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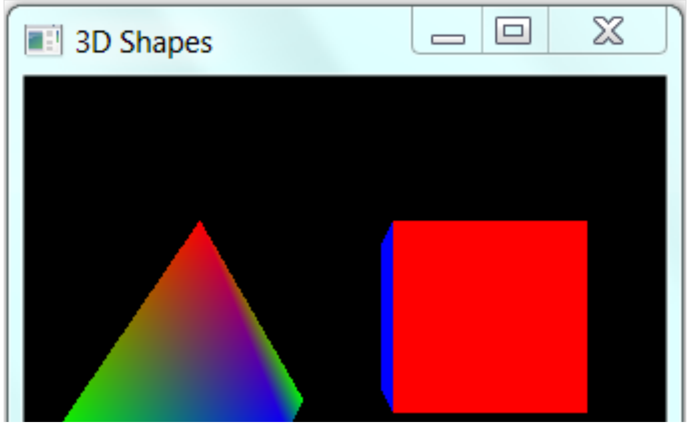
3D Graphics with OpenGL By Examples

I assume that you have some knowledge of OpenGL. Otherwise, read "Introduction to OpenGL with 2D Graphics".

1. Example 1: 3D Shapes (OGL01Shape3D.cpp)

This example is taken from Nehe OpenGL Tutorial Lesson # 5 (@ http://nehe.gamedev.net/), which displays a 3D color-cube and a pyramid. The cube is made of of 6 quads, each having different colors. The hallow pyramid is made up of 4 triangle, with different colors on each of the vertices.

```
/*
 * OGL01Shape3D.cpp: 3D Shapes
 */
#include <windows.h>  // for MS Windows
#include <GL/glut.h>  // GLUT, include glu.h and gl.h

/* Global variables */
char title[] = "3D Shapes";

/* Initialize OpenGL Graphics */
void initGL() {
   glClearColor(0.0f, 0.0f, 0.0f, 1.0f); // Set background color to black and opaque
   glClearDepth(1.0f);                   // Set background depth to farthest
   glEnable(GL_DEPTH_TEST);   // Enable depth testing for z-culling
   glDepthFunc(GL_LEQUAL);    // Set the type of depth-test
   glShadeModel(GL_SMOOTH);   // Enable smooth shading
   glHint(GL_PERSPECTIVE_CORRECTION_HINT, GL_NICEST);  // Nice perspective corrections
}

/* Handler for window-repaint event. Called back when the window first appears and
   whenever the window needs to be re-painted. */
void display() {
   glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT); // Clear color and depth buffers
   glMatrixMode(GL_MODELVIEW);     // To operate on model-view matrix

   // Render a color-cube consisting of 6 quads with different colors
   glLoadIdentity();                 // Reset the model-view matrix
   glTranslatef(1.5f, 0.0f, -7.0f);  // Move right and into the screen

   glBegin(GL_QUADS);                // Begin drawing the color cube with 6 quads
      // Top face (y = 1.0f)
      // Define vertices in counter-clockwise (CCW) order with normal pointing out
      glColor3f(0.0f, 1.0f, 0.0f);     // Green
      glVertex3f( 1.0f, 1.0f, -1.0f);
      glVertex3f(-1.0f, 1.0f, -1.0f);
      glVertex3f(-1.0f, 1.0f,  1.0f);
      glVertex3f( 1.0f, 1.0f,  1.0f);

      // Bottom face (y = -1.0f)
      glColor3f(1.0f, 0.5f, 0.0f);     // Orange
      glVertex3f( 1.0f, -1.0f,  1.0f);
      glVertex3f(-1.0f, -1.0f,  1.0f);
      glVertex3f(-1.0f, -1.0f, -1.0f);
      glVertex3f( 1.0f, -1.0f, -1.0f);

      // Front face  (z = 1.0f)
      glColor3f(1.0f, 0.0f, 0.0f);     // Red
      glVertex3f( 1.0f,  1.0f, 1.0f);
      glVertex3f(-1.0f,  1.0f, 1.0f);
      glVertex3f(-1.0f, -1.0f, 1.0f);
      glVertex3f( 1.0f, -1.0f, 1.0f);

      // Back face (z = -1.0f)
      glColor3f(1.0f, 1.0f, 0.0f);     // Yellow
      glVertex3f( 1.0f, -1.0f, -1.0f);
      glVertex3f(-1.0f, -1.0f, -1.0f);
      glVertex3f(-1.0f,  1.0f, -1.0f);
      glVertex3f( 1.0f,  1.0f, -1.0f);

      // Left face (x = -1.0f)
