Introduction to OpenGL ®

Graphics and Computation

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Notes

- These slides were presented to a third year computer science class in graphics and computation over a three year period (2006, 2007, 2008). The slides were the practical component introducing the students to OpenGL as part of a longer course in computer graphics. The introductory OpenGL component was taught over two lectures, but the students used OpenGL for the major project.
- There was some variation over the three years in which the material was presented, including one year (2007) where Java was used with JOGL. In 2006 and 2008 the course was taught in C using GLUT.
- The slides were originally done in PowerPoint and they have been convertex to LaTeXand Beamer.

OpenGL Version

Note that the OpenGL presented in these slides is pretty out of date. It represents early OpenGL 1.1-1.4 and does not include anything from OpenGL 2.0 or greater, so this material should **not** be used learn modern OpenGL is primarily provided here for historical reference.

Outline

OpenGL Background and History

- OpenGL = Open Graphics Library
- Developed at Silicon Graphics (SGI)
- Successor to IrisGL
- Cross Platform (Win32, Mac OS X, Unix, Linux)
- Only does 3D Graphics. No Platform Specifics (Windowing, Fonts, Input, GUI)
- Version 1.4 widely available
- Two Libraries
  - GL (Graphics Library)
  - GLU (Graphics Library Utilities)

Other Graphics Technologies

- Low level graphics
- OpenGL
- Scene Graphs, BSPs
    - OpenSceneGraph, Java3D, VRML, PLIB
- DirectX - Direct3D
- Can mix some DirectX with OpenGL (e.g. in Quake III OpenGL is used w/ DirectInput)

Platform Specifics

- Platform Specific OpenGL Interfaces
  - Windows - WGL
  - XWindows X11 - GLX
  - Mac OS X - CGL/AGL/NSOpenGL
  - Motif - GLwMwidget
  - Qt - QGLWidget, QGLContext
- GLUT - GL Utility Library (C, Python, ...)
- JOGL (Java)

The Drawing Process

```
ClearTheScreen();
DrawTheScene();
CompleteDrawing();
SwapBuffers();
```

- In animation there are usually two buffers.
- Drawing usually occurs on the background buffer.
- When it is complete, it is brought to the front (swapped).
- This gives a smooth animation without the viewer seeing the actual drawing taking place.
- Only the final image is viewed.
- The technique to swap the buffers will depend on which windowing library you are using with OpenGL.

Clearing the Window

```
glClearColor(0.0, 0.0, 0.0, 0.0);
glClear(GL_COLOR_BUFFER_BIT);
```

Typically you would clear the colour and depth buffers together.

```
glClearColor(0.0, 0.0, 0.0, 0.0);
glClearDepth(0.0);
glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
```

Setting the Colour

- Colour is specified in (R,G,B,A) form [Red, Green, Blue, Alpha].
- Each value being in the range of 0.0 to 1.0.
- There are many variants of the glColor command.

Specifying Colour with `glColor`

```
glColor4f(red, green, blue, alpha);
glColor3f(red, green, blue);

glColor3f(0.0, 0.0, 0.0); /* Black */
glColor3f(1.0, 0.0, 0.0); /* Red */
glColor3f(0.0, 1.0, 0.0); /* Green */
glColor3f(1.0, 1.0, 0.0); /* Yellow */
glColor3f(1.0, 0.0, 1.0); /* Magenta */
glColor3f(1.0, 1.0, 1.0); /* White */
```

Complete Drawing the Scene

Need to tell OpenGL you have finished drawing your scene:

```
glFinish();
```

or

```
glFlush();
```

For more information see:

`http://www.rush3d.com/reference/opengl-redbook-1.1/chapter02.html`

Drawing in OpenGL

- Use `glBegin()` to start drawing and `glEnd()` to stop.
- `glBegin()` can draw in many different styles.
- `glVertex3f(x,y,z)` specifies a point in 3D space.

