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 vertices in your geometry to the pixels that you see on the screen.

<table>
<thead>
<tr>
<th>MC = Model Coordinates</th>
<th>WC = World Coordinates</th>
<th>EC = Eye Coordinates</th>
<th>CC = Clip Coordinates</th>
<th>NDC = Normalized Device Coordinates</th>
<th>SC = Screen Coordinates</th>
</tr>
</thead>
</table>

MC

WC

EC

EC

Projection Transform

Per-vertex Lighting

View Transform

Model Transform

Viewport Transform

Fragment Processing, Texturing, Per-fragment Lighting

Rasterization

Framebuffer

Raster Ops
Computer Graphics

Geometry:

Where things are (e.g., coordinates)

Topology:

How things are connected

Geometry vs. Topology

Original Object

Geometry = changed
Topology = same (1-2-3-4-1)

Geometry = same
Topology = changed (1-2-4-3-1)

3D Coordinate Systems

Left-handed

Right-handed

OpenGL uses this one
Homer Simpson uses Right-handed Coordinates. Who are we to argue with Homer Simpson?

Right-handed 3D Coordinate System for a CNC Machine
Right-handed Positive Rotations

Right-Handed Coordinate System

Drawing in 3D

```c
GLfloat3( 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();
```

This is a wonderfully understandable way to start with 3D graphics – it is like holding a marker in your hand and sweeping out linework in the 3D air in front of you!

But it is also incredibly internally inefficient! We’ll talk about that later and what to do about it…
OpenGL Topologies – Polygon Requirements

Polygons must be:

- Convex and
- Planar

GL_TRIANGLES and GL_TRIANGLES are considered to be 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.

Convex

Stays within the polygon

Not Convex

Leaves 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
void glColor3f(float r, float g, float b);
```

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

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

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

Single Transformations

```c
void glMatrixMode(GLint mode);
glMatrixMode(GL_MODELVIEW);
```

```c
void glLoadIdentity();
glLoadIdentity();
```

```c
void glRotatef(GLfloat angles, GLfloat x, GLfloat y, GLfloat z);
glRotatef(angles, x, y, z);
```

```c
void glColor3f(GLfloat r, GLfloat g, GLfloat b);
gColor3f(r, g, b);
```

```c
void glBegin(GLenum mode);
void glBegin(GL_LINES);
```

```c
void glVertex3f(GLfloat x, GLfloat y, GLfloat z);
void glVertex3f(x, y, z);
```

```c
void glEnd();
void glEnd();
```

```c
void glEnd();
```
## Compound Transformations

```c
glMatrixMode( GL_MODELVIEW );
glLoadIdentity( )
glTranslatef( tx, ty, tz );  \[3.\]
glRotatef( degrees, ax, ay, az );  \[2.\]
glScalef( sx, sy, sz );  \[1.\]

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();
```

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

---

## 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 OpenGL Drawing State

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:

```
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.

1. Set the state
2. Draw with that state

You must set the transformations before you expect them to take effect!
Projecting an Object from 3D into 2D

Orthographic (or Parallel) projection

```
glOrtho( xl, xr,  yb, yt,  zn, zf );
```

Parallel lines remain parallel

Perspective projection

```
gluPerspective( fovy, aspect,  zn, zf );
```

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

The **Vanishing Point**

Perspective is more realistic-looking
OpenGL Projection Functions

- `glMatrixMode( GL_PROJECTION );`
- `glLoadIdentity( );`
- `glMatrixMode( GL_MODELVIEW );`
- `glLoadIdentity( );`
- `glMatrixMode( GL_PROJECTION );`  # Redundant use of projection functions
- `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( );`

Use one of (glOrtho, gluPerspective), but not both!
OpenGL Projection Functions

```c
glMatrixMode( GL_PROJECTION );
glLoadIdentity( );

if( WhichProjection == ORTHO )
    glOrtho( -2.f, 2.f, -2.f, 2.f, 0.1f, 1000.f );
else
    gluPerspective( 70.f, 1.f, 0.1f, 1000.f );

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

