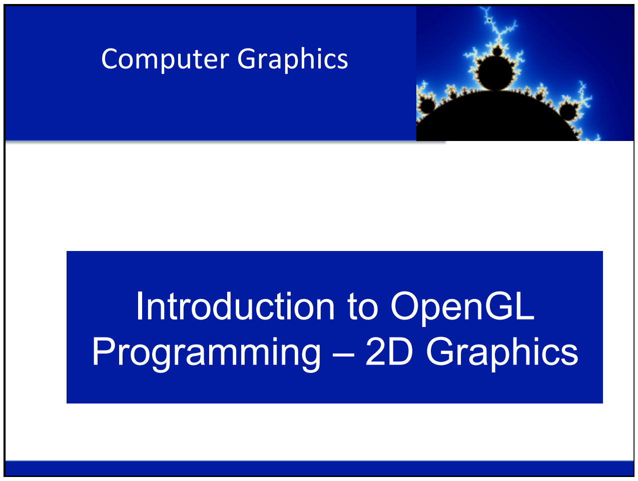
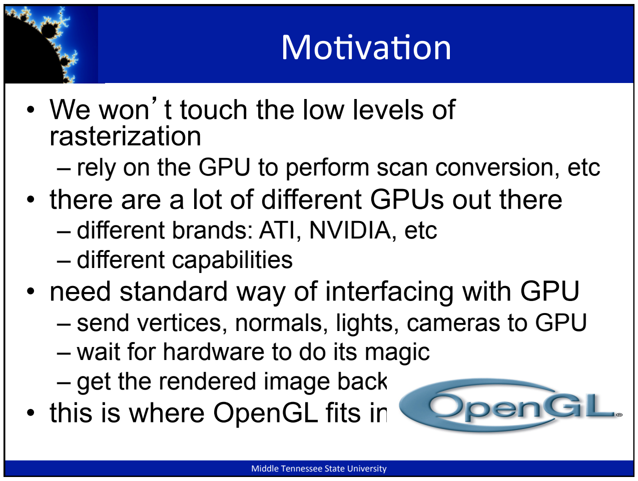


Computer Graphics

Introduction to OpenGL Programming – 2D Graphics



Motivation

- We won’t touch the low levels of rasterization
  - rely on the GPU to perform scan conversion, etc
- there are a lot of different GPUs out there
  - different brands: ATI, NVIDIA, etc
  - different capabilities
- need standard way of interfacing with GPU
  - send vertices, normals, lights, cameras to GPU
  - wait for hardware to do its magic
  - get the rendered image back
- this is where OpenGL fits in

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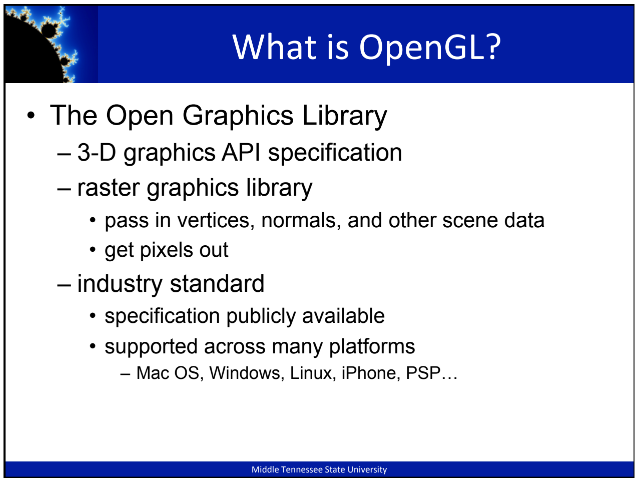

What is OpenGL?

- The Open Graphics Library
  - 3-D graphics API specification
  - raster graphics library
    - pass in vertices, normals, and other scene data
    - get pixels out
  - industry standard
    - specification publicly available
    - supported across many platforms
      - Mac OS, Windows, Linux, iPhone, PSP…

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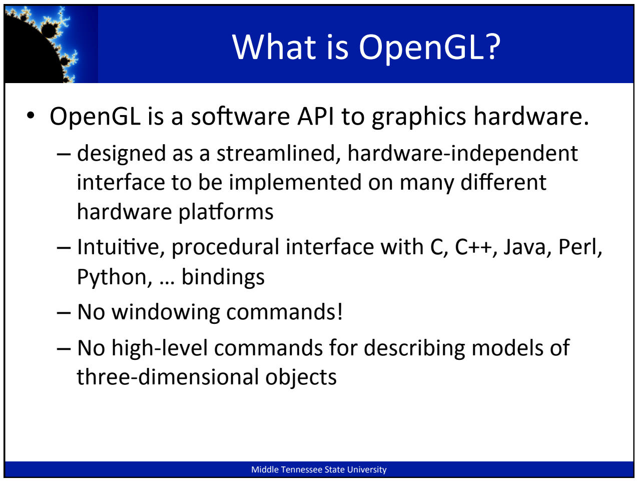

What is OpenGL?

- OpenGL is a software API to graphics hardware.
  - designed as a streamlined, hardware-independent interface to be implemented on many different hardware platforms
  - Intuitive, procedural interface with C, C++, Java, Perl, Python, … bindings
  - No windowing commands!
  - No high-level commands for describing models of three-dimensional objects

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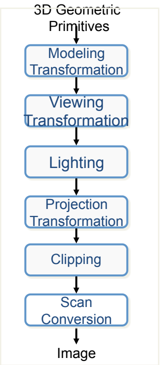
What Is OpenGL?

- A software interface to graphics hardware.
- The interface consists of about 250 commands (functions) to specify the objects and operations needed to produce 2D and 3D graphics
  - OpenGL geometric primitives include points, lines, polylines, and polygons. There is specific support for triangle and quadrilateral polynomials
  - Has texture mapping support.

OpenGL Libraries

- OpenGL core library
  - OpenGL32 on Windows
  - GL on most unix/linux systems
- OpenGL Utility Library (GLU)
  - Provides functionality in OpenGL core but avoids having to rewrite code
- OpenGL Utility Toolkit (GLUT)
  - Provides functionality common to all window systems
    - Open a window
    - Get input from mouse and keyboard
    - Menus
    - Event-driven
  - Code is portable but GLUT lacks the functionality of a good toolkit for a specific platform
    - No slide bars

