Programming with Legacy OpenGL (Pre OpenGL 3.1)

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Objectives

- Build a complete first program
  - Introduce a standard program structure using basic OpenGL (pre 3.1)
  - Why start with pre OpenGL 3.1 (legacy code)?
    - Easier learning curve
    - Familiarity with lots of existing code already written in it.
- Simple viewing
  - Two-dimensional viewing as a special case of three-dimensional viewing
- Initialization steps and program structure

OpenGL Functions

- Primitives
  - Points
  - Line Segments
  - Triangles
- Attributes
- Transformations
  - Viewing
  - Modeling
- Control (GLUT)
- Input (GLUT)
- Query

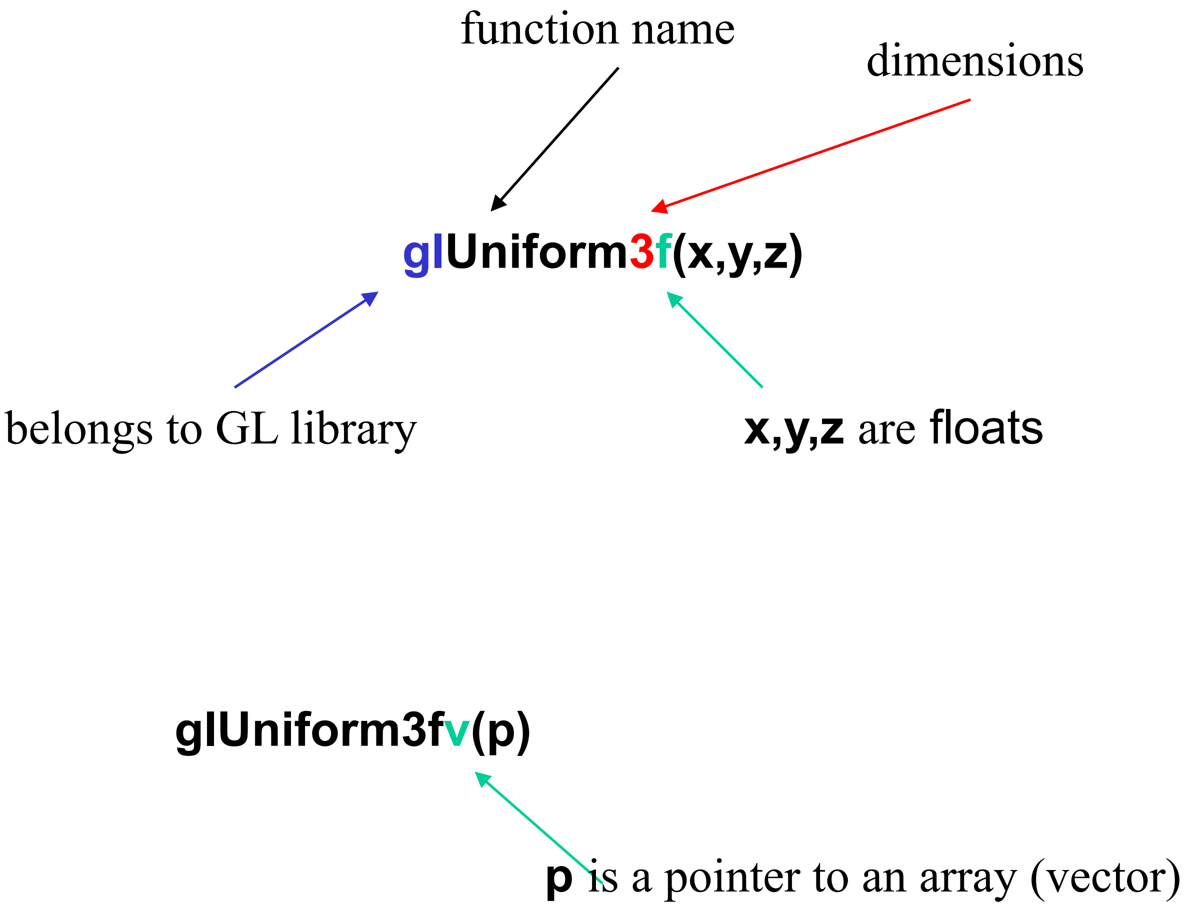
OpenGL State

- OpenGL is a state machine
- OpenGL functions are of two types
  - Primitive generating
    - Can cause output if primitive is visible
    - How vertices are processed and appearance of primitive are controlled by the state
  - State changing
    - Transformation functions
    - Attribute functions

Lack of Object Orientation

- OpenGL is not object oriented so there are multiple functions for a given logical function
  - **`glUniform3f`**
  - **`glUniform2i`**
  - **`glUniform3dv`**

OpenGL Function Format



function name

dimensions

glUniform3f(x,y,z)

belongs to GL library

x,y,z are **floats**

glUniform3fv(p)

p is a pointer to an array (vector)

Example (old style)

type of object

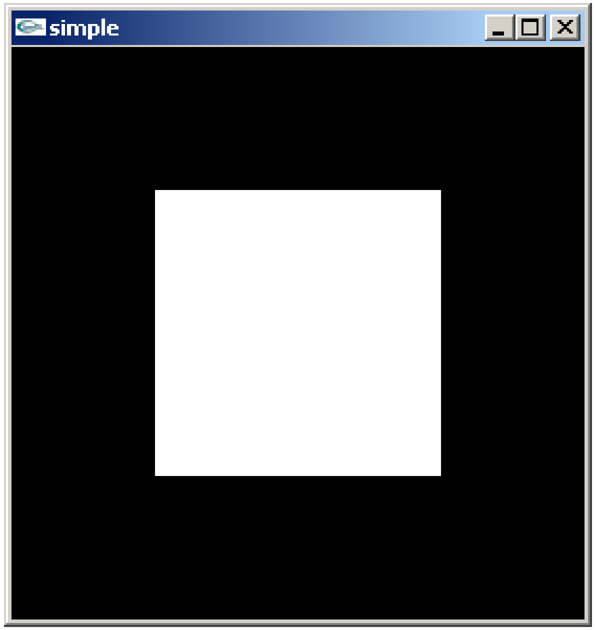
location of vertex

```
glBegin(GL_POLYGON)
 glVertex2f(0.0, 0.0);
 glVertex2f(0.0, 1.0);
 glVertex2f(1.0, 0.0);
glEnd( );
```

end of object definition

A Simple Program:
It Used to be Easy

```
#include <GL/glut.h>
void mydisplay(){
      glClear(GL_COLOR_BUFFER_BIT);
      glBegin(GL_QUAD);
            glVertex2f(-0.5,-0.5);
            glVertex2f(-0.5, 0.5);
            glVertex2f( 0.5, 0.5);
            glVertex2f( 0.5,-0.5);
      glEnd();
}
int main(int argc, char** argv){
      glutCreateWindow("simple");
      glutDisplayFunc(mydisplay);
      glutMainLoop();
}
```



