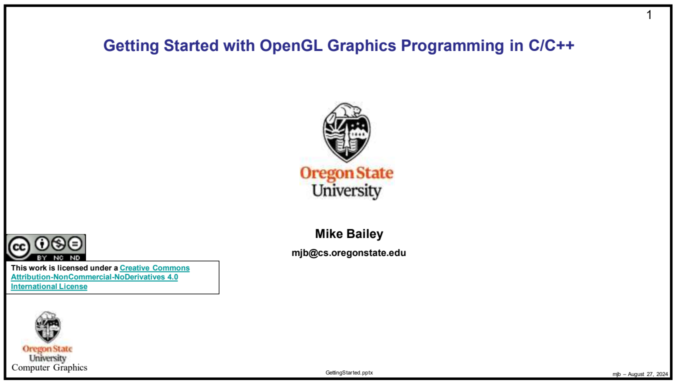
1
Getting Started with OpenGL Graphics Programming in C/C++
Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu
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Oregon State University Computer Graphics
GettingStarted.pptx
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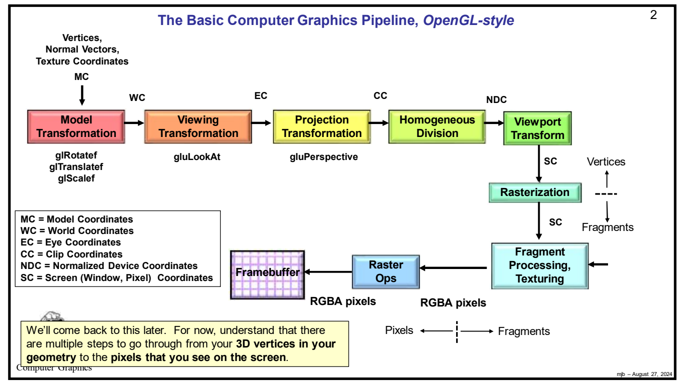
1


The Basic Computer Graphics Pipeline, OpenGL-style
2
Vertices, Normal Vectors, Texture Coordinates
MC
WC
EC
CC
NDC
Model Transformation
Viewing Transformation
Projection Transformation
Homogeneous Division
Viewport Transform
glRotatef
glTranslatef
glScalef
gluLookAt
gluPerspective
SC
Vertices
Rasterization
SC
Fragments
MC = Model Coordinates
WC = World Coordinates
EC = Eye Coordinates
CC = Clip Coordinates
NDC = Normalized Device Coordinates
SC = Screen (Window, Pixel) Coordinates
Framebuffer
Raster Ops
Fragment Processing, Texturing
RGBA pixels
RGBA pixels
We'll come back to this later. For now, understand that there are multiple steps to go through from your 3D vertices in your geometry to the pixels that you see on the screen.
Pixels
Fragments
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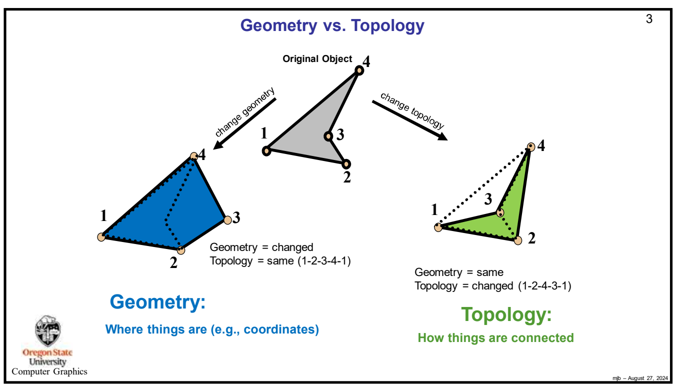
2


