Introduction to OpenGL

CS 4620
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Introduction

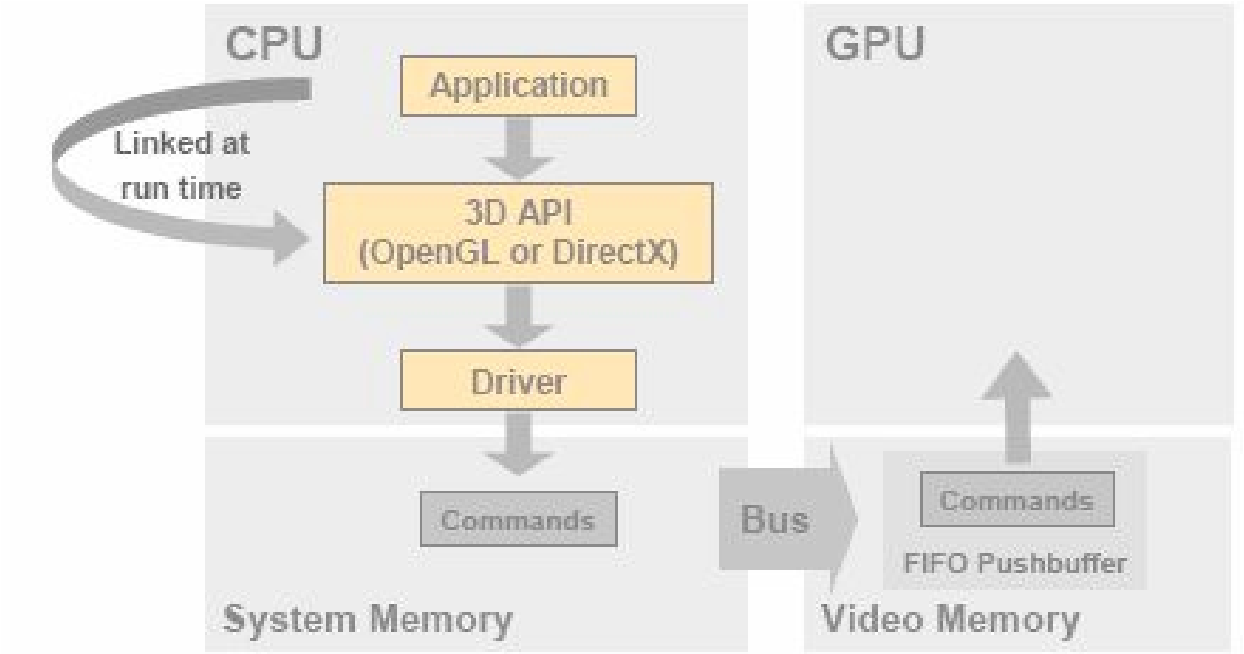
- Show how to produce graphics using OpenGL
- Introduce our framework for OpenGL programming

OpenGL

- Open Graphics Library
- API for GPU-accelerated 2D / 3D rendering
- Cross-platform (Windows, OS X, Linux, iOS, Android, ...)
- Developed by SGI in 1992
  - 2009: OpenGL 3.2
  - 2010: OpenGL 4.0
  - 2011: OpenGL 4.2
- Main alternative: Direct3D (Windows / XBox)

Why Use OpenGL?

- Tap massive power of GPU hardware to render images
- Use GPU without worrying about exact details of hardware



What OpenGL Does For Us

- Controls GPU
- Lets user specify resources...:
  - Geometry (vertices and primitives)
  - Textures
  - Shaders (programs that run in the graphics pipeline)
  - Etc.
- ...and use them:
  - Rasterize and draw geometry

How We'll Use OpenGL

- OpenGL version
  - We use 2.1, plus extensions
  - Some features in 2.1 are no longer commonly used
  - Code uses subset of features used in 3.x and 4.x
- JOGL
  - Java bindings for OpenGL API
- CS 4620 Framework
  - Simplifies creating and using OpenGL resources

Creating an OpenGL Program

GLCanvas

- Java UI component
- Can display images created by OpenGL
- OpenGL “context”
  - Stores OpenGL state (geometry, buffers, etc.)
  - Provides the framebuffer that we draw to

- Usage: create and put into a Java window

Events

- GL canvas can trigger certain events
  - Something happens (e.g. user resizes window)
  - Canvas broadcasts a message
  - Objects interested in the event can sign up as listeners
  - When event happens, OpenGL calls method in listener

- These events let us interact with OpenGL

GLEventListener

- Interface for classes that can listen for OpenGL events
- Implementations can perform OpenGL commands

- Usage:
  - Create class implementing GLEventListener
  - Implement four methods
  - Call GLCanvas.addGLListener

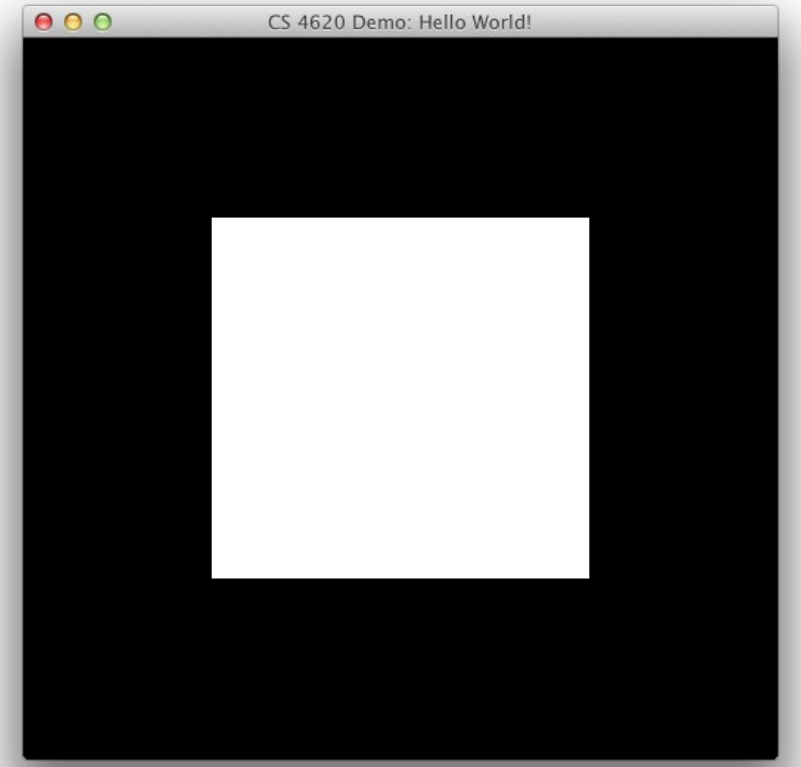
GLEventListener Methods

- init
  - Called once when OpenGL context is created
- display
  - Called when GLCanvas wants to update the image it shows
- resize
  - Called when canvas is resized
- dispose
  - Called when OpenGL context is destroyed

GLEventListener Methods

- init
  - Use to create GL resources (geometry, textures, etc.)
- display
  - Use to draw to the canvas
- resize
  - Use to update information based on new window size
- dispose
  - Use to free up GL resources

Demo: Hello World!



OpenGL Commands and Resources

Example: Hello World's display()

```
@Override
public void display(GLAutoDrawable drawable) {
    final GL2 gl = drawable.getGL().getGL2();

    gl.glClearColor(0.0f, 0.0f, 0.0f, 1.0f);
    gl.glClear(GL2.GL_COLOR_BUFFER_BIT);

    Program.use(gl, program);

    program.setColor(gl, 1.0f, 1.0f, 1.0f);
    boxArray.draw(gl);

    Program.unuse(gl);
}
```

OpenGL Commands

- final GL2 gl = drawable.getGL().getGL2()
  - Get OpenGL context for canvas
  - GL2 object exposes underlying C API for OpenGL
  - API calls: gl.glSomeCommandName

- gl.glClearColor(0.0f, 0.0f, 0.0f, 1.0f)
  - Set black as the color to use when clearing the screen
- gl.glClear(GL2.GL_COLOR_BUFFER_BIT)
  - Clear the display buffer using the color given by glClearColor

Framework Commands

- Program.use(gl, program)
  - Set which shader program the pipeline will use to draw geometry
  - More about this on another day...
- program.setColor(gl, 1.0f, 1.0f, 1.0f);
  - Tell shader program to draw geometry in white
- boxArray.draw(gl)
  - Draw the geometry described by boxArray
- Program.unuse(gl)
  - Tell OpenGL we are done drawing for now
- **Each of these has OpenGL commands under the hood**

Framework Commands

- Program.use(gl, program)
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  - Draw the geometry described by boxArray
- Program.unuse(gl)
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- **Each of these has OpenGL commands under the hood**

Framework commands that need access to OpenGL take the gl object as their first argument

Why Have a Framework?