Classic Rendering Pipeline



3D Geometric Primitives

Modeling Transformation

Viewing Transformation

Lighting

Projection Transformation

Clipping

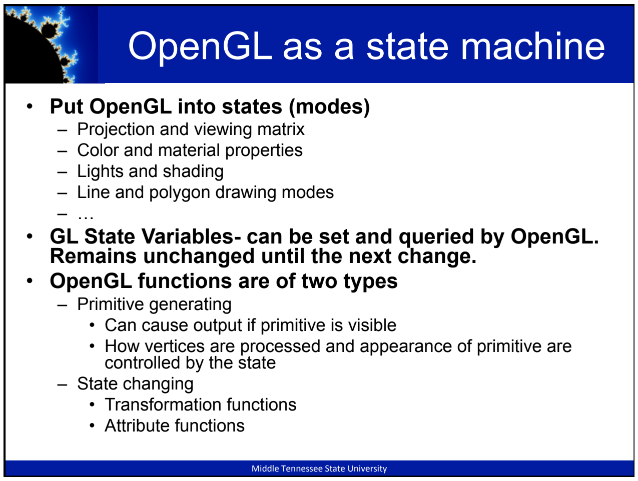
Scan Conversion

Image

OpenGL Architecture

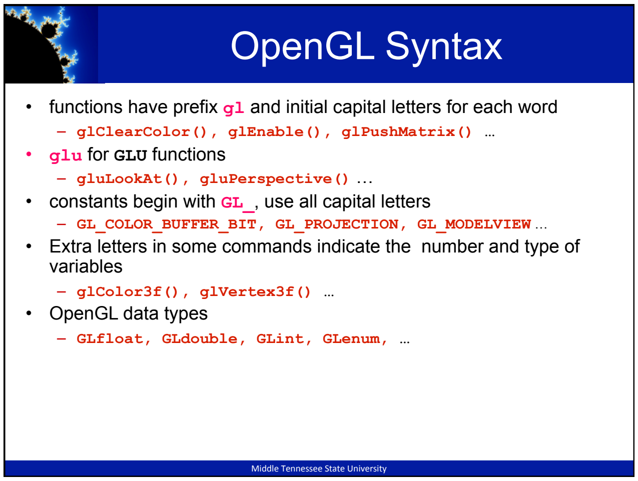
- OpenGL uses a client-server model
  - client sends commands to the server
  - server interprets, processes commands
  - note: client and server usually on the same computer, but need not be
    - your program = client
    - OpenGL/GPU = server
  - example interaction:

program	OpenGL/GPU
begin triangle normal (0, 0, -1) vertex (-1, 1, -1, 1) vertex (1, -1, -1, 1) vertex (-1, -1, -1, 1) end triangle	<scan converts the given triangle with normal (0,0,-1) on all vertices>



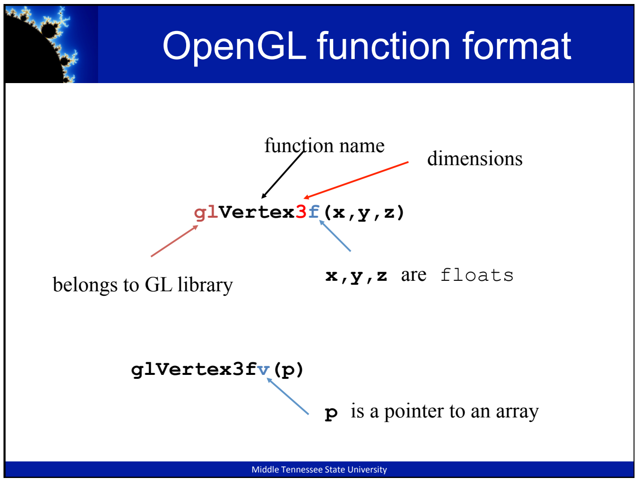
OpenGL as a state machine

- **Put OpenGL into states (modes)**
  - Projection and viewing matrix
  - Color and material properties
  - Lights and shading
  - Line and polygon drawing modes
  - …
- **GL State Variables- can be set and queried by OpenGL. Remains unchanged until the next change.**
- **OpenGL functions are of two types**
  - Primitive generating
    - Can cause output if primitive is visible
    - How vertices are processed and appearance of primitive are controlled by the state
  - State changing
    - Transformation functions
    - Attribute functions



OpenGL Syntax

- functions have prefix `gl` and initial capital letters for each word
  - `glClearColor(), glEnable(), glPushMatrix()` …
- `glu` for `GLU` functions
  - `gluLookAt(), gluPerspective()` …
- constants begin with `GL_`, use all capital letters
  - `GL_COLOR_BUFFER_BIT, GL_PROJECTION, GL_MODELVIEW` …
- Extra letters in some commands indicate the number and type of variables
  - `glColor3f(), glVertex3f()` …
- OpenGL data types
  - `GLfloat, GLdouble, GLint, GLenum,` …



OpenGL function format

function name

dimensions

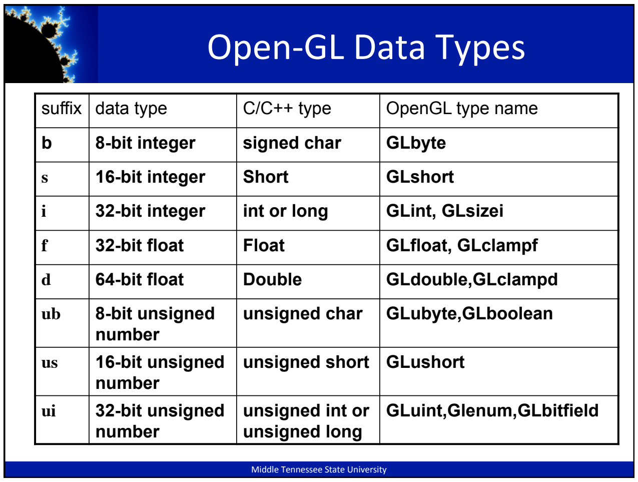
`glVertex3f(x,y,z)`

belongs to GL library

`x,y,z` are `floats`

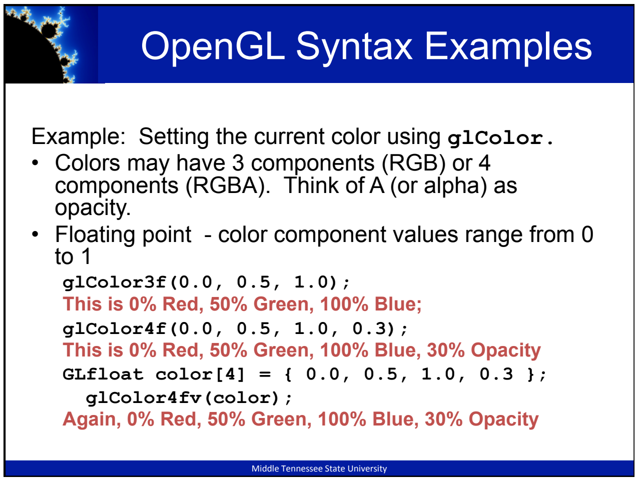
`glVertex3fv(p)`

`p` is a pointer to an array



Open-GL Data Types

suffix	data type	C/C++ type	OpenGL type name
b	8-bit integer	signed char	GLbyte
s	16-bit integer	Short	GLshort
i	32-bit integer	int or long	GLint, GLsizei
f	32-bit float	Float	GLfloat, GLclampf
d	64-bit float	Double	GLdouble,GLclampd
ub	8-bit unsigned number	unsigned char	GLubyte,GLboolean
us	16-bit unsigned number	unsigned short	GLushort
ui	32-bit unsigned number	unsigned int or unsigned long	GLuint,Glenum,GLbitfield



OpenGL Syntax Examples

Example: Setting the current color using `glColor`.

