- Do I need to create shadows?
- Do I need to create reflections and refractions?
- How good do the reflections and refractions need to be?

The Rendering Equation



Light arriving at Point P from everywhere

Light departing from Point P in the direction that we are viewing the scene from

$$B(P, d_0, \lambda) = E(P, d_0, \lambda) + \int_{\Omega} B(P, d_i, \lambda) f(\lambda, d_i, d_0)(d_i \cdot \hat{n}) d\Omega$$

This is the true rendering situation. Essentially, it is an energy balance:

In English, this says that the Light Shining from a point P =
Light emitted by that point + Reflectivity * Σ(Light arriving from all other points)

But, this is time-consuming to solve "exactly".
So, we need to know **how much of an approximation we need**

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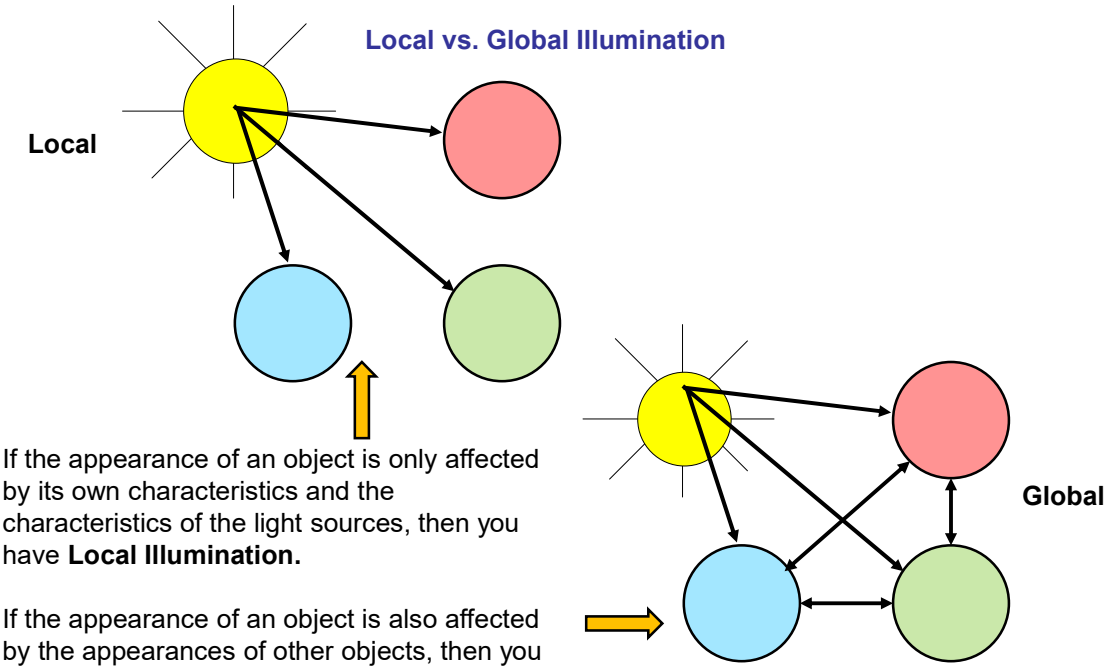
Local vs. Global Illumination



If the appearance of an object is only affected by its own characteristics and the characteristics of the light sources, then you have **Local Illumination.**

If the appearance of an object is also affected by the appearances of other objects, then you have **Global Illumination.**

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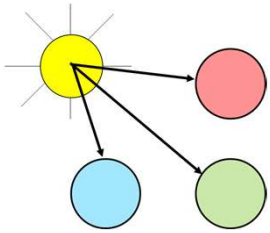
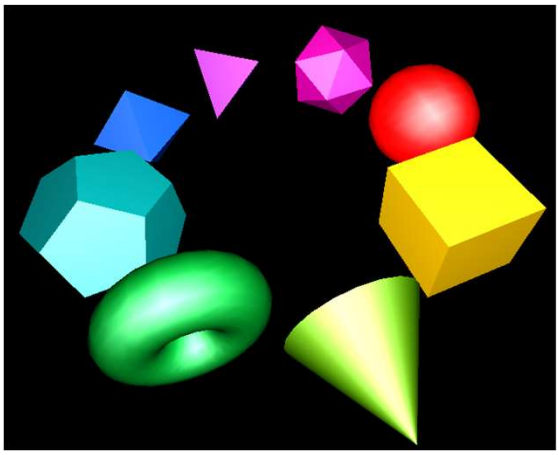
Local Illumination at Work



"If the appearance of an object is only affected by its own characteristics and the characteristics of the light sources, then you have **Local Illumination.**"



OpenGL rendering uses Local Illumination

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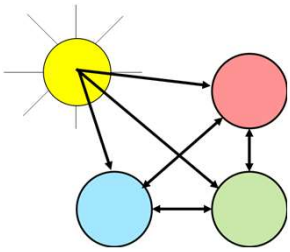
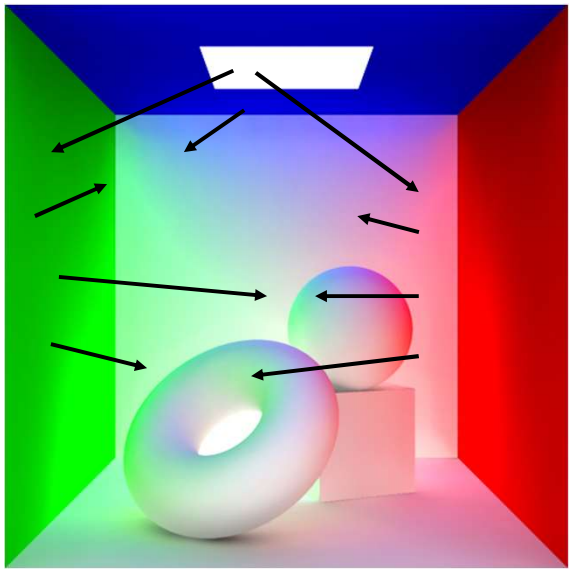
Global Illumination at Work



- The left wall is green.
- The right wall is red.
- The back wall is white.
- The ceiling is blue with a light source in the middle of it.
- The objects sitting on the floor are white.

"If the appearance of an object is also affected by the appearances of other objects, then you have **Global Illumination.**"



http://www.swardson.com/unm/tutorials/mentalRay3/

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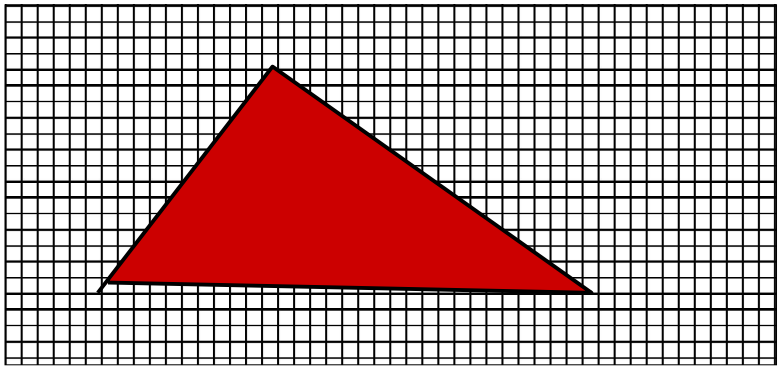
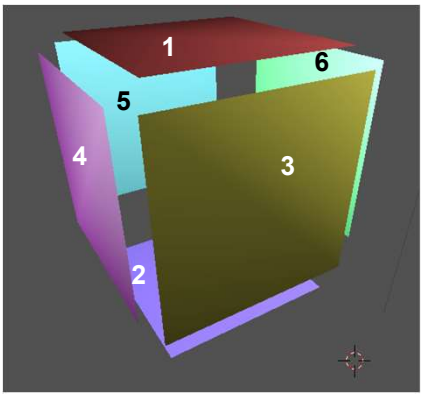
How Graphics Hardware Renders: Start with the Object, Works Towards the Pixels

- This is the kind of rendering you get on a graphics card (e.g., OpenGL).
- You have been doing this all along.
- Start with the geometry and project it onto the pixels.



Why do things in front look like they are *really* in front?