- You write:

  boxArray.draw(gl)

- Framework does:

```
gl.glBindVertexArray(boxArray.id);
gl.glBindBuffer(GL2.GL_ELEMENT_ARRAY_BUFFER, boxArray.indexBuffer.id);
gl.glDrawElements(boxArray.geometryType, boxArray.indexBuffer.numElements,
    boxArray.indexBuffer.format, 0);
gl.glBindBuffer(GL2.GL_ELEMENT_ARRAY_BUFFER, 0);
gl.glBindVertexArray(0);
```

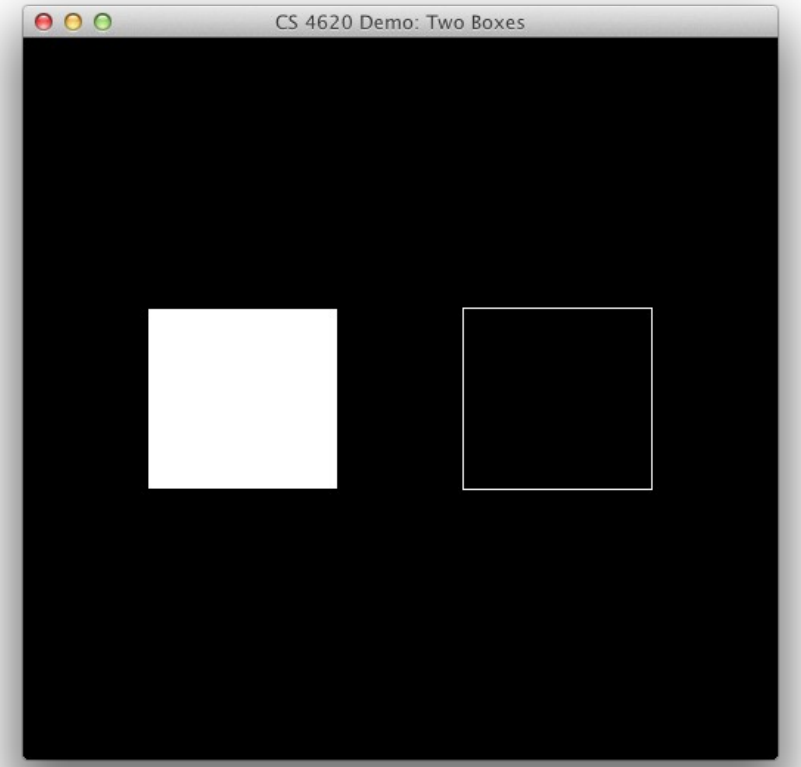
- Annoying to retype full sequence of commands for every draw

Framework and GL Resources

- OpenGL API has “objects” that hold rendering resources
  - Geometry, textures, shader programs, etc.
- Framework represents these with Java classes
  - Program (shader programs)
  - VertexBuffer, VertexArray (used to specify geometry)
- Constructing an object creates OpenGL resource
  - Object's data lives in GPU memory
  - Allows faster access while rendering

