Introduction to Computer Graphics with WebGL

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Programming with WebGL
Part 3: Shaders

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Objectives

- Simple Shaders
  - Vertex shader
  - Fragment shaders
- Programming shaders with GLSL
- Finish first program

Vertex Shader Applications

- Moving vertices
  - Morphing
  - Wave motion
  - Fractals
- Lighting
  - More realistic models
  - Cartoon shaders

Fragment Shader Applications

Per fragment lighting calculations

per vertex lighting

per fragment lighting

Fragment Shader Applications

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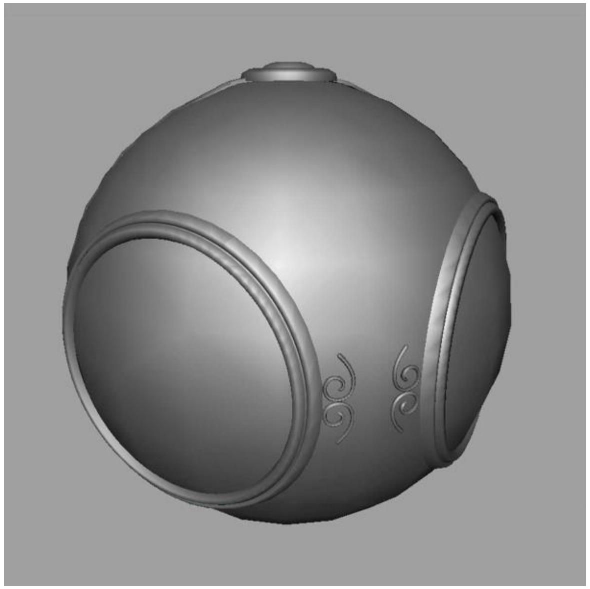
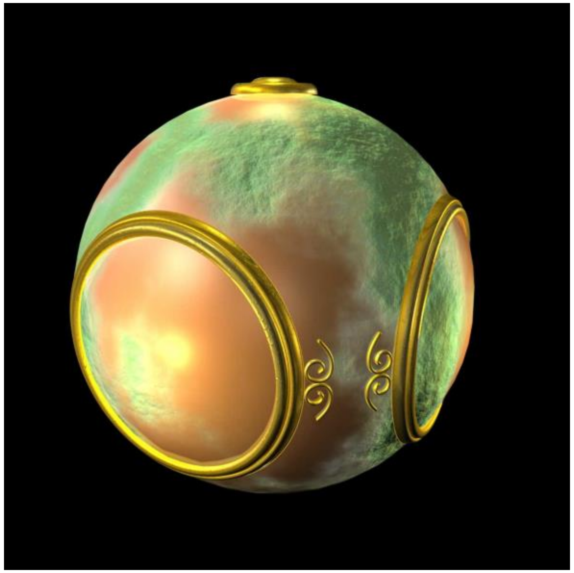
Texture mapping



smooth shading

environment mapping



bump mapping

Writing Shaders

- First programmable shaders were programmed in an assembly-like manner
- OpenGL extensions added functions for vertex and fragment shaders
- Cg (C for graphics) C-like language for programming shaders
  - Works with both OpenGL and DirectX
  - Interface to OpenGL complex
- OpenGL Shading Language (GLSL)

GLSL

- OpenGL Shading Language
- Part of OpenGL 2.0 and up
- High level C-like language
- New data types
  - Matrices
  - Vectors
  - Samplers
- As of OpenGL 3.1, application must provide shaders

Simple Vertex Shader

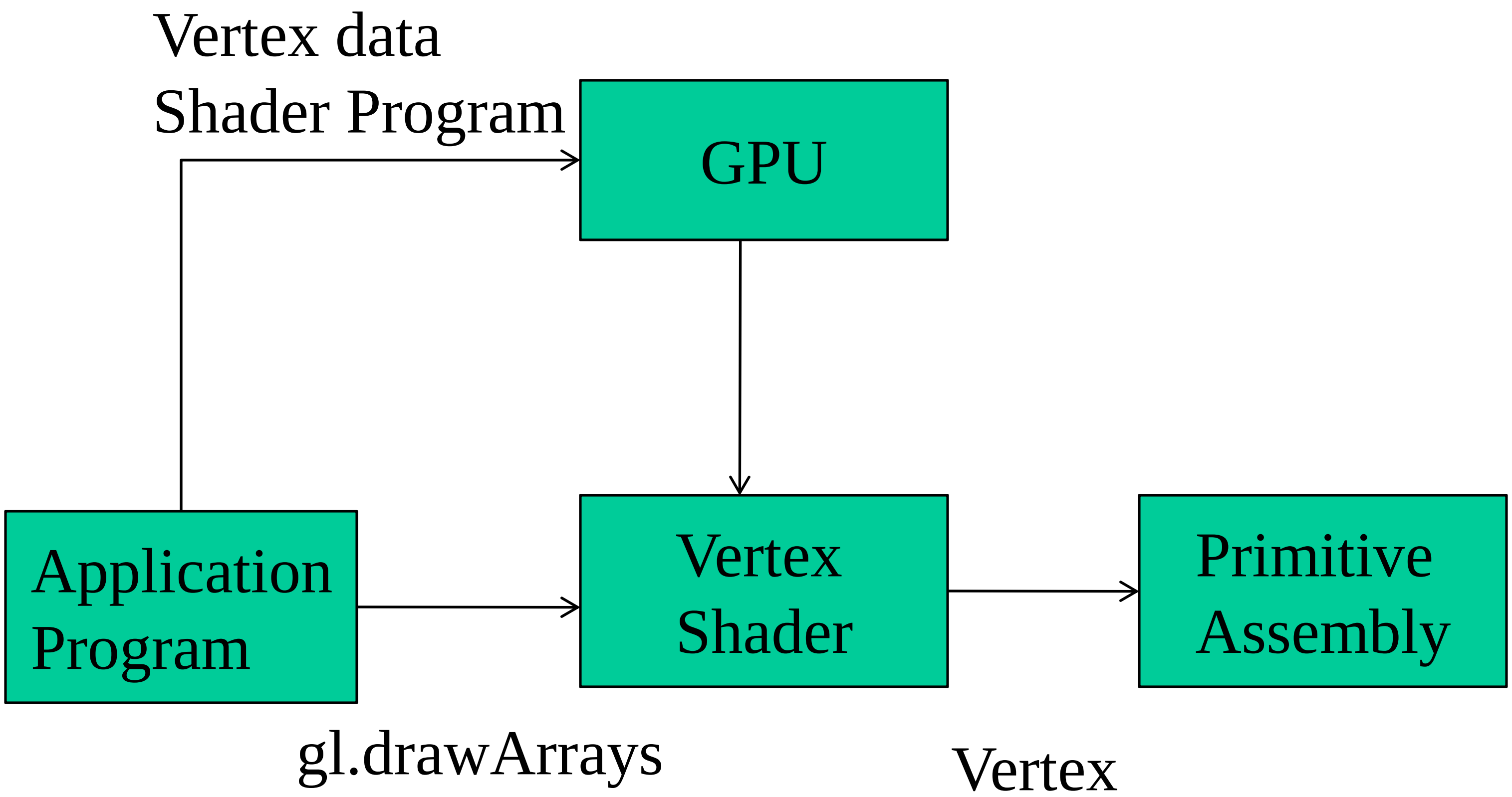
input from application

```
in vec4 vPosition;
void main(void)
{
    gl_Position = vPosition;
}
```

