INTRODUCTION TO OPENGL

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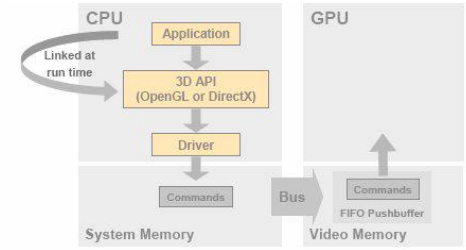
What is OpenGL?

- Open Graphics Library
- Low level API for 2D/3D rendering with GPU
  - For interactive applications
- Developed by SGI in 1992
  - 2009: OpenGL 3.2
  - 2010: OpenGL 4.0
  - 2011: OpenGL 4.2
- Competitor: Direct3D

Where does it work?



What OpenGL Does

- Control GPU to draw simple polygons.
- Utilize graphics pipeline.
  - Algorithm GPU uses to create 3D images
  - **Input:** Polygons & other information
  - **Output:** Image on framebuffer
  - **How:** Rasterization
  - More details in class next week.

What OpenGL Doesn't Do

- Manage UI
- Manage windows
- Decide where on screen to draw.
  - It's your job to tell OpenGL that.
- Draw curves or curved surfaces
  - Although can approximate them by fine polygons

Jargons

- Bitplane
  - Memory that holds 1 bit of info for each pixel
- Buffer
  - Group of bitplanes holding some info for each pixel
- Framebuffer
  - A buffer that hold the image that is displayed on the monitor.

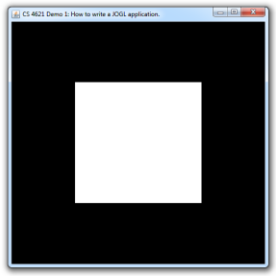
JOGL

Java OpenGL (JOGL)

- OpenGL originally written for C.
- JOGL = OpenGL binding for Java
- http://jogamp.org/jogl/www/

- Give Java interface to C OpenGL commands.
- Manage framebuffer.

Demo 1



GLCanvas

- UI component
- Can display images created by OpenGL.
- OpenGL "context"
  - Store OpenGL states.
  - Provides a default framebuffer to draw.

- Todo:
  - Create and stick it to a window.

Events

- GUI is often done by **event-driven programming**.
  - Certain UI components acts as *sensors*.
  - Something happen to them (i.e., the user click them)
  - UI components broadcast a message, called *events*.
  - Objects interested in such events can sign up as *listeners*.
  - Listeners run appropriate code when receiving a *event*.
    - Updating the display, update database, send info over the net, etc.

- GLCanvas broadcast 4 events related to OpenGL.

GLEventListener

- Handle events generated by GLCanvas.
- Implement to use OpenGL commands.

- Todo:
  - Create.
  - Implement 4 methods.
  - Call GLCanvas.addGLListener.

GLEventListener Methods

- init
  - Called once when OpenGL context is created.
- display
  - Called every time GLCanvas repaints itself.
- resize
  - Called every time GLCanvas resizes.
- dispose
  - Called before OpenGL context is destroyed.

GLEventListener Methods

- init
  - Implement to initialize OpenGL.
- display
  - Implement to draw stuffs.
- resize
  - Implement to deal with GLCanvas's resizing.
- displayChanged
  - Implement to free OpenGL resource.

GL Objects

- Store OpenGL states, commands, and constants
- Many classes based on OpenGL version.
  - GL2, GL3, GL4, GL2ES1, GL2ES2, etc.
- We use GL2.
  - Backward compatibility.
- Get instance from GLAutoDrawable.
  - Passed into every GLEventListener method.
  - final GL2 gl = new drawable.getGL().getGL2();