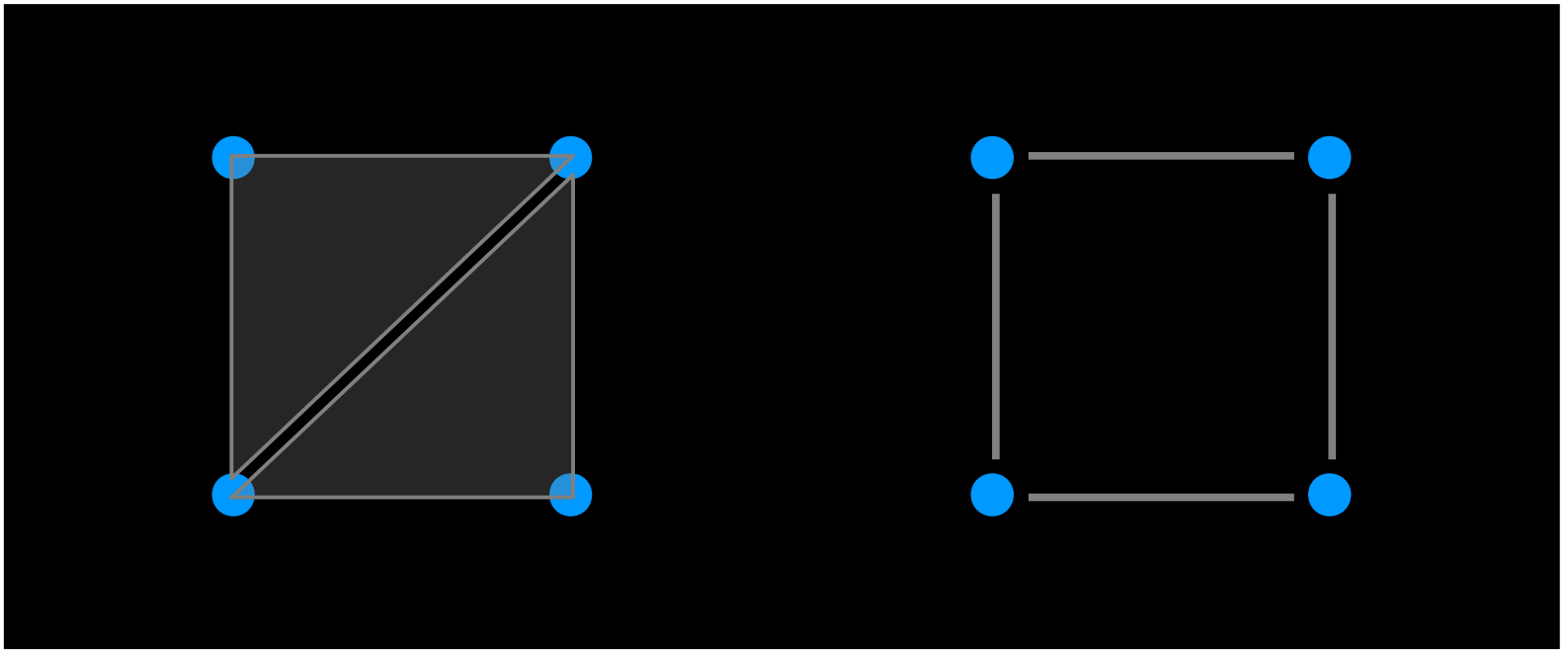
OpenGL Resources: Geometry

Demo: Two Boxes



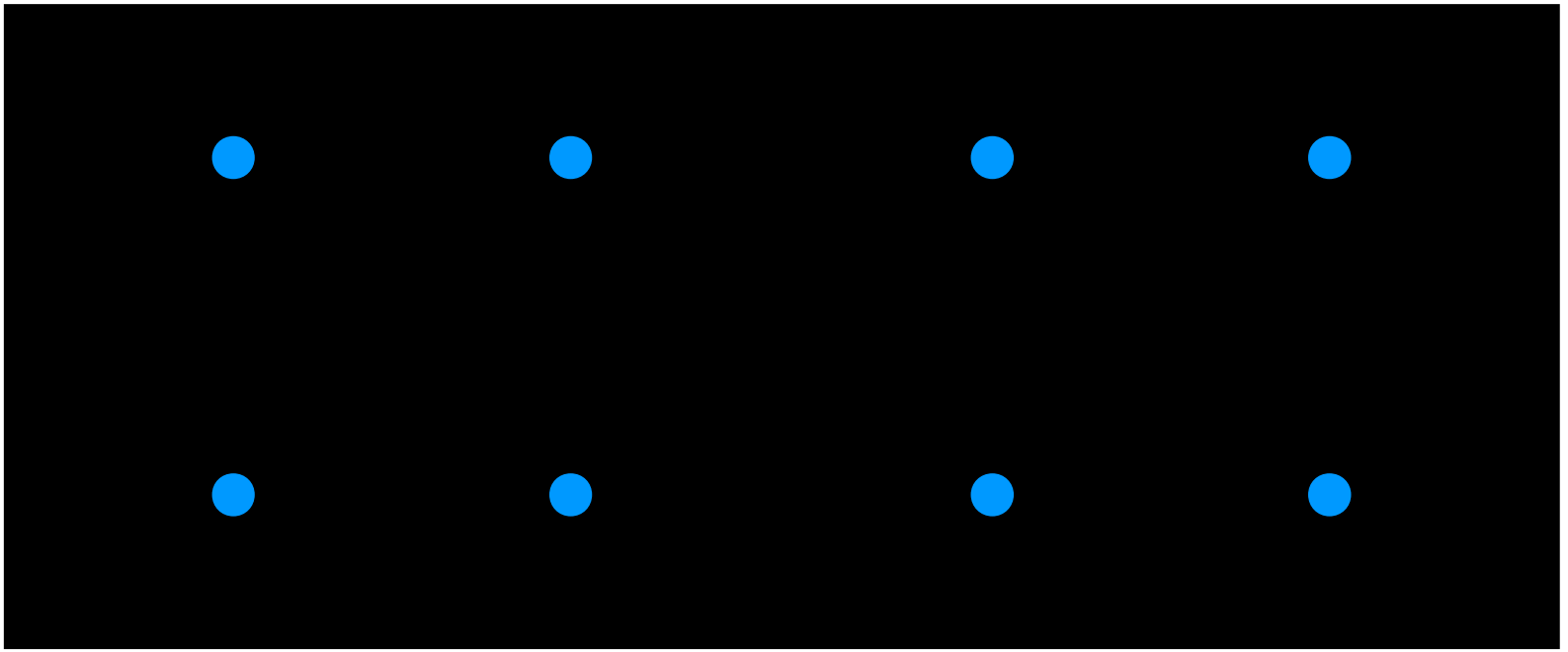
What We're Seeing

- Box on left: two triangles
- Box on right: four lines



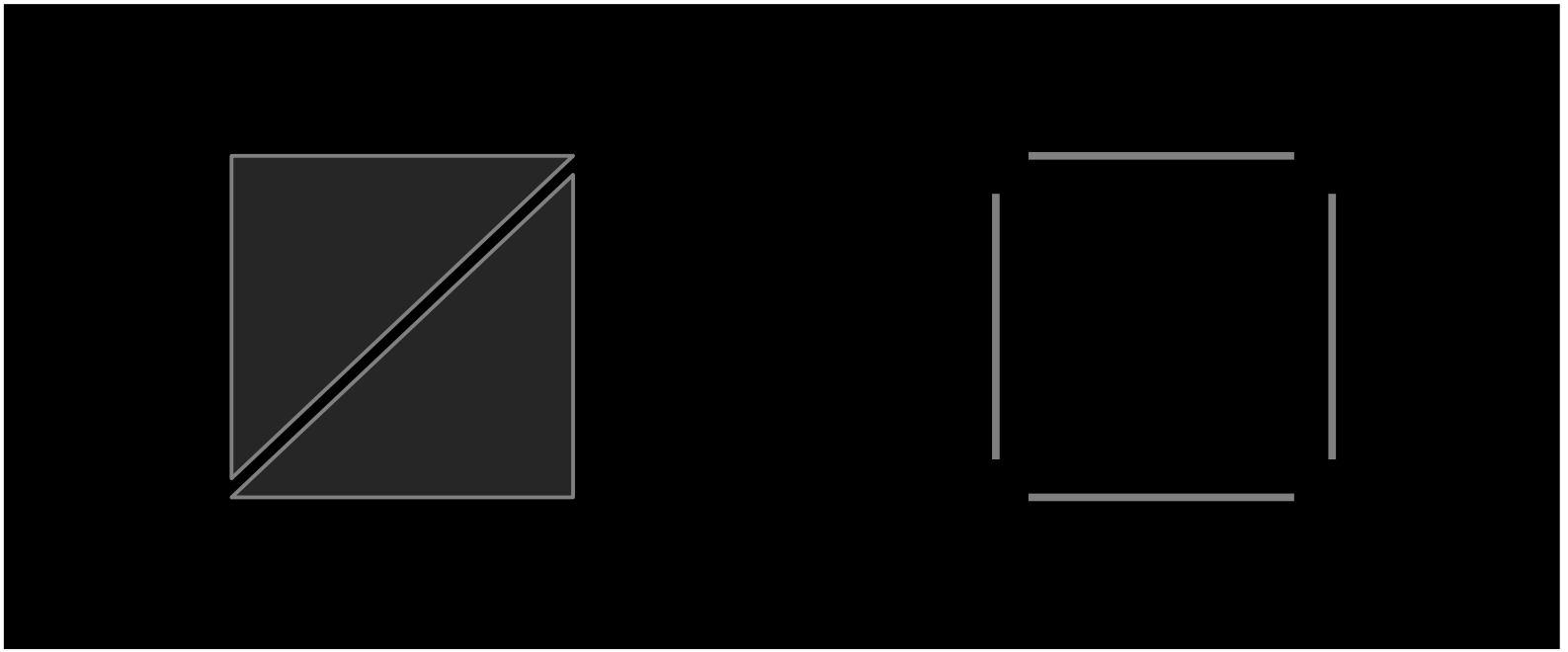
Vertices

- Foundation for all geometry
- OpenGL: specify with VertexBuffer



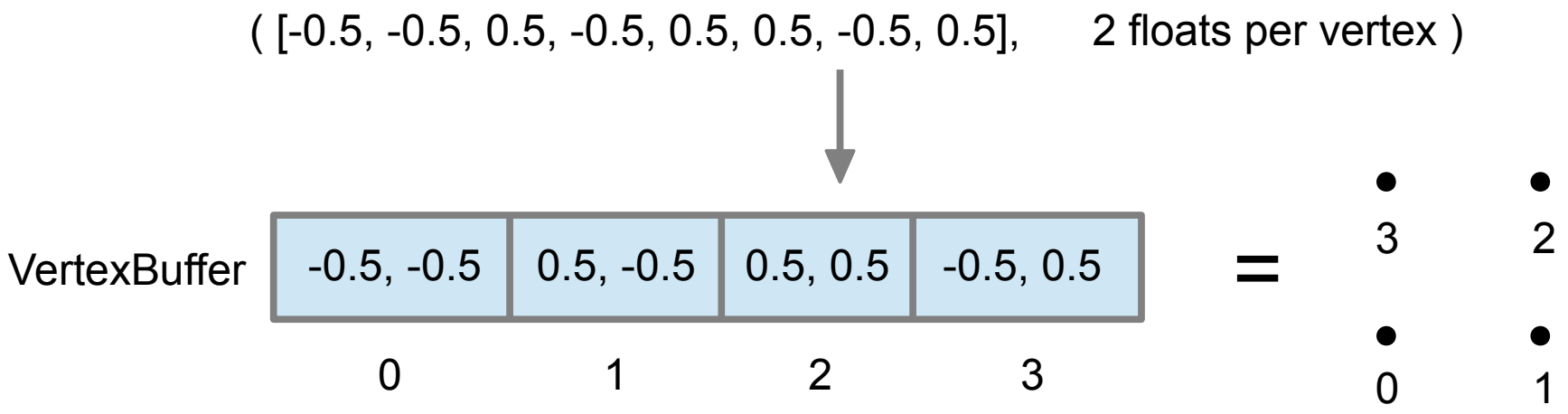
Primitives

- Basic shapes built from vertices; e.g. triangles, lines
  - Assemble to build more complicated shapes
- OpenGL: specify with VertexArray and IndexBuffer



Specifying Vertices: VertexBuffer

- OpenGL object to store vertices
- Info needed:
  - Array of floats representing vertices
  - How many dimensions per vertex (2D? 3D?)

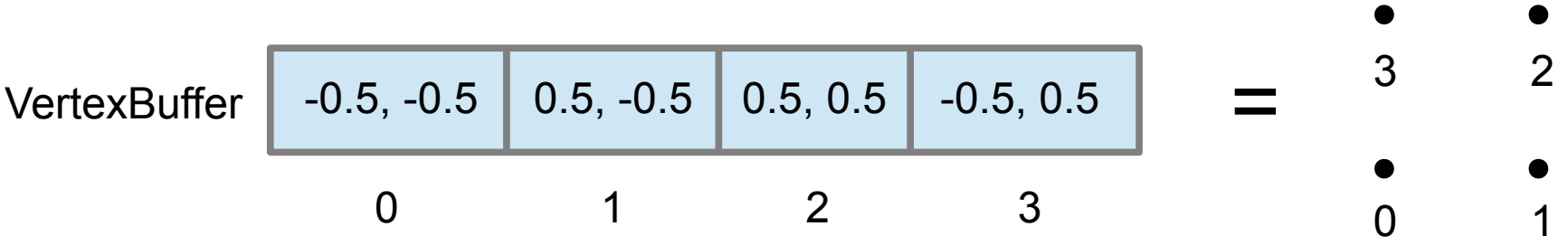


Specifying Vertices: TwoBoxes' init()

```
@Override
public void init(GLAutoDrawable drawable) {
    if(initialized)
        return;

    GL2 gl = drawable.getGL().getGL2();

    // define vertex positions
    float [] vertexPositions = {
           -0.5f, -0.5f,      // vertex 0
            0.5f, -0.5f,      // vertex 1
            0.5f,  0.5f,      // vertex 2
           -0.5f,  0.5f       // vertex 3
    };

    VertexBuffer vertexBuffer =
                        new VertexBuffer(gl, vertexPositions, 2);

    ...
```

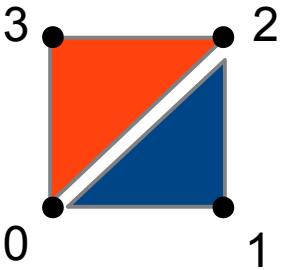
Grouping Vertices into Primitives

- VertexBuffer gives vertices in some order



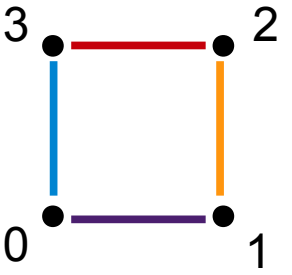
- Can re-order vertices to form primitives, so that:
  - Every three vertices form a triangle

[0, 1, 2, 0, 2, 3]



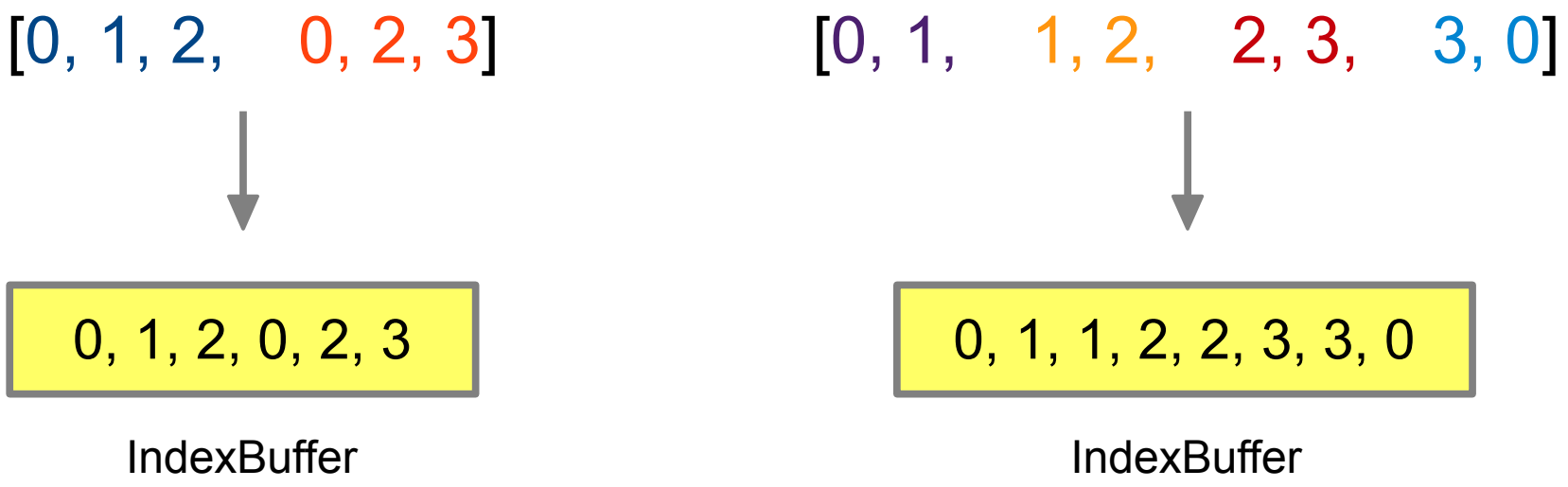
  - Every two vertices form a line

[0, 1, 1, 2, 2, 3, 3, 0]



