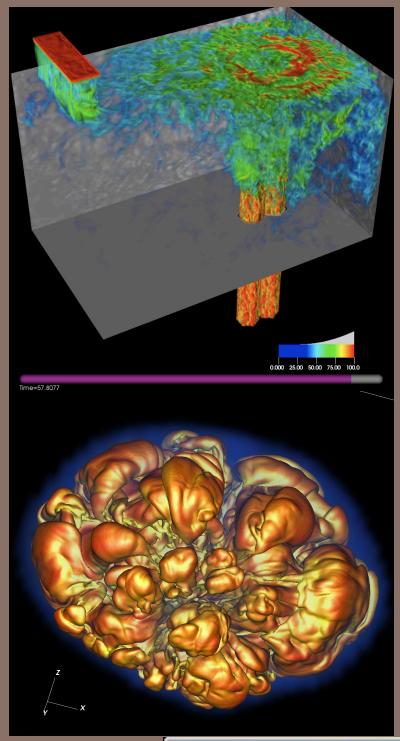
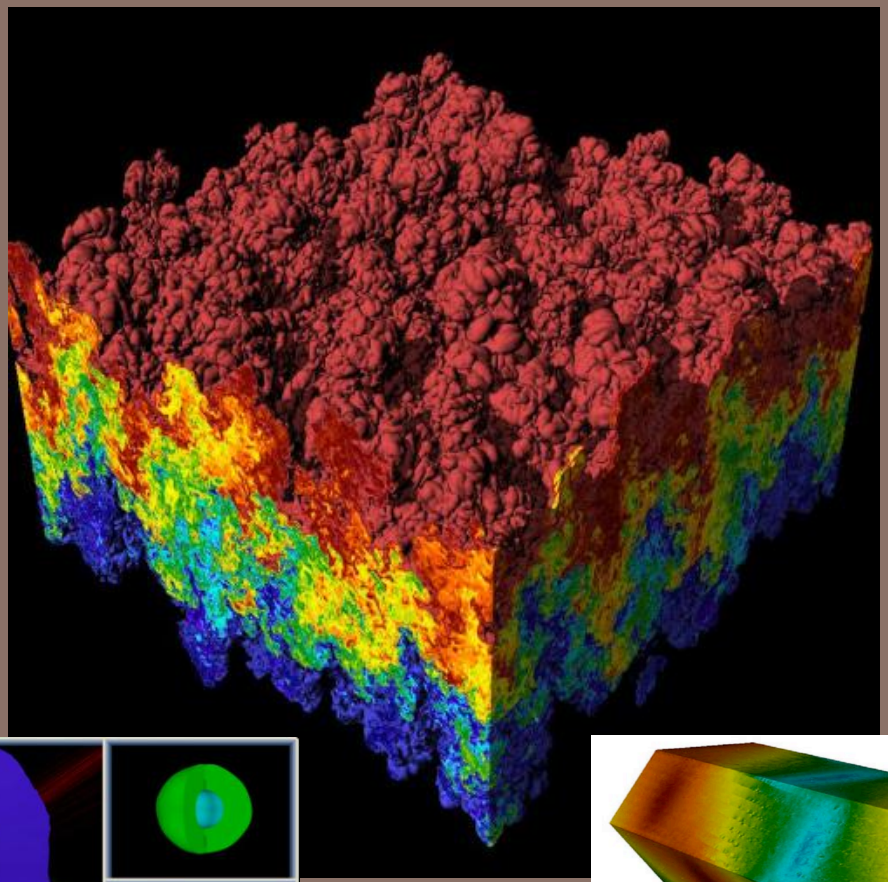
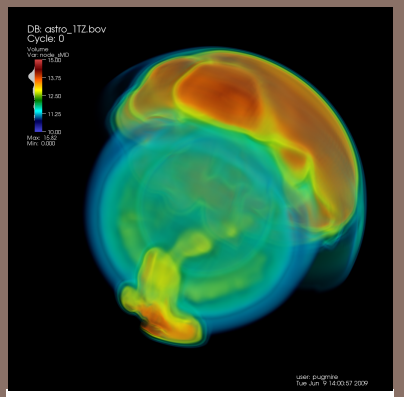
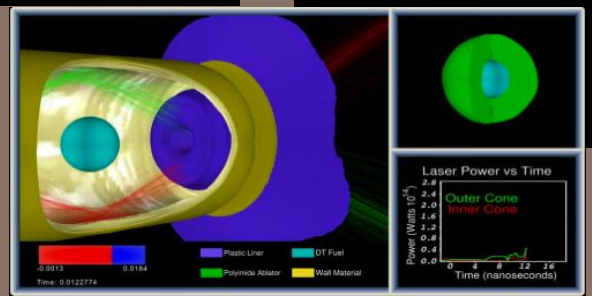
CIS 441/541: Introduction to Computer Graphics

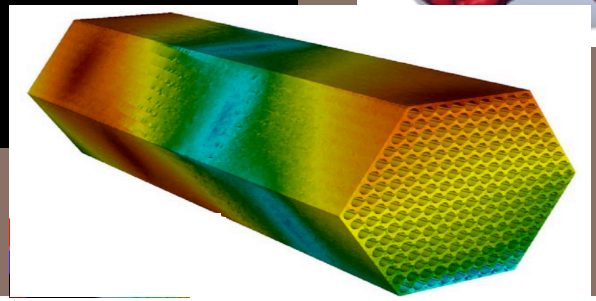
Lecture 17: 2D textures











Nov. 2nd, 2016

Hank Childs, University of Oregon

Announcements

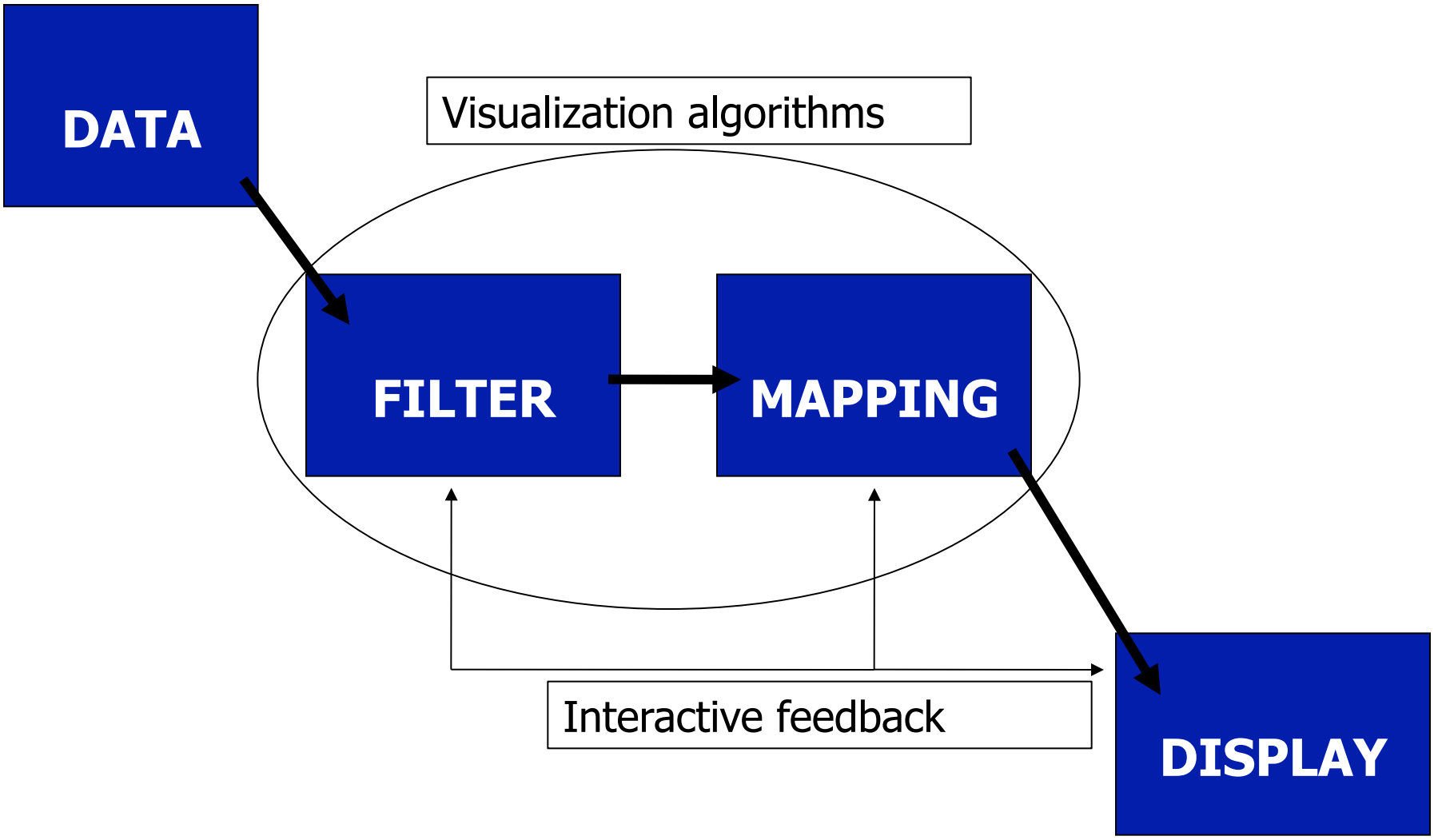
- Midterm on November 18th
- Old:
  - 441 students must do self-defined final project
- New:
  - 441 students do self-defined final project
  - -- or –
  - 441 students do additional projects, as defined by 541 students

Review

Windows and Events

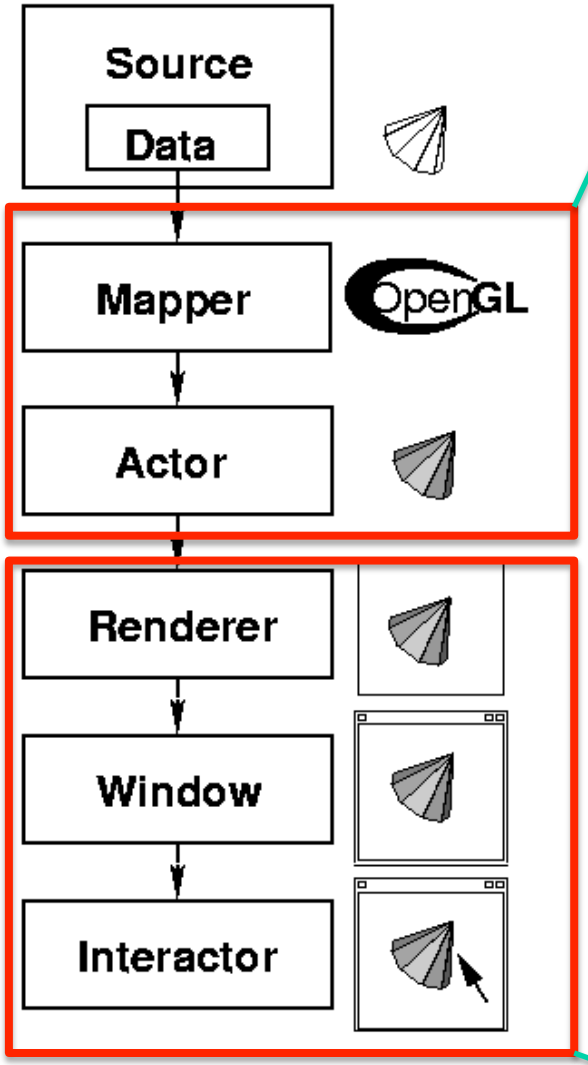
- Creating windows and dealing with events varies from platform to platform.
- Some packages provide implementations for key platforms (Windows, Unix, Mac) and abstractions for dealing with windows and events.
- GLUT: library for cross-platform windowing & events.
  - My experiments: doesn't work as well as it used to.
- VTK: library for visualization
  - But also contains cross-platform windowing & events.