must link to variable in application

built in variable

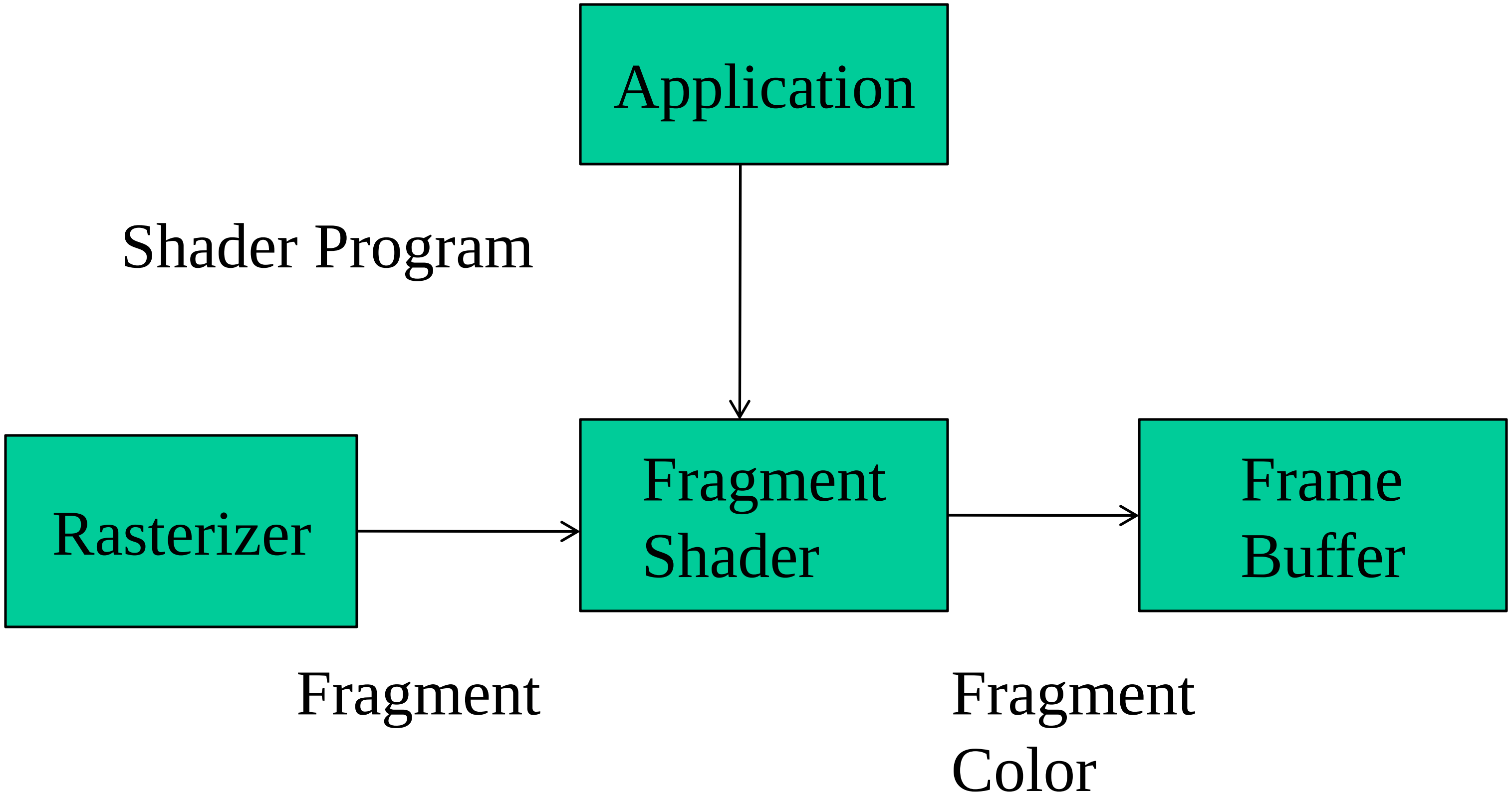
Execution Model



Simple Fragment Program

```
precision mediump float;
out vec4 fColor;
void main(void)
{
  fColor = vec4(1.0, 0.0, 0.0, 1.0);
}
```

Execution Model



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Data Types

- C types: int, float, bool
- Vectors:
  - float vec2, vec3, vec4
  - Also int (ivec) and boolean (bvec)
- Matrices: mat2, mat3, mat4
  - Stored by columns
  - Standard referencing m[row][column]
- C++ style constructors
  - vec3 a =vec3(1.0, 2.0, 3.0)
  - vec2 b = vec2(a)

No Pointers

- There are no pointers in GLSL
- We can use C structs which

 can be copied back from functions
- Because matrices and vectors are basic types they can be passed into and output from GLSL functions, e.g.

    mat3 func(mat3 a)
- variables passed by copying

Qualifiers

- GLSL has many of the same qualifiers such as `const` as C/C++
- Need others due to the nature of the execution model
- Variables can change
  - Once per primitive
  - Once per vertex
  - Once per fragment
  - At any time in the application
- Vertex attributes are interpolated by the rasterizer into fragment attributes

Attribute Qualifier

- Attribute-qualified variables can change at most once per vertex
- There are a few built in variables such as gl_Position but most have been deprecated
- User defined (in application program)
  - **`attribute float temperature`**
  - **`attribute vec3 velocity`**
  - recent versions of GLSL use **`in`** and **`out`** qualifiers to get to and from shaders

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Uniform Qualified

- Variables that are constant for an entire primitive
- Can be changed in application and sent to shaders
- Cannot be changed in shader
- Used to pass information to shader such as the time or a bounding box of a primitive or transformation matrices

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Varying Qualified

- Variables that are passed from vertex shader to fragment shader
- Automatically interpolated by the rasterizer
- With WebGL, GLSL uses the varying qualifier in both shaders

```
varying vec4 color;
```

- More recent versions of WebGL use **out** in vertex shader and **in** in the fragment shader

```
out vec4 color; //vertex shader
in vec4 color;  // fragment shader
```

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Our Naming Convention

- attributes passed to vertex shader have names beginning with v (vPosition, vColor) in both the application and the shader
  - Note that these are different entities with the same name
- Varying variables begin with f (fColor) in both shaders
  - must have same name
- Uniform variables are unadorned and can have the same name in application and shaders

Example: Vertex Shader

```
#version 300 es
attribute vec4 vColor;
out vec4 fColor;
void main()
{
  gl_Position = vPosition;
  fColor = vColor;
}
```

Corresponding Fragment Shader

```
#version 300 es
precision mediump float;
in vec4 fColor;
Out vec4 finalColor
void main()
{
    finalColor = fColor;
}
```

Sending Colors from Application

```
var cBuffer = gl.createBuffer();
gl.bindBuffer( gl.ARRAY_BUFFER, cBuffer );
gl.bufferData( gl.ARRAY_BUFFER, flatten(colors),
                              gl.STATIC_DRAW );

var vColor = gl.getAttribLocation( program, "vColor" );
gl.vertexAttribPointer( vColor, 3, gl.FLOAT, false, 0, 0 );
gl.enableVertexAttribArray( vColor );
```

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Sending a Uniform Variable

```
// in application
vec4 color = vec4(1.0, 0.0, 0.0, 1.0);
colorLoc = gl.getUniformLocation( program, ”color" );
gl.uniform4f( colorLoc, color);
// in fragment shader (similar in vertex shader)
uniform vec4 color;
Out vec4 finalColor
void main()
{
	finalColor = color;
}
```

Operators and Functions

- Standard C functions
  - Trigonometric
  - Arithmetic
  - Normalize, reflect, length
- Overloading of vector and matrix types

```
mat4 a;
vec4 b, c, d;
c = b*a; // a column vector stored as a 1d array
d = a*b; // a row vector stored as a 1d array
```