Your application might draw this cube's polygons in 1-2-3-4-5-6 order, but 1, 3, and 4 still need to look like they were drawn last:



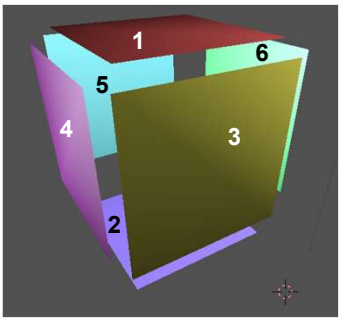
Solution #1: Sort your polygons in 3D by depth and draw them back-to-front.

In this case 1-2-3-4-5-6 becomes 5-6-2-4-1-3.

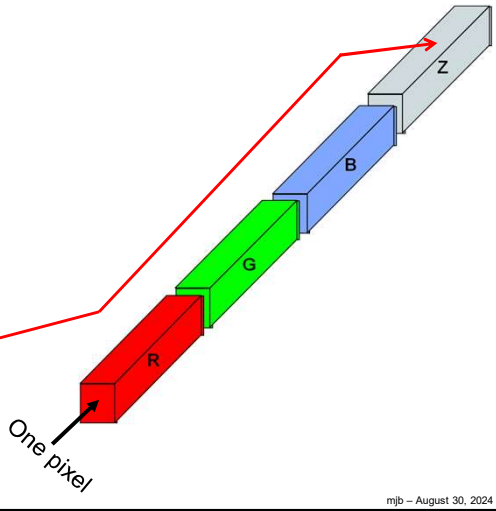
This is called the **Painter's Algorithm**. It sucked to have to do things this way.

Why do things in front look like they are *really* in front?

Your application might draw this cube's polygons in 1-2-3-4-5-6 order, but 1, 3, and 4 still need to look like they were drawn last:



Solution #2: Add an extension to the framebuffer to store the depth of each pixel. This is called a **Depth-buffer** or **Z-buffer** (or **Zed-buffer** in other parts of the world). Only allow pixel stores when the depth of the incoming pixel is closer to the viewer than the pixel that is already in that spot in the framebuffer.



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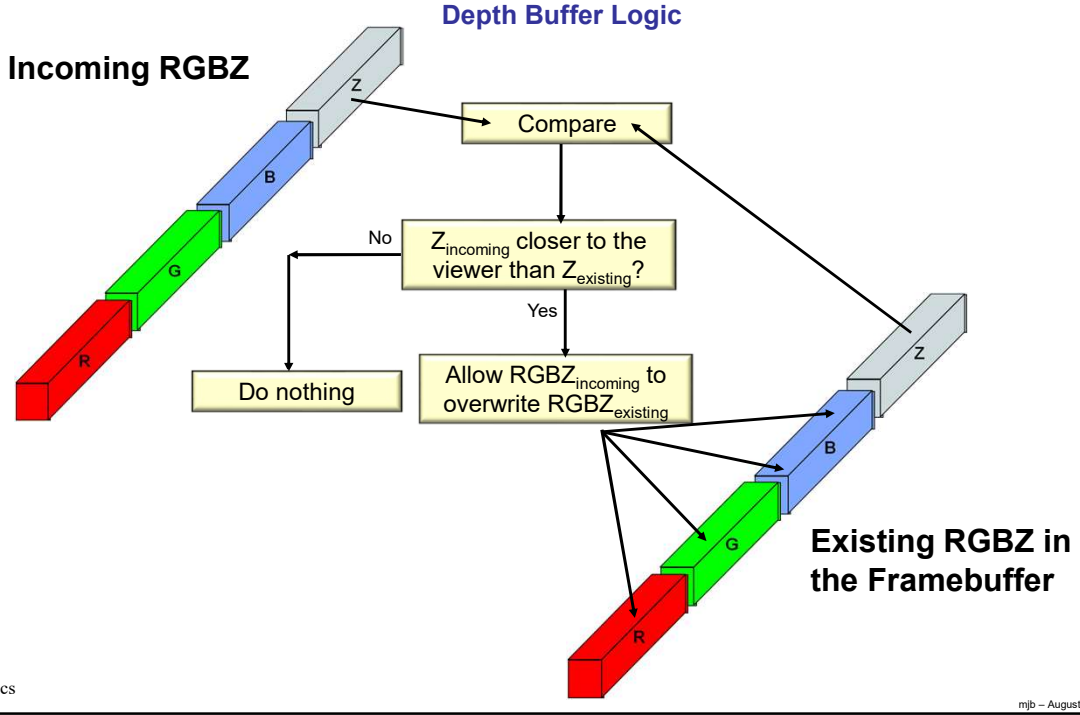
Depth Buffer Logic



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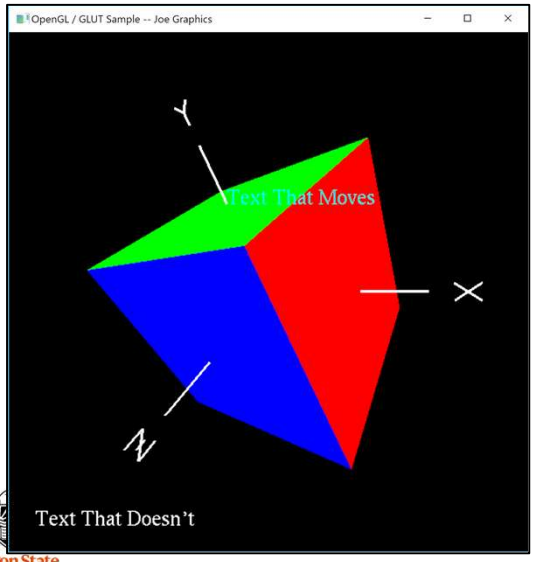
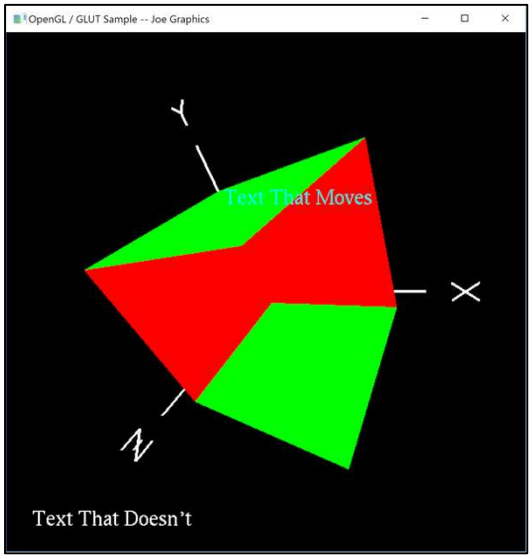
Why do things in front look like they are *really* in front?