- Colors may have 3 components (RGB) or 4 components (RGBA). Think of A (or alpha) as opacity.
- Floating point - color component values range from 0 to 1

```
glColor3f(0.0, 0.5, 1.0);
```

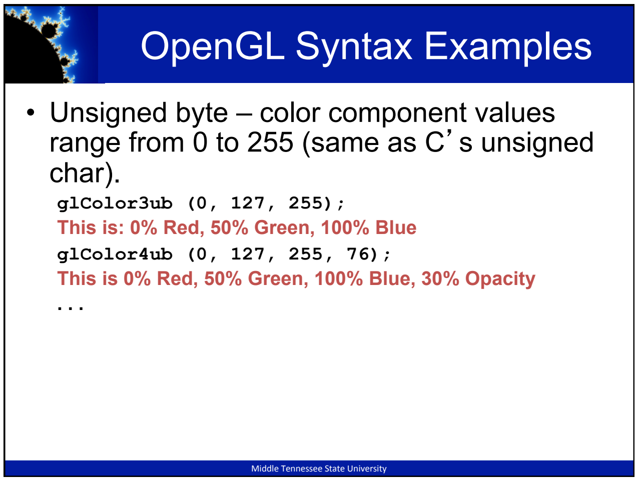
This is 0% Red, 50% Green, 100% Blue;

```
glColor4f(0.0, 0.5, 1.0, 0.3);
```

This is 0% Red, 50% Green, 100% Blue, 30% Opacity

```
GLfloat color[4] = { 0.0, 0.5, 1.0, 0.3 };
  glColor4fv(color);
```

Again, 0% Red, 50% Green, 100% Blue, 30% Opacity



OpenGL Syntax Examples

- Unsigned byte – color component values range from 0 to 255 (same as C's unsigned char).

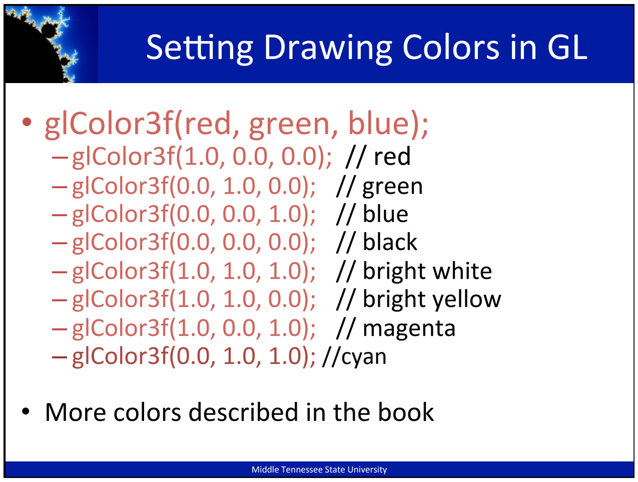
```
glColor3ub (0, 127, 255);
```

This is: 0% Red, 50% Green, 100% Blue

```
glColor4ub (0, 127, 255, 76);
```

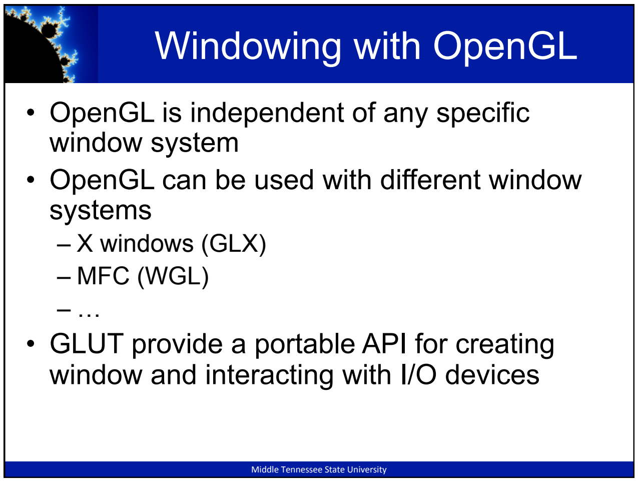
This is 0% Red, 50% Green, 100% Blue, 30% Opacity

```
. . .
```



Setting Drawing Colors in GL

- glColor3f(red, green, blue);
  - glColor3f(1.0, 0.0, 0.0); // red
  - glColor3f(0.0, 1.0, 0.0); // green
  - glColor3f(0.0, 0.0, 1.0); // blue
  - glColor3f(0.0, 0.0, 0.0); // black
  - glColor3f(1.0, 1.0, 1.0); // bright white
  - glColor3f(1.0, 1.0, 0.0); // bright yellow
  - glColor3f(1.0, 0.0, 1.0); // magenta
  - glColor3f(0.0, 1.0, 1.0); //cyan
- More colors described in the book



Windowing with OpenGL

- OpenGL is independent of any specific window system
- OpenGL can be used with different window systems
  - X windows (GLX)
  - MFC (WGL)
  - …
- GLUT provide a portable API for creating window and interacting with I/O devices

GLUT

- Developed by Mark Kilgard
- Hides the complexities of differing window system APIs
  - Default user interface for class projects
- Glut routines have prefix `glut`
  - `glutCreateWindow()` …
- Has very limited GUI interface
- **GLUI** is the C++ extension of glut that provides buttons, checkboxes, radio buttons, etc.

Glut Routines

- **Initialization:**

  `glutInit()` processes (and removes) command-line arguments that may be of interest to glut and the window system and does general initialization of Glut and OpenGL
  - Must be called before any other glut routines
- **Display Mode**:

  The next procedure, `glutInitDisplayMode()`, performs initializations informing OpenGL how to set up the frame buffer.

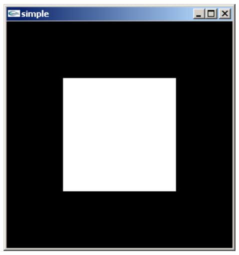
Display Mode	Meaning
GLUT_RGB	Use RGB colors
GLUT_RGBA	Use RGB plus alpha (for transparency)
GLUT_INDEX	Use indexed colors (not recommended)
GLUT_DOUBLE	Use double buffering (recommended)
GLUT_SINGLE	Use single buffering (not recommended)
GLUT_DEPTH	Use depth-buffer (for hidden surface removal.)