The visualization pipeline



We will replace these and write our own GL calls.

Cone.py Pipeline Diagram (type "python Cone.py" to run)



Either reads the data from a file or creates the data from scratch.

```
from vtkpython import *

cone = vtkConeSource()
cone.SetResolution(10)
```

Moves the data from VTK into OpenGL.

```
coneMapper = vtkPolyDataMapper()
coneMapper.SetInput(cone.GetOutput())
```

For setting colors, surface properties, and the position of the object.

```
coneActor = vtkActor()
coneActor.SetMapper(coneMapper)
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The rectangle of the computer screen that VTK draws into.

```
ren = vtkRenderer()
ren.AddActor(coneActor)
```

The window, including title bar and decorations.

```
renWin = vtkRenderWindow()
renWin.SetWindowName("Cone")
renWin.SetSize(300,300)
renWin.AddRenderer(ren)
```

Allows the mouse to be used to interact wth the data.

```
iren = vtkRenderWindowInteractor()
iren.SetRenderWindow(renWin)
iren.Initialize()
iren.Start()
```

We will re-use these.

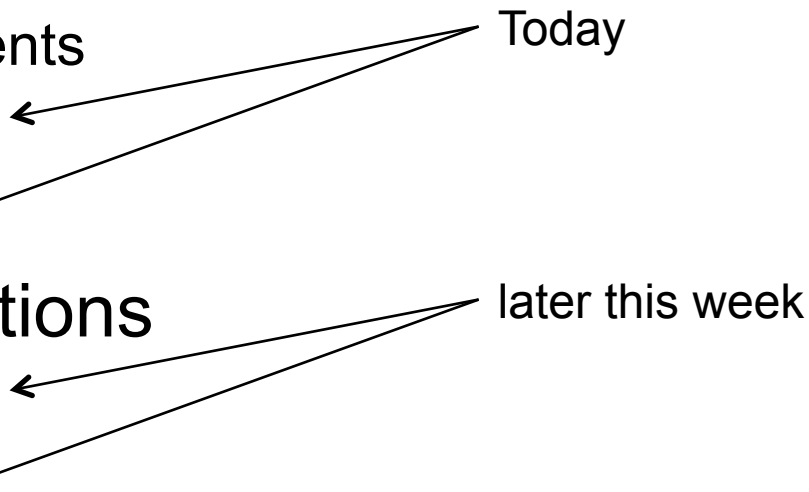
How to make a graphics program?

- Need to create a window
  - This window contains a “context” for OpenGL to render in.
- Need to be able to deal with events/ interactions
- Need to render graphics primitives
  - OpenGL!

Borrow Build

OpenGL Functions

- Primitives
  - Points
  - Line Segments
  - Polygons
- Attributes
- Transformations
  - Viewing
  - Modeling
- Control (VTK)
- Input (VTK)
- Query

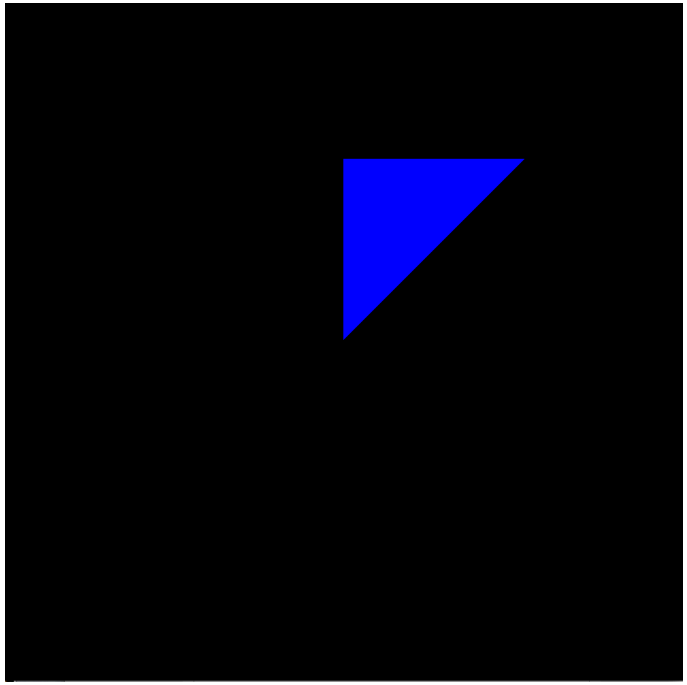


First OpenGL programs

- Remember: none of these programs have windowing or events
- They contain just the code to put primitives on the screen, with lighting and colors.

First OpenGL programs

```
class vtk441PolyDataMapper : public vtkOpenGLPolyDataMapper
{
 public:
   static vtk441PolyDataMapper *New();
   virtual void RenderPiece(vtkRenderer *ren, vtkActor *act)
   {
     glEnable(GL_COLOR_MATERIAL);
     float ambient[3] = { 1, 1, 1 };
     glMaterialfv(GL_FRONT_AND_BACK, GL_AMBIENT, ambient);
     glBegin(GL_TRIANGLES);
     glColor3ub(0, 0, 255);
     glVertex3f(0,0,0);
     glVertex3f(0,1,0);
     glVertex3f(1,1,0);
     glEnd();
   }
};
```



glEnable/glDisable: important functions

www.opengl.org/sdk/docs/man/xhtml/glEnable.xml

Name

glEnable — enable or disable server-side GL capab

C Specification

```
void glEnable(GLenum cap);
```

Parameters

cap

Specifies a symbolic constant indicating a GL capability.

C Specification

```
void glDisable(GLenum cap);
```

Parameters

cap

Specifies a symbolic constant indicating a GL capability.

Both `glEnable` and glDisable take a single argument, *`cap`*, which can assume one of the following values:

`GL_BLEND`

If enabled, blend the computed fragment color values with the values in the color buffers. See glBlendFunc.

`GL_CULL_FACE`

If enabled, cull polygons based on their winding in window coordinates. See glCullFace.

`GL_DEPTH_TEST`

If enabled, do depth comparisons and update the depth buffer. Note that even if the depth buffer exists and the depth mask is non-zero, the depth buffer is not updated if the depth test is disabled. See glDepthFunc and glDepthRangef.

`GL_DITHER`

If enabled, dither color components or indices before they are written to the color buffer.

`GL_POLYGON_OFFSET_FILL`

If enabled, an offset is added to depth values of a polygon's fragments produced by rasterization. See glPolygonOffset.

`GL_SAMPLE_ALPHA_TO_COVERAGE`

If enabled, compute a temporary coverage value where each bit is determined by the alpha value at the corresponding sample location. The temporary coverage value is then ANDed with the fragment coverage value.

`GL_SAMPLE_COVERAGE`

If enabled, the fragment's coverage is ANDed with the temporary coverage value. If `GL_SAMPLE_COVERAGE_INVERT` is set to `GL_TRUE`, invert the coverage value. See glSampleCoverage.

`GL_SCISSOR_TEST`

If enabled, discard fragments that are outside the scissor rectangle. See glScissor.

`GL_STENCIL_TEST`

If enabled, do stencil testing and update the stencil buffer. See glStencilFunc and glStencilOp.

First OpenGL programs

