the gamedesigninitiative at cornell university

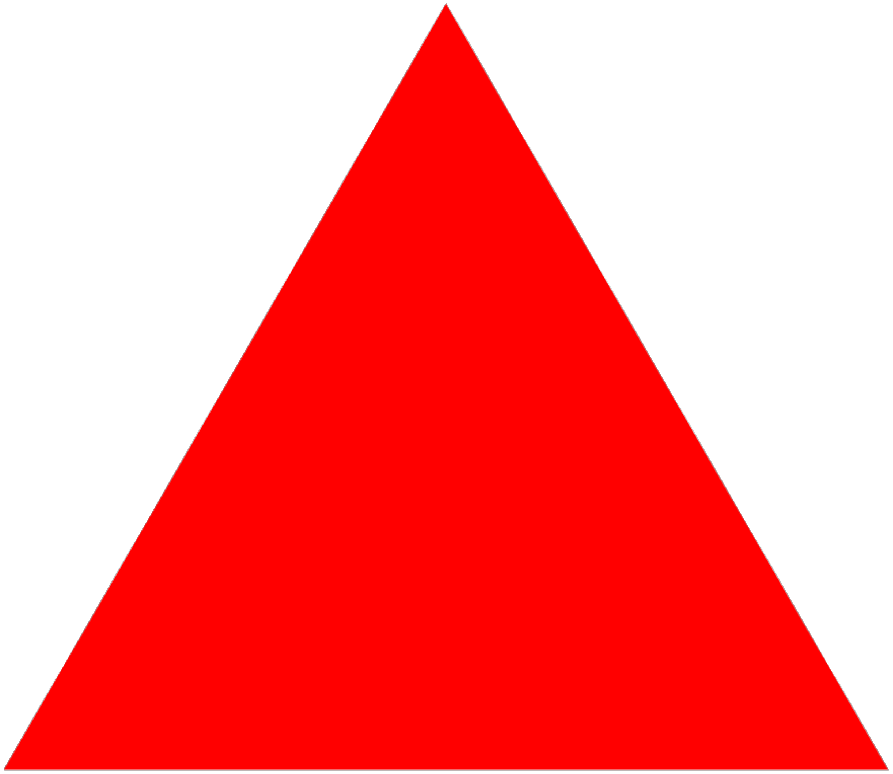
Lecture 10

The Graphics Pipeline

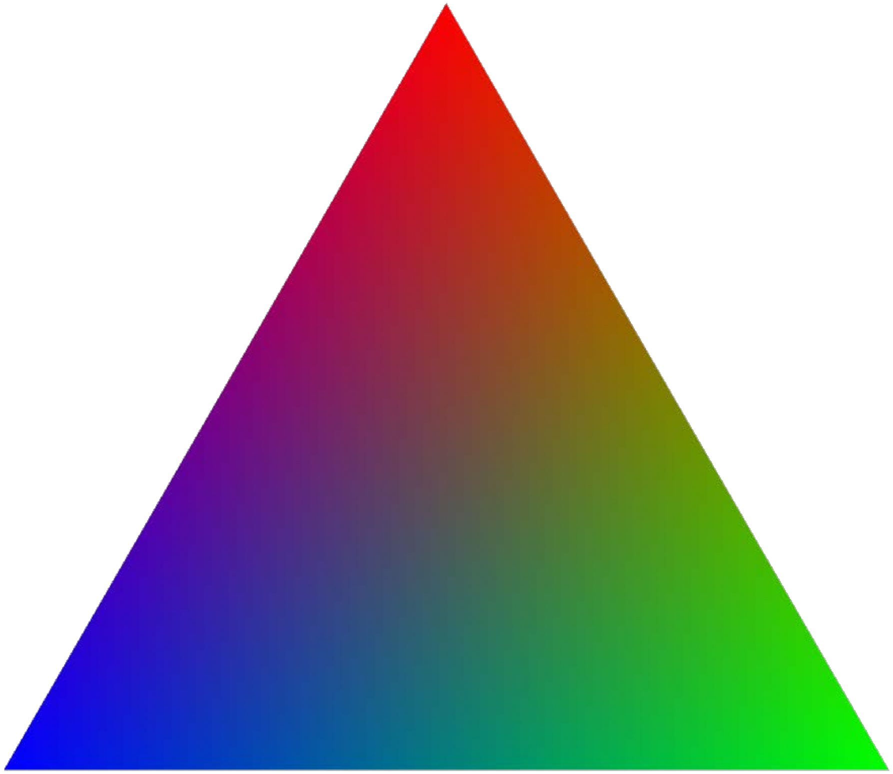
Caveat About Today's Lecture

- Today's focus is on **OpenGL**
  - **The** cross-platform graphics API for Indie games
  - **Vulkan** may take over, but not there yet
- CUGL uses **OpenGLES 3** for rendering
  - Is a proper subset of OpenGL 3.x
  - Designed with mobile devices in mind
- Much of what we say is true in other APIs
  - But the pipeline will be slightly different
  - In the case of Vulkan, a lot different