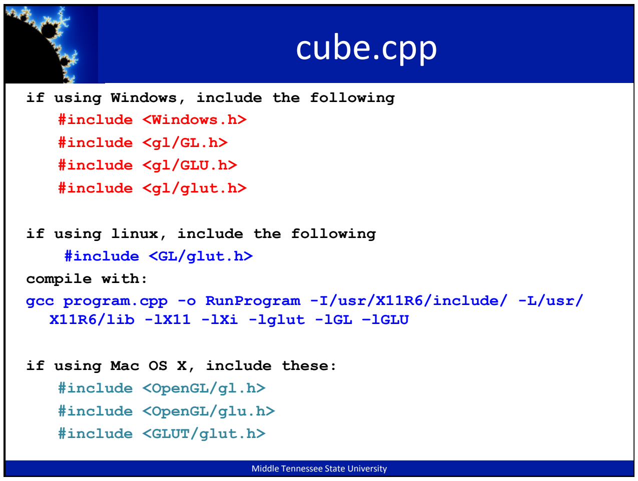
Glut Routines

- Window Setup
  - `glutInitWindowSize(int width, int height)`
  - `glutInitWindowPosition(int x, int y)`
  - `glutCreateWindow(char* title)`

A Simple Program

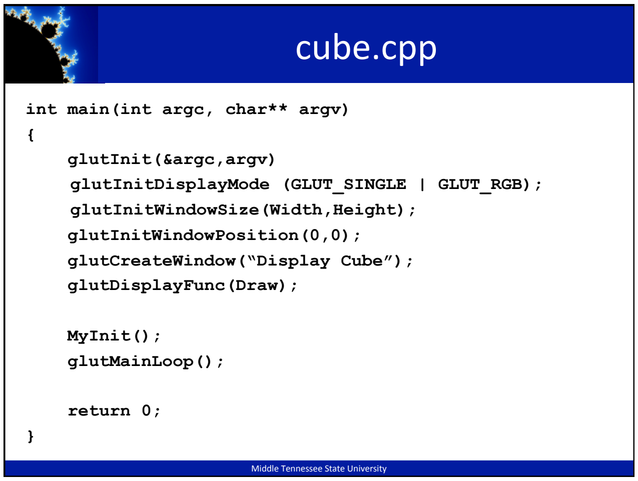
Generate a square on a solid background





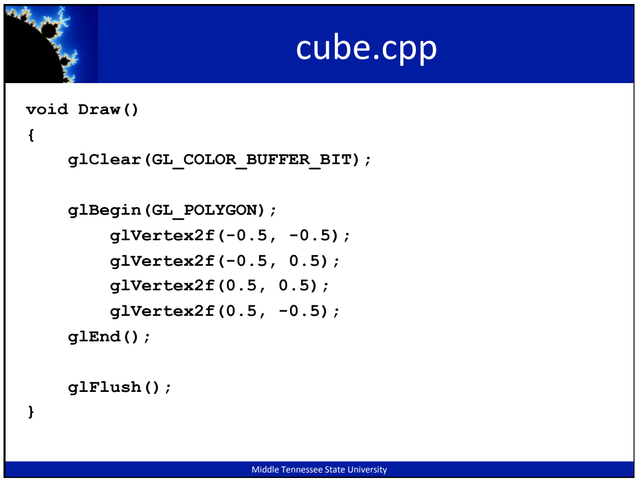
cube.cpp

```
if using Windows, include the following
    #include <Windows.h>
    #include <gl/GL.h>
    #include <gl/GLU.h>
    #include <gl/glut.h>

if using linux, include the following
     #include <GL/glut.h>
compile with:
gcc program.cpp -o RunProgram -I/usr/X11R6/include/ -L/usr/
   X11R6/lib -lX11 -lXi -lglut -lGL -lGLU

if using Mac OS X, include these:
    #include <OpenGL/gl.h>
    #include <OpenGL/glu.h>
    #include <GLUT/glut.h>
```



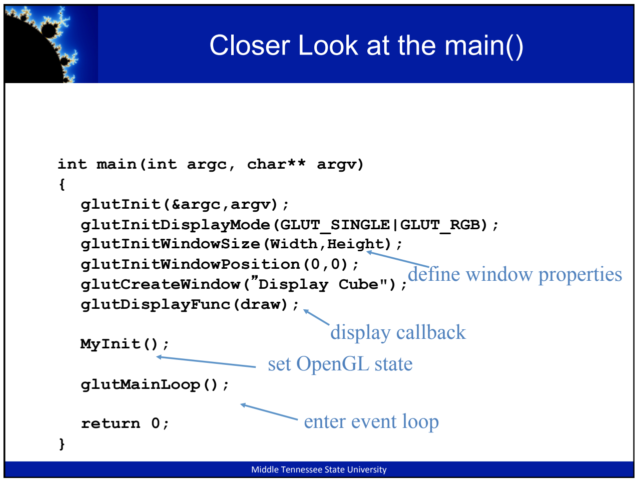
cube.cpp

```
int main(int argc, char** argv)
{
     glutInit(&argc,argv);
     glutInitDisplayMode (GLUT_SINGLE | GLUT_RGB);
     glutInitWindowSize(Width,Height);
     glutInitWindowPosition(0,0);
     glutCreateWindow(“Display Cube”);
     glutDisplayFunc(Draw);

     MyInit();
     glutMainLoop();

     return 0;
}
```



cube.cpp

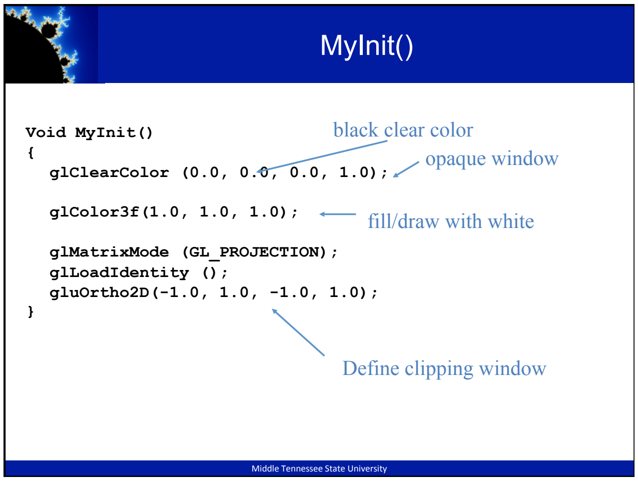
```
void Draw()
{
     glClear(GL_COLOR_BUFFER_BIT);

     glBegin(GL_POLYGON);
          glVertex2f(-0.5, -0.5);
          glVertex2f(-0.5, 0.5);
          glVertex2f(0.5, 0.5);
          glVertex2f(0.5, -0.5);
     glEnd();

     glFlush();
}
```



Closer Look at the main()

```
int main(int argc, char** argv)
{
   glutInit(&argc,argv);
   glutInitDisplayMode(GLUT_SINGLE|GLUT_RGB);
   glutInitWindowSize(Width,Height);
   glutInitWindowPosition(0,0);
   glutCreateWindow(”Display Cube");
   glutDisplayFunc(draw);

   MyInit();

   glutMainLoop();

   return 0;
}
```

define window properties
display callback
set OpenGL state
enter event loop



MyInit()