      glColor3f(0.0f, 0.0f, 1.0f);     // Blue
      glVertex3f(-1.0f,  1.0f,  1.0f);
      glVertex3f(-1.0f,  1.0f, -1.0f);
      glVertex3f(-1.0f, -1.0f, -1.0f);
      glVertex3f(-1.0f, -1.0f,  1.0f);

      // Right face (x = 1.0f)
      glColor3f(1.0f, 0.0f, 1.0f);     // Magenta
      glVertex3f(1.0f,  1.0f, -1.0f);
      glVertex3f(1.0f,  1.0f,  1.0f);
      glVertex3f(1.0f, -1.0f,  1.0f);
      glVertex3f(1.0f, -1.0f, -1.0f);
   glEnd();  // End of drawing color-cube

   // Render a pyramid consists of 4 triangles
   glLoadIdentity();                  // Reset the model-view matrix
   glTranslatef(-1.5f, 0.0f, -6.0f);  // Move left and into the screen

   glBegin(GL_TRIANGLES);           // Begin drawing the pyramid with 4 triangles
      // Front
      glColor3f(1.0f, 0.0f, 0.0f);     // Red
      glVertex3f( 0.0f, 1.0f, 0.0f);
      glColor3f(0.0f, 1.0f, 0.0f);     // Green
      glVertex3f(-1.0f, -1.0f, 1.0f);
      glColor3f(0.0f, 0.0f, 1.0f);     // Blue
      glVertex3f(1.0f, -1.0f, 1.0f);

      // Right
      glColor3f(1.0f, 0.0f, 0.0f);     // Red
      glVertex3f(0.0f, 1.0f, 0.0f);
      glColor3f(0.0f, 0.0f, 1.0f);     // Blue
      glVertex3f(1.0f, -1.0f, 1.0f);
      glColor3f(0.0f, 1.0f, 0.0f);     // Green
      glVertex3f(1.0f, -1.0f, -1.0f);

      // Back
      glColor3f(1.0f, 0.0f, 0.0f);     // Red
      glVertex3f(0.0f, 1.0f, 0.0f);
      glColor3f(0.0f, 1.0f, 0.0f);     // Green
      glVertex3f(1.0f, -1.0f, -1.0f);
      glColor3f(0.0f, 0.0f, 1.0f);     // Blue
      glVertex3f(-1.0f, -1.0f, -1.0f);

      // Left
      glColor3f(1.0f,0.0f,0.0f);       // Red
      glVertex3f( 0.0f, 1.0f, 0.0f);
      glColor3f(0.0f,0.0f,1.0f);       // Blue
      glVertex3f(-1.0f,-1.0f,-1.0f);
      glColor3f(0.0f,1.0f,0.0f);       // Green
      glVertex3f(-1.0f,-1.0f, 1.0f);
   glEnd();   // Done drawing the pyramid

   glutSwapBuffers();  // Swap the front and back frame buffers (double buffering)
}

/* 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 volume to match the viewport
   glMatrixMode(GL_PROJECTION);  // To operate on the Projection matrix
   glLoadIdentity();             // Reset
   // Enable perspective projection with fovy, aspect, zNear and zFar
   gluPerspective(45.0f, aspect, 0.1f, 100.0f);
}

/* 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
   glutInitWindowPosition(50, 50); // Position the window's initial top-left corner
   glutCreateWindow(title);          // 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;
}
```



GLUT Setup - `main()`

The program contains a `initGL()`, `display()` and `reshape()` functions.

The `main()` program:

1. `glutInit(&argc, argv);`

   Initializes the GLUT.

2. `glutInitWindowSize(640, 480);`
   `glutInitWindowPosition(50, 50);`

`glutCreateWindow(title);`
Creates a window with a title, initial width and height positioned at initial top-left corner.