Graphics Cards Draw Triangles



Triangles Can Be Colored

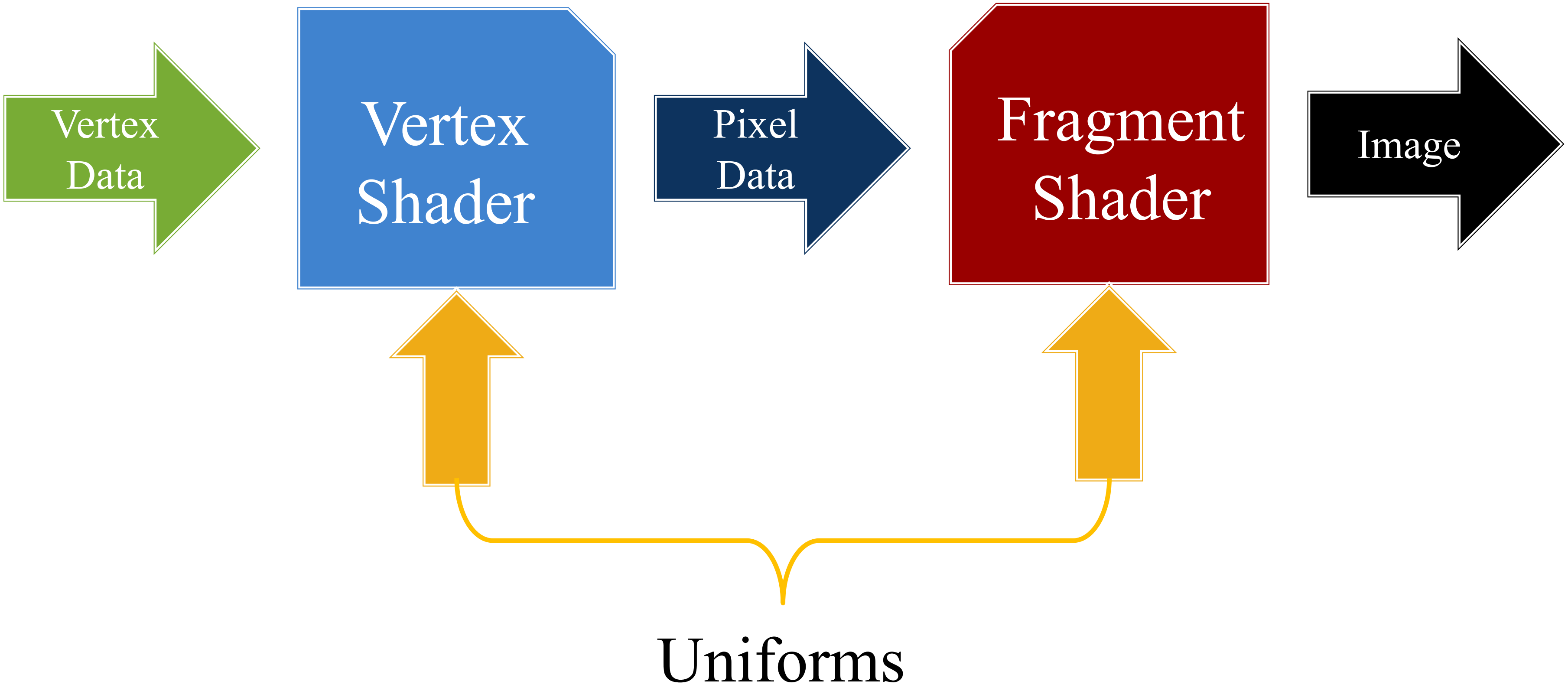


Triangles Can Be Textured

Triangles Can Be Both

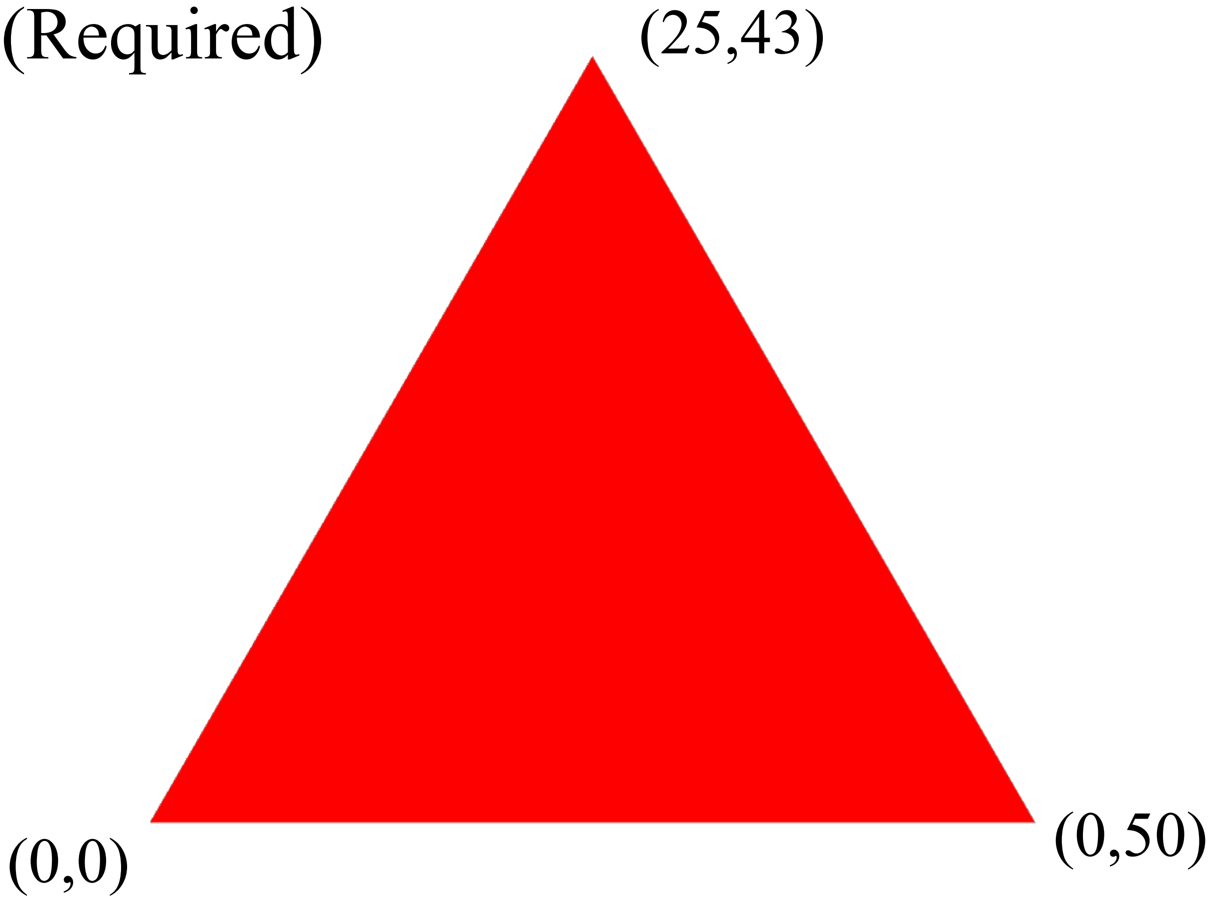
A Sprite is (Often) Two Triangles

Triangles are Drawn with Shaders



Vertex Data Defines the Triangle

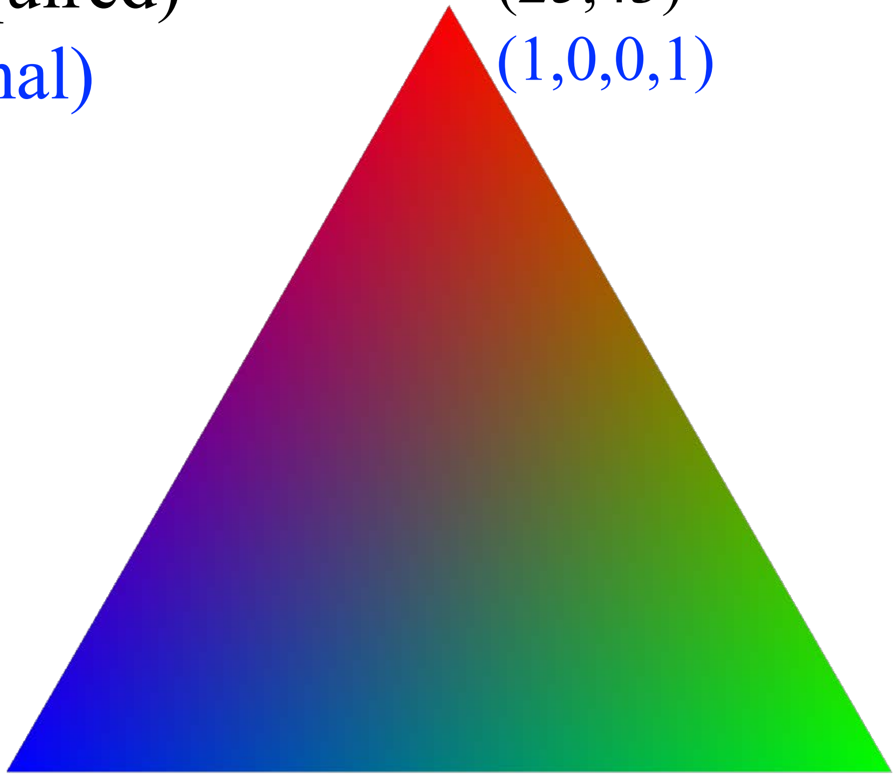
Position (Required)



Vertex Data Defines the Triangle

Position (Required)

Color (Optional)



(25,43)
(1,0,0,1)

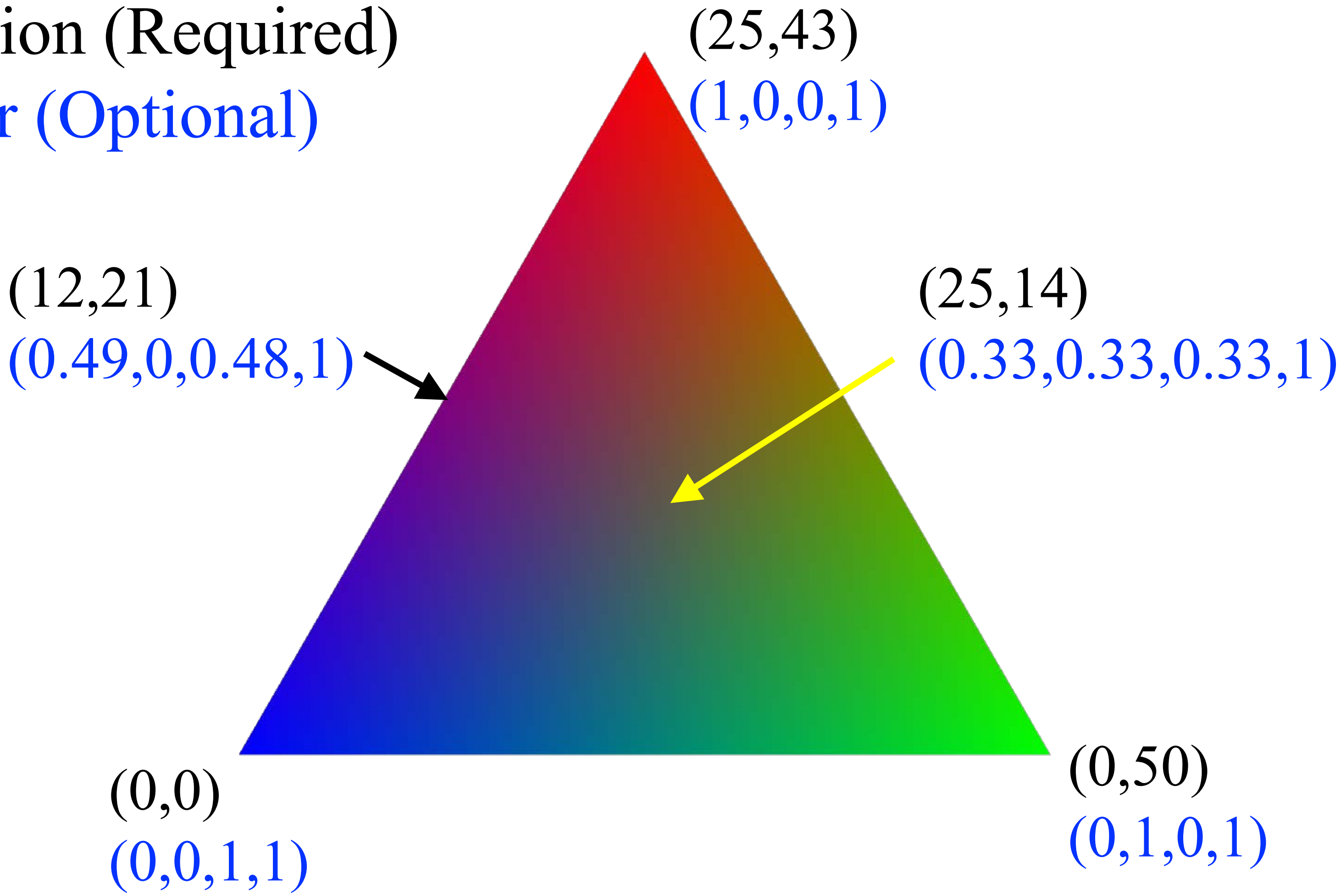
(0,0)
(0,0,1,1)

(0,50)
(0,1,0,1)

Vertex Shader **Interpolates** Pixels

Position (Required)

Color (Optional)



A Very Simple Shader

Vertex Shader

```
// Positions
in vec4 aPosition;

// Colors
in  vec4 aColor;
out vec4 outColor;

uniform mat4 uCamera;

// Interpolate position and color
void main(void) {
    gl_Position = uCamera*aPosition;
    outColor = aColor;
}
```

Input

Input

Fragment Shader

```
// The output color
out vec4 frag_color;

// Color result from
in vec4 outColor;

// Just use color computed
void main(void) {
    frag_color = outcolor;
}
```

Input

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```

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```

Uniforms "Never" Change

- We *stream* vertex data to the shader
  - Put all vertex data into a giant array
  - Send it all to graphics card at once
- Changing a uniform **breaks the stream**
  - Have to break up the array into parts
  - Send one part with first value of uniform
  - Send next part with second value of the uniform
- This can **slow down the framerate**
  - Unlikely in this class unless lots of sprites
  - But should be aware of the cost

Uniforms “Never” Change

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- Chang
  - Hav
  - Send
  - Send m

Will the camera
ever change?