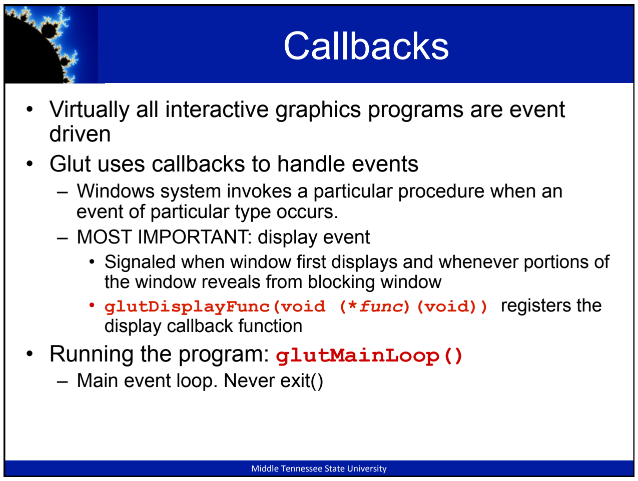
```
Void MyInit()
{
  glClearColor (0.0, 0.0, 0.0, 1.0);

  glColor3f(1.0, 1.0, 1.0);

  glMatrixMode (GL_PROJECTION);
  glLoadIdentity ();
  gluOrtho2D(-1.0, 1.0, -1.0, 1.0);
}
```

black clear color

opaque window

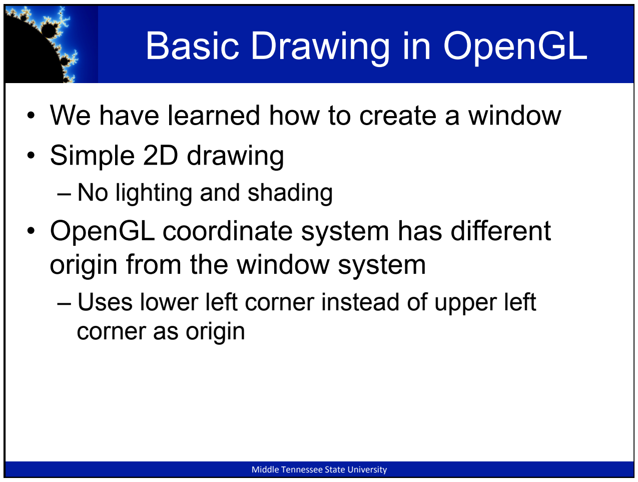
fill/draw with white

Define clipping window



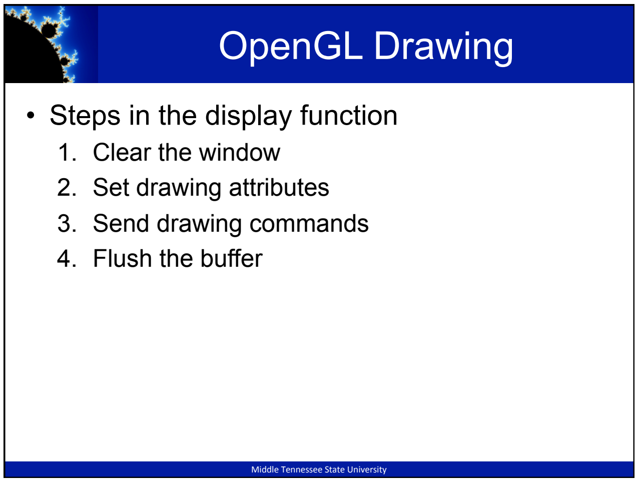
Callbacks

- Virtually all interactive graphics programs are event driven
- Glut uses callbacks to handle events
  - Windows system invokes a particular procedure when an event of particular type occurs.
  - MOST IMPORTANT: display event
    - Signaled when window first displays and whenever portions of the window reveals from blocking window
    - `glutDisplayFunc(void (*func)(void))` registers the display callback function
- Running the program: `glutMainLoop()`
  - Main event loop. Never exit()



Basic Drawing in OpenGL

- We have learned how to create a window
- Simple 2D drawing
  - No lighting and shading
- OpenGL coordinate system has different origin from the window system
  - Uses lower left corner instead of upper left corner as origin



OpenGL Drawing

- Steps in the display function
  1. Clear the window
  2. Set drawing attributes
  3. Send drawing commands
  4. Flush the buffer

Step 1: Clear the Window

- `glClear(GL_COLOR_BUFFER_BIT)`
  - clears the frame buffer by overwriting it with the background color.
  - Background color is a state set by `glClearColor(GLfloat r, GLfloat g, GLfloat b, GLfloat a)` in MyInit().
- `void glClear(Glbitfield mask)`
  - **Four masks:**
    - GL_COLOR_BUFFER_BIT
    - GL_DEPTH_BUFFER_BIT
    - GL_ACCUM_BUFFER_BIT
    - GL_STENCIL_BUFFER_BIT

Step 2: Drawing Attributes: Color

- `glColor3f(GLfloat r, GLfloat g, GLfloat b)` sets the drawing color
  - `glColor3d()`, `glColor3ui()` can also be used
  - Remember OpenGL is a state machine
  - Once set, the attribute applies to all subsequent defined objects until it is set to some other value
  - `glColor3fv()` takes a flat array as input

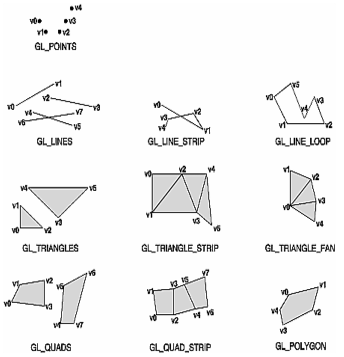
Step 2: Drawing Attributes

- Besides `glVertex()` commands, other attributes commands can also be used between `glBegin()` and `glEnd()`, e.g. `glColor3f()`.
- There are more drawing attributes than color
  - Point size: `glPointSize()`
  - Line width: `glLinewidth()`
  - Dash or dotted line: `glLineStipple()`
  - Polygon pattern: `glPolygonStipple()`
  - …

Step 3: Drawing Commands

- Simple Objects `glRectf()`
- Complex Objects
  - Use construct `glBegin(mode)` and `glEnd()` and a list of vertices in between
  - `glBegin(mode);`

```
    glVertex(v0);
    glVertex(v1);
    ...
glEnd();
```

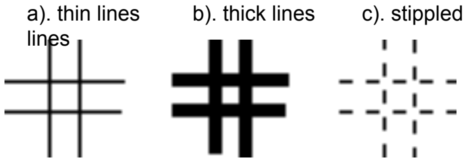


Drawing Lines

- glBegin (GL_LINES); //draws one line
  - glVertex2i (40, 100); // between 2 vertices
  - glVertex2i (202, 96);
- glEnd ();
- glFlush();
- If more than two vertices are specified between glBegin(GL_LINES) and glEnd() they are taken in pairs, and a separate line is drawn between each pair.

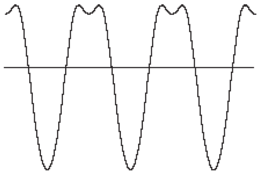
Line Attributes

- Color, thickness, stippling.
- glColor3f(); sets color.
- glLineWidth(4.0); sets thickness. The default thickness is 1.0.
- glLineStipple(2, 0x777);



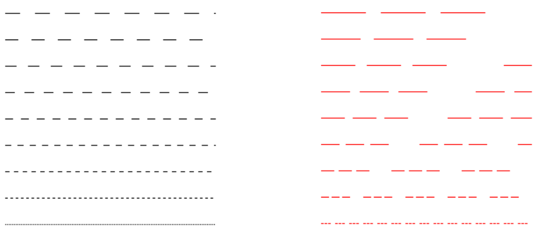
Graphing

- Drawing line graphs: connect each pair of (x, f(x)) values
- How would you design a program to accomplish this?