3. `glutDisplayFunc(display);`
   Registers `display()` as the re-paint event handler. That is, the graphics sub-system calls back `display()` when the window first appears and whenever there is a re-paint request.
4. `glutReshapeFunc(reshape);`
   Registers `reshape()` as the re-sized event handler. That is, the graphics sub-system calls back `reshape()` when the window first appears and whenever the window is re-sized.
5. `glutInitDisplayMode(GLUT_DOUBLE);`
   Enables double buffering. In `display()`, we use `glutSwapBuffers()` to signal to the GPU to swap the front-buffer and back-buffer during the next VSync (Vertical Synchronization).
6. `initGL();`
   Invokes the `initGL()` once to perform all one-time initialization tasks.
7. `glutMainLoop();`
   Finally, enters the event-processing loop.

One-Time Initialization Operations - `initGL()`

The `initGL()` function performs the one-time initialization tasks. It is invoked from `main()` once (and only once).

```
glClearColor(0.0f, 0.0f, 0.0f, 1.0f); // Set background color to black and opaque
glClearDepth(1.0f); // Set background depth to farthest
// In display()
glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
```

Set the clearing (background) color to black (R=0, G=0, B=0) and opaque (A=1), and the clearing (background) depth to the farthest (Z=1). In `display()`, we invoke `glClear()` to clear the color and depth buffer, with the clearing color and depth, before rendering the graphics. (Besides the color buffer and depth buffer, OpenGL also maintains an *accumulation buffer* and a *stencil buffer* which shall be discussed later.)

```
glEnable(GL_DEPTH_TEST); // Enable depth testing for z-culling
glDepthFunc(GL_LEQUAL); // Set the type of depth-test
```

We need to enable depth-test to remove the hidden surface, and set the function used for the depth test.

```
glShadeModel(GL_SMOOTH); // Enable smooth shading
```

We enable smooth shading in color transition. The alternative is GL_FLAT. Try it out and see the difference.

```
glHint(GL_PERSPECTIVE_CORRECTION_HINT, GL_NICEST); // Nice perspective corrections
```

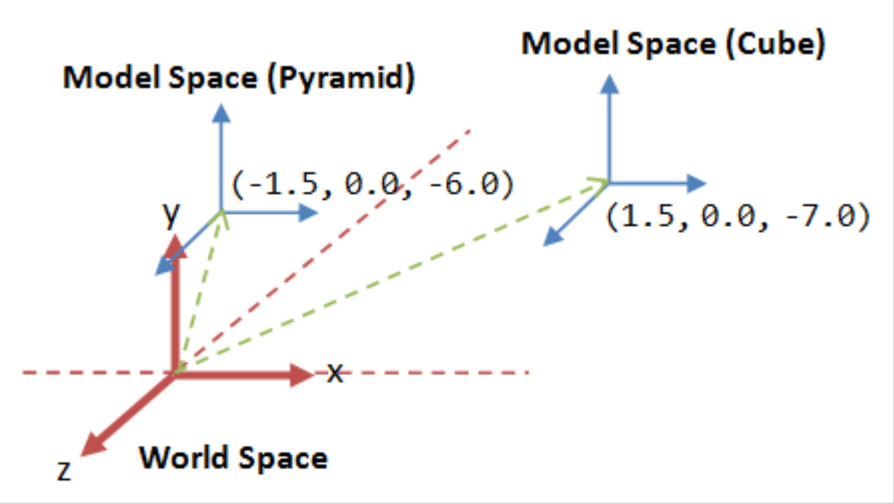
In graphics rendering, there is often a trade-off between processing speed and visual quality. We can use glHint() to decide on the trade-off. In this case, we ask for the best perspective correction, which may involve more processing. The default is GL_DONT_CARE.

Defining the Color-cube and Pyramid

OpenGL's object is made up of primitives (such as triangle, quad, polygon, point and line). A primitive is defined via one or more vertices. The color-cube is made up of 6 quads. Each quad is made up of 4 vertices, defined in counter-clockwise (CCW) order, such as the normal vector is pointing out, indicating the front face. All the 4 vertices have the same color. The color-cube is defined in its local space (called model space) with origin at the center of the cube with sides of 2 units.

Similarly, the pyramid is made up of 4 triangles (without the base). Each triangle is made up of 3 vertices, defined in CCW order. The 5 vertices of the pyramid are assigned different colors. The color of the triangles are interpolated (and blend smoothly) from its 3 vertices. Again, the pyramid is defined in its local space with origin at the center of the pyramid.

