OpenGL Tutorial

An Introduction on OpenGL with 2D Graphics

TABLE OF CONTENTS (HIDE)

1. Setting Up OpenGL

To set up OpenGL, depending on your programming platform, read:

- How to write OpenGL programs in C/C++.
- How to write OpenGL programs in Java: JOGL or LWJGL.
- How to write OpenGL|ES programs in Android.

1.1 Example 1: Setting Up OpenGL and GLUT (GL01Hello.cpp)

Make sure that you can run the "`GL01Hello.cpp`" described in "How to write OpenGL programs in C/C++", reproduced below:

```
/*
 * GL01Hello.cpp: Test OpenGL/GLUT C/C++ Setup
 * Tested under Eclipse CDT with MinGW/Cygwin and CodeBlocks with MinGW
 * To compile with -lfreeglut -lglu32 -lopengl32
 */
#include <windows.h>  // for MS Windows
#include <GL/glut.h>  // GLUT, include glu.h and gl.h

/* Handler for window-repaint event. Call back when the window first appears and
   whenever the window needs to be re-painted. */
void display() {
   glClearColor(0.0f, 0.0f, 0.0f, 1.0f); // Set background color to black and opaque
   glClear(GL_COLOR_BUFFER_BIT);         // Clear the color buffer (background)

   // Draw a Red 1x1 Square centered at origin
```

```
16      glBegin(GL_QUADS);              // Each set of 4 vertices form a quad
17         glColor3f(1.0f, 0.0f, 0.0f); // Red
18         glVertex2f(-0.5f, -0.5f);    // x, y
19         glVertex2f( 0.5f, -0.5f);
20         glVertex2f( 0.5f,  0.5f);
21         glVertex2f(-0.5f,  0.5f);
22      glEnd();
23
24      glFlush();  // Render now
25   }
26
27   /* Main function: GLUT runs as a console application starting at main()  */
28   int main(int argc, char** argv) {
29      glutInit(&argc, argv);                 // Initialize GLUT
30      glutCreateWindow("OpenGL Setup Test"); // Create a window with the given title
31      glutInitWindowSize(320, 320);   // Set the window's initial width & height
32      glutInitWindowPosition(50, 50); // Position the window's initial top-left corner
33      glutDisplayFunc(display); // Register display callback handler for window re-paint
34      glutMainLoop();           // Enter the event-processing loop
35      return 0;
36   }
```

```
#include <windows.h>
```

The header "`windows.h`" is needed for the Windows platform only.

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

We also included the GLUT header, which is guaranteed to include "`glu.h`" (for GL Utility) and "`gl.h`" (for Core OpenGL).

The rest of the program will be explained in due course.

2. Introduction

OpenGL (Open Graphics Library) is a cross-platform, hardware-accelerated, language-independent, industrial standard API for producing 3D (including 2D) graphics. Modern computers have dedicated GPU (Graphics Processing Unit) with its own memory to speed up graphics rendering. OpenGL is the software interface to graphics hardware. In other words, OpenGL graphic rendering commands issued by your applications could be directed to the graphic hardware and accelerated.

We use 3 sets of libraries in our OpenGL programs:

1. **Core OpenGL (GL)**: consists of hundreds of commands, which begin with a prefix "`gl`" (e.g., `glColor`, `glVertex`, `glTranslate`, `glRotate`). The Core OpenGL models an object via a set of geometric primitives such as point, line and polygon.
2. **OpenGL Utility Library (GLU)**: built on-top of the core OpenGL to provide important utilities (such as setting camera view and projection) and more building models (such as qradric surfaces and polygon tessellation). GLU commands start with a prefix "`glu`" (e.g., `gluLookAt`, `gluPerspective`).
3. **OpenGL Utilities Toolkit (GLUT)**: OpenGL is designed to be independent of the windowing system or operating system. GLUT is needed to interact with the Operating System (such as creating a window, handling key and mouse inputs); it also provides more building models (such as sphere and torus). GLUT commands start with a prefix of "`glut`" (e.g., `glutCreatewindow`, `glutMouseFunc`). GLUT is platform independent, which is built on top of platform-specific OpenGL extension such as GLX for X Window System, WGL for Microsoft Window, and AGL, CGL or Cocoa for Mac OS.
   Quoting from the opengl.org: "GLUT is designed for constructing small to medium sized OpenGL programs. While GLUT is well-suited to learning OpenGL and developing simple OpenGL applications, GLUT is not a full-featured toolkit so large applications requiring sophisticated user interfaces are better off using native window

system toolkits. *GLUT is simple, easy, and small.*"
Alternative of GLUT includes SDL, ...

4. **OpenGL Extension Wrangler Library (GLEW)**: "GLEW is a cross-platform open-source C/C++ extension loading library. GLEW provides efficient run-time mechanisms for determining which OpenGL extensions are supported on the target platform." Source and pre-build binary available at http://glew.sourceforge.net/. A standalone utility called "`glewinfo.exe`" (under the "`bin`" directory) can be used to produce the list of OpenGL functions supported by your graphics system.
5. Others.

3. Vertex, Primitive and Color

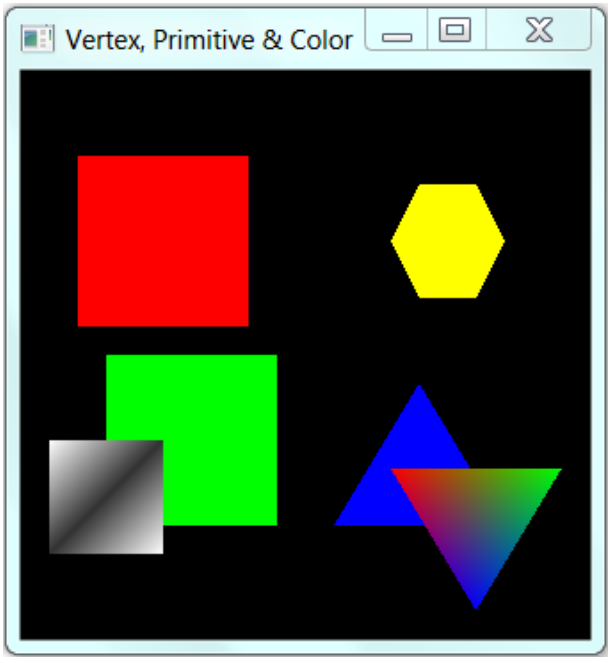
3.1 Example 2: Vertex, Primitive and Color (`GL02Primitive.cpp`)

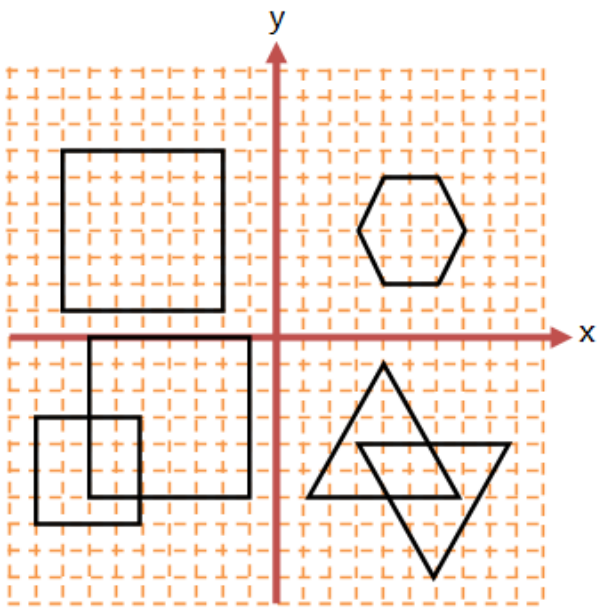
Try building and runnng this OpenGL C/C++ program:

```
/*
 * GL02Primitive.cpp: Vertex, Primitive and Color
 * Draw Simple 2D colored Shapes: quad, triangle and polygon.
 */
#include <windows.h>  // for MS Windows
#include <GL/glut.h>  // GLUT, include glu.h and gl.h

/* Initialize OpenGL Graphics */
void initGL() {
   // Set "clearing" or background color
   glClearColor(0.0f, 0.0f, 0.0f, 1.0f); // Black and opaque
}

/* Handler for window-repaint event. Call back when the window first appears and
   whenever the window needs to be re-painted. */
void display() {
   glClear(GL_COLOR_BUFFER_BIT);   // Clear the color buffer with current clearing color

   // Define shapes enclosed within a pair of glBegin and glEnd
   glBegin(GL_QUADS);              // Each set of 4 vertices form a quad
      glColor3f(1.0f, 0.0f, 0.0f); // Red
      glVertex2f(-0.8f, 0.1f);     // Define vertices in counter-clockwise (CCW) order
      glVertex2f(-0.2f, 0.1f);     //  so that the normal (front-face) is facing you
      glVertex2f(-0.2f, 0.7f);
      glVertex2f(-0.8f, 0.7f);

      glColor3f(0.0f, 1.0f, 0.0f); // Green
      glVertex2f(-0.7f, -0.6f);
      glVertex2f(-0.1f, -0.6f);
      glVertex2f(-0.1f,  0.0f);
      glVertex2f(-0.7f,  0.0f);

      glColor3f(0.2f, 0.2f, 0.2f); // Dark Gray
      glVertex2f(-0.9f, -0.7f);
      glColor3f(1.0f, 1.0f, 1.0f); // White
      glVertex2f(-0.5f, -0.7f);
      glColor3f(0.2f, 0.2f, 0.2f); // Dark Gray
      glVertex2f(-0.5f, -0.3f);
      glColor3f(1.0f, 1.0f, 1.0f); // White
      glVertex2f(-0.9f, -0.3f);
   glEnd();

   glBegin(GL_TRIANGLES);          // Each set of 3 vertices form a triangle
      glColor3f(0.0f, 0.0f, 1.0f); // Blue
```

```
45          glVertex2f(0.1f, -0.6f);
46          glVertex2f(0.7f, -0.6f);
47          glVertex2f(0.4f, -0.1f);
48
49          glColor3f(1.0f, 0.0f, 0.0f); // Red
50          glVertex2f(0.3f, -0.4f);
51          glColor3f(0.0f, 1.0f, 0.0f); // Green
52          glVertex2f(0.9f, -0.4f);
53          glColor3f(0.0f, 0.0f, 1.0f); // Blue
54          glVertex2f(0.6f, -0.9f);
55       glEnd();
56
57       glBegin(GL_POLYGON);            // These vertices form a closed polygon
58          glColor3f(1.0f, 1.0f, 0.0f); // Yellow
59          glVertex2f(0.4f, 0.2f);
60          glVertex2f(0.6f, 0.2f);
61          glVertex2f(0.7f, 0.4f);
62          glVertex2f(0.6f, 0.6f);
63          glVertex2f(0.4f, 0.6f);
64          glVertex2f(0.3f, 0.4f);
65       glEnd();
66
67       glFlush();  // Render now
68    }
69
70    /* Main function: GLUT runs as a console application starting at main()  */
71    int main(int argc, char** argv) {
72       glutInit(&argc, argv);          // Initialize GLUT
73       glutCreateWindow("Vertex, Primitive & Color");  // Create window with the given title
74       glutInitWindowSize(320, 320);   // Set the window's initial width & height
75       glutInitWindowPosition(50, 50); // Position the window's initial top-left corner
76       glutDisplayFunc(display);       // Register callback handler for window re-paint event
77       initGL();                       // Our own OpenGL initialization
78       glutMainLoop();                 // Enter the event-processing loop
79       return 0;
80    }
```

The expected output and the coordinates are as follows. Take note that 4 shapes have pure color, and 2 shapes have color blending from their vertices.





I shall explain the program in the following sections.

3.2 OpenGL as a State Machine

OpenGL operates as a *state machine*, and maintain a set of *state variables* (such as the foreground color, background color, and many more). In a state machine, once the value of a state variable is set, the value persists until a new value is given.

For example, we set the "clearing" (background) color to black *once* in `initGL()`. We use this setting to clear the window in the `display()` *repeatedly* (`display()` is called back whenever there is a window re-paint request) - the clearing color is not changed in the entire program.

```
// In initGL(), set the "clearing" or background color
glClearColor(0.0f, 0.0f, 0.0f, 1.0f);  // black and opaque

// In display(), clear the color buffer (i.e., set background) with the current "clearing" color
glClear(GL_COLOR_BUFFER_BIT);
```

Another example: If we use `glColor` function to set the current foreground color to "red", then "red" will be used for all the subsequent vertices, until we use another `glColor` function to change the foreground color.

In a state machine, everything shall remain until you explicitly change it!