```
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     glEnable(GL_COLOR_MATERIAL);
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     glColor3ub(0, 0, 255);
     glVertex3f(0,0,0);
     glColor3ub(0, 255, 0);
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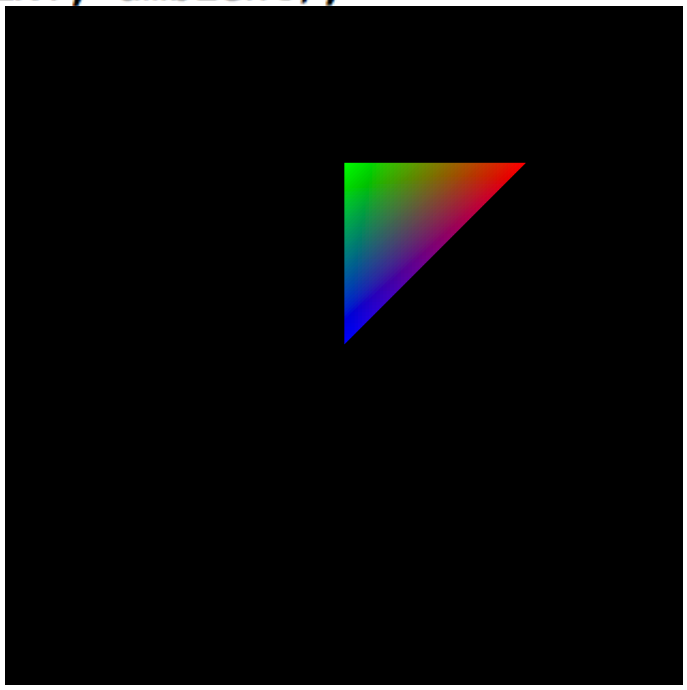
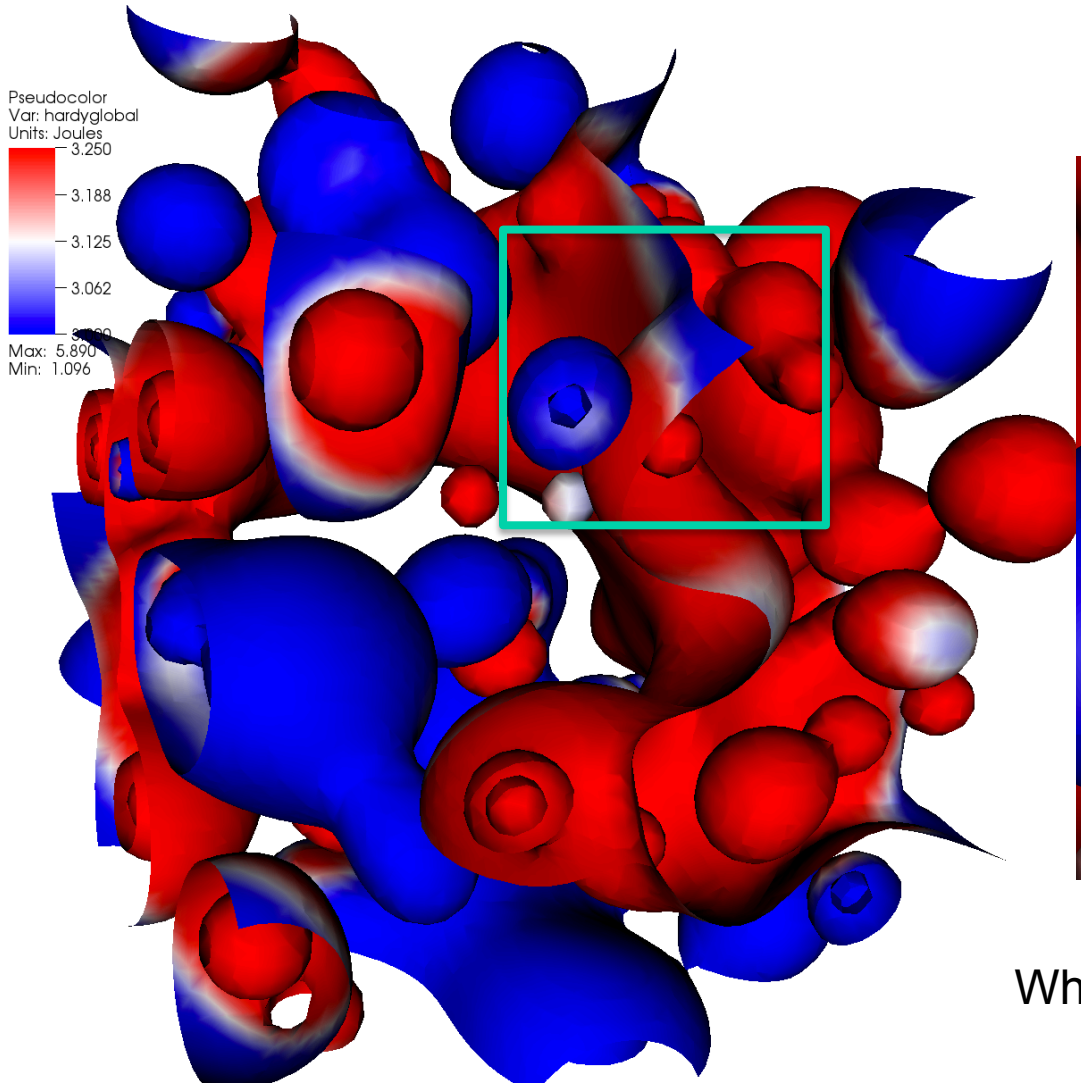
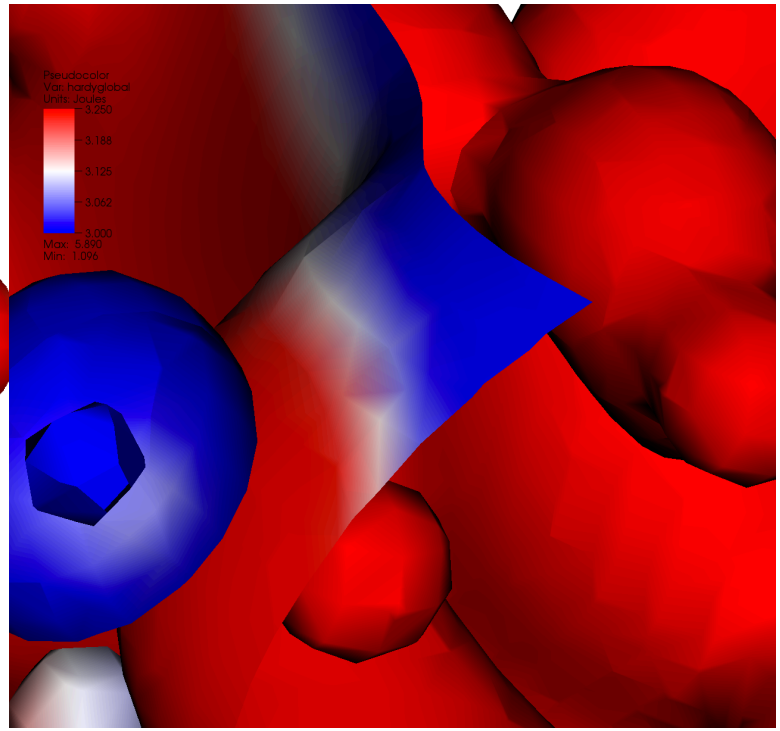
     glColor3ub(255, 0, 0);
     glVertex3f(1,1,0);
     glEnd();
   }
};
```



The University of New Mexico

Visualization use case





Why is there purple in this picture?

First OpenGL programs

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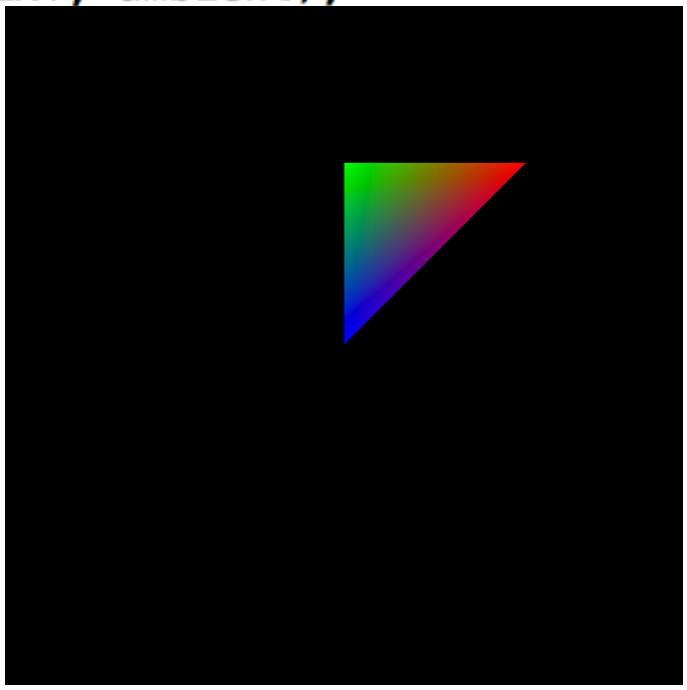
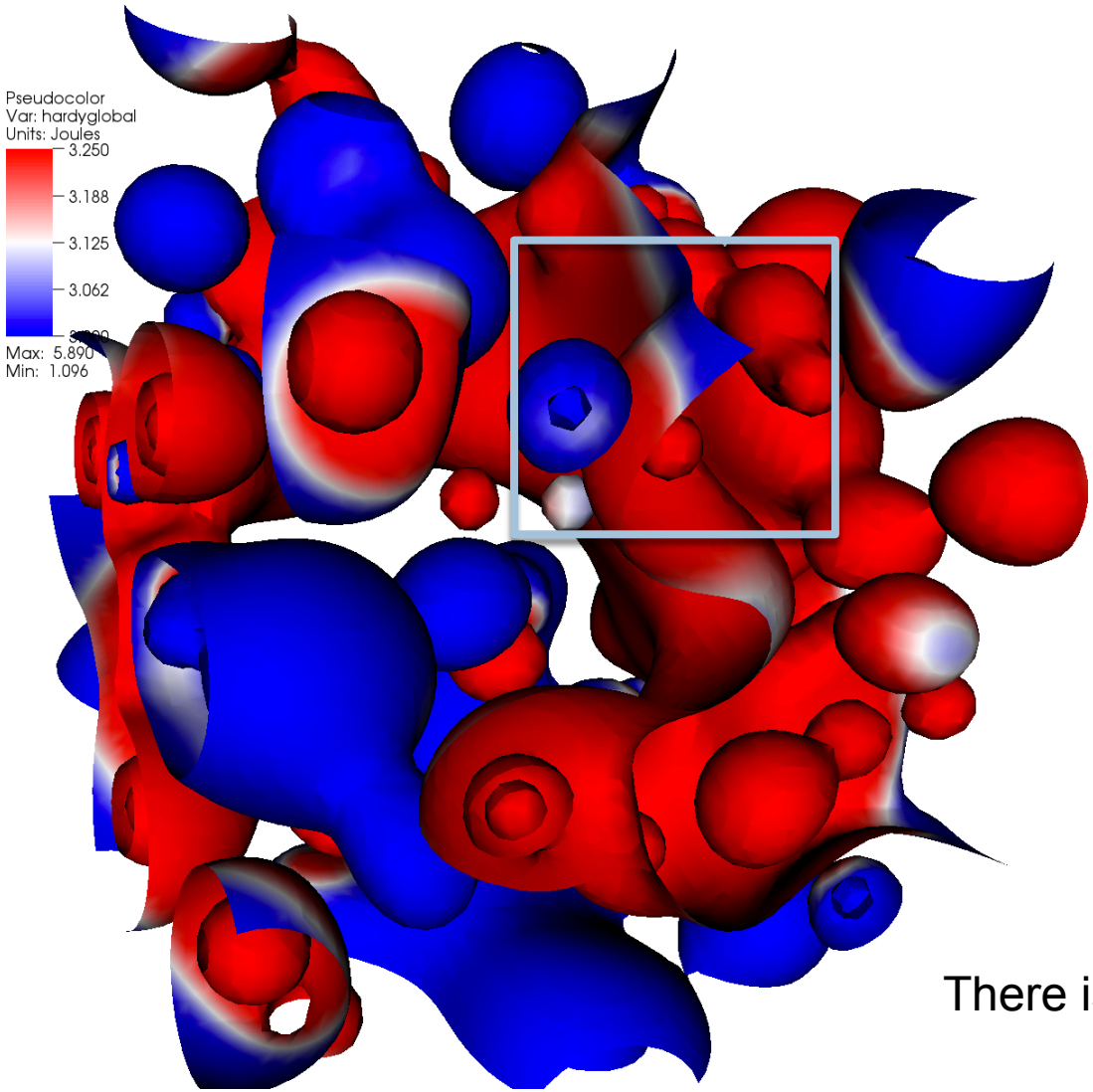
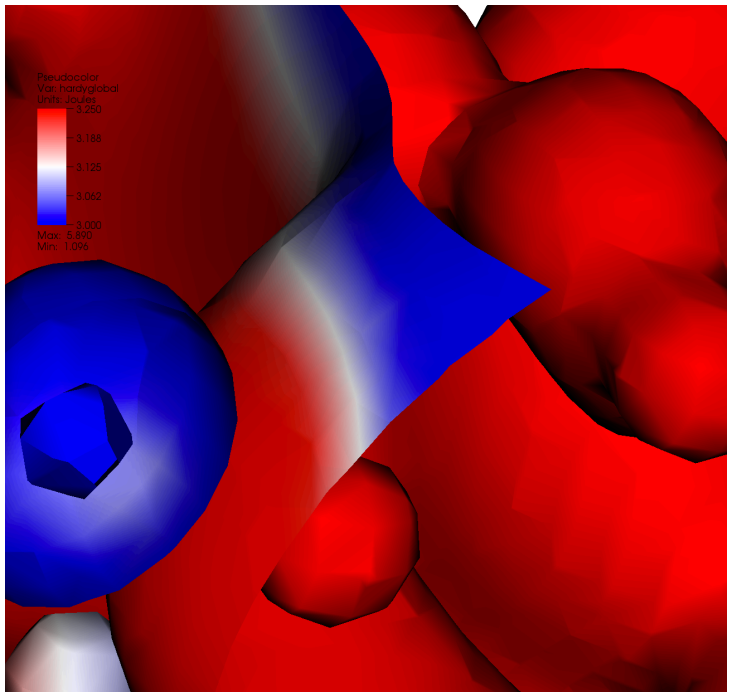


Textures: a better way to specify a color map





There is no purple when we use textures

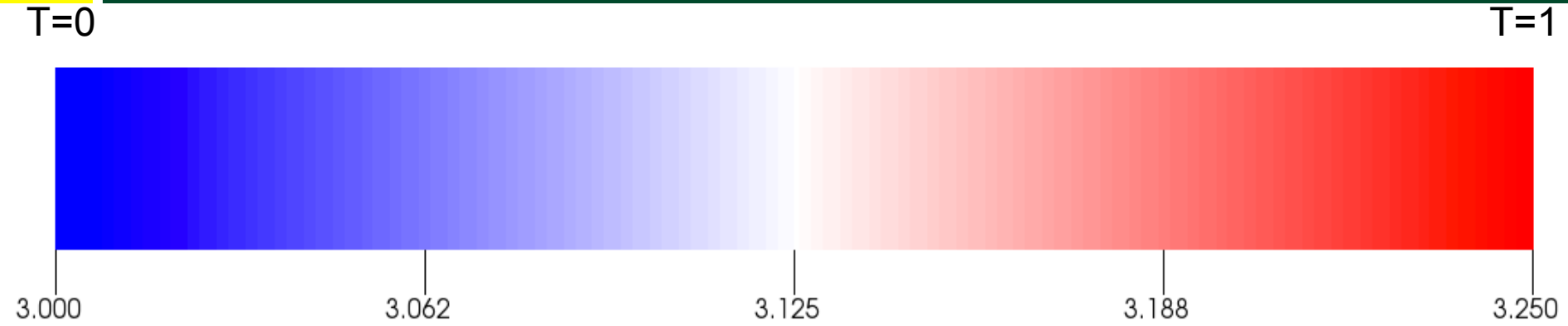
Textures

- "Textures" are a mechanism for adding "texture" to surfaces.
  - Think of texture of a cloth being applied to a surface
  - Typically used in 2D form
- We will start with a 1D form, and work our way up to 2D later.

1D textures: basic idea

- Store color map on GPU as a texture
  - An array of colors
- Old color interpolation of fragment on a scanline:
  - For (int j = 0 ; j < 3 ; j++)
    - RGB[j] = leftRGB[j] + proportion*(rightRGB[j]-leftRGB[j])
- New color interpolation of fragment on a scanline:
  - textureVal = leftTextureVal
    + proportion*(rightTextureVal-leftTextureVal)
  - RGB ← textureLookup[textureVal]

Example



- Triangle with vertices with scalar values 2.9, 3.3, and 3.1.
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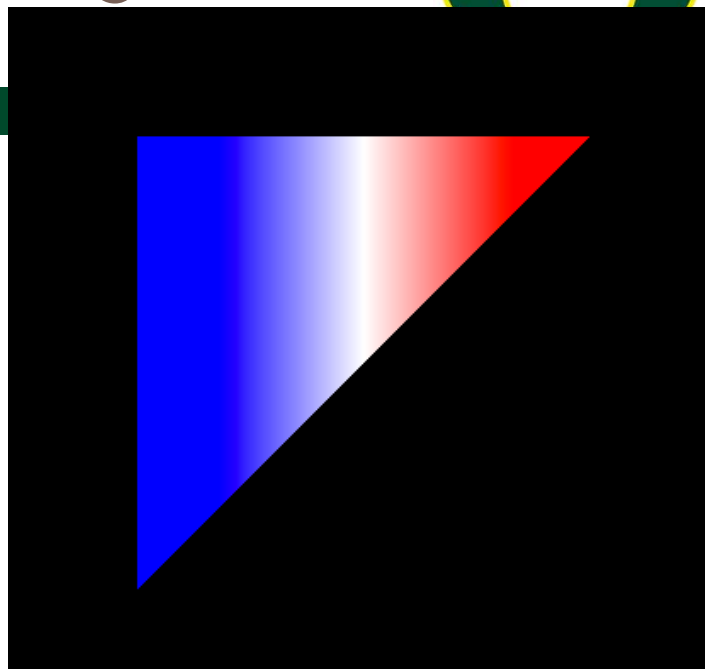
- Fragment colors come from interpolating texture coordinates and applying texture

First OpenGL Texture Program



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     };
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                  GL_UNSIGNED_BYTE, Texture3);
     glEnable(GL_COLOR_MATERIAL);
     glTexParameterf(GL_TEXTURE_1D, GL_TEXTURE_WRAP_S, GL_CLAMP_TO_EDGE);
     glTexParameterf(GL_TEXTURE_1D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);

     glEnable(GL_TEXTURE_1D);
     float ambient[3] = { 1, 1, 1 };
     glMaterialfv(GL_FRONT_AND_BACK, GL_AMBIENT, ambient);
     glBegin(GL_TRIANGLES);
     glTexCoord1f(0);
     glVertex3f(0,0,0);