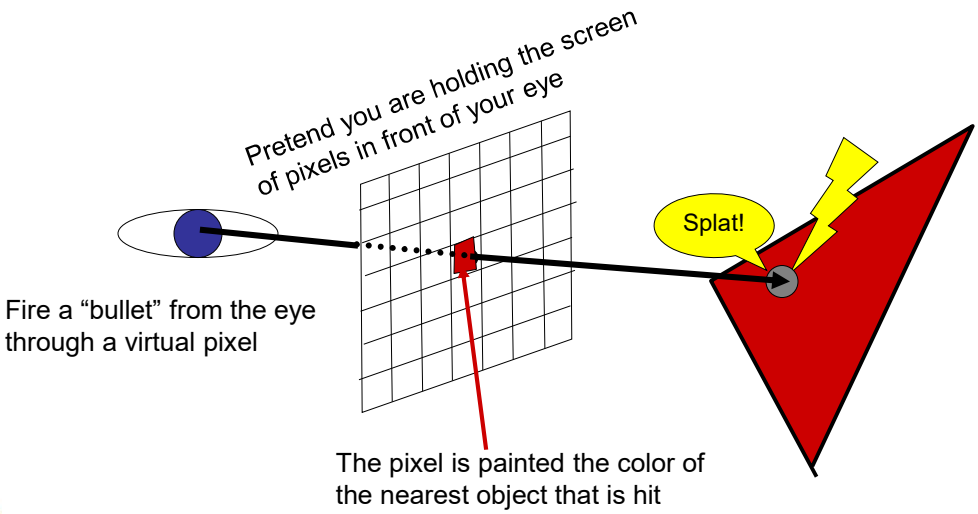


With Depth Buffer

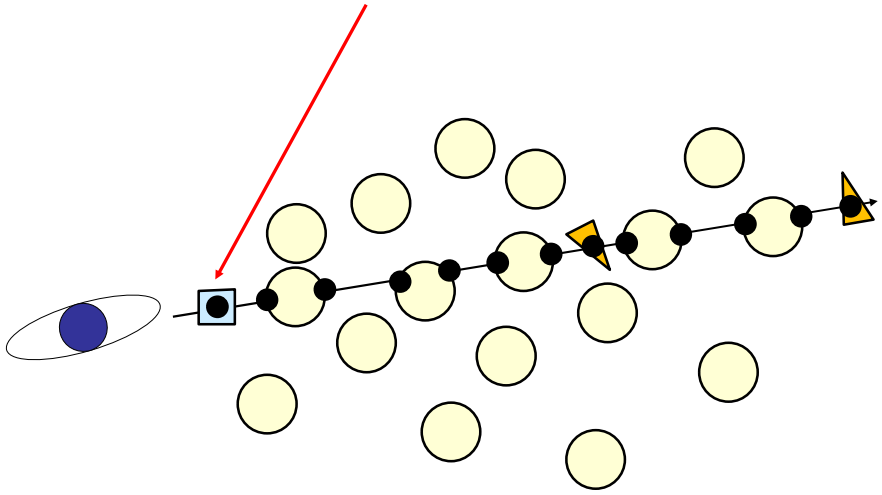


Without Depth Buffer

Ray-Tracing: Start at the Pixels, Work Towards the Objects

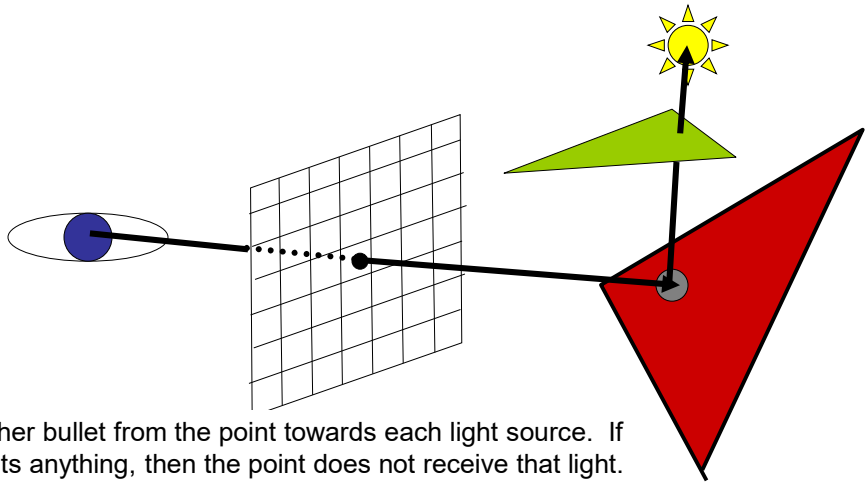


In a Ray-Tracing, each Ray ("bullet") typically hits a lot of Things – You Need to Find All the Hits, then Find the Nearest Hit and work from There



Ray-Tracing

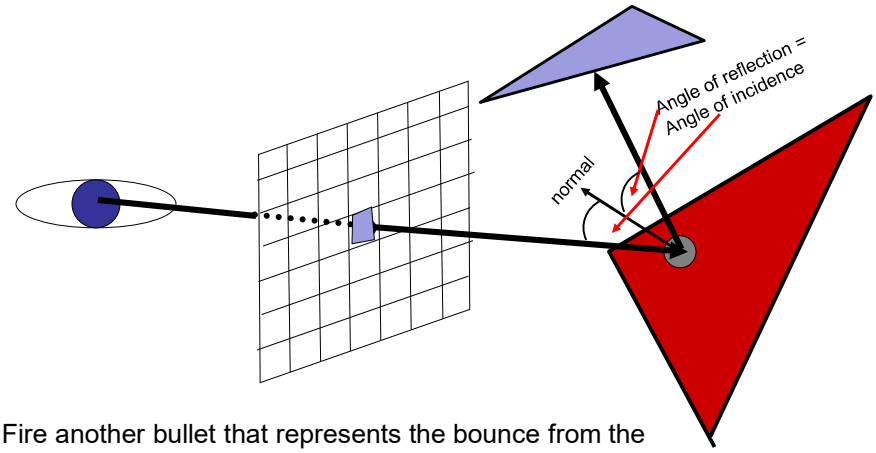
It's also straightforward to see if the closest intersection point lies in a shadow:



Fire another bullet from the point towards each light source. If the ray hits anything, then the point does not receive that light.

Ray-Tracing

It's also straightforward to handle reflection



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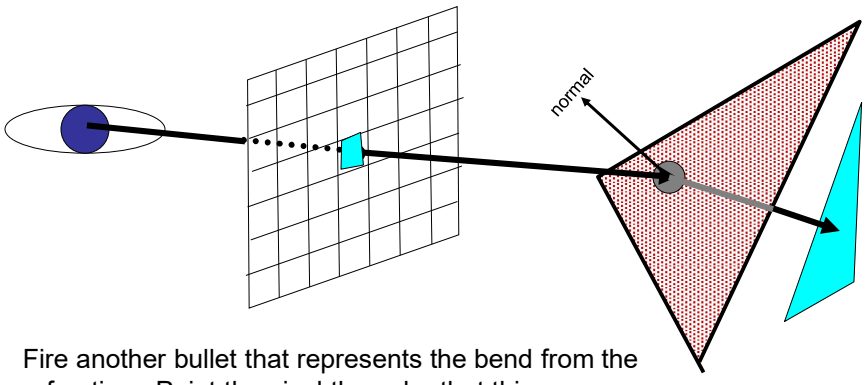
Fire another bullet that represents the bounce from the reflection. Paint the pixel the color that this ray sees.

Ray-Tracing

It's also straightforward to handle refraction



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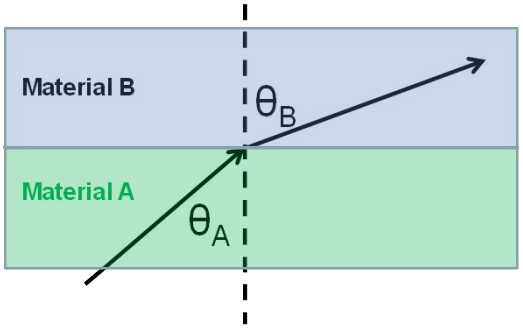
Fire another bullet that represents the bend from the refraction. Paint the pixel the color that this ray sees.

The Physics of Refraction



Snell's Law of Refraction:

$$\frac{\sin\Theta_B}{\sin\Theta_A} = \frac{\eta_A}{\eta_B}$$

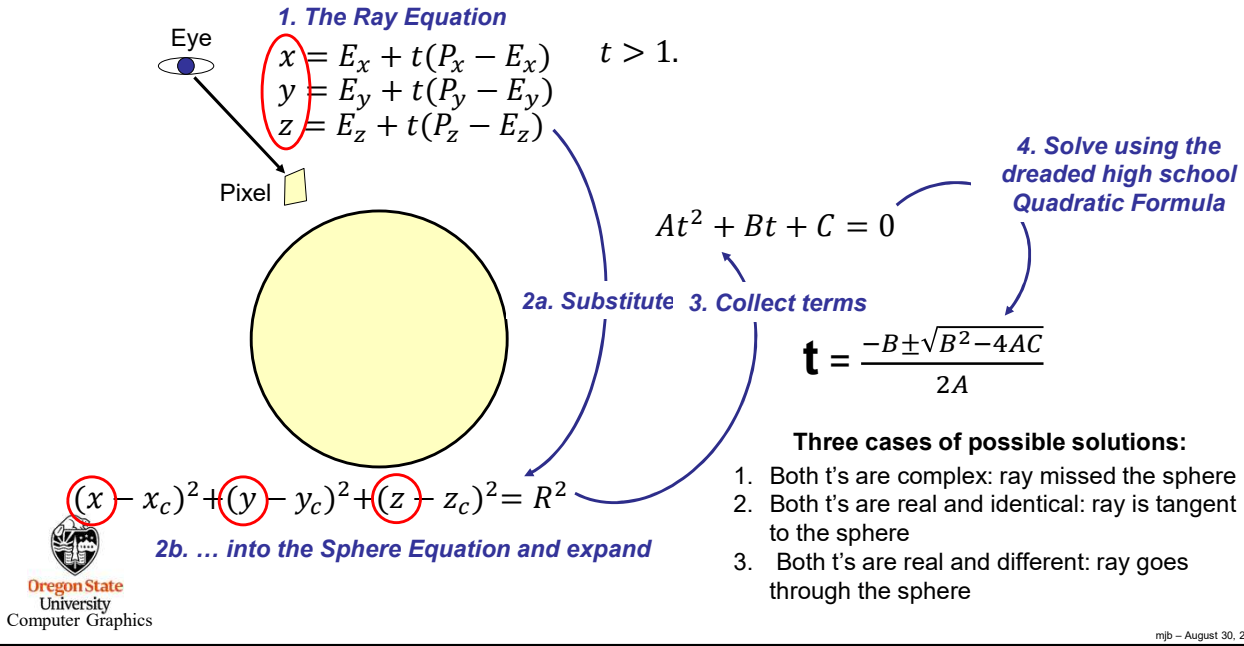
η ⇩

Material	Index of Refraction
Vacuum	1.00000
Air	1.00029
Ice	1.309
Water	1.333
Plexiglass	1.49
Glass	1.60
Diamond	2.42

http://en.wikipedia.org/wiki/Refractive_index

Refraction in Action ☺

An Example of How to Determine a Ray-Shape Intersection



Three cases of possible solutions:

1. Both t's are complex: ray missed the sphere
2. Both t's are real and identical: ray is tangent to the sphere
3. Both t's are real and different: ray goes through the sphere

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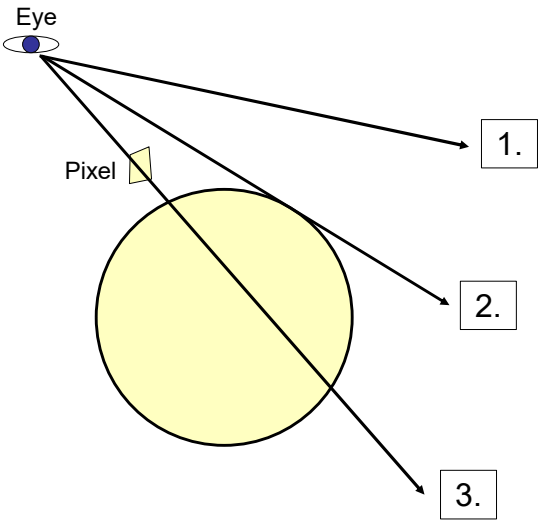
An Example of How to Determine a Ray-Shape Intersection



Three cases of possible solutions:

1. Both t's are complex: ray missed the sphere
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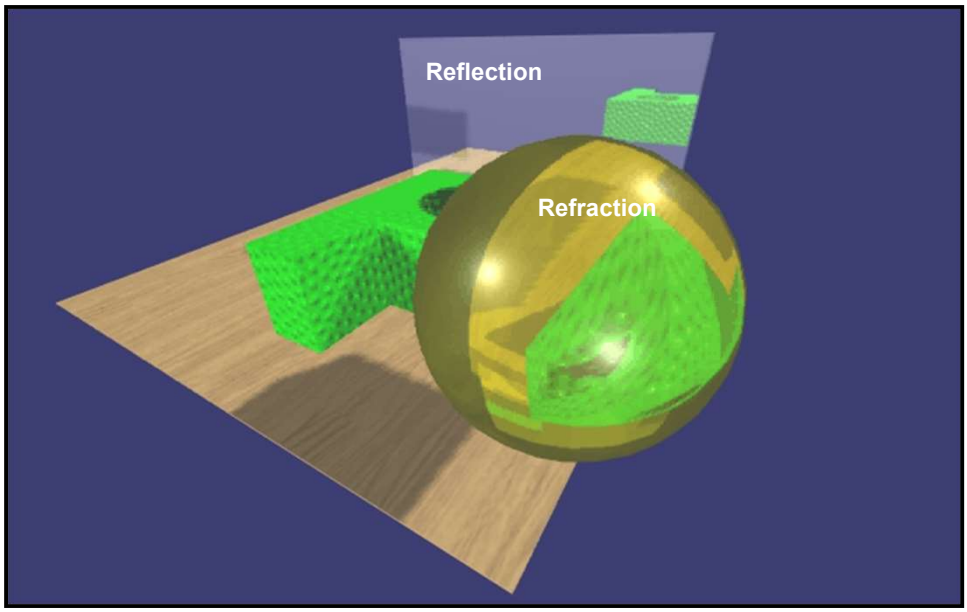
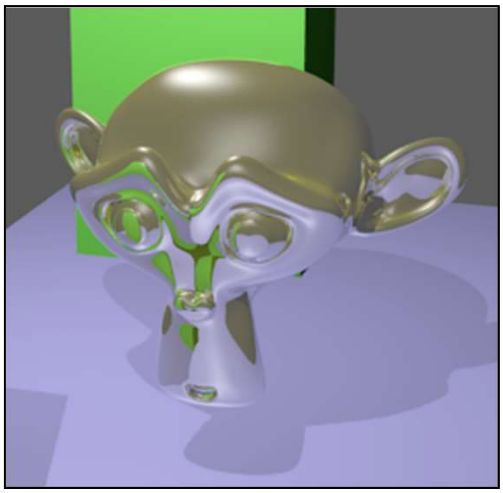
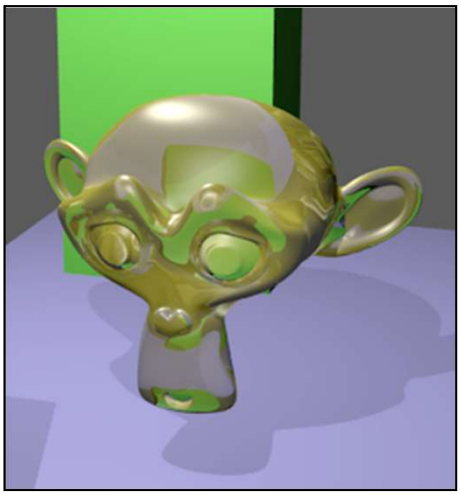
IronCAD Ray-Tracing Example



Blender Ray-Tracing Examples

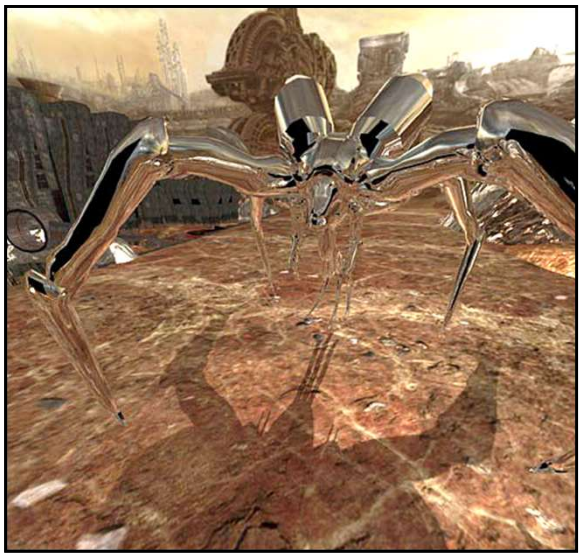


Reflection



Refraction

More Ray-tracing Examples



Quake 4 Ray-Tracing Project

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More Ray-Tracing Examples

IBM

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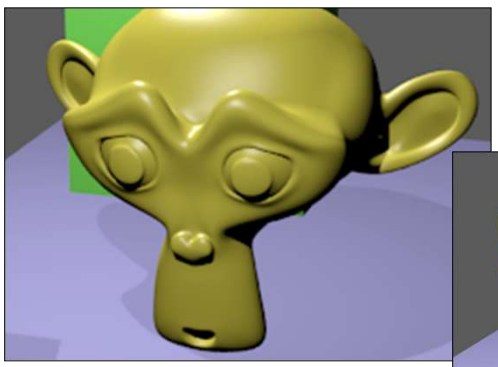
More Ray-Tracing Examples

Bunkspeed

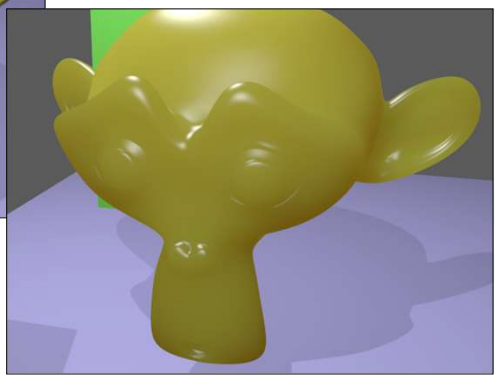
Subsurface Scattering

- Subsurface Scattering mathematically models light bouncing around within an object before coming back out.
- This is a good way to render skin, wax, milk, paraffin, etc.