3.3 Naming Convention for OpenGL Functions

An OpenGL functions:

- begins with lowercase `gl` (for core OpenGL), `glu` (for OpenGL Utility) or `glut` (for OpenGL Utility Toolkit).
- followed by the purpose of the function, in *camel case* (initial-capitalized), e.g., `glColor` to specify the drawing color, `glVertex` to define the position of a vertex.
- followed by specifications for the parameters, e.g., `glColor3f` takes three `float` parameters. `glVectex2i` takes two `int` parameters.
  (This is needed as C Language does not support function overloading. Different versions of the function need to be written for different parameter lists.)

The convention can be expressed as follows:

```
returnType glFunction[234][sifd] (type value, ...);  // 2, 3 or 4 parameters
returnType glFunction[234][sifd]v (type *value);     // an array parameter
```

The function may take 2, 3, or 4 parameters, in type of `s` (`GLshort`), `i` (`GLint`), `f` (`GLfloat`) or `d` (`GLdouble`). The 'v' (for vector) denotes that the parameters are kept in an array of 2, 3, or 4 elements, and pass into the function as an array pointer.

OpenGL defines its own *data types*:

- Signed Integers: `GLbyte` (8-bit), `GLshort` (16-bit), `GLint` (32-bit).
- Unsigned Integers: `GLubyte` (8-bit), `GLushort` (16-bit), `GLuint` (32-bit).
- Floating-point numbers: `GLfloat` (32-bit), `GLdouble` (64-bit), `GLclampf` and `GLclampd` (between 0.0 and 1.0).
- `GLboolean` (unsigned char with 0 for false and non-0 for true).
- `GLsizei` (32-bit non-negative integers).
- `GLenum` (32-bit enumerated integers).

The OpenGL types are defined via `typedef` in "`gl.h`" as follows:

```
typedef unsigned int    GLenum;
typedef unsigned char   GLboolean;
typedef unsigned int    GLbitfield;
typedef void            GLvoid;
typedef signed char     GLbyte;         /* 1-byte signed */
typedef short           GLshort;        /* 2-byte signed */
typedef int             GLint;          /* 4-byte signed */
typedef unsigned char   GLubyte;        /* 1-byte unsigned */
```

```
typedef unsigned short  GLushort;       /* 2-byte unsigned */
typedef unsigned int    GLuint;         /* 4-byte unsigned */
typedef int             GLsizei;        /* 4-byte signed */
typedef float           GLfloat;        /* single precision float */
typedef float           GLclampf;       /* single precision float in [0,1] */
typedef double          GLdouble;       /* double precision float */
typedef double          GLclampd;       /* double precision float in [0,1] */
```

OpenGL's *constants* begins with "GL_", "GLU_" or "GLUT_", in uppercase separated with underscores, e.g., GL_COLOR_BUFFER_BIT.

For examples,

```
glVertex3f(1.1f, 2.2f, 3.3f);        // 3 GLfloat parameters
glVertex2i(4, 5);                    // 2 GLint parameters
glColor4f(0.0f, 0.0f, 0.0f, 1.0f);   // 4 GLfloat parameters

GLdouble aVertex[] = {1.1, 2.2, 3.3};
glVertex3fv(aVertex);        // an array of 3 GLfloat values
```

3.4 One-time Initialization initGL()

The initGL() is meant for carrying out one-time OpenGL initialization tasks, such as setting the clearing color. initGL() is invoked once (and only once) in main().

3.5 Callback Handler display()

The function display() is known as a *callback event handler*. An event handler provides the *response* to a particular *event* (such as key-press, mouse-click, window-paint). The function display() is meant to be the handler for *window-paint* event. The OpenGL graphics system calls back display() in response to a window-paint request to re-paint the window (e.g., window first appears, window is restored after minimized, and window is resized). Callback means that the function is invoked by the system, instead of called by the your program.

The Display() runs when the window first appears and once per subsequent re-paint request. Observe that we included OpenGL graphics rendering code inside the display() function, so as to re-draw the entire window when the window first appears and upon each re-paint request.

3.6 Setting up GLUT - main()

GLUT provides high-level utilities to simplify OpenGL programming, especially in interacting with the Operating System (such as creating a window, handling key and mouse inputs). The following GLUT functions were used in the above program:

- glutInit: initializes GLUT, must be called before other GL/GLUT functions. It takes the same arguments as the main().

  ```
  void glutInit(int *argc, char **argv)
  ```

- glutCreateWindow: creates a window with the given title.

  ```
  int glutCreateWindow(char *title)
  ```

- glutInitWindowSize: specifies the initial window width and height, in pixels.

  ```
  void glutInitWindowSize(int width, int height)
  ```

- glutInitWindowPosition: positions the top-left corner of the initial window at (*x*, *y*). The coordinates (*x*, *y*), in term of pixels, is measured in window coordinates, i.e., origin (0, 0) is at the top-left corner of the screen; x-axis pointing right and y-axis pointing down.

  ```
  void glutInitWindowPosition(int x, int y)
  ```

- `glutDisplayFunc`: registers the callback function (or event handler) for handling window-paint event. The OpenGL graphic system calls back this handler when it receives a window re-paint request. In the example, we register the function `display()` as the handler.

```
void glutDisplayFunc(void (*func)(void))
```

- `glutMainLoop`: enters the infinite event-processing loop, i.e, put the OpenGL graphics system to wait for events (such as re-paint), and trigger respective event handlers (such as `display()`).

```
void glutMainLoop()
```

In the `main()` function of the example:

```
glutInit(&argc, argv);
glutCreateWindow("Vertex, Primitive & Color");
glutInitWindowSize(320, 320);
glutInitWindowPosition(50, 50);
```

We initialize the GLUT and create a window with a title, an initial size and position.

```
glutDisplayFunc(display);
```

We register `display()` function as the callback handler for window-paint event. That is, `display()` runs when the window first appears and whenever there is a request to re-paint the window.

```
initGL();
```

We call the `initGL()` to perform all the one-time initialization operations. In this example, we set the clearing (background) color once, and use it repeatably in the `display()` function.

```
glutMainLoop();
```

We then put the program into the event-handling loop, awaiting for events (such as window-paint request) to trigger off the respective event handlers (such as `display()`).

3.7 Color

We use `glColor` function to set the *foreground color*, and `glClearColor` function to set the *background* (or *clearing*) color.

```
void glColor3f(GLfloat red, GLfloat green, GLfloat blue)
void glColor3fv(GLfloat *colorRGB)
void glColor4f(GLfloat red, GLfloat green, GLfloat blue, GLfloat alpha)
void glColor4fv(GLfloat *colorRGBA)

void glClearColor(GLclampf red, GLclampf green, GLclampf blue, GLclampf alpha)
   // GLclampf in the range of 0.0f to 1.0f
```

Notes:

- Color is typically specified in `float` in the range `0.0f` and `1.0f`.
- Color can be specified using RGB (Red-Green-Blue) or RGBA (Red-Green-Blue-Alpha) components. The 'A' (or alpha) specifies the transparency (or opacity) index, with value of 1 denotes opaque (non-transparent and cannot see-thru) and value of 0 denotes total transparent. We shall discuss alpha later.

In the above example, we set the background color via `glClearColor` in `initGL()`, with R=0, G=0, B=0 (black) and A=1 (opaque and cannot see through).

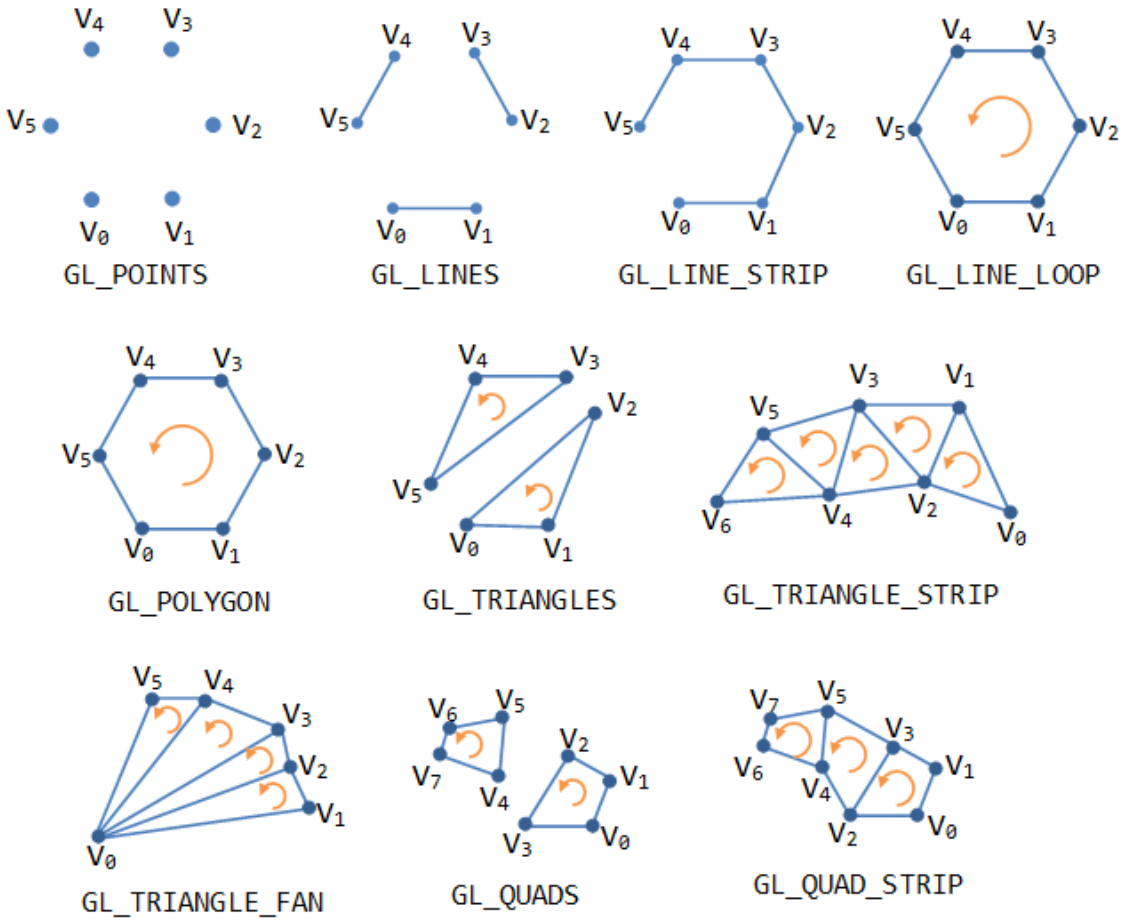
```
// In initGL(), set the "clearing" or background color
glClearColor(0.0f, 0.0f, 0.0f, 1.0f);  // Black and opaque
```

In `display()`, we set the vertex color via `glColor3f` for subsequent vertices. For example, R=1, G=0, B=0 (red).

```
// In display(), set the foreground color of the pixel
glColor3f(1.0f, 0.0f, 0.0f);  // Red
```

3.8 Geometric Primitives

In OpenGL, an object is made up of geometric primitives such as triangle, quad, line segment and point. A primitive is made up of one or more vertices. OpenGL supports the following primitives:



OpenGL Primitives

A geometric primitive is defined by specifying its vertices via `glVertex` function, enclosed within a pair `glBegin` and `glEnd`.

```
void glBegin(GLenum shape)
   void glVertex[234][sifd] (type x, type y, type z, ...)
   void glVertex[234][sifd]v (type *coords)
void glEnd()
```

`glBegin` specifies the type of geometric object, such as `GL_POINTS`, `GL_LINES`, `GL_QUADS`, `GL_TRIANGLES`, and `GL_POLYGON`. For types that end with 'S', you can define multiple objects of the same type in each `glBegin`/`glEnd` pair. For example, for `GL_TRIANGLES`, each set of three `glVertex`'s defines a triangle.

The vertices are usually specified in `float` precision. It is because integer is not suitable for trigonometric operations (needed to carry out transformations such as rotation). Precision of `float` is sufficient for carrying out intermediate operations, and render the objects finally into pixels on screen (with resolution of says 800x600, integral precision). `double` precision is often not necessary.

In the above example:

```
glBegin(GL_QUADS);
   .... 4 quads with 12x glVertex() ....
glEnd();
```

we define 3 color quads (`GL_QUADS`) with 12x `glVertex()` functions.

```
glColor3f(1.0f, 0.0f, 0.0f);
glVertex2f(-0.8f, 0.1f);
glVertex2f(-0.2f, 0.1f);
glVertex2f(-0.2f, 0.7f);
glVertex2f(-0.8f, 0.7f);
```

We set the color to red (R=1, G=0, B=0). All subsequent vertices will have the color of red. Take note that in OpenGL, color (and many properties) is applied to vertices rather than primitive shapes. The color of the a primitive shape is *interpolated* from its vertices.

