Computer Graphics

OpenGL Programming

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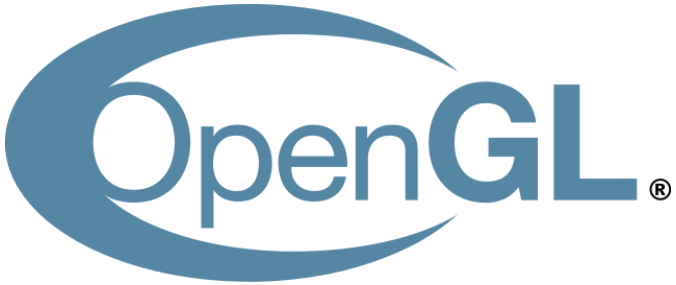
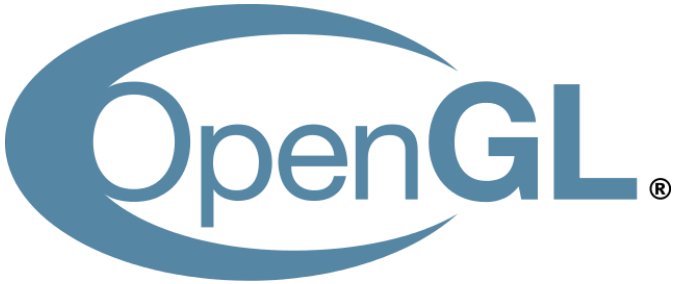
School of Data and Computer Science



Industry Standard API for Computer Graphics

What is OpenGL?

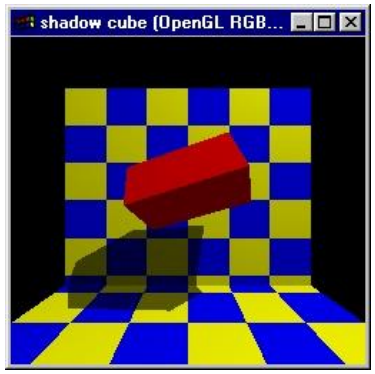
- The standard specification defining an API that interfaces with the computer's graphics system
  - Cross-language
  - Cross-platform
  - Vendor-independent



- Introduced in 1992 by Silicon Graphics Inc.

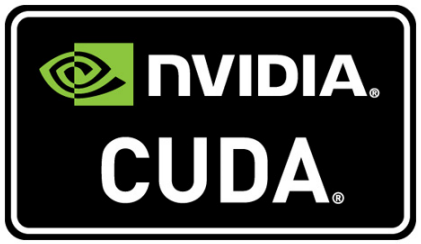
OpenGL (Open Graphics Library)

- OpenGL is a cross-language, multi-platform application programming interface (API) for rendering 2D and 3D computer graphics.
- Applications make calls to OpenGL , which then renders an image (by handling the graphics hardware) and displays it
- The API contains about 150 commands.
- is purely concerned with rendering, providing no APIs related to input, audio, or windowing.



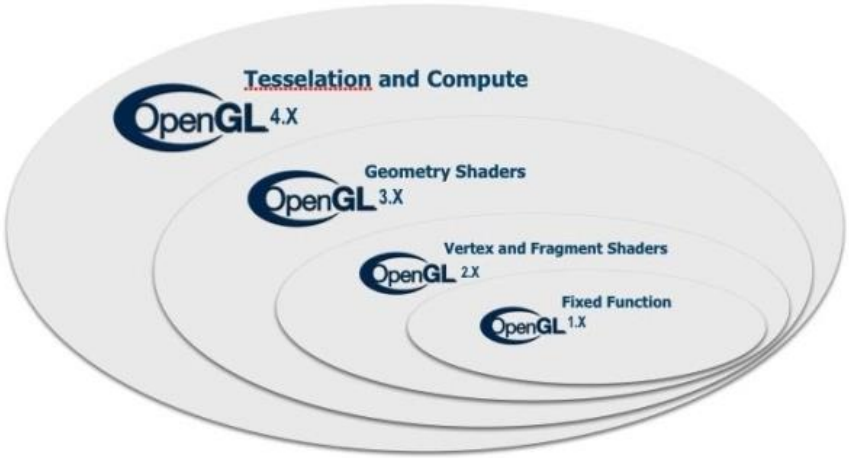
Not the Only One Choice

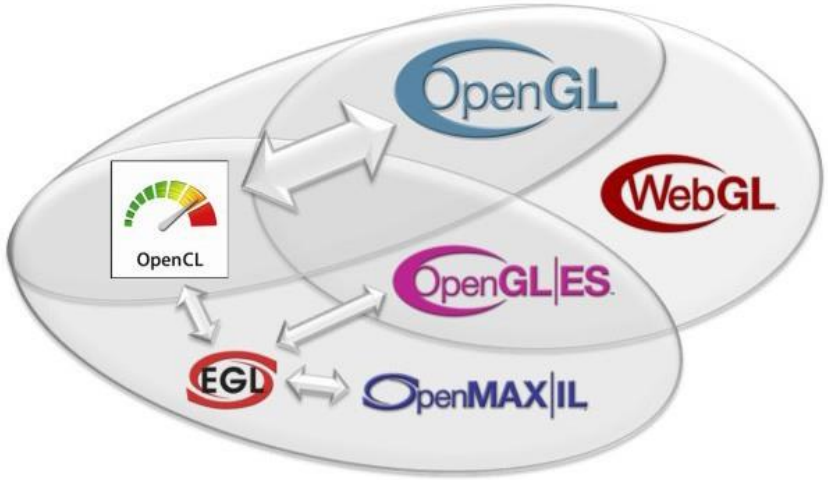
- Examples: NVIDIA CUDA, DirectX™, Windows Presentation Foundation™ (WPF), RenderMan™, HTML5 + WebGL™, JAVA 3D



Development of OpenGL

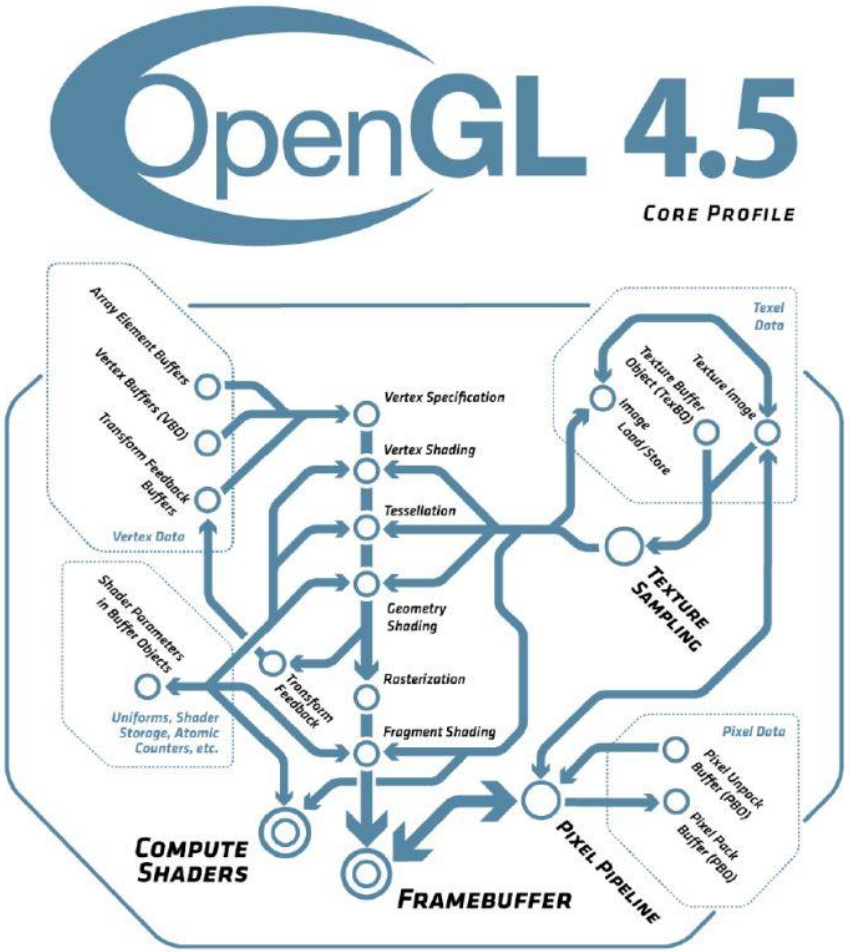
- OpenGL is an evolving API.
- New versions of the OpenGL specification are regularly released by the Khronos Group, each of which extends the API to support various new features.
- OpenGL 4.5 Release Date: August, 2014





What OpenGL Does

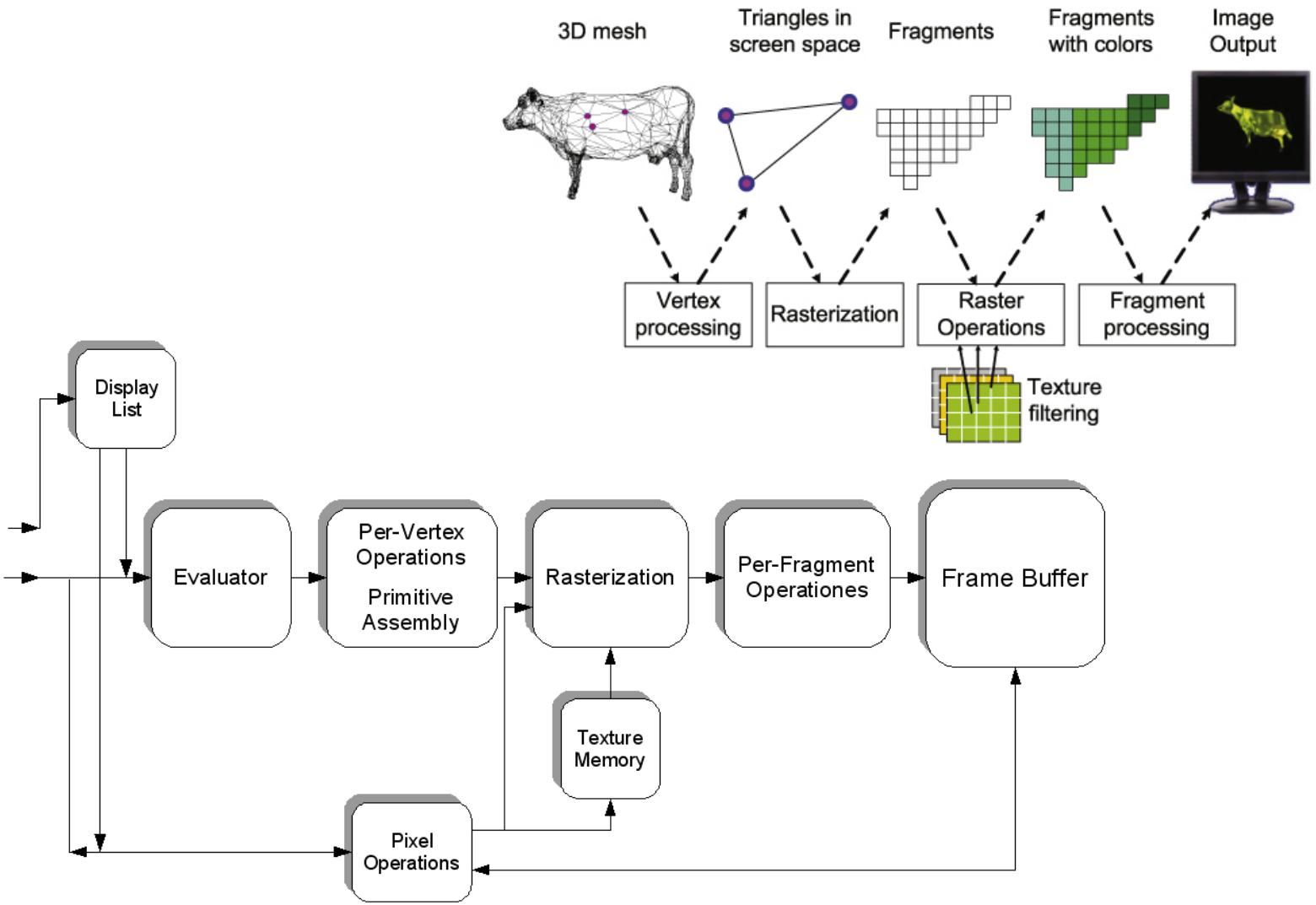
- Allow definition of object shapes, material properties and lighting
- Arrange objects and interprets synthetic camera in 3D space
- Coverts mathematical representations of objects into pixels (rasterization)
- Calculates the color of every object



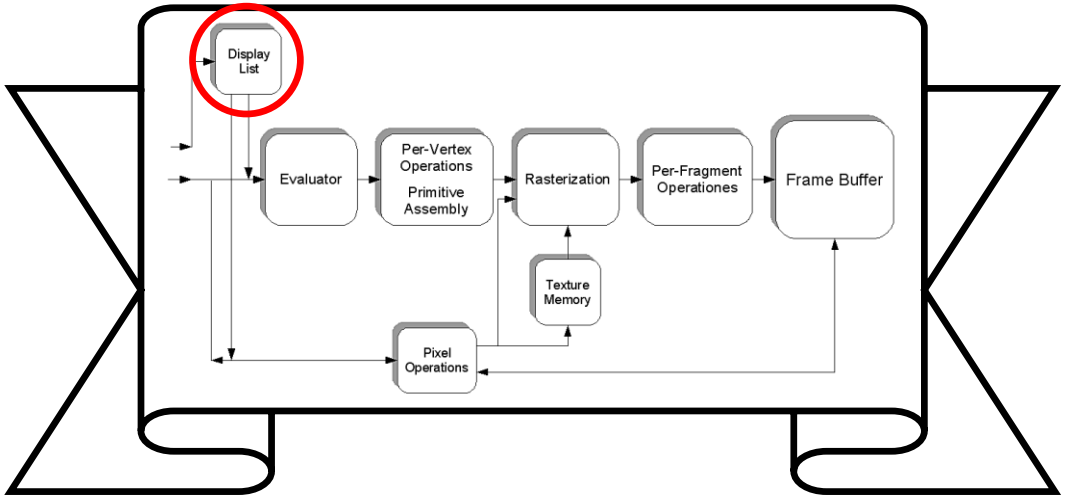
OpenGL and OpenGL Utility Toolkit

- No high-level rendering functions for complex objects
  - Build your shapes from primitives, points, lines, polygons, etc.
- The utility library GLUT provides additional support
  - (GLUT) is a library of utilities for OpenGL programs, which primarily perform system-level I/O with the host operating system.
  - Functions performed include window definition, window control, and monitoring of keyboard and mouse input.
  - Routines for drawing a number of geometric primitives (both in solid and wireframe mode) are also provided, including cubes, spheres and the Utah teapot.
  - GLUT also has some limited support for creating pop-up menus.