Model Transform



The objects are defined in their local spaces (model spaces). We need to transform them to the common world space, known as *model transform*.

To perform model transform, we need to operate on the so-called *model-view matrix* (OpenGL has a few transformation matrices), by setting the current matrix mode to model-view matrix:

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

We perform translations on cube and pyramid, respectively, to position them on the world space:

```
// Color-cube
glLoadIdentity(); // Reset model-view matrix
glTranslatef(1.5f, 0.0f, -7.0f); // Move right and into the screen
```

```
// Pyramid
glLoadIdentity();
glTranslatef(-1.5f, 0.0f, -6.0f); // Move left and into the screen
```

View Transform

The default camera position is:

```
gluLookAt(0.0, 0.0, 0.0, 0.0, 0.0, -100.0, 0.0, 1.0, 0.0)
```

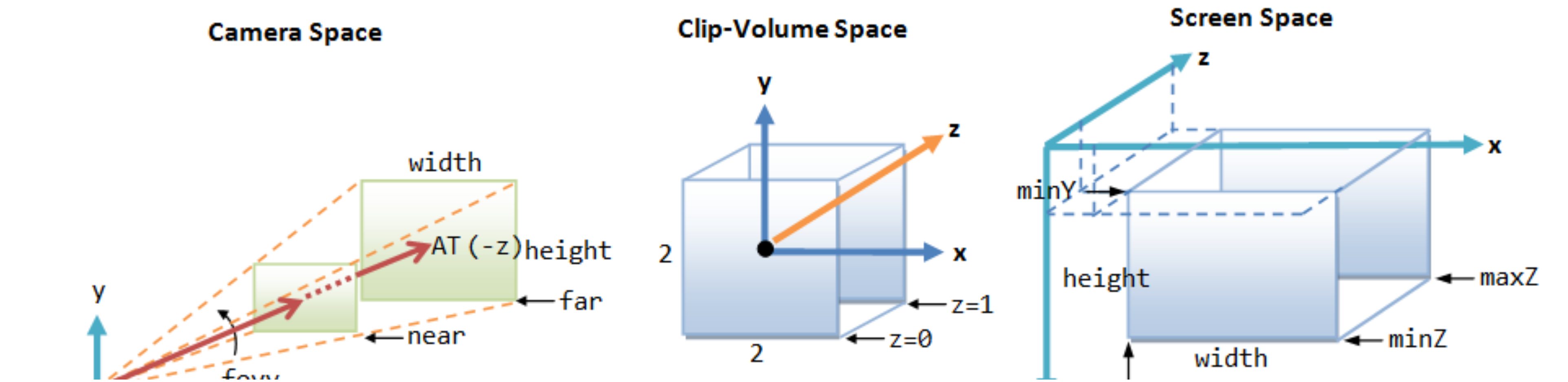
That is, `EYE=(0,0,0)` at the origin, `AT=(0,0,-100)` pointing at negative-z axis (into the screen), and `UP=(0,1,0)` corresponds to y-axis.

OpenGL graphics rendering pipeline performs so-called *view transform* to bring the *world space* to camera's *view space*. In the case of the default camera position, no transform is needed.

Viewport Transform

```
void reshape(GLsizei width, GLsizei height) {
   glViewport(0, 0, width, height);
```

The graphics sub-system calls back `reshape()` when the window first appears and whenever the window is resized, given the new window's `width` and `height`, in pixels. We set our application viewport to cover the entire window, top-left corner at (0, 0) of `width` and `height`, with default `minZ` of 0 and `maxZ` of 1. We also use the same aspect ratio of the viewport for the projection view frustum to prevent distortion. In the viewport, a pixel has (x, y) value as well as z-value for depth processing.



Projection Transform

```
GLfloat aspect = (GLfloat)width / (GLfloat)height; // Compute aspect ratio of window
glMatrixMode(GL_PROJECTION); // To operate on the Projection matrix
glLoadIdentity(); // Reset
gluPerspective(45.0f, aspect, 0.1f, 100.0f); // Perspective projection: fovy, aspect, near, far
```

A camera has limited field of view. The projection models the view captured by the camera. There are two types of projection: perspective projection and orthographic projection. In perspective projection, object further to the camera appears smaller compared with object of the same size nearer to the camera. In orthographic projection, the objects appear the same regardless of the z-value. Orthographic projection is a special case of perspective projection where the camera is placed very far away. We shall discuss the orthographic projection in the later example.