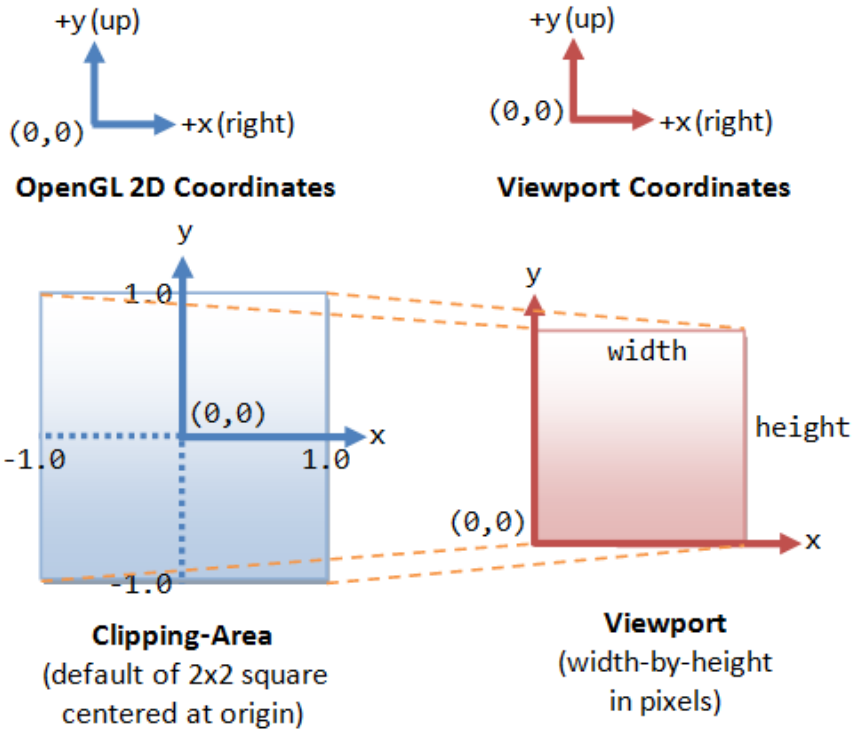
We similarly define a second quad in green.

For the third quad (as follows), the vertices have different color. The color of the quad surface is interpolated from its vertices, resulting in a shades of white to dark gray, as shown in the output.

```
glColor3f(0.2f, 0.2f, 0.2f);  // Dark Gray
glVertex2f(-0.9f, -0.7f);
glColor3f(1.0f, 1.0f, 1.0f);  // White
glVertex2f(-0.5f, -0.7f);
glColor3f(0.2f, 0.2f, 0.2f);  // Dark Gray
glVertex2f(-0.5f, -0.3f);
glColor3f(1.0f, 1.0f, 1.0f);  // White
glVertex2f(-0.9f, -0.3f);
```

3.9 2D Coordinate System and the Default View

The following diagram shows the OpenGL 2D Coordinate System, which corresponds to the everyday 2D Cartesian coordinates with origin located at the bottom-left corner.



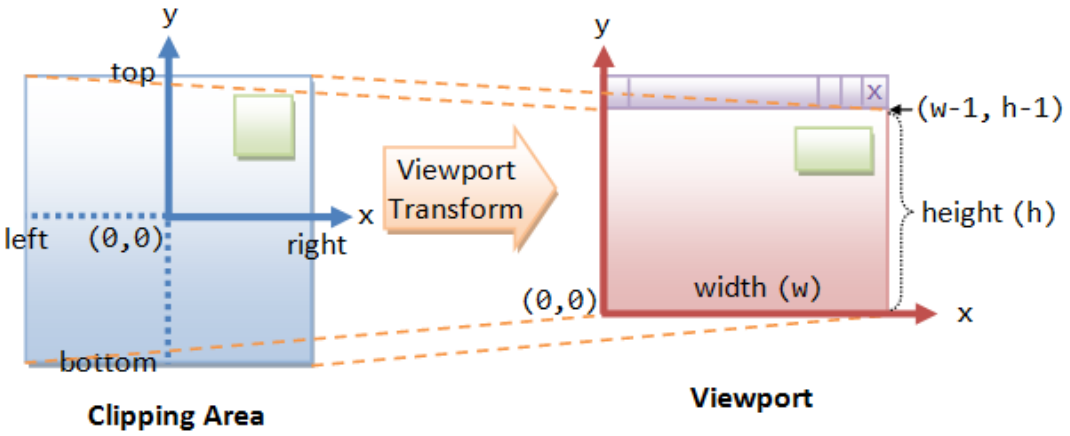
The default OpenGL 2D *clipping-area* (i.e., what is captured by the camera) is an orthographic view with x and y in the range of -1.0 and 1.0, i.e., a 2x2 square with centered at the origin. This clipping-area is mapped to the *viewport* on the screen. Viewport is measured in pixels.

Study the above example to convince yourself that the 2D shapes created are positioned correctly on the screen.

4. Clipping-Area & Viewport

Try dragging the corner of the window to make it bigger or smaller. Observe that all the shapes are distorted.

We can handle the re-sizing of window via a callback handler `reshape()`, which can be programmed to adjust the OpenGL clipping-area according to the window's aspect ratio.



Clipping Area and Viewport: Objects will be distorted if the aspect ratios of the clipping area and viewport are different.

Clipping Area: *Clipping area* refers to the area that can be seen (i.e., captured by the camera), measured in OpenGL coordinates.

The function `gluOrtho2D` can be used to set the clipping area of 2D orthographic view. Objects outside the clipping area will be *clipped* away and cannot be seen.

```
void gluOrtho2D(GLdouble left, GLdouble right, GLdouble bottom, GLdouble top)
   // The default clipping area is (-1.0, 1.0, -1.0, 1.0) in OpenGL coordinates,
   // i.e., 2x2 square centered at the origin.
```

To set the clipping area, we need to issue a series of commands as follows: we first select the so-called *projection matrix* for operation, and reset the projection matrix to identity. We then choose the 2D orthographic view with the desired clipping area, via `gluOrtho2D()`.

```
// Set to 2D orthographic projection with the specified clipping area
glMatrixMode(GL_PROJECTION);      // Select the Projection matrix for operation
glLoadIdentity();                 // Reset Projection matrix
gluOrtho2D(-1.0, 1.0, -1.0, 1.0); // Set clipping area's left, right, bottom, top
```

Viewport: *Viewport* refers to the display area on the window (screen), which is measured in pixels in screen coordinates (excluding the title bar).

The clipping area is mapped to the viewport. We can use `glViewport` function to configure the viewport.

```
void glViewport(GLint xTopLeft, GLint yTopLeft, GLsizei width, GLsizei height)
```

Suppose the the clipping area's (left, right, bottom, top) is (-1.0, 1.0, -1.0, 1.0) (in OpenGL coordinates) and the viewport's (xTopLeft, xTopRight, width, height) is (0, 0, 640, 480) (in screen coordinates in pixels), then the bottom-left corner (-1.0, -1.0) maps to (0, 0) in the viewport, the top-right corner (1.0, 1.0) maps to (639, 479). It is obvious that if the *aspect ratios* for the clipping area and the viewport are not the same, the shapes will be distorted.

Take note that in the earlier example, the windows' size of 320x320 has a square shape, with a aspect ratio consistent with the default 2x2 squarish clipping-area.

4.1 Example 3: Clipping-area and Viewport (`GL03Viewport.cpp`)

```
1  /*
2   * GL03Viewport.cpp: Clipping-area and Viewport
3   * Implementing reshape to ensure same aspect ratio between the
4   * clipping-area and the viewport.
5   */
6  #include <windows.h>  // for MS Windows
7  #include <GL/glut.h>  // GLUT, include glu.h and gl.h
8
```

```
/* Initialize OpenGL Graphics */
void initGL() {
   // Set "clearing" or background color
   glClearColor(0.0f, 0.0f, 0.0f, 1.0f); // Black and opaque
}

void display() {
   glClear(GL_COLOR_BUFFER_BIT);   // Clear the color buffer with current clearing color

   // Define shapes enclosed within a pair of glBegin and glEnd
   glBegin(GL_QUADS);              // Each set of 4 vertices form a quad
      glColor3f(1.0f, 0.0f, 0.0f); // Red
      glVertex2f(-0.8f, 0.1f);     // Define vertices in counter-clockwise (CCW) order
      glVertex2f(-0.2f, 0.1f);     //  so that the normal (front-face) is facing you
      glVertex2f(-0.2f, 0.7f);
      glVertex2f(-0.8f, 0.7f);

      glColor3f(0.0f, 1.0f, 0.0f); // Green
      glVertex2f(-0.7f, -0.6f);
      glVertex2f(-0.1f, -0.6f);
      glVertex2f(-0.1f,  0.0f);
      glVertex2f(-0.7f,  0.0f);

      glColor3f(0.2f, 0.2f, 0.2f); // Dark Gray
      glVertex2f(-0.9f, -0.7f);
      glColor3f(1.0f, 1.0f, 1.0f); // White
      glVertex2f(-0.5f, -0.7f);
      glColor3f(0.2f, 0.2f, 0.2f); // Dark Gray
      glVertex2f(-0.5f, -0.3f);
      glColor3f(1.0f, 1.0f, 1.0f); // White
      glVertex2f(-0.9f, -0.3f);
   glEnd();

   glBegin(GL_TRIANGLES);          // Each set of 3 vertices form a triangle
      glColor3f(0.0f, 0.0f, 1.0f); // Blue
      glVertex2f(0.1f, -0.6f);
      glVertex2f(0.7f, -0.6f);
      glVertex2f(0.4f, -0.1f);

      glColor3f(1.0f, 0.0f, 0.0f); // Red
      glVertex2f(0.3f, -0.4f);
      glColor3f(0.0f, 1.0f, 0.0f); // Green
      glVertex2f(0.9f, -0.4f);
      glColor3f(0.0f, 0.0f, 1.0f); // Blue
      glVertex2f(0.6f, -0.9f);
   glEnd();

   glBegin(GL_POLYGON);            // These vertices form a closed polygon
      glColor3f(1.0f, 1.0f, 0.0f); // Yellow
      glVertex2f(0.4f, 0.2f);
      glVertex2f(0.6f, 0.2f);
      glVertex2f(0.7f, 0.4f);
      glVertex2f(0.6f, 0.6f);
      glVertex2f(0.4f, 0.6f);
      glVertex2f(0.3f, 0.4f);
   glEnd();

   glFlush();  // Render now
}

/* Handler for window re-size event. Called back when the window first appears and
   whenever the window is re-sized with its new width and height */
```

```
71  void reshape(GLsizei width, GLsizei height) {  // GLsizei for non-negative integer
72     // Compute aspect ratio of the new window
73     if (height == 0) height = 1;                // To prevent divide by 0
74     GLfloat aspect = (GLfloat)width / (GLfloat)height;
75
76     // Set the viewport to cover the new window
77     glViewport(0, 0, width, height);
78
79     // Set the aspect ratio of the clipping area to match the viewport
80     glMatrixMode(GL_PROJECTION);  // To operate on the Projection matrix
81     glLoadIdentity();             // Reset the projection matrix
82     if (width >= height) {
83       // aspect >= 1, set the height from -1 to 1, with larger width
84        gluOrtho2D(-1.0 * aspect, 1.0 * aspect, -1.0, 1.0);
85     } else {
86        // aspect < 1, set the width to -1 to 1, with larger height
87       gluOrtho2D(-1.0, 1.0, -1.0 / aspect, 1.0 / aspect);
88     }
89  }
90
91  /* Main function: GLUT runs as a console application starting at main() */
92  int main(int argc, char** argv) {
93     glutInit(&argc, argv);          // Initialize GLUT
94     glutInitWindowSize(640, 480);   // Set the window's initial width & height - non-square
95     glutInitWindowPosition(50, 50); // Position the window's initial top-left corner
96     glutCreateWindow("Viewport Transform");  // Create window with the given title
97     glutDisplayFunc(display);       // Register callback handler for window re-paint event
98     glutReshapeFunc(reshape);       // Register callback handler for window re-size event
99     initGL();                       // Our own OpenGL initialization
100    glutMainLoop();                 // Enter the infinite event-processing loop
101    return 0;
102 }
```

A `reshape()` function, which is called back when the window first appears and whenever the window is re-sized, can be used to ensure consistent aspect ratio between clipping-area and viewport, as shown in the above example. The graphics sub-system passes the window's width and height, in pixels, into the `reshape()`.

```
GLfloat aspect = (GLfloat)width / (GLfloat)height;
```

We compute the aspect ratio of the new re-sized window, given its new `width` and `height` provided by the graphics sub-system to the callback function `reshape()`.