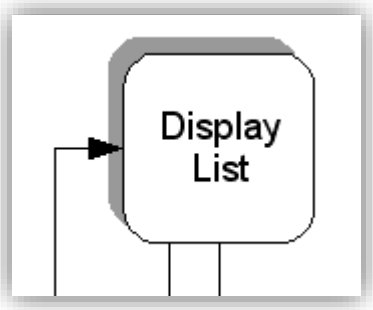
Simplified OpenGL Pipeline



Pieces of OpenGL Pipeline



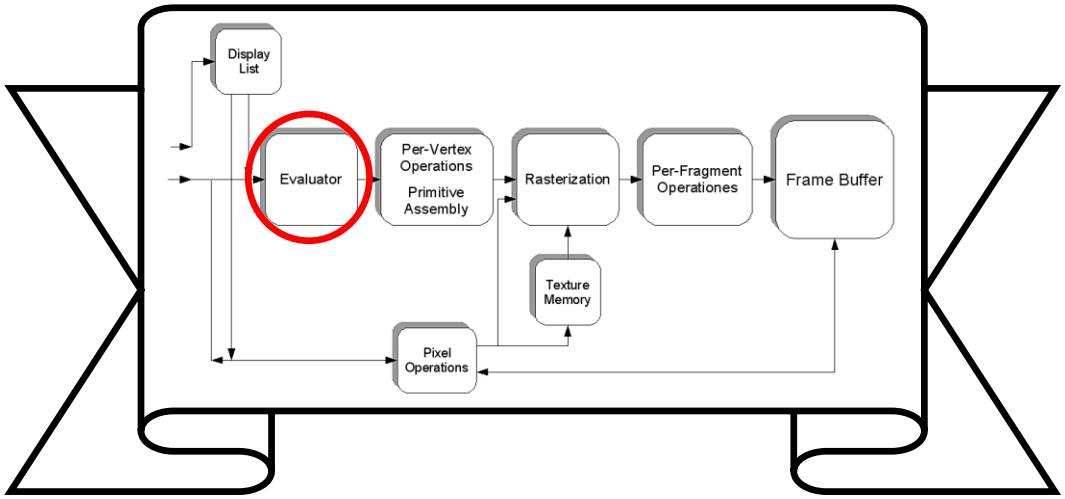
Stores "Subroutines (子程序)"



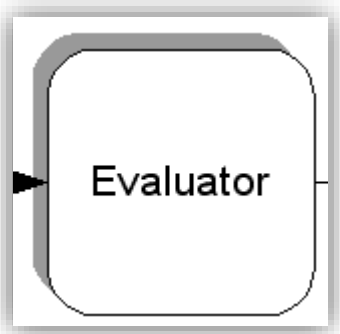
Faster!

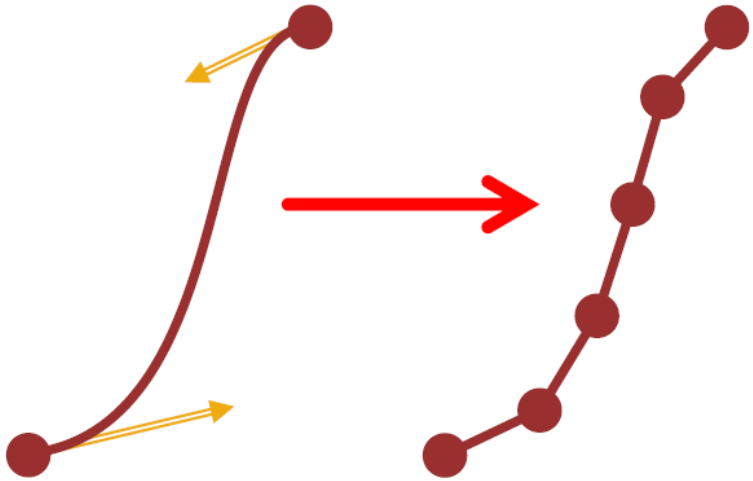
- *Pre-compiled*
- *Store on GPU*
- *Pre-compute transformations*

Pieces of OpenGL Pipeline

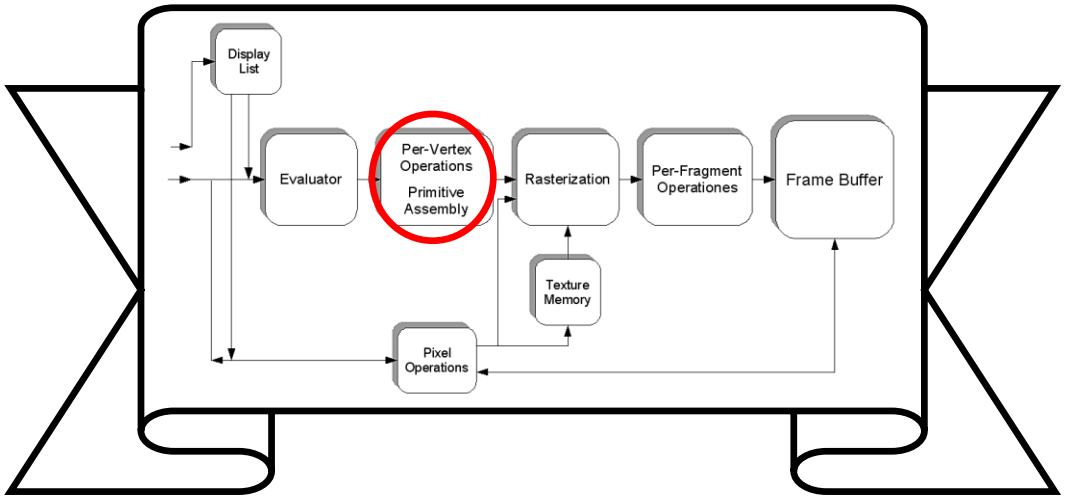


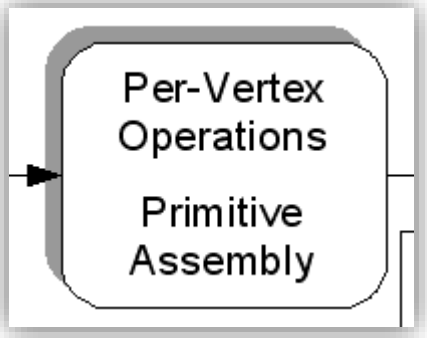
Construct geometric objects





Pieces of OpenGL Pipeline



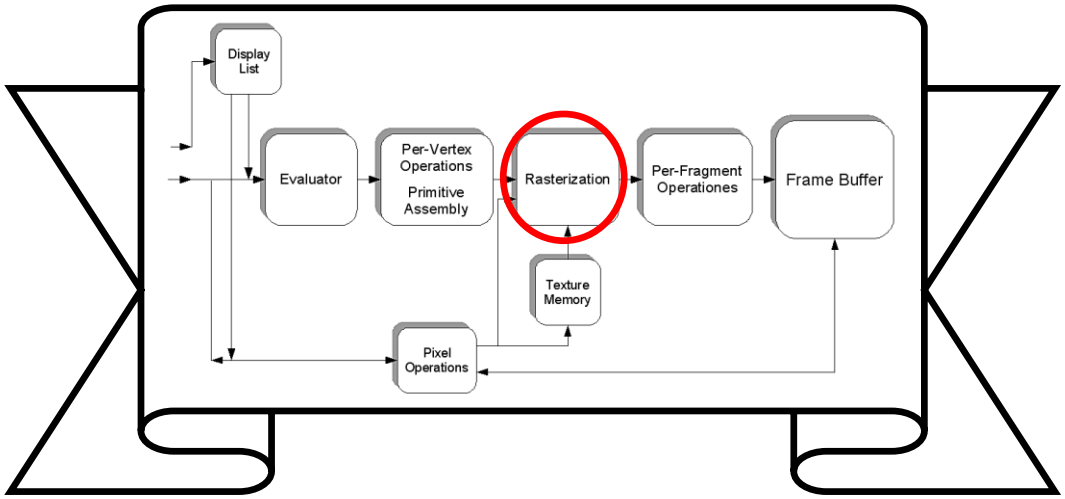


Change meshed geometry

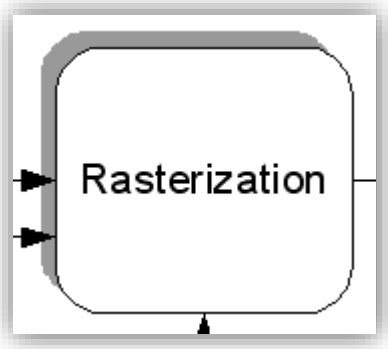
Store primitive shapes

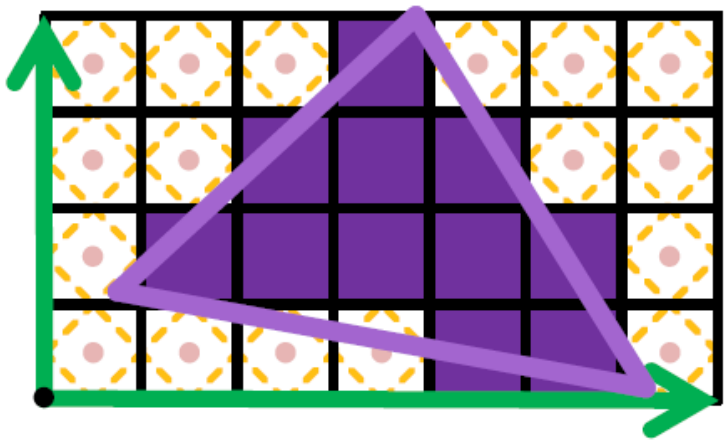
Includes clipping!