OPENGL COMMANDS

Demo 1's display method

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

    gl.glClearColor(0, 0, 0, 0);
    gl.glClear(GL2.GL_COLOR_BUFFER_BIT);

    gl.glColor3d(1.0, 1.0, 1.0);
    gl.glBegin(GL2.GL_POLYGON);
    {
        gl.glVertex3d(-0.5, -0.5, 0.0);
        gl.glVertex3d( 0.5, -0.5, 0.0);
        gl.glVertex3d( 0.5,  0.5, 0.0);
        gl.glVertex3d(-0.5,  0.5, 0.0);
    }
    gl.glEnd();
}
```

One Command at a Time

- gl.glClearColor(0, 0, 0, 0)
  - Change the color used to clear screen to black.
- gl.glClear(GL2.GL_COLOR_BUFFER_BIT)
  - Clear the buffers that store color with the color specified by glClearColor.
- glColor3d(1.0, 1.0, 1.0)
  - Change the current color to white.
  - All vertices drawn afterwards are white until told otherwise.

One Command at a Time

- glBegin(GL_POLYGON)
  - Tell OpenGL we will draw a polygon.
- glVertex3f(x, y, z)
  - Specify the polygon's vertices.
- glEnd()
  - Tell OpenGL that we're done specifying the geometry.

Command Naming

- In C,
  - commands = functions
  - No two functions can have the same name.
  - Some commands take different arguments but do the same thing.
- All commands of the form

gl <name> {1234} {b s i f d ub us ui} {v}

Number of Arguments

Argument type

Argument is a vector (array)

Argument Types in Command Names

Suffix	Data Type	Typical Corresponding C-Language Type	OpenGL Type Definition
b	8-bit integer	signed char	GLbyte
s	16-bit integer	short	GLshort
i	32-bit integer	long	GLint, GLsizei
f	32-bit floating-point	float	GLfloat, GLclampf
d	64-bit floating-point	double	GLdouble, GLclampd
ub	8-bit unsigned integer	unsigned char	GLubyte, GLboolean
us	16-bit unsigned integer	unsigned short	GLushort
ui	32-bit unsigned integer	unsigned long	GLuint, GLenum, GLbitfield

OpenGL is a State Machine

- OpenGL remembers values the user specified.
- Use these values until user changes it.
- Examples of stored values:
  - Color uses to clear screen
  - Color of vertices
  - Transformation matrices
- After calling glColor3f(1,1,1)
  - All vertices specified by glVertex afterwards are white.
  - Until the user calls glColor again with a different color.

Demo 2

```
gl.glBegin(GL2.GL_TRIANGLES);
{
    gl.glColor3f(1.0f, 0.5f, 0.5f);
    gl.glVertex3f( 0.0f,  0.5f, 0.0f);
    gl.glVertex3f(-0.25f, 0.0f, 0.0f);
    gl.glVertex3f( 0.25f, 0.0f, 0.0f);

    gl.glColor3f(0.5f, 1.0f, 0.5f);
    gl.glVertex3f( -0.25f,  0.0f, 0.0f);
    gl.glVertex3f( -0.5f,  -0.5f, 0.0f);
    gl.glVertex3f(  0.0f,  -0.5f, 0.0f);

    gl.glColor3f(0.5f, 0.5f, 1.0f);
    gl.glVertex3f( 0.25f,  0.0f, 0.0f);
    gl.glVertex3f( 0.0f,  -0.5f, 0.0f);
    gl.glVertex3f( 0.5f,  -0.5f, 0.0f);
}
gl.glEnd();
```

GEOMETRIC PRIMITIVES

Geometric Primitives in OpenGL

- 3 types of geometry OpenGL can draw:
  - Points
  - Line segments
  - Polygons
- No curves or curved surfaces.
- Can approximate curves by short line segments.

Vertices

- OpenGL specifies shapes by specifying its vertices.
  - Point:1 vertex
  - Lines: 2 vertices
  - N-gon: n vertices
- Vertices can have associated information.
  - Color
    - Specified by glColor
  - Normal
    - Specified by glNormal
  - Texture coordinate
    - Specified by glTexCoord
  - More on this later…

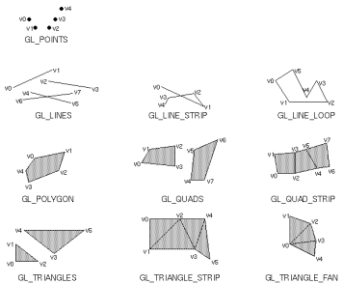
glVertex

- glVertex specifies one such vertex.
- Must be called between glBegin(…) and glEnd()
- Up to 4 arguments
  - Position (x, y, z, w) in homogeneous coordinate.
  - For 2 arguments
    - z = 0, w = 1
  - For 3 arguments
    - w = 1

Specifying Shapes

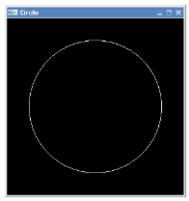
- Start with glBegin(<< shape type >>).
- Use glVertex to specify each vertex.
  - Do it in counterclockwise order.
  - The shape might not display otherwise.
- Stop with glEnd()

Avaiable Shapes



Demo 3