Geometry vs. Topology
3
Original Object
change geometry
change topology
Geometry = changed
Topology = same (1-2-3-4-1)
Geometry = same
Topology = changed (1-2-4-3-1)
Geometry:
Where things are (e.g., coordinates)
Topology:
How things are connected
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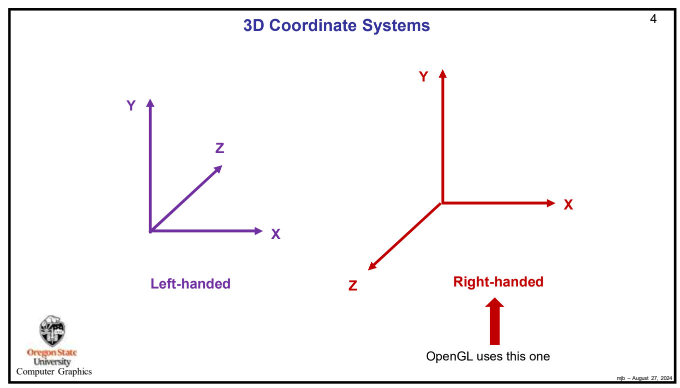
3


3D Coordinate Systems
4
Y
Z
X
Left-handed
Y
X
Z
Right-handed
OpenGL uses this one
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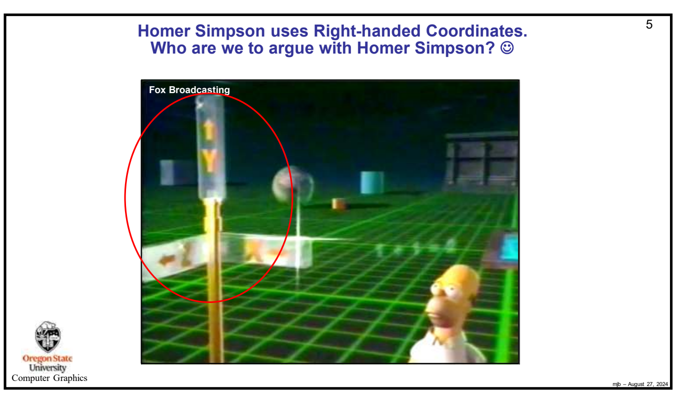
4


Homer Simpson uses Right-handed Coordinates.
Who are we to argue with Homer Simpson? ☺
5
Fox Broadcasting
Oregon State University Computer Graphics
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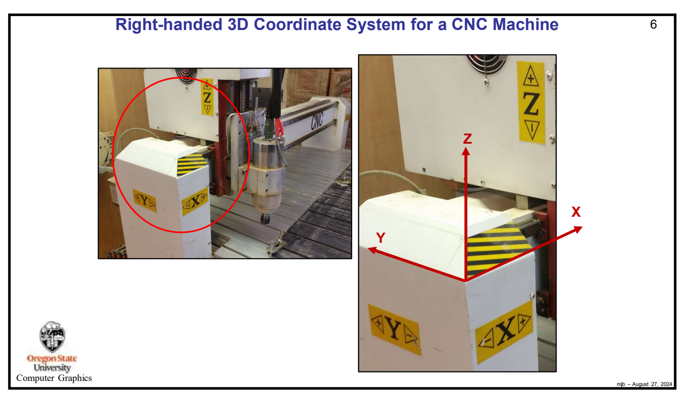
5


Right-handed 3D Coordinate System for a CNC Machine
6
Z
X
Y
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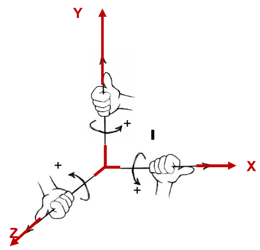
6

Right-handed Positive Rotations

7



Right-Handed Coordinate System

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7

Drawing in 3D

8

```
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( );
```

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

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 – 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…

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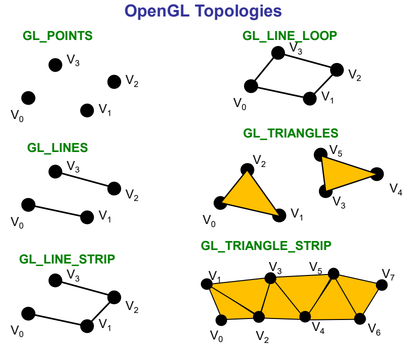
8