Swizzling and Selection

- Can refer to array elements by element using [] or selection (.) operator with
  - x, y, z, w
  - r, g, b, a
  - s, t, p, q
  - **`a[2], a.b, a.z, a.p`** are the same
- **Swizzling** operator lets us manipulate components

```
vec4 a, b;
a.yz = vec2(1.0, 2.0, 3.0, 4.0);
b = a.yxzw;
```

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Programming with WebGL
Part 4: Color and Attributes

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Objectives

- Expanding primitive set
- Adding color
- Vertex attributes

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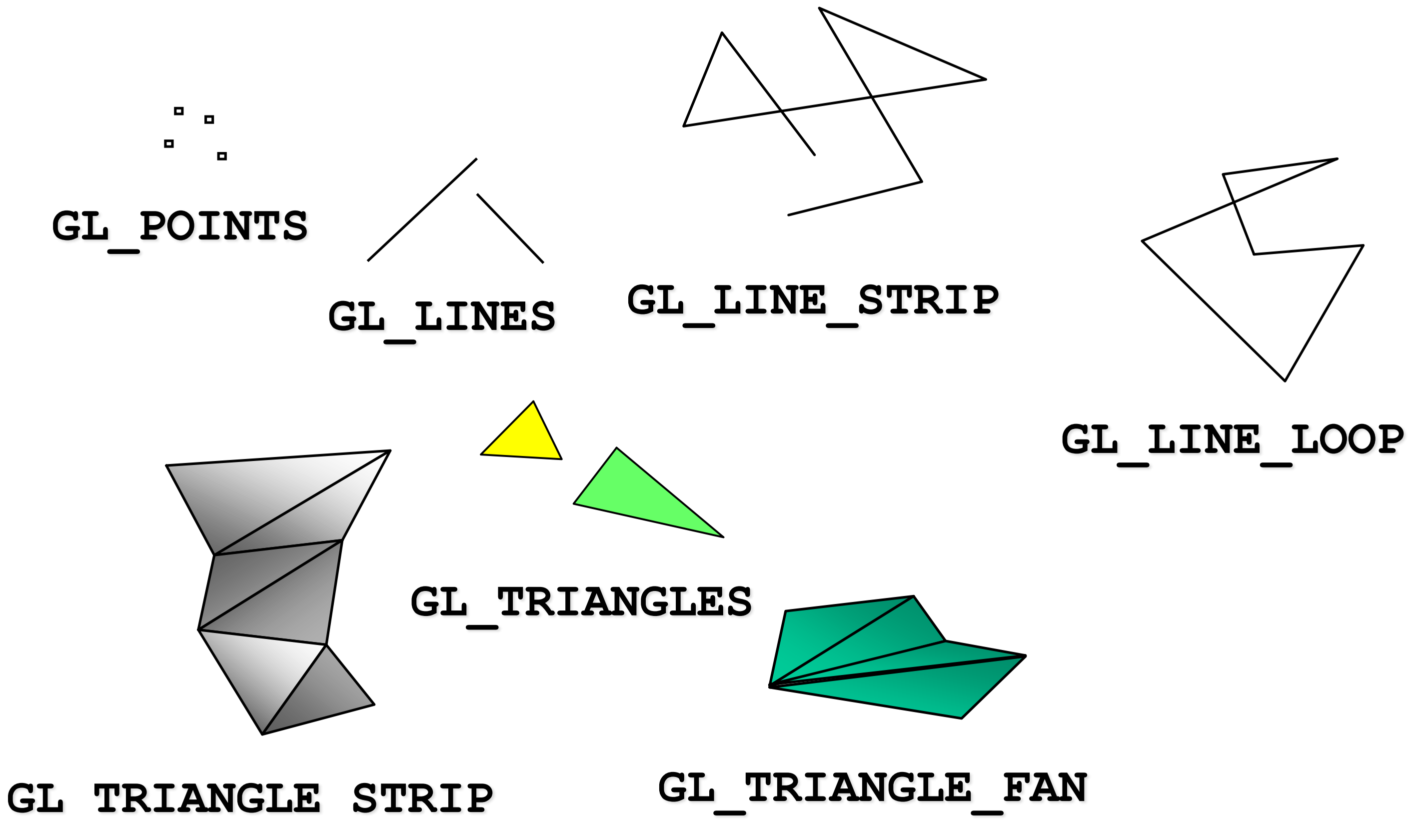
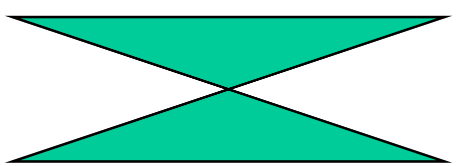
WebGLPrimitives



Polygon Issues

- WebGL will only display triangles
  - Simple: edges cannot cross
  - Convex: All points on line segment between two points in a polygon are also in the polygon
  - Flat: all vertices are in the same plane
- Application program must tessellate a polygon into triangles (triangulation)
- OpenGL 4.1 contains a tessellator but not WebGL



nonsimple polygon

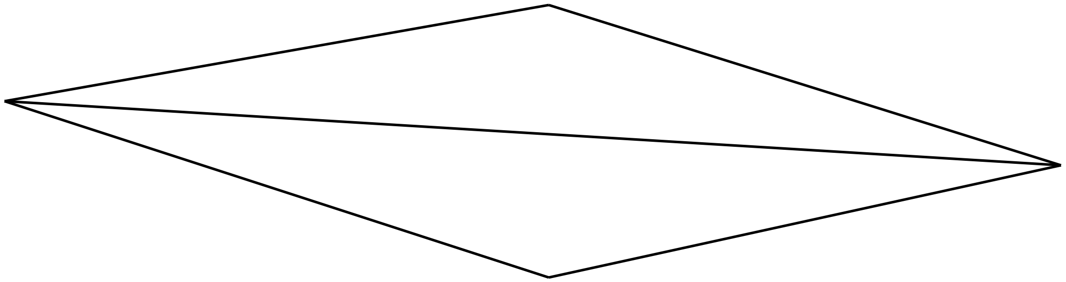
nonconvex polygon

Polygon Testing

- Conceptually simple to test for simplicity and convexity
- Time consuming
- Earlier versions assumed both and left testing to the application
- Present version only renders triangles
- Need algorithm to triangulate an arbitrary polygon

Good and Bad Triangles

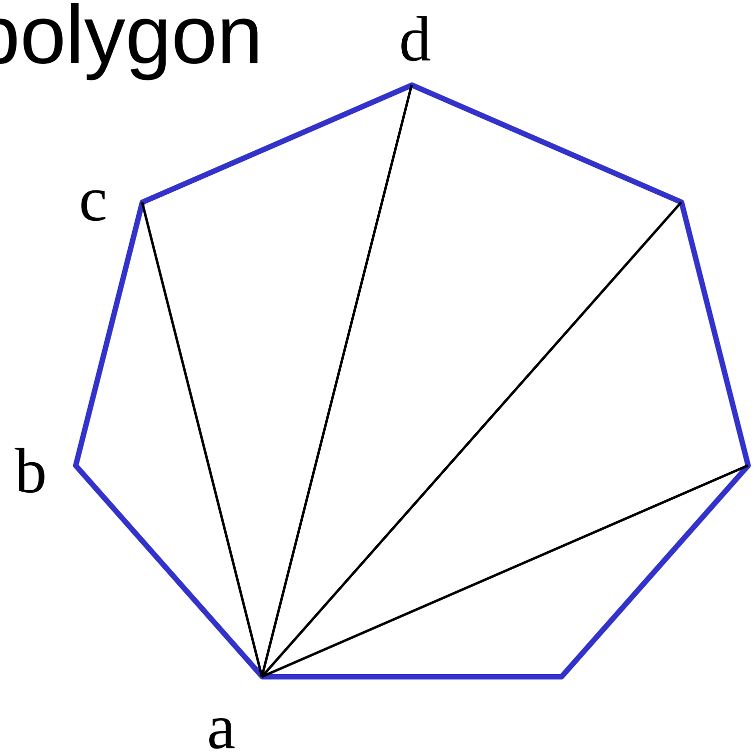
- Long thin triangles render badly



- Equilateral triangles render well
- Maximize minimum angle
- Delaunay triangulation for unstructured points