```
gl.glBegin(GL2.GL_LINE_LOOP);
for(int i=0;i<256;i++)
{
    double theta = 2*i*Math.PI/256;
    double y = 0.75*Math.sin(theta);
    double x = 0.75*Math.cos(theta);
    gl.glVertex2d(x,y);
}
gl.glEnd();
```

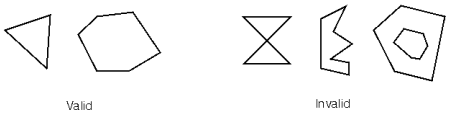


Polygons OpenGL Can Draw

- All the points on the polygon must lie on the same plane.
  - Otherwise, correctness of drawing is not guaranteed.
- **Notice:** All points on a triangle are coplanar.
  - Not true for other polygons.

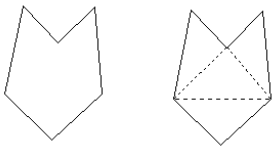
Polygons OpenGL Can Draw

- No edges must intersect.
- Must be convex.
- Must not have holes.



Drawing Arbitrary Polygons

- Decompose them into convex polygons.
  - Preferably triangles.

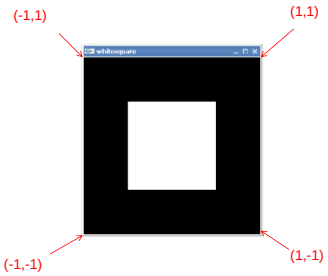


SETTING UP 2D COORDINATE SYSTEM

Default Viewing

- Eye at (0,0,1).
- Look in negative z direction.
- Orthographic projection
  - No foreshortening.
  - No sense of depth.
  - 2D coordinate system if don't care about z-axis.

Default Coordinate System



GLU

- OpenGL Utility Library
- C library usually ships with OpenGL
- Many useful functions:
  - Drawing of some curved surfaces.
  - Interpretation of OpenGL errors.
  - Simple camera setup.
- In JOGL,
  - Encapsulated by GLU class.
  - Create one when needed.
  - GLU glu = new GLU();

gluOrho2D

- glu.gluOrtho2D(double left, double right,
  double bottom, double top)
- Change the **projection matrix** to orthographic projection.
  - Details in CS 4620 lecture next week.
- For now, it sets the 2D coordinate system so that:
  - Bottom-left corner is (left, bottom)
  - Bottom-right corner (right, bottom)
  - Top-left corner is (left, top)
  - Top-right corner is (right, top)

gluOrtho2D

- Usage: Issue these three commands together.
  - gl.glMatrixMode(GL2.GL_PROJECTION);
  - gl.glLoadIdentity();
  - glu.gluOrtho2D(left, right, bottom, top);
- Will become clear afterwards why by next week.
- Only primitives drawn afterwards are affected.
  - Coordinate system is “defined” by projection matrix.
  - OpenGL remembers the matrix until it changes.

gluOrtho2D

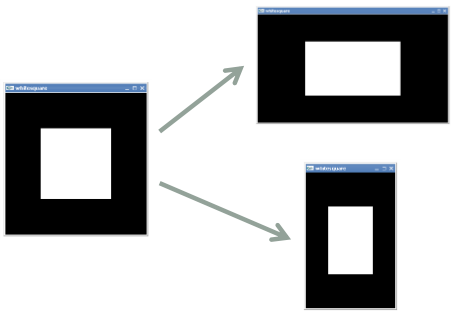

gluOrtho2D(-1,1,-1,1)


gluOrtho2D(-2,2,-2,2)

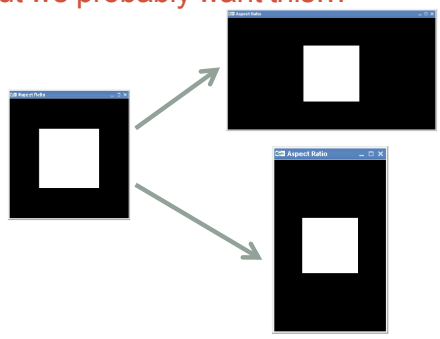

gluOrtho2D(-2,2,-1,1)


gluOrtho2D(-1,1,-2,2)

When Resizing Window



But we probably want this…



What We Want

- When resizing window, aspect ratio of drawn pictures remain the same.
- Keep the same drawing code.
  - No change to display method.
- Can do so by changing the coordinate system.

- When to do this?
  - Each time the window size change.
- Implement reshape method.

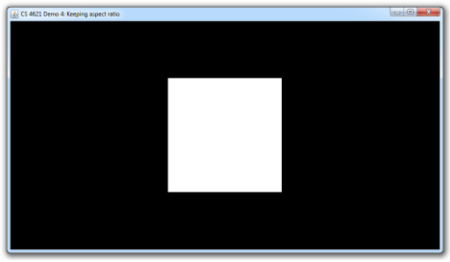
reshape

- public void reshape(GLAutoDrawable drawable, int x, int y, int width, int height);

- x, y
  - Coordinate of top-left corner of GLCanvas in pixels.

- width, height
  - Size of GLCanvas in pixels.

Demo 4



Demo 4's reshape

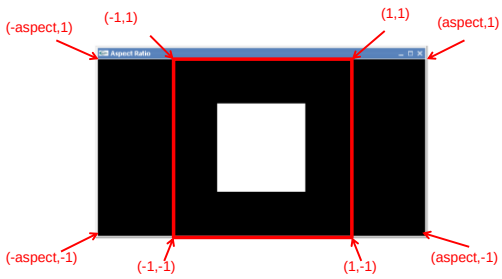
```
@Override
public void reshape(GLAutoDrawable drawable,
        int x, int y, int w, int h) {
    final GL2 gl = drawable.getGL().getGL2();
    final GLU glu = new GLU();