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```
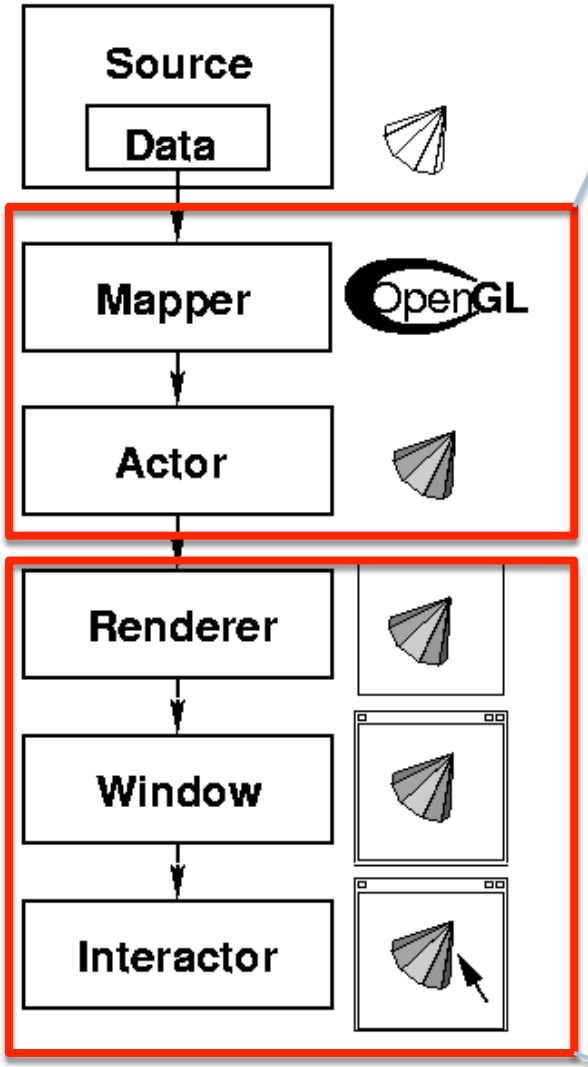

(advanced texture features & 2D textures on Weds)

Project 2A

We will replace these and write our own GL calls.

Cone.py Pipeline Diagram (type "python Cone.py" to run)



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iren.Start()
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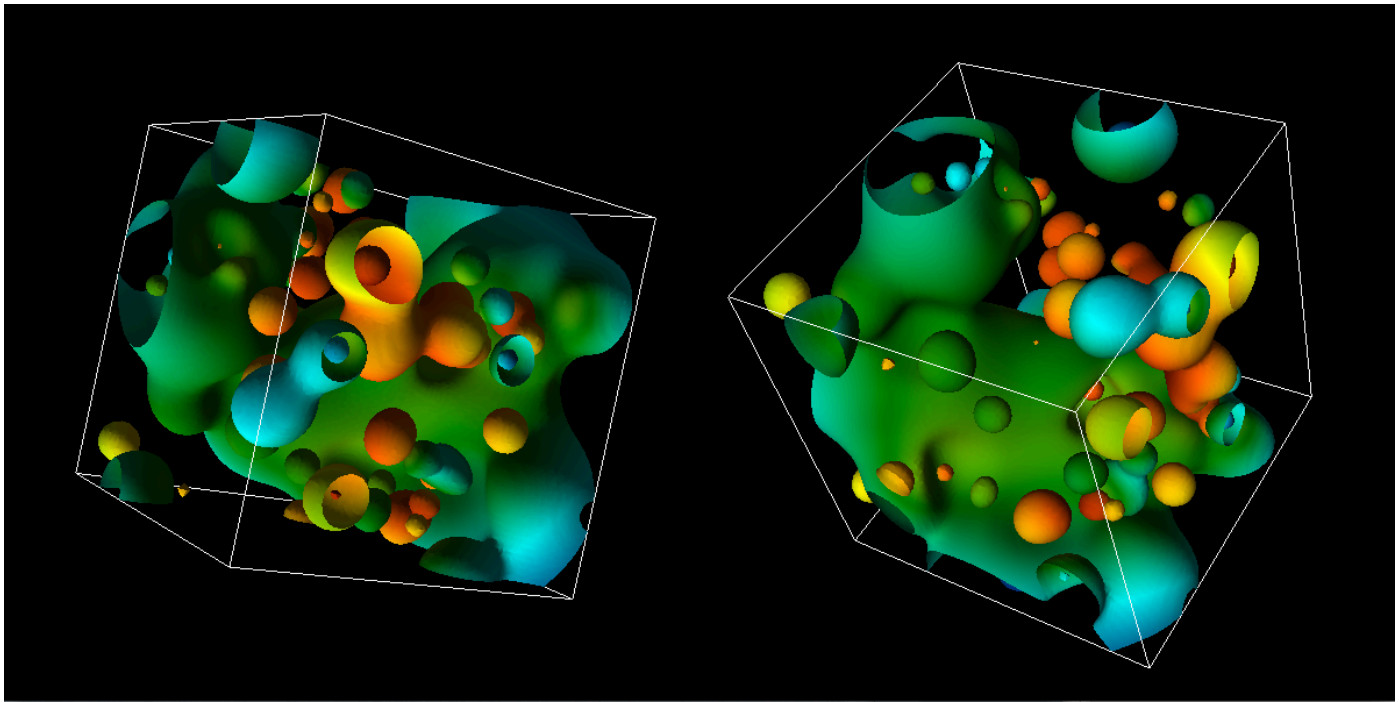
Project #2A (8%), Due Nov. 7th

- Goal: OpenGL program that does regular colors and textures
- New VTK-based project2A.cxx
- New CMakeLists.txt (but same as old ones)



Hints

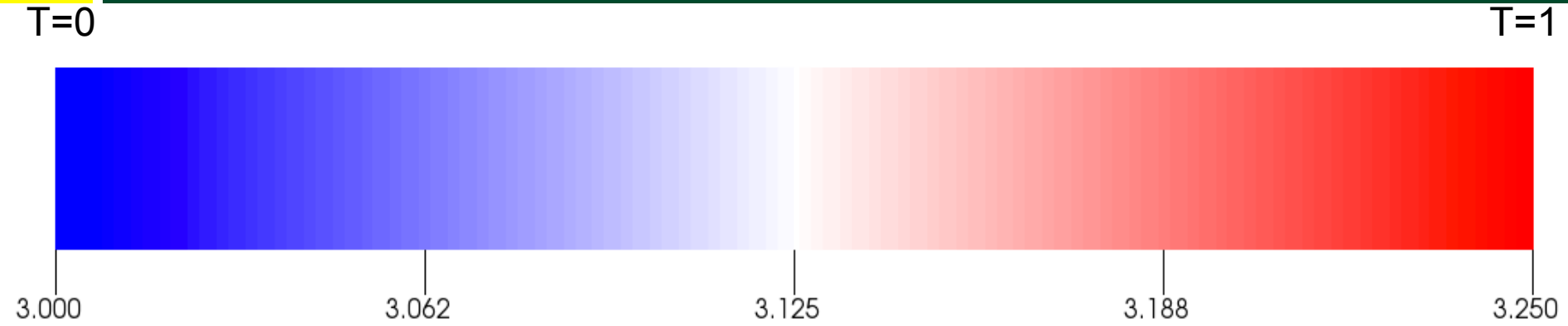
- I recommend you “walk before you run” & “take small bites”. OpenGL can be very punishing. Get a picture up and then improve on it. Make sure you know how to retreat to your previously working version at every step.
- OpenGL “state thrashing” is common and tricky to debug.
  - Get one window working perfectly.
  - Then make the second one work perfectly.
  - Then try to get them to work together.
    - Things often go wrong, when one program leaves the OpenGL state in a way that doesn’t suit another renderer.

Hints

- MAKE MANY BACKUPS OF YOUR PROGRAM

- If the program doesn't run with VTK 7, use VTK 6
- If you are having issues on your laptop with a GL program, then use Room 100
  - (There's only 2 of these projects)

Example



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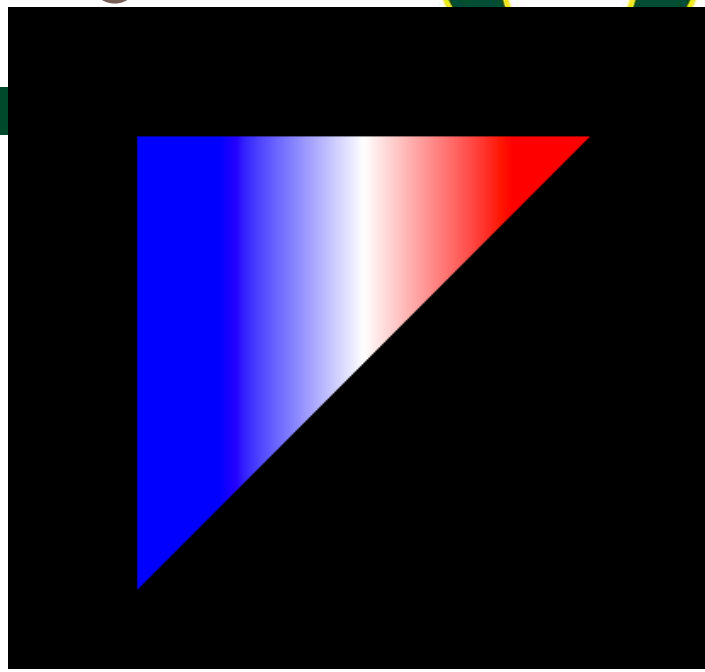
First OpenGL Texture Program



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     GLubyte Texture3[9] = {
          0, 0, 255,   // blue
          255, 255, 255,   // white
          255, 0, 0, // red
     };
     glTexImage1D(GL_TEXTURE_1D, 0, GL_RGB, 3, 0, GL_RGB,
                  GL_UNSIGNED_BYTE, Texture3);
     glEnable(GL_COLOR_MATERIAL);
     glTexParameterf(GL_TEXTURE_1D, GL_TEXTURE_WRAP_S, GL_CLAMP_TO_EDGE);
     glTexParameterf(GL_TEXTURE_1D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);

     glEnable(GL_TEXTURE_1D);
     float ambient[3] = { 1, 1, 1 };
     glMaterialfv(GL_FRONT_AND_BACK, GL_AMBIENT, ambient);
     glBegin(GL_TRIANGLES);
     glTexCoord1f(0);
     glVertex3f(0,0,0);
     glTexCoord1f(0.0);
     glVertex3f(0,1,0);
     glTexCoord1f(1.);
     glVertex3f(1,1,0);
     glEnd();
   }
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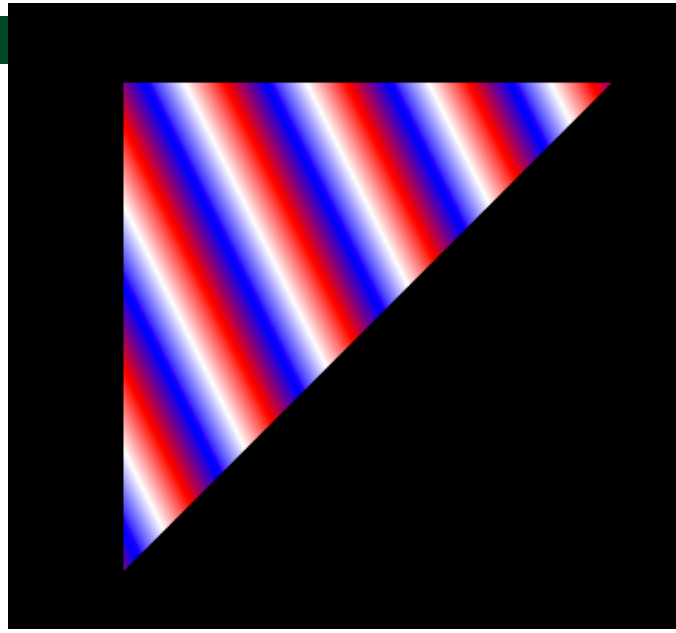
```