GLUT

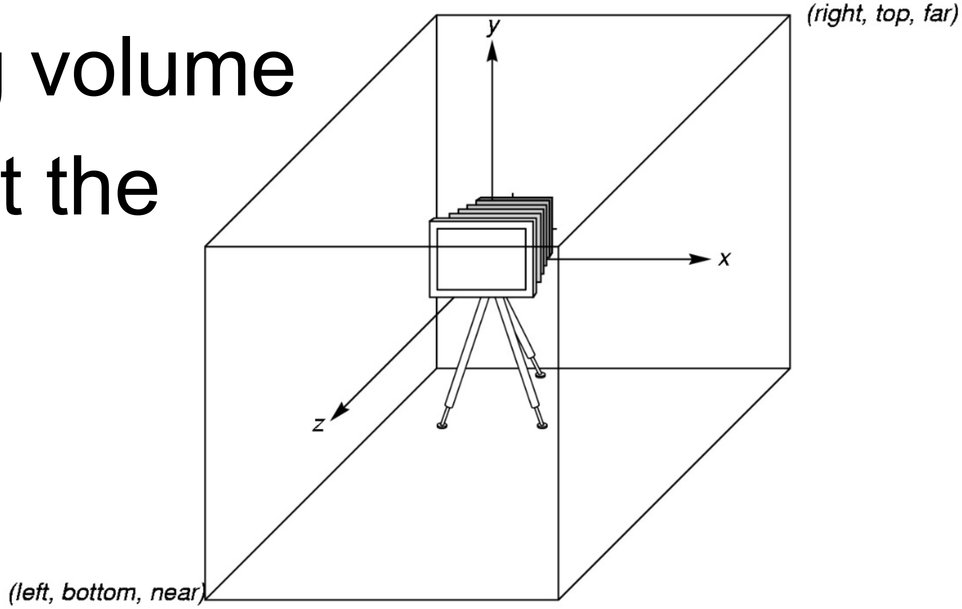
- OpenGL Utility Toolkit (GLUT)
  - Provides functionality common to all window systems
    - Open a window
    - Get input from mouse and keyboard
    - Menus
    - Event-driven
  - Code is portable but GLUT lacks the functionality of a good toolkit for a specific platform
    - No sliders, spinboxes, combo boxes, radio buttons, …
    - We will use Qt instead

Event Loop

- Note that the program specifies a *display callback* function named **`mydisplay`**
  - Every glut program must have a display callback
  - The display callback is executed whenever OpenGL decides the display must be refreshed, for example when the window is opened
  - The **`main`** function ends with the program entering an event loop

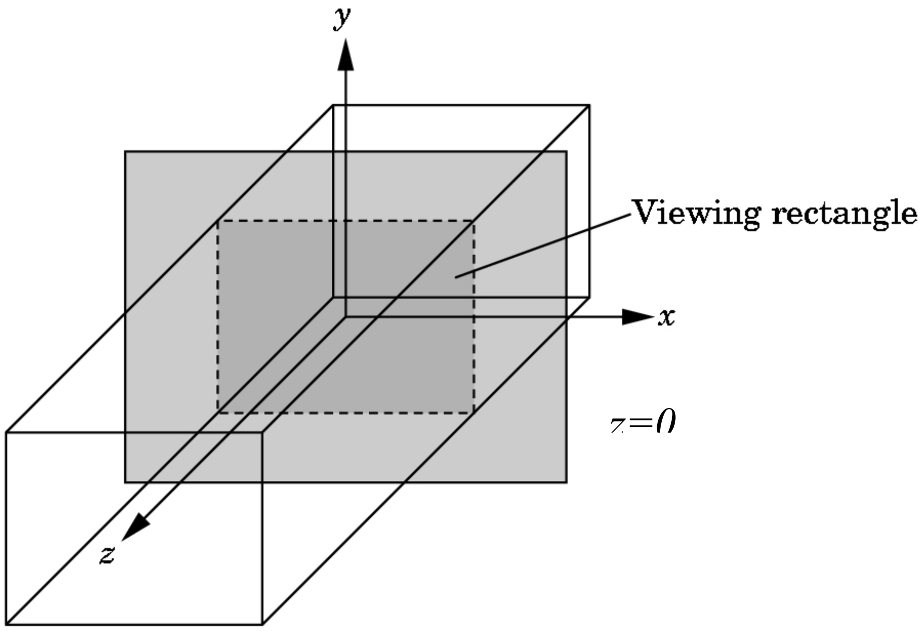
OpenGL Camera

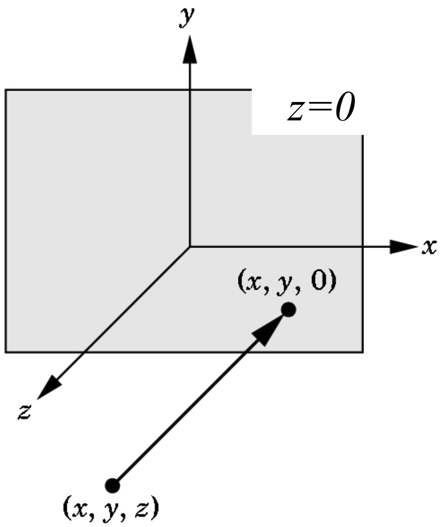
- OpenGL places a camera at the origin in object space pointing in the negative z direction
- The default viewing volume is a box centered at the origin with sides of length 2



Orthographic Viewing

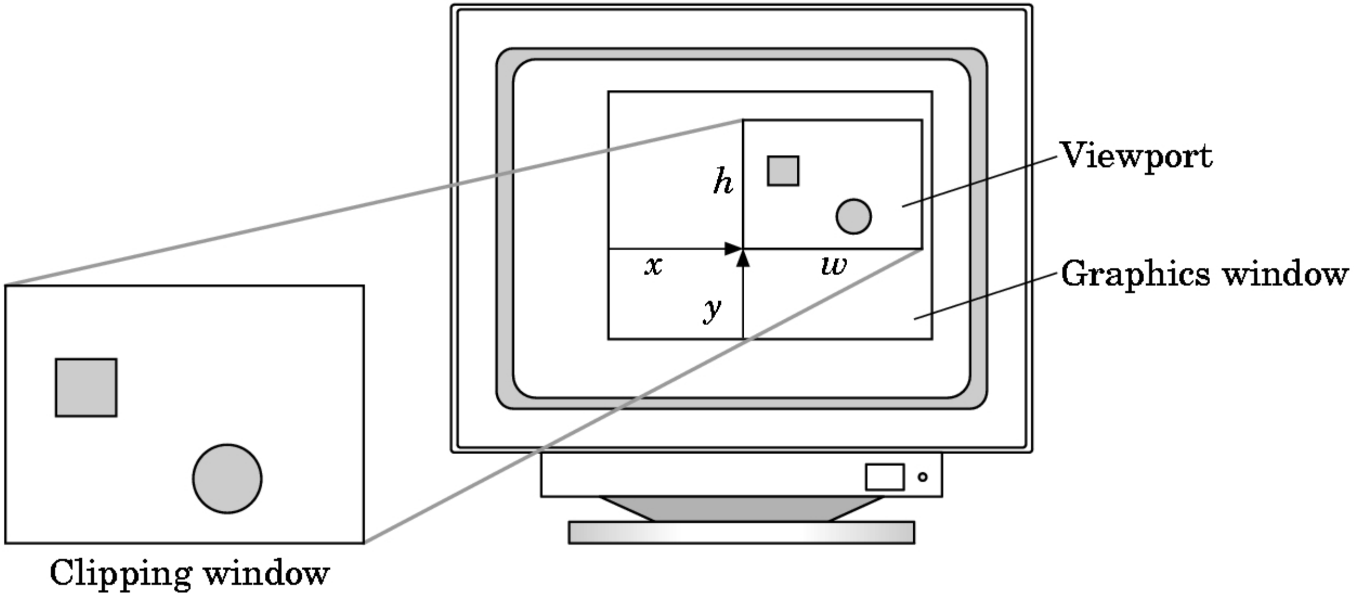
In the default orthographic view, points are projected forward along the *z* axis onto the plane *z=0*