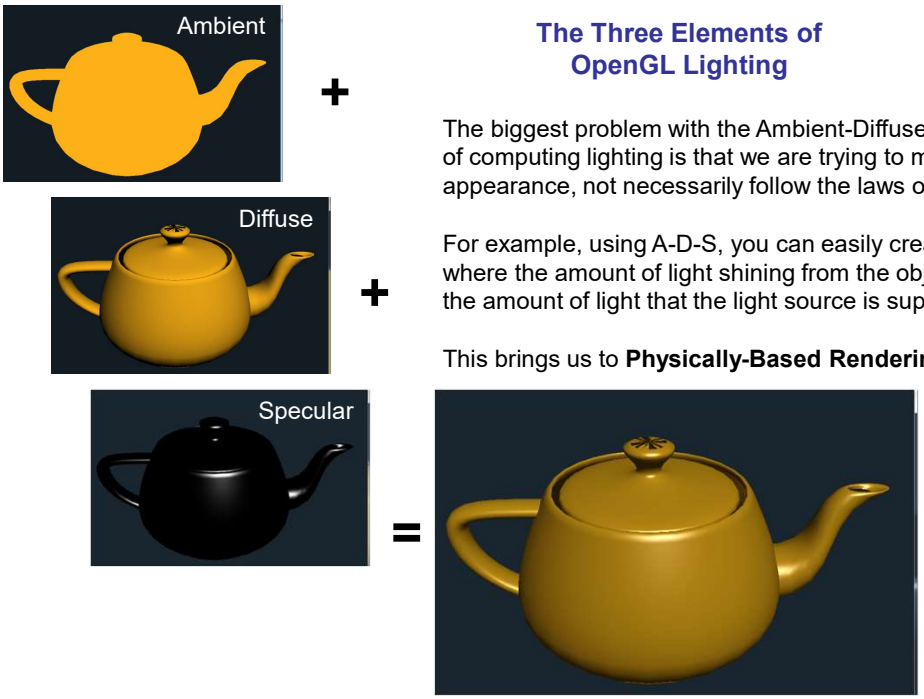


Original rendering

Subsurface scattering



The Three Elements of OpenGL Lighting



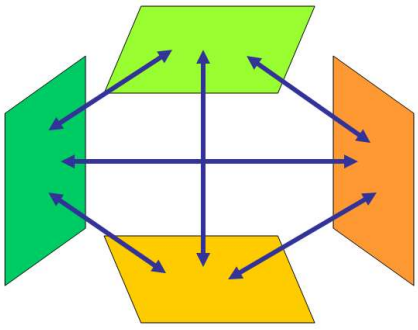
The biggest problem with the Ambient-Diffuse-Specular way of computing lighting is that we are trying to match an appearance, not necessarily follow the laws of physics.

For example, using A-D-S, you can easily create a scene where the amount of light shining from the objects exceeds the amount of light that the light source is supplying!

This brings us to **Physically-Based Rendering (PBR).**

Radiosity

Based on the idea that all surfaces gather light intensity from all other surfaces



The fundamental radiosity equation is an energy balance that says:

"The light energy leaving surface *i* equals the amount of light energy generated by surface *i* plus surface *i*'s reflectivity times the amount of light energy arriving from all other surfaces"

$$B_i A_i = E_i A_i + \rho_i \sum_j B_j A_j F_{j \to i}$$

This is a good approximation to the **Rendering Equation**

The Radiosity Equation

$$B_i A_i = E_i A_i + \rho_i \sum_j B_j A_j F_{j \to i}$$

B_i is the light energy intensity shining from surface element *i*

A_i is the area of surface element *i*

E_i is the internally-generated light energy intensity for surface element *i*

ρ_i is surface element *i*'s reflectivity

$F_{j \to i}$ is referred to as the **Shape Factor**, and describes what percent of the energy leaving surface element *j* arrives at surface element *i*

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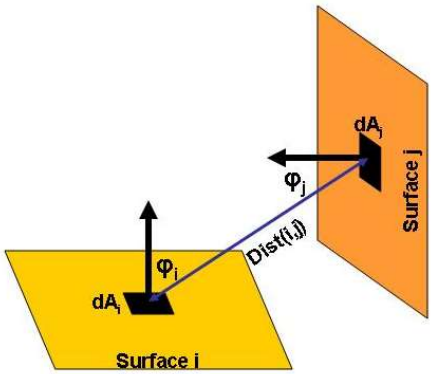
The Radiosity Shape Factor



$$F_{j \to i} = \int_{Ai} \int_{A_j} visibility(di, dj) \frac{\cos\Theta_i \cos\Theta_j}{\pi Dist(di, dj)^2} dA_j dA_i$$

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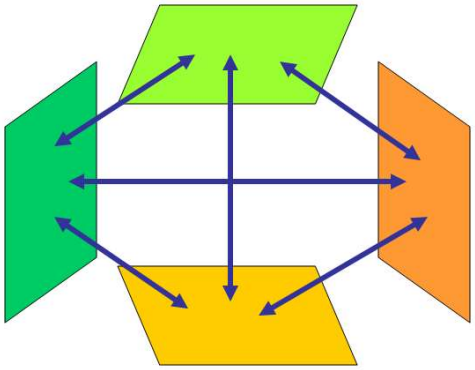
I know what you're thinking:
It seems to you that the light just keeps propagating and you never actually get an answer?



To many people, radiosity seems like this:

Use x to get y y = 3x + 5

Then use y to get x x = y - 7

"x produces y, then y produces x,
then x produces y, then …"

Not really – it is simply N equations, N unknowns – you solve for the unique solution

$$\begin{aligned} -3x + y &= 5 \\ x - y &= -7 \end{aligned}$$

x = 1
y = 8

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The Radiosity Matrix Equation

$$B_i A_i = E_i A_i + \rho_i \sum_j B_j A_j F_{j \to i} \quad \Longrightarrow \quad B_i A_i - \rho_i \sum_j B_j A_j F_{j \to i} = E_i A_i$$

Expand for each surface element, and re-arrange
to **solve for the surface intensities, the *B*'s**:

$$\begin{bmatrix} 1-\rho_1 F_{1\to1} & -\rho_1 F_{1\to2} & \bullet\bullet\bullet & -\rho_1 F_{1\to N} \\ -\rho_2 F_{2\to1} & 1-\rho_2 F_{2\to2} & \bullet\bullet\bullet & -\rho_2 F_{2\to N} \\ \bullet\bullet\bullet & \bullet\bullet\bullet & \bullet\bullet\bullet & \bullet\bullet\bullet \\ -\rho_N F_{N\to1} & -\rho_N F_{N\to2} & \bullet\bullet\bullet & 1-\rho_N F_{N\to N} \end{bmatrix} \begin{Bmatrix} B_1 \\ B_2 \\ \bullet\bullet\bullet \\ B_N \end{Bmatrix} = \begin{Bmatrix} E_1 \\ E_2 \\ \bullet\bullet\bullet \\ E_N \end{Bmatrix}$$

This is a lot of equations!