Textures with GL_REPEAT



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   {
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          0, 0, 255,   // blue
          255, 255, 255,   // white
          255, 0, 0, // red
     };
     glTexImage1D(GL_TEXTURE_1D, 0, GL_RGB, 3, 0, GL_RGB,
                  GL_UNSIGNED_BYTE, Texture3);
     glEnable(GL_COLOR_MATERIAL);
     glTexParameterf(GL_TEXTURE_1D, GL_TEXTURE_WRAP_S, GL_REPEAT);
     glTexParameterf(GL_TEXTURE_1D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);

     glEnable(GL_TEXTURE_1D);
     float ambient[3] = { 1, 1, 1 };
     glMaterialfv(GL_FRONT_AND_BACK, GL_AMBIENT, ambient);
     glBegin(GL_TRIANGLES);
     glTexCoord1f(-2);
     glVertex3f(0,0,0);
     glTexCoord1f(0);
     glVertex3f(0,1,0);
     glTexCoord1f(4.);
     glVertex3f(1,1,0);
     glEnd();
   }
};
```
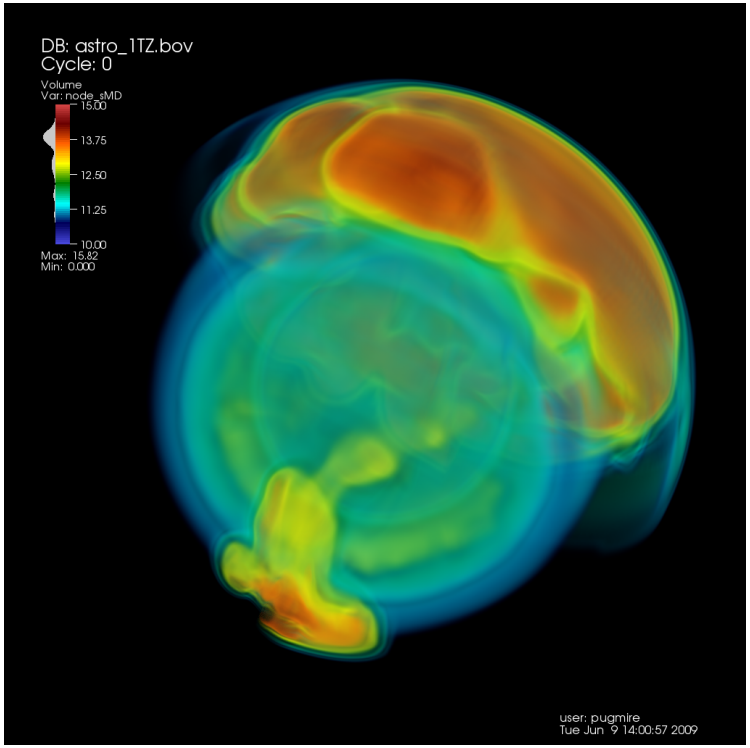

1D, 2D, 3D textures

- 2D textures most common
- 1D textures: color maps (e.g., what we just did)
- 3D textures: "volume rendering"
  - Use combination of opacity and color (i.e., RGBA)



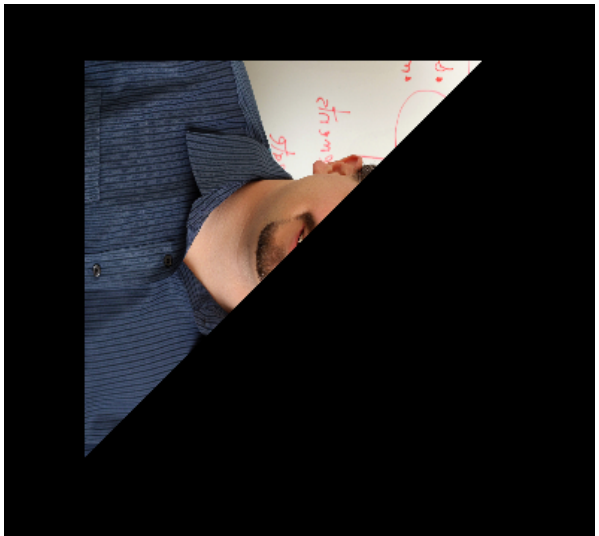
2D Textures

- Pre-rendered images painted onto geometry
- glTexImage1D → glTexImage2D
- GL_TEXTURE_WRAP_S → GL_TEXTURE_WRAP_S + GL_TEXTURE_WRAP_T
- glTexCoord1f → glTexCoord2f

2D Texture Program

```
class vtk441PolyDataMapper : public vtkOpenGLPolyDataMapper
{
 public:
   static vtk441PolyDataMapper *New();

   virtual void RenderPiece(vtkRenderer *ren, vtkActor *act)
   {
     vtkJPEGReader *rdr = vtkJPEGReader::New();
     rdr->SetFileName("HankChilds_345.jpg");
     rdr->Update();
     vtkImageData *img = rdr->GetOutput();
     int dims[3];
     img->GetDimensions(dims);
     unsigned char *buffer = (unsigned char *) img->GetScalarPointer(0,0,0);
     glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB, dims[0], dims[1], 0, GL_RGB,
                  GL_UNSIGNED_BYTE, buffer);
     glEnable(GL_COLOR_MATERIAL);
     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_MIN_FILTER, GL_NEAREST);
     glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_NEAREST);

     glEnable(GL_TEXTURE_2D);
     float ambient[3] = { 1, 1, 1 };
     glMaterialfv(GL_FRONT_AND_BACK, GL_AMBIENT, ambient);
     glBegin(GL_TRIANGLES);
     glTexCoord2f(0,0);
     glVertex3f(0,0,0);
     glTexCoord2f(1, 0);
     glVertex3f(0,1,0);
     glTexCoord2f(1., 1.);
     glVertex3f(1,1,0);
     glEnd();
   }
};
```

What do we expect the output to be?

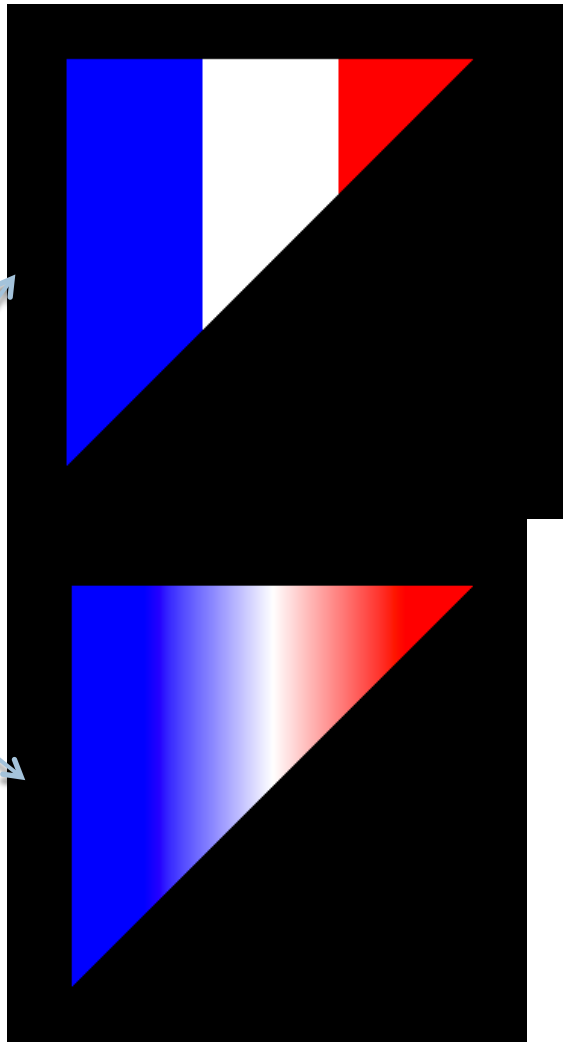


GL_TEXTURE_MIN_FILTER / GL_TEXTURE_MAG_FILTER

- Minifying: texture bigger than triangle.
  - How to map multiple texture elements onto a pixel?
    - GL_NEAREST: pick closest texture
    - GL_LINEAR: average neighboring textures
- Magnifying (GL_TEXTURE_MAG_FILTER): triangle bigger than texture
  - How to map single texture element onto multiple pixels?
    - GL_NEAREST: no interpolation
    - GL_LINEAR: interpolate with neighboring textures

GL_TEXTURE_MAG_FILTER with NEAREST and LINEAR