Viewports

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



Program Structure

- Most OpenGL programs have a similar structure that consists of the following functions
  - **`main()`**:
    - Opens main window with control panel and OpenGL canvas
    - Enters event loop (last executable statement)
  - **`initializeGL()`**: sets the state variables
    - Viewing
    - Attributes
  - **`resizeGL()`**: handles window resizing event
    - Sets viewport
    - Sets viewing coordinates for orthographic or perspective projection
  - **`paintGL ()`**: render scene
    - Clear framebuffer
    - Call glVertex*() to draw primitives (triangles, polygons)

initializeGL()

black clear color

opaque window

```
void initializeGL()
{
 glClearColor (0.0, 0.0, 0.0, 1.0);

 glColor3f(1.0, 1.0, 1.0);

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

fill with white

viewing volume

Transformations and Viewing

- In OpenGL, the projection is carried out by a projection matrix (transformation)
- There is only one set of transformation functions so we must set the matrix mode first

```
glMatrixMode (GL_PROJECTION)
```

- Transformation functions are incremental so we start with an identity matrix and alter it with a projection matrix that gives the view volume

```
glLoadIdentity ();
glOrtho(-1.0, 1.0, -1.0, 1.0, -1.0, 1.0);
```

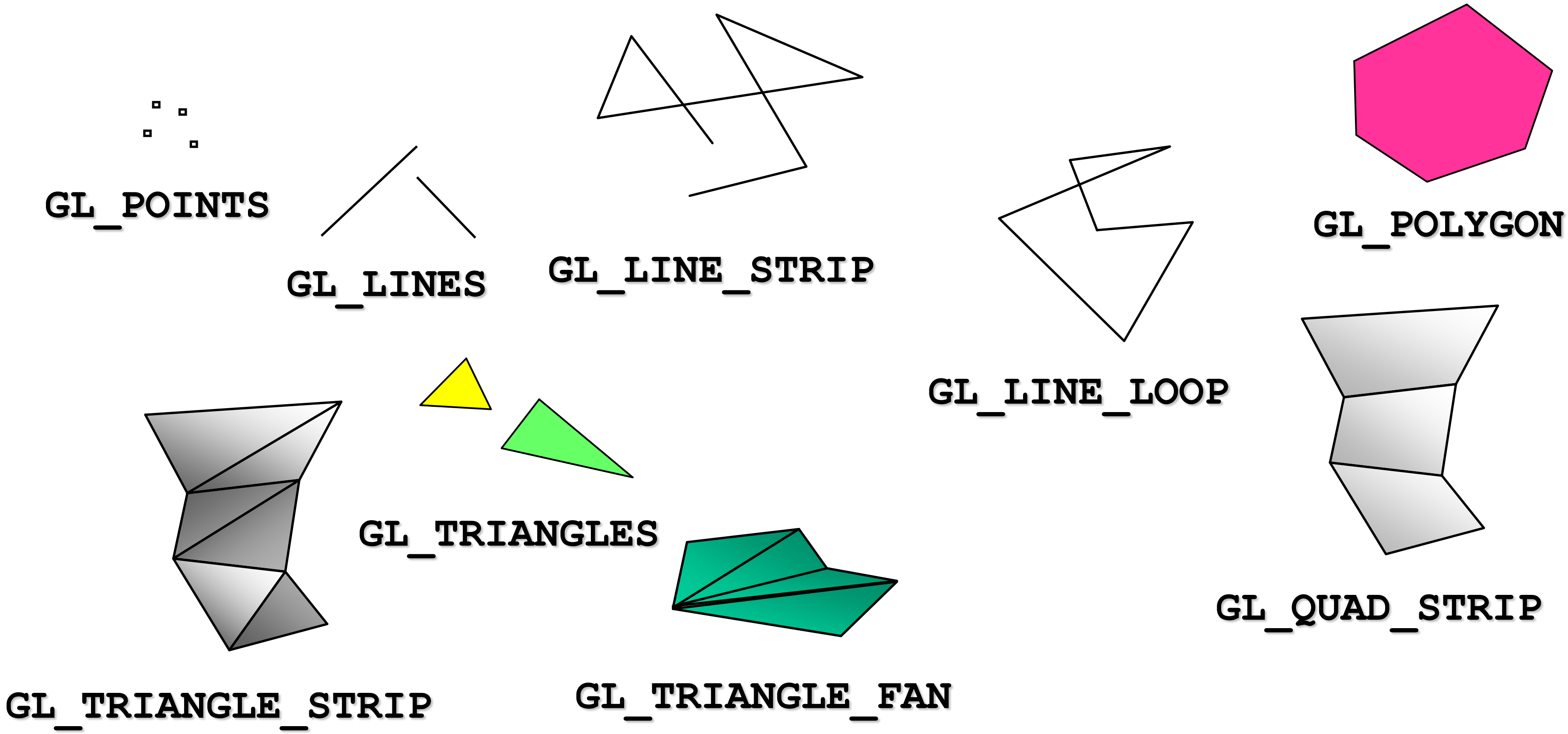
2D and 3D Viewing

- In `glOrtho(left, right, bottom, top, near, far)` the near and far distances are measured <u>from</u> the camera
- 2D vertex commands place all vertices in the plane z=0
- In 2D, the view or clipping volume becomes a *clipping window*

paintGL()