To set the projection, we need to operate on the projection matrix. (Recall that we operated on the model-view matrix in model transform.)

We set the matrix mode to projection matrix and reset the matrix. We use the `gluPerspective()` to enable perspective projection, and set the fovy (view angle from the bottom-plane to the top-plane), aspect ratio (width/height), zNear and zFar of the *View Frustum* (truncated pyramid). In this example, we set the fovy to 45°. We use the same aspect ratio as the viewport to avoid distortion. We set the zNear to 0.1 and zFar to 100 (z=-100). Take that note the color-cube (1.5, 0, -7) and the pyramid (-1.5, 0, -6) are contained within the View Frustum.

The *projection transform* transforms the *view frustum* to a 2x2x1 cuboid *clipping-volume* centered on the near plane (z=0). The subsequent *viewport transform* transforms the *clipping-volume* to the *viewport* in screen space. The viewport is set earlier via the `glViewport()` function.

2. Example 2: 3D Shape with Animation (OGL02Animation.cpp)

Let's modify the previous example to carry out animation (rotating the cube and pyramid).

```
/*
 * OGL02Animation.cpp: 3D Shapes with animation
 */
#include <windows.h>  // for MS Windows
#include <GL/glut.h>  // GLUT, include glu.h and gl.h

```

```
/* Global variables */
char title[] = "3D Shapes with animation";
GLfloat anglePyramid = 0.0f;  // Rotational angle for pyramid [NEW]
GLfloat angleCube = 0.0f;     // Rotational angle for cube [NEW]
int refreshMills = 15;        // refresh interval in milliseconds [NEW]

/* Initialize OpenGL Graphics */
void initGL() {
   glClearColor(0.0f, 0.0f, 0.0f, 1.0f); // Set background color to black and opaque
   glClearDepth(1.0f);                   // Set background depth to farthest
   glEnable(GL_DEPTH_TEST);   // Enable depth testing for z-culling
   glDepthFunc(GL_LEQUAL);    // Set the type of depth-test
   glShadeModel(GL_SMOOTH);   // Enable smooth shading
   glHint(GL_PERSPECTIVE_CORRECTION_HINT, GL_NICEST);  // Nice perspective corrections
}

/* Handler for window-repaint event. Called back when the window first appears and
   whenever the window needs to be re-painted. */
void display() {
   glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT); // Clear color and depth buffers
   glMatrixMode(GL_MODELVIEW);     // To operate on model-view matrix

   // Render a color-cube consisting of 6 quads with different colors
   glLoadIdentity();                 // Reset the model-view matrix
   glTranslatef(1.5f, 0.0f, -7.0f);  // Move right and into the screen
   glRotatef(angleCube, 1.0f, 1.0f, 1.0f);  // Rotate about (1,1,1)-axis [NEW]

   glBegin(GL_QUADS);                // Begin drawing the color cube with 6 quads
      // Top face (y = 1.0f)
      // Define vertices in counter-clockwise (CCW) order with normal pointing out
      glColor3f(0.0f, 1.0f, 0.0f);     // Green
      glVertex3f( 1.0f, 1.0f, -1.0f);
      glVertex3f(-1.0f, 1.0f, -1.0f);
      glVertex3f(-1.0f, 1.0f,  1.0f);
      glVertex3f( 1.0f, 1.0f,  1.0f);

      // Bottom face (y = -1.0f)
      glColor3f(1.0f, 0.5f, 0.0f);     // Orange
      glVertex3f( 1.0f, -1.0f,  1.0f);
      glVertex3f(-1.0f, -1.0f,  1.0f);
      glVertex3f(-1.0f, -1.0f, -1.0f);
      glVertex3f( 1.0f, -1.0f, -1.0f);

      // Front face  (z = 1.0f)
      glColor3f(1.0f, 0.0f, 0.0f);     // Red
      glVertex3f( 1.0f,  1.0f, 1.0f);
      glVertex3f(-1.0f,  1.0f, 1.0f);
      glVertex3f(-1.0f, -1.0f, 1.0f);
      glVertex3f( 1.0f, -1.0f, 1.0f);

      // Back face (z = -1.0f)