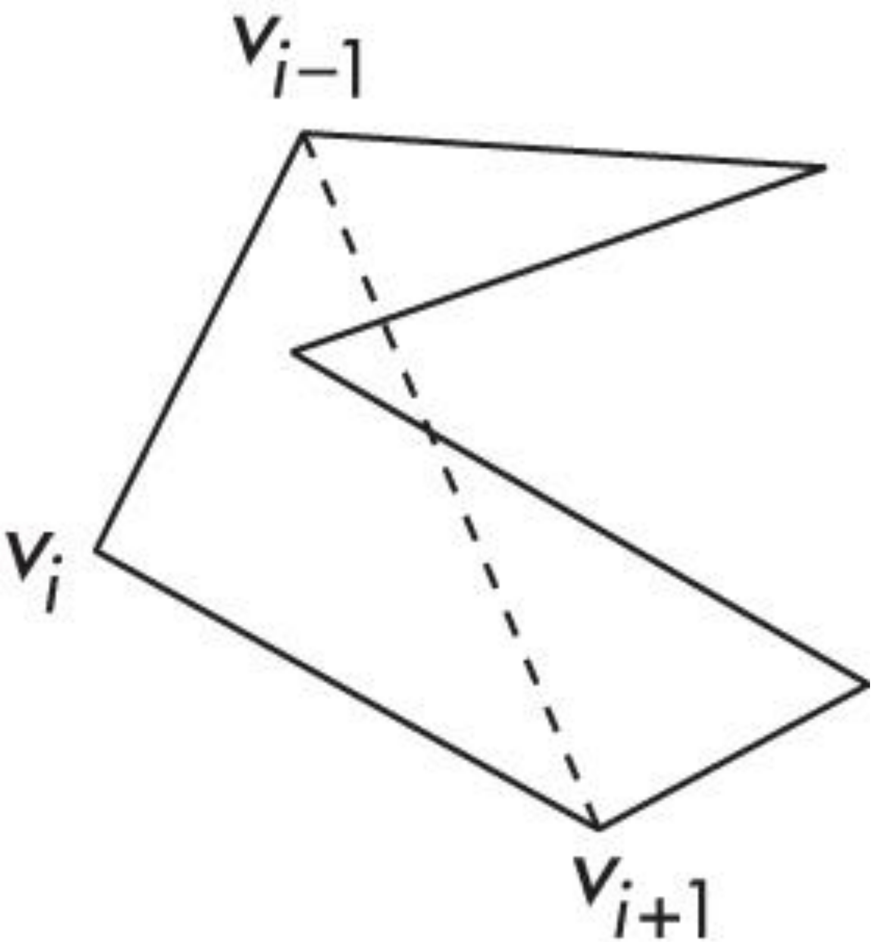
Triangularization

- Convex polygon



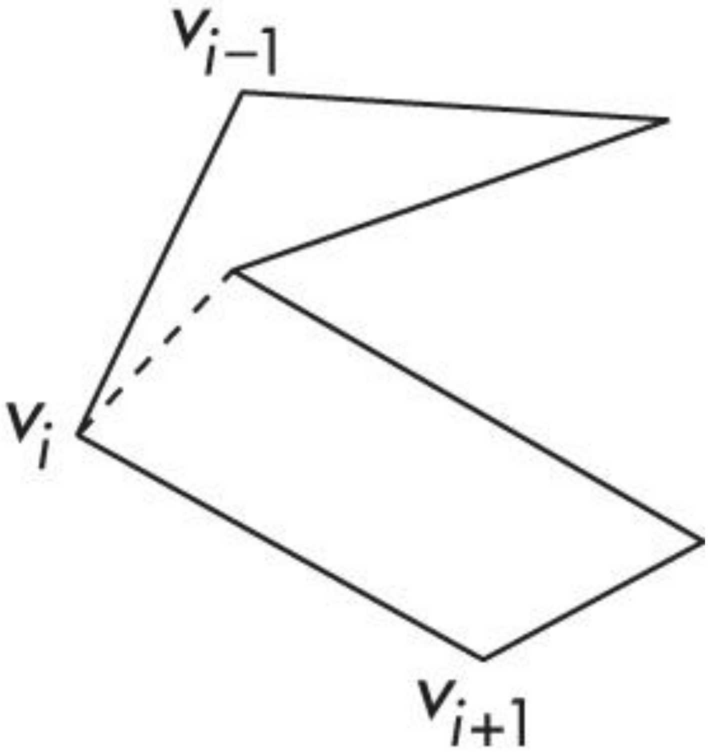
- Start with abc, remove b, then acd, ….

Non-convex (concave)



Recursive Division

- Find leftmost vertex and split

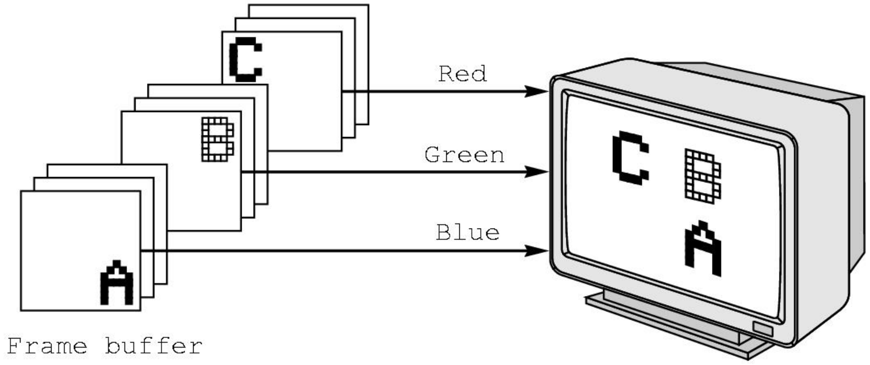


Attributes

- Attributes determine the appearance of objects
  - Color (points, lines, polygons)
  - Size and width (points, lines)
  - Stipple pattern (lines, polygons)
  - Polygon mode
    - Display as filled: solid color or stipple pattern
    - Display edges
    - Display vertices
- Only a few (gl_PointSize) are supported by WebGL functions

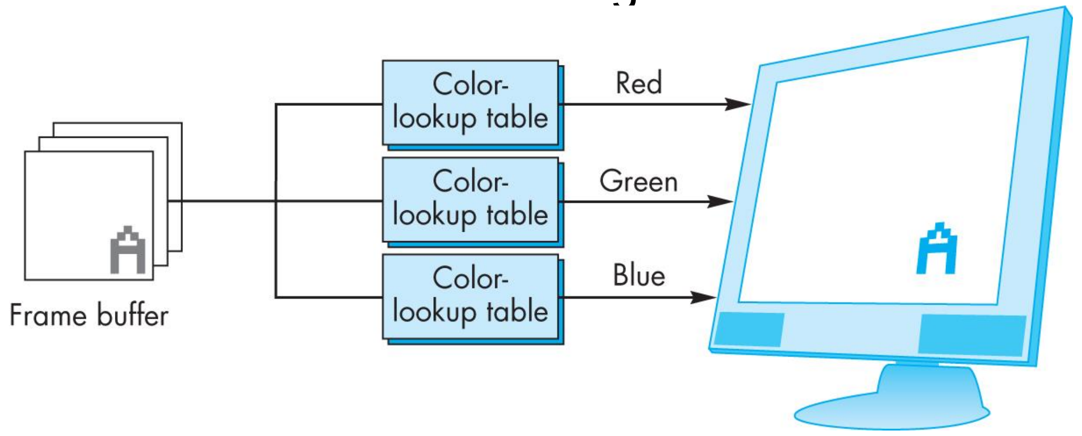
RGB color

- Each color component is stored separately in the frame buffer
- Usually 8 bits per component in buffer
- Color values can range from 0.0 (none) to 1.0 (all) using floats or over the range from 0 to 255 using unsigned bytes