    if (w == 0) w = 1;
    if (h == 0) h = 1;

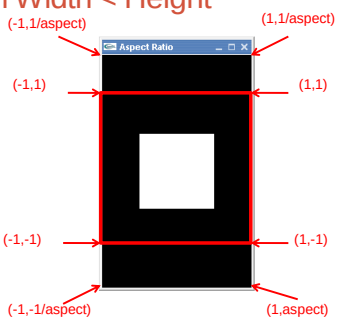
    double aspect = w * 1.0 / h;

    gl.glMatrixMode(GL2.GL_PROJECTION);
    gl.glLoadIdentity();
    if (w > h)
        glu.gluOrtho2D(-aspect, aspect, -1, 1);
    else
        glu.gluOrtho2D(-1, 1, -1/aspect, 1/aspect);
}
```

When Width > Height



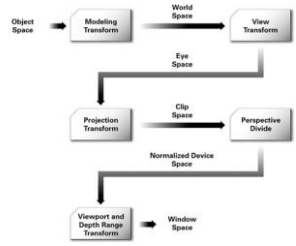
When Width < Height



TRANSFORMS

OpenGL Vertex Transformations

- Coordinates specified by glVertex are transformed.
- End result: window coordinate (in pixels)



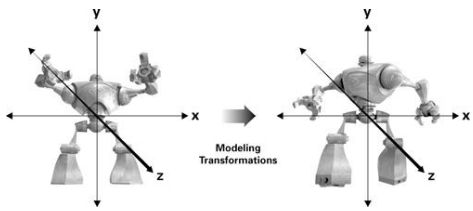
OpenGL Vertex Transformation

$$\begin{bmatrix} x_w \\ y_w \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} \text{Viewport} \\ \text{Transform} \end{bmatrix} \begin{bmatrix} \text{Perspective} \\ \text{Divide} \end{bmatrix} \begin{bmatrix} \text{Projection} \\ \text{Transform} \end{bmatrix} \begin{bmatrix} \text{View} \\ \text{Transform} \end{bmatrix} \begin{bmatrix} \text{Model} \\ \text{Transform} \end{bmatrix} \begin{bmatrix} x_o \\ y_o \\ z_o \\ 1 \end{bmatrix}$$

Modeling Transform

- Object space
  - Coordinate system used by modeler.
  - Local to the 3D geometric model being created.
  - What is specified by glVertex is in this space.
- World space
  - Coordinate system of the scene.
  - Used to position models relative to one another.
- Modeling transform
  - Object space → world space.
- Can also
  - Change positions of parts relative to one another.

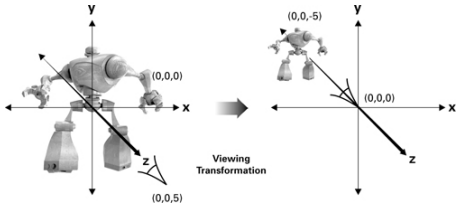
Modeling Transform



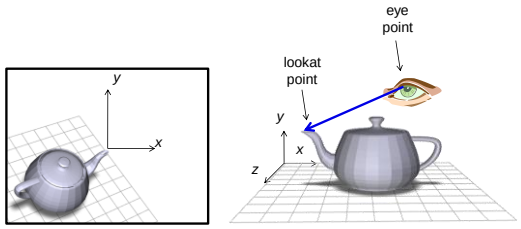
View Transform

- Used to set the camera.
- Eye space is a coordinate system where:
  - Eye is at (0,0,0).
  - Look in negative z direction.
  - Y-axis is “up.”
- Much like camera setup of PA1.
- View transform
  - world space → eye space

View Transform



View Transform



Modelview Matrix

- OpenGL combines modeling transform and view transform into one transform.
- Modelview transform
  - object space → eye space

$$\begin{bmatrix} Modelview \end{bmatrix} = \begin{bmatrix} View \end{bmatrix} \begin{bmatrix} Model \end{bmatrix}$$

Manipulating Modelview Matrix

- OpenGL keeps a number of 4x4 matrices as states.
  - Modelview