Drawing a Polygon

```
glBegin(GL_POLYGON);
glVertex3f(0.0, 0.0, 0.0);
glVertex3f(0.0, 3.0, 1.0);
glVertex3f(3.0, 3.0, 3.0);
glVertex3f(4.0, 1.5, 1.0);
glVertex3f(3.0, 0.0, 0.0);
glEnd();
```

glBegin Drawing Modes

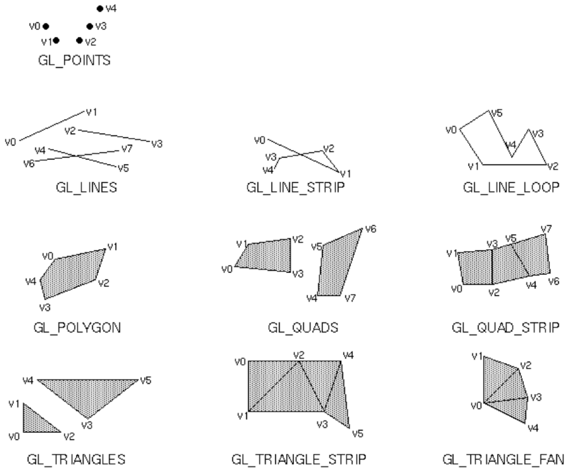
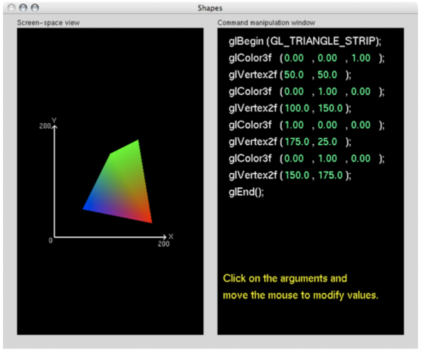


Diagram: Copyright OpenGL Programming Guide. Addison-Wesley.

Mixing Geometry with Colour

Specifying vertices can be mixed with colour and other types of commands for interesting drawing results.

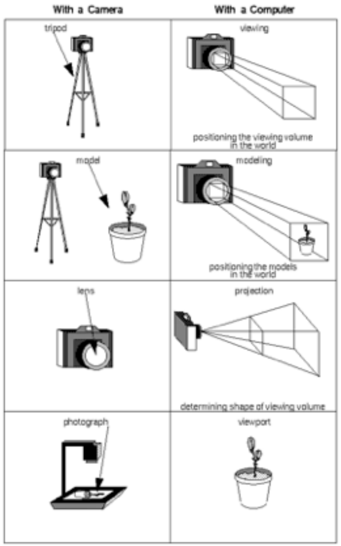
```
glBegin(GL_POLYGON);
glColor3f(1.0, 0.0, 0.0);
glVertex3f(0.0, 0.0, 0.0);
glColor3f(0.0, 1.0, 0.0)
glVertex3f(3.0, 1.0, 0.0);
glColor3f(0.0, 0.0, 1.0);
glVertex3f(3.0, 0.0, 0.0);
glEnd();
```



```
glBegin (GL_TRIANGLE_STRIP);
glColor3f  (0.00  , 0.00  , 1.00  );
glVertex2f (50.0  , 50.0  );
glColor3f  (0.00  , 1.00  , 0.00  );
glVertex2f (100.0 , 150.0 );
glColor3f  (1.00  , 0.00  , 0.00  );
glVertex2f (175.0 , 25.0  );
glColor3f  (0.00  , 1.00  , 0.00  );
glVertex2f (150.0 , 175.0 );
glEnd();
```

Click on the arguments and move the mouse to modify values.

Viewing the Scene: The Camera



With a Camera
With a Computer
tripod
viewing
positioning the viewing volume in the world
model
modeling
positioning the models in the world
lens
projection
determining shape of viewing volume
photograph
viewport

Diagram: Copyright OpenGL Programming Guide. Addison-Wesley.