Pieces of OpenGL Pipeline

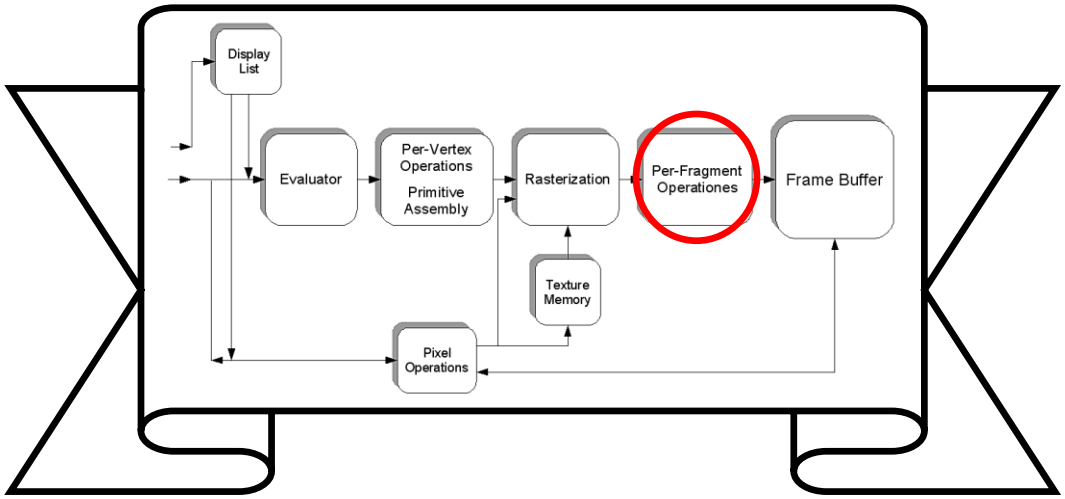


Rasterization

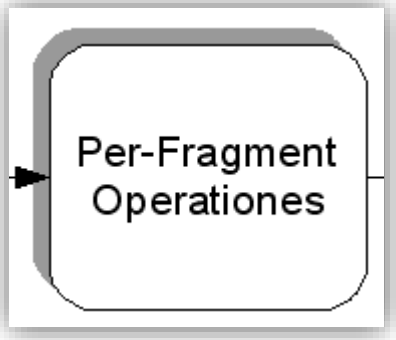


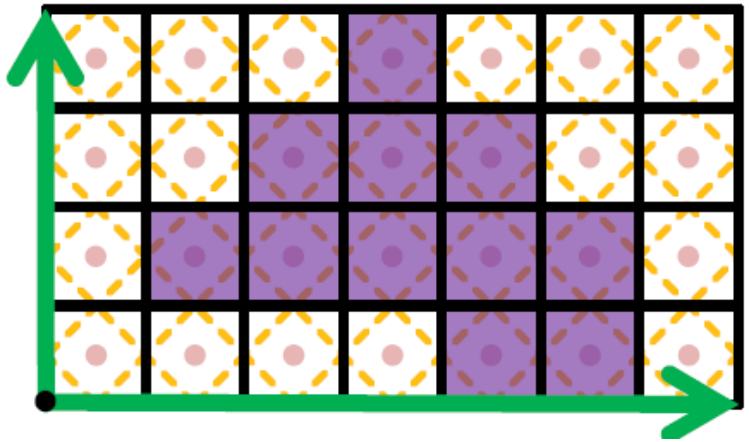


Pieces of OpenGL Pipeline

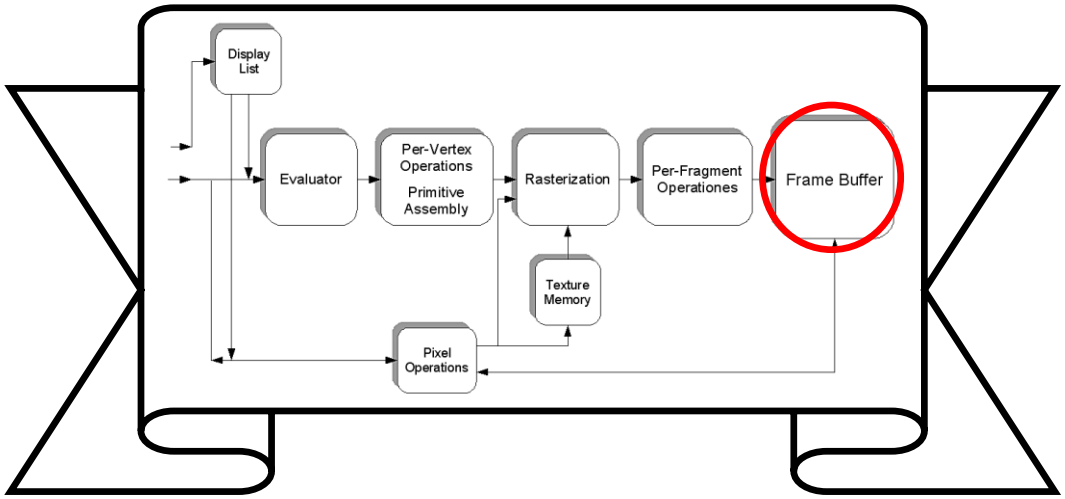


Modify and combine per-pixel information

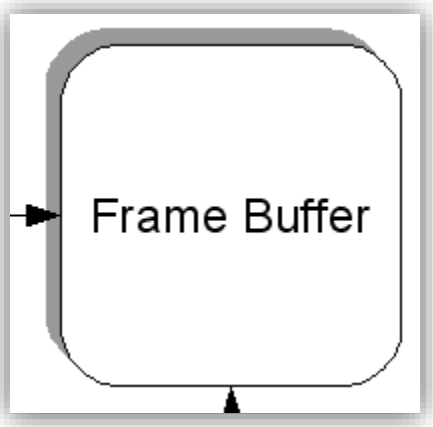


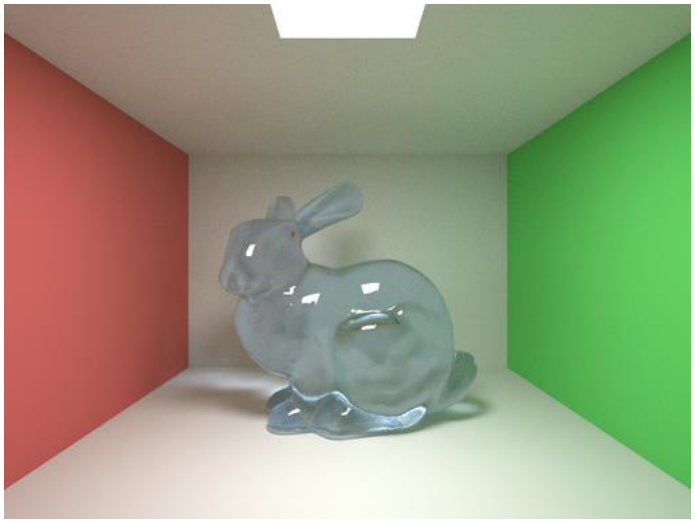


Pieces of OpenGL Pipeline



Prepare image to be displayed





Related API

- **opengl32.lib (OpenGL Kernel Library)**
  - Part of OpenGL
  - Use the prefix of gl (ex: glBegin())
- **GLU (OpenGL Utility Library)**
  - Part of OpenGL
  - Use the prefix of glu (ex: gluLookAt())
- **GLUT (OpenGL Utility Toolkit)**
  - Not officially part of OpenGL
  - Provide common features for window system
  - create window, mouse and keyboard, menu, event-driven
  - Lack of modern GUI support (e.g. scroller)
  - Use the prefix of glut (ex: glutDisplayFunc())
- **GLUI (on top of GLUT)**
  - C++ interface library
  - Provide buttons, checkboxes, radio buttons etc.

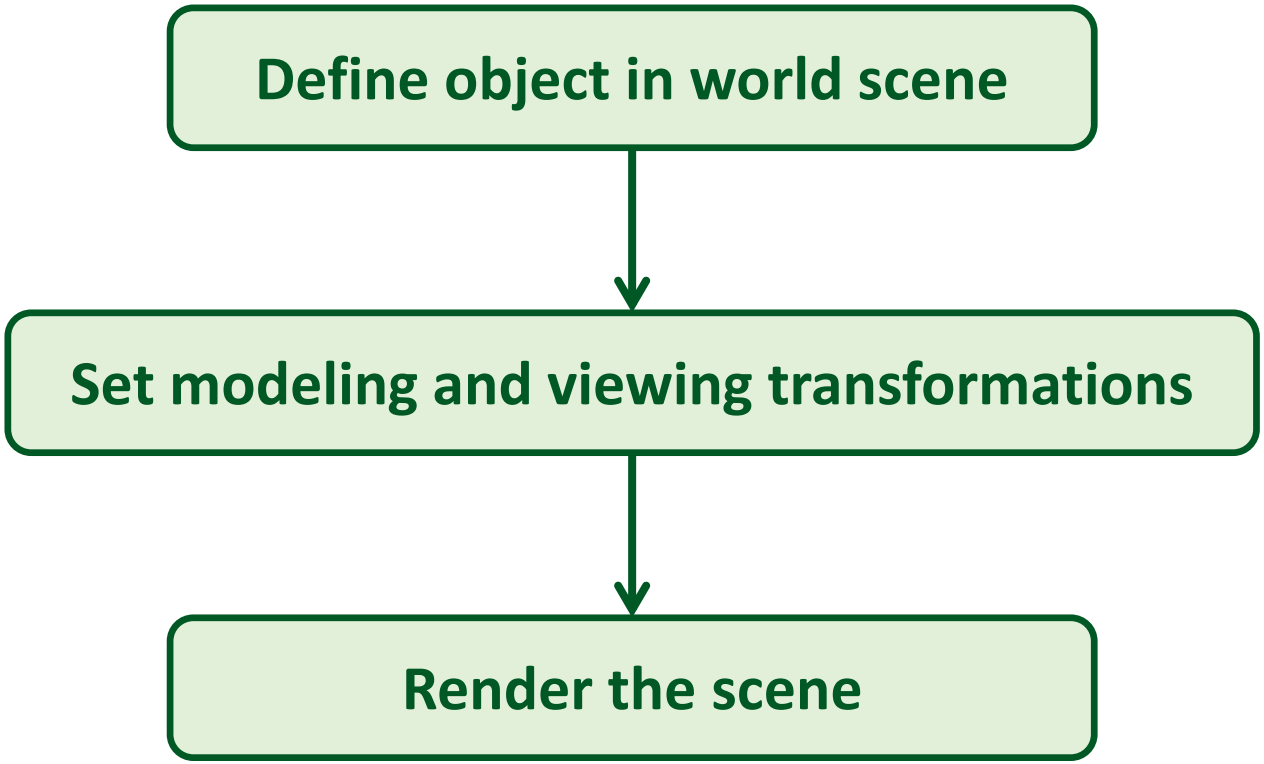
Installing GLUT - The OpenGL Utility Toolkit

- On Windows:
  - Download from OpenGL website:
  - https://www.opengl.org/resources/libraries/glut/glut_downloads.php
  - glut-3.7.6-bin has the dll/lib/header that are required
  - Copy glut.dll to {Windows DLL dir}\glut32.dll
  - Copy glut.lib to {VC++ lib path}\glut32.lib
  - Copy glut.h to {VC++ include path}\GL\glut.h

Using GLUT

- Only need to include glut.h
  - #include <GL\glut.h>
  - Automatically includes gl.h and glu.h
- Lighthouse3D has a good GLUT tutorial
  - http://www.lighthouse3d.com/tutorials/

Stages in OpenGL



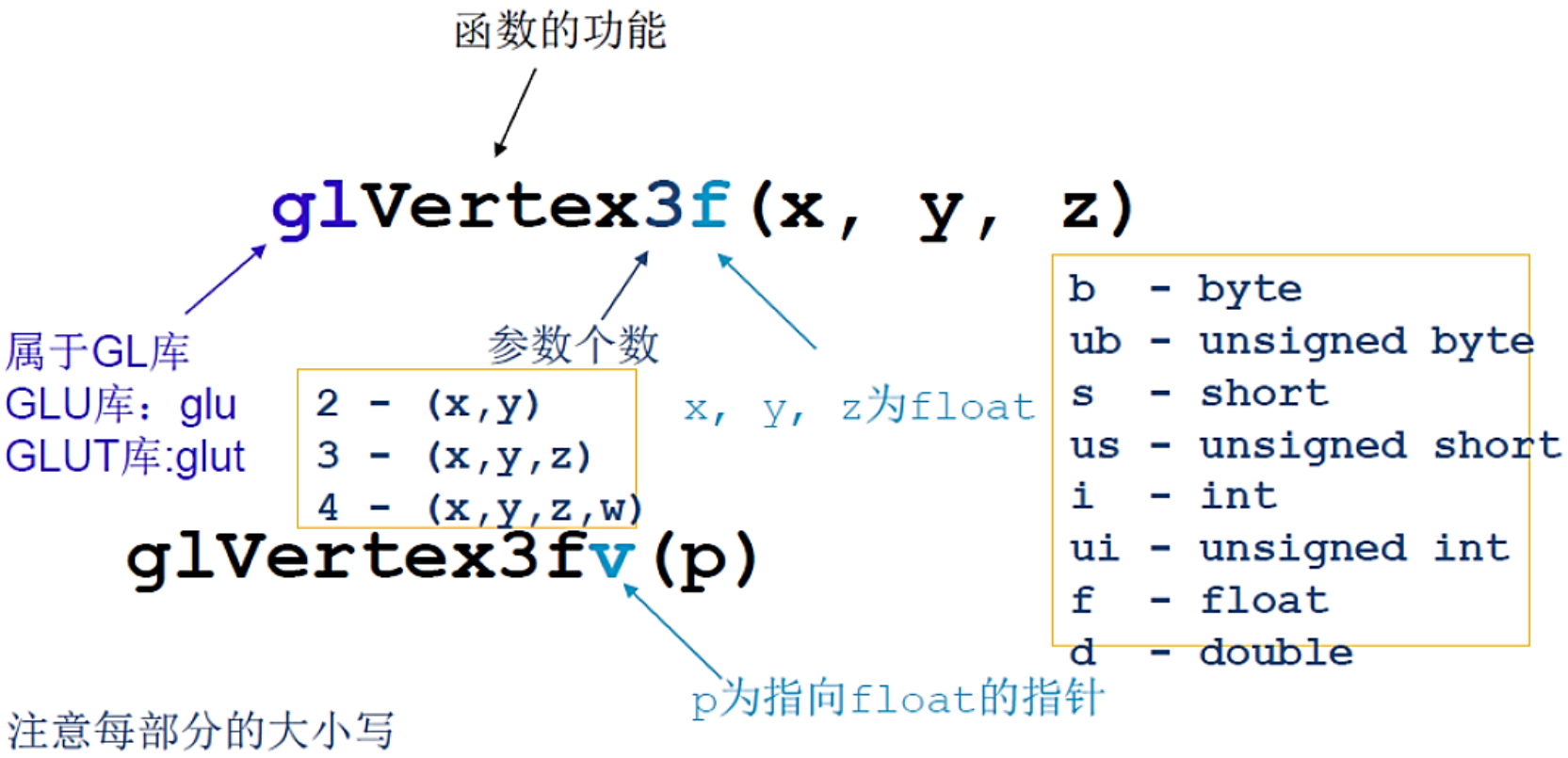
How OpenGL Works

- OpenGL is a state machine
  - You give it orders to set the current state of any one of its internal variables, or to query for its current status
  - The current state won't change until you specify otherwise
  - Each of the system's state variables has a default value

Functions of OpenGL

- Primitive - WHAT - Point, Edge, Polygon
- Attribute - HOW
- Transformation - Viewing & Modeling
- Input - provided by GLUT
- Control - provided by GLUT
- Query