```
void paintGL()
{
     glClear(GL_COLOR_BUFFER_BIT);
     glBegin(GL_POLYGON);
          glVertex2f(-0.5,-0.5);
          glVertex2f(-0.5, 0.5);
          glVertex2f( 0.5, 0.5);
          glVertex2f( 0.5,-0.5);
     glEnd();
     glFlush();
}
```

Pre-OpenGL 3.1 Primitives



GL_POINTS

GL_LINES

GL_LINE_STRIP

GL_LINE_LOOP

GL_POLYGON

GL_TRIANGLES

GL_QUAD_STRIP

GL_TRIANGLE_STRIP

GL_TRIANGLE_FAN

Example: Drawing an Arc

- Given a circle with radius *r*, centered at (*x*,*y*), draw an arc of the circle that sweeps out an angle θ.

$$(x, y) = (x_0 + r\cos\theta, y_0 + r\sin\theta),$$

$$\text{for } 0 \le \theta \le 2\pi.$$

Example Using Line Strip Primitive

```
void drawArc(float x, float y, float r,
             float t0, float sweep)
{
      float t, dt;       // angle
      int   n = 30;      // # of segments
      int   i;

      t = t0 * PI/180.0;          // radians
      dt = sweep * PI/(180*n); // increment

      glBegin(GL_LINE_STRIP);
      for(i=0; i<=n; i++, t += dt)
            glVertex2f(x + r*cos(t), y + r*sin(t));
      glEnd();
}
```

Color and State

- The color as set by `glColor` becomes part of the state and will be used until changed
    - Colors and other attributes are not part of the object but are assigned when the object is rendered
- We can create conceptual *vertex colors* by code such as

```
glColor
glVertex
glColor
glVertex
```

First Assignment: Tessellation and Twist

- Consider rotating a 2D point about the origin

$$x' = x\cos\theta - y\sin\theta$$

$$y' = x\sin\theta + y\cos\theta$$

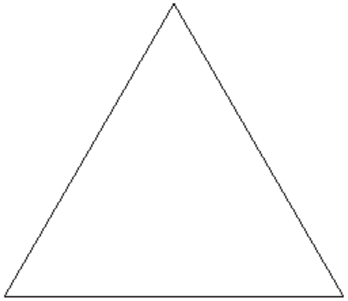
- Now let amount of rotation depend on distance from origin giving us **twist**

$$x' = x\cos(d\theta) - y\sin(d\theta)$$

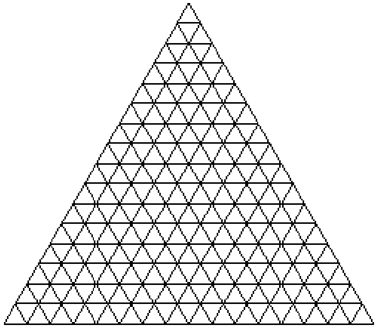
$$y' = x\sin(d\theta) + y\cos(d\theta)$$

$$d \propto \sqrt{x^2 + y^2}$$

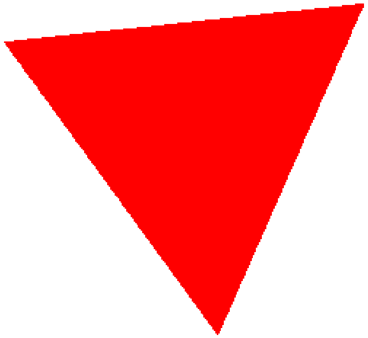
Example



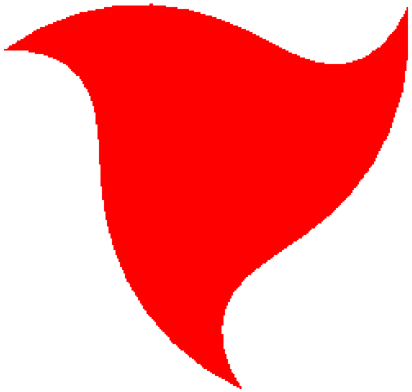
triangle



tessellated triangle



twist without tessellation



twist after tessellation

initializeGL()

```
void initializeGL()
{
 // init vertex and color buffers
 initBuffers();

  // init state variables
  glClearColor (0.0, 0.0, 0.0, 1.0);
  glColor3f(1.0, 1.0, 1.0);
}
```

resizeGL()

```
void resizeGL(int w, int h)
{
        // compute aspect ratio
        float ar = (float) w / h;

        // set xmax, ymax
        float xmax, ymax;
        if(ar > 1.0) {          // wide screen
                xmax = ar;
                ymax = 1.;
        } else {                // tall screen
                xmax = 1.;
                ymax = 1/ar;
        }

        // set viewport to occupy full canvas
        glViewport(0, 0, w, h);

        // init viewing coordinates for orthographic projection
        glLoadIdentity();
        glOrtho(-xmax, xmax, -ymax, ymax, -1.0, 1.0);
}
```

paintGL()

```
typedef QVector2D vec2;
typedef QVector3D vec3;
std::vector<vec2> m_points;
std::vector<vec3> m_colors;

void paintGL()
{
    // clear canvas with background values
    glClear(GL_COLOR_BUFFER_BIT);

    // draw all points in m_points
    for(uint i=0, j=0; i<m_colors.size(); ++i) {
        // set color
        glColor3f(m_colors[i][0], m_colors[i][1], m_colors[i][2]);

        glBegin(GL_TRIANGLES);
                glVertex2f(m_points[j][[0], m_points[j][1]); j++;
                glVertex2f(m_points[j][[0], m_points[j][1]); j++;
                glVertex2f(m_points[j][[0], m_points[j][1]); j++;
        glEnd();
    }
}
```

initBuffers()

```
void initBuffers()
{
 // init triangle vertices
 const vec2 v[] = {
        vec2( 0.0 ,  0.75),
        vec2( 0.65, -0.375),
        vec2(-0.65, -0.375)
 };

 // recursively subdivide triangle;
 // store vertices and colors in m_points[] and m_colors[]
 divideTriangle(v[0], v[1], v[2], m_subdivisions);
}
```

divideTriangle()

```
void divideTriangle(vec2 a, vec2 b, vec2 c, int count)
{
 if(count > 0) {
       vec2 ab = vec2((a[0]+b[0]) / 2.0, (a[1]+b[1]) / 2.0);
       vec2 ac = vec2((a[0]+c[0]) / 2.0, (a[1]+c[1]) / 2.0);
       vec2 bc = vec2((b[0]+c[0]) / 2.0, (b[1]+c[1]) / 2.0);
       divideTriangle( a, ab, ac, count-1);
       divideTriangle( b, bc, ab, count-1);
       divideTriangle( c, ac, bc, count-1);
       divideTriangle(ab, ac, bc, count-1);
 } else triangle(a, b, c);
}
```

triangle()

```
void triangle(vec2 a, vec2 b, vec2 c)
{
 if(m_updateColor) {
      m_colors.push_back(vec3((float) rand()/RAND_MAX,
                              (float) rand()/RAND_MAX,
                              (float) rand()/RAND_MAX));
  }

  // init geometry
  m_points.push_back(rotTwist(a));
  m_points.push_back(rotTwist(b));
  m_points.push_back(rotTwist(c));
}
```

rotTwist()