OpenGL Vertices

- OpenGL uses a 4-component vector to represent a vertex.
- Known as homogenous coordinate system [2] where typically $w = 1$.
- In 2D-space $z = 0$.

$$v = \begin{pmatrix} x \\ y \\ z \\ w \end{pmatrix}$$

[2] For further information on homogenous coordinate systems as used in projective geometry and in OpenGL, see Appendix G of the Red Book `http://www.rush3d.com/reference/opengl-redbook-1.1/appendixg.html`

Vertex Transformations

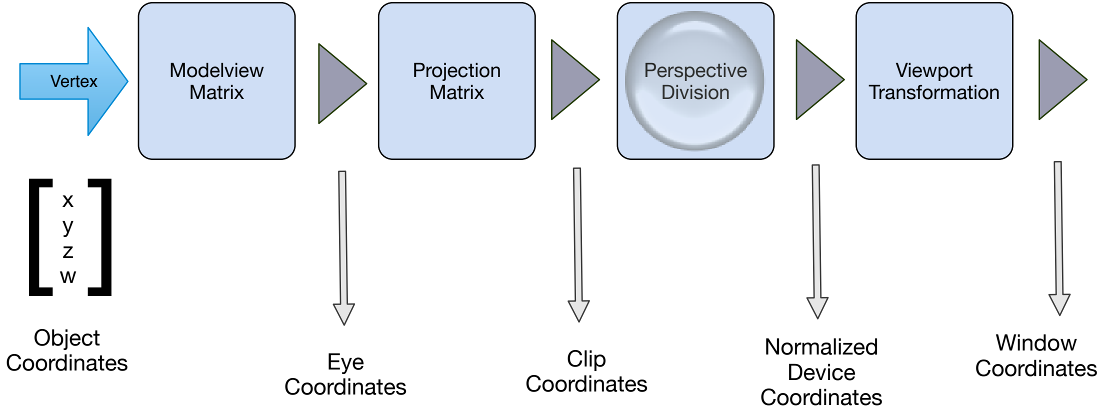


Diagram adapted from the OpenGL Programming Guide. Addison-Wesley.

Vertex Transformation as Matrix Multiplication

$$v' = Mv$$

$$M = \begin{pmatrix} m_1 & m_5 & m_9 & m_{13} \\ m_2 & m_6 & m_{10} & m_{14} \\ m_3 & m_7 & m_{11} & m_{15} \\ m_4 & m_8 & m_{12} & m_{16} \end{pmatrix}$$

The ModelView Matrix

```
glMatrixMode(GL_MODELVIEW);
```

Specifying the `ModelView` matrix is analogous to:

- Positioning and aiming the camera (viewing transformation)
- Positioning and orienting the model (modeling transformation)

The Projection Matrix

```
glMatrixMode(GL_PROJECTION);
```

- Specifiying the `Projection` matrix is like chosing a lens for a camera.
- It lets you specify parameters such as the field of view.

OpenGL Matrix Operations

Identity Matrix

$$I = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

```
glMatrixMode(mode);
glLoadIdentity();
glMultMatrix();
glLoadMatrix();
```

Perspective Projection (glFrustrum)

```
glFrustrum(left, right, bottom, top, near, far);
```

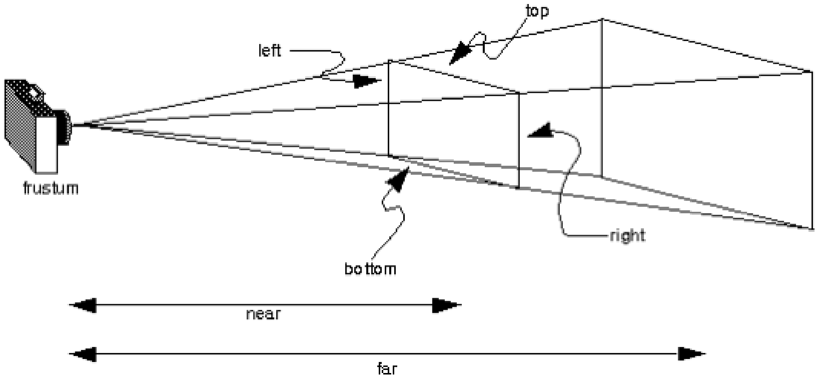


Diagram: Copyright OpenGL Programming Guide. Addison-Wesley.