- This can **slow down the framerate**
  - Unlikely in this class unless lots of sprites
  - But should be aware of the cost

Images Have Texture Coordinates

(0,0)

(1,0)

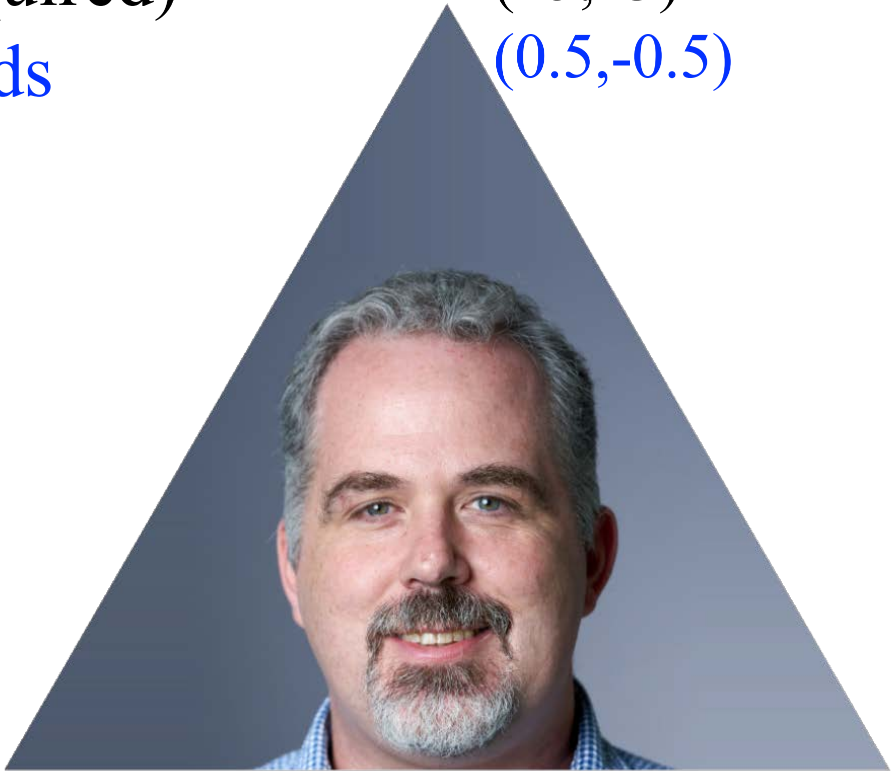
(0,1)

(1,1)

Vertex Data Can Include Texture Data

Position (Required)

Texture Coords (Optional)



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(0,0)
(-0.37,1)

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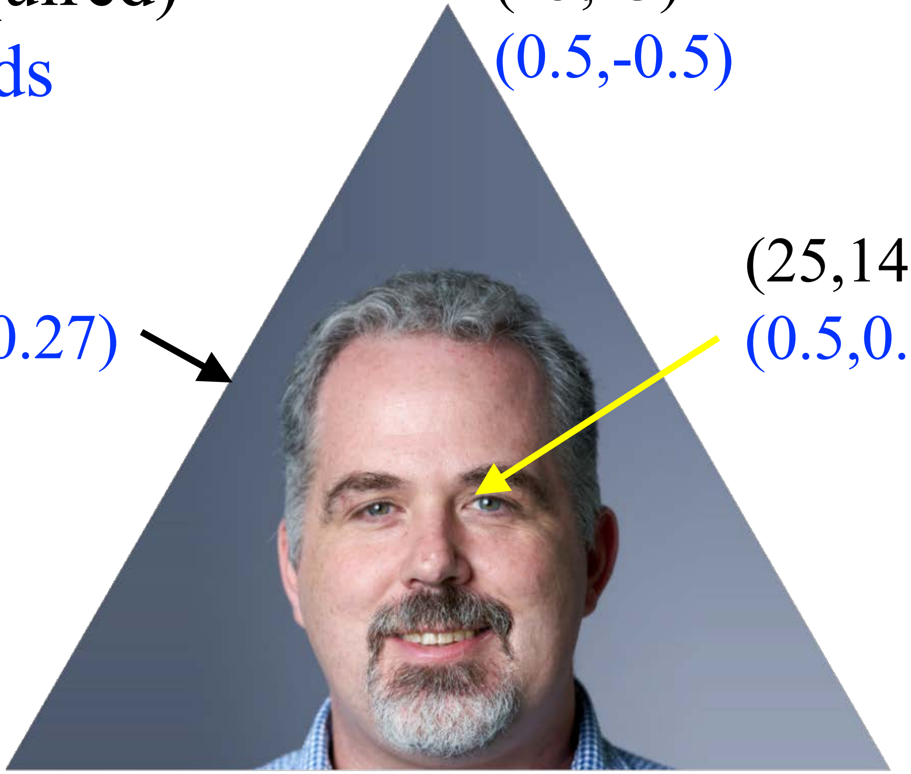

(25,43)
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(12,21)
(0.048,0.27)

(25,14)
(0.5,0.51)

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(-0.37,1)

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Fragment Shader

```
// The output color
out vec4 frag_color;

// Texture coord from vertex shader
in vec4 outCoord;

uniform sampler2D uTexture;

// Use texture to compute color
void main(void) {
    frag_color = texture(uTexture,
                         outCoord);
}
```

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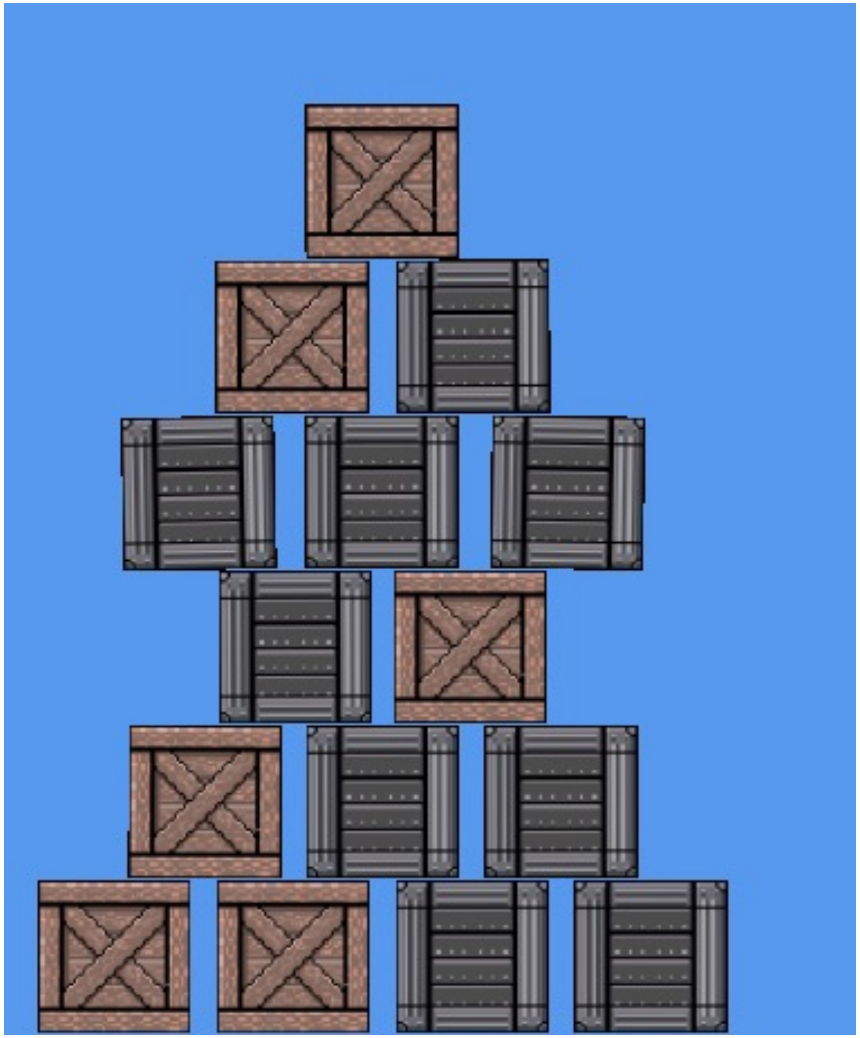
Changing the texture
stalls the stream

How Does a SpriteBatch Work?