```c
glOrtho( xleft, xright, ybottom, ytop, znear, zfar );
gluPerspective( fovy, aspect, znear, zfar );
```
The Perspective Viewing Frustum

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

\[
\text{fovy} = \text{vertical field of view angle (degrees)}
\]

(good values are 50-100°)

Arbitrary Viewing

\[
\text{glMatrixMode}( \text{GL_PROJECTION} );
\]
\[
\text{glLoadIdentity}();
\]
\[
\text{gluPerspective}( \text{fovy, aspect, zn, zf} );
\]
\[
\text{glMatrixMode}( \text{GL_MODELVIEW} );
\]
\[
\text{glLoadIdentity}();
\]

\[
\text{gluLookAt}( \text{ex, ey, ez, lx, ly, lz, ux, uy, uz} );
\]

\[
\text{glTranslatef}( \text{tx, ty, tz} );
\]
\[
\text{glRotatef}( \text{degrees, ax, ay, az} );
\]
\[
\text{glScalef}( \text{sx, sy, sz} );
\]
\[
\text{glColor3f}( \text{r, g, b} );
\]
\[
\text{glBegin}( \text{GL_LINE_STRIP} );
\]
\[
\text{glVertex3f}( \text{x0, y0, z0} );
\]
\[
\text{glVertex3f}( \text{x1, y1, z1} );
\]
\[
\text{glVertex3f}( \text{x2, y2, z2} );
\]
\[
\text{glVertex3f}( \text{x3, y3, z3} );
\]
\[
\text{glVertex3f}( \text{x4, y4, z4} );
\]
\[
\text{glEnd}();
\]
How Can You Be Sure You See Your Scene?

```c
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:

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

or:

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

Be sure the y:x aspect ratios match!!

`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);`  
`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();`

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

`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);`  
`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();`  

...
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"
const char *WINDOWTITLE = { "OpenGL / GLUT Sample -- Joe Graphics" };  
const char *GLUITITLE   = { "User Interface Window" };  
const int GLUITRUE  = { true  };  
const int GLUIFALSE = { false };  
const int 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
};

const GLfloat BACKCOLOR[4] = { 0., 0., 0., 1. };  
const GLfloat AXES_WIDTH   = { 3. };  
char * ColorNames[3] =  
{
    "Red",
    "Yellow",
    "Green",
    "Cyan",
    "Blue",
    "Magenta",
    "White",
    "Black"
};
const GLfloat Colors[3][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] );
```
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;
}

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:
    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] );
    glutReshapeFunc( Resize );
    glutDisplayFunc( Display );
    glutKeyboardFunc( Keyboard );
    glutMouseFunc( MouseButton );
    glutMotionFunc( MouseMotion );
    glutTimerFunc( -1, NULL, 0 );
    glutIdleFunc( NULL );
GLenum err = glewInit();
if( err != GLEW_OK )
{
      fprintf( stderr, "glewInit Error\n" );
}

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

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:

glMatrixMode( GL_MODELVIEW );
gLoadIdentity( );

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

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

// rotate the scene:

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

// uniformly scale the scene:

if( Scale < MINSCALE )
    Scale = MINSCALE;
gScalef( (GLfloat)Scale, (GLfloat)Scale, (GLfloat)Scale );

Display( ), III

// set the fog parameters:

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

// possibly draw the axes:

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

// draw the current object:

gCallList( BoxList );

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

Display Lists have their own noteset.
Display( ), IV

// draw some gratuitous text that just rotates on top of the scene:

glDisable( GL_DEPTH_TEST );
gColor3f( 0., 1., 1. );
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

gDisable( GL_DEPTH_TEST );
gMatrixMode( GL_PROJECTION );
gLoadIdentity( );
gluOrtho2D( 0., 100., 0., 100. );
gMatrixMode( GL_MODELVIEW );
gLoadIdentity( );
gColor3f( 1., 1., 1. );
DoRasterString( 5., 5., 0., "Text That Doesn't" );

// swap the double-buffered framebuffers:

glutSwapBuffers( );

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

flush();

You draw into here

This is called the update

"swap buffers" changes the role of the two framebuffers

You draw into here

This is called the refresh

The monitor displays from here

The monitor displays from here
The OSU ColorPicker Program

Sidebar: How Did We Make the Transition from Vertices to Pixels?

Vertices

- Model Transform
- View Transform
- Per-vertex Lighting
- Projection Transform
- Homogeneous Division
- Viewport Transform
- NDC

Pixels

- Framebuffer
- Raster Ops
- Fragment Processing, Texturing, Per-fragment Lighting
- Rasterization
- SC

Vertices

- MC = Model Coordinates
- WC = World Coordinates
- EC = Eye Coordinates
- CC = Clip Coordinates
- NDC = Normalized Device Coordinates

Pixels

- SC = Screen Coordinates
Sidebar: How Did We Make the Transition from Vertices to Pixels?

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, the word "pixel" is defined as having its full RGBA already computed. A fragment does not yet have its final RGBA computed, but all of the information needed to compute the RGBA is available to it.

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!