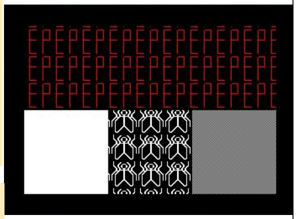
Step 2: Drawing Attributes

```
glLineStipple() demo: stipple0.cpp
```



Step 2: Drawing Attributes

```
GLubyte fly[] = {
     0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
     0x03, 0x80, 0x01, 0xC0, 0x06, 0xC0, 0x03, 0x60,
     0x04, 0x60, 0x06, 0x20, 0x04, 0x30, 0x0C, 0x20,
     0x04, 0x18, 0x18, 0x20, 0x04, 0x0C, 0x30, 0x20,
     0x04, 0x06, 0x60, 0x20, 0x44, 0x03, 0xC0, 0x22,
     0x44, 0x01, 0x80, 0x22, 0x44, 0x01, 0x80, 0x22,
     0x44, 0x01, 0x80, 0x22, 0x44, 0x01, 0x80, 0x22,
     0x44, 0x01, 0x80, 0x22, 0x44, 0x01, 0x80, 0x22,
     0x66, 0x01, 0x80, 0x66, 0x33, 0x01, 0x80, 0xCC,
     0x19, 0x81, 0x81, 0x98, 0x0C, 0xC1, 0x83, 0x30,
     0x07, 0xe1, 0x87, 0xe0, 0x03, 0x3f, 0xfc, 0xc0,
     0x03, 0x31, 0x8c, 0xc0, 0x03, 0x33, 0xcc, 0xc0,
     0x06, 0x64, 0x26, 0x60, 0x0c, 0xcc, 0x33, 0x30,
     0x18, 0xcc, 0x33, 0x18, 0x10, 0xc4, 0x23, 0x08,
     0x10, 0x63, 0xC6, 0x08, 0x10, 0x30, 0x0c, 0x08,
     0x10, 0x18, 0x18, 0x08, 0x10, 0x00, 0x00, 0x08};
```

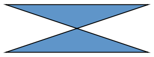


```
glRectf(25.0, 25.0, 125.0, 125.0);
glEnable(GL_POLYGON_STIPPLE);
glPolygonStipple(fly);
glRectf (125.0, 25.0, 225.0, 125.0);
```

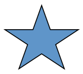
glPolygonStipple()

Polygon Issues

- OpenGL will only display polygons correctly that are
  - Simple: edges cannot cross
  - Convex: All points on line segment between two points in a polygon are also in the polygon
  - Flat: all vertices are in the same plane
- User program can check if above true
  - OpenGL will produce output if these conditions are violated but it may not be what is desired
- Triangles satisfy all conditions



nonsimple polygon



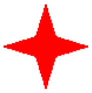
nonconvex polygon

Polygon Issues

- How to draw a circle?
  - circle_list demo

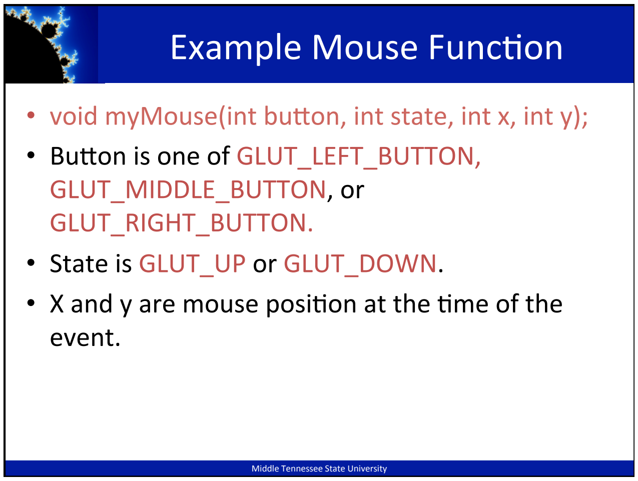
```
//glBegin(GL_POLYGON);  // for solid circle
glBegin(GL_LINE_STRIP);   // for unfilled circle
// Generate the points of the circle
 for( int i=0; i<=numPoints; i++ )
{
            angle = i * (2.0*PI/numPoints);
            x = cos( angle )*radius;
            y = sin( angle )*radius;
            glVertex2f( x, y );
}
```

- How to draw this?
  - Polygon symbol
  - polygonSymbol demo



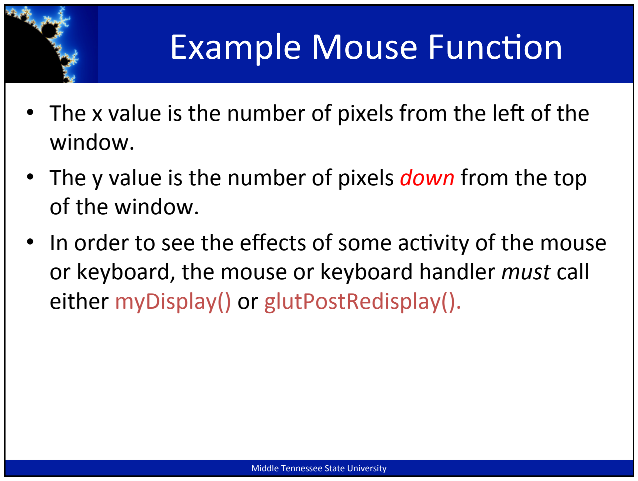
Simple User Interaction with Mouse and Keyboard

- Register functions:
  - glutMouseFunc (myMouse);
  - glutKeyboardFunc (myKeyboard);
- Write the function(s)
- NOTE that any drawing you do when you use these functions must be done IN the mouse or keyboard function, OR in a function called from within mouse or keyboard callback functions.



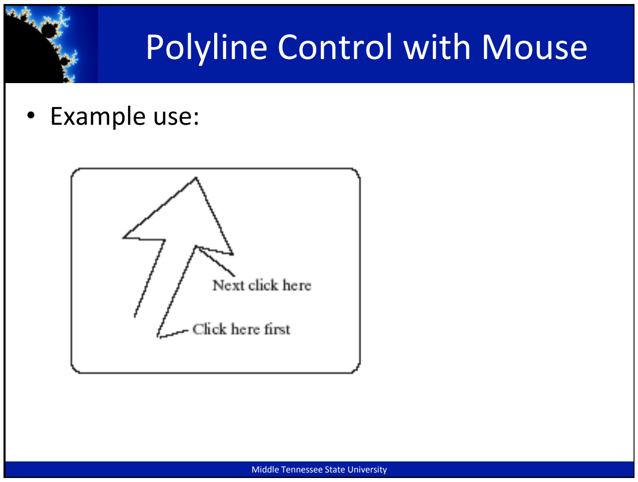
Example Mouse Function

- void myMouse(int button, int state, int x, int y);
- Button is one of GLUT_LEFT_BUTTON, GLUT_MIDDLE_BUTTON, or GLUT_RIGHT_BUTTON.
- State is GLUT_UP or GLUT_DOWN.
- X and y are mouse position at the time of the event.