- SpriteBatch has a **shader**
  - Methods create vertices
  - Vertices have color, texture
  - Sends vertices to shader
- Groups data by **uniforms**
  - Adds all vertices to a set
  - Breaks set into *batches*
  - Uniforms fixed each batch
- Each texture is a **new batch**
  - How often do you switch?

How Does a SpriteBatch Work?

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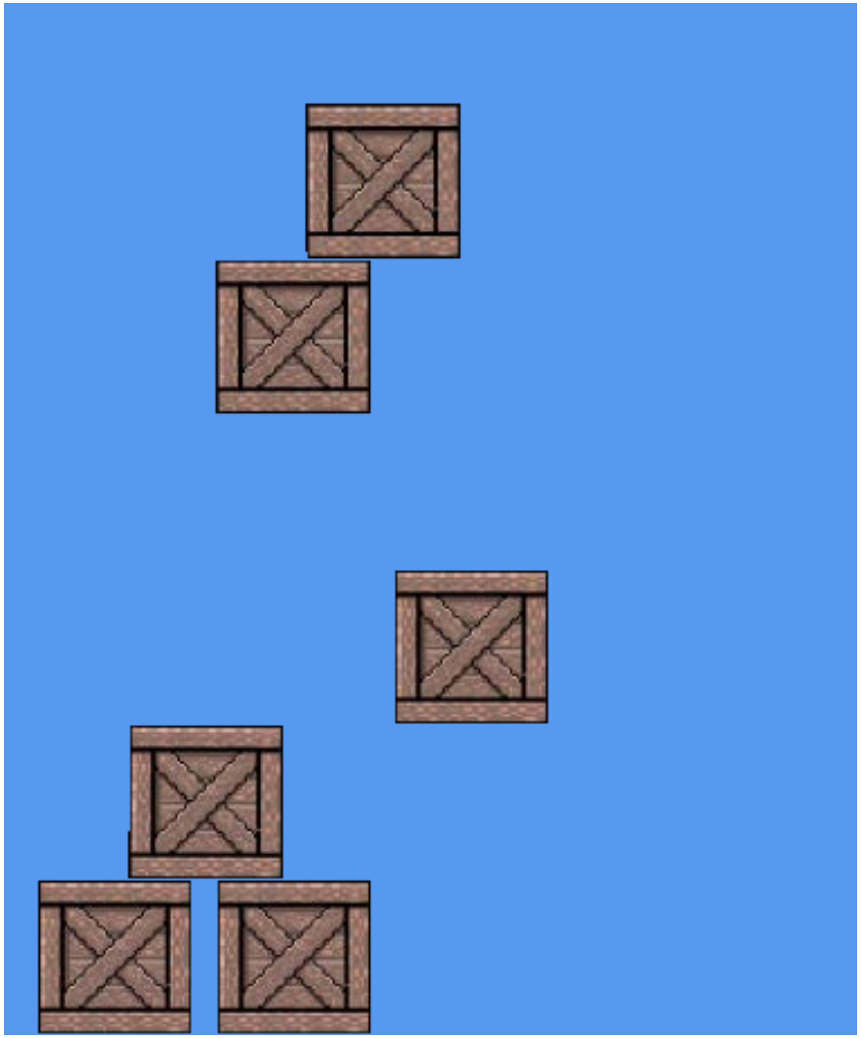

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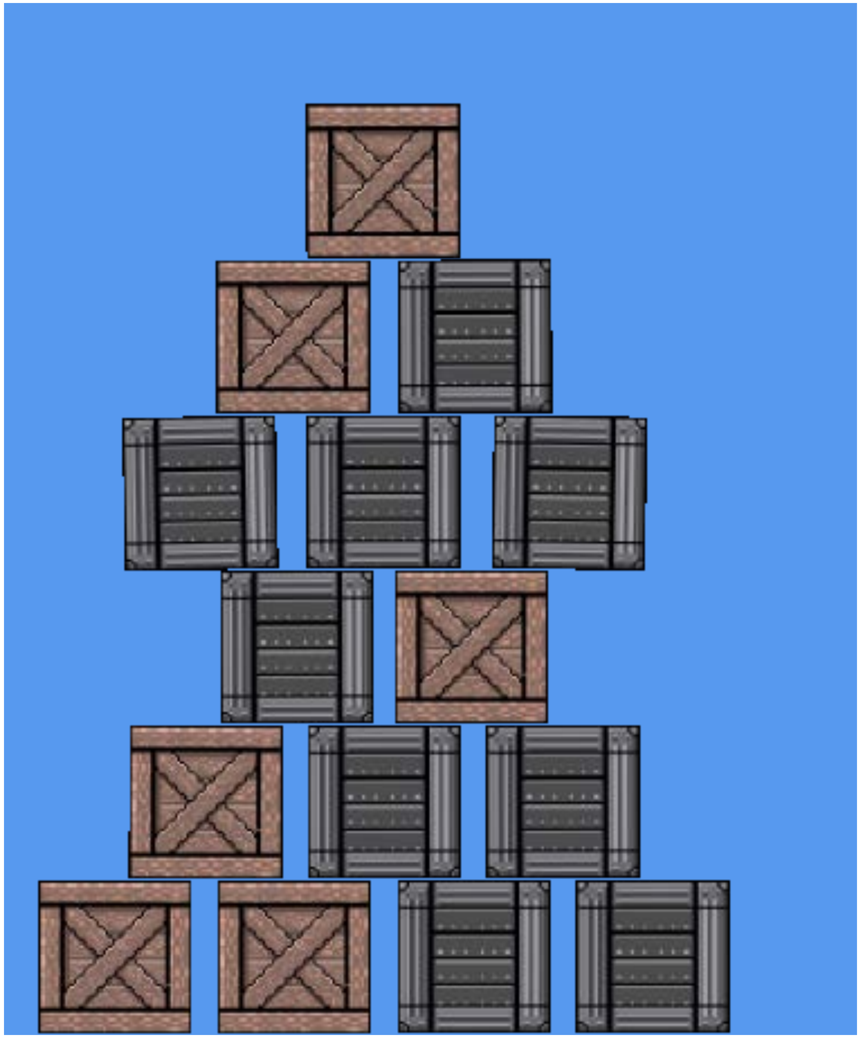

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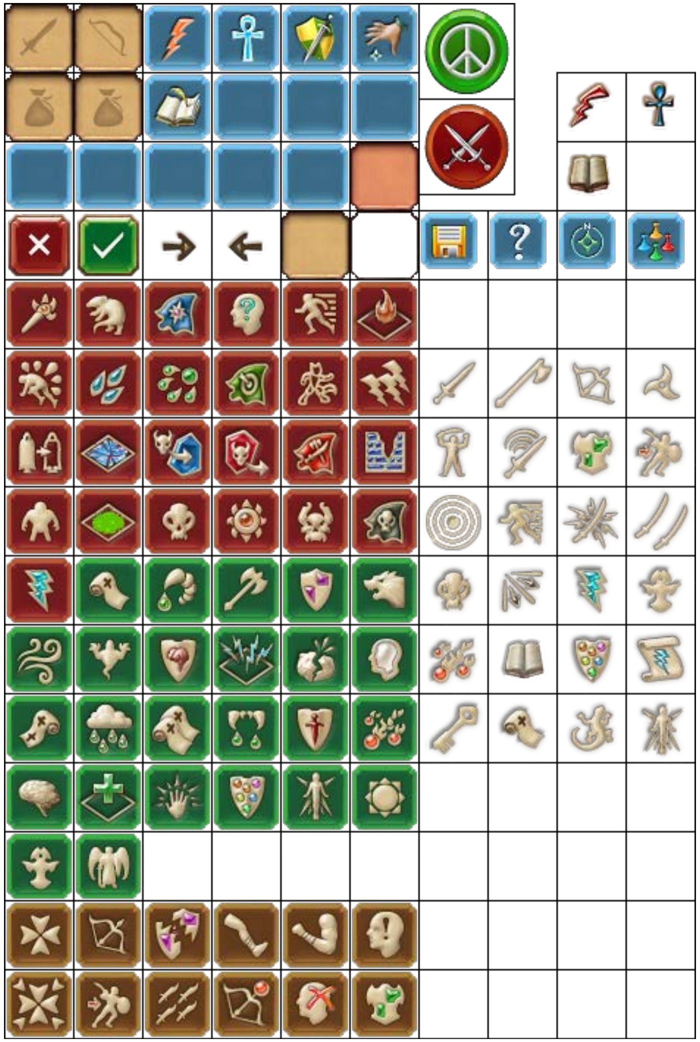
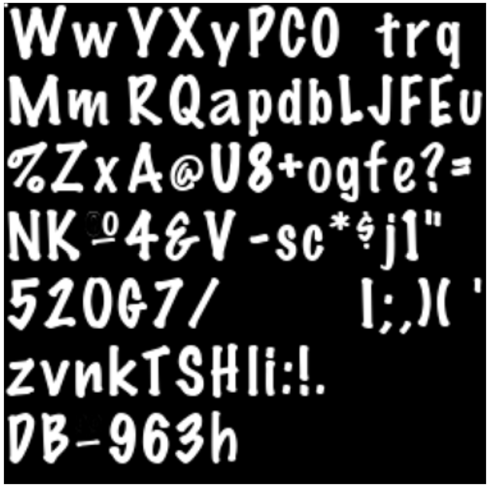
Optimizing Performance: **Atlases**