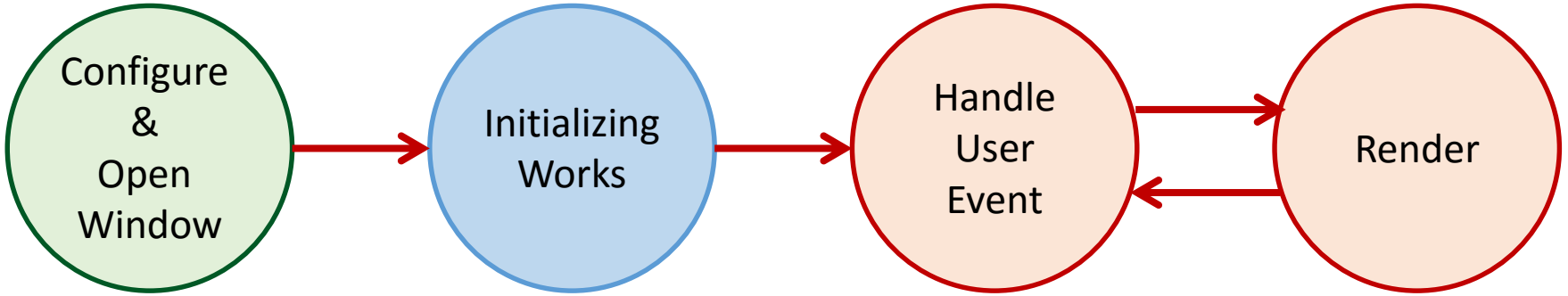
Function Format of OpenGL



OpenGL Hello World

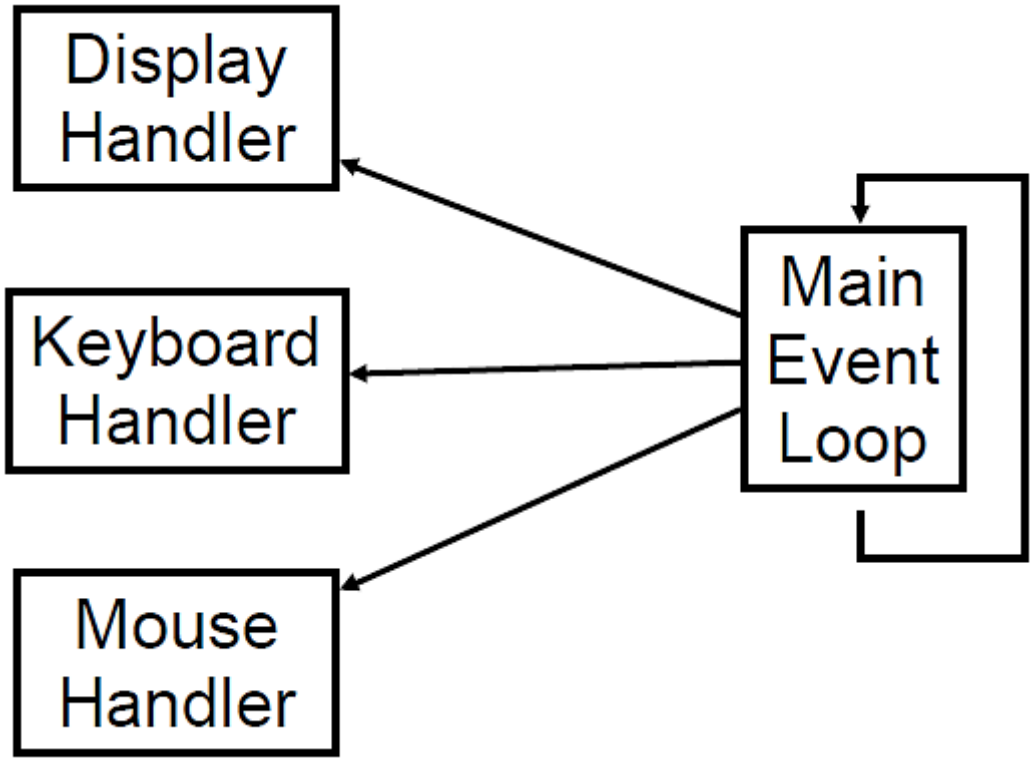
- Prerequisite
- Head Files:
  - #include <GL/gl.h>
  - #include <GL/glu.h>
  - #include <GL/glut.h>
- Library Files:
  - Compiled files folder\opengl32.lib glu32.lib glut32.lib
  - C:\Windows\System32\opengl32.dll glu32.dll glut32.dll

Basic Structure Of OpenGL Program



- NOT Object-Oriented!!
- Use states to control
- Infinite Loop

Event Driven Programming



2D demo

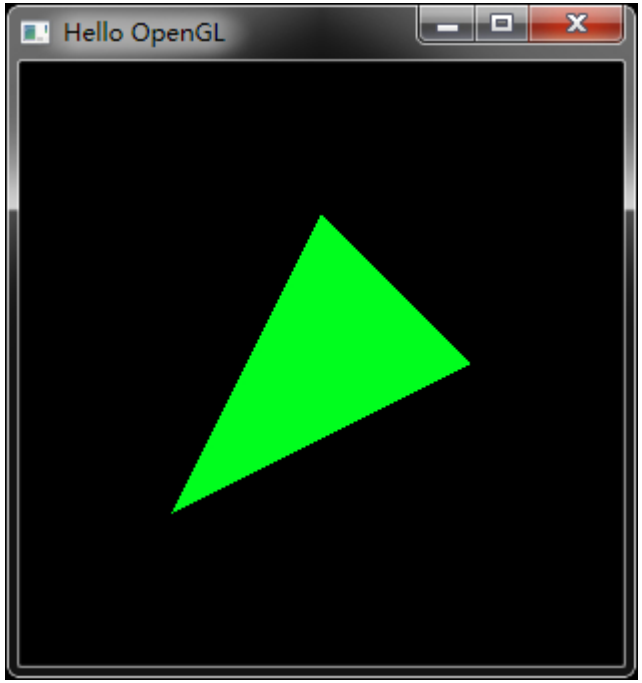
```
#include<gl/glut.h>

void renderScene(void)
{
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
    glBegin(GL_TRIANGLES);
    glColor3f(0.0f, 1.0f, 0.0f);
    glVertex3f(-0.5,-0.5,0.0);
    glVertex3f(0.5,0.0,0.0);
    glVertex3f(0.0,0.5,0.0);
    glEnd();
    glFlush();
}

int main(int argc, char *argv[])
{
    glutInit(&argc, argv);
    glutCreateWindow("Hello OpenGL");
    glutDisplayFunc(renderScene);
    glutMainLoop();
    return 0;
}
```

Less than 20 lines!

Not that HARD



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    glVertex3f(0.5,0.0,0.0);
    glVertex3f(0.0,0.5,0.0);
    glEnd();
    glFlush();
}

int main(int argc, char *argv[])
{
    glutInit(&argc, argv);
    glutCreateWindow("Hello OpenGL");
    glutDisplayFunc(renderScene);
    glutMainLoop();
    return 0;
}
```

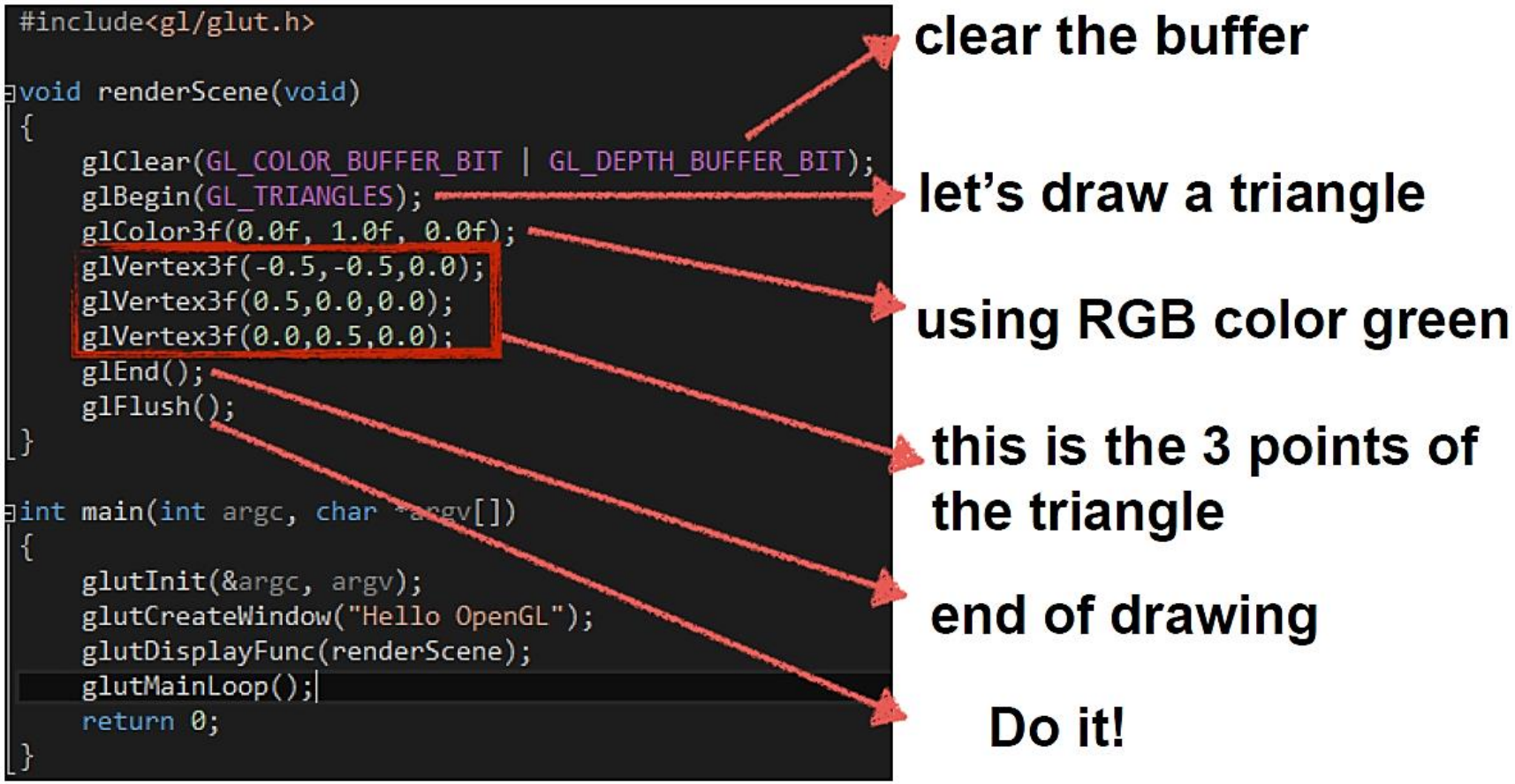
initialise GLUT

create window with title

tell the program how to redraw the window (callback)

Event Handler Loops

2D demo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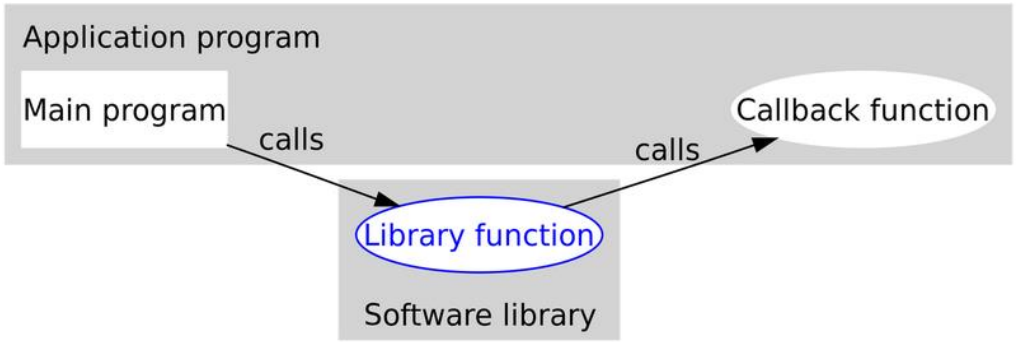
glVertex3f(0.5,0.0,0.0);
glVertex3f(0.0,0.5,0.0);
glEnd();
glFlush();
}
int main(int argc, char *argv[])
{
glutInit(&argc, argv);
glutCreateWindow("Hello OpenGL");
glutDisplayFunc(renderScene);
glutMainLoop();
return 0;
}
clear the buffer
let's draw a triangle
using RGB color green
this is the 3 points of the triangle
end of drawing
Do it!

Structure of GLUT-Assisted Programs

- GLUT relies on user-defined callback functions, which it calls whenever some event occurs
  - Function to display the screen
  - Function to resize the viewport
  - Functions to handle keyboard and mouse events

Callbacks

- Wiki: In computer programming, a callback is a reference to a piece of executable code, that is passed as an argument to other code. This allows a lower-level software layer to call a subroutine (or function) defined in a higher-level layer.
- Usage
  - Callbacks allow the user of a function to fine-tune it at runtime, another use is in error signaling.
  - Callbacks may also be used to control whether a function acts or not.
- In C/C++: function pointer



Callbacks

- Typically, the **main thread** will **just run in a loop**, **waiting for events to occur** - for example, for the user to move his mouse in your window, or click one of your buttons.
- The GUI framework will provide a mechanism for you **to pass it function pointers**, which it will then associate with certain events. When an event occurs, the event loop will invoke any callback functions you've provided for that event.
- Often, the callback function will **have parameters**, and the event dispatcher (事件调度器) will **provide you with extra information** about the event (perhaps the exact x,y coordinates of the mouse, for example) through the arguments it calls your callback function with.

Display Callback

Called when window is redrawn

```
void redraw()
{
  glClear(GL_COLOR_BUFFER_BIT);

  glBegin(GL_QUADS);
  glColor3f(1, 0, 0);
    glVertex3f(-0.5,  0.5, 0.5);
    glVertex3f( 0.5,  0.5, 0.5);
    glVertex3f( 0.5, -0.5, 0.5);
    glVertex3f(-0.5, -0.5, 0.5);
  glEnd(); // GL_QUADS

  glutSwapBuffers();
}
```

Reshape Callback

Called when the window is resized

```
void reshape(int w, int h)
{
   glViewport(0.0,0.0,w,h);

   glMatrixMode(GL_PROJECTION);
   glLoadIdentity();
   glOrtho(0.0,w,0.0,h, -1.0, 1.0);

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

Mouse Callback

Called when the mouse button is pressed

```
void mousebutton(int button, int state, int x, int y)
{
   if (button==GLUT_LEFT_BUTTON && state==GLUT_DOWN)
   {
      rx = x; ry = winHeight – y;
   }
}
```

Called when the mouse is moved with button down

```
void motion(int x, int y)
{
   rx = x; ry = winHeight – y;
}
```

Closing the program

- There is no idea to close the current program by OpenGL in previous programs.
- However, we can do the close operation by simple mouse callback.

```
void mouse(GLint btn, GLint state, GLint x, GLint y)
{
   if (btn == GLUT_RIGHT_BUTTON && state == GLUT_DOWN)
       exit(0);
}
```

Keyboard Callback

Called when a button is pressed

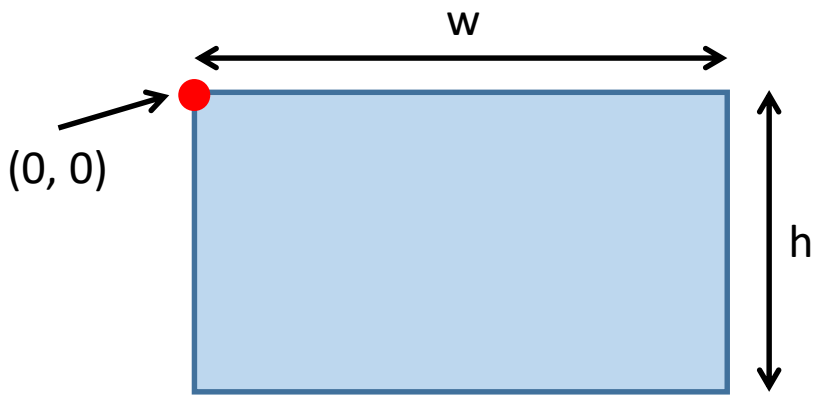
```
void keyboardCB(unsigned char key, int x, int y)
{
  switch(key)
  { case 'a': cout<<"a Pressed"<<endl; break; }
}
```

Called when a special button is pressed

```
void special(int key, int x, int y)
{
  switch(key)
  { case GLUT_F1_KEY:
     cout<<“F1 Pressed"<<endl; break; }
}
```

Position (定位)

- The position on the screen is usually in pixels and the origin is in the upper left corner
  - The display is in a top-down manner to refresh the display
- A World Coordinate in OpenGL application，its origin in the lower left corner
  - **y := h - y**



Get the height of window

- To finish the change of y coordinate, we need to know the window size.
  - The height would be changed in the procedure of the program running.
  - Need a global variant to track the changing.
  - The new height will return a callback function for shape changing.
  - Also use the glGetIntv() and glGetFloat() to obtain.