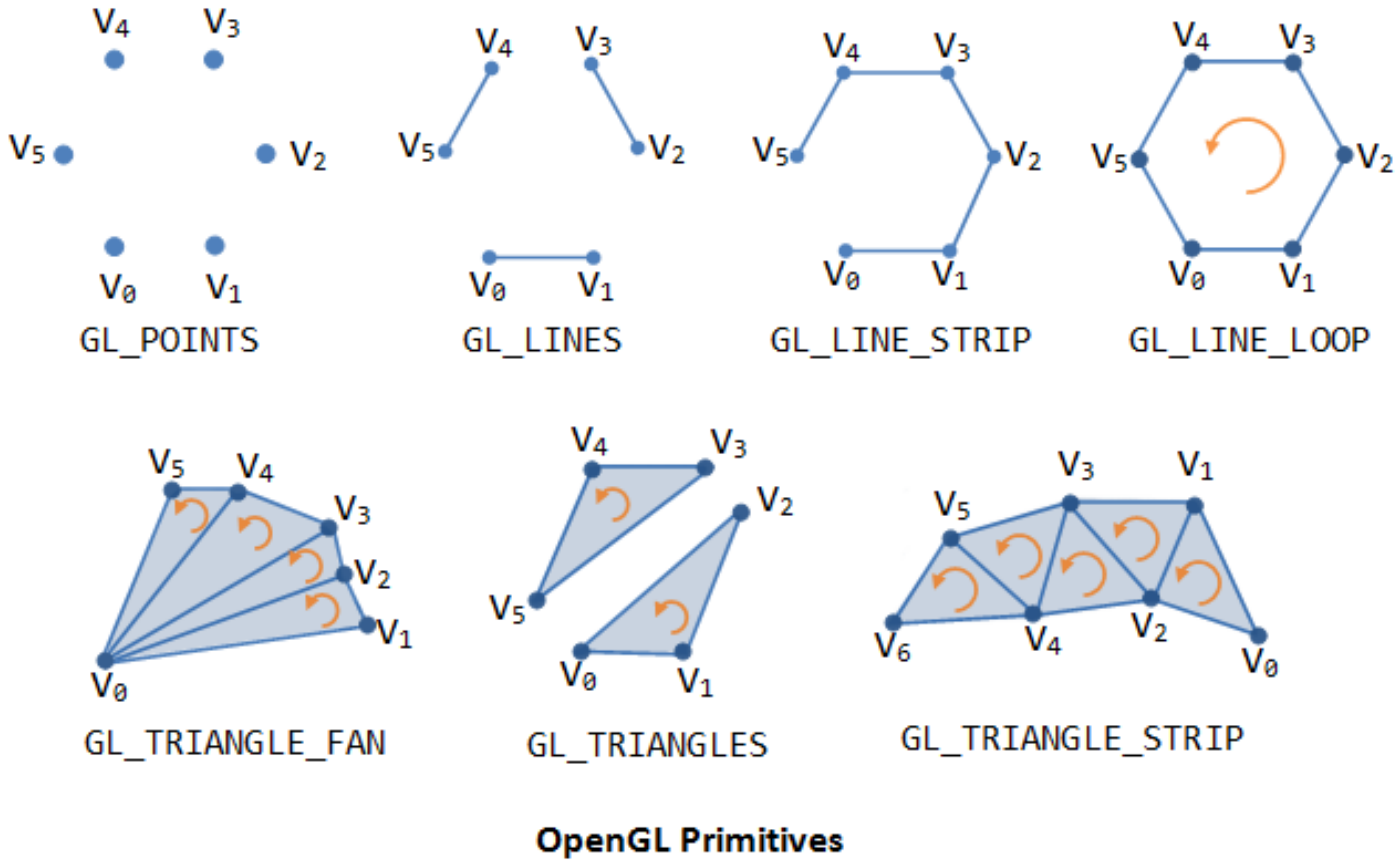
Grouping Vertices: IndexBuffer

- OpenGL object to store sequence of vertex indices
- Info needed:
  - List of integer indices



Ways to Group: GL Primitives

- OpenGL declares several primitive types
- Determine how to group a sequence of verts into primitives



OpenGL Primitives

(adapted from http://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html)

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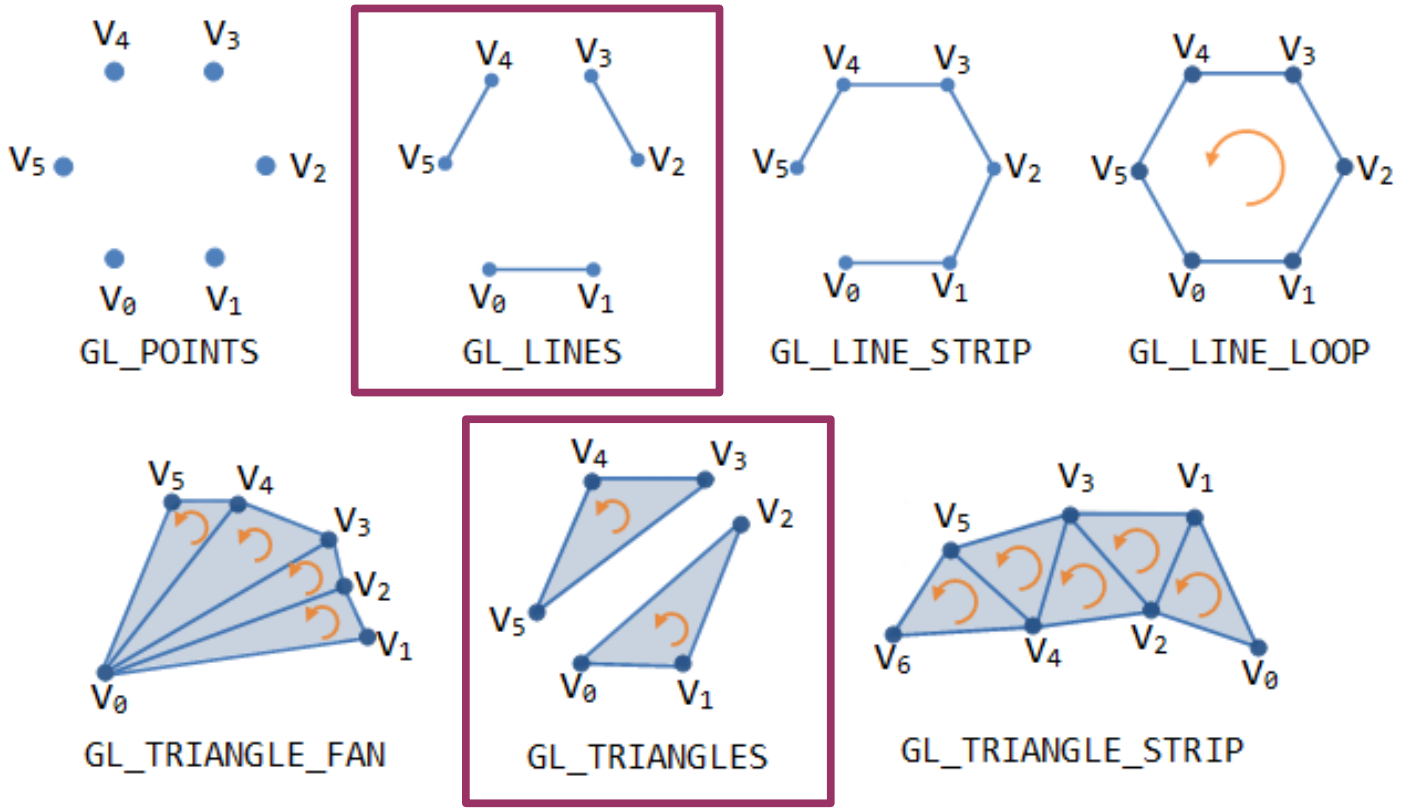


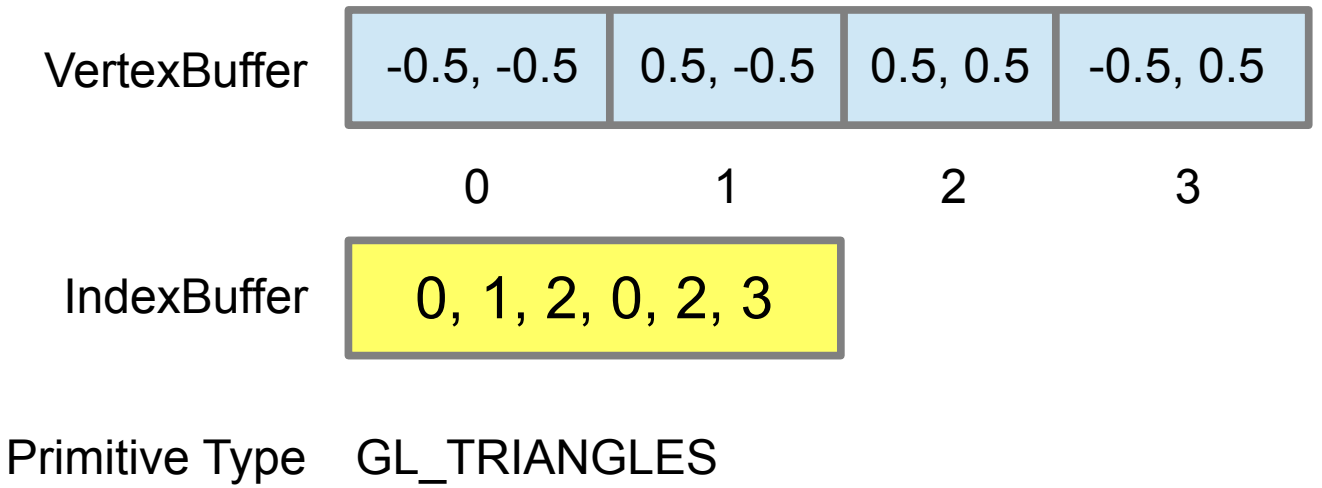
OpenGL Primitives

(adapted from http://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html)

