The Basic Computer Graphics Pipeline

We'll come back to this later. For now, understand that there are multiple steps to go from your 3D geometry to pixels on the screen.
Geometry: Where things are (e.g., coordinates)

Topology: How things are connected

3D Coordinate Systems

Left-handed

Right-handed
Since Homer Simpson uses Right-handed Coordinates, then we will too.

Right-handed 3D Coordinate System for a CNC Machine.
Right-handed Coordinate System

Right-handed Positive Rotations

Drawing in 3D

```cpp
setColor3f( r, g, b );
begin( GL_LINE_STRIP );
glVertex3f( x0, y0, z0 );
glVertex3f( x1, y1, z1 );
glVertex3f( x2, y2, z2 );
glVertex3f( x3, y3, z3 );
glVertex3f( x4, y4, z4 );
end();
```

Set any display-characteristics state that you want to have in effect when you do the drawing.

Begin the drawing. Use the current state’s display-characteristics. Here is the topology to be used with these vertices.

This is a wonderfully understandable way to start with 3D graphics, but it is also incredibly inefficient! We’ll talk about that later…
**OpenGL Topologies**

- **GL_POINTS**
  - $V_0$, $V_1$, $V_2$, $V_3$

- **GL_LINES**
  - $V_0$, $V_1$, $V_2$, $V_3$

- **GL_LINE_STRIP**
  - $V_1$, $V_2$, $V_3$

- **GL_LINE_LOOP**
  - $V_0$, $V_1$, $V_2$, $V_3$

- **GL_TRIANGLES**
  - $V_0$, $V_1$, $V_2$, $V_3$

- **GL_TRIANGLE_STRIP**
  - $V_0$, $V_1$, $V_2$, $V_3$, $V_4$

- **GL_TRIANGLE_FAN**
  - $V_0$, $V_1$, $V_2$, $V_3$, $V_4$

- **GL_QUADS**
  - $V_0$, $V_1$, $V_2$, $V_3$

- **GL_QUAD_STRIP**
  - $V_0$, $V_1$, $V_2$, $V_3$, $V_4$

- **GL_POLYGON**
  - $V_0$, $V_1$, $V_2$, $V_3$, $V_4$, $V_5$, $V_6$, $V_7$
OpenGL Topologies – Polygon Requirements

Polygons must be:

- **Convex** and
- **Planar**

For that reason, GL_TRIANGLES_STRIP and GL_TRIANGLES are considered preferable to GL_QUAD_STRIP and GL_QUADS. GL_POLYGON is rarely used.

OpenGL Topologies -- Orientation

Polygons are traditionally:

- **CCW** when viewed from outside the solid object

It doesn’t matter much, but there is an advantage in being **consistent**
OpenGL Topologies – Vertex Order Matters

GL_LINE_LOOP

Probably what you meant to do

GL_LINE_LOOP

Probably not what you meant to do

This disease is referred to as “The Bowtie” 😊

What does “Convex Polygon” Mean?

We can go all mathematical here, but let’s go visual instead. In a convex polygon, a line between any two points inside the polygon never leaves the inside of the polygon.
Why is there a Requirement for Polygons to be Convex?

Graphics polygon-filling hardware can be highly optimized if you know that, no matter what direction you fill the polygon in, there will be two and only two intersections between the scanline and the polygon's edges.

Convex

Not Convex

2 edge intersections

4 edge intersections

What if you need to display Polygons that are not Convex?

There are two good solutions I know of (and there are probably more):

1. OpenGL’s utility (gluXxx) library has a built-in tessellation capability to break a non-convex polygon into convex polygons.

2. There is an open source library to break a non-convex polygon into convex polygons. It is called **Polypartition**, and the source code can be found here:

   https://github.com/ivanfratric/polypartition

If you ever need to do this, contact me. I have working code for each approach…
Why is there a Requirement for Polygons to be Planar?

Graphics hardware assumes that a polygon has a definite front and a definite back, and that you can only see one of them at a time.

OpenGL Drawing Can Be Done Procedurally

Listing a lot of vertices explicitly gets old in a hurry.