Perspective Projection (gluPerspective) from GLU

```
gluPerspective(fovy, aspect, near, far);
```

- `fovy` : field of view in degrees, in the y direction
- `aspect` : aspect ratio that determines the field of view in the x direction (ratio of width to height)

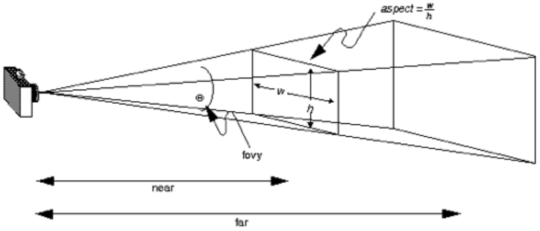


Diagram: Copyright OpenGL Programming Guide. Addison-Wesley.

Orthographics (Parallel) Projection - glOrtho

```
glOrtho(left, right, bottom, top, near, far);
```

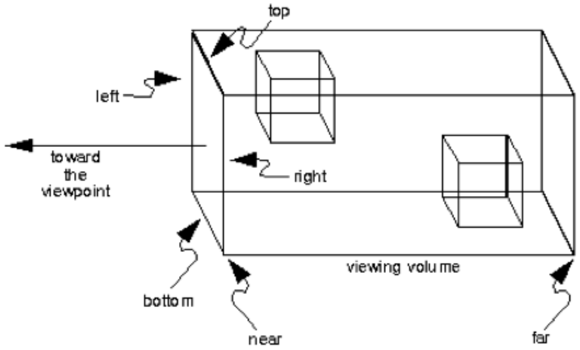
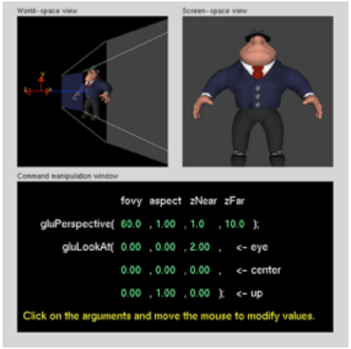


Diagram: Copyright OpenGL Programming Guide. Addison-Wesley.

gluLookAt

Specifies the camera position, the point where the camera is pointing, and the orientation vector of the camera.

```
gluLookAt(eyex, eyey, eyez, centerx, centery, centerz, upx, upy, upz);
```



```
                fovy  aspect  zNear  zFar
gluPerspective( 60.0 , 1.00  , 1.0  , 10.0  );
     gluLookAt( 0.00 , 0.00  , 2.00 ,   <- eye
                0.00 , 0.00  , 0.00 ,   <- center
                0.00 , 1.00  , 0.00 );  <- up
Click on the arguments and move the mouse to modify values.
```

Screenshot from Nate Robin's OpenGL Tutors `https://user.xmission.com/~nate/tutors.html`

Translation Transformation

```
glTranslatef(x, y, z);
```

$$T = \begin{pmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad T^{-1} = \begin{pmatrix} 1 & 0 & 0 & -x \\ 0 & 1 & 0 & -y \\ 0 & 0 & 1 & -z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$v' = Tv$$

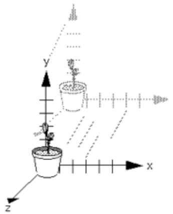


Diagram: Copyright OpenGL Programming Guide. Addison-Wesley.

Rotation Transformations

```
glRotatef(angle, x, y,z);
```

Specifies an angle and an axis (x,y,z) to rotate around.

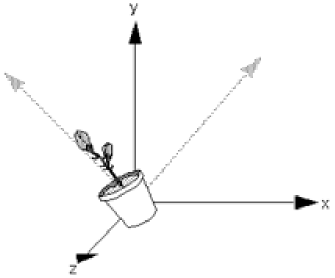


Diagram: Copyright OpenGL Programming Guide. Addison-Wesley.