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Radiosity Examples

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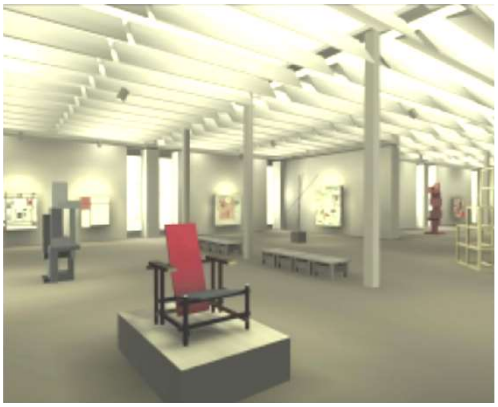


Cornell University

Radiosity Examples

AR Toolkit

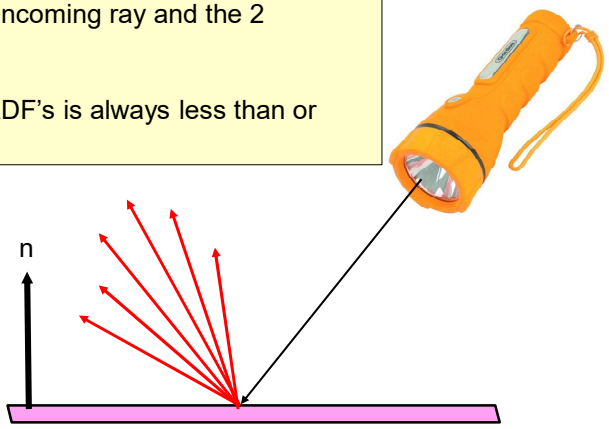
Autodesk

Path Tracing: When light hits a surface, it bounces in particular ways depending on the angle and the material

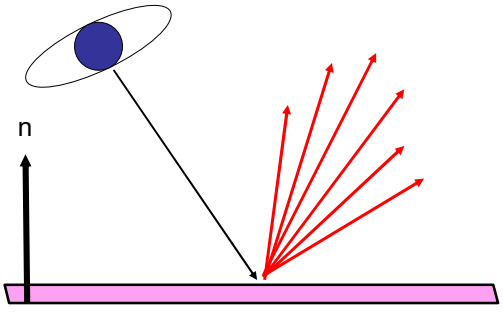
This distribution of bounced light rays is called the **Bidirectional Reflectance Distribution Function**, or **BRDF**.

For a given material, the BRDF behavior of a light ray is a function of 4 variables: the 2 spherical coordinates of the incoming ray and the 2 spherical coordinates of the outgoing ray.

The outgoing light energy in the outgoing BRDF's is always less than or equal to the amount of light that shines in.

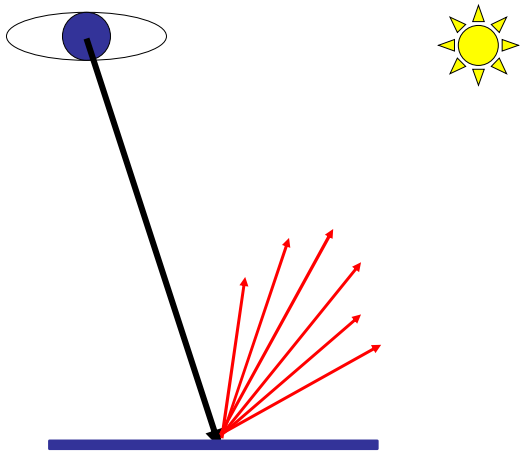


Usually it is easier to trace from the eye

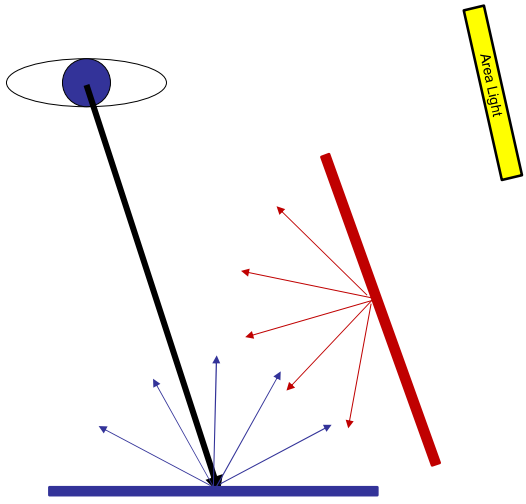


Path Tracing

Somewhat like ray-tracing, somewhat like radiosity where light can bounce around the scene but this has more sophisticated effects.



Path Tracing



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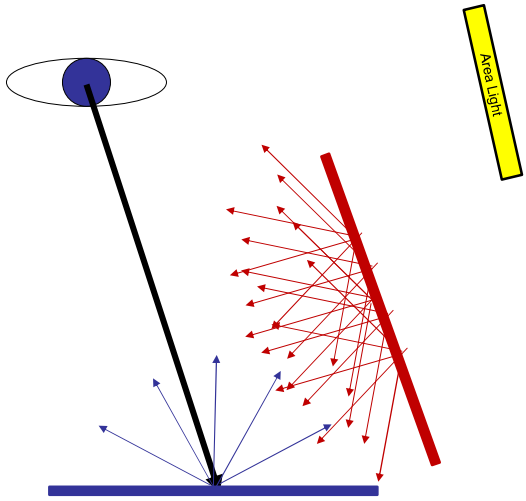
Path Tracing



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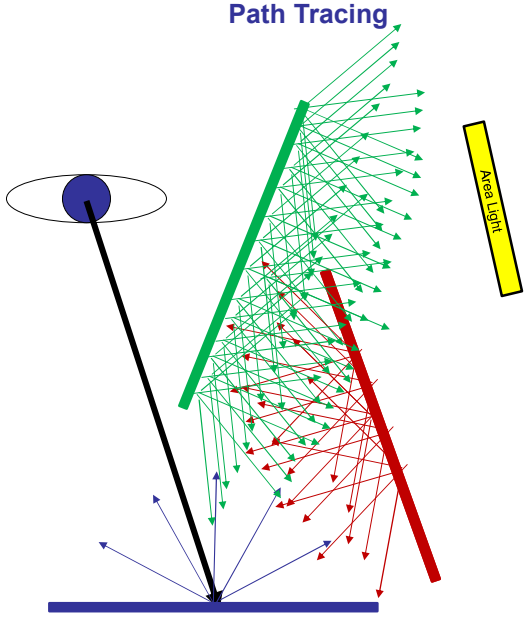
Path Tracing



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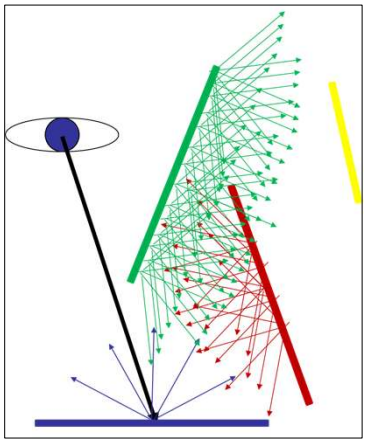
Path Tracing



Clearly this is capable of spawning an infinite number of rays. How do we handle this?

Monte Carlo simulation to the rescue!

Each time a ray hits a surface, use the equation at that point. Continue until:

1. Nothing is hit
2. A light is hit
3. Some maximum number of bounces are found

$$LightGathered = \frac{\sum_0^{N-1} ResultOfRaysCastInRandomDirection}{N}$$

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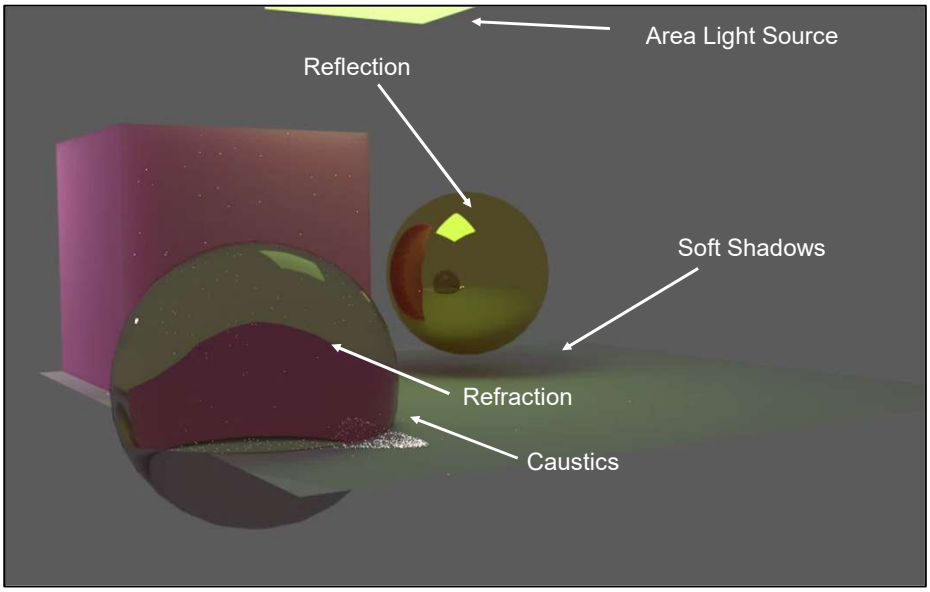
Recurse by applying this equation for all ray hits (yikes!)