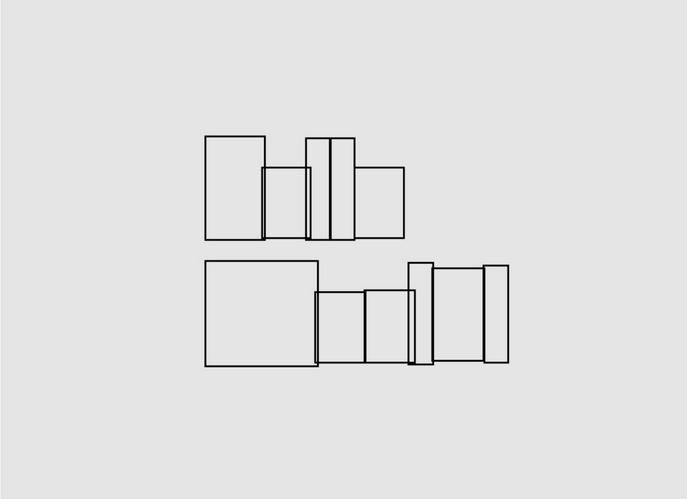
- **Idea**: Never switch textures
  - Sprite sheet is many images
  - We can draw part of texture
  - One texture for everything?
- Called a **texture atlas**
  - Supported in CUGL
  - See file loading.json
  - Ideal for **interface design**
- Has some **disadvantages**
  - Textures cannot repeat
  - Recall texture size limits



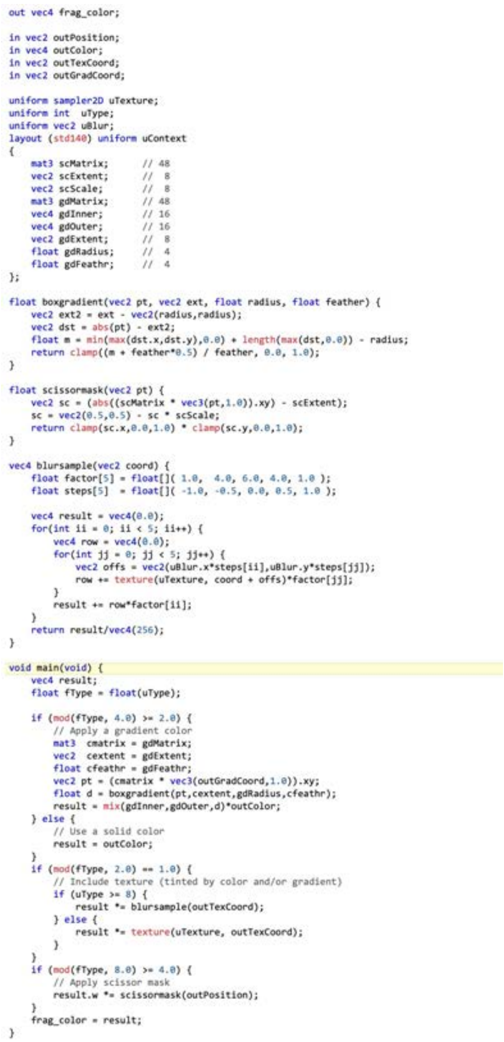
Aside: This is How Fonts Work

- Each Font creates an **atlas**
  - Reason you must specify size
  - Atlas limited to 512x512
  - Multiple atlases if necessary
- TextLayout makes **vertices**
  - Quads made from font metrics
  - Includes *kerning*, *alignments*
  - Vertices include texture cords
- This makes text **very fast**
  - Generating vertices is quick
  - Actual font cached in atlas(es)





The SpriteBatch Shader



```
out vec4 frag_color;

in vec2 outPosition;
in vec4 outColor;
in vec2 outTexCoord;
in vec2 outGradCoord;

uniform sampler2D uTexture;
uniform int  uType;
uniform vec2 uBlur;
layout (std140) uniform uContext
{
    mat3 scMatrix;      // 48
    vec2 scExtent;      //  8
    vec2 scScale;       //  8
    mat3 gdMatrix;      // 48
    vec4 gdInner;       // 16
    vec4 gdOuter;       // 16
    vec2 gdExtent;      //  8
    float gdRadius;     //  4
    float gdFeathr;     //  4
};

float boxgradient(vec2 pt, vec2 ext, float radius, float feather) {
    vec2 ext2 = ext - vec2(radius,radius);
    vec2 dst = abs(pt) - ext2;
    float m = min(max(dst.x,dst.y),0.0) + length(max(dst,0.0)) - radius;
    return clamp((m + feather*0.5) / feather, 0.0, 1.0);
}

float scissormask(vec2 pt) {
    vec2 sc = (abs((scMatrix * vec3(pt,1.0)).xy) - scExtent);
    sc = vec2(0.5,0.5) - sc * scScale;
    return clamp(sc.x,0.0,1.0) * clamp(sc.y,0.0,1.0);
}

vec4 blursample(vec2 coord) {
    float factor[5] = float[]( 1.0,  4.0, 6.0, 4.0, 1.0 );
    float steps[5]  = float[]( -1.0, -0.5, 0.0, 0.5, 1.0 );

    vec4 result = vec4(0.0);
    for(int ii = 0; ii < 5; ii++) {
        vec4 row = vec4(0.0);
        for(int jj = 0; jj < 5; jj++) {
            vec2 offs = vec2(uBlur.x*steps[ii],uBlur.y*steps[jj]);
            row += texture(uTexture, coord + offs)*factor[jj];
        }
        result += row*factor[ii];
    }
    return result/vec4(256);
}

void main(void) {
    vec4 result;
    float fType = float(uType);

    if (mod(fType, 4.0) >= 2.0) {
        // Apply a gradient color
        mat3  cmatrix = gdMatrix;
        vec2  cextent = gdExtent;
        float cfeathr = gdFeathr;
        vec2 pt = (cmatrix * vec3(outGradCoord,1.0)).xy;
        float d = boxgradient(pt,cextent,gdRadius,cfeathr);
        result = mix(gdInner,gdOuter,d)*outColor;
    } else {
        // Use a solid color
        result = outColor;
    }
    if (mod(fType, 2.0) == 1.0) {
        // Include texture (tinted by color and/or gradient)
        if (uType >= 8) {
            result *= blursample(outTexCoord);
        } else {
            result *= texture(uTexture, outTexCoord);
        }
    }
    if (mod(fType, 8.0) >= 4.0) {
        // Apply scissor mask
        result.w *= scissormask(outPosition);
    }
    frag_color = result;
}
```

- Provides support for
    - Solid/vertex colors
    - Color gradients (linear, radial)
    - Textures/texture coords
    - Gaussian blur
    - Scissoring/masking
- Not "**user-serviceable**"
    - Do not try to replace this
    - Will break all the UI code
- Want a **custom shader**?
    - Make a new **pipeline**

The Shader Class

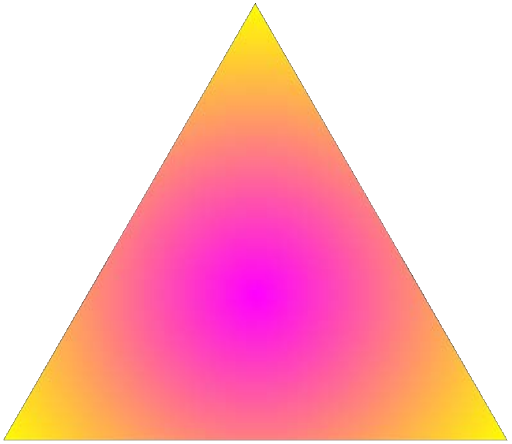
- `Shader::alloc(const string vsrc, const string fsrc)`
  - Returns nullptr if shader compilation fails
  - Also gives helpful error message in output
- The shaders are **strings**, not **files**
  - You could load files and read into strings
  - But this means pipeline *waits* on asset loading
  - Better to put directly in your source code
- CUGL approach: **raw strings**
  - Write shader code into a header file
  - Special include assigns contents to a variable

Using a Shader Object

- Activate it with bind() command
  - Can only have one shader at a time
  - This method makes it the active shader
  - Call unbind() to release it.
  - Like begin/end with SpriteBatch
- Assign **uniforms** to shader with **setters**
  - `s->setUniformMat4("uCamera",cam->getCombined());`
  - Support for primitives and all CUGL math objects
  - Applies to both vertex and fragment uniforms
  - But not texture; that is special

Make a Vertex Type

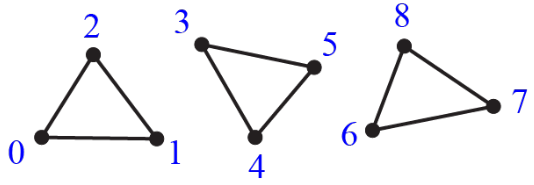
- Can be **any class** of your making
  - Should have **position** (Vec2, Vec3, or Vec4)
  - Can have anything else that you want
  - There are (almost) no restrictions
- **Example**: SpriteVertex2
  - Position (Vec2)
  - Color (unsigned int)
  - Texture coords (Vec2)
  - Gradient coords (Vec2)