The graphics card can’t tell how the numbers in the glVertex3f calls were produced: both explicitly listed and procedurally computed look the same to glVertex3f.

```c
// Explicitly listed
glColor3f( r, g, b );
 glBegin( GL_LINE_LOOP );
 glVertex3f( x0, y0, 0. );
 glVertex3f( x1, y1, 0. );
 ...
 glEnd( );

// Procedurally computed
GLfloat dang = 2. * M_PI / (GLfloat)( NUMSEGS - 1 );
GLfloat ang = 0.;
 glBegin( GL_LINE_LOOP );
 for( int i = 0; i < NUMSEGS; i++ )
  {
   glVertex3f( RADIUS*cos(ang), RADIUS*sin(ang), 0. );
   ang += dang;
  }
 glEnd( );
```
glColor3f(r, g, b);

0.0 ≤ r, g, b ≤ 1.0

This is referred to as “Additive Color”

Cyan = Green + Blue
Magenta = Red + Blue
Yellow = Red + Green
White = Red + Green + Blue

Transformations

Translation
Rotation
Scaling
OpenGL Transformations

```c
glTranslatef( tx, ty, tz );
```

```c
glRotatef( degrees, ax, ay, az );
```

```c
glScalef( sx, sy, sz );
```

Single Transformations

```c
glMatrixMode( GL_MODELVIEW );
glLoadIdentity();
```

```c
glRotatef( degrees, ax, ay, az );
```

```c
gIColor3f( r, g, b );
glBegin( GL_LINE_STRIP );
    glVertex3f( x0, y0, z0 );
    glVertex3f( x1, y1, z1 );
    glVertex3f( x2, y2, z2 );
    glVertex3f( x3, y3, z3 );
    glVertex3f( x4, y4, z4 );
glEnd();
```
Compound Transformations

```c
glMatrixMode( GL_MODELVIEW );
glLoadIdentity( )

3. These transformations “add up”, and look like they take effect in this order

glTranslatef( tx, ty, tz );
glRotatef( degrees, ax, ay, az );
glScalef( sx, sy, sz );
glColor3f( r, g, b );
glBegin( GL_LINE_STRIP );
   glVertex3f( x0, y0, z0 );
   glVertex3f( x1, y1, z1 );
   glVertex3f( x2, y2, z2 );
   glVertex3f( x3, y3, z3 );
   glVertex3f( x4, y4, z4 );
glEnd( );
```

Why do the Compound Transformations Take Effect in Reverse Order?

Envision fully-parenthesizing what is going on. In that case, it makes perfect sense that the most recently-set transformation would take effect first.
Order Matters!
Compound Transformations are Not Commutative

The designers of OpenGL could have put lots and lots of arguments on the glVertex3f call to totally define the appearance of your drawing, like this:

```c
glVertex3f( x, y, z,   r, g, b,   m00, ..., m33,   s, t,   nx, ny, nz,  linewidth, ...   );
```

Yuch! That would have been ugly. Instead, they decided to let you create a “current drawing state”. You set all of these characteristics first, then they take effect when you do the drawing. They continue to remain in effect for future drawing calls, until you change them.

```c
glMatrixMode( GL_MODELVIEW );
gLoadIdentity();
glTranslatex( tx, ty, tz );
glRotatex( degrees, ax, ay, az );
glScalex( sx, sy, sz );
gsColor3x( r, g, b );
gBegin( GL_LINE_STRIP );
gVertex3f( x0, y0, z0 );
gVertex3f( x1, y1, z1 );
gVertex3f( x2, y2, z2 );
gVertex3f( x3, y3, z3 );
gVertex3f( x4, y4, z4 );
gEnd();
```
Projecting an Object from 3D into 2D

Orthographic (or Parallel) projection

\[ \text{glOrtho}( x_l, x_r, y_b, y_t, z_n, z_f ); \]

Perspective projection

\[ \text{gluPerspective}( \text{fovy}, \text{aspect}, z_n, z_f ); \]