Physically-Based Rendering using the Blender *Cycles* Renderer



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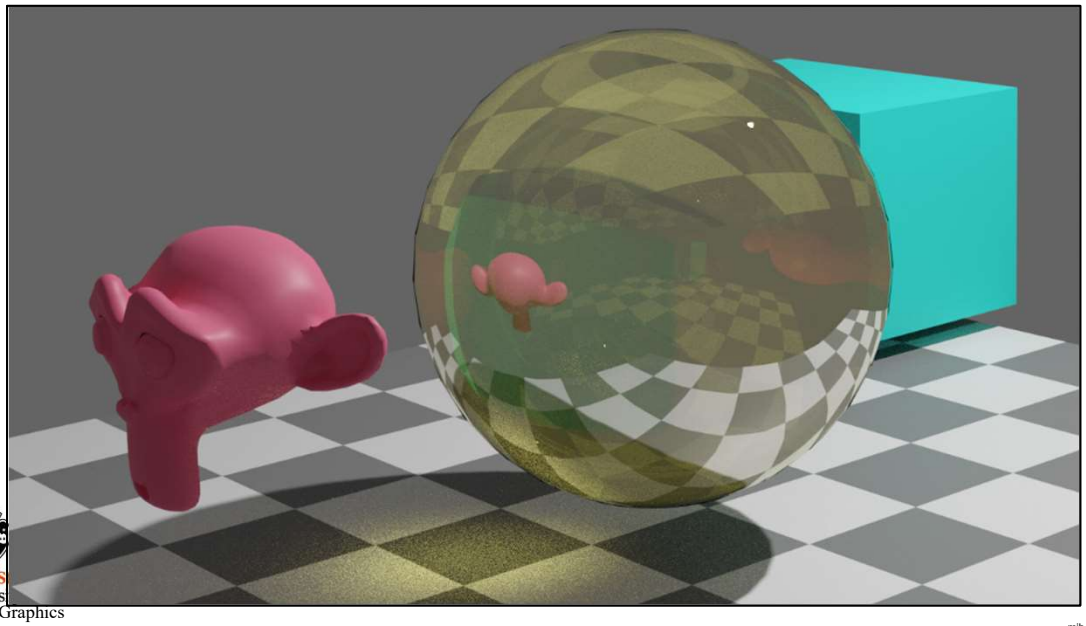
Physically-Based Rendering using the Blender *Cycles* Renderer



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Interesting Mix of Surface Properties: Mmmmm, Gummies!

Image by Grace Todd

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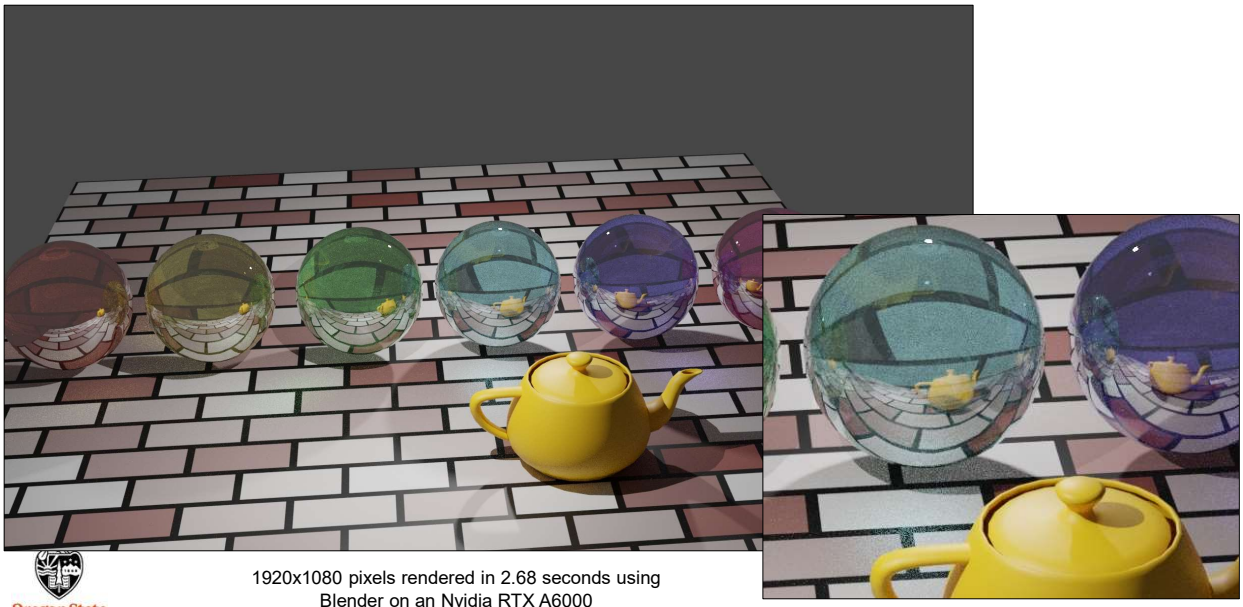
Hardware Ray-Tracing



1920x1080 pixels rendered in 2.68 seconds using Blender on an Nvidia RTX A6000

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Another Physically-Based Rendering Example