OpenGL - GLUT Example

```
#include <gl/glut.h>
#include <stdlib.h>
static GLfloat spin = 0.0;
void init( void )
{
  glClearColor( 0.0, 0.0, 0.0, 0.0 );
  glShadeModel( GL_FLAT );
}
```

```
void display( void )
{
glClear( GL_COLOR_BUFFER_BIT );
glPushMatrix();
glRotatef( spin, 0.0, 0.0, 1.0 );
glColor3f( 1.0, 1.0, 1.0 );
glRectf( -25.0, -25.0, 25.0, 25.0 );
glPopMatrix();
glutSwapBuffers();
}
```

OpenGL - GLUT Example

```
void spinDisplay( void )
{
    spin += 2.0;
    if( spin > 360.0 )
     spin -= 360.0;
    glutPostRedisplay();
}
```

```
void reshape( int w, int h )
{
    glViewport( 0, 0, (GLsizei) w, (GLsizei)
    h );
    glMatrixMode( GL_PROJECTION );
    glLoadIdentity();
    glOrtho( -50.0, 50.0, -50.0, 50.0, -1.0, 1.0 );
    glMatrixMode( GL_MODELVIEW );
    glLoadIdentity();
}
```

OpenGL - GLUT Example

```
void mouse( int button, int state, int x, int y )
{
    switch( button )
    {
     case GLUT_LEFT_BUTTON:
            if( state == GLUT_DOWN )
                glutIdleFunc( spinDisplay );
            break;
     case GLUT_RIGHT_BUTTON:
            if( state == GLUT_DOWN )
                glutIdleFunc( NULL );
            break;
     default:    break;
    }
}
```

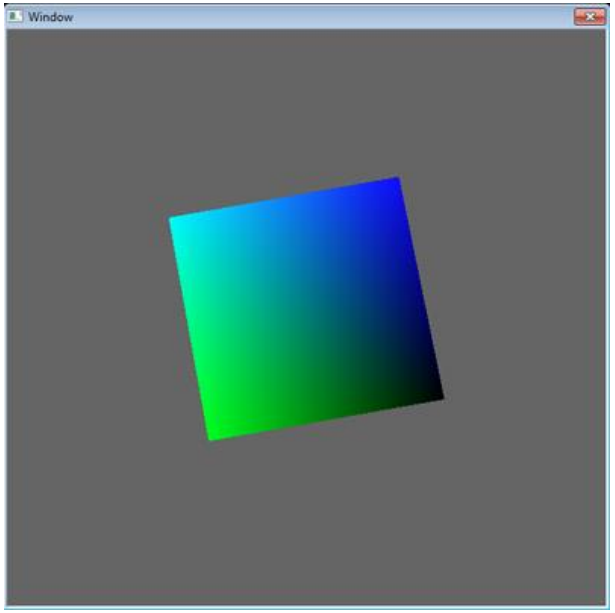
```
int main( int argc, char ** argv )
{
    glutInit( &argc, argv );
    glutInitDisplayMode( GLUT_DOUBLE | GLUT_RGB );
    glutInitWindowSize( 250, 250 );
    glutInitWindowPosition( 100, 100 );
    glutCreateWindow( argv[ 0 ] );

    init();
    glutDisplayFunc( display );
    glutReshapeFunc( reshape );
    glutMouseFunc( mouse );
    glutMainLoop();
    return 0;
}
```

Details of OpenGL Program

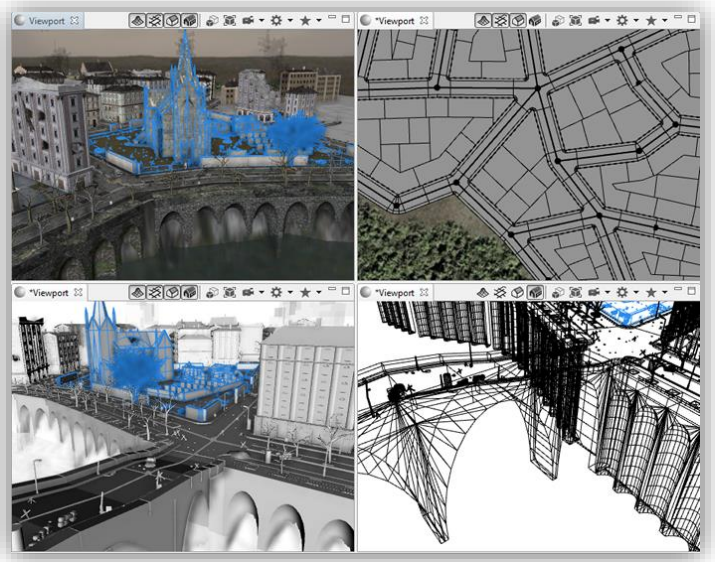
Contexts and Viewports?

- Each OpenGL application creates a context to issue rendering commands to.
- The application must also define a viewport, a region of pixels on the screen that can see the context.
- Can be
  - Part of a window
  - An entire window
  - The whole screen



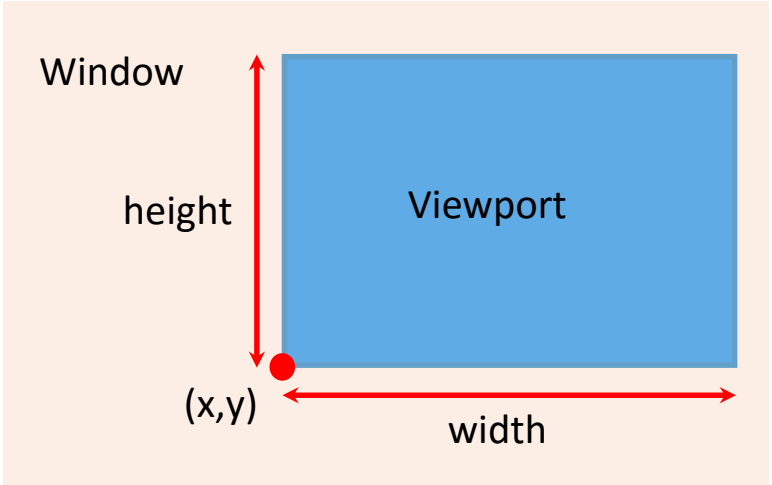
Viewport

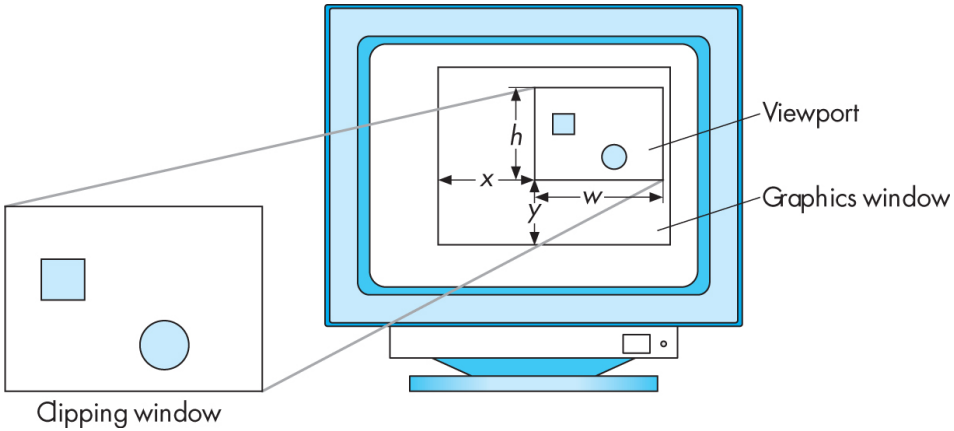
- The viewport is the part of the window your drawing is displayed to
  - By default, the viewport is the entire window
- Modifying the viewport is analogous to changing the size of the final picture
  - From the camera analogy
- Can have multiple viewports in the same window for a split-screen effect



Setting the Viewport

- glViewport(int x, int y, int width, int height)
  - (x, y) is the location of the origin (lower-left) within the window
  - (width, height) is the size of the viewport
- The aspect ratio of the viewport should be the **same** as that of the viewing volume



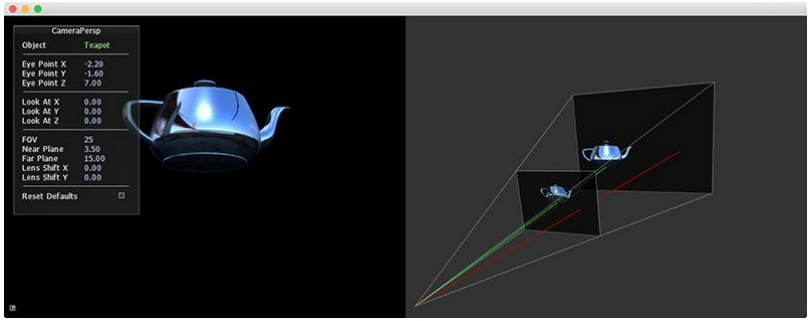


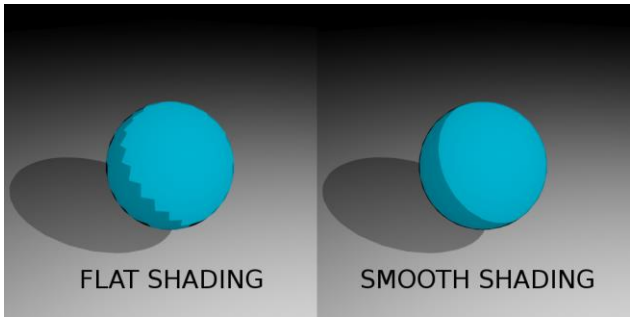
OpenGL as a State Machine

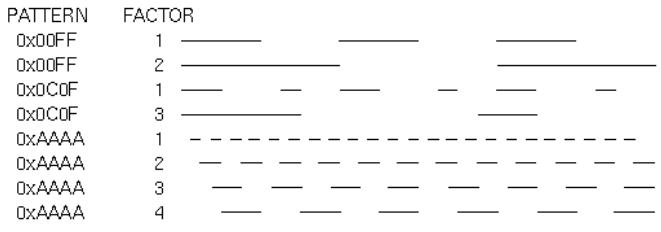
- Put a value into various states, then it will remain in effect until being changed.
  - e.g. glColor*()
- Many state variables are enabled or disabled with glEnable(), glDisable()
  - e.g. glEnable(GL_LIGHT0)

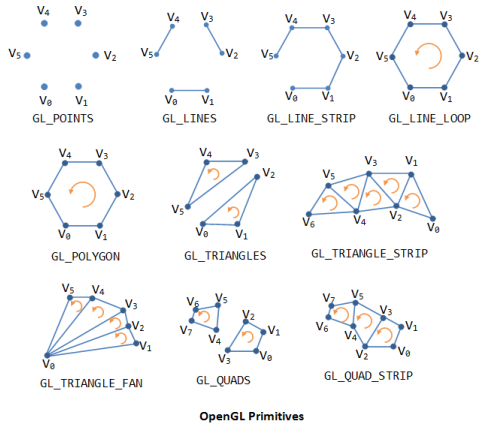
OpenGL State

- Some attributes of the OpenGL state
  - Current color
  - Camera properties (location, orientation, field of view, etc.)
  - Lighting model (flat, smooth, etc.)
  - Type of primitive being drawn
  - Line width, dotted line or full line,…
  - And many more...