      glColor3f(1.0f, 1.0f, 0.0f);     // Yellow
      glVertex3f( 1.0f, -1.0f, -1.0f);
      glVertex3f(-1.0f, -1.0f, -1.0f);
      glVertex3f(-1.0f,  1.0f, -1.0f);
      glVertex3f( 1.0f,  1.0f, -1.0f);

      // Left face (x = -1.0f)
      glColor3f(0.0f, 0.0f, 1.0f);     // Blue
      glVertex3f(-1.0f,  1.0f,  1.0f);
      glVertex3f(-1.0f,  1.0f, -1.0f);
      glVertex3f(-1.0f, -1.0f, -1.0f);
      glVertex3f(-1.0f, -1.0f,  1.0f);

      // Right face (x = 1.0f)
      glColor3f(1.0f, 0.0f, 1.0f);     // Magenta
      glVertex3f(1.0f,  1.0f, -1.0f);
      glVertex3f(1.0f,  1.0f,  1.0f);
      glVertex3f(1.0f, -1.0f,  1.0f);
      glVertex3f(1.0f, -1.0f, -1.0f);
   glEnd();  // End of drawing color-cube

   // Render a pyramid consists of 4 triangles
   glLoadIdentity();                  // Reset the model-view matrix
   glTranslatef(-1.5f, 0.0f, -6.0f);  // Move left and into the screen
   glRotatef(anglePyramid, 1.0f, 1.0f, 0.0f);  // Rotate about the (1,1,0)-axis [NEW]

   glBegin(GL_TRIANGLES);           // Begin drawing the pyramid with 4 triangles
      // Front
      glColor3f(1.0f, 0.0f, 0.0f);     // Red
      glVertex3f( 0.0f, 1.0f, 0.0f);
      glColor3f(0.0f, 1.0f, 0.0f);     // Green
      glVertex3f(-1.0f, -1.0f, 1.0f);
      glColor3f(0.0f, 0.0f, 1.0f);     // Blue
      glVertex3f(1.0f, -1.0f, 1.0f);

      // Right
      glColor3f(1.0f, 0.0f, 0.0f);     // Red
      glVertex3f(0.0f, 1.0f, 0.0f);
      glColor3f(0.0f, 0.0f, 1.0f);     // Blue
      glVertex3f(1.0f, -1.0f, 1.0f);
      glColor3f(0.0f, 1.0f, 0.0f);     // Green
      glVertex3f(1.0f, -1.0f, -1.0f);

      // Back
      glColor3f(1.0f, 0.0f, 0.0f);     // Red
      glVertex3f(0.0f, 1.0f, 0.0f);
      glColor3f(0.0f, 1.0f, 0.0f);     // Green
      glVertex3f(1.0f, -1.0f, -1.0f);
      glColor3f(0.0f, 0.0f, 1.0f);     // Blue
      glVertex3f(-1.0f, -1.0f, -1.0f);

      // Left
      glColor3f(1.0f,0.0f,0.0f);       // Red
      glVertex3f( 0.0f, 1.0f, 0.0f);
      glColor3f(0.0f,0.0f,1.0f);       // Blue
      glVertex3f(-1.0f,-1.0f,-1.0f);
      glColor3f(0.0f,1.0f,0.0f);       // Green
      glVertex3f(-1.0f,-1.0f, 1.0f);
   glEnd();   // Done drawing the pyramid

   glutSwapBuffers();  // Swap the front and back frame buffers (double buffering)

   // Update the rotational angle after each refresh [NEW]
   anglePyramid += 0.2f;
   angleCube -= 0.15f;
}

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

/* 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 volume to match the viewport
   glMatrixMode(GL_PROJECTION);  // To operate on the Projection matrix
   glLoadIdentity();             // Reset
   // Enable perspective projection with fovy, aspect, zNear and zFar
   gluPerspective(45.0f, aspect, 0.1f, 100.0f);
}

/* 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
   glutInitWindowPosition(50, 50); // Position the window's initial top-left corner
   glutCreateWindow(title);          // 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
   glutTimerFunc(0, timer, 0);     // First timer call immediately [NEW]
   glutMainLoop();                 // Enter the infinite event-processing loop
   return 0;
}
```

The new codes are:

```
GLfloat anglePyramid = 0.0f; // Rotational angle for pyramid [NEW]
GLfloat angleCube = 0.0f; // Rotational angle for cube [NEW]
int refreshMills = 15; // refresh interval in milliseconds [NEW]
```

We define two global variables to keep track of the current rotational angles of the cube and pyramid. We also define the refresh period as 15 msec (66 frames per second).