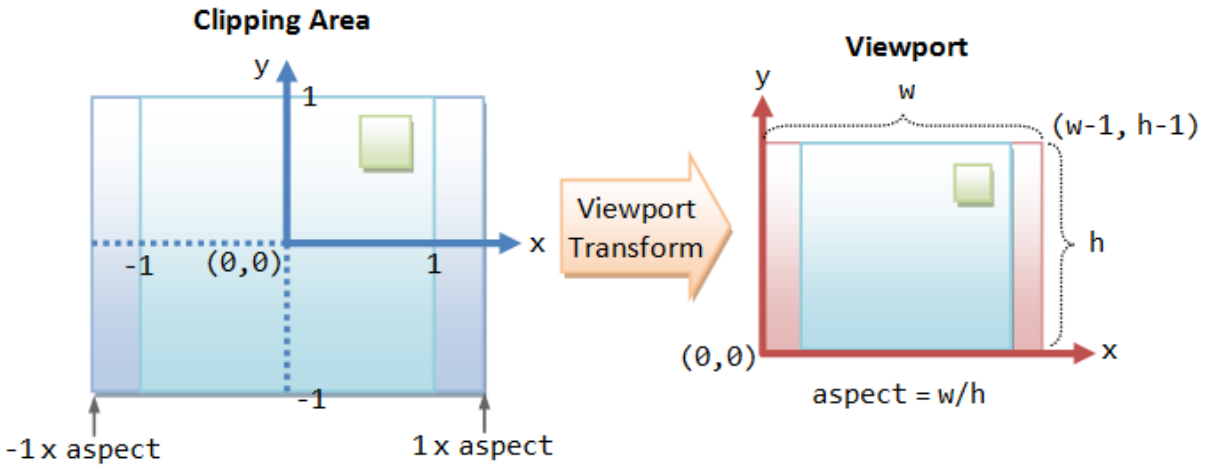
```
glViewport(0, 0, width, height);
```

We set the viewport to cover the entire new re-sized window, in pixels.
Try setting the viewport to cover only a quarter (lower-right qradrant) of the window via `glViewport(0, 0, width/2, height/2)`.

```
glMatrixMode(GL_PROJECTION);
glLoadIdentity();
if (width >= height) {
   gluOrtho2D(-1.0 * aspect, 1.0 * aspect, -1.0, 1.0);
} else {
   gluOrtho2D(-1.0, 1.0, -1.0 / aspect, 1.0 / aspect);
}
```

We set the aspect ratio of the clipping area to match the viewport. To set the clipping area, we first choose the operate on the projection matrix via `glMatrixMode(GL_PROJECTION)`. OpenGL has two matrices, a projection matrix (which deals with camera projection such as setting the clipping area) and a model-view matrix (for transforming the objects from their local spaces to the common world space). We reset the projection matrix via `glLoadIdentity()`.

Finally, we invoke `gluOrtho2D()` to set the clipping area with an aspect ratio matching the viewport. The shorter side has the range from -1 to +1, as illustrated below:



Clipping Area and Viewport: same aspect ratio for the clipping area and viewport to ensure that the objects are not distorted.

We need to register the `reshape()` callback handler with GLUT via `glutReshapeFunc()` in the `main()` as follows:

```
int main(int argc, char** argv) {
   glutInitWindowSize(640, 480);
   ......
   glutReshapeFunc(reshape);
}
```

In the above `main()` function, we specify the initial window size to `640x480`, which is non-squarish. Try re-sizing the window and observe the changes.

Note that the `reshape()` runs at least *once* when the window first appears. It is then called back whenever the window is re-shaped. On the other hand, the `initGL()` runs once (and only once); and the `display()` runs in response to window re-paint request (e.g., after the window is re-sized).

5. Translation & Rotation

In the above sample, we positioned each of the shapes by defining their vertices with respective to the *same* origin (called *world space*). It took me quite a while to figure out the absolute coordinates of these vertices.

Instead, we could position each of the shapes by defining their vertices with respective to their own center (called *model space* or *local space*). We can then use translation and/or rotation to position the shapes at the desired locations in the world space, as shown in the following revised `display()` function.

5.1 Example 4: Translation and Rotation (`GL04ModelTransform.cpp`)

```
1  /*
2   * GL04ModelTransform.cpp: Model Transform - Translation and Rotation
3   * Transform primitives from their model spaces to world space.
4   */
5  #include <windows.h>  // for MS Windows
6  #include <GL/glut.h>  // GLUT, include glu.h and gl.h
7
8  /* Initialize OpenGL Graphics */
9  void initGL() {
10    // Set "clearing" or background color
11    glClearColor(0.0f, 0.0f, 0.0f, 1.0f); // Black and opaque
12 }
13
14 /* Handler for window-repaint event. Call back when the window first appears and
15    whenever the window needs to be re-painted. */
16 void display() {
17    glClear(GL_COLOR_BUFFER_BIT);    // Clear the color buffer
```

```
18      glMatrixMode(GL_MODELVIEW);      // To operate on Model-View matrix
19      glLoadIdentity();                // Reset the model-view matrix
20
21      glTranslatef(-0.5f, 0.4f, 0.0f); // Translate left and up
22      glBegin(GL_QUADS);               // Each set of 4 vertices form a quad
23         glColor3f(1.0f, 0.0f, 0.0f);  // Red
24         glVertex2f(-0.3f, -0.3f);     // Define vertices in counter-clockwise (CCW) order
25         glVertex2f( 0.3f, -0.3f);     //  so that the normal (front-face) is facing you
26         glVertex2f( 0.3f,  0.3f);
27         glVertex2f(-0.3f,  0.3f);
28      glEnd();
29
30      glTranslatef(0.1f, -0.7f, 0.0f); // Translate right and down
31      glBegin(GL_QUADS);               // Each set of 4 vertices form a quad
32         glColor3f(0.0f, 1.0f, 0.0f); // Green
33         glVertex2f(-0.3f, -0.3f);
34         glVertex2f( 0.3f, -0.3f);
35         glVertex2f( 0.3f,  0.3f);
36         glVertex2f(-0.3f,  0.3f);
37      glEnd();
38
39      glTranslatef(-0.3f, -0.2f, 0.0f); // Translate left and down
40      glBegin(GL_QUADS);                // Each set of 4 vertices form a quad
41         glColor3f(0.2f, 0.2f, 0.2f); // Dark Gray
42         glVertex2f(-0.2f, -0.2f);
43         glColor3f(1.0f, 1.0f, 1.0f); // White
44         glVertex2f( 0.2f, -0.2f);
45         glColor3f(0.2f, 0.2f, 0.2f); // Dark Gray
46         glVertex2f( 0.2f,  0.2f);
47         glColor3f(1.0f, 1.0f, 1.0f); // White
48         glVertex2f(-0.2f,  0.2f);
49      glEnd();
50
51      glTranslatef(1.1f, 0.2f, 0.0f); // Translate right and up
52      glBegin(GL_TRIANGLES);          // Each set of 3 vertices form a triangle
53         glColor3f(0.0f, 0.0f, 1.0f); // Blue
54         glVertex2f(-0.3f, -0.2f);
55         glVertex2f( 0.3f, -0.2f);
56         glVertex2f( 0.0f,  0.3f);
57      glEnd();
58
59      glTranslatef(0.2f, -0.3f, 0.0f);     // Translate right and down
60      glRotatef(180.0f, 0.0f, 0.0f, 1.0f); // Rotate 180 degree
61         glBegin(GL_TRIANGLES);               // Each set of 3 vertices form a triangle
62         glColor3f(1.0f, 0.0f, 0.0f); // Red
63         glVertex2f(-0.3f, -0.2f);
64         glColor3f(0.0f, 1.0f, 0.0f); // Green
65         glVertex2f( 0.3f, -0.2f);
66         glColor3f(0.0f, 0.0f, 1.0f); // Blue
67         glVertex2f( 0.0f,  0.3f);
68      glEnd();
69
70      glRotatef(-180.0f, 0.0f, 0.0f, 1.0f); // Undo previous rotate
71      glTranslatef(-0.1f, 1.0f, 0.0f);      // Translate right and down
72      glBegin(GL_POLYGON);                  // The vertices form one closed polygon
73         glColor3f(1.0f, 1.0f, 0.0f); // Yellow
74         glVertex2f(-0.1f, -0.2f);
75         glVertex2f( 0.1f, -0.2f);
76         glVertex2f( 0.2f,  0.0f);
77         glVertex2f( 0.1f,  0.2f);
78         glVertex2f(-0.1f,  0.2f);
79         glVertex2f(-0.2f,  0.0f);
```

```
   glEnd();

   glFlush();   // Render now
}

/* Handler for window re-size event. Called back when the window first appears and
   whenever the window is re-sized with its new width and height */
void reshape(GLsizei width, GLsizei height) {  // GLsizei for non-negative integer
   // Compute aspect ratio of the new window
   if (height == 0) height = 1;                // To prevent divide by 0
   GLfloat aspect = (GLfloat)width / (GLfloat)height;

   // Set the viewport to cover the new window
   glViewport(0, 0, width, height);

   // Set the aspect ratio of the clipping area to match the viewport
   glMatrixMode(GL_PROJECTION);  // To operate on the Projection matrix
   glLoadIdentity();
   if (width >= height) {
     // aspect >= 1, set the height from -1 to 1, with larger width
      gluOrtho2D(-1.0 * aspect, 1.0 * aspect, -1.0, 1.0);
   } else {
      // aspect < 1, set the width to -1 to 1, with larger height
     gluOrtho2D(-1.0, 1.0, -1.0 / aspect, 1.0 / aspect);
   }
}

/* Main function: GLUT runs as a console application starting at main() */
int main(int argc, char** argv) {
   glutInit(&argc, argv);          // Initialize GLUT
   glutInitWindowSize(640, 480);   // Set the window's initial width & height - non-square
   glutInitWindowPosition(50, 50); // Position the window's initial top-left corner
   glutCreateWindow("Model Transform");  // Create window with the given title
   glutDisplayFunc(display);       // Register callback handler for window re-paint event
   glutReshapeFunc(reshape);       // Register callback handler for window re-size event
   initGL();                       // Our own OpenGL initialization
   glutMainLoop();                 // Enter the infinite event-processing loop
   return 0;
}
```

```
glMatrixMode(GL_MODELVIEW); // To operate on model-view matrix
glLoadIdentity();           // Reset
```

Translation and rotation are parts of so-called *model transform*, which transform from the objects from the local space (or model space) to the common world space. To carry out model transform, we set the matrix mode to mode-view matrix (`GL_MODELVIEW`) and reset the matrix. (Recall that in the previous example, we set the matrix mode to projection matrix (`GL_PROJECTION`) to set the clipping area.)

OpenGL is operating as a state machine. That is, once a state is set, the value of the state persists until it is changed. In other words, once the coordinates are translated or rotated, all the subsequent operations will be based on this coordinates.

Translation is done via `glTranslate` function:

```
void gltranslatef (GLfloat x, GLfloat y, GLfloat z)
   // where (x, y, z) is the translational vector
```

Take note that `glTranslatef` function must be placed outside the `glBegin`/`glEnd`, where as `glColor` can be placed inside `glBegin`/`glEnd`.

Rotation is done via `glRotatef` function:

```
void glRotatef (GLfloat angle, GLfloat x, GLfloat y, GLfloat z)
   // where angle specifies the rotation in degree, (x, y, z) forms the axis of rotation.
```

Take note that the rotational angle is measured in degrees (instead of radians) in OpenGL.

In the above example, we translate within the x-y plane (z=0) and rotate about the z-axis (which is normal to the x-y plane).

6. Animation

6.1 Idle Function

To perform animation (e.g., rotating the shapes), you could register an `idle()` callback handler with GLUT, via `glutIdleFunc` command. The graphic system will call back the `idle()` function when there is no other event to be processed.

```
void glutIdleFunc(void (*func)(void))
```

In the `idle()` function, you could issue `glutPostRedisplay` command to post a window re-paint request, which in turn will activate `display()` function.

```
void idle() {
   glutPostRedisplay();   // Post a re-paint request to activate display()
}
```

Take note that the above is equivalent to registering `display()` as the `idle` function.

```
// main
glutIdleFunc(display);
```

6.2 Double Buffering

Double buffering uses two display buffers to smoothen animation. The next screen is prepared in a *back* buffer, while the current screen is held in a *front* buffer. Once the preparation is done, you can use `glutSwapBuffer` command to swap the front and back buffers.

To use double buffering, you need to make two changes:

1. In the `main()`, include this line before creating the window:

   ```
   glutInitDisplayMode(GLUT_DOUBLE);  // Set double buffered mode
   ```

2. In the `display()` function, replace `glFlush()` with `glutSwapBuffers()`, which swap the front and back buffers.

Double buffering should be used in animation. For static display, single buffering is sufficient. (Many graphics hardware always double buffered, so it is hard to see the differences.)