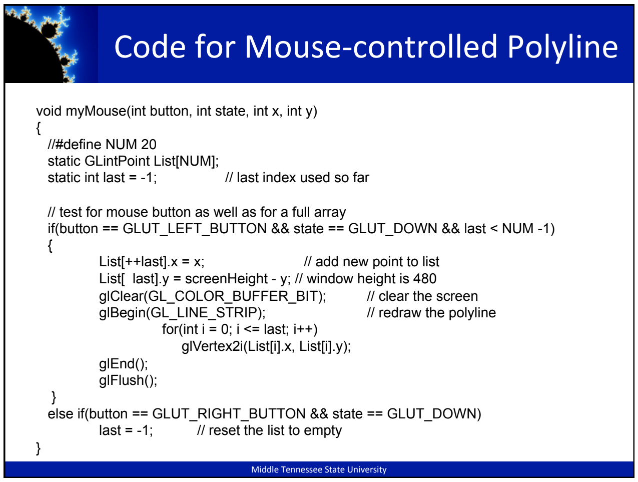
Example Mouse Function

- The x value is the number of pixels from the left of the window.
- The y value is the number of pixels *down* from the top of the window.
- In order to see the effects of some activity of the mouse or keyboard, the mouse or keyboard handler *must* call either myDisplay() or glutPostRedisplay().



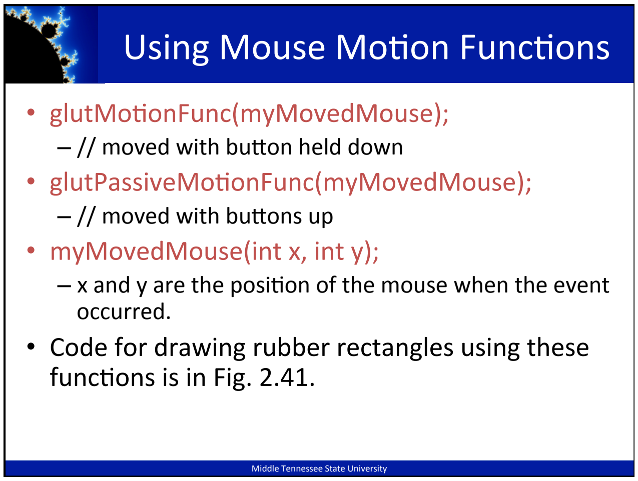
Polyline Control with Mouse

- Example use:



Code for Mouse-controlled Polyline

```
void myMouse(int button, int state, int x, int y)
{
   //#define NUM 20
   static GLintPoint List[NUM];
   static int last = -1;                // last index used so far

   // test for mouse button as well as for a full array
   if(button == GLUT_LEFT_BUTTON && state == GLUT_DOWN && last < NUM -1)
   {
            List[++last].x = x;                        // add new point to list
            List[  last].y = screenHeight - y; // window height is 480
            glClear(GL_COLOR_BUFFER_BIT);          // clear the screen
            glBegin(GL_LINE_STRIP);                  // redraw the polyline
                        for(int i = 0; i <= last; i++)
                            glVertex2i(List[i].x, List[i].y);
            glEnd();
            glFlush();
    }
   else if(button == GLUT_RIGHT_BUTTON && state == GLUT_DOWN)
            last = -1;          // reset the list to empty
}
```



Using Mouse Motion Functions

- glutMotionFunc(myMovedMouse);
  - // moved with button held down
- glutPassiveMotionFunc(myMovedMouse);
  - // moved with buttons up
- myMovedMouse(int x, int y);
  - x and y are the position of the mouse when the event occurred.
- Code for drawing rubber rectangles using these functions is in Fig. 2.41.

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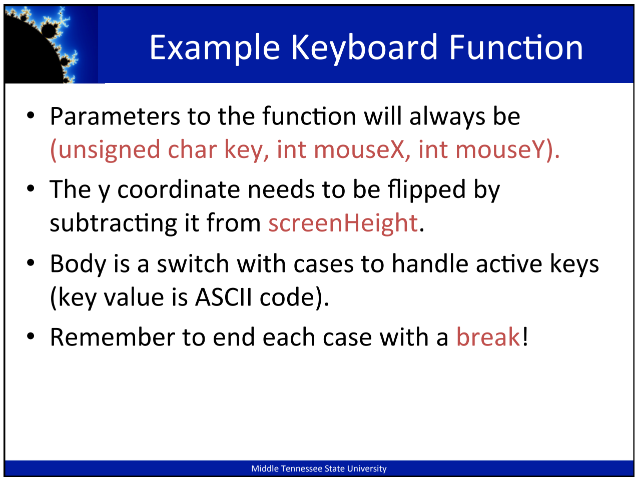

Example Keyboard Function

- Parameters to the function will always be (unsigned char key, int mouseX, int mouseY).
- The y coordinate needs to be flipped by subtracting it from screenHeight.
- Body is a switch with cases to handle active keys (key value is ASCII code).
- Remember to end each case with a break!

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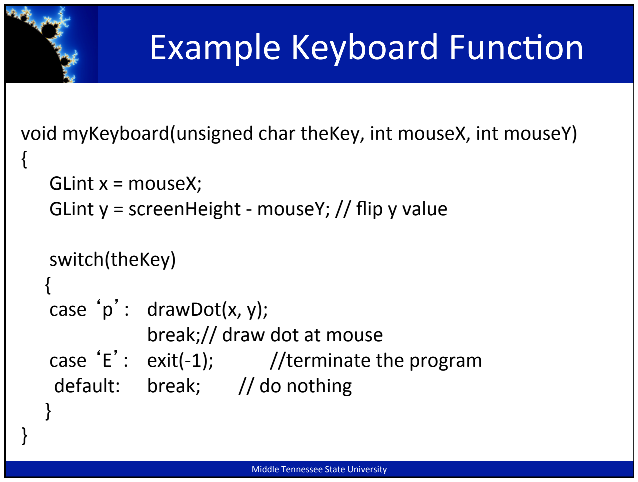

Example Keyboard Function

```
void myKeyboard(unsigned char theKey, int mouseX, int mouseY)
{
    GLint x = mouseX;
    GLint y = screenHeight - mouseY; // flip y value

    switch(theKey)
   {
    case ‘p’:   drawDot(x, y);
                break;// draw dot at mouse
    case ‘E’:   exit(-1);        //terminate the program
     default:   break;      // do nothing
   }
}
```

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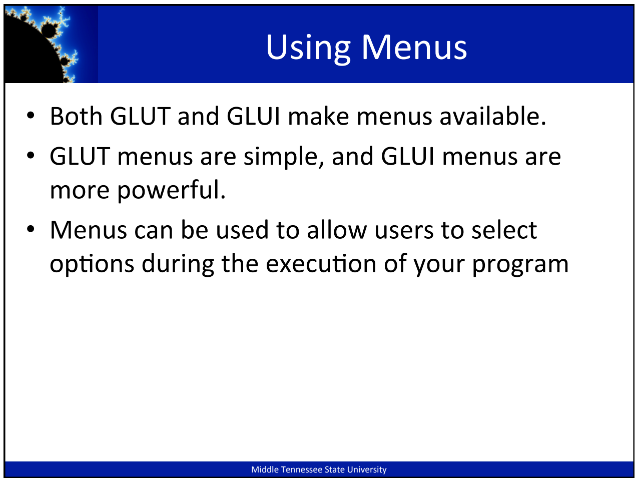