  - Projection
  - Texture
- glMatrixMode
  - Specify which matrix to manipulate
  - For modelview matrix:

```
gl.glMatrixMode(GL2.GL_MODELVIEW);
```

- Always manipulate outside glBegin(…) glEnd() block.
  - Invalid operation otherwise.

Commands for Manipulating Matrices

- Say OpenGL keeps the current matrix as M.
- glLoadIdentity()
  - Set M = I.
- glLoadMatrixd(double[] a, int s)
  - Variant: glLoadMatrixf
  - a = array of at least 16 doubles.
  - a has elements of the matrix in column major order.
  - Set:

$$M = \begin{bmatrix} a[s+0] & a[s+4] & a[s+8] & a[s+12] \\ a[s+1] & a[s+5] & a[s+9] & a[s+13] \\ a[s+2] & a[s+6] & a[s+10] & a[s+14] \\ a[s+3] & a[s+7] & a[s+11] & a[s+15] \end{bmatrix}$$

Commands for Manipulating Matrices

- glTranslated(double x, double y, double z)
  - Set M = MT where T is a 3D translation matrix.

$$T = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- glScaled(double a, double b, double c)
  - Set M = MS where S is a 3D scaling matrix.

$$S = \begin{bmatrix} a & 0 & 0 & 0 \\ 0 & b & 0 & 0 \\ 0 & 0 & c & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Commands for Manipulating Matrices

- glRotated(double angle, double x, double y, double z)
  - Set M = MR where R is a 3D translation matrix.
  - angle = angle of rotation in degrees.
  - (x,y,z) is the axis of rotation.
  - More details in CS 4620 lecture.
  - For 2D rotation, rotate around the z-axis. For example:

```
gl.glRotated(30, 0, 0, 1);
```

Example 1

```
gl.glMatrixMode(GL2.GL_MODELVIEW);
gl.glLoadIdentity();

gl.glTranslated(1,2,3);

gl.glBegin(GL_POINTS);
{
    gl.glVertex3f(1,1,1);
}
gl.glEnd();
```

Example 1

```
gl.glMatrixMode(GL2.GL_MODELVIEW);
gl.glLoadIdentity();

gl.glTranslatef(1,2,3);

gl.glBegin(GL_POINTS);
{
    gl.glVertex3f(1,1,1);
}
gl.glEnd();
```

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Example 1

```
gl.glMatrixMode(GL2.GL_MODELVIEW);
gl.glLoadIdentity();

gl.glTranslatef(1,2,3);

gl.glBegin(GL_POINTS);
{
    gl.glVertex3f(1,1,1);
}
gl.glEnd();
```

$$M = M \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 2 \\ 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 2 \\ 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Example 1