6.3 Example 5: Animation using Idle Function (`GL05IdleFunc.cpp`)

The following program rotates all the shapes created in our previous example using idle function with double buffering.

```
1  /*
2   * GL05IdleFunc.cpp: Translation and Rotation
3   * Transform primitives from their model spaces to world space (Model Transform).
4   */
5  #include <windows.h>  // for MS Windows
6  #include <GL/glut.h>  // GLUT, include glu.h and gl.h
7
8  // Global variable
9  GLfloat angle = 0.0f;  // Current rotational angle of the shapes
10
```

```
/* Initialize OpenGL Graphics */
void initGL() {
   // Set "clearing" or background color
   glClearColor(0.0f, 0.0f, 0.0f, 1.0f); // Black and opaque
}

/* Called back when there is no other event to be handled */
void idle() {
   glutPostRedisplay();   // Post a re-paint request to activate display()
}

/* Handler for window-repaint event. Call back when the window first appears and
   whenever the window needs to be re-painted. */
void display() {
   glClear(GL_COLOR_BUFFER_BIT);   // Clear the color buffer
   glMatrixMode(GL_MODELVIEW);     // To operate on Model-View matrix
   glLoadIdentity();               // Reset the model-view matrix

   glPushMatrix();                     // Save model-view matrix setting
   glTranslatef(-0.5f, 0.4f, 0.0f);    // Translate
   glRotatef(angle, 0.0f, 0.0f, 1.0f); // rotate by angle in degrees
   glBegin(GL_QUADS);                  // Each set of 4 vertices form a quad
      glColor3f(1.0f, 0.0f, 0.0f);     // Red
      glVertex2f(-0.3f, -0.3f);
      glVertex2f( 0.3f, -0.3f);
      glVertex2f( 0.3f,  0.3f);
      glVertex2f(-0.3f,  0.3f);
   glEnd();
   glPopMatrix();                      // Restore the model-view matrix

   glPushMatrix();                     // Save model-view matrix setting
   glTranslatef(-0.4f, -0.3f, 0.0f);   // Translate
   glRotatef(angle, 0.0f, 0.0f, 1.0f); // rotate by angle in degrees
   glBegin(GL_QUADS);
      glColor3f(0.0f, 1.0f, 0.0f); // Green
      glVertex2f(-0.3f, -0.3f);
      glVertex2f( 0.3f, -0.3f);
      glVertex2f( 0.3f,  0.3f);
      glVertex2f(-0.3f,  0.3f);
   glEnd();
   glPopMatrix();                      // Restore the model-view matrix

   glPushMatrix();                     // Save model-view matrix setting
   glTranslatef(-0.7f, -0.5f, 0.0f);   // Translate
   glRotatef(angle, 0.0f, 0.0f, 1.0f); // rotate by angle in degrees
   glBegin(GL_QUADS);
      glColor3f(0.2f, 0.2f, 0.2f); // Dark Gray
      glVertex2f(-0.2f, -0.2f);
      glColor3f(1.0f, 1.0f, 1.0f); // White
      glVertex2f( 0.2f, -0.2f);
      glColor3f(0.2f, 0.2f, 0.2f); // Dark Gray
      glVertex2f( 0.2f,  0.2f);
      glColor3f(1.0f, 1.0f, 1.0f); // White
      glVertex2f(-0.2f,  0.2f);
   glEnd();
   glPopMatrix();                      // Restore the model-view matrix

   glPushMatrix();                     // Save model-view matrix setting
   glTranslatef(0.4f, -0.3f, 0.0f);    // Translate
   glRotatef(angle, 0.0f, 0.0f, 1.0f); // rotate by angle in degrees
   glBegin(GL_TRIANGLES);
      glColor3f(0.0f, 0.0f, 1.0f); // Blue
```

```
      glVertex2f(-0.3f, -0.2f);
      glVertex2f( 0.3f, -0.2f);
      glVertex2f( 0.0f,  0.3f);
   glEnd();
   glPopMatrix();                     // Restore the model-view matrix

   glPushMatrix();                    // Save model-view matrix setting
   glTranslatef(0.6f, -0.6f, 0.0f);   // Translate
   glRotatef(180.0f + angle, 0.0f, 0.0f, 1.0f); // Rotate 180+angle degree
   glBegin(GL_TRIANGLES);
      glColor3f(1.0f, 0.0f, 0.0f); // Red
      glVertex2f(-0.3f, -0.2f);
      glColor3f(0.0f, 1.0f, 0.0f); // Green
      glVertex2f( 0.3f, -0.2f);
      glColor3f(0.0f, 0.0f, 1.0f); // Blue
      glVertex2f( 0.0f,  0.3f);
   glEnd();
   glPopMatrix();                     // Restore the model-view matrix

   glPushMatrix();                    // Save model-view matrix setting
   glTranslatef(0.5f, 0.4f, 0.0f);    // Translate
   glRotatef(angle, 0.0f, 0.0f, 1.0f); // rotate by angle in degrees
   glBegin(GL_POLYGON);
      glColor3f(1.0f, 1.0f, 0.0f); // Yellow
      glVertex2f(-0.1f, -0.2f);
      glVertex2f( 0.1f, -0.2f);
      glVertex2f( 0.2f,  0.0f);
      glVertex2f( 0.1f,  0.2f);
      glVertex2f(-0.1f,  0.2f);
      glVertex2f(-0.2f,  0.0f);
   glEnd();
   glPopMatrix();                     // Restore the model-view matrix

   glutSwapBuffers();   // Double buffered - swap the front and back buffers

   // Change the rotational angle after each display()
   angle += 0.2f;
}

/* Handler for window re-size event. Called back when the window first appears and
   whenever the window is re-sized with its new width and height */
void reshape(GLsizei width, GLsizei height) {  // GLsizei for non-negative integer
   // Compute aspect ratio of the new window
   if (height == 0) height = 1;                // To prevent divide by 0
   GLfloat aspect = (GLfloat)width / (GLfloat)height;

   // Set the viewport to cover the new window
   glViewport(0, 0, width, height);

   // Set the aspect ratio of the clipping area to match the viewport
   glMatrixMode(GL_PROJECTION);  // To operate on the Projection matrix
   glLoadIdentity();
   if (width >= height) {
     // aspect >= 1, set the height from -1 to 1, with larger width
      gluOrtho2D(-1.0 * aspect, 1.0 * aspect, -1.0, 1.0);
   } else {
      // aspect < 1, set the width to -1 to 1, with larger height
     gluOrtho2D(-1.0, 1.0, -1.0 / aspect, 1.0 / aspect);
   }
}

/* Main function: GLUT runs as a console application starting at main() */
```

```
int main(int argc, char** argv) {
   glutInit(&argc, argv);          // Initialize GLUT
   glutInitDisplayMode(GLUT_DOUBLE);  // Enable double buffered mode
   glutInitWindowSize(640, 480);   // Set the window's initial width & height - non-square
   glutInitWindowPosition(50, 50); // Position the window's initial top-left corner
   glutCreateWindow("Animation via Idle Function");  // Create window with the given title
   glutDisplayFunc(display);       // Register callback handler for window re-paint event
   glutReshapeFunc(reshape);       // Register callback handler for window re-size event
   glutIdleFunc(idle);             // Register callback handler if no other event
   initGL();                       // Our own OpenGL initialization
   glutMainLoop();                 // Enter the infinite event-processing loop
   return 0;
}
```

In the above example, instead of accumulating all the translations and undoing the rotations, we use `glPushMatrix` to save the current state, perform transformations, and restore the saved state via `glPopMatrix`. (In the above example, we can also use `glLoadIdentity` to reset the matrix before the next transformations.)

```
GLfloat angle = 0.0f;  // Current rotational angle of the shapes
```

We define a global variable called `angle` to keep track of the rotational angle of all the shapes. We will later use `glRotatef` to rotate all the shapes to this angle.

```
angle += 0.2f;
```

At the end of each refresh (in `display()`), we update the rotational angle of all the shapes.

```
glutSwapBuffers();                // Swap front- and back framebuffer

glutInitDisplayMode(GLUT_DOUBLE);  // In main(), enable double buffered mode
```

Instead of `glFlush()` which flushes the framebuffer for display immediately, we enable double buffering and use `glutSwapBuffer()` to swap the front- and back-buffer during the VSync for smoother display.

```
void idle() {
   glutPostRedisplay();   // Post a re-paint request to activate display()
}

glutIdleFunc(idle);       // In main() - Register callback handler if no other event
```

We define an `idle()` function, which posts a re-paint request and invoke `display()`, if there is no event outstanding. We register this `idle()` function in `main()` via `glutIdleFunc()`.

6.4 Double Buffering & Refresh Rate

When double buffering is enabled, `glutSwapBuffers` synchronizes with the screen refresh interval (VSync). That is, the buffers will be swapped at the same time when the monitor is putting up a new frame. As the result, `idle()` function, at best, refreshes the animation at the same rate as the refresh rate of the monitor (60Hz for LCD/LED monitor). It may operates at half the monitor refresh rate (if the computations takes more than 1 refresh interval), one-third, one-fourth, and so on, because it need to wait for the VSync.

6.5 Timer Function

With `idle()`, we have no control to the refresh interval. We could register a `Timer()` function with GLUT via `glutTimerFunc`. The `Timer()` function will be called back at the specified fixed interval.

```
void glutTimerFunc(unsigned int millis, void (*func)(int value), value)
   // where millis is the delay in milliseconds, value will be passed to the timer function.
```