OpenGL Input

- All inputs (i.e. geometry) to an OpenGL context are defined as vertex lists
- glVertex (*)
  - * = nt OR ntv
  - n - number (2, 3, 4)
  - t - type (i = integer, f = float, etc.)
  - v - vector

OpenGL Types

Suffix	Data Type	Typical Corresponding C-Language Type	OpenGL Type Definition
b	8-bit integer	signed char	GLbyte
s	16-bit integer	short	GLshort
i	32-bit integer	long	GLint, GLsizei
f	32-bit floating-point	float	GLfloat, GLclampf
d	64-bit floating-point	double	GLdouble, GLclampd
ub	8-bit unsigned integer	unsigned char	GLubyte, GLboolean
us	16-bit unsigned integer	unsigned short	GLushort
ui	32-bit unsigned integer	unsigned long	GLuint, GLenum, GLbitfield

OpenGL Input

- Examples:
  - glVertex2i(5, 4);
    - Specifies a vertex at location (5, 4) on the z = 0 plane
    - “2” tells the system to expect a 2-vector (a vertex defined in 2D)
    - “i” tells the system that the vertex will have integer locations

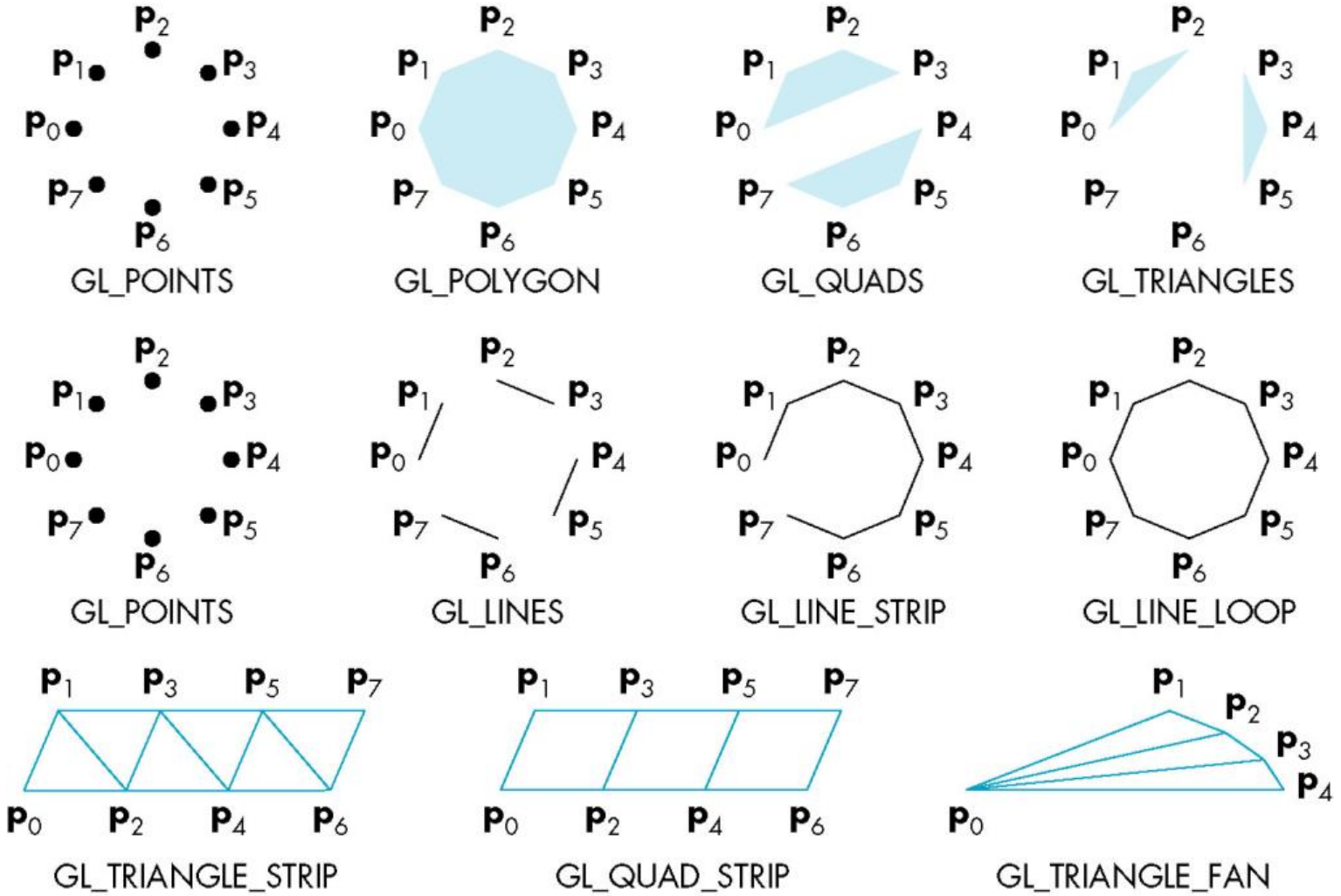
OpenGL Input

- More examples:
  - glVertex3f(.25, .25, .5);
  - double vertex[3] = {1.0, .33, 3.14159};
    glVertex3dv(vertex);
    - “v” tells the system to expect the coordinate list in a single data structure, instead of a list of n numbers

OpenGL Primitive Types

- All geometry is specified by vertex lists
  - But can draw multiple types of things
    - Points
    - Lines
    - Triangles
    - etc.
- The different things the system knows how to draw are the system **primitives**

OpenGL Primitive Types



Specifying the OpenGL Primitive Type

- glBegin(primitiveType);

  // A list of glVertex* calls goes here

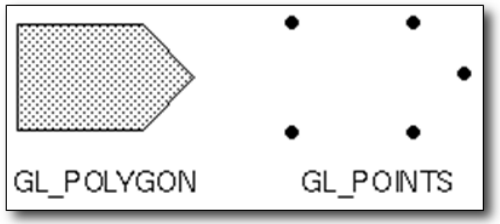
  // ...

  glEnd();

- primitiveType can be any of several things

```
glBegin(GL_POLYGON);
  glVertex2f(0.0, 0.0);
  glVertex2f(0.0, 3.0);
  glVertex2f(3.0, 3.0);
  glVertex2f(4.0, 1.5);
  glVertex2f(3.0, 0.0);
glEnd();
```

```
glBegin(GL_POINTS);
  glVertex2f(0.0, 0.0);
  glVertex2f(0.0, 3.0);
  glVertex2f(3.0, 3.0);
  glVertex2f(4.0, 1.5);
  glVertex2f(3.0, 0.0);
glEnd();
```



Color in OpenGL

- OpenGL colors are typically defined as RGB components
  - each of which is a float in the range [0.0, 1.0]

- For the screen's background:
  - glClearColor(0.0, 0.0, 0.0); // black color
  - glClear(GL_COLOR_BUFFER_BIT);
- For objects:
  - glColor3f(1.0, 1.0, 1.0); // white color

- GLUT_RGB and GLUT_RGBA
- alpha channel

- glColor3f (1.0, 1.0, 1.0);
- glColor3i (0, 255, 255);
- glColor3fv (colorArray);

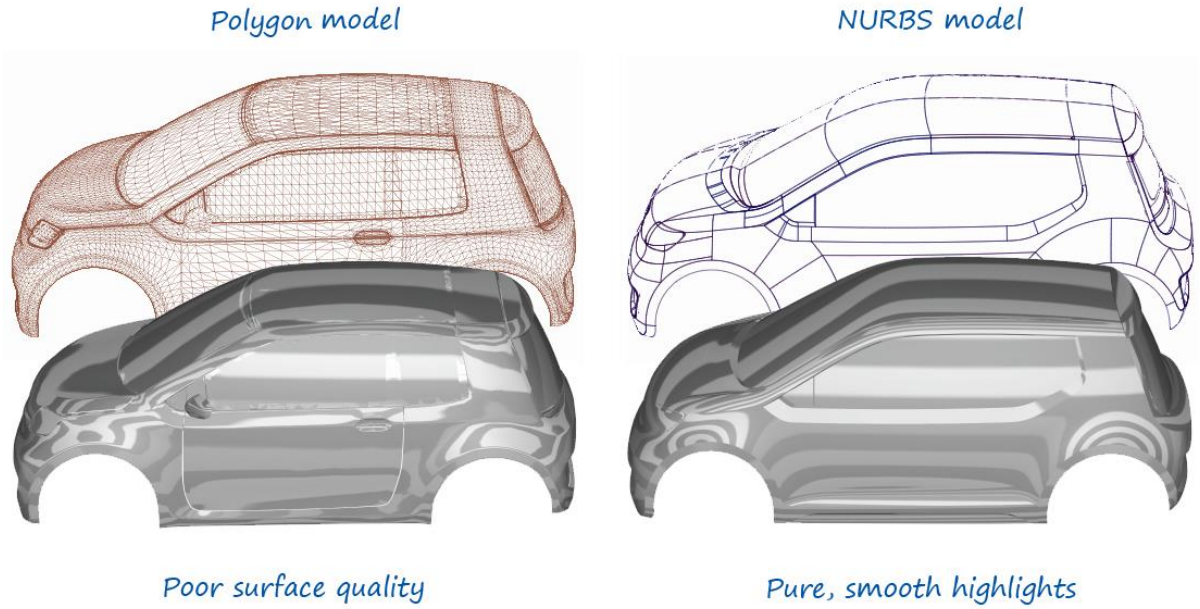
Polygon Display Modes

- glPolygonMode(GLenum face, GLenum mode);
  - Faces: GL_FRONT, GL_BACK, GL_FRONT_AND_BACK
  - Modes: GL_FILL, GL_LINE, GL_POINT
  - By default, both the front and back face are drawn filled
- glFrontFace(GLenum mode);
  - Mode is either GL_CCW (default) or GL_CW
- glCullFace(Glenum mode);
  - Mode is either GL_FRONT, GL_BACK, GL_FRONT_AND_BACK;
- You must enable and disable culling with
  - glEnable(GL_CULL_FACE) or glDisable(GL_CULL_FACE);

Drawing Other Objects

- GLU contains calls to draw cylinders, cons, and more complex surfaces called NURBS.

- GLUT contains calls to draw spheres and cubes.



Finishing Up Your OpenGL Program

- OpenGL commands are not executed immediately
  - They are put into a command buffer that gets fed to the hardware
- When you're done drawing, need to send the commands to the graphics hardware
  - –glFlush() or glFinish()

glFlush vs. glFinish

- glFlush();
  - Forces all issued commands to begin execution
  - Returns immediately (asynchronous)
- glFinish();
  - Forces all issued commands to begin execution
  - Does not return until execution is complete (synchronous)

Matrices in OpenGL

- Vertices are transformed by 2 matrices:
  - **ModelView**
    - Maps 3D to 3D
    - Transforms vertices from object coordinates to eye coordinates
  - **Projection**
    - Maps 3D to 2D (sort of)
    - Transforms vertices from eye coordinates to screen coordinates

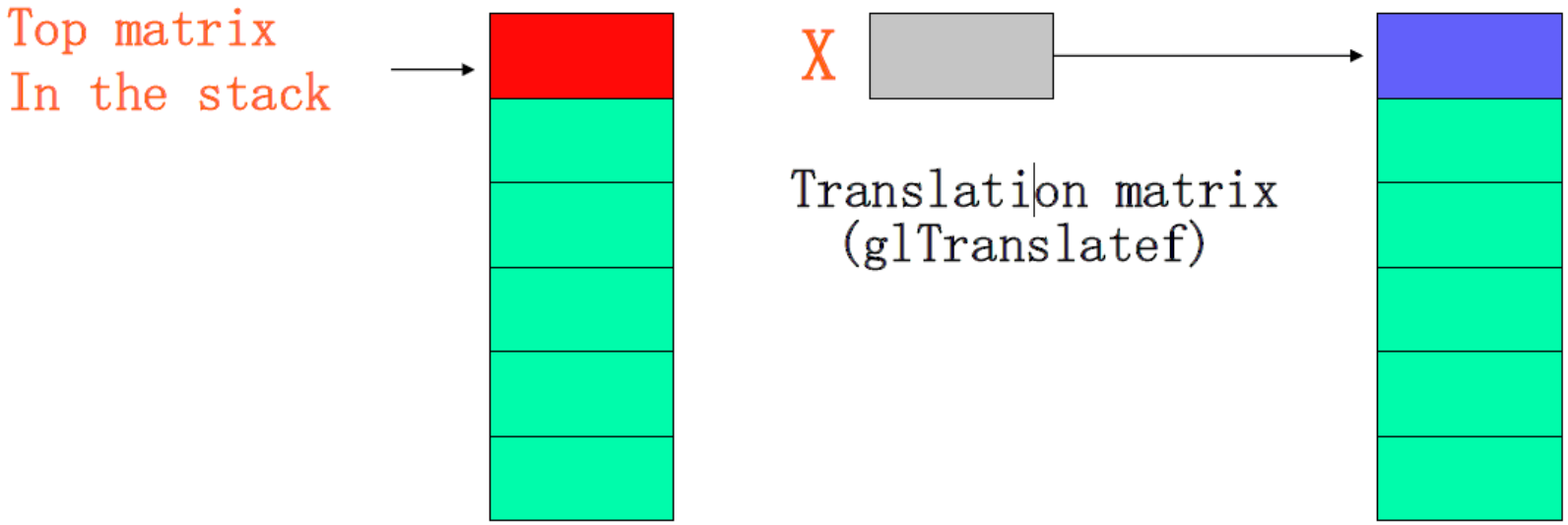
Matrix in OpenGL

- There are two matrix stacks.
  - ModelView matrix (GL_MODELVIEW)
  - Projection matrix (GL_PROJECTION)
- When we call functions of transformation, we should change to the appropriate matrix stack first.

```
glMatrixMode(GL_MODELVIEW);
//now we are in modelview matrix stack!
//do modelview transformation here…..
glMatrixMode(GL_PROJECTION);
//now we are in projection matrix stack!
//do projection transformation here….
```

Matrix in OpenGL

- Matrix multiplications always apply to the top of matrix stack.