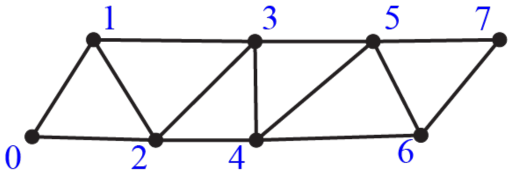
Create a Geometry

- Need two things to **define shape**
  - An array of vertices
  - An array of indices
- Indices refer to **array positions**
  - Used to create triangles
  - Meaning depends on command
- `Poly2` does all of this for you!
  - But it only has position data
  - Only supports triangle **lists**
- For more, see class `Mesh<T>`

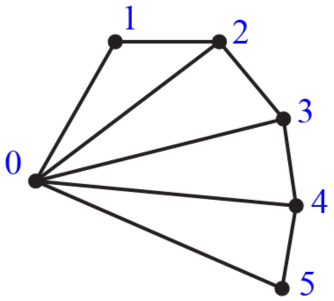
Triangle List



Triangle Strip



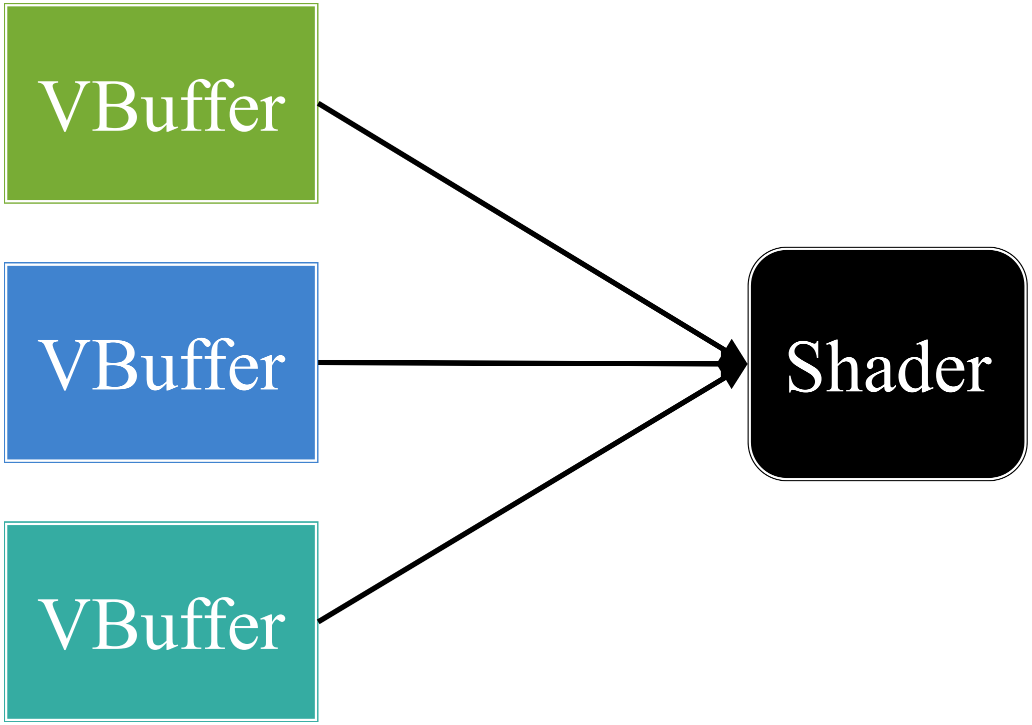
Triangle Fan



Create a VertexBuffer Object

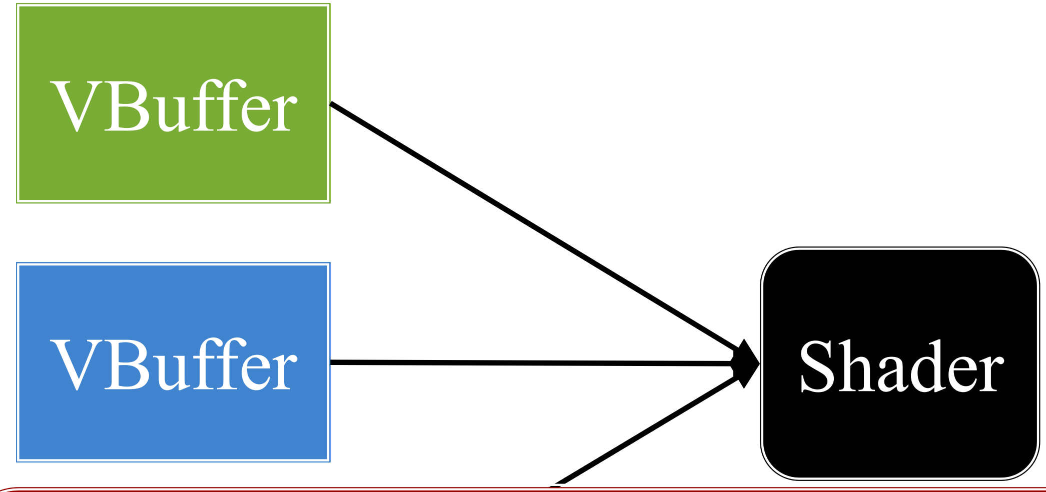
- VertexBuffer::alloc(sizeof(VertexClass))
  - sizeof tells it number of bytes per vertex
  - Stream size is determined when you **load** vertices
- v->setupAttribute("var",bytes,type1,type2,loc)
  - Maps shader variable to slot in vertex class
  - See documentation/example for how to do this
- v->attach(shader)
  - Tell vertex buffer to send data to the shader
  - This is how the shader gets the vertex data!

VertexBuffer vs Shader



Have a **many-one** relationship

VertexBuffer vs Shader



Set active VertexBuffer with bind/unbind

Have a **many-one** relationship

Loading Data Into Vertex Buffer

- v->loadVertexData(array,size)
  - Loads the array of vertices
  - Remembers until you load new data
- v->loadIndexData(array,size)
  - Loads the array of indices
  - Should be updated when the vertices are
- v->draw(command,index_count,index_start)
  - Tells how to interpret the indices (list, strip, fan)
  - Does the actual drawing at this time (not delayed)

Aside: Static Draw vs Stream Draw

Static Draw

- Vertex buffer is **fixed**
  - Object altered via *uniforms*
  - **Example**: Transform matrix
- Used if **lots of vertices**
  - Uniform changes stall drawing
  - But reloading vertices is worse
- Common in **3d rendering**
  - Models are **large meshes**
  - Each model its own buffer

Stream Draw

- Vertex buffer **changes often**
  - Always updating position
  - Always updating geometry
- Used if **low complexity**
  - Few vertices per object (quads)
  - Can't give each sprite a buffer
- Common in **2d rendering**
  - Data is very **heterogeneous**
  - How `SpriteBatch` works

Last Step: Textures

- Textures are **not** set by a shader method
  - Data is way too big for normal uniforms
  - All data is stored in a `Texture` object
- This object has its own `bind`/`unbind`
  - Call bind to make it the **active texture**
  - Call unbind to remove it/have no texture
- Possible to have **more than one texture**
  - Each shader texture variable has a slot (0-10)
  - Can call `bind(slot)` to put it in a slot

Putting It All Together

```
shader->bind();
vbuffer->bind();   // Binds shader if necessary
texture->bind();   // Make active texture in slot 0
vbuffer->draw(mesh.command,mesh.indices.size(),0);
...  // More drawing commands
texture->unbind();  // If need to change texture
... // More drawing commands
vbuffer->unbind();  // If need to change buffer
shader->unbind();  // If need to change shader
```

Putting It All Together

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vbuffer->bind();   // Binds shader if necessary
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```

See Pipeline Demo

Combining With Scene Graphs

```
void CustomNode::draw(const std::shared_ptr<SpriteBatch>& batch,
                      const Affine2& transform, Color4 tint) {

    // Stop the previous graphics pipeline
    batch->end();

    // Adjust pipeline camera by the node transform
    Mat4 camera = _scene->getCombined()*transform;

    // Custom drawing code
    …
    …

    // Restart the sprite batch
    batch->begin(_scene->getCombined());
}
```

Two Final Classes

UniformBuffer

- Used if **many** uniforms
  - Setting each uniform slow
  - Put uniforms in byte array
  - Set pointer to byte array
- Permits uniform **streaming**
  - Dual of `VertexBuffer`
- Used by `SpriteBatch`
  - Holds gradients, scissors
  - See code for usage