Rotation Matrices

$$\texttt{glRotate3f}(\alpha,\ 1,\ 0,\ 0) : R_x(\alpha) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) & 0 \\ 0 & \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\texttt{glRotate3f}(\alpha,\ 0,\ 1,\ 0) : R_y(\alpha) = \begin{pmatrix} \cos(\alpha) & 0 & \sin(\alpha) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\alpha) & 0 & \cos(\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\texttt{glRotate3f}(\alpha,\ 0,\ 0,\ 1) : R_z(\alpha) = \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) & 0 & 0 \\ \sin(\alpha) & \cos(\alpha) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Scaling Transformations

```
glScale(x, y, z);
```

$$S = \begin{pmatrix} x & 0 & 0 & 0 \\ 0 & y & 0 & 0 \\ 0 & 0 & z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad S^{-1} = \begin{pmatrix} \frac{1}{x} & 0 & 0 & 0 \\ 0 & \frac{1}{y} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{1}{z} & 1 \end{pmatrix}$$

$$v' = Sv$$

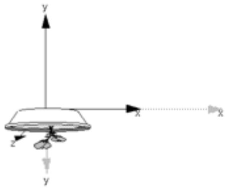
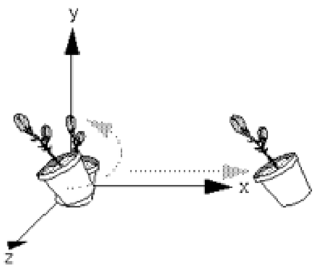


Diagram: Copyright OpenGL Programming Guide. Addison-Wesley.

Order of Transformations



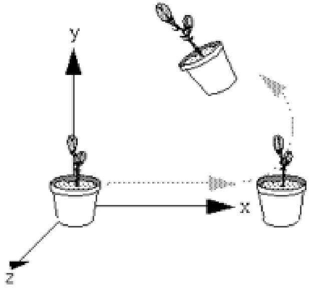
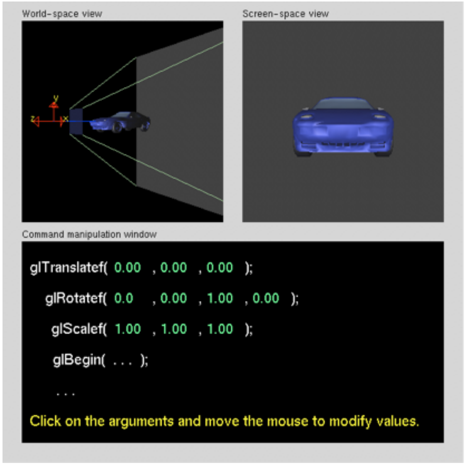


Diagram: Copyright OpenGL Programming Guide. Addison-Wesley.

Transformations in Action



```
glTranslatef( 0.00  , 0.00  , 0.00  );
   glRotatef( 0.0   , 0.00  , 1.00  , 0.00  );
    glScalef( 1.00  , 1.00  , 1.00  );
     glBegin( . . . );
      . . .
```

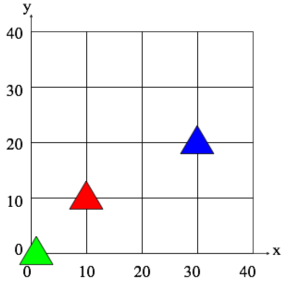
Click on the arguments and move the mouse to modify values.

Diagram: Copyright OpenGL Programming Guide. Addison-Wesley.

The Matrix Stack

`glPushMatrix()` and `glPopMatrix()`

```
glPushMatrix();
glTranslatef(10, 10, 0);
DrawRedTriangle();
  glPushMatrix();
  glTranslatef(20, 10, 0);
  DrawBlueTriangle();
  glPopMatrix();
glPopMatrix();
DrawGreenTriangle();
```



OpenGL Lighting

- Eight available lights (individually toggled)
- Lighting types:
  - Emitted
  - Ambient
  - Diffues
  - Specular
- Material colours and properties
- Lighting demo

Setting up an OpenGL Light

```
GLfloat lightAmbient[] = { 0.4, 0.5, 0.0, 1.0 };
GLfloat lightDiffuse[] = { 1.0, 1.0, 1.0, 1.0 };
GLfloat lightSpecular[] = { 1.0, 1.0, 1.0, 1.0};
GLfloat lightPosition[] = {1.0, 1.0, 1.0, 0.0};

glLightfv(GL_LIGHT0, GL_AMBIENT, lightAmbient);
glLightfv(GL_LIGHT0, GL_DIFFUSE, lightDiffuse);
glLightfv(GL_LIGHT0, GL_SPECULAR, lightSpecular);
glLightfv(GL_LIGHT0, GL_POSITION, lightPosition);

glEnable(GL_LIGHT0);
glEnable(GL_LIGHTING);
```

glLight{if}[v](light, pname, param)