Parallel lines remain parallel

Parallel lines appear to converge

"Vanishing Point"

Projecting on Object from 3D to 2D

Parallel/Orthographic is good for lining things up and comparing sizes

Perspective is more realistic-looking
OpenGL Projection Functions

glMatrixMode( GL_PROJECTION );
glLoadIdentity( );

Use one of these, but not both!

glOrtho( xl, xr, yb, yt, zn, zf );
gluPerspective( fovy, aspect, zn, zf );

...and:

glMatrixMode( GL_MODELVIEW );
glLoadIdentity( );

gluLookAt( ex, ey, ez, lx, ly, lz, ux, uy, uz );

glTranslatef( tx, ty, tz );
glRotatef( degrees, ax, ay, az );
glScalef( sx, sy, sz );

glColor3f( r, g, b );
glBegin( GL_LINE_STRIP );
glVertex3f( x0, y0, z0 );
glVertex3f( x1, y1, z1 );
glVertex3f( x2, y2, z2 );
glVertex3f( x3, y3, z3 );
glVertex3f( x4, y4, z4 );

glEnd( );

How the Viewing Volumes Look from the Outside

Parallel/Orthographic

Perspective
The Perspective Viewing Frustum

\[ \text{gluPerspective}( \text{fovy}, \text{aspect}, \text{zn}, \text{zf}); \]

- \textit{fovy} = vertical field of view angle (degrees)
- (good values are 50-100°)

Arbitrary Viewing

\begin{verbatim}
glMatrixMode( GL_PROJECTION );
gLoadIdentity( );
gluPerspective( fpvy, aspect, zn, zf );
glMatrixMode( GL_MODELVIEW );
gLoadIdentity( );
gluLookAt( ex, ey, ez, lx, ly, lz, ux, uy, uz );
glTranslatef( tx, ty, tz );
glRotatef( degrees, ax, ay, az );
glScalef( sx, sy, sz );
glColor3f( r, g, b );
glBegin( GL_LINE_STRIP );
glVertex3f( x0, y0, z0 );
glVertex3f( x1, y1, z1 );
glVertex3f( x2, y2, z2 );
glVertex3f( x3, y3, z3 );
glVertex3f( x4, y4, z4 );
glEnd( );
\end{verbatim}
How Can You Be Sure You See Your Scene?

gluPerspective( fovy, aspect, zn, zf );

gluLookAt( ex, ey, ez, lx, ly, lz, ux, uy, uz );

Here's a good way to start:

1. Set \( lx, ly, lz \) to be the average of all the vertices
2. Set \( ux, uy, uz \) to be \( 0., 1., 0. \).
3. Set \( ex=lx \) and \( ey=ly \)
4. Now, you change \( \Delta E \) or \( fovy \) so that the object fits in the viewing volume:

\[
\tan\left(\frac{fovy}{2}\right) = \frac{H}{2 \Delta E}
\]

Giving:

\[
fovy = 2\arctan\left[\frac{H}{2\Delta E}\right]
\]

or:

\[
\Delta E = \frac{H}{2\tan\left(\frac{fovy}{2}\right)}
\]
**Specifying a Viewport**

Be sure the y:x aspect ratios match!!

```c
glViewport( ixl, iyb, idx, idy );
glMatrixMode( GL_PROJECTION );
gluPerspective( fovy, aspect, zn, zf );
glMatrixMode( GL_MODELVIEW );
gluLookAt( ex, ey, ez, lx, ly, lz, ux, uy, uz );
glLoadIdentity( );
glMatrixMode( GL_PROJECTION );
gluPerspective( fovy, aspect, zn, zf );
glMatrixMode( GL_MODELVIEW );
glLoadIdentity( );
glTranslatef( tx, ty, tz );
glPushMatrix( );
glRotatef( degrees, ax, ay, az );
glScalef( sx, sy, sz );
glColor3f( r, g, b );
glBegin( GL_LINE_STRIP );
  glVertex3f( x0, y0, z0 );
  glVertex3f( x1, y1, z1 );
  glVertex3f( x2, y2, z2 );
  glVertex3f( x3, y3, z3 );
  glVertex3f( x4, y4, z4 );
glEnd( );
glPopMatrix( );
```

Viewports use the upper-left corner as (0,0) and their Y goes down

Note: setting the viewport is not part of setting either the Modelview or the Projection transformations.