```
class vtk441PolyDataMapper : public vtkOpenGLPolyDataMapper
{
 public:
   static vtk441PolyDataMapper *New();

   virtual void RenderPiece(vtkRenderer *ren, vtkActor *act)
   {
     GLubyte Texture3[9] = {
          0, 0, 255,   // blue
          255, 255, 255,   // white
          255, 0, 0, // red
     };
     glTexImage1D(GL_TEXTURE_1D, 0, GL_RGB, 3, 0, GL_RGB, GL_UNSIGNED_BYTE,
Texture3);
     glEnable(GL_COLOR_MATERIAL);
     glTexParameterf(GL_TEXTURE_1D, GL_TEXTURE_WRAP_S, GL_CLAMP_TO_EDGE);
    ------
     glTexParameterf(GL_TEXTURE_1D, GL_TEXTURE_MAG_FILTER, GL_NEAREST);
    --- OR ---
     glTexParameterf(GL_TEXTURE_1D, GL_TEXTURE_MAG_FILTER, GL_LINEAR);
    ------
     glTexParameterf(GL_TEXTURE_1D, GL_TEXTURE_MIN_FILTER, GL_NEAREST);

     glEnable(GL_TEXTURE_1D);
     float ambient[3] = { 1, 1, 1 };
     glMaterialfv(GL_FRONT_AND_BACK, GL_AMBIENT, ambient);
     glBegin(GL_TRIANGLES);
     glTexCoord1f(0.);
     glVertex3f(0,0,0);
     glTexCoord1f(0.0);
     glVertex3f(0,1,0);
     glTexCoord1f(1.);
     glVertex3f(1,1,0);
     glEnd();
   }
};
```



2D Texture Program

```
virtual void RenderPiece(vtkRenderer *ren, vtkActor *act)
{
  vtkJPEGReader *rdr = vtkJPEGReader::New();
  rdr->SetFileName("HankChilds_345.jpg");
  rdr->Update();
  vtkImageData *img = rdr->GetOutput();
  int dims[3];
  img->GetDimensions(dims);
  unsigned char *buffer = (unsigned char *) img->GetScalarP
  glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB, dims[0], dims[1], 0,
               GL_UNSIGNED_BYTE, buffer);
  glEnable(GL_COLOR_MATERIAL);
  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_MIN_FILTER, GL_NEAREST);
  glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_NEAREST);

  glEnable(GL_TEXTURE_2D);
  float ambient[3] = { 1, 1, 1 };
  glMat
  glBeg
  glTex
  glVer
  glTex
  glVer
  glTex
  glVer

  glTex
  glVer
  glTexC
  glVertex3f(1.1,0,0);
  glTexCoord2f(0, 0);
  glVertex3f(0.1,0,0);

  glEnd();
}
```

Texture is not 1:1, should probably scale geometry.

This is a terrible program … why?

glBindTexture: tell the GPU about the texture once and re-use it!

```
class vtk441PolyDataMapper : public vtkOpenGLPolyDataMapper
{
 public:
   static vtk441PolyDataMapper *New();

   GLuint texture;
   bool   initialized;

   vtk441PolyDataMapper()
   {
     initialized = false;
   }
   void SetUpTexture()
   {
     glGenTextures(1, &texture);
     glBindTexture(GL_TEXTURE_2D, texture);

     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_MIN_FILTER, GL_NEAREST);
     glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_NEAREST);

     vtkJPEGReader *rdr = vtkJPEGReader::New();
     rdr->SetFileName("HankChilds_345.jpg");
     rdr->Update();
     vtkImageData *img = rdr->GetOutput();
     int dims[3];
     img->GetDimensions(dims);
     unsigned char *buffer = (unsigned char *) img->GetScalarPointer(0,0,0);
     glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB, dims[0], dims[1], 0, GL_RGB,
                  GL_UNSIGNED_BYTE, buffer);
     initialized = true;
   }
```

```
   virtual void RenderPiece(vtkRenderer *ren, vtkActor *act
   {
     if (!initialized)
        SetUpTexture();
     glEnable(GL_COLOR_MATERIAL);

     glBindTexture(GL_TEXTURE_2D, texture);
     glEnable(GL_TEXTURE_2D);
     float ambient[3] = { 1, 1, 1 };
     glMaterialfv(GL_FRONT_AND_BACK, GL_AMBIENT, ambient);
     glBegin(GL_TRIANGLES);
     glTexCoord2f(0,0);
     glVertex3f(0,0,0);
     glTexCoord2f(1, 0);
     glVertex3f(0,1,0);
     glTexCoord2f(1., 1.);
     glVertex3f(1,1,0);

     glTexCoord2f(1., 1.);
     glVertex3f(1.1,1,0);
     glTexCoord2f(0,1);
     glVertex3f(1.1,0,0);
     glTexCoord2f(0, 0);
     glVertex3f(0.1,0,0);

     glEnd();
   }
};
```

Outline

- Review
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Geometry Specification: glBegin

Name

glBegin — delimit the vertices of a primitive or a group of like primitives

C Specification

`void` **`glBegin`**`(`GLenum *mode*`);`

Parameters

mode

Specifies the primitive or primitives that will be created from vertices presented between `glBegin` and the subsequent glEnd. Ten symbolic constants are accepted: `GL_POINTS`, `GL_LINES`, `GL_LINE_STRIP`, `GL_LINE_LOOP`, `GL_TRIANGLES`, `GL_TRIANGLE_STRIP`, `GL_TRIANGLE_FAN`, `GL_QUADS`, `GL_QUAD_STRIP`, and `GL_POLYGON`.

C Specification

`void` **`glEnd`**`(` *void*`);`

Description

`glBegin` and glEnd delimit the vertices that define a primitive or a group of like primitives. `glBegin` accepts a single argument that specifies in which of ten ways the vertices are interpreted. Taking n as an integer count starting at one, and N as the total number of vertices specified, the interpretations are as follows:

Geometry Primitives

`GL_POINTS`

Treats each vertex as a single point. Vertex n defines point n. N points are drawn.

`GL_LINES`

Treats each pair of vertices as an independent line segment. Vertices 2 ☒ n - 1 and 2 ☒ n define line n. N 2 lines are drawn.

`GL_LINE_STRIP`

Draws a connected group of line segments from the first vertex to the last. Vertices n and n + 1 define line n. N - 1 lines are drawn.

`GL_LINE_LOOP`

Draws a connected group of line segments from the first vertex to the last, then back to the first. Vertices n and n + 1 define line n. The last line, however, is defined by vertices N and 1 . N lines are drawn.

Geometry Primitives

`GL_TRIANGLES`

Treats each triplet of vertices as an independent triangle. Vertices 3 ☒ n - 2 , 3 ☒ n - 1 , and 3 ☒ n define triangle n. N 3 triangles are drawn.

`GL_TRIANGLE_STRIP`

Draws a connected group of triangles. One triangle is defined for each vertex presented after the first two vertices. For odd n, vertices n, n + 1 , and n + 2 define triangle n. For even n, vertices n + 1 , n, and n + 2 define triangle n. N - 2 triangles are drawn.

`GL_TRIANGLE_FAN`

Draws a connected group of triangles. One triangle is defined for each vertex presented after the first two vertices. Vertices 1 , n + 1 , and n + 2 define triangle n. N - 2 triangles are drawn.

Geometry Primitives

`GL_QUADS`

Treats each group of four vertices as an independent quadrilateral. Vertices 4 ☒ n - 3 , 4 ☒ n - 2 , 4 ☒ n - 1 , and 4 ☒ n define quadrilateral n. N 4 quadrilaterals are drawn.

`GL_QUAD_STRIP`

Draws a connected group of quadrilaterals. One quadrilateral is defined for each pair of vertices presented after the first pair. Vertices 2 ☒ n - 1 , 2 ☒ n , 2 ☒ n + 2 , and 2 ☒ n + 1 define quadrilateral n. N 2 - 1 quadrilaterals are drawn. Note that the order in which vertices are used to construct a quadrilateral from strip data is different from that used with independent data.

`GL_POLYGON`

Draws a single, convex polygon. Vertices 1 through N define this polygon.

What can go inside a glBegin?

Only a subset of GL commands can be used between `glBegin` and glEnd. The commands are glVertex, glColor, glSecondaryColor, glIndex, glNormal, glFogCoord, glTexCoord, glMultiTexCoord, glVertexAttrib, glEvalCoord, glEvalPoint, glArrayElement, glMaterial, and glEdgeFlag. Also, it is acceptable to use glCallList or glCallLists to execute display lists that include only the preceding commands. If any other GL command is executed between `glBegin` and glEnd, the error flag is set and the command is ignored.

Outline

- Review
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- Lighting model
- Shading model
- Material model

Lighting

- glEnable(GL_LIGHTING);
  - Tells OpenGL you want to have lighting.
- Eight lights
  - Enable and disable individually
    - glEnable(GL_LIGHT0)
    - glDisable(GL_LIGHT7)
  - Set attributes individually
    - glLightfv(GL_LIGHTi, ARGUMENT, VALUES)

glLightfv parameters

- Ten parameters (ones you will use):

`GL_AMBIENT`

params contains four fixed-point or floating-point values that specify the ambient RGBA intensity of the light. Both fixed-point and floating-point values are mapped directly. Neither fixed-point nor floating-point values are clamped. The initial ambient light intensity is (0, 0, 0, 1).

`GL_DIFFUSE`

params contains four fixed-point or floating-point values that specify the diffuse RGBA intensity of the light. Both fixed-point and floating-point values are mapped directly. Neither fixed-point nor floating-point values are clamped. The initial value for `GL_LIGHT0` is (1, 1, 1, 1). For other lights, the initial value is (0, 0, 0, 0).

`GL_SPECULAR`

params contains four fixed-point or floating-point values that specify the specular RGBA intensity of the light. Both fixed-point and floating-point values are mapped directly. Neither fixed-point nor floating-point values are clamped. The initial value for `GL_LIGHT0` is (1, 1, 1, 1). For other lights, the initial value is (0, 0, 0, 0).

`GL_POSITION`

params contains four fixed-point or floating-point values that specify the position of the light in homogeneous object coordinates. Both fixed-point and floating-point values are mapped directly. Neither fixed-point nor floating-point values are clamped.

The position is transformed by the modelview matrix when `glLight` is called (just as if it were a point), and it is stored in eye coordinates. If the w component of the position is 0, the light is treated as a directional source. Diffuse and specular lighting calculations take the light's direction, but not its actual position, into account, and attenuation is disabled. Otherwise, diffuse and specular lighting calculations are based on the actual location of the light in eye coordinates, and attenuation is enabled. The initial position is (0, 0, 1, 0); thus, the initial light source is directional, parallel to, and in the direction of the - z axis.

glLightfv in action

For each light source, we can set an RGBA for the diffuse, specular, and ambient components:

```
glEnable(GL_LIGHTING);
glEnable(GL_LIGHT0);
GLfloat diffuse0[4] = { 0.7, 0.7, 0.7, 1 };
glLightfv(GL_LIGHT0, GL_DIFFUSE, diffuse0);
… // set ambient, specular, position
glDisable(GL_LIGHT1); // do we need to do this?
…
glDisable(GL_LIGHT7); // do we need to do this?
```

How do we tell OpenGL about the surface normals?

- Flat shading:

```
glNormal3f(0, 0.707, -0.707);
glVertex3f(0, 0, 0);
glVertex3f(1, 1, 0);
glVertex3f(1, 0, 0);
```

- Smooth shading:

```
glNormal3f(0, 0.707, -0.707);
glVertex3f(0, 0, 0);
glNormal3f(0, 0.707, +0.707);
glVertex3f(1, 1, 0);
glNormal3f(1, 0, 0);
glVertex3f(1, 0, 0);
```

Distance and Direction

- The source colors are specified in RGBA
- The position is given in homogeneous coordinates
  - If w =1.0, we are specifying a finite location
  - If w =0.0, we are specifying a parallel source with the given direction vector

glLightfv parameters (2)

- Ten parameters (ones you will never use)

`GL_SPOT_DIRECTION`

params contains three fixed-point or floating-point values that specify the direction of the light in homogeneous object coordinates. Both fixed-poin and floating-point values are mapped directly. Neither fixed-point nor floating-point values are clamped.

The spot direction is transformed by the upper 3x3 of the modelview matrix when `glLight` is called, and it is stored in eye coordinates. It is significant only when `GL_SPOT_CUTOFF` is not 180, which it is initially. The initial direction is (0, 0, -1).

`GL_SPOT_EXPONENT`

params is a single fixed-point or floating-point value that specifies the intensity distribution of the light. Fixed-point and floating-point values are mapped directly. Only values in the range [0, 128] are accepted.

Effective light intensity is attenuated by the cosine of the angle between the direction of the light and the direction from the light to the vertex being lighted, raised to the power of the spot exponent. Thus, higher spot exponents result in a more focused light source, regardless of the spot cutoff angle (see `GL_SPOT_CUTOFF`, next paragraph). The initial spot exponent is 0, resulting in uniform light distribution.

`GL_SPOT_CUTOFF`

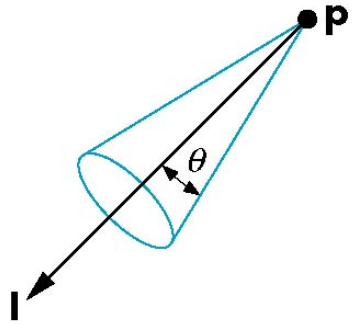
params is a single fixed-point or floating-point value that specifies the maximum spread angle of a light source. Fixed-point and floating-point values are mapped directly. Only values in the range [0, 90] and the special value 180 are accepted. If the angle between the direction of the light and the direction from the light to the vertex being lighted is greater than the spot cutoff angle, the light is completely masked. Otherwise, its intensity is controlled by the spot exponent and the attenuation factors. The initial spot cutoff is 180, resulting in uniform light distribution.

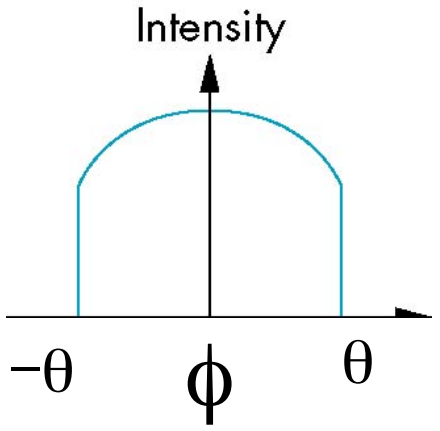
`GL_CONSTANT_ATTENUATION`, `GL_LINEAR_ATTENUATION`, `GL_QUADRATIC_ATTENUATION`

params is a single fixed-point or floating-point value that specifies one of the three light attenuation factors. Fixed-point and floating-point values are mapped directly. Only nonnegative values are accepted. If the light is positional, rather than directional, its intensity is attenuated by the reciprocal of the sum of the constant factor, the linear factor times the distance between the light and the vertex being lighted, and the quadratic factor times the square of the same distance. The initial attenuation factors are (1, 0, 0), resulting in no attenuation.

Spotlights

- Use `glLightv` to set
  - Direction `GL_SPOT_DIRECTION`
  - Cutoff `GL_SPOT_CUTOFF`
  - Attenuation `GL_SPOT_EXPONENT`
    - Proportional to $\cos^{\alpha}\phi$





What happens with multiple lights?