Parameter Name	**Default Value**	**Meaning**
GL_AMBIENT	(0.0, 0.0, 0.0, 1.0)	ambient RGBA intensity of light
GL_DIFFUSE	(1.0, 1.0, 1.0, 1.0)	diffuse RGBA intensity of light
GL_SPECULAR	(1.0, 1.0, 1.0, 1.0)	specular RGBA intensity of light
GL_POSITION	(0.0, 0.0, 1.0, 0.0)	(*x, y, z, w*) position of light
GL_SPOT_DIRECTION	(0.0, 0.0, -1.0)	(*x, y, z*) direction of spotlight
GL_SPOT_EXPONENT	0.0	spotlight exponent
GL_SPOT_CUTOFF	180.0	spotlight cutoff angle
GL_CONSTANT_ATTENUATION	1.0	constant attenuation factor
GL_LINEAR_ATTENUATION	0.0	linear attenuation factor
GL_QUADRATIC_ATTENUATION	0.0	quadratic attenuation factor

Material Properties

`glMaterial{if}[v](GLenum face, GLenum pname, TYPE param);`

```
GLfloat material[] = {0.1, 0.5, 0.8, 1.0 };
glMaterialfv(GL_FRONT_AND_BACK, GL_AMBIENT_AND_DIFFUSE, material);

GLfloat matSpecular[] = { 1.0, 1.0, 1.0, 1.0 };
GLfloat lowShininess[] = { 5.0 };

glMaterialfv(GL_FRONT, GL_SPECULAR, matSpecular);
glMaterialfv(GL_FRONT, GL_SHININESS, lowShininess);
```

glMaterial Default Parameters

Parameter Name	**Default Value**	**Meaning**
GL_AMBIENT	(0.2, 0.2, 0.2, 1.0)	ambient color of material
GL_DIFFUSE	(0.8, 0.8, 0.8, 1.0)	diffuse color of material
GL_AMBIENT_AND_DIFFUSE		ambient and diffuse color of material
GL_SPECULAR	(0.0, 0.0, 0.0, 1.0)	specular color of material
GL_SHININESS	0.0	specular exponent
GL_EMISSION	(0.0, 0.0, 0.0, 1.0)	emissive color of material
GL_COLOR_INDEXES	(0,1,1)	ambient, diffuse, and specular color indices

Teapots Materials Example

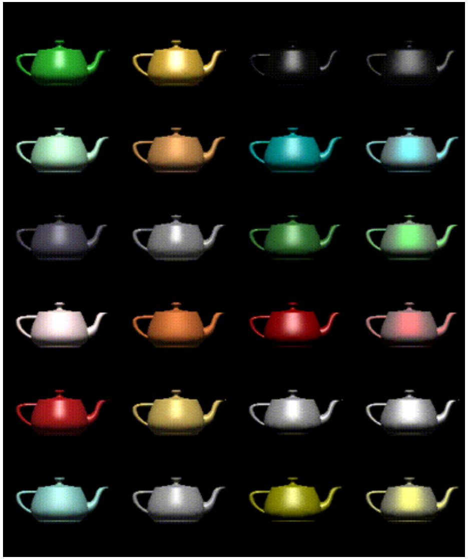
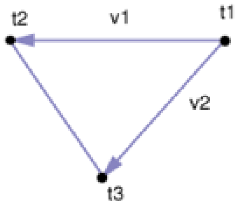
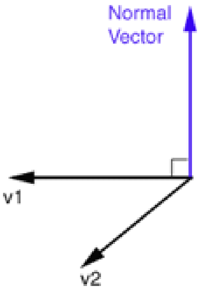
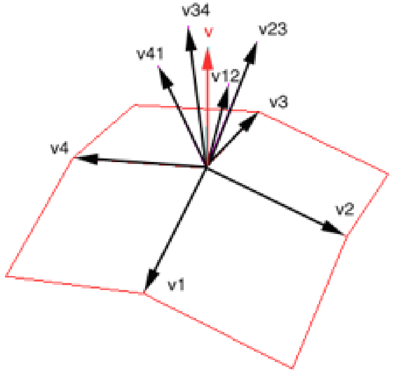


Diagram: Copyright OpenGL Programming Guide. Addison-Wesley.