---

**Saving and Restoring the Current Transformation**

```c
glViewport( ixl, iyb, idx, idy );
glMatrixMode( GL_PROJECTION );
glLoadIdentity( );
gluPerspective( fovy, aspect, zn, zf );
glMatrixMode( GL_MODELVIEW );
glLoadIdentity( );
gluLookAt( ex, ey, ez, lx, ly, lz, ux, uy, uz );
glLoadIdentity( );
glMatrixMode( GL_PROJECTION );
gluPerspective( fovy, aspect, zn, zf );
glMatrixMode( GL_MODELVIEW );
glLoadIdentity( );
glTranslatef( tx, ty, tz );
glPushMatrix( );
glRotatef( degrees, ax, ay, az );
glScalef( sx, sy, sz );
glColor3f( r, g, b );
glBegin( GL_LINE_STRIP );
  glVertex3f( x0, y0, z0 );
  glVertex3f( x1, y1, z1 );
  glVertex3f( x2, y2, z2 );
  glVertex3f( x3, y3, z3 );
  glVertex3f( x4, y4, z4 );
glEnd( );
glPopMatrix( );
glPopMatrix( );
```
sample.cpp Program Structure

• #includes
• Consts and #defines
• Global variables
• Function prototypes
• Main program
• InitGraphics function
• Display callback
• Keyboard callback

#include <stdio.h>
#include <stdlib.h>
#include <ctype.h>
#define _USE_MATH_DEFINES
#include <math.h>
#ifdef WIN32
#include <windows.h>
#pragma warning(disable:4996)
#include "glew.h"
#endif
#include <GL/gl.h>
#include <GL/glu.h>
#include "glut.h"
consts and #defines

const char *WINDOWTITLE = { "OpenGL / GLUT Sample -- Joe Graphics" };  
const char *GLUITITLE = { "User Interface Window" };  
const int GLUITRUE = { true };  
const int GLUIFALSE = { false };  
#define ESCAPE 0x1b  
const int INIT_WINDOW_SIZE = { 600 };  
const float BOXSIZE = { 2.f };  
const float ANGFACT = { 1. };  
const float SCLFACT = { 0.005f };  
const float MINSCALE = { 0.05f };  
const int LEFT = { 4 };  
const int MIDDLE = { 2 };  
const int RIGHT = { 1 };  
enum Projections {  
  ORTHO,  
  PERSP  
};  
enum ButtonVals  
{  
  RESET,  
  QUIT  
};  
enum Colors  
{  
  RED,  
  YELLOW,  
  GREEN,  
  CYAN,  
  BLUE,  
  MAGENTA,  
  WHITE,  
  BLACK  
};

consts are always preferred over #defines.  
But, Visual Studio does not allow consts to  
be used in case statements or as array sizes.

Initialized Global Variables

const GLfloat BACKCOLOR[] = { 0., 0., 0., 1. };  
const GLfloat AXES_WIDTH = { 3. };  
char * ColorNames[] =  
{  
  "Red",  
  "Yellow",  
  "Green",  
  "Cyan",  
  "Blue",  
  "Magenta",  
  "White",  
  "Black"  
};  
const GLfloat Colors[][3] =  
{  
  { 1., 0., 0. }, // red  
  { 1., 1., 0. }, // yellow  
  { 0., 1., 0. }, // green  
  { 0., 1., 1. }, // cyan  
  { 0., 0., 1. }, // blue  
  { 1., 0., 1. }, // magenta  
  { 1., 1., 1. }, // white  
  { 0., 0., 0. } // black  
};  
const GLfloat FOGCOLOR[4] = { .0, .0, .0, 1. };  
const GLenum FOGMODE = { GL_LINEAR };  
const GLfloat FOGDENSITY = { 0.30f };  
const GLfloat FOGSTART = { 1.5 };  
const GLfloat FOGEND = { 4. };
Global Variables

```c
int ActiveButton; // current button that is down
GLuint AxesList; // list to hold the axes
int AxesOn; // 0 means to draw the axes
int DebugOn; // 0 means to print debugging info
int DepthCueOn; // 0 means to use intensity depth cueing
GLuint BoxList; // object display list
int MainWindow; // window id for main graphics window
float Scale; // scaling factor
int WhichColor; // index into Colors[]
int WhichProjection; // ORTHO or PERSP
int Xmouse, Ymouse; // mouse values
float Xrot, Yrot; // rotation angles in degrees
```