```
vec2 rotTwist(vec2 p)
{
  float d = m_twist ? sqrt(p[0]*p[0] + p[1]*p[1]) : 1;
  float sinTheta = sin(d*m_theta);
  float cosTheta = cos(d*m_theta);
  return vec2(p[0]*cosTheta - p[1]*sinTheta,
              p[0]*sinTheta + p[1]*cosTheta);
}
```

`(p.x()*p.x() + p.y()*p.y())`

Programming with OpenGL: Sierpinski Gasket Example (3D)

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Objectives

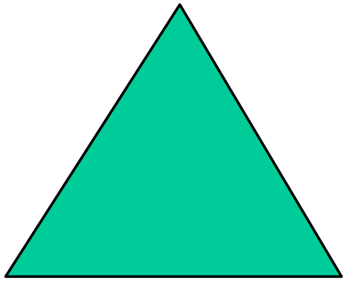
- Develop a more sophisticated 3D example
  - Sierpinski gasket: a fractal
- Introduce hidden-surface removal

Three-dimensional Applications

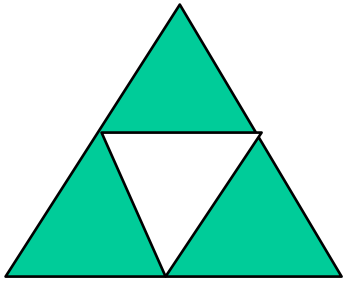
- In OpenGL, two-dimensional applications are a special case of three-dimensional graphics
- Going to 3D
  - Not much changes
  - Use **`vec3, glUniform3f`**
  - Have to worry about the order in which primitives are rendered or use hidden-surface removal

Sierpinski Gasket (2D)

- Start with a triangle



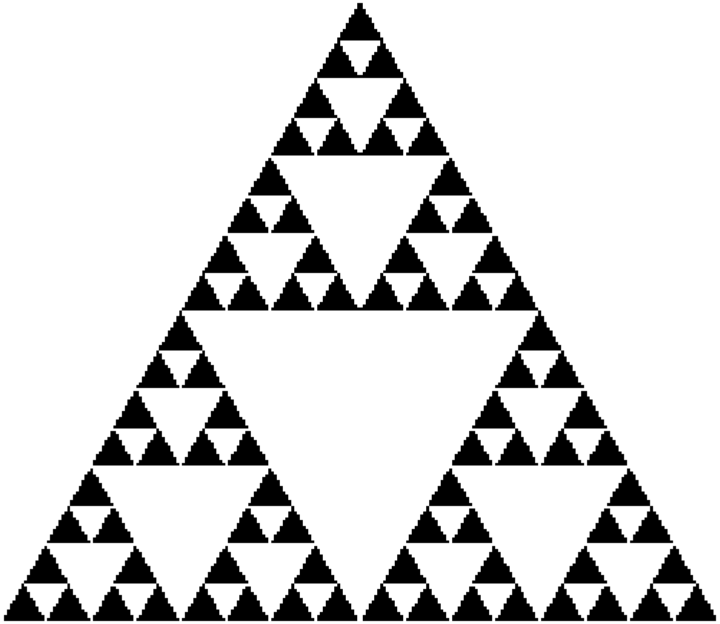
- Connect bisectors of sides and remove central triangle



- Repeat

Example

- Five subdivisions



The gasket as a fractal

- Consider the filled area (black) and the perimeter (the length of all the lines around the filled triangles)
- As we continue subdividing
  - the area goes to zero
  - but the perimeter goes to infinity
- This is not an ordinary geometric object
  - It is neither two- nor three-dimensional
- It is a *fractal* (fractional dimension) object

Gasket Program

```
// initial triangle
vec2 v[3] = {vec2(-1.0, -0.58),
             vec2( 1.0, -0.58),
             vec2( 0.0,  1.15)};

int n; // number of recursive steps
```

Draw one triangle

```
// display one triangle
void triangle(vec2 a, vec2 b, vec2 c)
{
      static int i =0;

      points[ i ] = a;
      points[i+1] = b;
      points[i+2] = c;
      i += 3;
}
```

Triangle Subdivision

```
// triangle subdivision using vertex numbers
void divide_triangle(vec2 a, vec2 b, vec2 c, int m)
{
    vec2 ab, ac, bc;

    if(m > 0){
        ab = (a + b)/2;
        ac = (a + c)/2;
        bc = (b + c)/2;
        divide_triangle(a, ab, ac, m-1);
        divide_triangle(c, ac, bc, m-1);
        divide_triangle(b, bc, ab, m-1);
    }
    // else, draw triangle at end of recursion
    else triangle(a,b,c);
}
```

display and init Functions

```
void paintGL()
{
    glClear(GL_COLOR_BUFFER_BIT);
    glDrawArrays(GL_TRIANGLES, 0, NumVertices);
}

void initializeGL()
{
      ...
      // v: initial triangle vertices
      // n: number of recursive steps
     divide_triangle(v[0], v[1], v[2], n);
      ...
}
```

Moving to 3D

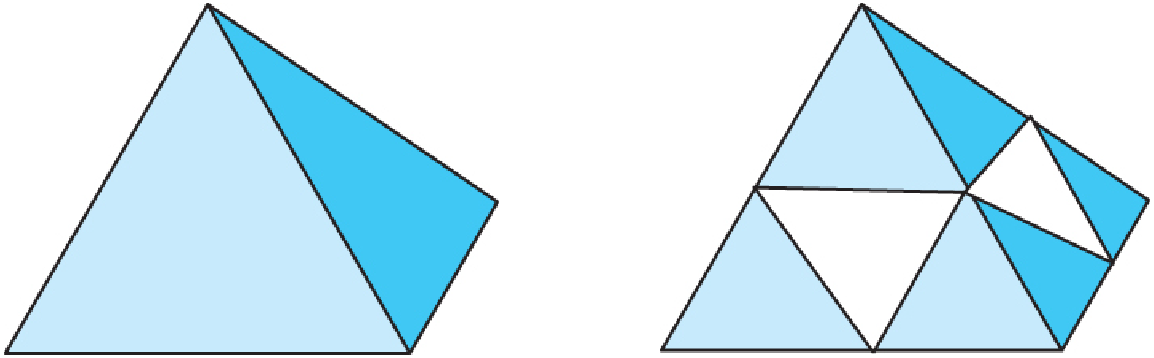
- We can easily make the program three-dimensional by using

```
vec3 v[3]
```

and starting with a tetrahedron

3D Gasket

- We can subdivide each of the four faces



- Appears as if we remove a solid tetrahedron from the center leaving four smaller tetrahedra
- Code almost identical to 2D example

Triangle code