6.6 Example 6: Animation via Timer Function (`GL06TimerFunc.cpp`)

The following modifications rotate all the shapes created in the earlier example counter-clockwise by 2 degree per 30 milliseconds.

```
/*
 * GL06TimerFunc.cpp: Translation and Rotation
 * Transform primitives from their model spaces to world space (Model Transform).
 */
#include <windows.h>  // for MS Windows
#include <GL/glut.h>  // GLUT, include glu.h and gl.h

// global variable
GLfloat angle = 0.0f;  // rotational angle of the shapes
int refreshMills = 30; // refresh interval in milliseconds

/* Initialize OpenGL Graphics */
void initGL() {
   // Set "clearing" or background color
   glClearColor(0.0f, 0.0f, 0.0f, 1.0f); // Black and opaque
}

/* Called back when timer expired */
void Timer(int value) {
   glutPostRedisplay();      // Post re-paint request to activate display()
   glutTimerFunc(refreshMills, Timer, 0); // next Timer call milliseconds later
}

/* Handler for window-repaint event. Call back when the window first appears and
   whenever the window needs to be re-painted. */
void display() {
   glClear(GL_COLOR_BUFFER_BIT);   // Clear the color buffer
   glMatrixMode(GL_MODELVIEW);     // To operate on Model-View matrix
   glLoadIdentity();               // Reset the model-view matrix

   glPushMatrix();                     // Save model-view matrix setting
   glTranslatef(-0.5f, 0.4f, 0.0f);    // Translate
   glRotatef(angle, 0.0f, 0.0f, 1.0f); // rotate by angle in degrees
   glBegin(GL_QUADS);                  // Each set of 4 vertices form a quad
      glColor3f(1.0f, 0.0f, 0.0f);     // Red
      glVertex2f(-0.3f, -0.3f);
      glVertex2f( 0.3f, -0.3f);
      glVertex2f( 0.3f,  0.3f);
      glVertex2f(-0.3f,  0.3f);
   glEnd();
   glPopMatrix();                      // Restore the model-view matrix

   glPushMatrix();                     // Save model-view matrix setting
   glTranslatef(-0.4f, -0.3f, 0.0f);   // Translate
   glRotatef(angle, 0.0f, 0.0f, 1.0f); // rotate by angle in degrees
   glBegin(GL_QUADS);
      glColor3f(0.0f, 1.0f, 0.0f); // Green
      glVertex2f(-0.3f, -0.3f);
      glVertex2f( 0.3f, -0.3f);
      glVertex2f( 0.3f,  0.3f);
      glVertex2f(-0.3f,  0.3f);
   glEnd();
   glPopMatrix();                      // Restore the model-view matrix

   glPushMatrix();                     // Save model-view matrix setting
   glTranslatef(-0.7f, -0.5f, 0.0f);   // Translate
   glRotatef(angle, 0.0f, 0.0f, 1.0f); // rotate by angle in degrees
   glBegin(GL_QUADS);
      glColor3f(0.2f, 0.2f, 0.2f); // Dark Gray
```

```
      glVertex2f(-0.2f, -0.2f);
      glColor3f(1.0f, 1.0f, 1.0f); // White
      glVertex2f( 0.2f, -0.2f);
      glColor3f(0.2f, 0.2f, 0.2f); // Dark Gray
      glVertex2f( 0.2f,  0.2f);
      glColor3f(1.0f, 1.0f, 1.0f); // White
      glVertex2f(-0.2f,  0.2f);
   glEnd();
   glPopMatrix();                     // Restore the model-view matrix

   glPushMatrix();                    // Save model-view matrix setting
   glTranslatef(0.4f, -0.3f, 0.0f);   // Translate
   glRotatef(angle, 0.0f, 0.0f, 1.0f); // rotate by angle in degrees
   glBegin(GL_TRIANGLES);
      glColor3f(0.0f, 0.0f, 1.0f); // Blue
      glVertex2f(-0.3f, -0.2f);
      glVertex2f( 0.3f, -0.2f);
      glVertex2f( 0.0f,  0.3f);
   glEnd();
   glPopMatrix();                     // Restore the model-view matrix

   glPushMatrix();                    // Save model-view matrix setting
   glTranslatef(0.6f, -0.6f, 0.0f);   // Translate
   glRotatef(180.0f + angle, 0.0f, 0.0f, 1.0f); // Rotate 180+angle degree
   glBegin(GL_TRIANGLES);
      glColor3f(1.0f, 0.0f, 0.0f); // Red
      glVertex2f(-0.3f, -0.2f);
      glColor3f(0.0f, 1.0f, 0.0f); // Green
      glVertex2f( 0.3f, -0.2f);
      glColor3f(0.0f, 0.0f, 1.0f); // Blue
      glVertex2f( 0.0f,  0.3f);
   glEnd();
   glPopMatrix();                     // Restore the model-view matrix

   glPushMatrix();                    // Save model-view matrix setting
   glTranslatef(0.5f, 0.4f, 0.0f);    // Translate
   glRotatef(angle, 0.0f, 0.0f, 1.0f); // rotate by angle in degrees
   glBegin(GL_POLYGON);
      glColor3f(1.0f, 1.0f, 0.0f); // Yellow
      glVertex2f(-0.1f, -0.2f);
      glVertex2f( 0.1f, -0.2f);
      glVertex2f( 0.2f,  0.0f);
      glVertex2f( 0.1f,  0.2f);
      glVertex2f(-0.1f,  0.2f);
      glVertex2f(-0.2f,  0.0f);
   glEnd();
   glPopMatrix();                     // Restore the model-view matrix

   glutSwapBuffers();   // Double buffered - swap the front and back buffers

   // Change the rotational angle after each display()
   angle += 2.0f;
}

/* Handler for window re-size event. Called back when the window first appears and
   whenever the window is re-sized with its new width and height */
void reshape(GLsizei width, GLsizei height) {  // GLsizei for non-negative integer
   // Compute aspect ratio of the new window
   if (height == 0) height = 1;                // To prevent divide by 0
   GLfloat aspect = (GLfloat)width / (GLfloat)height;

   // Set the viewport to cover the new window
```

```
122     glViewport(0, 0, width, height);
123
124     // Set the aspect ratio of the clipping area to match the viewport
125     glMatrixMode(GL_PROJECTION);  // To operate on the Projection matrix
126     glLoadIdentity();
127     if (width >= height) {
128       // aspect >= 1, set the height from -1 to 1, with larger width
129        gluOrtho2D(-1.0 * aspect, 1.0 * aspect, -1.0, 1.0);
130     } else {
131        // aspect < 1, set the width to -1 to 1, with larger height
132       gluOrtho2D(-1.0, 1.0, -1.0 / aspect, 1.0 / aspect);
133     }
134  }
135
136  /* Main function: GLUT runs as a console application starting at main() */
137  int main(int argc, char** argv) {
138     glutInit(&argc, argv);          // Initialize GLUT
139     glutInitDisplayMode(GLUT_DOUBLE);  // Enable double buffered mode
140     glutInitWindowSize(640, 480);   // Set the window's initial width & height - non-square
141     glutInitWindowPosition(50, 50); // Position the window's initial top-left corner
142     glutCreateWindow("Animation via Idle Function");  // Create window with the given title
143     glutDisplayFunc(display);       // Register callback handler for window re-paint event
144     glutReshapeFunc(reshape);       // Register callback handler for window re-size event
145     glutTimerFunc(0, Timer, 0);     // First timer call immediately
146     initGL();                       // Our own OpenGL initialization
147     glutMainLoop();                 // Enter the infinite event-processing loop
148     return 0;
149  }
```

```
void Timer(int value) {
   glutPostRedisplay();                  // Post re-paint request to activate display()
   glutTimerFunc(refreshMills, Timer, 0); // next Timer call milliseconds later
}
```

We replace the `idle()` function by a `timer()` function, which post a re-paint request to invoke `display()`, after the timer expired.

```
glutTimerFunc(0, Timer, 0);     // First timer call immediately
```

In `main()`, we register the `timer()` function, and activate the `timer()` immediately (with initial timer = 0).

6.7 More GLUT functions

- `glutInitDisplayMode`: requests a display with the specified mode, such as color mode (`GLUT_RGB`, `GLUT_RGBA`, `GLUT_INDEX`), single/double buffering (`GLUT_SINGLE`, `GLUT_DOUBLE`), enable depth (`GLUT_DEPTH`), joined with a bit OR '`|`'.

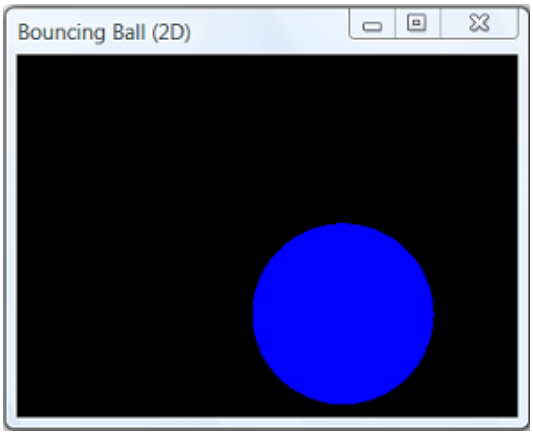
  ```
  void glutInitDisplayMode(unsigned int displayMode)
  ```

  For example,

  ```
  glutInitDisplayMode(GLUT_RGBA | GLUT_DOUBLE | GLUT_DEPTH);
     // Use RGBA color, enable double buffering and enable depth buffer
  ```

6.8 Example 7: A Bouncing Ball (`GL07BouncingBall.cpp`)

This example shows a ball bouncing inside the window. Take note that circle is not a primitive geometric shape in OpenGL. This example uses `TRIANGLE_FAN` to compose a circle.




```
/*
 * GL07BouncingBall.cpp: A ball bouncing inside the window
 */
#include <windows.h>  // for MS Windows
#include <GL/glut.h>  // GLUT, includes glu.h and gl.h
#include <Math.h>     // Needed for sin, cos
#define PI 3.14159265f

// Global variables
char title[] = "Bouncing Ball (2D)";  // Windowed mode's title
int windowWidth  = 640;     // Windowed mode's width
int windowHeight = 480;     // Windowed mode's height
int windowPosX   = 50;      // Windowed mode's top-left corner x
int windowPosY   = 50;      // Windowed mode's top-left corner y

GLfloat ballRadius = 0.5f;   // Radius of the bouncing ball
GLfloat ballX = 0.0f;         // Ball's center (x, y) position
GLfloat ballY = 0.0f;
GLfloat ballXMax, ballXMin, ballYMax, ballYMin; // Ball's center (x, y) bounds
GLfloat xSpeed = 0.02f;      // Ball's speed in x and y directions
GLfloat ySpeed = 0.007f;
int refreshMillis = 30;      // Refresh period in milliseconds

// Projection clipping area
GLdouble clipAreaXLeft, clipAreaXRight, clipAreaYBottom, clipAreaYTop;

/* Initialize OpenGL Graphics */
void initGL() {
   glClearColor(0.0, 0.0, 0.0, 1.0); // Set background (clear) color to black
}

/* Callback handler for window re-paint event */
void display() {
   glClear(GL_COLOR_BUFFER_BIT);  // Clear the color buffer
   glMatrixMode(GL_MODELVIEW);    // To operate on the model-view matrix
   glLoadIdentity();              // Reset model-view matrix

   glTranslatef(ballX, ballY, 0.0f);  // Translate to (xPos, yPos)
   // Use triangular segments to form a circle
   glBegin(GL_TRIANGLE_FAN);
      glColor3f(0.0f, 0.0f, 1.0f);  // Blue
      glVertex2f(0.0f, 0.0f);       // Center of circle
      int numSegments = 100;
      GLfloat angle;
      for (int i = 0; i <= numSegments; i++) { // Last vertex same as first vertex
         angle = i * 2.0f * PI / numSegments;  // 360 deg for all segments
         glVertex2f(cos(angle) * ballRadius, sin(angle) * ballRadius);
      }
   glEnd();
```

```
50
51      glutSwapBuffers();  // Swap front and back buffers (of double buffered mode)
52
53      // Animation Control - compute the location for the next refresh
54      ballX += xSpeed;
55      ballY += ySpeed;
56      // Check if the ball exceeds the edges
57      if (ballX > ballXMax) {
58         ballX = ballXMax;
59         xSpeed = -xSpeed;
60      } else if (ballX < ballXMin) {
61         ballX = ballXMin;
62         xSpeed = -xSpeed;
63      }
64      if (ballY > ballYMax) {
65         ballY = ballYMax;
66         ySpeed = -ySpeed;
67      } else if (ballY < ballYMin) {
68         ballY = ballYMin;
69         ySpeed = -ySpeed;
70      }
71   }
72
73   /* Call back when the windows is re-sized */
74   void reshape(GLsizei width, GLsizei height) {
75      // Compute aspect ratio of the new window
76      if (height == 0) height = 1;                // To prevent divide by 0
77      GLfloat aspect = (GLfloat)width / (GLfloat)height;
78
79      // Set the viewport to cover the new window
80      glViewport(0, 0, width, height);
81
82      // Set the aspect ratio of the clipping area to match the viewport
83      glMatrixMode(GL_PROJECTION);  // To operate on the Projection matrix
84      glLoadIdentity();             // Reset the projection matrix
85      if (width >= height) {
86         clipAreaXLeft   = -1.0 * aspect;
87         clipAreaXRight  = 1.0 * aspect;
88         clipAreaYBottom = -1.0;
89         clipAreaYTop    = 1.0;
90      } else {
91         clipAreaXLeft   = -1.0;
92         clipAreaXRight  = 1.0;
93         clipAreaYBottom = -1.0 / aspect;
94         clipAreaYTop    = 1.0 / aspect;
95      }
96      gluOrtho2D(clipAreaXLeft, clipAreaXRight, clipAreaYBottom, clipAreaYTop);
97      ballXMin = clipAreaXLeft + ballRadius;
98      ballXMax = clipAreaXRight - ballRadius;
99      ballYMin = clipAreaYBottom + ballRadius;
100     ballYMax = clipAreaYTop - ballRadius;
101  }
102
103  /* Called back when the timer expired */
104  void Timer(int value) {
105     glutPostRedisplay();    // Post a paint request to activate display()
106     glutTimerFunc(refreshMillis, Timer, 0); // subsequent timer call at milliseconds
107  }
108
109  /* Main function: GLUT runs as a console application starting at main() */
110  int main(int argc, char** argv) {
111     glutInit(&argc, argv);            // Initialize GLUT
```

```
   glutInitDisplayMode(GLUT_DOUBLE); // Enable double buffered mode
   glutInitWindowSize(windowWidth, windowHeight);  // Initial window width and height
   glutInitWindowPosition(windowPosX, windowPosY); // Initial window top-left corner (x, y)
   glutCreateWindow(title);      // Create window with given title
   glutDisplayFunc(display);     // Register callback handler for window re-paint
   glutReshapeFunc(reshape);     // Register callback handler for window re-shape
   glutTimerFunc(0, Timer, 0);   // First timer call immediately
   initGL();                     // Our own OpenGL initialization
   glutMainLoop();               // Enter event-processing loop
   return 0;
}
```

[TODO] Explanation

7. Handling Keyboard Inputs with GLUT

We can register callback functions to handle keyboard inputs for normal and special keys, respectively.