OpenGL Topologies

9



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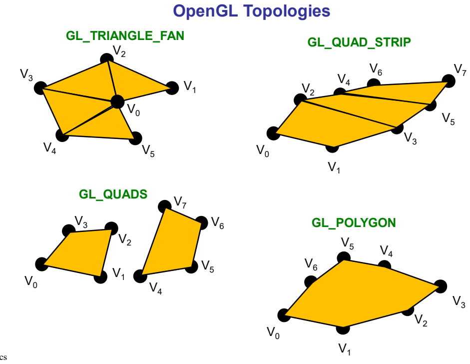
9

OpenGL Topologies

10



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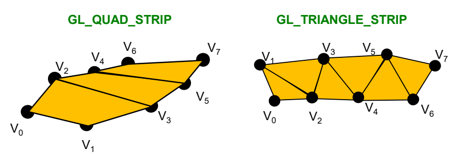
OpenGL Topologies – Polygon Requirements

11

Polygons must be:

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

GL_TRIANGLE_STRIP and GL_TRIANGLES are considered to be preferable to GL_QUAD_STRIP and GL_QUADS. GL_POLYGON is rarely used.



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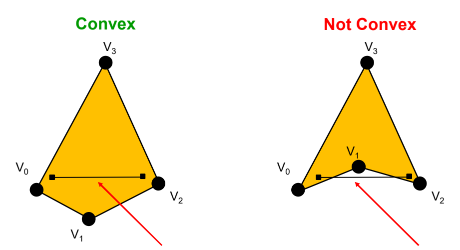
11

What does "Convex Polygon" Mean?

12

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.



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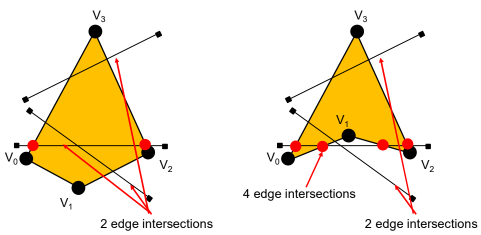
Why is there a Requirement for Polygons to be Convex?

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



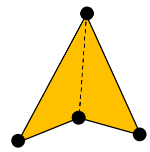
13

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…

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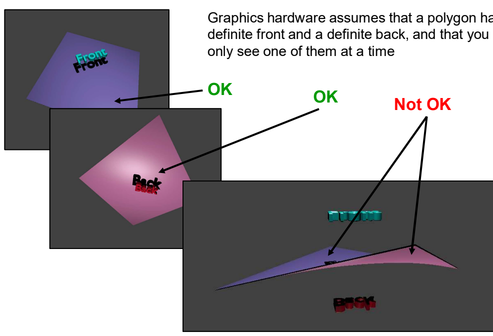
Why is there a Requirement for Polygons to be Planar?

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



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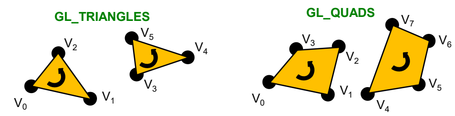
OpenGL Topologies -- Orientation

Polygons are traditionally:

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



It doesn't matter much, but there is an advantage in being ***consistent***

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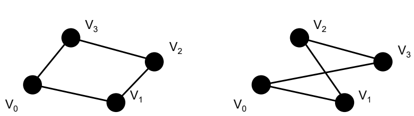
OpenGL Topologies – Vertex Order Matters



Probably what you meant to do

Probably not what you meant to do

This disease is referred to as "The Bowtie" ☺

17

OpenGL Drawing Can Be Done *Procedurally*

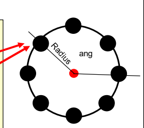

```
glColor3f( r, g, b );
glBegin( GL_LINE_LOOP );
        glVertex3f( x0, y0, 0. );
        glVertex3f( x1, y1, 0. );
        . . .
glEnd( );
```

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.

Draw a circle using lines:

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



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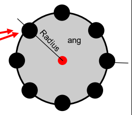
OpenGL Drawing Can Be Done *Procedurally*

The graphics card can't tell how the numbers in the glVertex3f calls were produced.

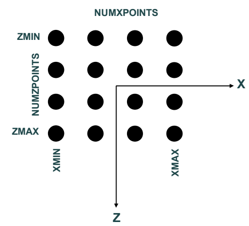
Both explicitly-listed and procedurally-computed look the same to glVertex3f.