Function Prototypes

```c
void Animate( );
void Display( );
void DoAxesMenu( int );
void DoColorMenu( int );
void DoDepthMenu( int );
void DoDebugMenu( int );
void DoMainMenu( int );
void DoProjectMenu( int );
void DoRasterString( float, float, float, char * );
void DoStrokeString( float, float, float, float, char * );
float ElapsedSeconds( );
void InitGraphics( );
void InitLists( );
void InitMenus( );
void Keyboard( unsigned char, int, int );
void MouseButton( int, int, int, int );
void MouseMotion( int, int );
void Reset( );
void Resize( int, int );
void Visibility( int );
void Axes( float );
void HsvRgb( float[3], float [3] );
```
Main Program

int main( int argc, char * argv[] )
{
    // turn on the glut package:
    // (do this before checking argc and argv since it might
    // pull some command line arguments out)
    glutInit( &argc, argv );
    // setup all the graphics stuff:
    InitGraphics();
    // create the display structures that will not change:
    InitLists();
    // init all the global variables used by Display();
    // this will also post a redisplay
    Reset();
    // setup all the user interface stuff:
    InitMenus();
    // draw the scene once and wait for some interaction:
    // (this will never return)
    glutSetWindow( MainWindow );
    glutMainLoop();
    // this is here to make the compiler happy:
    return 0;
}

InitGraphics(), I

void InitGraphics() {
    // request the display modes:
    // ask for red-green-blue-alpha color, double-buffering, and z-buffering:
    glutInitDisplayMode( GLUT_RGBA | GLUT_DOUBLE | GLUT_DEPTH );
    // set the initial window configuration:
    glutInitWindowPosition( 0, 0 );
    glutInitWindowSize( INIT_WINDOW_SIZE, INIT_WINDOW_SIZE );
    // open the window and set its title:
    MainWindow = glutCreateWindow( WINDOWTITLE );
    glutSetWindowTitle( WINDOWTITLE );
    // set the framebuffer clear values:
    glClearColor( BACKCOLOR[0], BACKCOLOR[1], BACKCOLOR[2], BACKCOLOR[3] );
    glutSetWindow( MainWindow );
    glutDisplayFunc( Display );
    glutReshapeFunc( Resize );
    glutKeyboardFunc( Keyboard );
    glutMouseFunc( MouseButton );
    glutMotionFunc( MouseMotion );
    glutTimerFunc( -1, NULL, 0 );
    glutIdleFunc( NULL );
```c
#ifdef WIN32
  GLenum err = glewInit();
  if( err != GLEW_OK )
  {
    fprintf( stderr, "GLEW Error\n" );
  }
#endif
```

```c
void Display()
{
  // set which window we want to do the graphics into:
  glutSetWindow( MainWindow );

  // erase the background:
  glDrawBuffer( GL_BACK );
  glClear( GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT );
  glEnable( GL_DEPTH_TEST );

  // specify shading to be flat:
  glShadeModel( GL_FLAT );

  // set the viewport to a square centered in the window:
  GLsizei vx = glutGet( GLUT_WINDOW_WIDTH );
  GLsizei vy = glutGet( GLUT_WINDOW_HEIGHT );
  GLsizei v = vx < vy ? vx : vy;                  // minimum dimension
  GLint xl = ( vx - v ) / 2;
  GLint yb = ( vy - v ) / 2;
  glViewport( xl, yb,  v, v );
```
Display( ), II