```
// display one triangle
void triangle(vec3 a, vec3 b, vec3 c)
{
      static int i = 0;

      points[ i ] = a;
      points[i+1] = b;
      points[i+2] = c;
      i += 3
}
```

Subdivision code

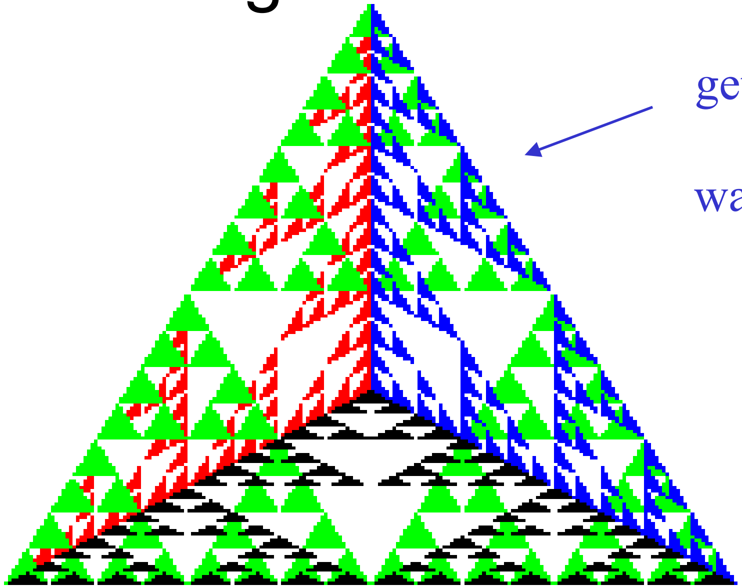
```
// triangle subdivision using vertex numbers
void divide_triangle(vec3 a, vec3 b, vec3 c, int m)
{
    vec3 ab, ac, bc;

    if(m > 0){
        ab = (a + b)/2;
        ac = (a + c)/2;
        bc = (b + c)/2;
        divide_triangle(a, ab, ac, m-1);
        divide_triangle(c, ac, bc, m-1);
        divide_triangle(b, bc, ab, m-1);
    }
    // else, draw triangle at end of recursion
    else triangle(a,b,c);
}
```

Tetrahedron code

```
void tetrahedron(int m)
{
    glColor3f(1.0,0.0,0.0);
    divide_triangle(v[0], v[1], v[2], m);

    glColor3f(0.0,1.0,0.0);
    divide_triangle(v[3], v[2], v[1], m);

    glColor3f(0.0,0.0,1.0);
    divide_triangle(v[0], v[3], v[1], m);

    glColor3f(0.0,0.0,0.0);
    divide_triangle(v[0], v[2], v[3], m);
}
```

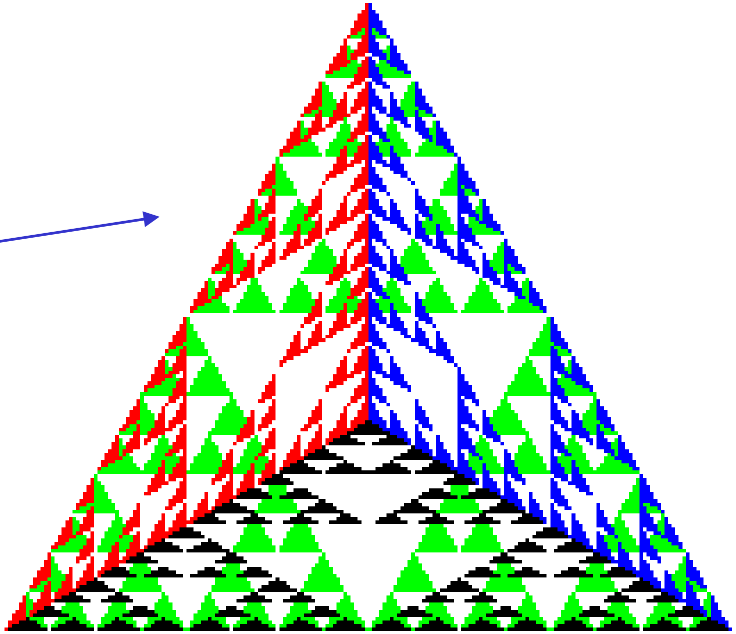
Almost Correct

- Because the triangles are drawn in the order they are specified in the program, the front triangles are not always rendered in front of triangles behind them



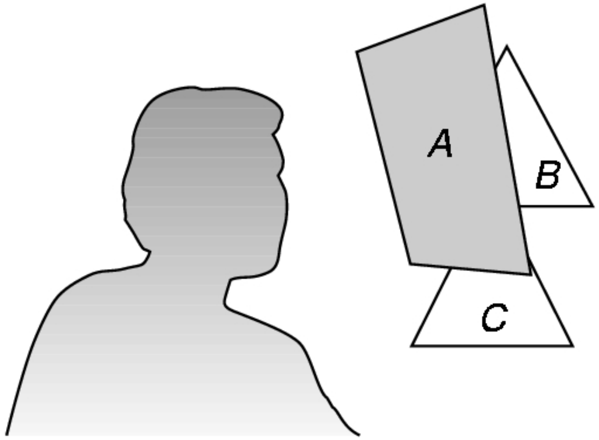
get this

want this



Hidden-Surface Removal

- We want to see only those surfaces in front of other surfaces
- OpenGL uses a *hidden-surface* method called the *z*-buffer algorithm that saves depth information as objects are rendered so that only the front objects appear in the image



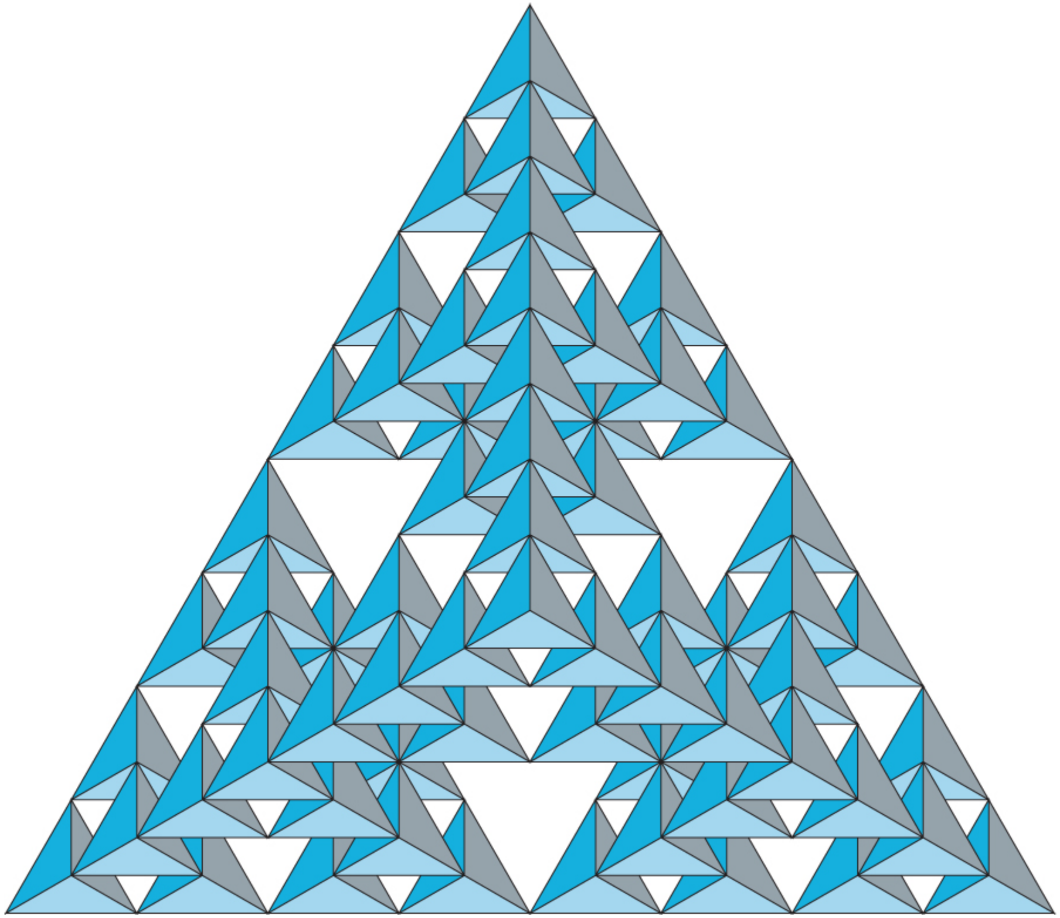
Using the Z-buffer algorithm

- The algorithm uses an extra buffer, the z-buffer, to store depth information as geometry travels down the pipeline
- It must be
  - Enabled in **`initializeGL()`**
    - **`glEnable(GL_DEPTH_TEST)`**
  - Cleared in the **`paintGL()`**
    - **`glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT)`**

Surface vs. Volume Subdvision

- In our example, we divided the surface of each face
- We could also divide the volume using the same midpoints
- The midpoints define four smaller tetrahedrons, one for each vertex
- Keeping only these tetrahedrons removes a *volume* in the middle

Volume Subdivision



Input and Interaction

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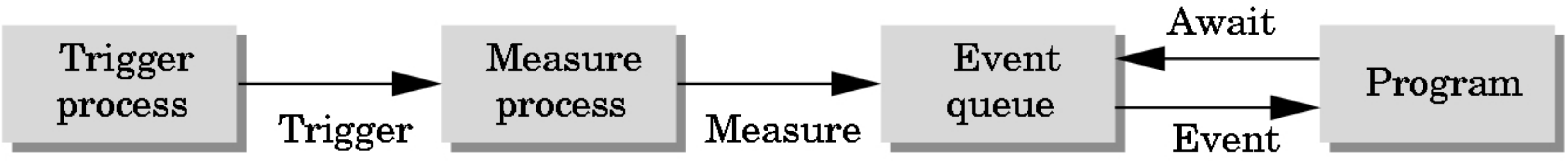
Objectives

- Event-driven input
- Callback functions / slot functions
- Window resize functions
    - Alter aspect ratio
    - Preserve aspect ratio

Event Mode

- Most systems have more than one input device, each if which can be triggered at an arbitrary time by a user
- Each trigger generates an *event* whose measure is put in an *event queue* which can be examined by the user program



Event Types

- Window: resize, expose, iconify
- Mouse: click one or more buttons
- Motion: move mouse
- Keyboard: press or release a key

Callbacks

- Programming interface for event-driven input
- Define a *callback function* for each type of event the graphics system recognizes
- In Qt, this function is known as the *slot function*
- This user-supplied function is executed when the event occurs
- Qt example:

```
QSlider  m_sliderTheta;
QSpinBox m_spinBoxTheta;
connect(m_sliderTheta,  SIGNAL(valueChanged(int)), this, SLOT(changeTheta(int)));
connect(m_spinBoxTheta, SIGNAL(valueChanged(int)), this, SLOT(changeTheta(int)));
```

changeTheta()

```
void changeTheta(int angle)
{
    // update slider and spinbox
    m_sliderTheta->blockSignals(true);
    m_sliderTheta->setValue(angle);
    m_sliderTheta->blockSignals(false);

    m_spinBoxTheta->blockSignals(true);
    m_spinBoxTheta->setValue(angle);
    m_spinBoxTheta->blockSignals(false);

    m_theta = angle * (M_PI/180.);    // convert to radians
    m_points.clear();    // clears points vector
    initBuffers();       // recalculates points
    updateGL();          // redraw: invokes paintGL()
}
```

Qt Event Loop

- Remember that the last line in **`main.c`** for a program using Qt must be `return app.exec();`

```
#include “MainWindow.h”          // UI window header

int main(int argc, char **argv)
{
 QApplication app(argc, argv);   // create application
 MainWindow window;              // create UI window
 window.showMaximized();         // display window
 return app.exec();              // infinite processing loop
}
```

Infinite Event Loop

- In each pass through the event loop, Qt
  - looks at the events in the queue
  - for each event in the queue, Qt executes the appropriate slot function if one is defined
  - if no slot is defined for the event, the event is ignored

paintGL()

- The paintGL() function is executed whenever Qt determines that the window should be refreshed, for example
  - When the window is first opened
  - When the window is reshaped
  - When a window is exposed
  - When the user program decides it wants to change the display
- Every Qt/OpenGL program must have a paintGL()

Posting Displays

- Many events may invoke paintGL()
  - Can lead to multiple executions of the display callback on a single pass through the event loop
- We can avoid this problem by instead using