Draw a circle using polygons:

```
glColor3f( r, g, b );
float dang = 2. * M_PI / (float)( NUMSEGS – 1 );
float ang = 0.;
glBegin( GL_TRIANGLE_FAN );
        glVertex3f( 0., 0., 0. );              // center point
        for( int i = 0; i < NUMSEGS; i++ )
        {
                glVertex3f( RADIUS*cos(ang),  RADIUS*sin(ang),  0. );
                ang += dang;
        }
glEnd( );
```



OpenGL Drawing Can Be Done *Procedurally*



Draw a grid:

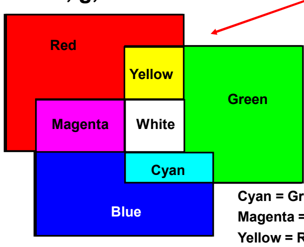
```
glColor3f( r, g, b );
float dx = (XMAX-XMIN) / (float)( NUMXPOINTS – 1 );
float dz = (ZMAX-ZMIN) / (float)( NUMZPOINTS – 1 );
float z = ZMIN;
for( int i = 0; i < NUMZPOINTS; i++ )
{
        float x = XMIN;
        glBegin( GL_LINE_STRIP );
        for( int j = 0; j < NUMXPOINTS; j++ )
        {
                float y = 0;
                // could do something in here to vary y:
                glVertex3f( x, y, z );
                x += dx;
        }
        glEnd( );
        z += dz;
}
```


Color

glColor3f(r, g, b);

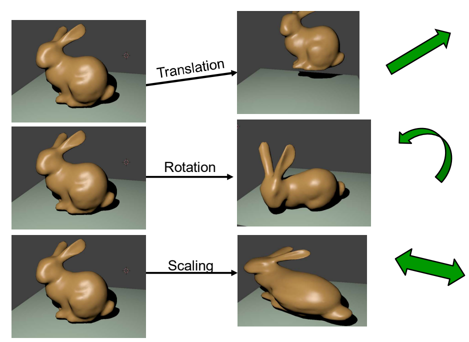
0.0 ≤ r, g, b ≤ 1.0

This is referred to as **"Additive Color"**

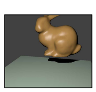


Cyan = Green + Blue
Magenta = Red + Blue
Yellow = Red + Green
White = Red + Green + Blue

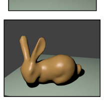
Transformations



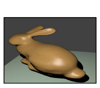
OpenGL Transformations



glTranslatef(tx, ty, tz);



glRotatef(*degrees*, ax, ay, az);



glScalef(sx, sy, sz);

Single Transformations


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

glRotatef(degrees, ax, ay, az);

```
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( );
```

Compound Transformations

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```
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 take effect in this order

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Why do the Compound Transformations Take Effect in Reverse Order?

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```
3. ( glTranslatef( tx, ty, tz );
2.   ( glRotatef( degrees,  ax, ay, az );
1.     ( glScalef( sx, sy, sz );
         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( );
       ) 1.
     ) 2.
   ) 3.
```

Envision fully-parenthesizing what is going on. In that case, it makes perfect sense that the most recently-set transformation would take effect first.

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Order Matters! Compound Transformations are Not Commutative

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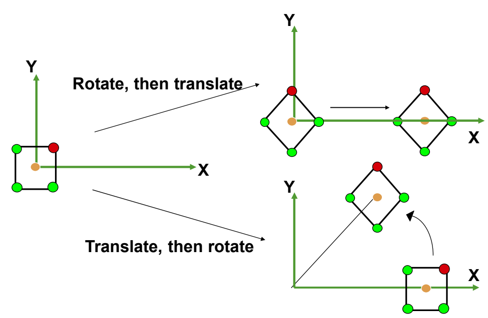

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The OpenGL Drawing State

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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.

You must set the transformations and colors before you can expect them to take effect!

1. Set the state

```
glMatrixMode( GL_MODELVIEW );
glLoadIdentity( )

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

2. Draw with that state

```
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( );
```

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Projecting an Object from 3D into 2D