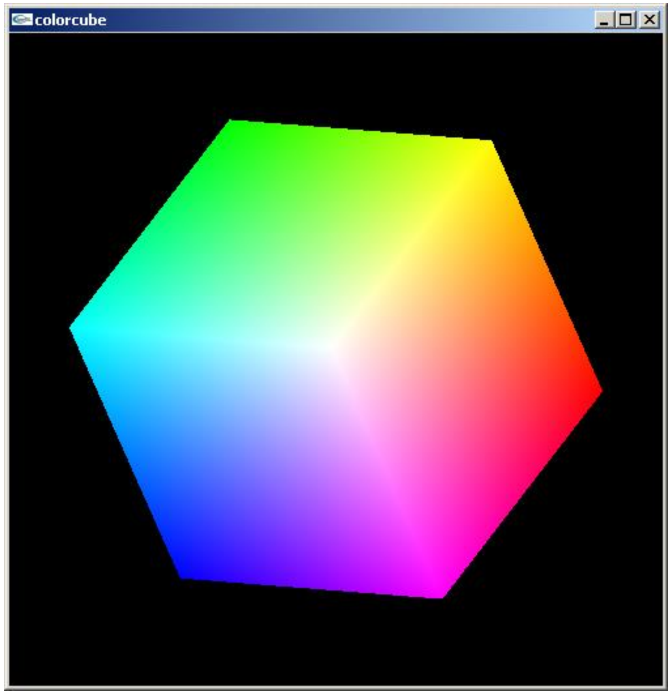
Indexed Color

- Colors are indices into tables of RGB values
- Requires less memory
  - indices usually 8 bits
  - not as important now
    - Memory inexpensive
    - Need more colors for shading



Smooth Color

- Default is *smooth* shading
  - Rasterizer interpolates vertex colors across visible polygons
- Alternative is *flat shading*
  - Color of first vertex determines fill color
  - Handle in shader



Setting Colors

- Colors are ultimately set in the fragment shader but can be determined in either shader or in the application
- Application color: pass to vertex shader as a uniform variable or as a vertex attribute
- Vertex shader color: pass to fragment shader as varying variable
- Fragment color: can alter via shader code

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Programming with WebGL
Part 5: More GLSL

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Objectives

- Coupling shaders to applications
  - Reading
  - Compiling
  - Linking
- Vertex Attributes
- Setting up uniform variables
- Example applications

Linking Shaders with Application

- Read shaders
- Compile shaders
- Create a program object
- Link everything together
- Link variables in application with variables in shaders
  - Vertex attributes
  - Uniform variables

Program Object

- Container for shaders
  - Can contain multiple shaders
  - Other GLSL functions

```
var program = gl.createProgram();

gl.attachShader( program, vertShdr );
gl.attachShader( program, fragShdr );
gl.linkProgram( program );
```

Reading a Shader

- Shaders are added to the program object and compiled
- Usual method of passing a shader is as a null-terminated string using the function
- gl.shaderSource(fragShdr, fragElem.text);
- If shader is in HTML file, we can get it into application by getElementById method
- If the shader is in a file, we can write a reader to convert the file to a string

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Adding a Vertex Shader

```
var vertShdr;
var vertElem =
    document.getElementById( vertexShaderId );

vertShdr = gl.createShader( gl.VERTEX_SHADER );

gl.shaderSource( vertShdr, vertElem.text );
gl.compileShader( vertShdr );

// after program object created
gl.attachShader( program, vertShdr );
```

Shader Reader

- Following code may be a security issue with some browsers if you try to run it locally
  - Cross Origin Request

```
function getShader(gl, shaderName, type) {
        var shader = gl.createShader(type);
        shaderScript = loadFileAJAX(shaderName);
        if (!shaderScript) {
            alert("Could not find shader source:
                    "+shaderName);
        }
}
```

Precision Declaration

- In GLSL for WebGL we must specify desired precision in fragment shaders
  - artifact inherited from OpenGL ES
  - ES must run on very simple embedded devices that may not support 32-bit floating point
  - All implementations must support mediump
  - No default for float in fragment shader
- Can use preprocessor directives (#ifdef) to check if highp supported and, if not, default to mediump

Pass Through Fragment Shader

```
#ifdef GL_FRAGMENT_SHADER_PRECISION_HIGH
  precision highp float;
#else
  precision mediump float;
#endif
in vec4 fcolor; out vec4 finalColor;
void main(void)
{
    finalColor = fcolor;
}
```

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Programming with WebGL
Part 6: Three Dimensions

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Objectives

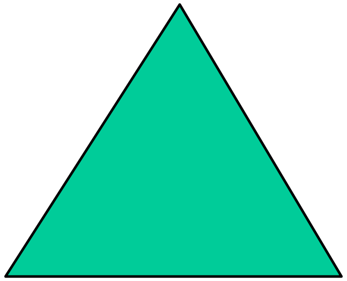
- Develop a more sophisticated three-dimensional example
    - Sierpinski gasket: a fractal
- Introduce hidden-surface removal

Three-dimensional Applications

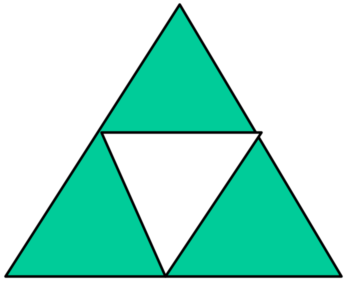
- In WebGL, two-dimensional applications are a special case of three-dimensional graphics
- Going to 3D
  - Not much changes
  - Use **`vec3, gl.uniform3f`**
  - Have to worry about the order in which primitives are rendered or use hidden-surface removal

Sierpinski Gasket (2D)

- Start with a triangle



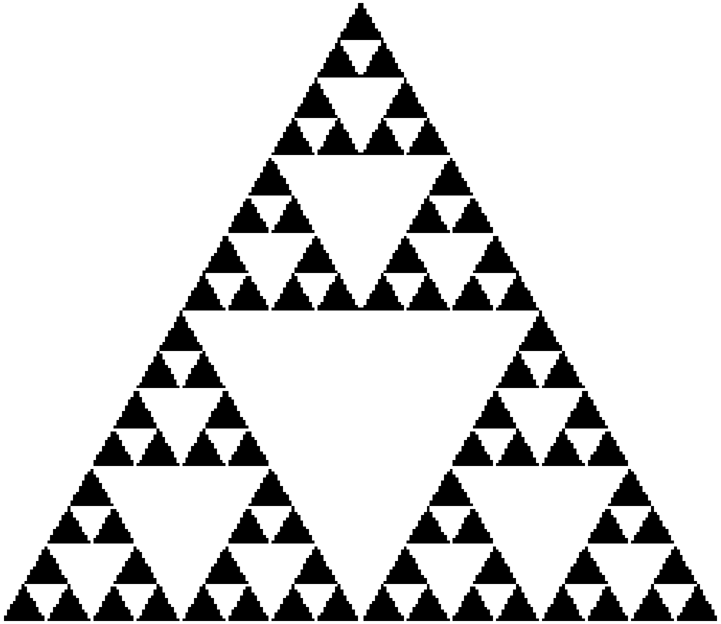
- Connect bisectors of sides and remove central triangle