RenderTarget

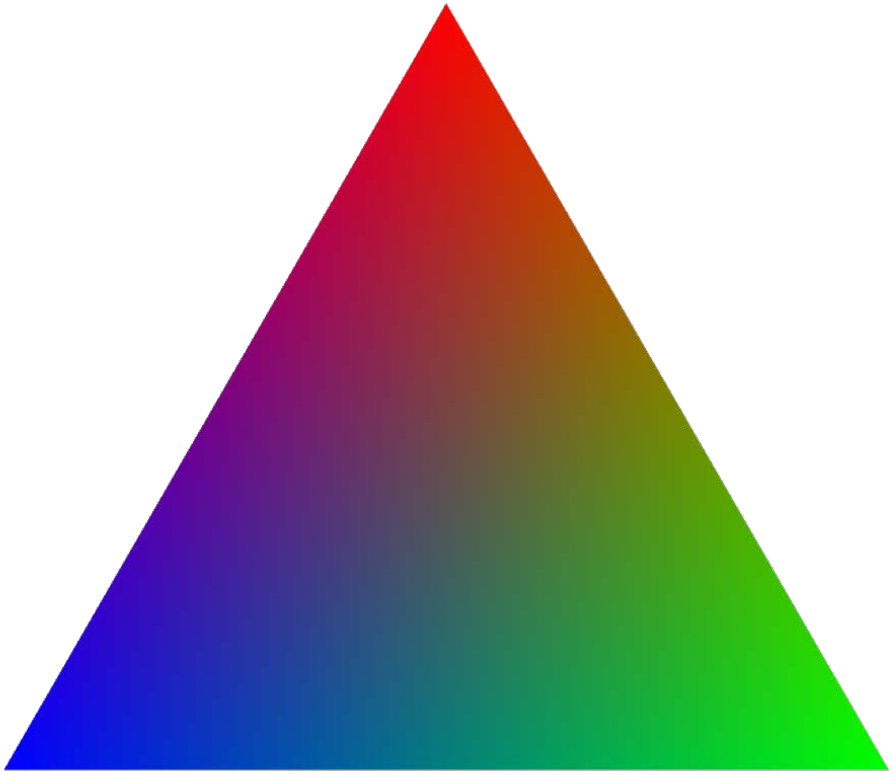
- Used to **render offscreen**
  - Draw to a special buffer
  - Turn buffer into a texture
  - Apply texture to shapes
- Great for **special effects**
  - Render screen to texture
  - Apply 2nd shader to texture
- Used in `Scene2Texture`
  - See documentation

Summary

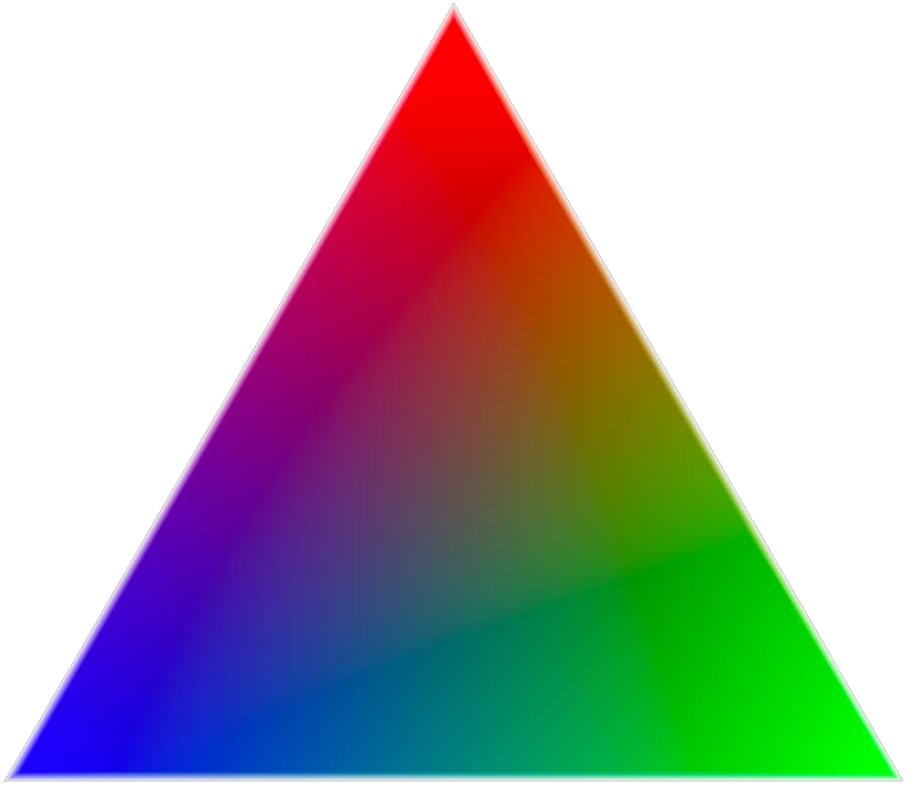
- CUGL uses **OpenGLES 3** for rendering
  - Uses shaders to produces triangles on screen
  - SpriteBatch makes all of this very easy
- Custom shaders require a **separate pipeline**
  - Need a Shader to output to screen
  - Need a Mesh to define the geometry
  - Need a VertexBuffer to pass Mesh to Shader
  - (Optional) Need a Texture to fill in triangles
- Want more? Take **CS 5625**