Putting it Together

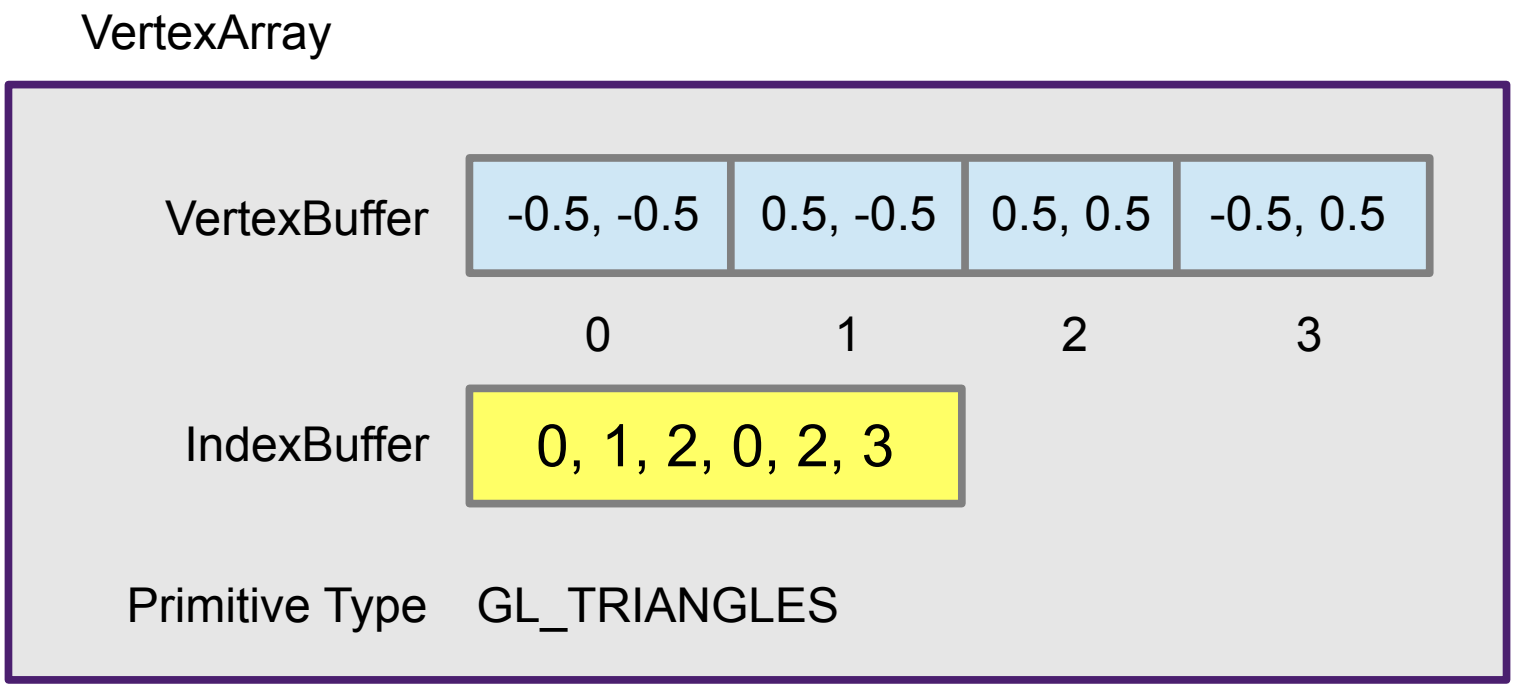
- VertexBuffer: what the vertices are
- IndexBuffer: in what order to put them
- Primitive Type: how to group ordered vertices into primitives

- Together, fully describes geometry



Putting it Together: VertexArray

- OpenGL object to fully describe a piece of geometry
- Can be drawn by OpenGL
- Info needed:
  - VertexBuffer, IndexBuffer, primitive type



VertexArray in TwoBoxes' init()

```
... // earlier, filled VertexBuffer vertexPositions

int [] linesIndices = {
    0, 1,
    1, 2,
    2, 3,
    3, 0
};
int [] trianglesIndices = {
    0, 1, 2,
    0, 2, 3
};
// make index buffers
linesBuffer = new IndexBuffer(gl, linesIndices);
trianglesBuffer = new IndexBuffer(gl, trianglesIndices);

...
```

VertexArray in TwoBoxes' init()

```
...
// earlier: made VertexBuffer vertexBuffer
// filled IndexBuffer linesBuffer, trianglesBuffer

boxArray = new VertexArray(gl, GL2.GL_TRIANGLES);
boxArray.setIndexBuffer(gl, trianglesBuffer);
boxArray.setAttributeBuffer(gl, TwoDimProgram.VERTEX_INDEX,
                                vertexBuffer);

boxLinesArray = new VertexArray(gl, GL2.GL_LINES);
boxLinesArray.setIndexBuffer(gl, linesBuffer);
boxLinesArray.setAttributeBuffer(gl, TwoDimProgram.VERTEX_INDEX,
                                     vertexBuffer);
```

VertexArray in TwoBoxes' init()

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...
// earlier: made VertexBuffer vertexBuffer
// filled IndexBuffer linesBuffer, trianglesBuffer

boxArray = new VertexArray(gl, GL2.GL_TRIANGLES);
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boxLinesArray = new VertexArray(gl, GL2.GL_LINES);
boxLinesArray.setIndexBuffer(gl, linesBuffer);
boxLinesArray.setAttributeBuffer(gl, TwoDimProgram.VERTEX_INDEX,
                                 vertexBuffer);
```

- Construct VertexArray and say what primitives we will build
- One will make triangles, the other lines

VertexArray in TwoBoxes' init()

```
...
// earlier: made VertexBuffer vertexBuffer
// filled IndexBuffer linesBuffer, trianglesBuffer

boxArray = new VertexArray(gl, GL2.GL_TRIANGLES);
boxArray.setIndexBuffer(gl, trianglesBuffer);
boxArray.setAttributeBuffer(gl, TwoDimProgram.VERTEX_INDEX,
                            vertexBuffer);

boxLinesArray = new VertexArray(gl, GL2.GL_LINES);
boxLinesArray.setIndexBuffer(gl, linesBuffer);
boxLinesArray.setAttributeBuffer(gl, TwoDimProgram.VERTEX_INDEX,
                                 vertexBuffer);
```

- Tell array how to order the vertices when building primitives
- Triangles and lines will need different vertex orders

VertexArray in TwoBoxes' init()

```
...
// earlier: made VertexBuffer vertexBuffer
// filled IndexBuffer linesBuffer, trianglesBuffer

boxArray = new VertexArray(gl, GL2.GL_TRIANGLES);
boxArray.setIndexBuffer(gl, trianglesBuffer);
boxArray.setAttributeBuffer(gl, TwoDimProgram.VERTEX_INDEX,
                                vertexBuffer);

boxLinesArray = new VertexArray(gl, GL2.GL_LINES);
boxLinesArray.setIndexBuffer(gl, linesBuffer);
boxLinesArray.setAttributeBuffer(gl, TwoDimProgram.VERTEX_INDEX,
                                     vertexBuffer);
```

- Tell arrays what vertex data to use
- Both boxes use the same buffer of four vertices

VertexArray in TwoBoxes' init()

```
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// earlier: made VertexBuffer vertexBuffer
// filled IndexBuffer linesBuffer, trianglesBuffer

boxArray = new VertexArray(gl, GL2.GL_TRIANGLES);
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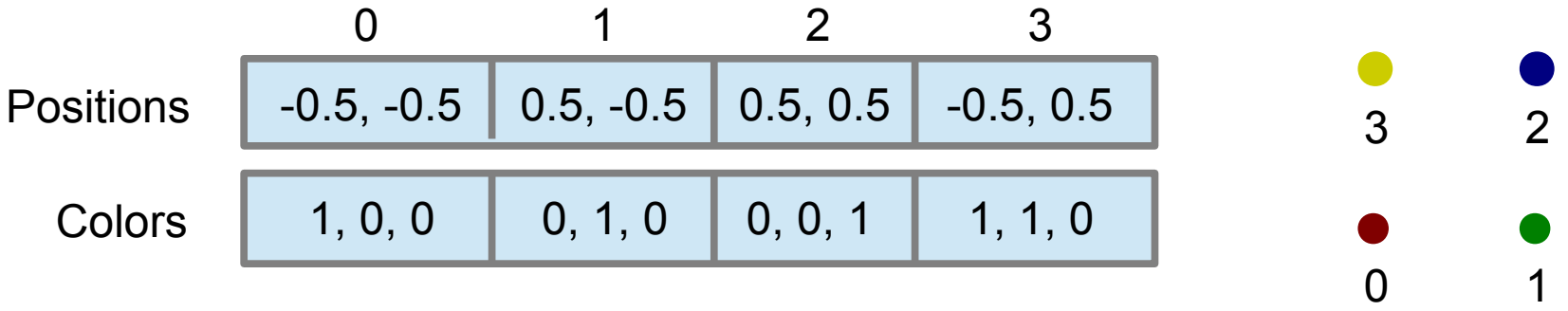
boxArray.setAttributeBuffer(gl, TwoDimProgram.VERTEX_INDEX,
                                vertexBuffer);