Using Menus

- Both GLUT and GLUI make menus available.
- GLUT menus are simple, and GLUI menus are more powerful.
- Menus can be used to allow users to select options during the execution of your program

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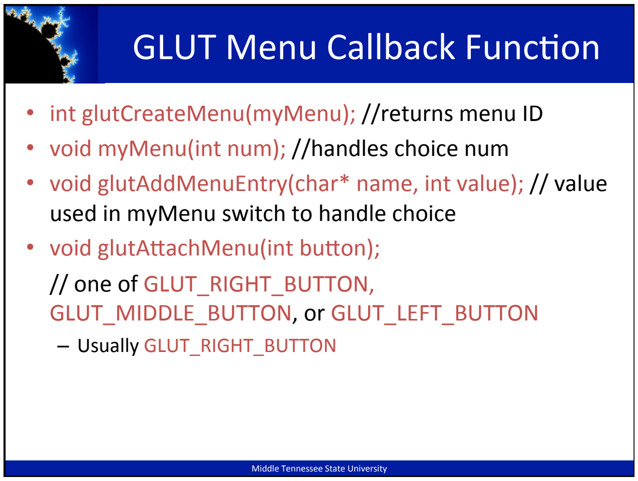
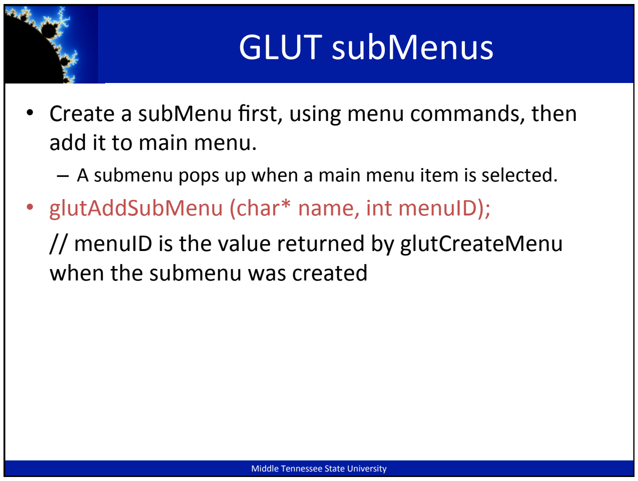


GLUT Menu Callback Function

- int glutCreateMenu(myMenu); //returns menu ID
- void myMenu(int num); //handles choice num
- void glutAddMenuEntry(char* name, int value); // value used in myMenu switch to handle choice
- void glutAttachMenu(int button);

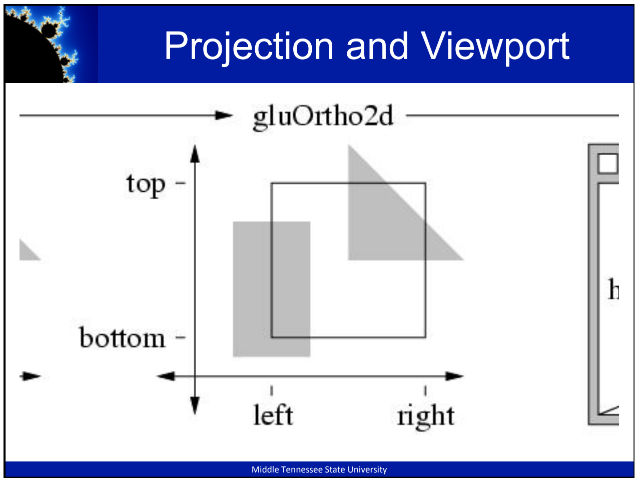
  // one of GLUT_RIGHT_BUTTON, GLUT_MIDDLE_BUTTON, or GLUT_LEFT_BUTTON
  - Usually GLUT_RIGHT_BUTTON



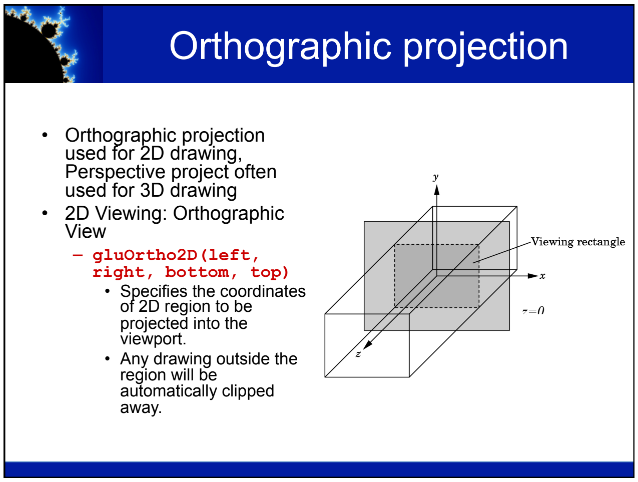
GLUT subMenus

- Create a subMenu first, using menu commands, then add it to main menu.
  - A submenu pops up when a main menu item is selected.
- glutAddSubMenu (char* name, int menuID);

  // menuID is the value returned by glutCreateMenu when the submenu was created



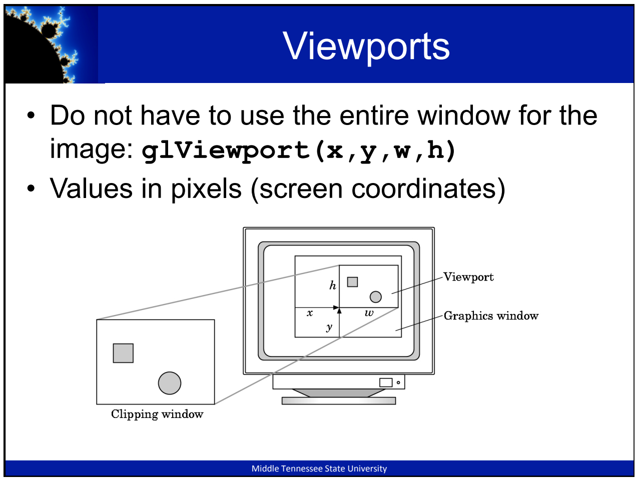
Projection and Viewport



Orthographic projection

- Orthographic projection used for 2D drawing, Perspective project often used for 3D drawing
- 2D Viewing: Orthographic View
  - gluOrtho2D(left, right, bottom, top)
    - Specifies the coordinates of 2D region to be projected into the viewport.
    - Any drawing outside the region will be automatically clipped away.

y
Viewing rectangle
x
z=0
z



Viewports

- Do not have to use the entire window for the image: **`glViewport(x,y,w,h)`**
- Values in pixels (screen coordinates)