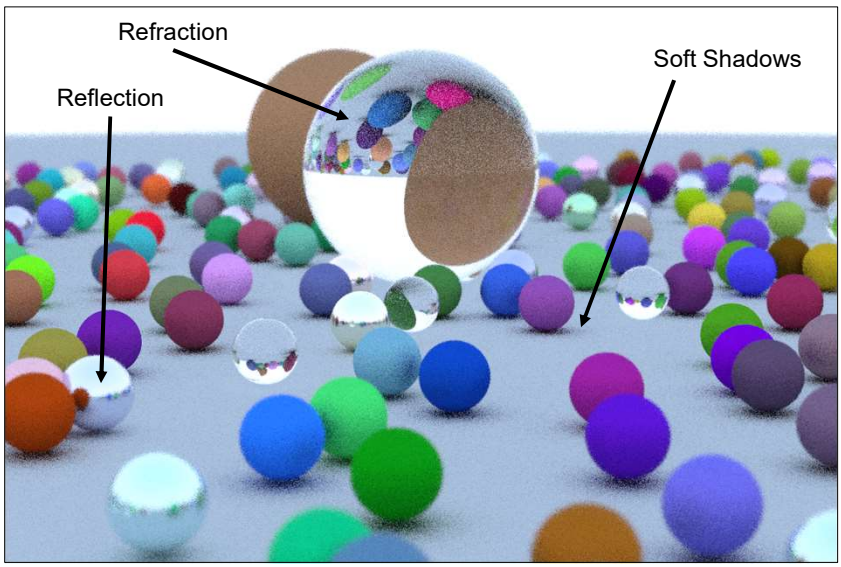

Image by Josiah Blaisdell

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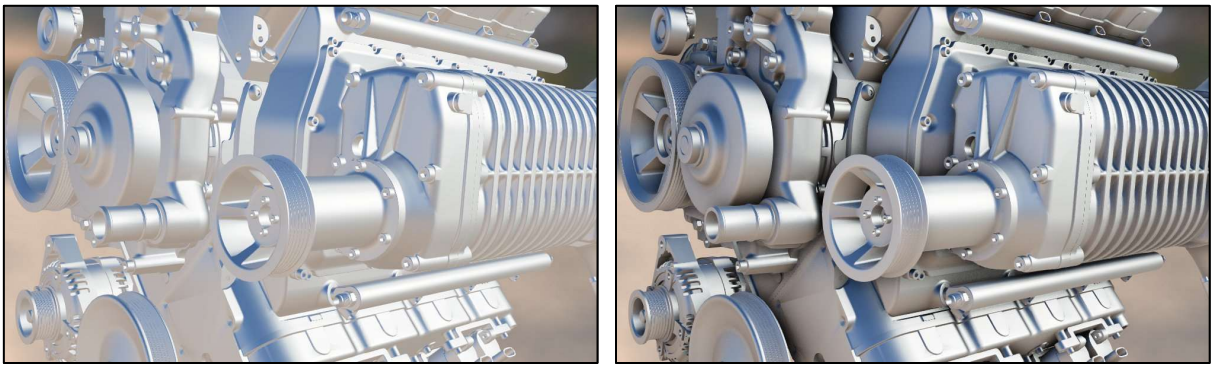
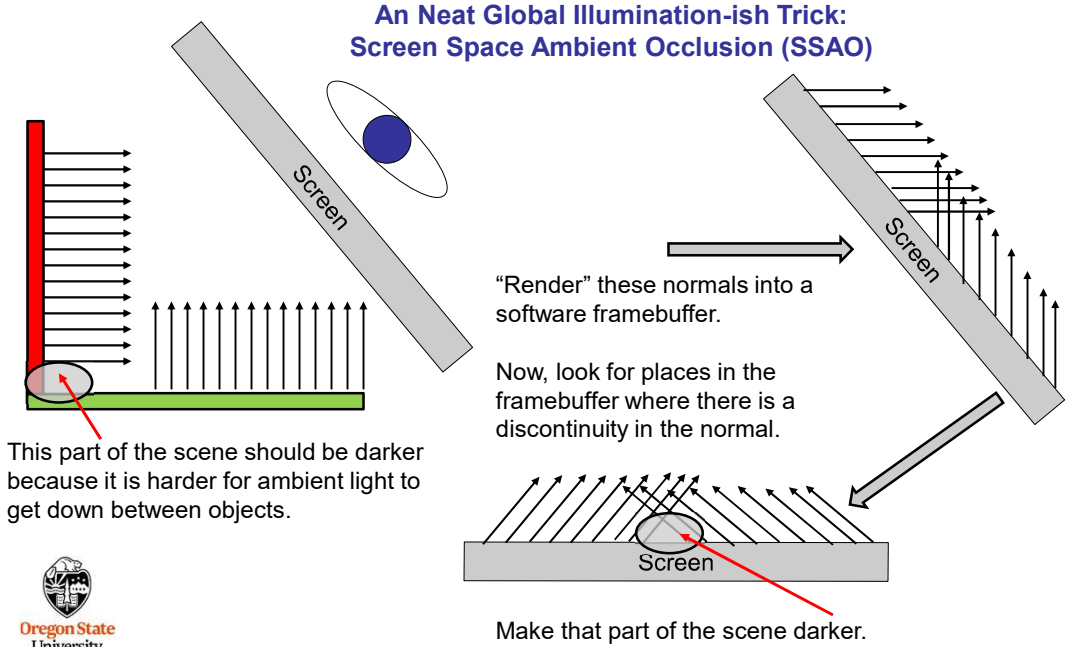
An Neat Global Illumination-ish Trick: Screen Space Ambient Occlusion (SSAO)



Kitware

An Neat Global Illumination-ish Trick: Screen Space Ambient Occlusion (SSAO)



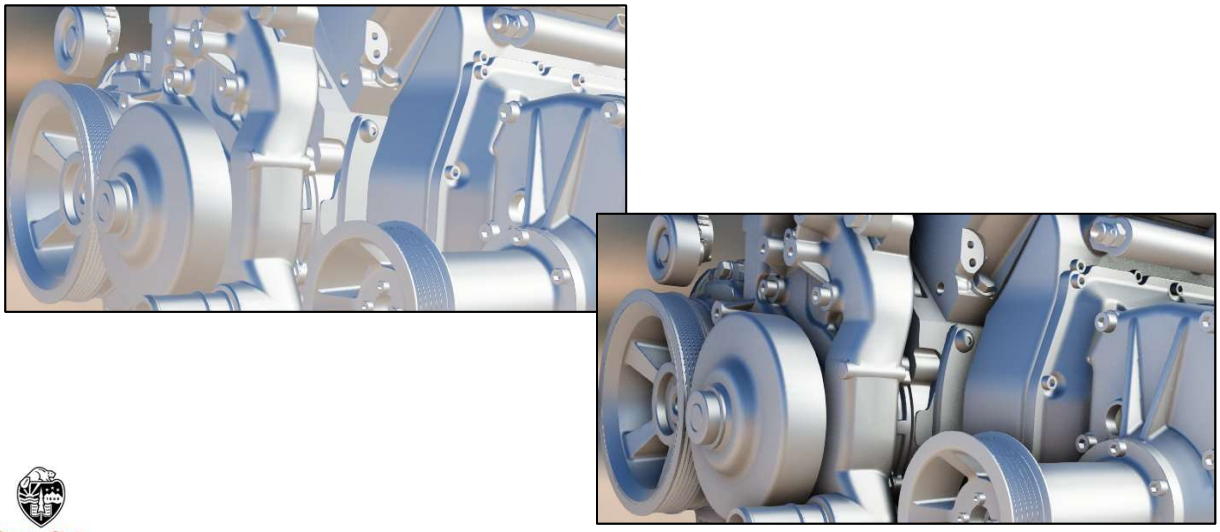
This part of the scene should be darker because it is harder for ambient light to get down between objects.

"Render" these normals into a software framebuffer.

Now, look for places in the framebuffer where there is a discontinuity in the normal.

Make that part of the scene darker.

A Neat Global Illumination-ish Trick: Screen Space Ambient Occlusion (SSAO)



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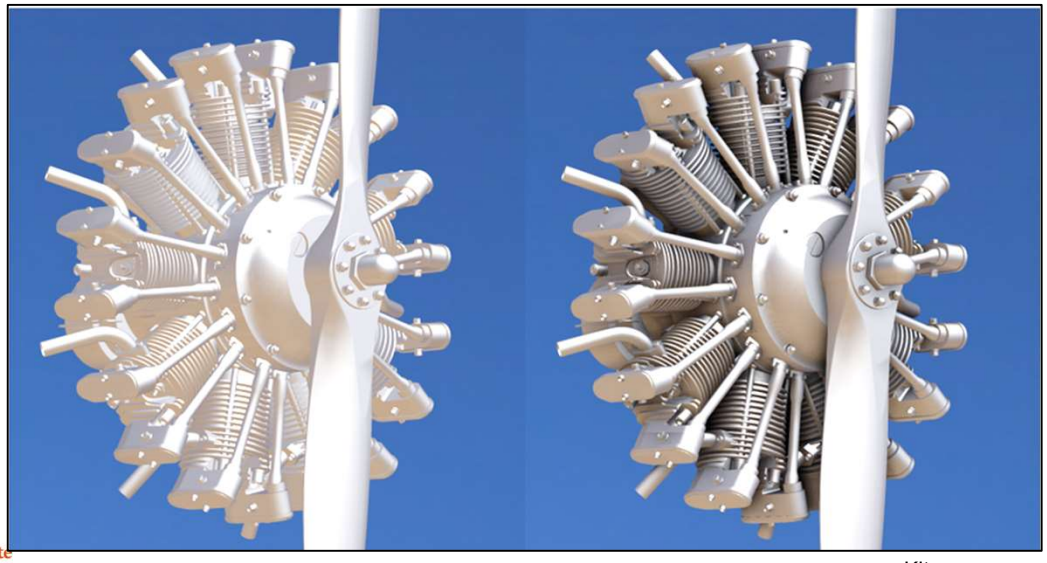
A Neat Global Illumination-ish Trick: Screen Space Ambient Occlusion (SSAO)



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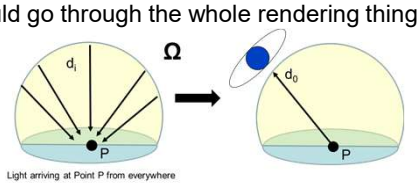
Something New:
Neural Radiance Fields -- NeRFs

What if you want to know what an object looks like no matter where other light is coming from and no matter where you view it from? You could go through the whole rendering thing from every viewing angle…



…but that would be time consuming and would preclude any sort of real-time scene manipulation.

In the NeRFs technique, you precompute, for every incoming light direction how much of that ends up in every outgoing viewing direction. Then, when interacting with the scene, you don't need to do any actual "rendering". You just track the radiance outputs from an object and use those as inputs to other objects and use those precomputed values to see what comes out of that object.

How can we lookup that information quickly?

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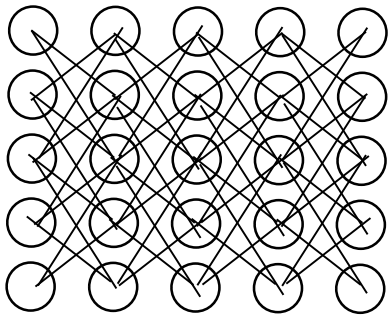
NeRFs: Machine Learning to the Rescue!

For each object, you train a neural network …



…on the pre-rendered data so that a radiance input to that object can quickly be turned into a radiance output from that object

This is very new technique, but something worth keeping an eye on!

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