boxLinesArray = new VertexArray(gl, GL2.GL_LINES);
boxLinesArray.setIndexBuffer(gl, linesBuffer);
boxLinesArray.setAttributeBuffer(gl, TwoDimProgram.VERTEX_INDEX,
                                     vertexBuffer);
```

- What is this about?

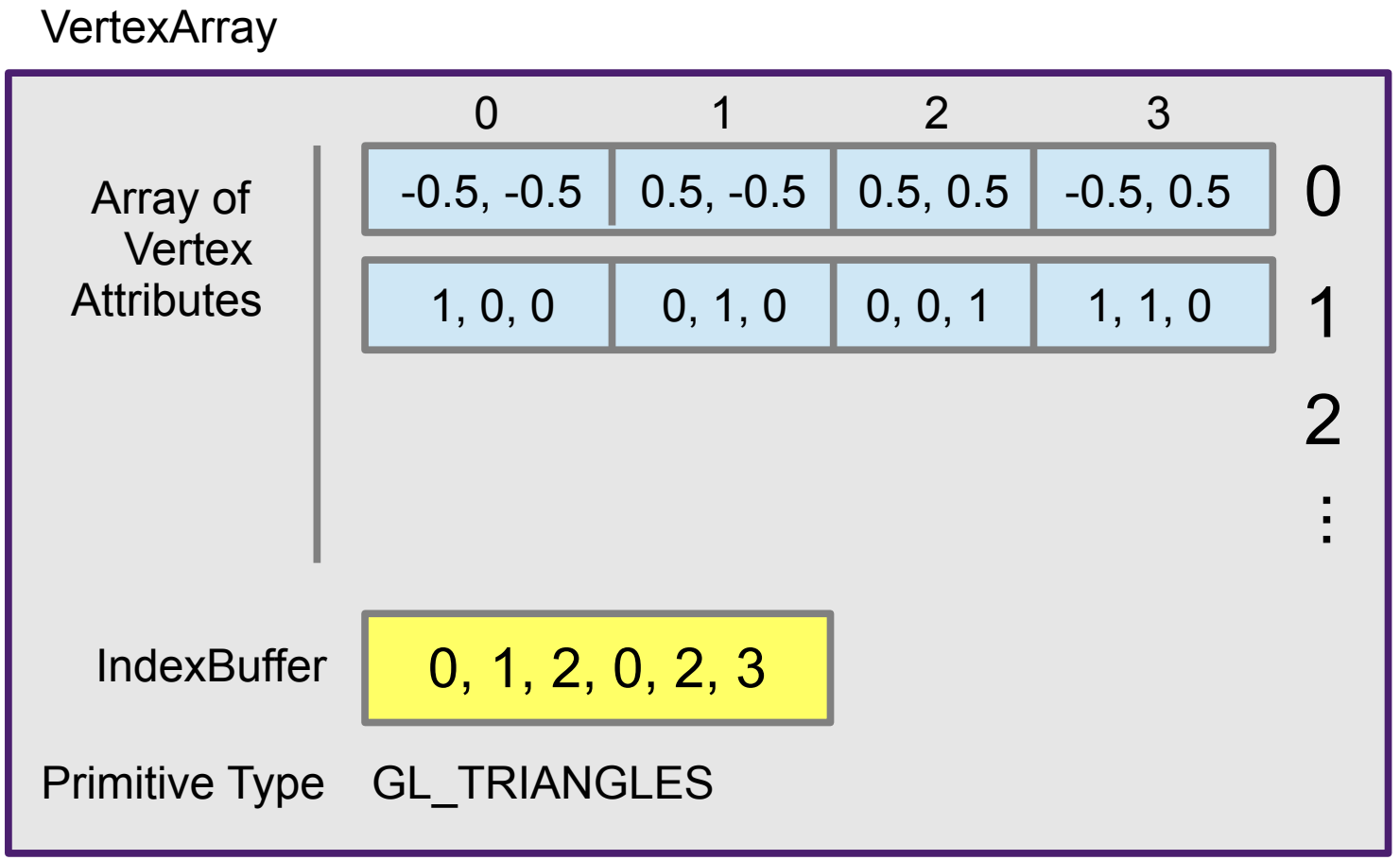
Vertices are More than Positions

- A vertex has a position
- But it can also have other attributes:
  - Normal vector
  - Color
  - Texture coordinate
  - etc.
- Use multiple VertexBuffers to store this info



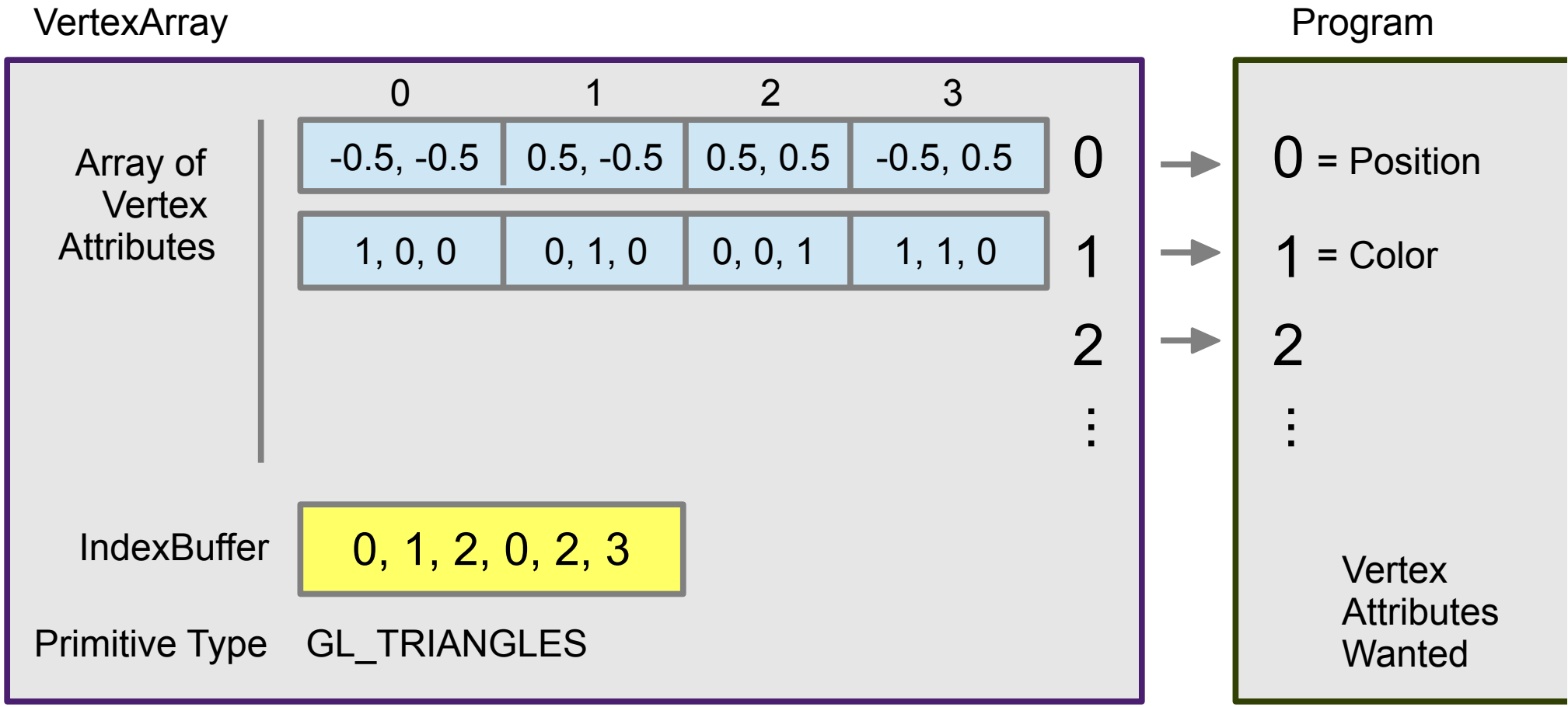
The Full Power of VertexArray

- Accepts multiple VertexBuffers specifying different attributes
- Each buffer mapped to some index in array of attributes

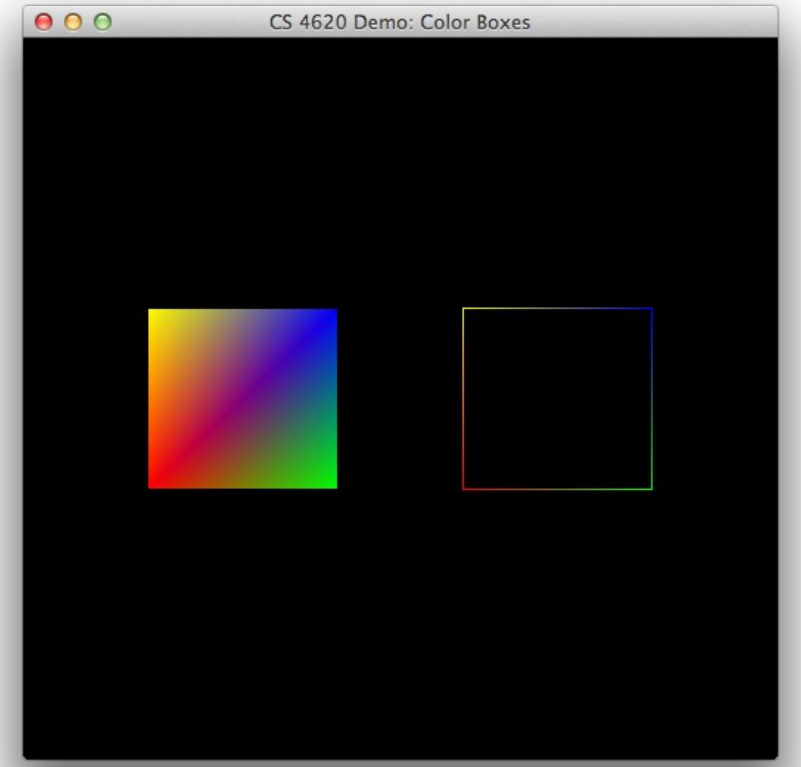


Attribute Indices

- Shader program draws vertices using same array of attributes
- Program declares where it wants each attribute to be



Demo: Color Boxes



ColorBoxes' init()

```
@Override
    public void init(GLAutoDrawable drawable) {

        ... // fill vertexBuffer as before

        float [] vertexColors = {
                1.0f, 0.0f, 0.0f,  // vertex 0
                0.0f, 1.0f, 0.0f,  // vertex 1
                0.0f, 0.0f, 1.0f,  // vertex 2
                1.0f, 1.0f, 0.0f   // vertex 3
        };

        VertexBuffer colorsBuffer =
                            new VertexBuffer(gl, vertexColors, 3);
        ...
```

ColorBoxes' init()

```
... // fill IndexBuffers trianglesBuffer and linesBuffer
boxArray = new VertexArray(gl, GL2.GL_TRIANGLES);
boxArray.setIndexBuffer(gl, trianglesBuffer);
boxArray.setAttributeBuffer(gl, TwoDimColorProgram.VERTEX_INDEX,
                            vertexBuffer);
boxArray.setAttributeBuffer(gl, TwoDimColorProgram.COLOR_INDEX,
                            colorsBuffer);

boxLinesArray = new VertexArray(gl, GL2.GL_LINES);
boxLinesArray.setIndexBuffer(gl, linesBuffer);
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```

- Put vertex positions at index where shader program wants them

ColorBoxes' init()