- 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

- HTML file
  - Same as in other examples
  - Pass through vertex shader
  - Fragment shader sets color
  - Read in JS file
- Code in files gasket2.html and gasket2.js in folder 02

Gasket Program

```
var points = [];
var NumTimesToSubdivide = 5;

/* initial triangle */

 var vertices = [
        vec2( -1, -1 ),
        vec2(  0,  1 ),
        vec2(  1, -1 )
    ];

divideTriangle( vertices[0],vertices[1],
     vertices[2], NumTimesToSubdivide);
```

Draw one triangle

```
/* display one triangle  */

function triangle( a, b, c ){
    points.push( a, b, c );
}
```

Triangle Subdivision

```
function divideTriangle( a, b, c, count ){
 // check for end of recursion
    if ( count === 0 ) {
    triangle( a, b, c );
    }
    else {
//bisect the sides
    var ab = mix( a, b, 0.5 );
    var ac = mix( a, c, 0.5 );
    var bc = mix( b, c, 0.5 );
    --count;
// three new triangles
    divideTriangle( a, ab, ac, count );
    divideTriangle( c, ac, bc, count );
    divideTriangle( b, bc, ab, count );
    }
}
```

init()

```
var program = initShaders(gl,"vertex-shader",
 "fragment-shader" );
gl.useProgram( program );
var bufferId = gl.createBuffer();
gl.bindBuffer( gl.ARRAY_BUFFER, bufferId );
gl.bufferData(gl.ARRAY_BUFFER,flatten(points),
 gl.STATIC_DRAW );
var positionLoc = gl.getAttribLocation(
 program, “aPosition" );
gl.vertexAttribPointer(positionLoc,2,
 gl.FLOAT, false, 0, 0 );
gl.enableVertexAttribArray( positionLoc );
render();
```

Render Function

```
function render(){
    gl.clear( gl.COLOR_BUFFER_BIT );
    gl.drawArrays( gl.TRIANGLES, 0, points.length
 );
}
```

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Programming with WebGL
Part 6: Three Dimensions

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Moving to 3D

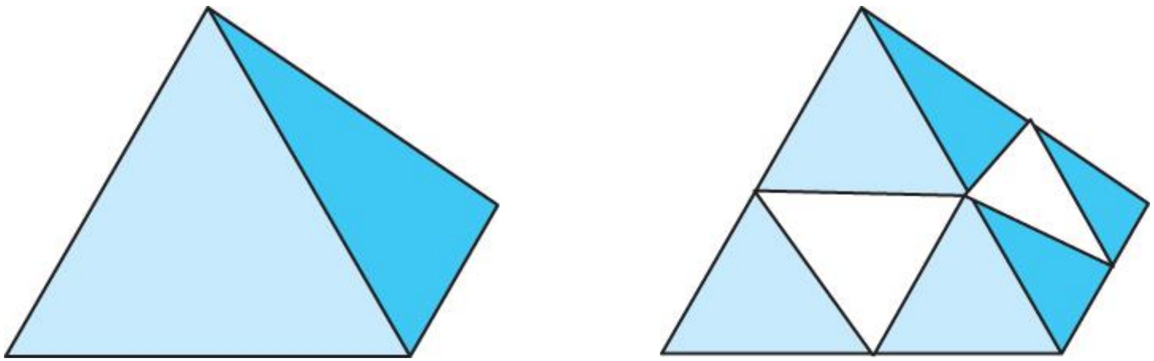
- We can easily make the program three-dimensional by using three dimensional points and starting with a tetrahedron

```
var vertices = [
  vec3(  0.0000,  0.0000, -1.0000 ),
  vec3(  0.0000,  0.9428,  0.3333 ),
  vec3( -0.8165, -0.4714,  0.3333 ),
  vec3(  0.8165, -0.4714,  0.3333 )    ];
```

subdivide each face

3D Gasket

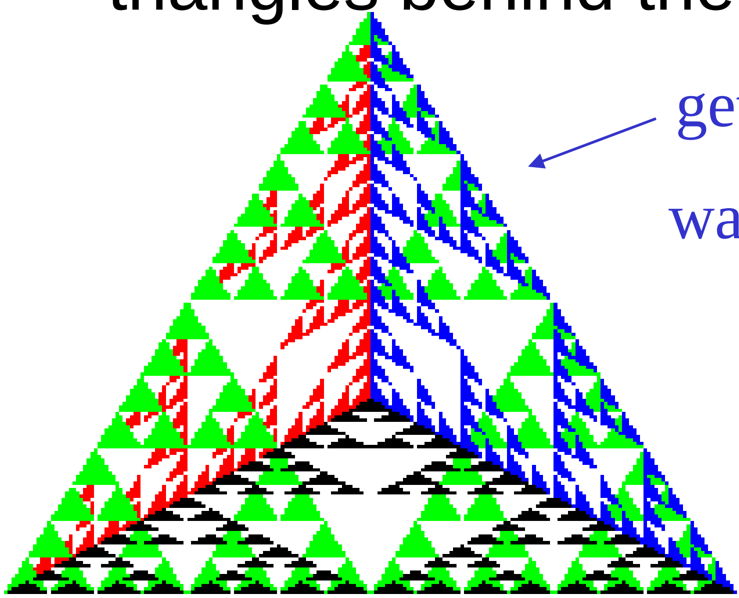
- We can subdivide each of the four faces



- Appears as if we remove a solid tetrahedron from the center leaving four smaller tetrahedra
- Code almost identical to 2D example, available as 02/gasket4.html (gasket4.js)