Normal Vectors

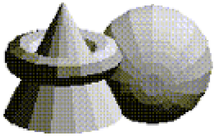


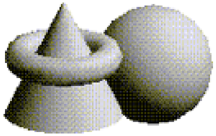




Normal Vectors – `glNormal()`

```
glBegin(GL_POLYGON);
    glNormal3fv(n0);
    glVertex3fv(v0);
    glNormal3fv(n1);
    glVertex3fv(v1);
    glNormal3fv(n2);
    glVertex3fv(v2);
    glNormal3fv(n3);
    glVertex3fv(v3);
glEnd();
```





Shading

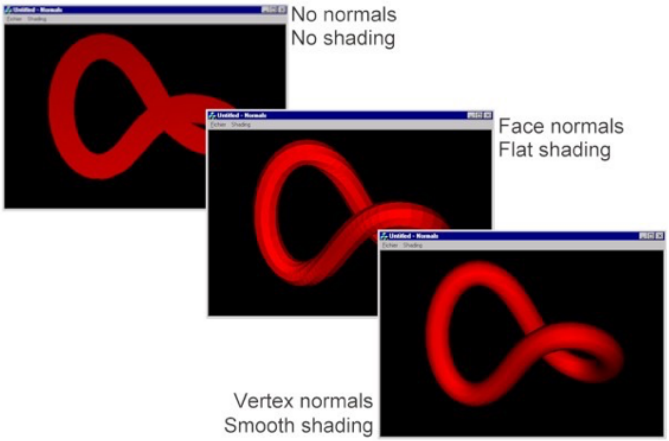


Diagram from: `http://www.codeguru.com/Cpp/G-M/opengl/article.php/c2681/`

Hidden Surface Removal

In order for OpenGL to remove hidden surfaces, you need to enable depth testing for the depth buffer.

```
glEnable(GL_DEPTH_TEST);
while (1)
{
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
    GetCurrentViewingPosition();
    DrawObjectA();
    DrawObjectB();
}
```

GLUT

- GLUT = GL UtilityLibrary
- Easy, stable, simple to use library for showing OpenGL demos.
- Limited to simple windows, mouse/keyboard input, and some simple 3D shapes.
- Most OpenGL demos and code on th eweb use GLUT.
- Default implementation in C (bindings for many languages available: Python, Perl etc)

Example GLUT Program in C

```c
#include <GL/gl.h>
#include <GL/glu.h>
#include <GL/glut.h>

int main(int argc, char** argv)
{
    glutInitDisplayMode(GLUT_RGB | GLUT_DEPTH | GLUT_DOUBLE);
    glutInitWindowSize(1024, 768);
    glutInitWindowPosition(0, 0);
    glutInit(argc, argv);

    glutCreateWindow("OpenGL␣Demo");
    glutReshapeFunc(reshape);
    glutDisplayFunc(display);
    glutIdleFunc(display);
    glutKeyboardFunc(keyboard);
    glutMouseFunc(mouse);
    glutMotionFunc(motion);
    InitGL();
    glutMainLoop();
}
```