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... // fill IndexBuffers trianglesBuffer and linesBuffer
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                            colorsBuffer);

boxLinesArray = new VertexArray(gl, GL2.GL_LINES);
boxLinesArray.setIndexBuffer(gl, linesBuffer);
boxLinesArray.setAttributeBuffer(gl, TwoDimColorProgram.VERTEX_INDEX,
                                 vertexBuffer);
boxLinesArray.setAttributeBuffer(gl, TwoDimColorProgram.COLOR_INDEX,
                                 colorsBuffer);
```

- Put vertex colors at index where shader program wants them

Transformations

Representing Transformations

- We will use Matrix3f, Matrix4f classes
  - Set matrix contents:

```
Matrix3f translate = new Matrix3f(1.0f, 0.0f, 3.0f,
                                  0.0f, 1.0f, -4.0f,
                                  0.0f, 0.0f, 1.0f);
```

  - Copy matrices:

```
Matrix3f translateAgain = new Matrix3f(translate);
```

  - Multiply matrices:

```
translate.mul(translateAgain);
// translate = translate * translateAgain
```

  - Transform points:

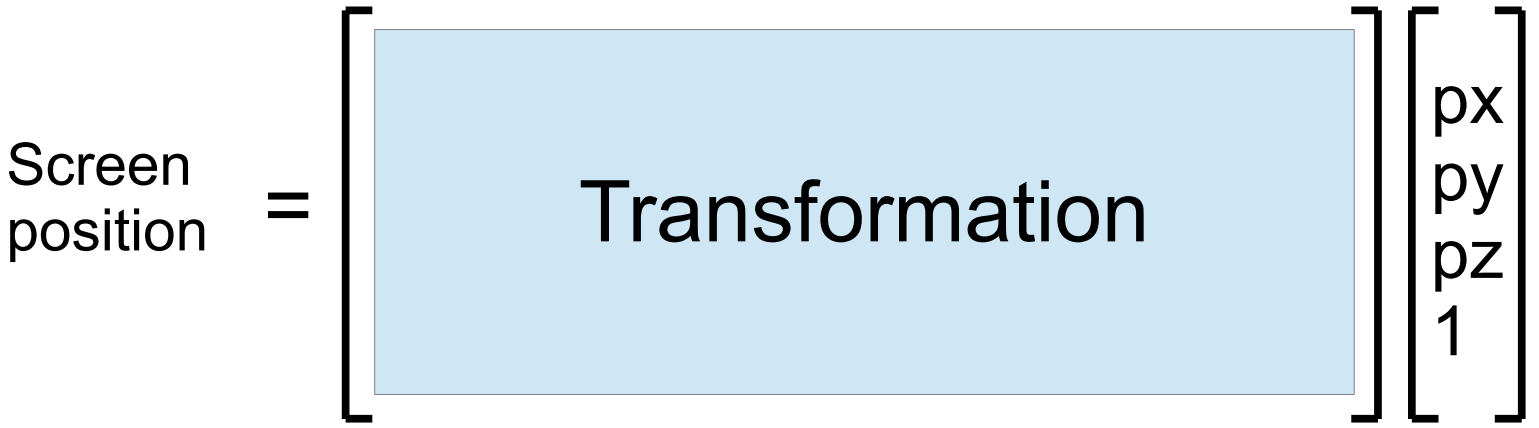
```
Vertex3f vert = new Vertex3f(2.0f, 0.0f, 1.0f);
translate.transform(vert);  // vert = translate * vert
```

Transforms Class

- Provides various useful transformation matrices
  - Identity matrices
  - Translations, scales, rotations
  - Projection matrices
- Command names indicate dimension:
  - translate3DH(): 4x4 matrix, expects 3D homogeneous coords
  - identity3D(): 3x3 matrix, expects 3D non-homogeneous coords

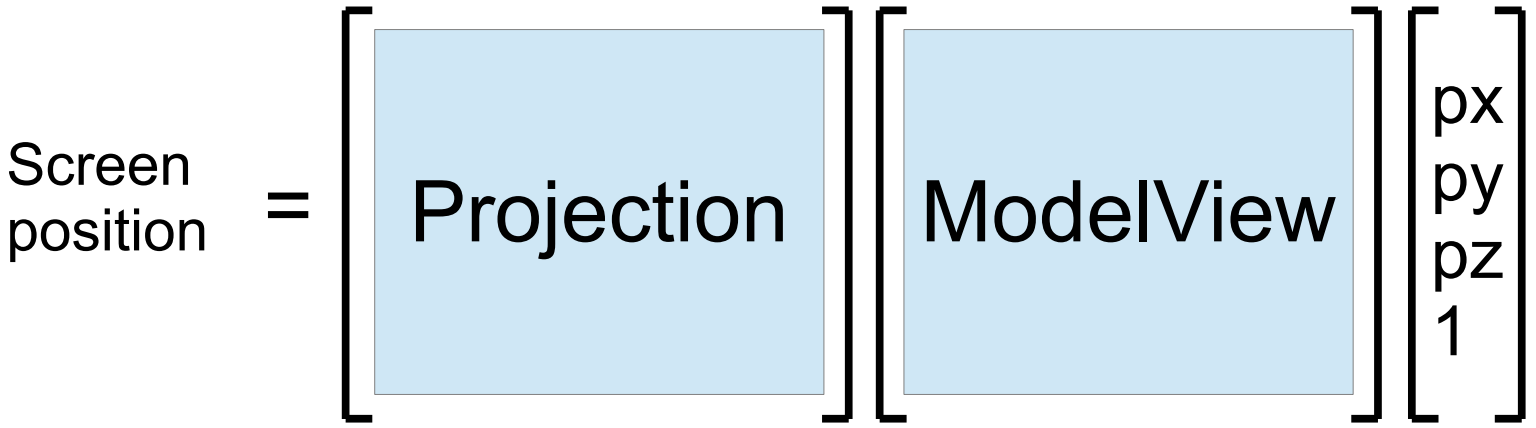
Transforming a Vertex

- VertexArray gives vertices to shader program
- Program transforms them onto screen before drawing



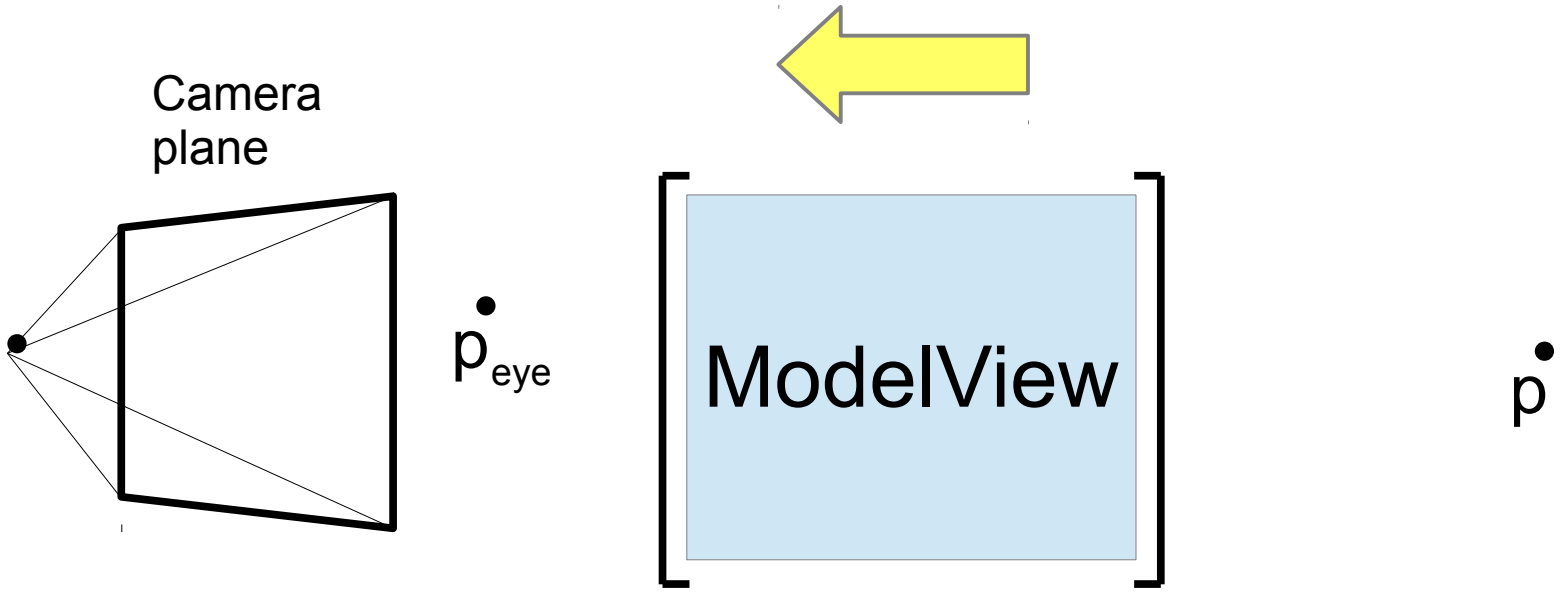
Transforming a Vertex

- Applies two transforms: Projection and ModelView
- Very basic description now; will discuss topic more later



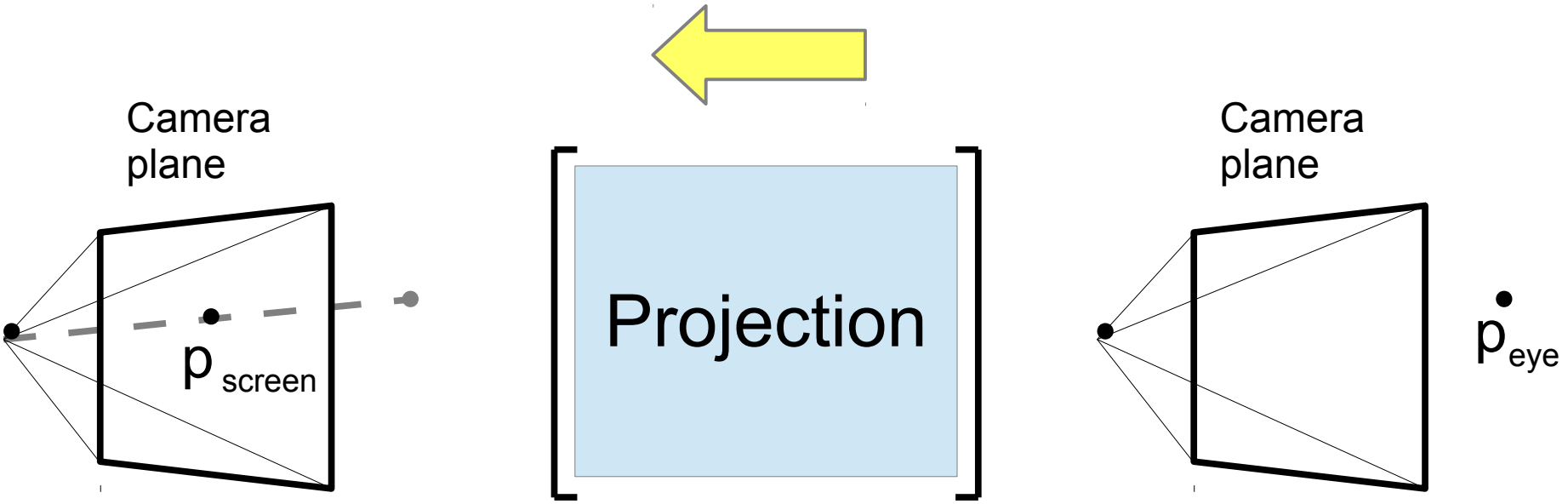
ModelView matrix

- Transforms vertex into coordinates of the viewer
- Modify matrix to transform objects to different places



Projection matrix

- Projects point down onto camera plane
- Usually set matrix once at beginning of display()

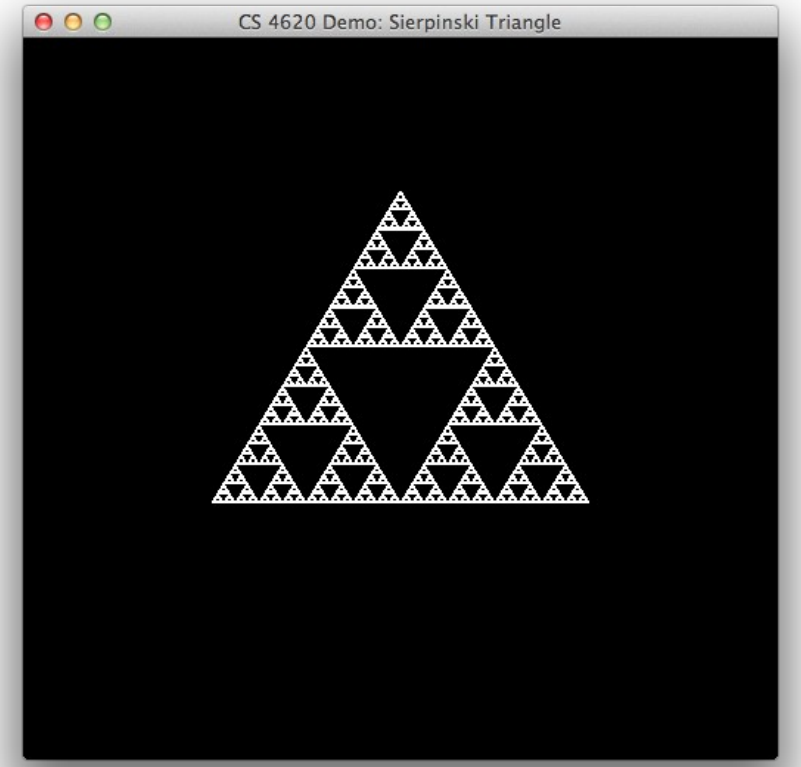


Setting Matrices

- You tell the shader program what matrices to use
  - program.setProjection(projectionMatrix);
  - program.setModelView(modelViewMatrix);

- **Program keeps drawing with the same matrices until you change them**
- Common use pattern:
  - program.setModelView(transformForThisObject);
  - thisObject.draw()

Demo: Sierpinski Triangle

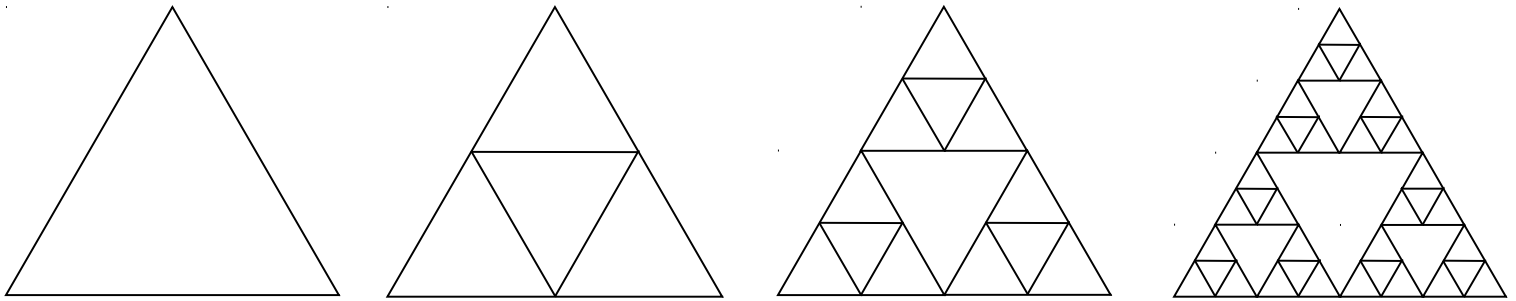


Sierpinski's draw()