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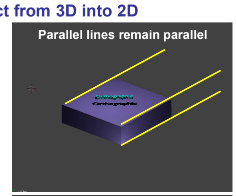
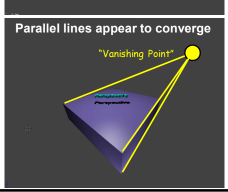
Orthographic (or Parallel) projection

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



Perspective projection

gluPerspective(fovy, aspect, zn, zf);



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Projecting on Object from 3D to 2D

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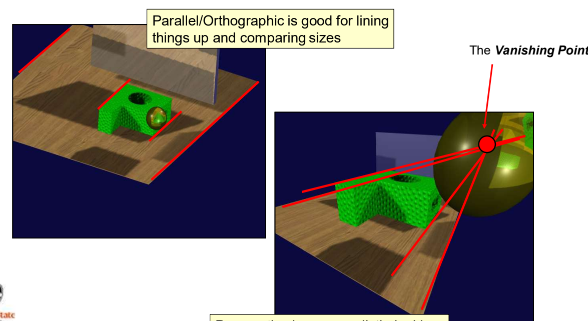
Parallel/Orthographic is good for lining things up and comparing sizes

The ***Vanishing Point***



Perspective is more realistic-looking

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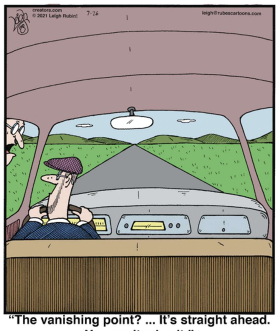

https://www.gocomics.com/rubes

"The vanishing point? ... It's straight ahead. You can't miss it."

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OpenGL Projection Functions

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

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

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

```
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( );
```

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OpenGL Projection Functions

```
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( );
```

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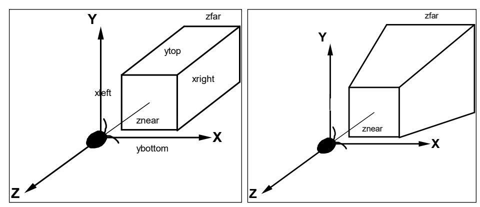
How the Viewing Volumes Look from the Outside

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



Parallel/Orthographic   Perspective

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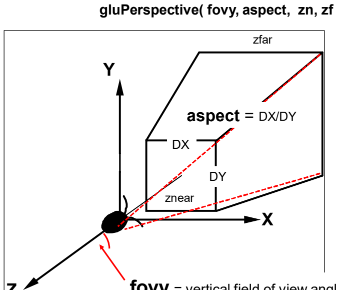
The Perspective Viewing Frustum

gluPerspective(fovy, aspect, zn, zf);



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

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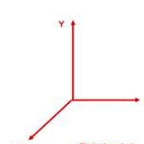
Arbitrary Viewing

```
glMatrixMode( GL_PROJECTION );
glLoadIdentity( );
gluPerspective( fovy, aspect, zn, zf );

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

Eye Position *Look-at Position* *Up vector*

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( );
```



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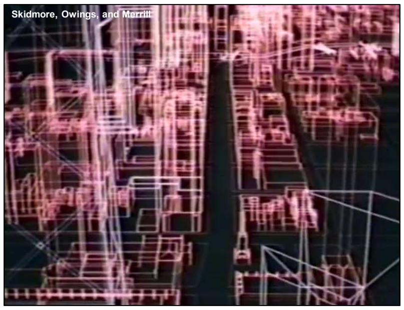
Chicago Fly-through: Changing Eye, Look, and Up



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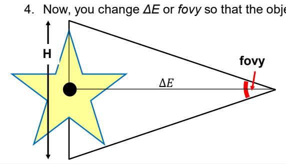
How Can You Be Sure You See Your Scene?

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 ΔE or *fovy* so that the object fits in the viewing volume:



$$tan(\frac{fovy}{2}) = \frac{H/2}{\Delta E}$$

Giving:

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

or:

$$\Delta E = \frac{H}{2tan(\frac{fovy}{2})}$$

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Specifying a Viewport

Be sure the y:x aspect ratios match!!