WARNING! OpenGL Matrices

- In C/C++, we are used to row-major matrices
- In OpenGL, matrices are specified in column-major order

$$\begin{bmatrix} A_0 & A_1 & A_2 & A_3 \\ A_4 & A_5 & A_6 & A_7 \\ A_8 & A_9 & A_{10} & A_{11} \\ A_{12} & A_{13} & A_{14} & A_{15} \end{bmatrix}$$

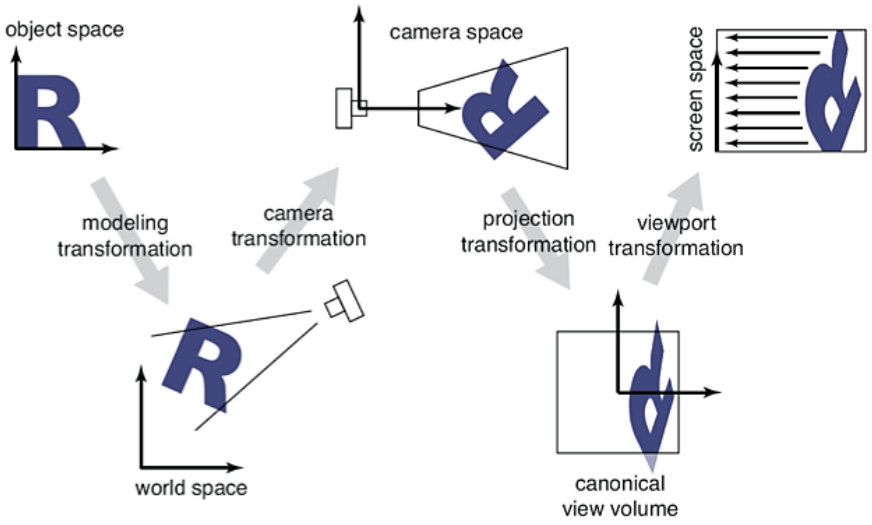
Row-Major Order

$$\begin{bmatrix} A_0 & A_4 & A_8 & A_{12} \\ A_1 & A_5 & A_9 & A_{13} \\ A_2 & A_6 & A_{10} & A_{14} \\ A_3 & A_7 & A_{11} & A_{15} \end{bmatrix}$$

Column-Major Order

The ModelView Matrix

- Modeling Transformation
  - Perform rotate, translate, scale and combinations of these transformations to the object.
- Viewing Transformation
  - To positioning and aiming the camera



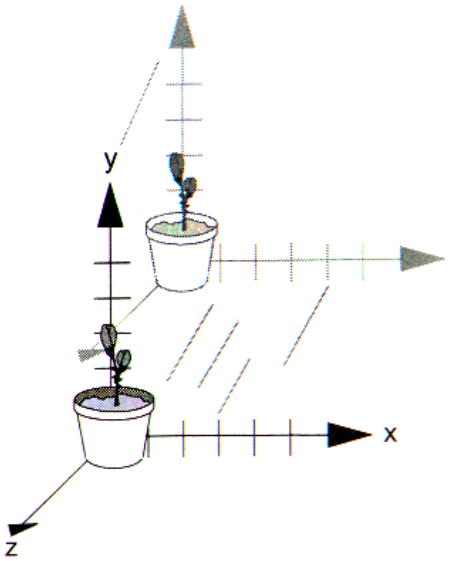
The ModelView Matrix

- In OpenGL, the viewing and modeling transforms are combined into a single matrix - the modelview matrix
  - Viewing Transform - positioning the camera
  - Modeling Transform - positioning the object
- Why?
  - Consider how you would “translate” a fixed object with a real camera

Modeling Transformations

- glTranslate{fd}(x, y, z)
  - Multiplies current matrix by a matrix that moves an object by x,y,z

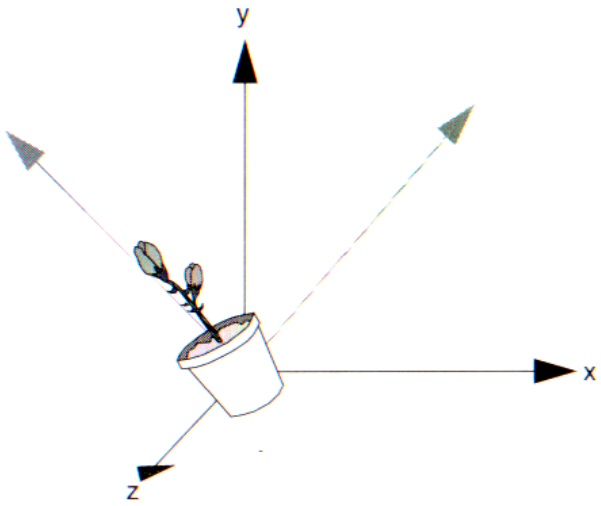
glTranslatef(0, 0, -1)



Modeling Transformations

- glRotate{fd}(angle, x, y, z)
  - Multiplies current matrix by a matrix that rotates an object in a counterclockwise direction about the ray from origin to (x,y,z) with angle as the degrees

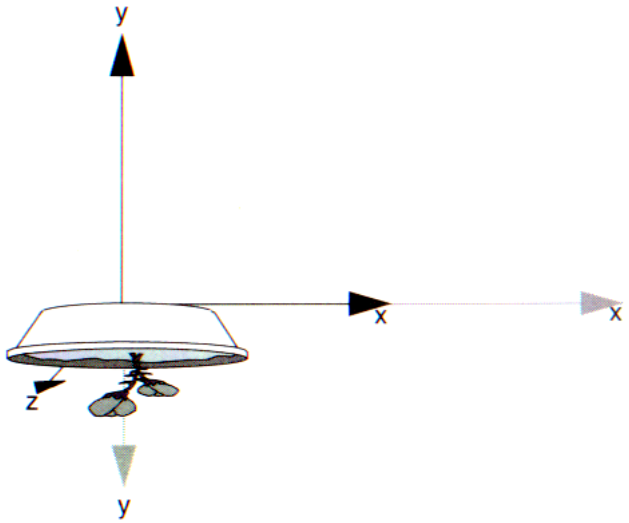
glRotatef(45.0, 0, 0, 1)



Modeling Transformations

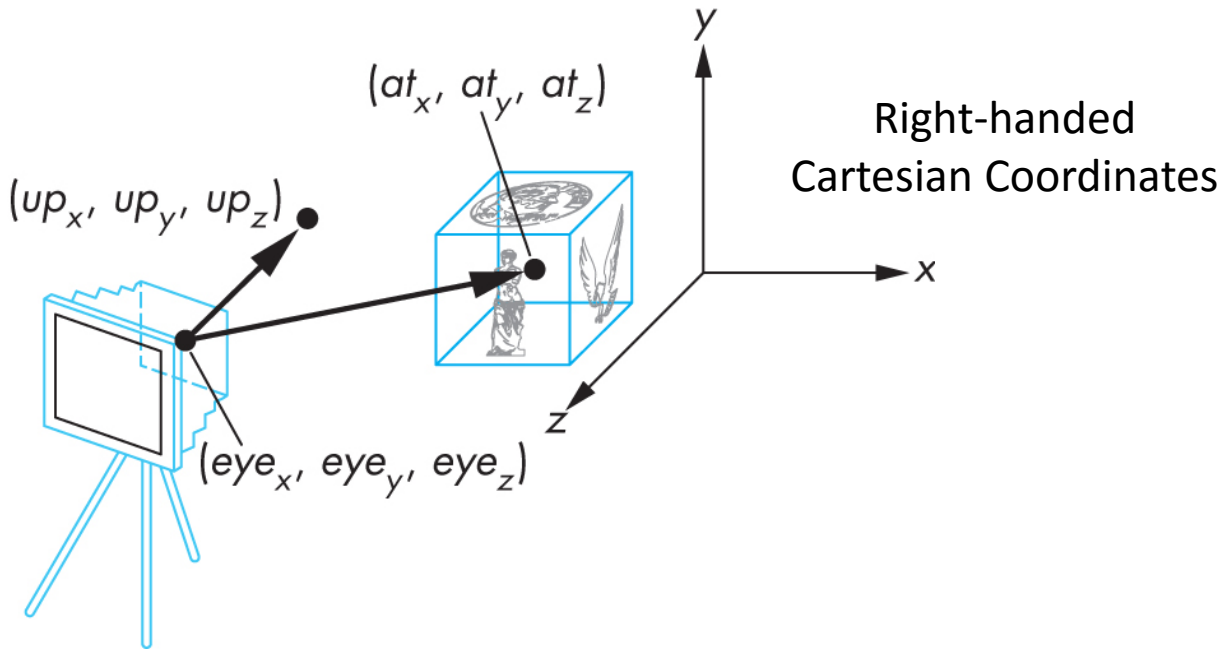
- glScale{fd} (x, y, z)
  - Multiplies current matrix by a matrix that scales an object along axes.

glScalef(2.0, -0.5, 1.0)



Viewing Transformations

- gluLookAt (eyex, eyey, eyez, atx, aty, atz, upx, upy, upz);
- By default the camera is at the origin, looking down negative z, and the up vector is the positive y axis



Using OpenGL Matrices

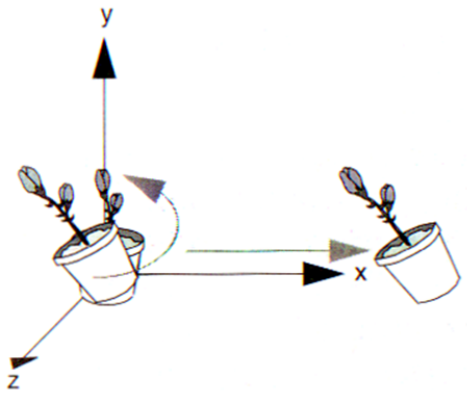
- **Use the following function to specify which matrix you are changing:**
  - glMatrixMode(whichMatrix): whichMatrix = GL_PROJECTION | GL_MODELVIEW
- **To guarantee a "fresh start", use glLoadIdentity():**
  - Loads the identity matrix into the active matrix
- **To load a user-defined matrix into the current matrix:**
  - glLoadMatrix{fd}(TYPE *m)
- **To multiply the current matrix by a user defined matrix:**
  - glMultMatrix{fd}(TYPE *m)
- SUGGESTION: To avoid row-/column-major confusion, specify matrices as m[16] instead of m[4][4]

Transforms in OpenGL

- OpenGL uses 4x4 matrices for all its transforms
  - But you don’t have to build them all by hand!
- glRotate{fd}(angle, x, y, z)
  - Rotates counter-clockwise by angle degrees about the vector (x, y, z)
- glTranslate{fd}(x, y, z)
- glScale{fd}(x, y, z)

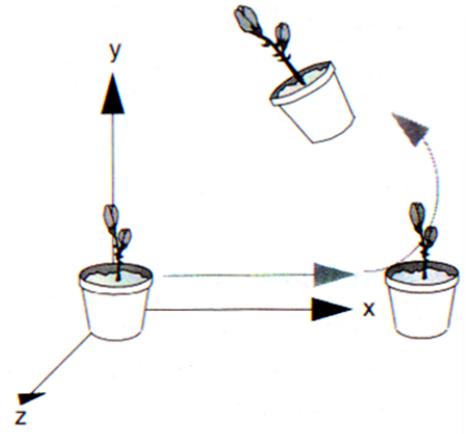
Order of Transforms

- In OpenGL, **the last** transform in a list is applied **FIRST**
  - Think back to right-multiplication of transforms



Rotate then Translate

```
glTranslatef( 1, 0, 0 );
glRotatef( 45.0, 0, 0, 1 );
drawObject();
```



Translate then Rotate

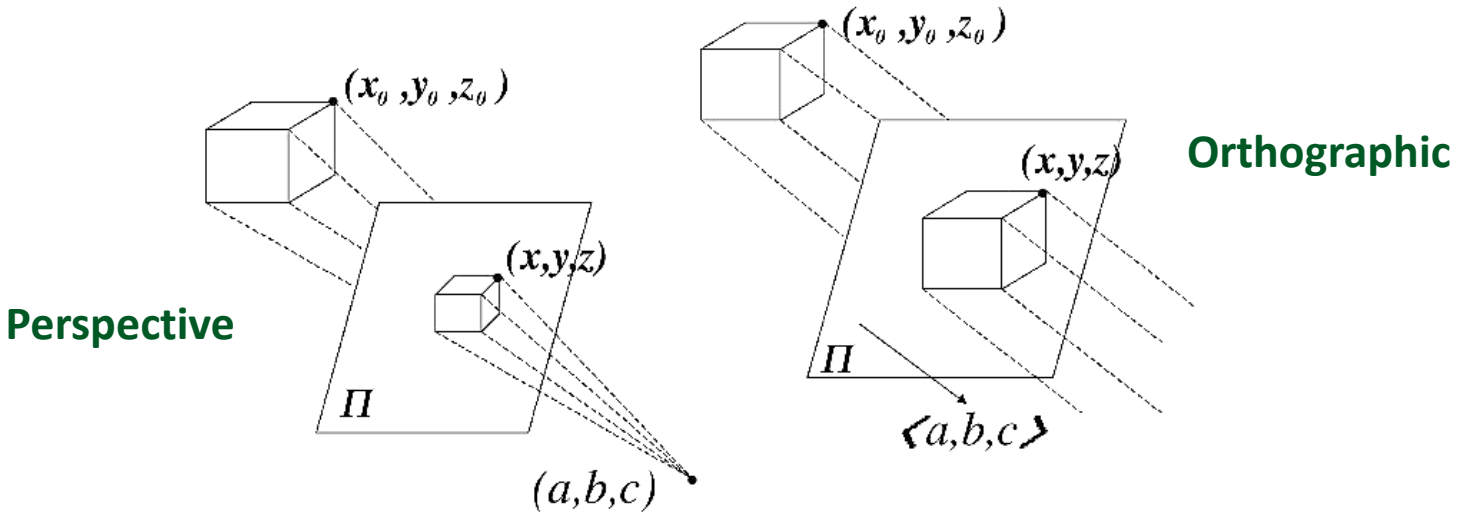
```
glRotatef( 45.0, 0, 0, 1 );
glTranslatef( 1, 0, 0 );
drawObject();
```

Projection Transforms

- The projection matrix defines the viewing volume
  - Used for 2 things:
    - Projects an object onto the screen
    - Determines how objects are clipped
- The viewpoint (the location of the “camera”) that we’ve been talking about is at one end of the viewing volume

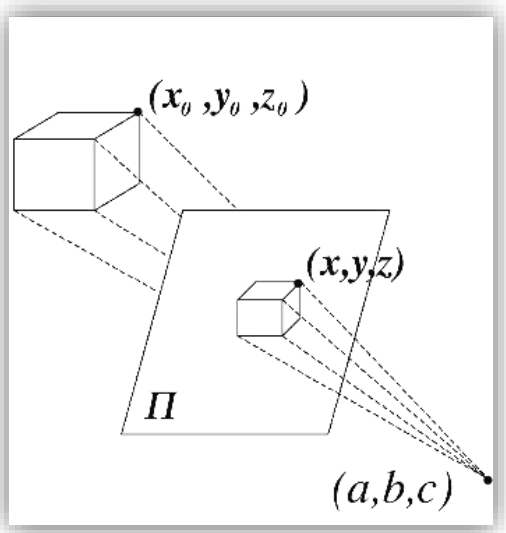
Projection Transform

- Perspective
  - Viewing volume is a truncated pyramid
    - aka frustum
- Orthographic
  - Viewing volume is a box