```
@Override
public void display(GLAutoDrawable drawable) {
    final GL2 gl = drawable.getGL().getGL2();

    gl.glClearColor(0.0f, 0.0f, 0.0f, 1.0f);
    gl.glClear(GL2.GL_COLOR_BUFFER_BIT);

    Program.use(gl, program);

    program.setProjection(gl,
                Transforms.ortho2DH(-1.0f, 1.0f, -1.0f, 1.0f));
    program.setColor(gl, 1.0f, 1.0f, 1.0f);

    sierpinski(gl, Transforms.identity2DH(), 8);

    Program.unuse(gl);
}
```

Recursively Drawing Fractal

- Define “levels” of Sierpinski triangles



- Recursive function sierpinski(gl, modelView, k)
  - Level 0: a single triangle
  - Build level k recursively from three copies of level k-1
  - Use modelView matrix to transform the three copies
- Example of drawing a hierarchy

sierpinski()

```
void sierpinski(GL2 gl, Matrix3f modelView, int k)
{
     if (k == 0)
          triangle(gl, modelView);
     else
     {
          Matrix3f next;

          // make next = modelView * (transform to top corner)
          next = new Matrix3f(modelView);
          next.mul(Transforms.translate2DH(0.0f, 0.5f / sqrt(3.0f)));
          next.mul(Transforms.scale2DH(0.5f));
          sierpinski(gl, next, k-1);

          // make next = modelView * (transform to bottom right corner)
          next = new Matrix3f(modelView);
          next.mul(Transforms.translate2DH(0.25f, -0.25f / sqrt(3.0f)));
          next.mul(Transforms.scale2DH(0.5f));
          sierpinski(gl, next, k-1);

          // make next = modelView * (transform to bottom left corner)
          next = new Matrix3f(modelView);
          next.mul(Transforms.translate2DH(-0.25f, -0.25f / sqrt(3.0f)));
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          sierpinski(gl, next, k-1);
     }
}
```
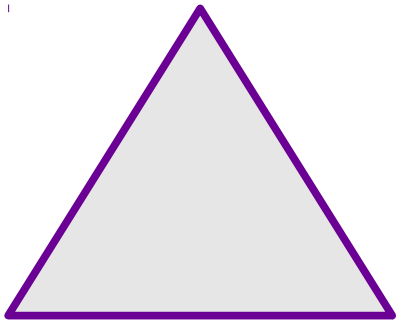

sierpinski()

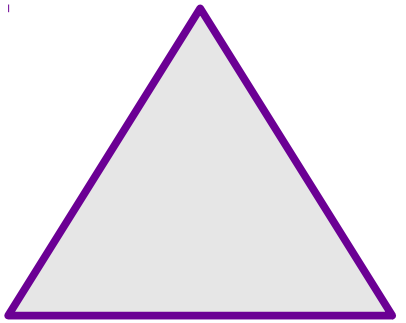
modelView

```
void sierpinski(GL2 gl, Matrix3f modelView, int k)
{

  if (k == 0)
      triangle(gl, modelView);









}
```



sierpinski()

modelView



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      next.mul(Transforms.scale2DH(0.5f));
      sierpinski(gl, next, k-1);
  }

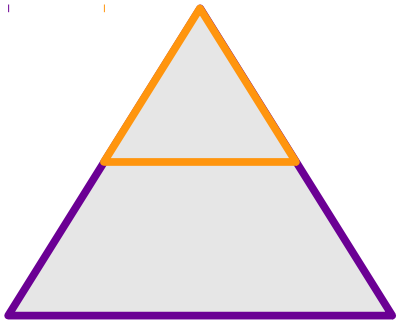



}
```

sierpinski()

modelView

next



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      sierpinski(gl, next, k-1);
  }




}
```
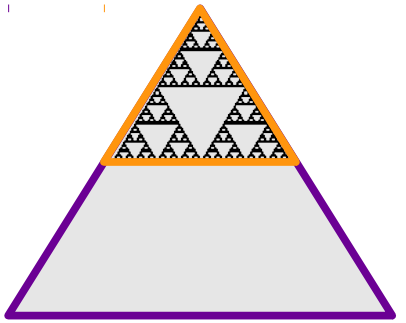

sierpinski()

modelView

next



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      sierpinski(gl, next, k-1);
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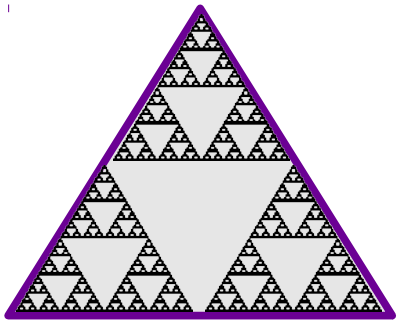
}
```

sierpinski()

modelView

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          sierpinski(gl, next, k-1);
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}
```