// set the viewing volume:
// remember that the Z clipping values are actually
given as DISTANCES IN FRONT OF THE EYE

// set the viewing volume:
// remember that the Z clipping values are actually
given as DISTANCES IN FRONT OF THE EYE

glMatrixMode( GL_PROJECTION );
gLoadIdentity( );
if( WhichProjection == ORTHO )
    glOrtho( -3., 3., -3., 3., 0.1, 1000. );
else
    gluPerspective( 90., 1., 0.1, 1000. );

// place the objects into the scene:

// place the objects into the scene:

glMatrixMode( GL_MODELVIEW );
gLoadIdentity( );

// set the eye position, look-at position, and up-vector:

// set the eye position, look-at position, and up-vector:

gluLookAt( 0., 0., 3., 0., 0., 0., 0., 1., 0. );

// rotate the scene:

// rotate the scene:

glRotatef( (GLfloat)Yrot, 0., 1., 0. );
glRotatef( (GLfloat)Xrot, 1., 0., 0. );

// uniformly scale the scene:

// uniformly scale the scene:

if( Scale < MINSCALE )
    Scale = MINSCALE;

else
    glScalef( (GLfloat)Scale, (GLfloat)Scale, (GLfloat)Scale );

// set the fog parameters:

// set the fog parameters:

if( DepthCueOn != 0 )
{
    glFogi( GL_FOG_MODE, FOGMODE );
glFogf( GL_FOG_COLOR, FOGCOLOR );
glFogf( GL_FOG_DENSITY, FOGDENSITY );
glFogf( GL_FOG_START, FOGSTART );
glFogf( GL_FOG_END, FOGEND );
glEnable( GL_FOG );
}
else
{
    glDisable( GL_FOG );
}

// possibly draw the axes:

// possibly draw the axes:

if( AxesOn != 0 )
{
    glColor3fv( &Colors[WhichColor][0] );
glCallList( AxesList );
}

// draw the current object:

// draw the current object:

glCallList( BoxList );

Replay the graphics commands from a previously-stored Display List.

Display Lists have their own noteset.
// draw some gratuitous text that just rotates on top of the scene:
Display( GL_RGB );
DoRasterString( 0., 1., 0., "Text That Moves" );

// draw some gratuitous text that is fixed on the screen:
// the projection matrix is reset to define a scene whose
// world coordinate system goes from 0-100 in each axis
// this is called "percent units", and is just a convenience
// the modelview matrix is reset to identity as we don't
// want to transform these coordinates
Display( GL_RGB );
Display( GL_PROJECTION );
Display( GL_MODELVIEW );
DoRasterString( 5., 5., 0., "Text Doesn't" );

// swap the double-buffered framebuffers:
Display( );

// be sure the graphics buffer has been sent:
// note: be sure to use glFlush() here, not glFinish() !
Display( );
Display( );

// swap the double-buffered framebuffers:
Display( );

// update the window
Display( );

"swap buffers" changes the role of the two framebuffers

The monitor displays from here
This is called the refresh

You draw into here
This is called the update

You draw into here
The monitor displays from here
Extra Topics:
(Don’t need to get started with OpenGL programming)
Subtractive Colors (CMYK)

Sidebar: Subtractive Colors (CMYK)
Sidebar: Hue-Saturation-Value (HSV) -- Another way to specify additive color

The HsvRgb function is in your sample code.

float hsv[3], rgb[3];
HsvRgb( hsv, rgb );
setColor3fv( rgb );

0. ≤ s, v, r, g, b ≤ 1.
0. ≤ h ≤ 360.

The OSU ColorPicker Program

Red, Green, Blue  Hue, Saturation, Value
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.

A fragment is a “pixel-to-be”. In computer graphics, “pixel” is defined as having its full RGBA already computed. A fragment does not yet but all of the information needed to compute the RGBA is there.

A fragment is turned into a pixel by the fragment processing operation.

In CS 457/557, you will do some pretty snazzy things with your own fragment processing code!