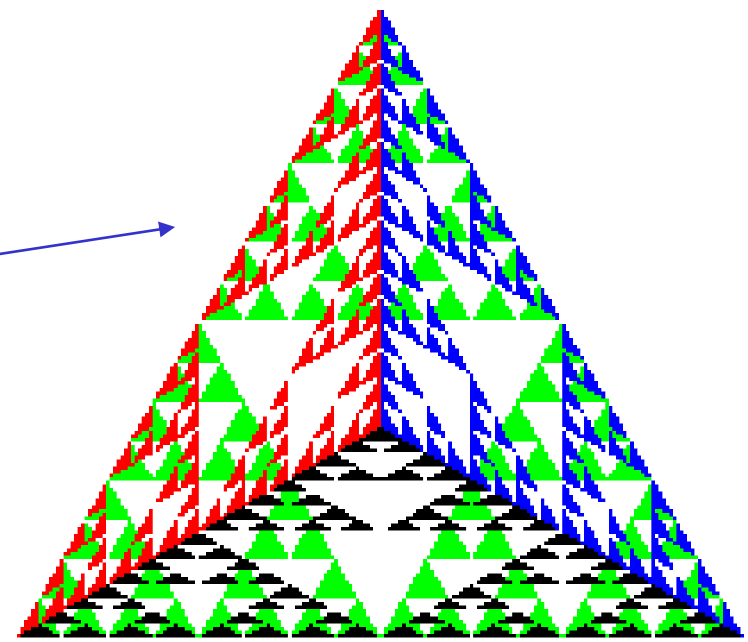
Almost Correct

- 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



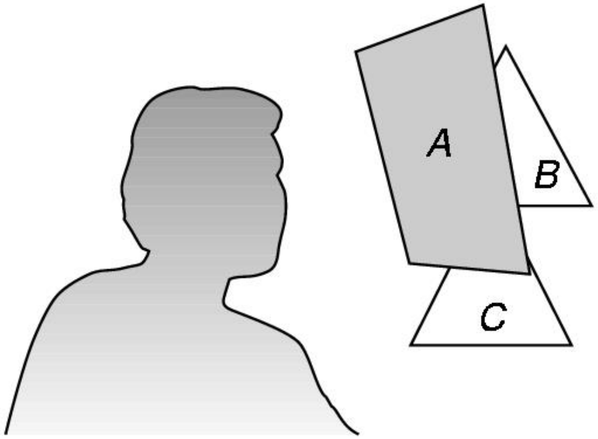
get this

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



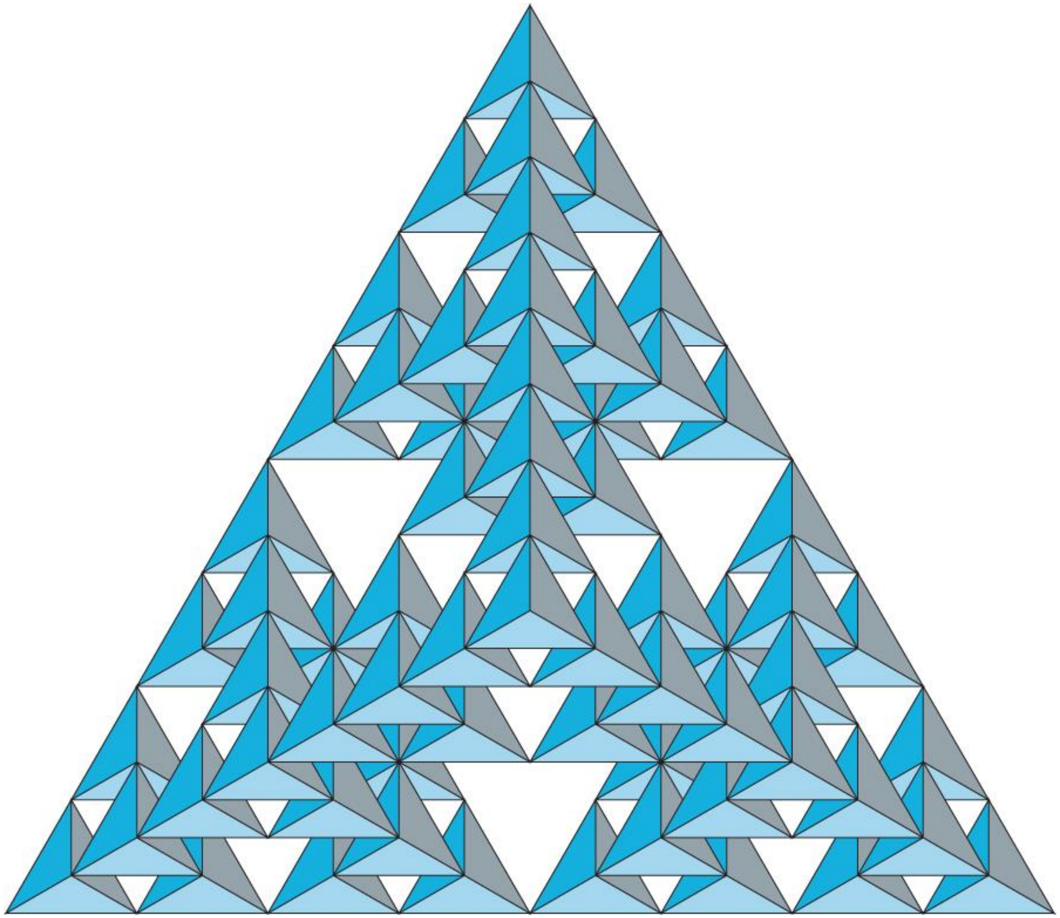
Using the *z*-buffer algorithm

- The algorithm uses an extra buffer, the z-buffer, to store depth information as geometry travels down the pipeline
- Depth buffer is required to be available in WebGL
- It must be
  - Enabled
    - **`gl.enable(gl.DEPTH_TEST)`**
  - Cleared in for each render
    - **`gl.clear(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
- See text for code

Volume Subdivision



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Incremental and Quaternion Rotation

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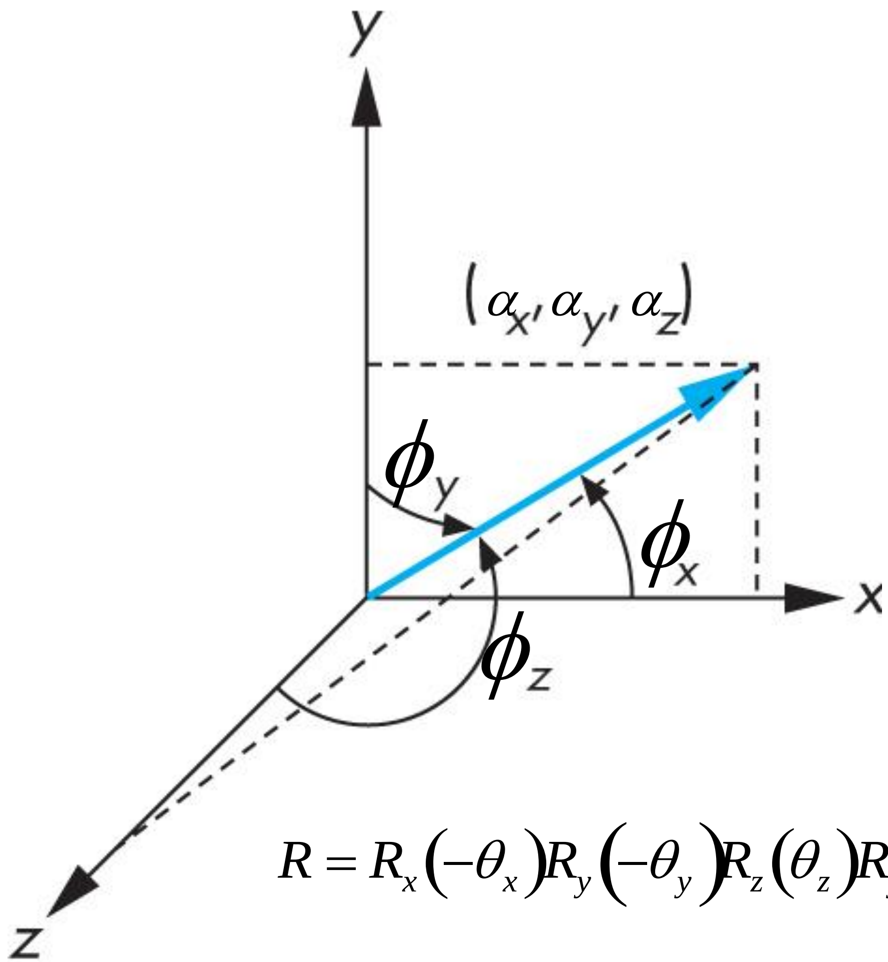
Objectives

- This is an optional lecture that
  - Illustrates the difference between using direction angles and Euler angles
  - Considers issues with incremental rotation
  - Introduces quaternions as an alternate to rotation matrices

Specifying a Rotation

- Pre 3.1 OpenGL had a function glRotate (theta, dx, dy dz) which incrementally changed the current rotation matrix by a rotation with fixed point of the origin about a vector in the direction (dx, dy, dz)
- We implemented rotate in MV.js
- Implementations of Rotate often decompose the general rotation into a sequence of rotations about the coordinate axes as in Chapter 4.