- `glutKeyboardFunc`: registers callback handler for keyboard event.

```
void glutKeyboardFunc (void (*func)(unsigned char key, int x, int y)
   // key is the char pressed, e.g., 'a' or 27 for ESC
   // (x, y) is the mouse location in Windows' coordinates
```

- `glutSpecialFunc`: registers callback handler for special key (such as arrow keys and function keys).

```
void glutSpecialFunc (void (*func)(int specialKey, int x, int y)
   // specialKey: GLUT_KEY_* (* for LEFT, RIGHT, UP, DOWN, HOME, END, PAGE_UP, PAGE_DOWN, F1,...F12).
   // (x, y) is the mouse location in Windows' coordinates
```

7.1 Example 8: Switching between Full-Screen and Windowed-mode (GL08FullScreen.cpp)

For the bouncing ball program, the following special-key handler toggles between *full-screen* and *windowed modes* using F1 key.

```
/*
 * GL08FullScreen.cpp: Switching between full-screen mode and windowed-mode
 */
#include <windows.h>  // for MS Windows
#include <GL/glut.h>  // GLUT, includes glu.h and gl.h
#include <Math.h>     // Needed for sin, cos
#define PI 3.14159265f

// Global variables
char title[] = "Full-Screen & Windowed Mode";  // Windowed mode's title
int windowWidth  = 640;     // Windowed mode's width
int windowHeight = 480;     // Windowed mode's height
int windowPosX   = 50;      // Windowed mode's top-left corner x
int windowPosY   = 50;      // Windowed mode's top-left corner y

GLfloat ballRadius = 0.5f;   // Radius of the bouncing ball
GLfloat ballX = 0.0f;         // Ball's center (x, y) position
GLfloat ballY = 0.0f;
GLfloat ballXMax, ballXMin, ballYMax, ballYMin; // Ball's center (x, y) bounds
GLfloat xSpeed = 0.02f;      // Ball's speed in x and y directions
GLfloat ySpeed = 0.007f;
int refreshMillis = 30;      // Refresh period in milliseconds

// Projection clipping area
GLdouble clipAreaXLeft, clipAreaXRight, clipAreaYBottom, clipAreaYTop;
```

```
26
27  bool fullScreenMode = true; // Full-screen or windowed mode?
28
29  /* Initialize OpenGL Graphics */
30  void initGL() {
31     glClearColor(0.0, 0.0, 0.0, 1.0); // Set background (clear) color to black
32  }
33
34  /* Callback handler for window re-paint event */
35  void display() {
36     glClear(GL_COLOR_BUFFER_BIT);  // Clear the color buffer
37     glMatrixMode(GL_MODELVIEW);    // To operate on the model-view matrix
38     glLoadIdentity();              // Reset model-view matrix
39
40     glTranslatef(ballX, ballY, 0.0f);  // Translate to (xPos, yPos)
41     // Use triangular segments to form a circle
42     glBegin(GL_TRIANGLE_FAN);
43        glColor3f(0.0f, 0.0f, 1.0f);  // Blue
44        glVertex2f(0.0f, 0.0f);       // Center of circle
45        int numSegments = 100;
46        GLfloat angle;
47        for (int i = 0; i <= numSegments; i++) { // Last vertex same as first vertex
48           angle = i * 2.0f * PI / numSegments;  // 360 deg for all segments
49           glVertex2f(cos(angle) * ballRadius, sin(angle) * ballRadius);
50        }
51     glEnd();
52
53     glutSwapBuffers();  // Swap front and back buffers (of double buffered mode)
54
55     // Animation Control - compute the location for the next refresh
56     ballX += xSpeed;
57     ballY += ySpeed;
58     // Check if the ball exceeds the edges
59     if (ballX > ballXMax) {
60        ballX = ballXMax;
61        xSpeed = -xSpeed;
62     } else if (ballX < ballXMin) {
63        ballX = ballXMin;
64        xSpeed = -xSpeed;
65     }
66     if (ballY > ballYMax) {
67        ballY = ballYMax;
68        ySpeed = -ySpeed;
69     } else if (ballY < ballYMin) {
70        ballY = ballYMin;
71        ySpeed = -ySpeed;
72     }
73  }
74
75  /* Call back when the windows is re-sized */
76  void reshape(GLsizei width, GLsizei height) {
77     // Compute aspect ratio of the new window
78     if (height == 0) height = 1;                // To prevent divide by 0
79     GLfloat aspect = (GLfloat)width / (GLfloat)height;
80
81     // Set the viewport to cover the new window
82     glViewport(0, 0, width, height);
83
84     // Set the aspect ratio of the clipping area to match the viewport
85     glMatrixMode(GL_PROJECTION);  // To operate on the Projection matrix
86     glLoadIdentity();             // Reset the projection matrix
87     if (width >= height) {
```

```
      clipAreaXLeft   = -1.0 * aspect;
      clipAreaXRight  = 1.0 * aspect;
      clipAreaYBottom = -1.0;
      clipAreaYTop    = 1.0;
   } else {
      clipAreaXLeft   = -1.0;
      clipAreaXRight  = 1.0;
      clipAreaYBottom = -1.0 / aspect;
      clipAreaYTop    = 1.0 / aspect;
   }
   gluOrtho2D(clipAreaXLeft, clipAreaXRight, clipAreaYBottom, clipAreaYTop);
   ballXMin = clipAreaXLeft + ballRadius;
   ballXMax = clipAreaXRight - ballRadius;
   ballYMin = clipAreaYBottom + ballRadius;
   ballYMax = clipAreaYTop - ballRadius;
}

/* Called back when the timer expired */
void Timer(int value) {
   glutPostRedisplay();    // Post a paint request to activate display()
   glutTimerFunc(refreshMillis, Timer, 0); // subsequent timer call at milliseconds
}

/* Callback handler for special-key event */
void specialKeys(int key, int x, int y) {
   switch (key) {
      case GLUT_KEY_F1:    // F1: Toggle between full-screen and windowed mode
         fullScreenMode = !fullScreenMode;         // Toggle state
         if (fullScreenMode) {                     // Full-screen mode
            windowPosX   = glutGet(GLUT_WINDOW_X); // Save parameters for restoring later
            windowPosY   = glutGet(GLUT_WINDOW_Y);
            windowWidth  = glutGet(GLUT_WINDOW_WIDTH);
            windowHeight = glutGet(GLUT_WINDOW_HEIGHT);
            glutFullScreen();                      // Switch into full screen
         } else {                                          // Windowed mode
            glutReshapeWindow(windowWidth, windowHeight); // Switch into windowed mode
            glutPositionWindow(windowPosX, windowPosX);   // Position top-left corner
         }
         break;
   }
}

/* Main function: GLUT runs as a console application starting at main() */
int main(int argc, char** argv) {
   glutInit(&argc, argv);            // Initialize GLUT
   glutInitDisplayMode(GLUT_DOUBLE); // Enable double buffered mode
   glutInitWindowSize(windowWidth, windowHeight);  // Initial window width and height
   glutInitWindowPosition(windowPosX, windowPosY); // Initial window top-left corner (x, y)
   glutCreateWindow(title);      // Create window with given title
   glutDisplayFunc(display);     // Register callback handler for window re-paint
   glutReshapeFunc(reshape);     // Register callback handler for window re-shape
   glutTimerFunc(0, Timer, 0);   // First timer call immediately
   glutSpecialFunc(specialKeys); // Register callback handler for special-key event
   glutFullScreen();             // Put into full screen
   initGL();                     // Our own OpenGL initialization
   glutMainLoop();               // Enter event-processing loop
   return 0;
}
```

[TODO] Explanation

[TODO] Using `glVertex` to draw a Circle is inefficient (due to the compute-intensive `sin()` and `cos()` functions). Try using GLU's quadric.

7.2 Example 9: Key-Controlled (`GL09KeyControl.cpp`)

For the bouncing ball program, the following key and special-key handlers provide exits with ESC (27), increase/decrease y speed with up-/down-arrow key, increase/decrease x speed with left-/right-arrow key, increase/decrease ball's radius with PageUp/PageDown key.

```
/*
 * GL09KeyControl.cpp: A key-controlled bouncing ball
 */
#include <windows.h>  // for MS Windows
#include <GL/glut.h>  // GLUT, include glu.h and gl.h
#include <Math.h>     // Needed for sin, cos
#define PI 3.14159265f

// Global variables
char title[] = "Full-Screen & Windowed Mode";  // Windowed mode's title
int windowWidth  = 640;     // Windowed mode's width
int windowHeight = 480;     // Windowed mode's height
int windowPosX   = 50;      // Windowed mode's top-left corner x
int windowPosY   = 50;      // Windowed mode's top-left corner y

GLfloat ballRadius = 0.5f;   // Radius of the bouncing ball
GLfloat ballX = 0.0f;        // Ball's center (x, y) position
GLfloat ballY = 0.0f;
GLfloat ballXMax, ballXMin, ballYMax, ballYMin; // Ball's center (x, y) bounds
GLfloat xSpeed = 0.02f;      // Ball's speed in x and y directions
GLfloat ySpeed = 0.007f;
int refreshMillis = 30;      // Refresh period in milliseconds

// Projection clipping area
GLdouble clipAreaXLeft, clipAreaXRight, clipAreaYBottom, clipAreaYTop;

bool fullScreenMode = true; // Full-screen or windowed mode?

/* Initialize OpenGL Graphics */
void initGL() {
   glClearColor(0.0, 0.0, 0.0, 1.0); // Set background (clear) color to black
}

/* Callback handler for window re-paint event */
void display() {
   glClear(GL_COLOR_BUFFER_BIT);  // Clear the color buffer
   glMatrixMode(GL_MODELVIEW);    // To operate on the model-view matrix
   glLoadIdentity();              // Reset model-view matrix

   glTranslatef(ballX, ballY, 0.0f);  // Translate to (xPos, yPos)
   // Use triangular segments to form a circle
   glBegin(GL_TRIANGLE_FAN);
      glColor3f(0.0f, 0.0f, 1.0f);  // Blue
      glVertex2f(0.0f, 0.0f);       // Center of circle
      int numSegments = 100;
      GLfloat angle;
      for (int i = 0; i <= numSegments; i++) { // Last vertex same as first vertex
         angle = i * 2.0f * PI / numSegments;  // 360 deg for all segments
         glVertex2f(cos(angle) * ballRadius, sin(angle) * ballRadius);
      }
   glEnd();

```

```
   glutSwapBuffers();  // Swap front and back buffers (of double buffered mode)

   // Animation Control - compute the location for the next refresh
   ballX += xSpeed;
   ballY += ySpeed;
   // Check if the ball exceeds the edges
   if (ballX > ballXMax) {
      ballX = ballXMax;
      xSpeed = -xSpeed;
   } else if (ballX < ballXMin) {
      ballX = ballXMin;
      xSpeed = -xSpeed;
   }
   if (ballY > ballYMax) {
      ballY = ballYMax;
      ySpeed = -ySpeed;
   } else if (ballY < ballYMin) {
      ballY = ballYMin;
      ySpeed = -ySpeed;
   }
}

/* Call back when the windows is re-sized */
void reshape(GLsizei width, GLsizei height) {
   // Compute aspect ratio of the new window
   if (height == 0) height = 1;                // To prevent divide by 0
   GLfloat aspect = (GLfloat)width / (GLfloat)height;

   // Set the viewport to cover the new window
   glViewport(0, 0, width, height);

   // Set the aspect ratio of the clipping area to match the viewport
   glMatrixMode(GL_PROJECTION);  // To operate on the Projection matrix
   glLoadIdentity();             // Reset the projection matrix
   if (width >= height) {
      clipAreaXLeft   = -1.0 * aspect;
      clipAreaXRight  = 1.0 * aspect;
      clipAreaYBottom = -1.0;
      clipAreaYTop    = 1.0;
   } else {
      clipAreaXLeft   = -1.0;
      clipAreaXRight  = 1.0;
      clipAreaYBottom = -1.0 / aspect;
      clipAreaYTop    = 1.0 / aspect;
   }
   gluOrtho2D(clipAreaXLeft, clipAreaXRight, clipAreaYBottom, clipAreaYTop);
   ballXMin = clipAreaXLeft + ballRadius;
   ballXMax = clipAreaXRight - ballRadius;
   ballYMin = clipAreaYBottom + ballRadius;
   ballYMax = clipAreaYTop - ballRadius;
}

/* Called back when the timer expired */
void Timer(int value) {
   glutPostRedisplay();    // Post a paint request to activate display()
   glutTimerFunc(refreshMillis, Timer, 0); // subsequent timer call at milliseconds
}

/* Callback handler for normal-key event */
void keyboard(unsigned char key, int x, int y) {
   switch (key) {
      case 27:     // ESC key
```

```
         exit(0);
         break;
   }
}

/* Callback handler for special-key event */
void specialKeys(int key, int x, int y) {
   switch (key) {
      case GLUT_KEY_F1:    // F1: Toggle between full-screen and windowed mode
         fullScreenMode = !fullScreenMode;         // Toggle state
         if (fullScreenMode) {                     // Full-screen mode
            windowPosX   = glutGet(GLUT_WINDOW_X); // Save parameters for restoring later
            windowPosY   = glutGet(GLUT_WINDOW_Y);
            windowWidth  = glutGet(GLUT_WINDOW_WIDTH);
            windowHeight = glutGet(GLUT_WINDOW_HEIGHT);
            glutFullScreen();                      // Switch into full screen
         } else {                                         // Windowed mode
            glutReshapeWindow(windowWidth, windowHeight); // Switch into windowed mode
            glutPositionWindow(windowPosX, windowPosX);   // Position top-left corner
         }
         break;
      case GLUT_KEY_RIGHT:    // Right: increase x speed
         xSpeed *= 1.05f; break;
      case GLUT_KEY_LEFT:     // Left: decrease x speed
         xSpeed *= 0.95f; break;
      case GLUT_KEY_UP:       // Up: increase y speed
         ySpeed *= 1.05f; break;
      case GLUT_KEY_DOWN:     // Down: decrease y speed
         ySpeed *= 0.95f; break;
      case GLUT_KEY_PAGE_UP:  // Page-Up: increase ball's radius
         ballRadius *= 1.05f;
         ballXMin = clipAreaXLeft + ballRadius;
         ballXMax = clipAreaXRight - ballRadius;
         ballYMin = clipAreaYBottom + ballRadius;
         ballYMax = clipAreaYTop - ballRadius;
         break;
      case GLUT_KEY_PAGE_DOWN: // Page-Down: decrease ball's radius
         ballRadius *= 0.95f;
         ballXMin = clipAreaXLeft + ballRadius;
         ballXMax = clipAreaXRight - ballRadius;
         ballYMin = clipAreaYBottom + ballRadius;
         ballYMax = clipAreaYTop - ballRadius;
         break;
   }
}

/* Main function: GLUT runs as a console application starting at main() */
int main(int argc, char** argv) {
   glutInit(&argc, argv);            // Initialize GLUT
   glutInitDisplayMode(GLUT_DOUBLE); // Enable double buffered mode
   glutInitWindowSize(windowWidth, windowHeight);  // Initial window width and height
   glutInitWindowPosition(windowPosX, windowPosY); // Initial window top-left corner (x, y)
   glutCreateWindow(title);      // Create window with given title
   glutDisplayFunc(display);     // Register callback handler for window re-paint
   glutReshapeFunc(reshape);     // Register callback handler for window re-shape
   glutTimerFunc(0, Timer, 0);   // First timer call immediately
   glutSpecialFunc(specialKeys); // Register callback handler for special-key event
   glutKeyboardFunc(keyboard);   // Register callback handler for special-key event
   glutFullScreen();             // Put into full screen
   initGL();                     // Our own OpenGL initialization
   glutMainLoop();               // Enter event-processing loop
```

```
   return 0;
}
```