```
glEnable(GL_LIGHT0);
glEnable(GL_LIGHT1);
```

- → the effects of these lights are additive.
  - Individual shading factors are added and combined
  - Effect is to make objects brighter and brighter
    - Same as handling of high specular factors for 1E

Global Ambient Light

- Ambient light depends on color of light sources
  - A red light in a white room will cause a red ambient term that disappears when the light is turned off
- OpenGL also allows a global ambient term that is often helpful for testing
  - **`glLightModelfv(GL_LIGHT_MODEL_AMBIENT, global_ambient)`**
    - **VTK turns this on by default!**
      - **Affects lighting of materials colored with glColor, but not glTexCoord1f!!**

Outline

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Polygonal Shading

- Shading calculations are done for each vertex
  - Vertex colors become vertex shades
- By default, vertex shades are interpolated across the polygon
  - `glShadeModel(GL_SMOOTH);`
- If we use `glShadeModel(GL_FLAT);` the color at the first vertex will determine the shade of the whole polygon
  - We will come back to this in a few slides

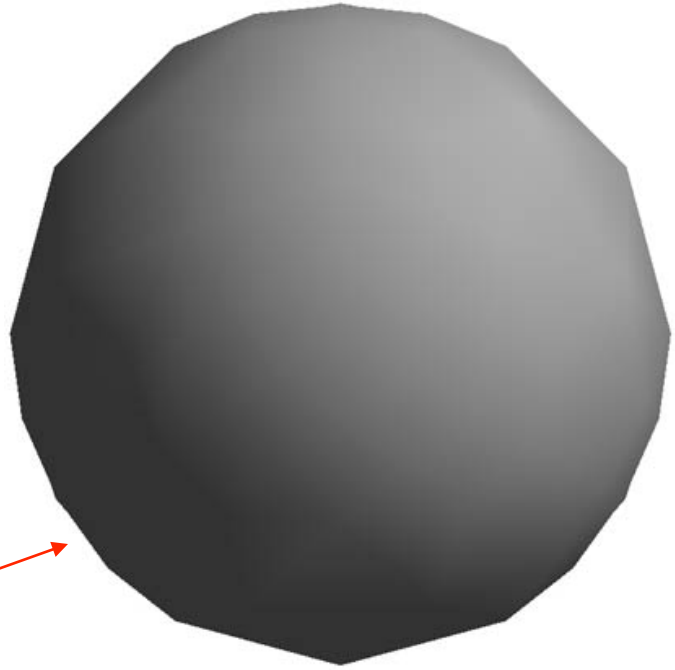
Polygon Normals

- Polygons have a single normal
  - Shades at the vertices as computed by the Phong model can be almost same
  - Identical for a distant viewer (default) or if there is no specular component
- Consider model of sphere
- Different normals at

each vertex, want single normal

Smooth Shading

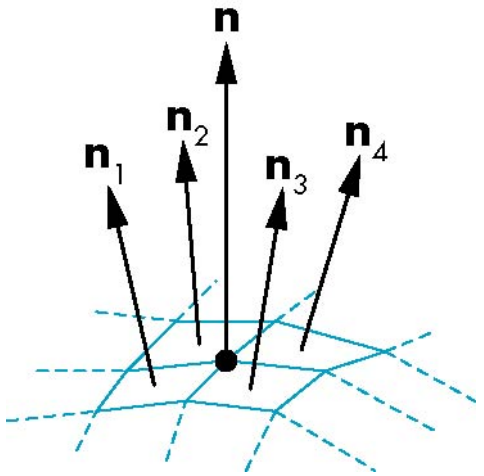
- We can set a new normal at each vertex
- Easy for sphere model
  - If centered at origin $\mathbf{n} = \mathbf{p}$
- Now smooth shading works
- Note *silhouette edge*



Mesh Shading

- The previous example is not general because we knew the normal at each vertex analytically
- For polygonal models, Gouraud proposed we use the average of the normals around a mesh vertex

$$\mathbf{n} = (\mathbf{n}_1+\mathbf{n}_2+\mathbf{n}_3+\mathbf{n}_4)/\ |\mathbf{n}_1+\mathbf{n}_2+\mathbf{n}_3+\mathbf{n}_4|$$



glShadeModel

glShadeModel — select flat or smooth shading

C Specification

`void` **`glShadeModel`**(GLenum *mode*);

Parameters

mode

Specifies a symbolic value representing a shading technique. Accepted values are `GL_FLAT` and `GL_SMOOTH`. The initial value is `GL_SMOOTH`.

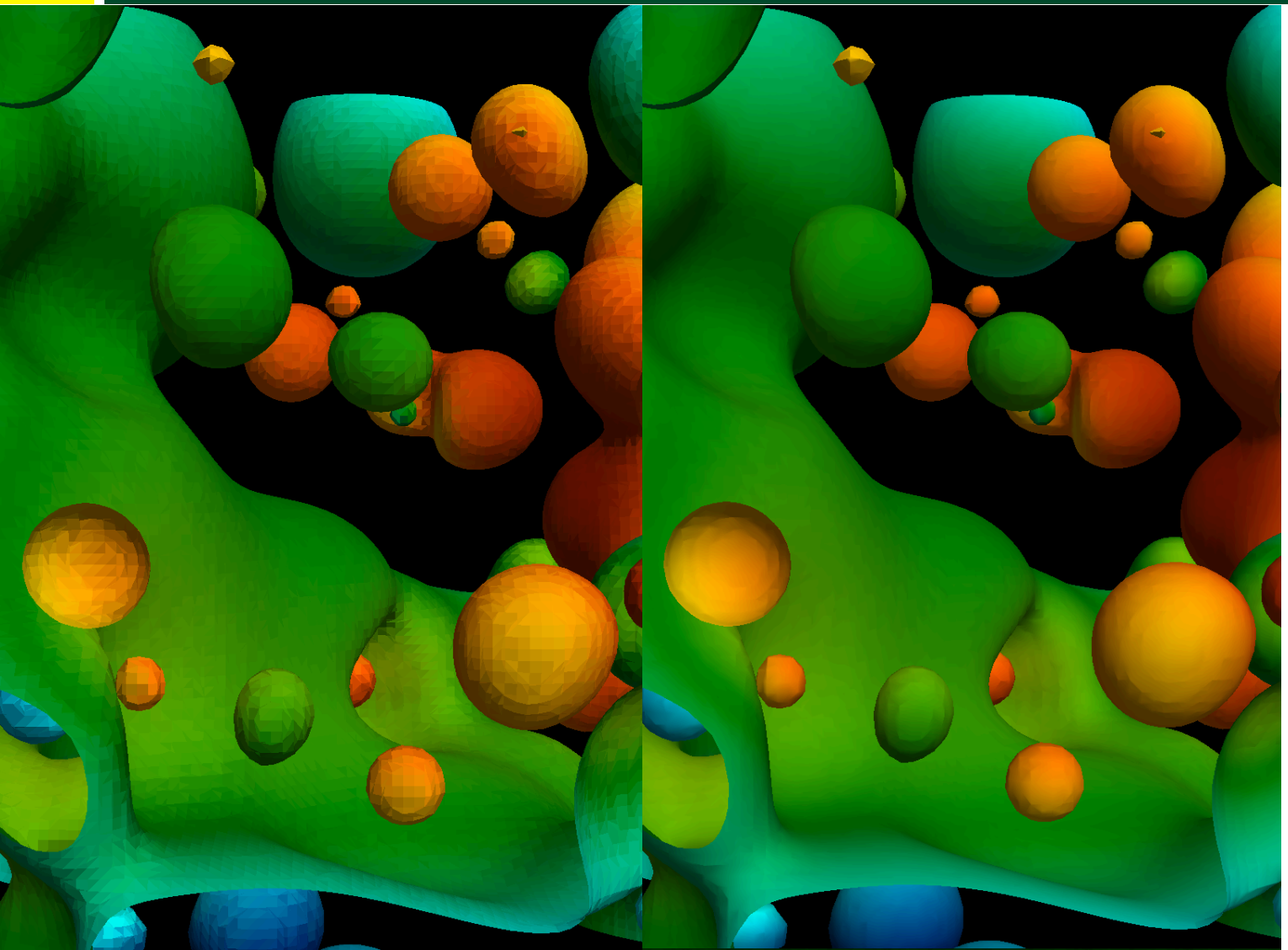
Description

GL primitives can have either flat or smooth shading. Smooth shading, the default, causes the computed colors of vertices to be interpolated as the primitive is rasterized, typically assigning different colors to each resulting pixel fragment. Flat shading selects the computed color of just one vertex and assigns it to all the pixel fragments generated by rasterizing a single primitive. In either case, the computed color of a vertex is the result of lighting if lighting is enabled, or it is the current color at the time the vertex was specified if lighting is disabled.

Flat and smooth shading are indistinguishable for points. Starting when glBegin is issued and counting vertices and primitives from 1, the GL gives each flat-shaded line segment i the computed color of vertex i + 1 , its second vertex. Counting similarly from 1, the GL gives each flat-shaded polygon the computed color of the vertex listed in the following table. This is the last vertex to specify the polygon in all cases except single polygons, where the first vertex specifies the flat-shaded color.

Primitive Type of Polygon i	Vertex
Single polygon (i == 1)	1
Triangle strip	i + 2
Triangle fan	i + 2
Independent triangle	3 × i
Quad strip	2 × i + 2
Independent quad	4 × i

glShadeModel



glShadeModel affects normals and colors

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glMaterial: coarser controls for color

- You specify how much light is reflected for the material type.
- Command:

  glMaterialfv(FACE_TYPE, PARAMETER, VALUE(S))
- FACE_TYPE =
  - GL_FRONT_AND_BACK
  - ~~GL_FRONT~~
  - ~~GL_BACK~~

(We will talk about this on Friday)

glMaterialfv Parameters

`GL_AMBIENT`

params contains four fixed-point or floating-point values that specify the ambient RGBA reflectance of the material. The values are not clamped. The initial ambient reflectance is (0.2, 0.2, 0.2, 1.0).

`GL_DIFFUSE`

params contains four fixed-point or floating-point values that specify the diffuse RGBA reflectance of the material. The values are not clamped. The initial diffuse reflectance is (0.8, 0.8, 0.8, 1.0).

`GL_SPECULAR`

params contains four fixed-point or floating-point values that specify the specular RGBA reflectance of the material. The values are not clamped. The initial specular reflectance is (0, 0, 0, 1).

glMaterialfv Parameters

`GL_EMISSION`

params contains four fixed-point or floating-point values that specify the RGBA emitted light intensity of the material. The values are not clamped. The initial emission intensity is (0, 0, 0, 1).

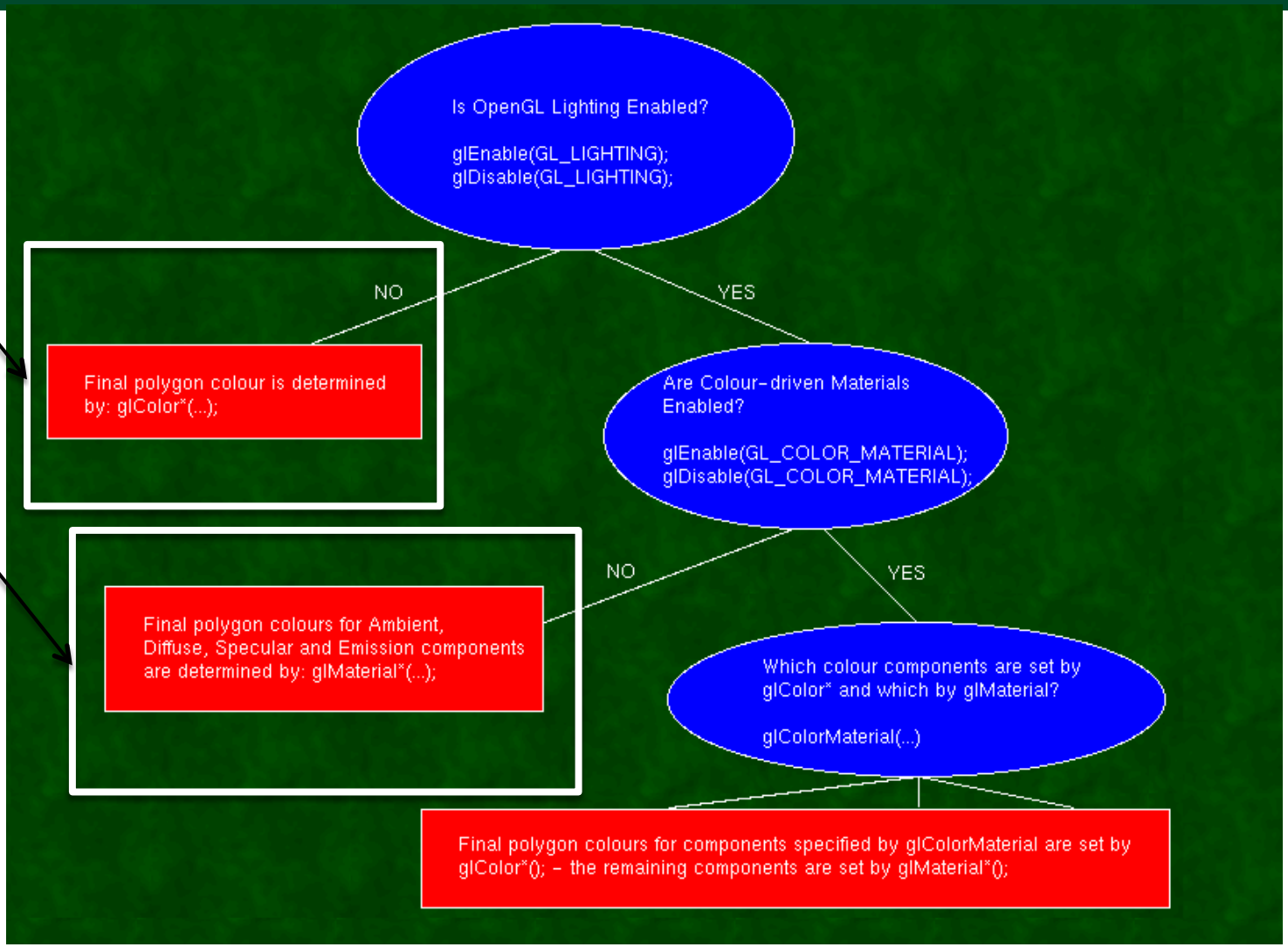
`GL_SHININESS`

params is a single fixed-point or floating-point value that specifies the RGBA specular exponent of the material. Only values in the range [0, 128] are accepted. The initial specular exponent is 0.

`GL_AMBIENT_AND_DIFFUSE`

Equivalent to calling `glMaterial` twice with the same parameter values, once with `GL_AMBIENT` and once with `GL_DIFFUSE`.

OpenGL: very complex model for lighting and colors



glMaterial not used

glColor is no-op

http://www.sjbaker.org/steve/omniv/opengl_lighting.html

Basic OpenGL light model

- The OpenGL light model presumes that the light that reaches your eye from the polygon surface arrives by four different mechanisms:
  - AMBIENT
  - DIFFUSE
  - SPECULAR
  - EMISSION - in this case, the light is actually emitted by the polygon - equally in all directions.

http://www.sjbaker.org/steve/omniv/opengl_lighting.html

Difference between lights and materials

- There are three light colours for each light:
  - Ambient, Diffuse and Specular (set with glLight)
- There are four colors for each surface
  - Same three + Emission(set with glMaterial).
- All OpenGL implementations support at least eight light sources - and the glMaterial can be changed at will for each polygon

http://www.sjbaker.org/steve/omniv/opengl_lighting.html

Interactions between lights and materials

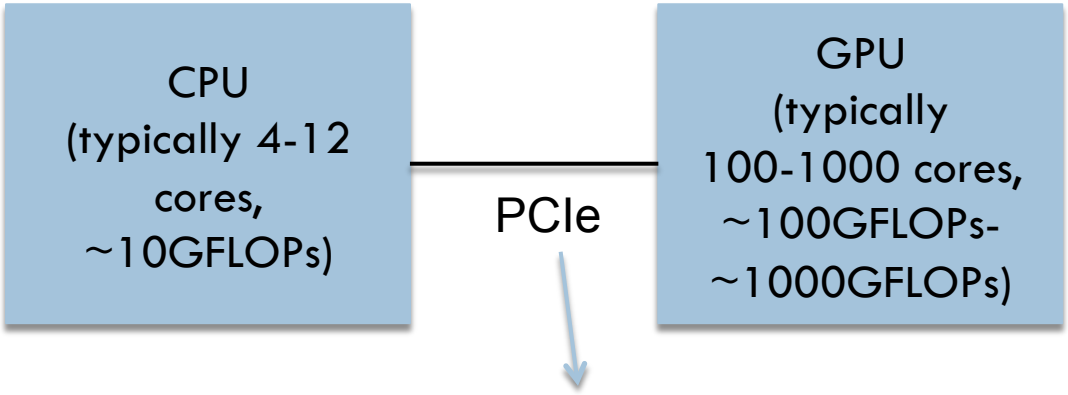
- The final polygon colour is the sum of all four light components, each of which is formed by multiplying the glMaterial colour by the glLight colour (modified by the directionality in the case of Diffuse and Specular).
- Since there is no Emission colour for the glLight, that is added to the final colour without modification.

http://www.sjbaker.org/steve/omniv/opengl_lighting.html

Bonus slides: display lists

CPU and GPU

- Most common configuration has CPU and GPU on separate dies
  - I.e., plug GPU in CPU



What are the performance ramifications of this architecture?

Display lists

- Idea:
  - send geometry and settings to GPU once, give it an identifier
  - GPU stores geometry and settings
  - Just pass the identifier for every subsequent render

Display lists

- Generate an idenfitier:

  ```
  GLUint displayList = glGenLists(1);
  ```

- Tell GPU that all subsequent geometry is part of the list:

  ```
  glNewList(displayList,GL_COMPILE);
  ```

- Specify geometry (i.e., glVertex, etc)
- Tell GPU we are done specifying geometry:

  ```
  glEndList();
  ```

- Later on, tell GPU to render all the geometry and settings associated with our list:

  ```
  glCallList(displayList);
  ```

Display lists in action

```
for (int frame = 0 ; frame < nFrames ; frame++)
{
   SetCamera(frame, nFrames);
   glBegin(GL_TRIANGLES);
   for (int i = 0 ; i < triangles.size() ; i++)
   {
       for (int j = 0 ; j < 3 ; j++)
       {
           glColor3ubv(triangles[i].colors[j]);
           glColor3fv(triangles[i].vertices[j]);
   }
   glEnd();
}
```

```
GLUint displayList = glGenLists(1);
glNewList(displayList, GL_COMPILE);
glBegin(GL_TRIANGLES);
for (int i = 0 ; i < triangles.size() ; i++)
{
    for (int j = 0 ; j < 3 ; j++)
    {
        glColor3ubv(triangles[i].colors[j]);
        glColor3fv(triangles[i].vertices[j]);
}
glEnd();
glEndList();

for (int frame = 0 ; frame < nFrames ; frame++)
{
   SetCamera(frame, nFrames);
   glCallList(displayList);
}
```

What are the performance ramifications between the two?

glNewList

- GL_COMPILE
  - Make the display list for later use.
- GL_COMPILE_AND_EXECUTE
  - Make the display list and also execute it as you go.