Euler from Direction Angles



$$R = R_x(-\theta_x)R_y(-\theta_y)R_z(\theta_z)R_y(\theta_y)R_x(\theta_x)$$

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Efficiency

$$R = R_x(-\theta_x)R_y(-\theta_y)R_z(\theta_z)R_y(\theta_y)R_x(\theta_x)$$

should be able to write as

$$R = R_x(\varphi_x)R_y(\varphi_y)R_z(\varphi_z)$$

If we knew the angles, we could use RotateX, RotateY and RotateZ from mat.h

But is this an efficient method?
No, we can do better with quaterions

Incremental Rotation

$$R(t+dt) = R(t)R_z(\theta_z)R_y(\theta_y)R_x(\theta_x)$$

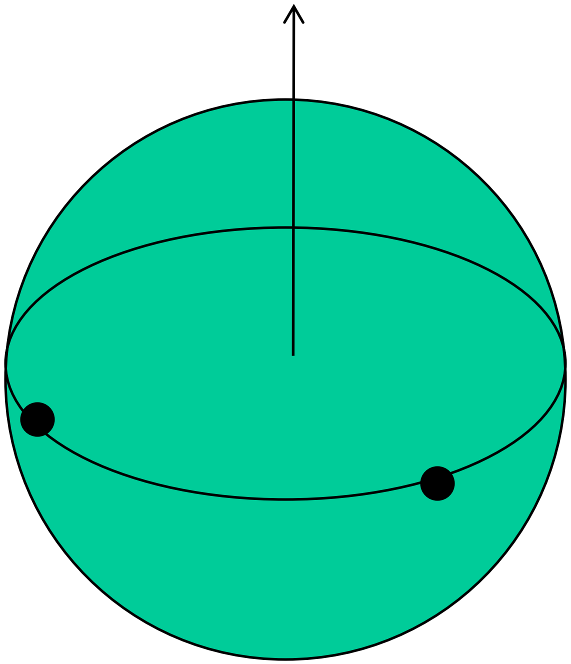
where θ_x, θ_y and θ_z are small angles

For small angles $\sin\theta \approx \theta$

$$\cos\theta \approx 1$$

$$R_z(\theta_z)R_y(\theta_y)R_x(\theta_x) \approx \begin{bmatrix} 1 & -\theta_z & \theta_y & 0 \\ \theta_z & 1 & -\theta_x & 0 \\ -\theta_y & \theta_x & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Great Circles



Rotation and Great Circles

- Shortest path between two points on a sphere is the great circle passing through the two points
- Corresponding to each great circle is vector normal to the circle
- Rotation about this vector carries us from the first point to the second

Quaternion Rotation

Definition: $a = (q_0, q_1, q_2, q_3) = (q_0, \mathbf{q})$

Quaternian Arithmetic: $a + b = (a_0 + b_0, \mathbf{a} + \mathbf{b})$

$$ab = (a_0 b_0 - \mathbf{a} \bullet \mathbf{b},\ a_0 \mathbf{b} + b_0 \mathbf{a} + \mathbf{a} \times \mathbf{b})$$

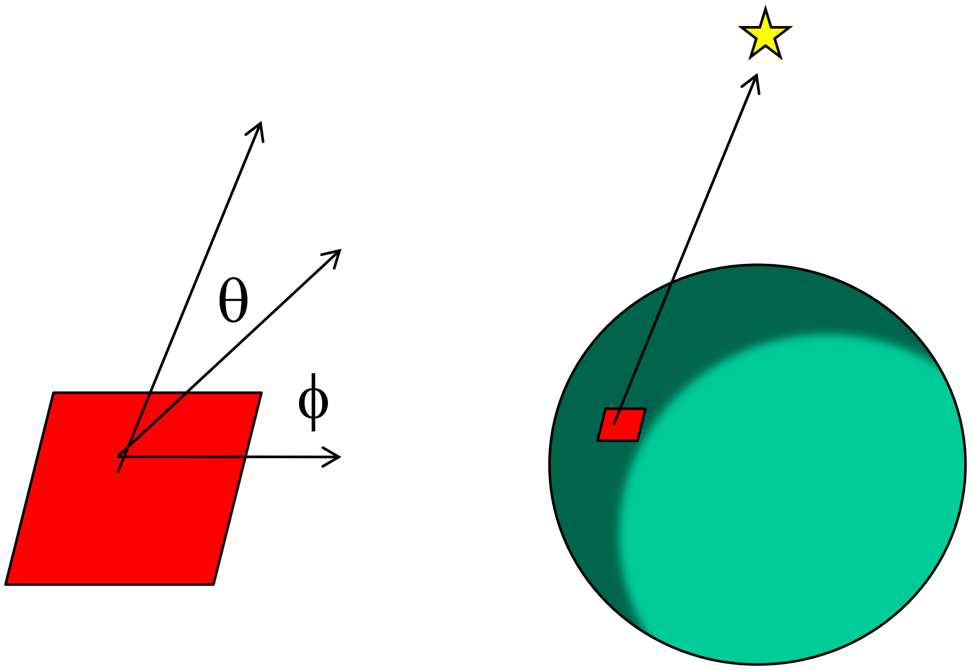
$$|a|^2 = (q_0^2, \mathbf{q} \bullet \mathbf{q}) \qquad a^{-1} = \frac{1}{|a|^2}(q_0, \textbf{-q})$$

Representing a 3D point: $p = (0, \mathbf{p})$

Representing a Rotation: $r = \left(\cos\frac{\theta}{2}, \sin\frac{\theta}{2}\mathbf{v}\right)$

Rotating a Point: $p' = r p r^{-1}$

Looking at the North Star



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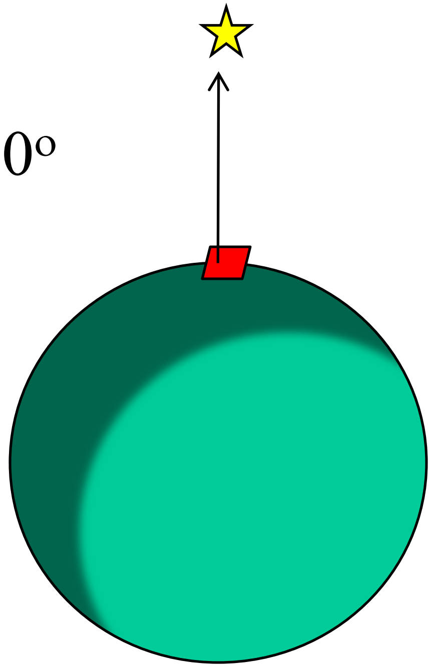
At North Pole



$\theta = 90^{o}$

$\phi = ?$

Gimbal Lock

- Suppose you rotate about the y axis by 90º
- This action removes a degree of freedom

$$R_z(\theta_z)R_y(\theta_y)R_x(\theta_x) \approx \begin{bmatrix} 0 & \sin(\theta_x - \theta_z) & \cos(\theta_x - \theta_z) & 0 \\ 0 & \cos(\theta_x - \theta_z) & -\sin(\theta_x - \theta_z) & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Quaternions and Computer Graphics

- (Re)discovered by both aerospace and animation communities
- Used for head mounted display in virtual and augmented reality
- Used for smooth camera paths
- Caveat: quaternions do not preserve up direction

Working with Quaternians

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- Quaternion arithmetic works well for representing rotations around the origin
- There is no simple way to convert a quaternion to a matrix representation
- Usually copy elements back and forth between quaternions and matrices
- Can use directly without rotation matrices in the virtual trackball
- Quaternion shaders are simple