```
gl.glMatrixMode(GL2.GL_MODELVIEW);
gl.glLoadIdentity();

gl.glTranslatef(1,2,3);

gl.glBegin(GL_POINTS);
{
    gl.glVertex3f(1,1,1);
}
gl.glEnd();
```

$$v_{world} = M v_{object} = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 2 \\ 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 2 \\ 3 \\ 4 \\ 1 \end{bmatrix}$$

Example 2

```
gl.glMatrixMode(GL2.GL_MODELVIEW);
gl.glLoadIdentity();

gl.glTranslatef(1,2,3);
gl.glScalef(10,10,10);

gl.glBegin(GL_POINTS);
{
    gl.glVertex3f(1,1,1);
}
gl.glEnd();
```

Example 2

```
gl.glMatrixMode(GL2.GL_MODELVIEW);
gl.glLoadIdentity();

gl.glTranslatef(1,2,3);
gl.glScalef(10,10,10);

gl.glBegin(GL_POINTS);
{
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}
gl.glEnd();
```

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Example 2

```
gl.glMatrixMode(GL2.GL_MODELVIEW);
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gl.glTranslatef(1,2,3);
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Example 2

```
gl.glMatrixMode(GL2.GL_MODELVIEW);
gl.glLoadIdentity();

gl.glTranslatef(1,2,3);
gl.glScalef(10,10,10);

gl.glBegin(GL_POINTS);
{
    gl.glVertex3f(1,1,1);
}
gl.glEnd();
```

$$M = M \begin{bmatrix} 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 \\ 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 2 \\ 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 \\ 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 10 & 0 & 0 & 1 \\ 0 & 10 & 0 & 2 \\ 0 & 0 & 10 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Example 2

```
gl.glMatrixMode(GL2.GL_MODELVIEW);
gl.glLoadIdentity();

gl.glTranslatef(1,2,3);
gl.glScalef(10,10,10);

gl.glBegin(GL_POINTS);
{
    gl.glVertex3f(1,1,1);
}
gl.glEnd();
```

$$v_{world} = M v_{object} = \begin{bmatrix} 10 & 0 & 0 & 1 \\ 0 & 10 & 0 & 2 \\ 0 & 0 & 10 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 12 \\ 13 \\ 14 \\ 1 \end{bmatrix}$$

Interpreting Matrix Commands

- They transform **the coordinate system**.

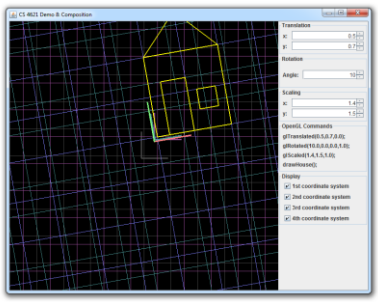
```
gl.glMatrixMode(GL2.GL_MODELVIEW);
gl.glLoadIdentity();
```

Origin at (0,0,0)

```
gl.glTranslatef(1,2,3);
```

Origin at (1,2,3)

Demo 5, 6, 7, 8

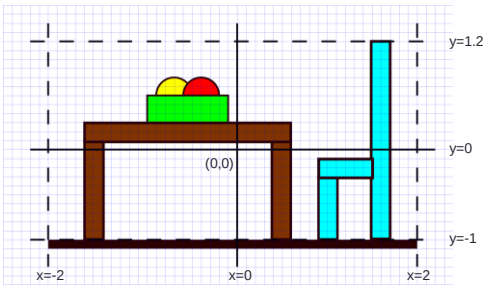


MATRIX STACK

Matrix Stack

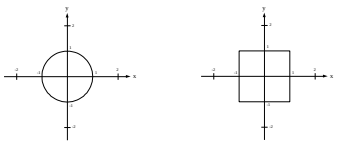
- OpenGL maintains a stack of 4x4 matrices.
- Useful when doing hierarchical transformations.
  - Rendering scene graphs.
  - Rendering fractals.
- Stack manipulation commands
  - glPushMatrix()
  - glPopMatrix()