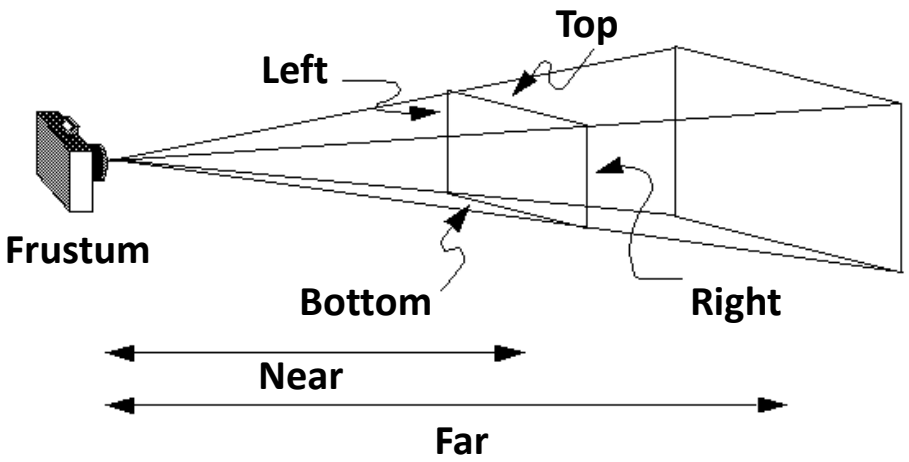
Perspective Projection

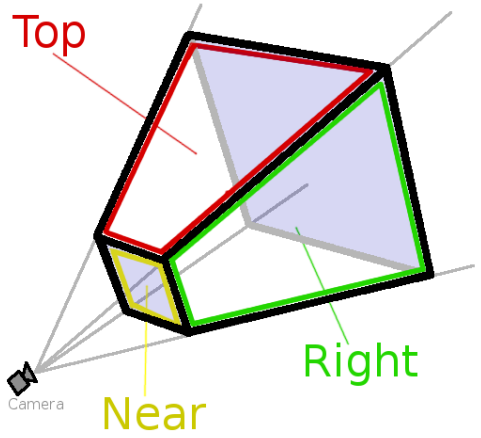
- The most noticeable effect of perspective projection is foreshortening
- OpenGL provides several functions to define a viewing frustum
  - glFrustum(...)
  - gluPerspective(...)



glFrustum (视锥体/视景体)

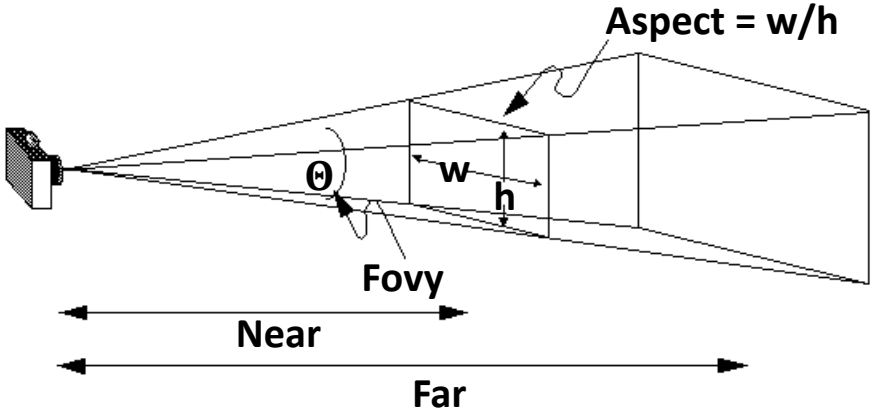
- glFrustum(GLdouble left, GLdouble right, GLdouble bottom, GLdouble top, GLdouble near, GLdouble far)
  - (left, bottom, -near) and (right, top, -near) are the bottom-left and top-right corners of the near clip plane
  - far is the distance to the far clip plane
  - near and far should always be positive





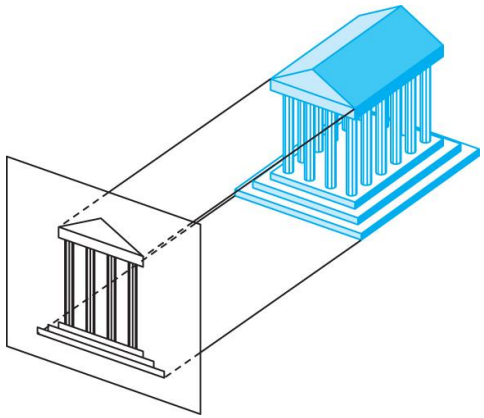
gluPerspective (透视图)

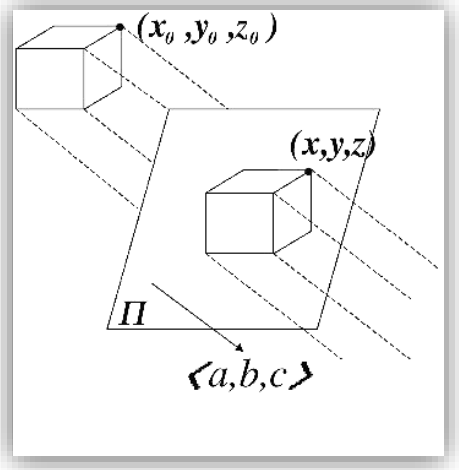
- This GL Utility Library function provides a more intuitive way (I think) to define a frustum
- gluPerspective(GLdouble fovy, GLdouble aspect, GLdouble near, GLdouble far)
  - fovy - field of view in y (in degrees)
  - aspect - aspect ratio (width / height)
  - near and far - same as with glFrustum()



Orthographic Projection

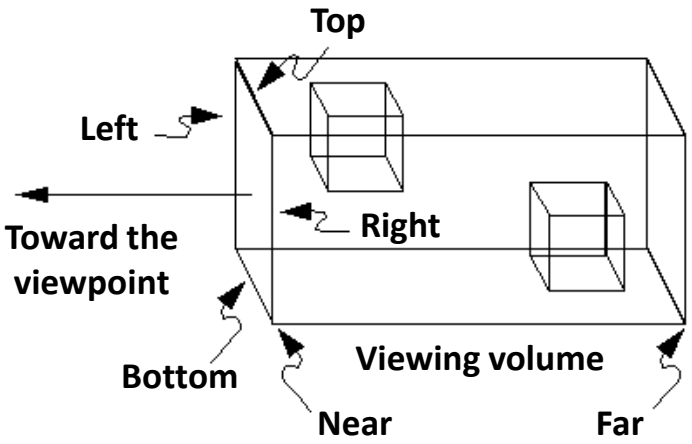
- With orthographic projection, there is no foreshortening (透视收缩)
  - Distance from the camera does not change apparent size
- Again, there are several functions that can define an orthographic projection
  - glOrtho()
  - gluOrtho2D()

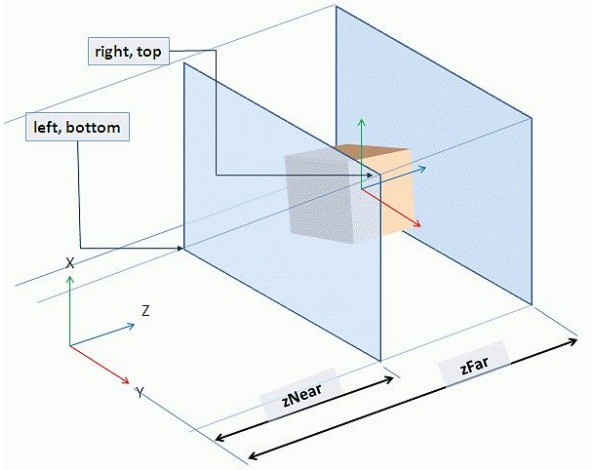




glOrtho

- glOrtho(GLdouble left, GLdouble right, GLdouble bottom, GLdouble top, GLdouble near, GLdouble far)
  - Arguments are the same as glPerspective()
  - (left, bottom, -near) and (right, top, -near) are the bottom-left and top-right corners of the near clip plane
  - near and far can be any values, but they should not be the same

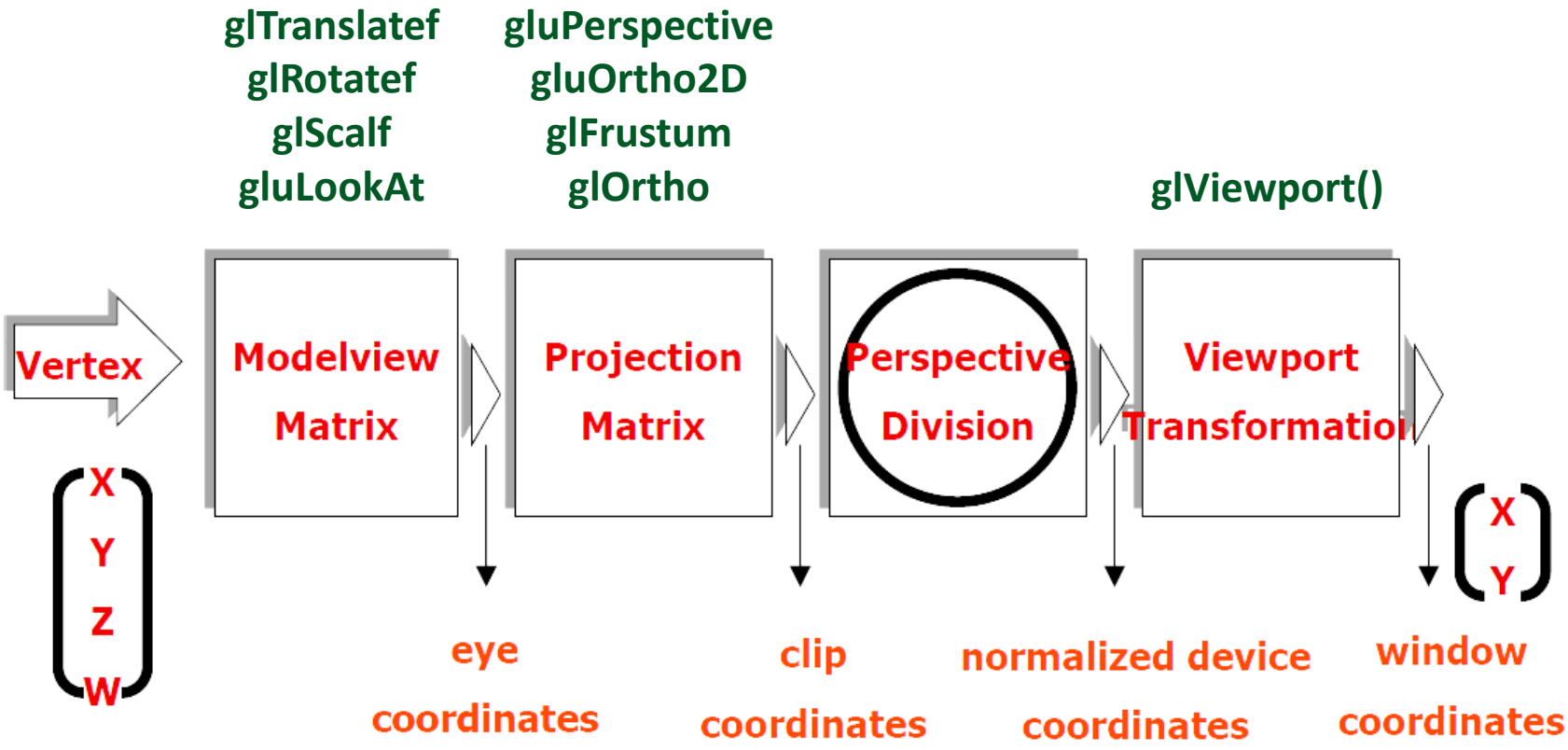




gluOrtho2D

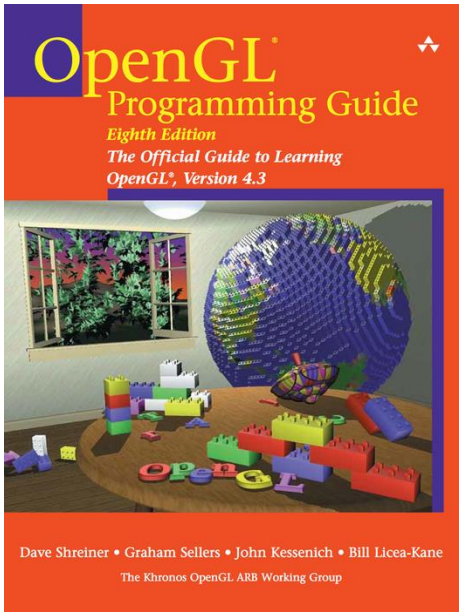
- This GL Utility Library function provides a more intuitive way (I think) to define a frustum
- gluOrtho2D(GLdouble left, GLdouble right, GLdouble bottom, GLdouble top)
  - (left, bottom) and (right, top) define the (x, y) coordinates of the bottom-left and top-right corners of the clipping region
  - Automatically clips to between -1.0 and 1.0 in z
- In 2D mode, frustum is equal to viewport

OpenGL Transformations



References

- OpenGL officially website:
  - http://www.opengl.org
- NeHe's OpenGL course (useful installation guides included)
  - http://www.yakergong.net/nehe/ (Chinese)
- The Red Book (OpenGL Programming Guide)



An PDF version is available online:

http://www.ics.uci.edu/~gopi/CS211B/opengl_programming_guide_8th_edition.pdf

FLTK

- Fast Light Toolkit
- Cross-Platform C++ GUI Toolkit
- Provides more full-featured UI functionality than GLUT
- Also supports GLUT code through emulation
- Download from http://www.fltk.org