Advanced Technique

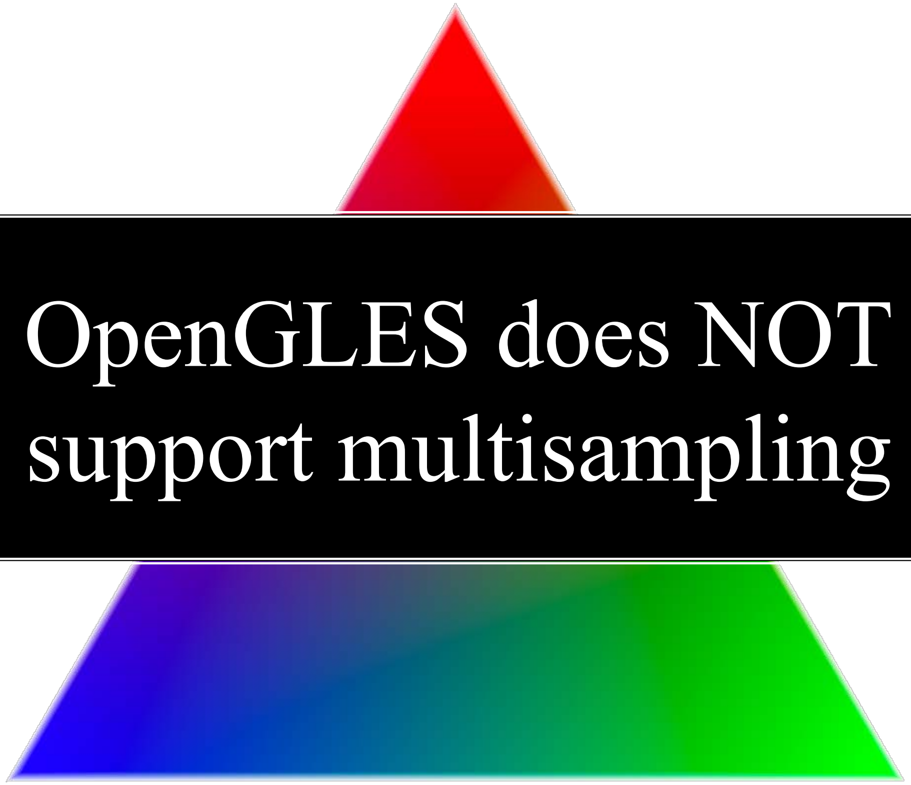
Triangles Have Hard Edges



Sometimes Want Softer Edges

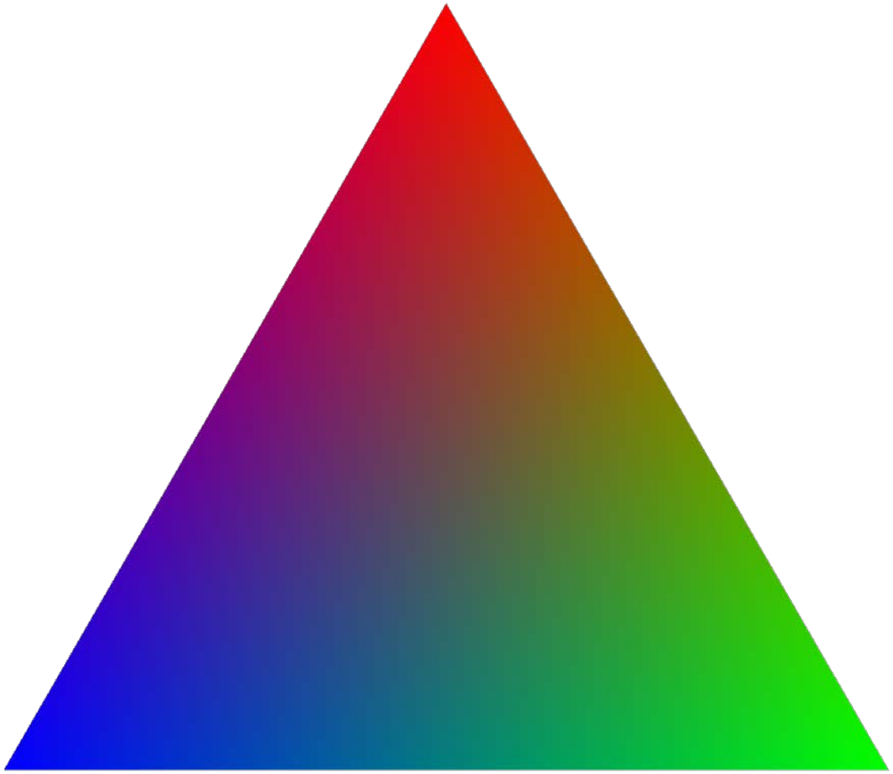


Sometimes Want Softer Edges

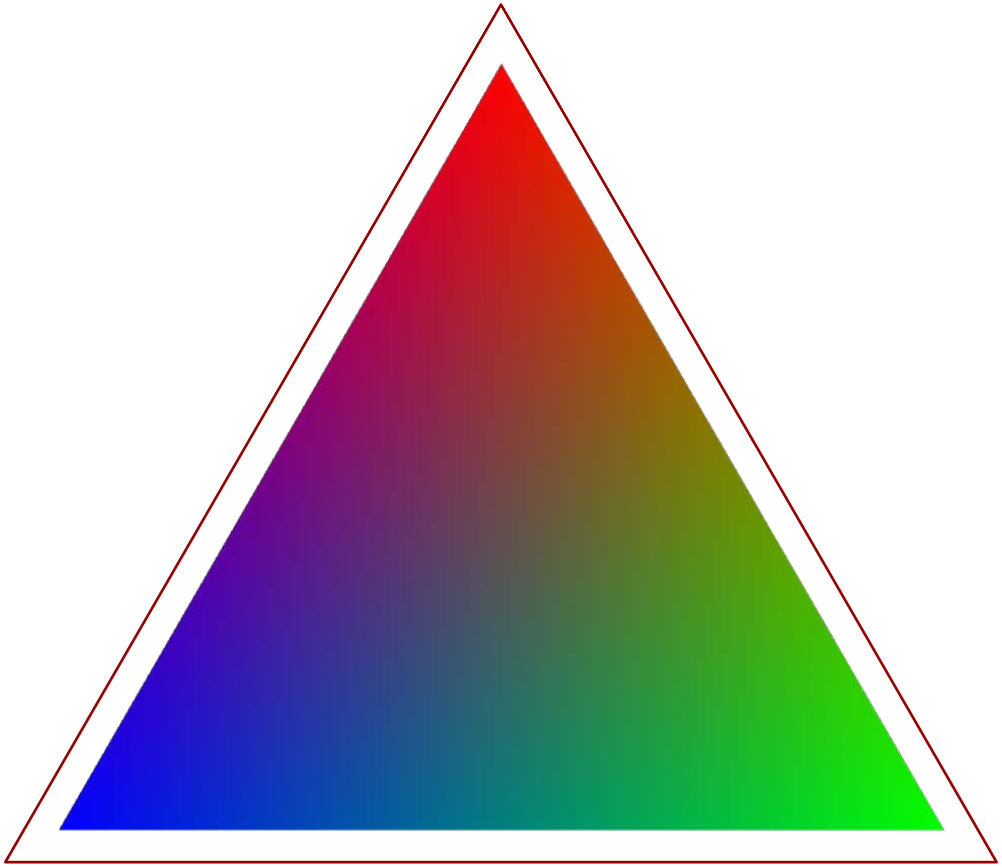


OpenGLES does NOT support multisampling

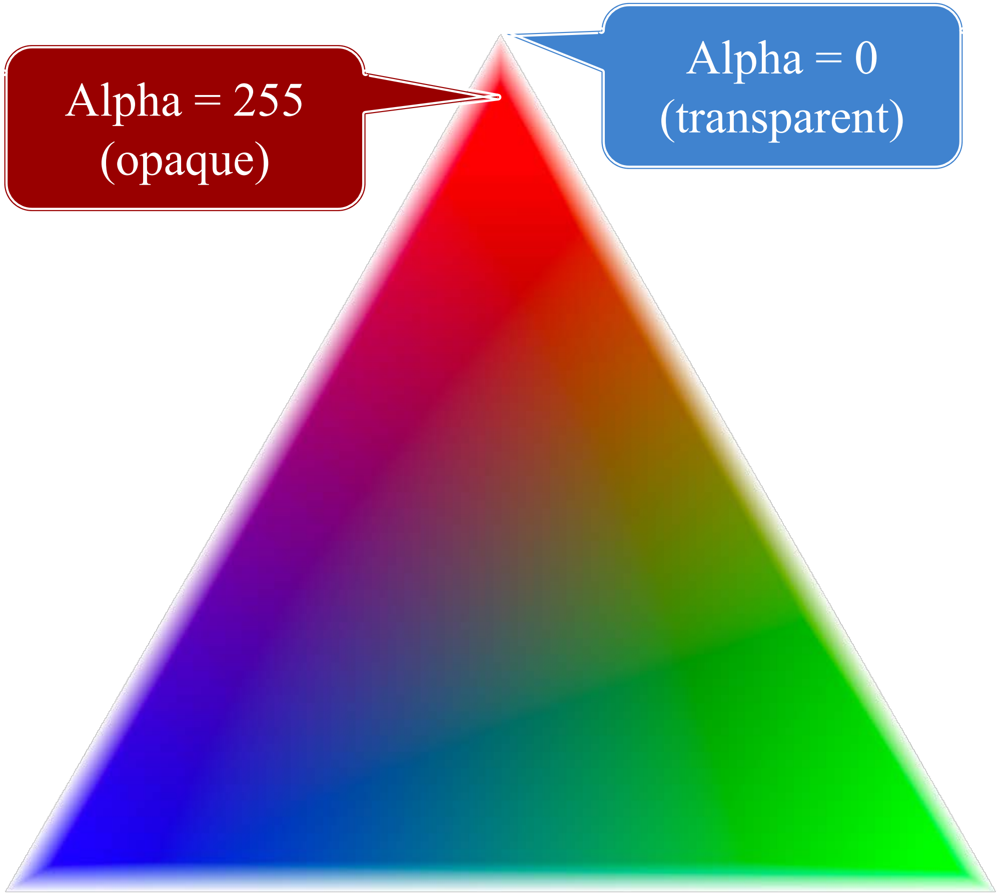
Extrude The Triangle Boundary



Extrude The Triangle Boundary



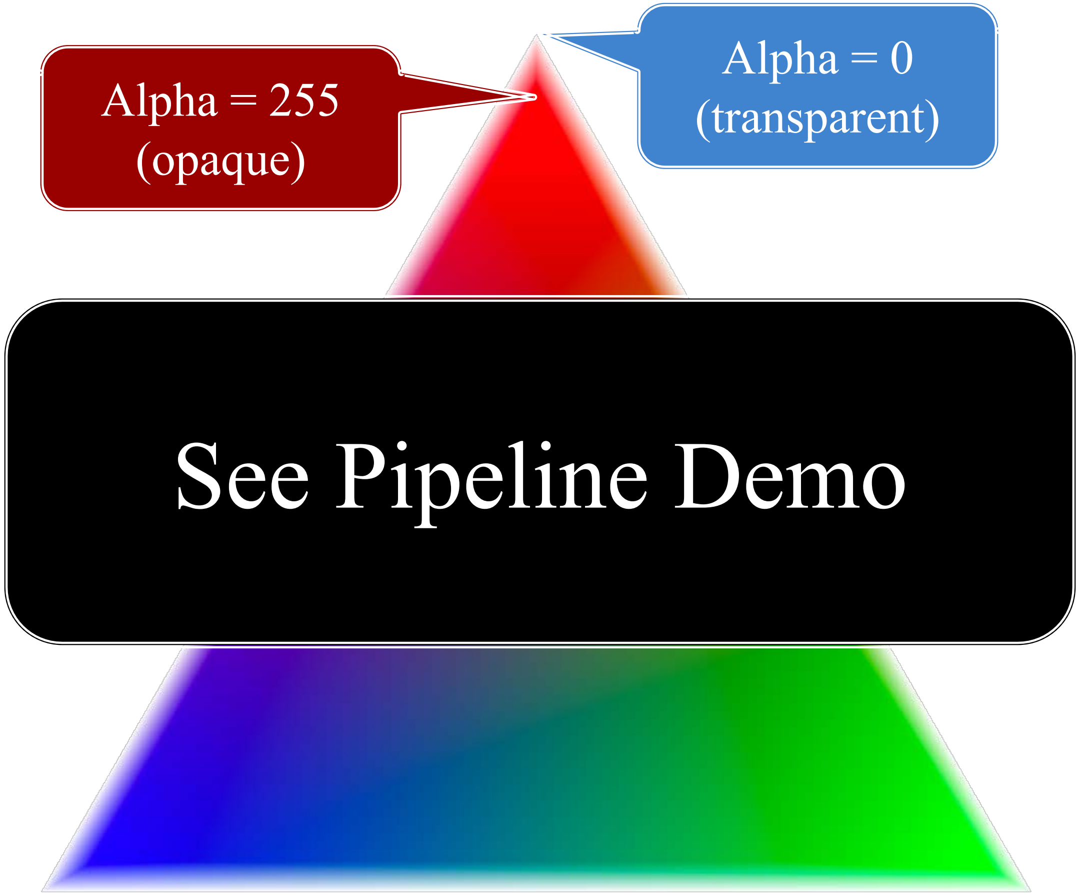
Use Alpha to Fade Out Extrusion



Alpha = 255
(opaque)

Alpha = 0
(transparent)

Use Alpha to Fade Out Extrusion



Alpha = 255 (opaque)

Alpha = 0 (transparent)

See Pipeline Demo