Scene

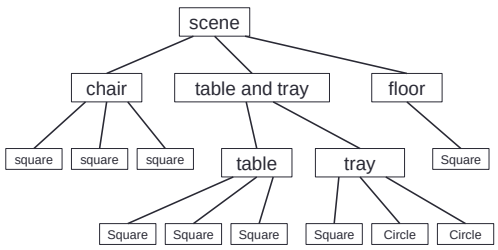


Primitives

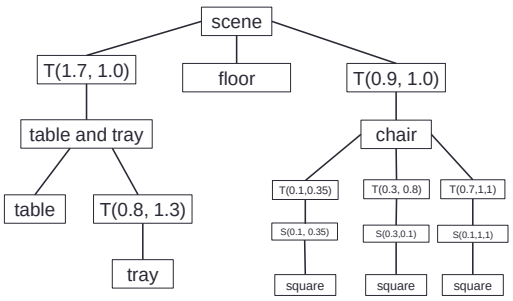
- Suppose we wrote two methods:
  - circle(): draw a unit sphere centered at (0,0)
  - square(): draw a square of size length 2 centered at (0,0)
- Want to use the above methods to draw the scene.



Scene Hierarchy



Scene Graph



Scene Graph → Code

```
void scene(GL2 gl)
{
    gl.glPushMatrix();
    gl.glTranslated(-1.7, -1.0, 0.0);
    tableAndTray(gl);
    gl.glPopMatrix();

    floor(gl);

    gl.glPushMatrix();
    gl.glTranslated(0.9, -1.0, 0.0);
    chair(gl);
    gl.glPopMatrix();
}
```

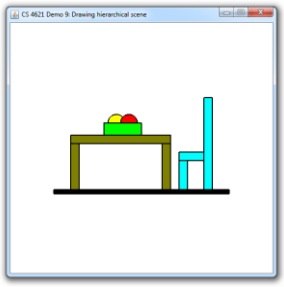
Scene Graph → Code

```
void chair(GL2 gl)
{
    gl.glPushMatrix();
    gl.glTranslated(0.1, 0.35, 0.0);
    gl.glScaled(0.1, 0.35, 1.0);
    square(gl, 0.0, 1.0, 1.0);
    gl.glPopMatrix();

    gl.glPushMatrix();
    gl.glTranslated(0.3, 0.8, 0.0);
    gl.glScaled(0.3, 0.1, 1.0);
    square(gl, 0.0, 1.0, 1.0);
    gl.glPopMatrix();

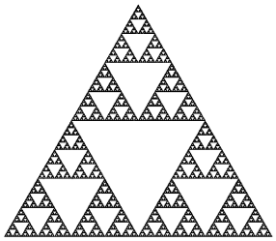
    gl.glPushMatrix();
    gl.glTranslated(0.7, 1.1, 0.0);
    gl.glScaled(0.1, 1.1, 1.0);
    square(gl, 0.0, 1.0, 1.0);
    gl.glPopMatrix();
}
```

Demo 9



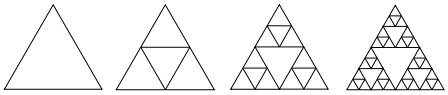
Drawing Fractals

- Sierpinski Triangle



Drawing Fractals

- We can define “levels” of Sierpinski triangles.



- Recursive definition
  - Level k+1 is made from arranging 3 copies of Level k.
- The one on last slide is Level 8.

Code

```
void sierpinski(GL2 gl, int k)
{
    if (k == 0)
        triangle(gl);
    else
    {
        gl.glPushMatrix();
        gl.glTranslated(0.0, 0.5 / Math.sqrt(3.0), 0.0);
        gl.glScaled(0.5, 0.5, 0.5);
        sierpinski(gl, k-1);
        gl.glPopMatrix();

        gl.glPushMatrix();
        gl.glTranslated(0.25, -0.25 / Math.sqrt(3.0), 0.0);
        gl.glScaled(0.5, 0.5, 0.5);
        sierpinski(gl, k-1);
        gl.glPopMatrix();

        gl.glPushMatrix();
        gl.glTranslated(-0.25, -0.25 / Math.sqrt(3.0), 0.0);
        gl.glScaled(0.5, 0.5, 0.5);
        sierpinski(gl, k-1);
        gl.glPopMatrix();
    }
}
```

Demo 10