```
updateGL();  // if using QGLWidget
update();    // if using QOpenGLWidget
```

  which sets a flag.

- Qt checks to see if the flag is set at the end of the event loop
- If set, then the paintGL() function is executed

Animating a Display

- When we redraw the display through the display callback, we usually start by clearing the window
  - `glClear(GL_COLOR_BUFFER_BIT)`

then draw the altered display

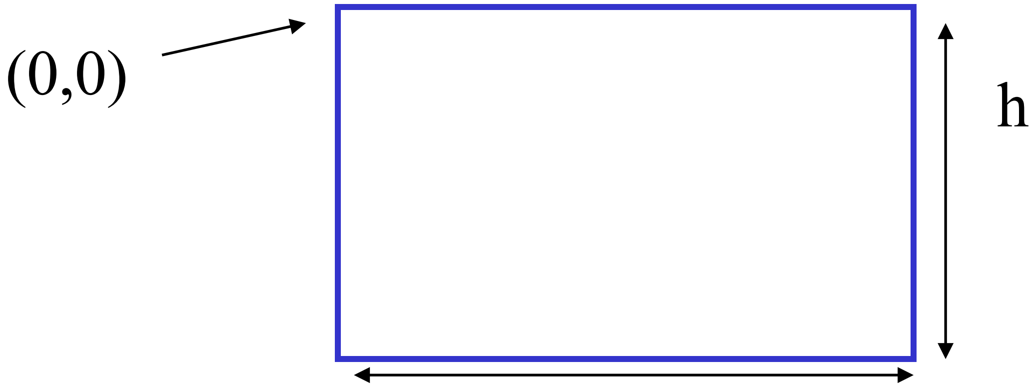
- Problem: the drawing of information in the frame buffer is decoupled from the display of its contents
  - Graphics systems use dual ported memory
- Hence we can see partially drawn display

Double Buffering

- Instead of one color buffer, we use two
  - **Front Buffer**: one that is displayed but not written to
  - **Back Buffer**: one that is written to but not displayed
- Handled automatically by QGLWidget() in Qt.

Positioning

- Positions in the screen window are usually measured in pixels with the origin at the top-left corner
  - Consequence of refresh done from top to bottom
- OpenGL uses a world coordinate system with origin at the bottom left
  - Must invert *y* coordinate returned by callback by height of window
  - $y = h - y;$



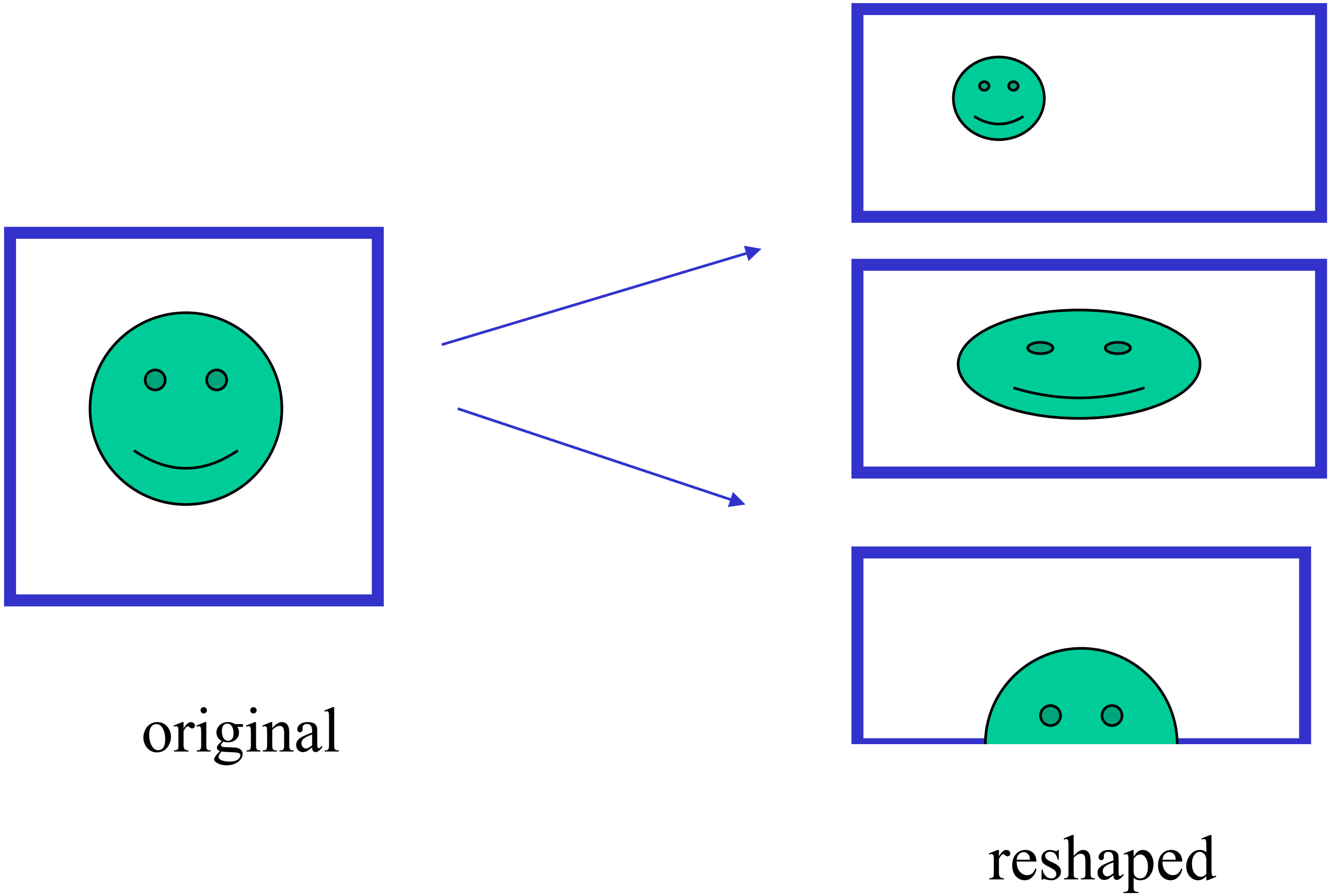
Obtaining the window size

- To invert the *y* position we need the window height
  - Height can change during program execution
  - Track with a global variable
  - New height returned to reshape callback resizeGL()

Reshaping the window

- We can reshape and resize the OpenGL display window by pulling the corner of the window
- What happens to the display?
  - Must redraw from application
  - Two possibilities
    - Display part of world
    - Display whole world but force to fit in new window
      - Can alter aspect ratio

Reshape possibilities



original

reshaped

resizeGL()

- The `resizeGL()` function is a good place to put camera functions because it is invoked when the window is first opened

```
void resizeGL(int w, int h)
```

Pre-OpenGL 3.0: Reshape Example #1

- This reshape fct *does not preserve* shapes; it ignores the aspect ratio between the viewport and world window

```
void resizeGL(int w, int h)
{
       // set viewport to occupy full window
       glViewport(0, 0, w, h);

       // init viewing coordinates for orthographic projection
       glMatrixMode(GL_PROJECTION);
       glLoadIdentity();
       glOrtho(-1., 1., -1., 1., -1., 1.);
}
```

Pre-OpenGL 3.0: Reshape Example #2

- This reshape fct *preserves* shapes by making the viewport and world window have the same aspect ratio

```
void resizeGL(int w, int h)
{
        // compute aspect ratio
        float ar = (float) w / h;

        // set xmax, ymax
        float xmax, ymax;
        if(ar > 1.0) {  // wide screen
                xmax = ar;
                ymax = 1;
        } else {                // tall screen
                xmax = 1;
                ymax = 1 / ar;
        }
        glViewport(0, 0, w, h);
        glMatrixMode(GL_PROJECTION);
        glLoadIdentity();
        glOrtho(-xmax, xmax, -ymax, ymax, 1., 1.);
}
```

Modern OpenGL:
Reshape Example (with Qt)

- This reshape fct *preserves* shapes by making the viewport and world window have the same aspect ratio. Uses Qt.

```
Qmatrix4x4 m_projection;
void resizeGL(int w, int h)
{
        // compute aspect ratio
        float ar = (float) w / h;

        // set xmax, ymax
        float xmax, ymax;
        if(ar > 1.0) {   // wide screen
                xmax = ar;
                ymax = 1;
        } else {         // tall screen
                xmax = 1;
                ymax = 1 / ar;
        }
        glViewport(0, 0, w, h);
        m_projection.setToIdentity();
        m_projection.ortho(-xmax, xmax, -ymax, ymax, 1., 1.);
}
```