Typical InitGL() Function

```
void InitGL(void)
{
    glClearColor(0.0, 0.0, 0.0, 0.0);
    glClearDepth(1.0);
    glDepthFunc(GL_LEQUAL);
    glEnable(GL_DEPTH_TEST);
    glEnable(GL_COLOR_MATERIAL);
    glShadeModel(GL_SMOOTH);
    glColorMaterial(GL_FRONT_AND_BACK, GL_AMBIENT_AND_DIFFUSE);
    glEnable(GL_BLEND);

    glLightModel(GL_LIGHT_MODEL_AMBIENT, [0.5, 0.5, 0.5, 1.0]);
    glLightfv(GL_LIGHT0, GL_AMBIENT, (0.4, 0.4, 0.4, 1.0));
    glLightfv(GL_LIGHT0, GL_DIFFUSE, (0.4, 0.4, 0.4, 1.0));
    glLightfv(GL_LIGHT0, GL_POSITION, (0.0, 0.0, -100.0, 1.0));
    glEnable(GL_NORMALIZE);
    glEnable(GL_LIGHTING);
    glEnable(GL_LIGHT0);

    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    gluPerspective(fovy, aspect, zNear, zFar);
    glMatrixMode(GL_MODELVIEW);
}
```

Typical GLUT Reshape Function

```
void reshape(int width, int height);
{
    glViewport(0, 0, width, height);
    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    gluPerspective(fovy, aspect, zNear, zFar);
}
```

Typical GLUT Display Function

```
void display(void)
{
    UpdateWorld();

    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    gluPerspective(fovy, aspect, zNear, zFar);
    glMatrixMode(GL_MODELVIEW);
    glLoadIdentity();
    gluLookAt(0.0, 0.0, 150.0,
              0.0, 0.0, 0.0, 0.0, 1.0, 0.0);

    RenderScene();
    glutSwapBuffers();
}
```

GLUT on Unix (command line)

Compiling a GLUT Program on Unix/Linux

```
gcc main.c -I/usr/X11R6/include -L/usr/X11R6/lib
-lGL -lGLU -lglut -lm
```

On Unix or Linux systems includes should be:

```
#include <GL/gl.h>
#include <GL/glu.h>
#include <GL/glut.h>
```

GLUT on Mac OS X (command line)

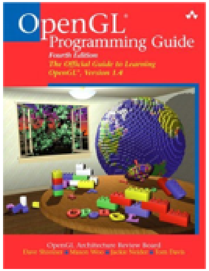
Compiling a GLUT Program on Mac OS X

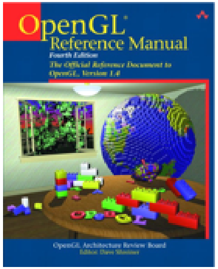
```
gcc main.c -F/System/Library/Frameworks
-framework GLUT -framework OpenGL
```

Using frameworks on Mac OS X, includes should be:

```
#include <GLUT/glut.h>
#include <OpenGL/gl.h>
#include <OpenGL/glu.h>
```

OpenGL Books


OpenGL
Programming Guide
Fourth Edition
The Official Guide to Learning OpenGL, Version 1.4
OpenGL Architecture Review Board


OpenGL
Reference Manual
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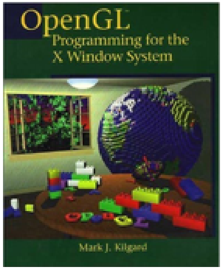
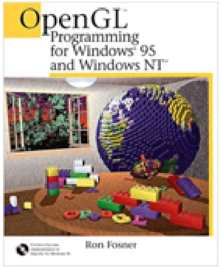
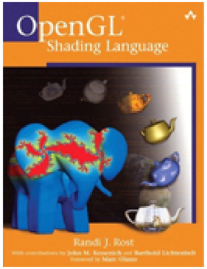
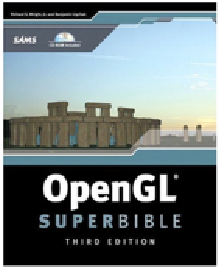
The Official Reference Document to OpenGL, Version 1.4
OpenGL Architecture Review Board









Resources

- OpenGL Home Page http://www.opengl.org
- OpenGL Tutors http://www.xmission.com/~nate/tutors.html
- NeHe Tutorials: http://nehe.gamedev.net
- OpenGL Red Book (Programming Manual) http://www.glprogramming.com/red/
- OpenGL Blue Book (Reference Manual)http://www.glprogramming.com/blue/
- Using GLUT with Visual C++ Express Edition http://www.cs.rit.edu/~wrc/courses/common/cg1/doc/visual/GLUT_with_VCppEE.pdf