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

To perform animation, we define a function called `timer()`, which posts a re-paint request to activate `display()` when the timer expired, and then run the timer again. In `main()`, we perform the first `timer()` call via `glutTimerFunc(0, timer, 0)`.

```
glRotatef(angleCube, 1.0f, 1.0f, 1.0f); // Rotate the cube about (1,1,1)-axis [NEW]
......
glRotatef(anglePyramid, 1.0f, 1.0f, 0.0f); // Rotate about the (1,1,0)-axis [NEW]
......
anglePyramid += 0.2f; // update pyramid's angle
angleCube -= 0.15f; // update cube's angle
```

In `display()`, we rotate the cube and pyramid based on their rotational angles, and update the angles after each refresh.

3. Example 3: Orthographic Projection (OGL03Orthographic.cpp)

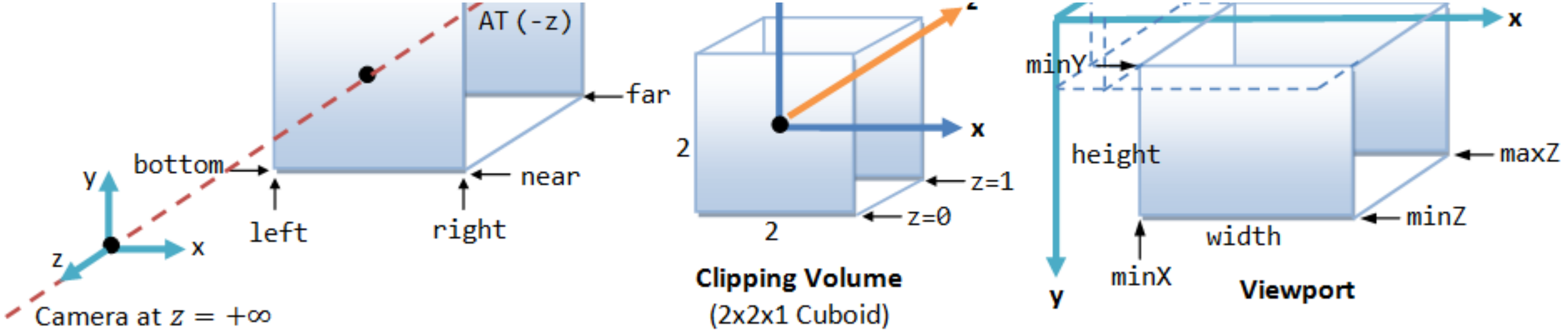
As mentioned, OpenGL support two type of projections: perspective and orthographic. In orthographic projection, an object appears to be the same size regardless of the depth. Orthographic is a special case of perspective projection, where the camera is placed very far away.

To use orthographic projection, change the `reshape()` function to invoke `glOrtho()`.

```
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 volume to match the viewport
   glMatrixMode(GL_PROJECTION);  // To operate on the Projection matrix
   glLoadIdentity();             // Reset

   // Set up orthographic projection view [NEW]
   if (width >= height) {
     // aspect >= 1, set the height from -1 to 1, with larger width
      glOrtho(-3.0 * aspect, 3.0 * aspect, -3.0, 3.0, 0.1, 100);
   } else {
      // aspect < 1, set the width to -1 to 1, with larger height
     glOrtho(-3.0, 3.0, -3.0 / aspect, 3.0 / aspect, 0.1, 100);
   }
}
```

In this example, we set the cross-section of view-volume according to the aspect ratio of the viewport, and depth from 0.1 to 100, corresponding to z=-0.1 to z=-100. Take note that the cube and pyramid are contained within the view-volume.

Camera Space
Clip-Volume Space
Screen Space
top
y
z



4. Example 4: Vertex Array

In the earlier example, drawing a cube requires at least 24 `glVertex` functions and a pair of `glBegin` and `glEnd`. Function calls may involve high overhead and hinder the performance. Furthermore, each vertex is specified and processed three times.

Link to OpenGL/Computer Graphics References and Resources

Latest version tested: ???
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