[TODO] Explanation

8. Handling Mouse Inputs with GLUT

Similarly, we can register callback function to handle mouse-click and mouse-motion.

- `glutMouseFunc`: registers callback handler for mouse click.

```
void glutMouseFunc(void (*func)(int button, int state, int x, int y)
   // (x, y) is the mouse-click location.
   // button: GLUT_LEFT_BUTTON, GLUT_RIGHT_BUTTON, GLUT_MIDDLE_BUTTON
   // state: GLUT_UP, GLUT_DOWN
```

- `glutMotionFunc`: registers callback handler for mouse motion (when the mouse is clicked and moved).

```
void glutMotionFunc(void (*func)(int x, int y)
   // where (x, y) is the mouse location in Window's coordinates
```

8.1 Example 10: Mouse-Controlled (`GL10MouseControl.cpp`)

For the bouncing ball program, the following mouse handler pause the movement with left-mouse click, and resume with right-mouse click.

```
/*
 * GL10MouseControl.cpp: A mouse-controlled bouncing ball
 */
#include <windows.h>  // for MS Windows
#include <GL/glut.h>  // GLUT, include glu.h and gl.h
#include <Math.h>     // Needed for sin, cos
#define PI 3.14159265f

// Global variables
char title[] = "Full-Screen & Windowed Mode";  // Windowed mode's title
int windowWidth  = 640;     // Windowed mode's width
int windowHeight = 480;     // Windowed mode's height
int windowPosX   = 50;      // Windowed mode's top-left corner x
int windowPosY   = 50;      // Windowed mode's top-left corner y

GLfloat ballRadius = 0.5f;   // Radius of the bouncing ball
GLfloat ballX = 0.0f;        // Ball's center (x, y) position
GLfloat ballY = 0.0f;
GLfloat ballXMax, ballXMin, ballYMax, ballYMin; // Ball's center (x, y) bounds
GLfloat xSpeed = 0.02f;      // Ball's speed in x and y directions
GLfloat ySpeed = 0.007f;
int refreshMillis = 30;      // Refresh period in milliseconds

// Projection clipping area
GLdouble clipAreaXLeft, clipAreaXRight, clipAreaYBottom, clipAreaYTop;

bool fullScreenMode = true; // Full-screen or windowed mode?
bool paused = false;         // Movement paused or resumed
GLfloat xSpeedSaved, ySpeedSaved;  // To support resume

/* Initialize OpenGL Graphics */
void initGL() {
   glClearColor(0.0, 0.0, 0.0, 1.0); // Set background (clear) color to black
}

```

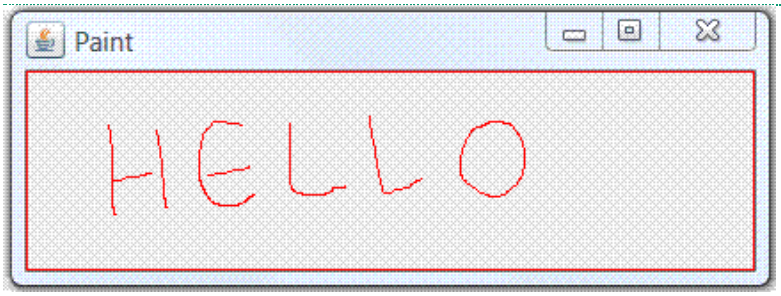
```
/* Callback handler for window re-paint event */
void display() {
   glClear(GL_COLOR_BUFFER_BIT);  // Clear the color buffer
   glMatrixMode(GL_MODELVIEW);    // To operate on the model-view matrix
   glLoadIdentity();              // Reset model-view matrix

   glTranslatef(ballX, ballY, 0.0f);  // Translate to (xPos, yPos)
   // Use triangular segments to form a circle
   glBegin(GL_TRIANGLE_FAN);
      glColor3f(0.0f, 0.0f, 1.0f);  // Blue
      glVertex2f(0.0f, 0.0f);       // Center of circle
      int numSegments = 100;
      GLfloat angle;
      for (int i = 0; i <= numSegments; i++) { // Last vertex same as first vertex
         angle = i * 2.0f * PI / numSegments;  // 360 deg for all segments
         glVertex2f(cos(angle) * ballRadius, sin(angle) * ballRadius);
      }
   glEnd();

   glutSwapBuffers();  // Swap front and back buffers (of double buffered mode)

   // Animation Control - compute the location for the next refresh
   ballX += xSpeed;
   ballY += ySpeed;
   // Check if the ball exceeds the edges
   if (ballX > ballXMax) {
      ballX = ballXMax;
      xSpeed = -xSpeed;
   } else if (ballX < ballXMin) {
      ballX = ballXMin;
      xSpeed = -xSpeed;
   }
   if (ballY > ballYMax) {
      ballY = ballYMax;
      ySpeed = -ySpeed;
   } else if (ballY < ballYMin) {
      ballY = ballYMin;
      ySpeed = -ySpeed;
   }
}

/* Call back when the windows is re-sized */
void reshape(GLsizei width, GLsizei height) {
   // Compute aspect ratio of the new window
   if (height == 0) height = 1;                // To prevent divide by 0
   GLfloat aspect = (GLfloat)width / (GLfloat)height;

   // Set the viewport to cover the new window
   glViewport(0, 0, width, height);

   // Set the aspect ratio of the clipping area to match the viewport
   glMatrixMode(GL_PROJECTION);  // To operate on the Projection matrix
   glLoadIdentity();             // Reset the projection matrix
   if (width >= height) {
      clipAreaXLeft   = -1.0 * aspect;
      clipAreaXRight  = 1.0 * aspect;
      clipAreaYBottom = -1.0;
      clipAreaYTop    = 1.0;
   } else {
      clipAreaXLeft   = -1.0;
      clipAreaXRight  = 1.0;
      clipAreaYBottom = -1.0 / aspect;
```

```
      clipAreaYTop    = 1.0 / aspect;
   }
   gluOrtho2D(clipAreaXLeft, clipAreaXRight, clipAreaYBottom, clipAreaYTop);
   ballXMin = clipAreaXLeft + ballRadius;
   ballXMax = clipAreaXRight - ballRadius;
   ballYMin = clipAreaYBottom + ballRadius;
   ballYMax = clipAreaYTop - ballRadius;
}

/* Called back when the timer expired */
void Timer(int value) {
   glutPostRedisplay();    // Post a paint request to activate display()
   glutTimerFunc(refreshMillis, Timer, 0); // subsequent timer call at milliseconds
}

/* Callback handler for normal-key event */
void keyboard(unsigned char key, int x, int y) {
   switch (key) {
      case 27:     // ESC key
         exit(0);
         break;
   }
}

/* Callback handler for special-key event */
void specialKeys(int key, int x, int y) {
   switch (key) {
      case GLUT_KEY_F1:    // F1: Toggle between full-screen and windowed mode
         fullScreenMode = !fullScreenMode;         // Toggle state
         if (fullScreenMode) {                     // Full-screen mode
            windowPosX   = glutGet(GLUT_WINDOW_X); // Save parameters for restoring later
            windowPosY   = glutGet(GLUT_WINDOW_Y);
            windowWidth  = glutGet(GLUT_WINDOW_WIDTH);
            windowHeight = glutGet(GLUT_WINDOW_HEIGHT);
            glutFullScreen();                      // Switch into full screen
         } else {                                          // Windowed mode
            glutReshapeWindow(windowWidth, windowHeight); // Switch into windowed mode
            glutPositionWindow(windowPosX, windowPosX);   // Position top-left corner
         }
         break;
      case GLUT_KEY_RIGHT:    // Right: increase x speed
         xSpeed *= 1.05f; break;
      case GLUT_KEY_LEFT:     // Left: decrease x speed
         xSpeed *= 0.95f; break;
      case GLUT_KEY_UP:       // Up: increase y speed
         ySpeed *= 1.05f; break;
      case GLUT_KEY_DOWN:     // Down: decrease y speed
         ySpeed *= 0.95f; break;
      case GLUT_KEY_PAGE_UP:  // Page-Up: increase ball's radius
         ballRadius *= 1.05f;
         ballXMin = clipAreaXLeft + ballRadius;
         ballXMax = clipAreaXRight - ballRadius;
         ballYMin = clipAreaYBottom + ballRadius;
         ballYMax = clipAreaYTop - ballRadius;
         break;
      case GLUT_KEY_PAGE_DOWN: // Page-Down: decrease ball's radius
         ballRadius *= 0.95f;
         ballXMin = clipAreaXLeft + ballRadius;
         ballXMax = clipAreaXRight - ballRadius;
         ballYMin = clipAreaYBottom + ballRadius;
         ballYMax = clipAreaYTop - ballRadius;
         break;
```

```
   }
}

/* Callback handler for mouse event */
void mouse(int button, int state, int x, int y) {
   if (button == GLUT_LEFT_BUTTON && state == GLUT_DOWN) { // Pause/resume
      paused = !paused;          // Toggle state
      if (paused) {
         xSpeedSaved = xSpeed;  // Save parameters for restore later
         ySpeedSaved = ySpeed;
         xSpeed = 0;            // Stop movement
         ySpeed = 0;
      } else {
         xSpeed = xSpeedSaved;  // Restore parameters
         ySpeed = ySpeedSaved;
      }
   }
}

/* Main function: GLUT runs as a console application starting at main() */
int main(int argc, char** argv) {
   glutInit(&argc, argv);            // Initialize GLUT
   glutInitDisplayMode(GLUT_DOUBLE); // Enable double buffered mode
   glutInitWindowSize(windowWidth, windowHeight);  // Initial window width and height
   glutInitWindowPosition(windowPosX, windowPosY); // Initial window top-left corner (x, y)
   glutCreateWindow(title);      // Create window with given title
   glutDisplayFunc(display);     // Register callback handler for window re-paint
   glutReshapeFunc(reshape);     // Register callback handler for window re-shape
   glutTimerFunc(0, Timer, 0);   // First timer call immediately
   glutSpecialFunc(specialKeys); // Register callback handler for special-key event
   glutKeyboardFunc(keyboard);   // Register callback handler for special-key event
   glutFullScreen();             // Put into full screen
   glutMouseFunc(mouse);   // Register callback handler for mouse event
   initGL();                     // Our own OpenGL initialization
   glutMainLoop();               // Enter event-processing loop
   return 0;
}
```

[TODO] Explanation

8.2 Example 11: A Simple Paint program



[TODO] Use mouse-motion and `GL_LINE_STRIP`.

Link to OpenGL/Computer Graphics References and Resources

Latest version tested: Eclipse CDT /MinGW
Last modified: July, 2012

Feedback, comments, corrections, and errata can be sent to Chua Hock-Chuan (ehchua@ntu.edu.sg) | HOME