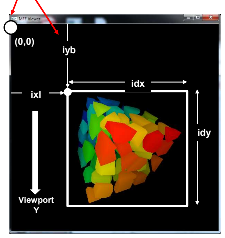
Viewports use the upper-left corner as (0,0) and their Y goes down

```
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( );
```



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

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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( );
   . . .
```

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sample.cpp Program Structure

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

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#includes


```
#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"
```

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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 };
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
};
```

Change this to be your name!

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


```
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


```
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 );
```

InitGraphics( ), II

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


Display( ), I

```
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 );
glLoadIdentity( );
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 );
glLoadIdentity( );

// 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;
glScalef( (GLfloat)Scale, (GLfloat)Scale, (GLfloat)Scale );
```


Display( ), III

```
// set the fog parameters:

if( DepthCueOn != 0 )
{
        glFogi( GL_FOG_MODE, FOGMODE );
        glFogfv( 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:

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

// draw the current object:

glCallList( 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 );
        glColor3f( 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

        glDisable( GL_DEPTH_TEST );
        glMatrixMode( GL_PROJECTION );
        glLoadIdentity( );
        gluOrtho2D( 0., 100.,     0., 100. );
        glMatrixMode( GL_MODELVIEW );
        glLoadIdentity( );
        glColor3f( 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( ) !

        glFlush( );
}
```

(x,y,z), to be *translated* by the ModelView matrix

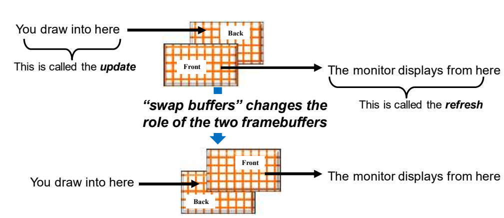
glutSwapBuffers( )

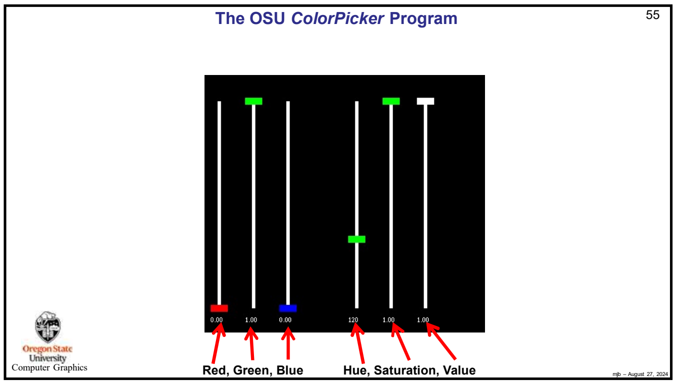
```
// swap the double-buffered framebuffers:

glutSwapBuffers( );
```

glutInitDisplayMode(GLUT_RGBA | **GLUT_DOUBLE** | GLUT_DEPTH);

glDrawBuffer(**GL_BACK**);





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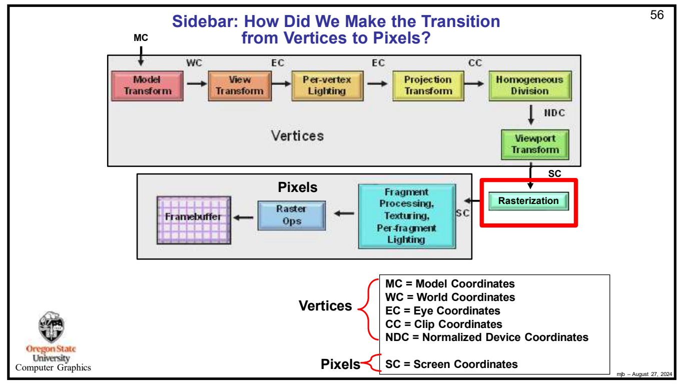

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Sidebar: How Did We Make the Transition from Vertices to Pixels?

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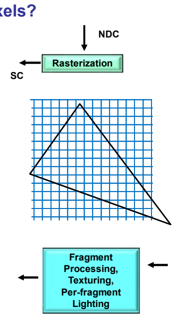
There is a piece of hardware called the **Rasterizer**. Its job is to interpolate a line or polygon, defined by vertices, into a collection of **fragments**. Think of it as filling in squares on graph paper.

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!



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