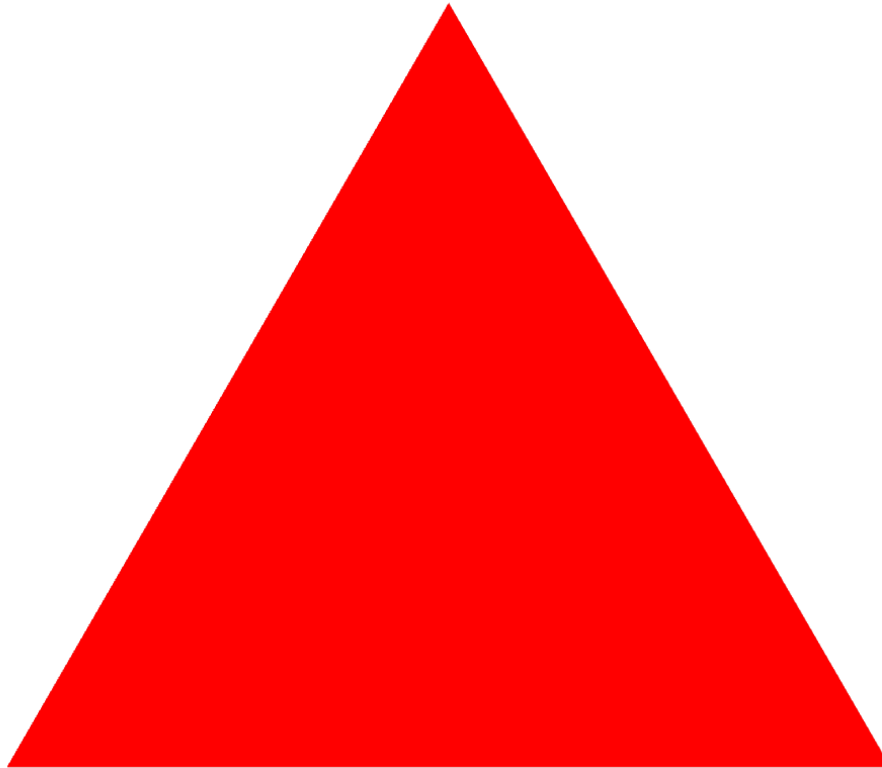
Lecture 12

The Graphics Pipeline (Overview)

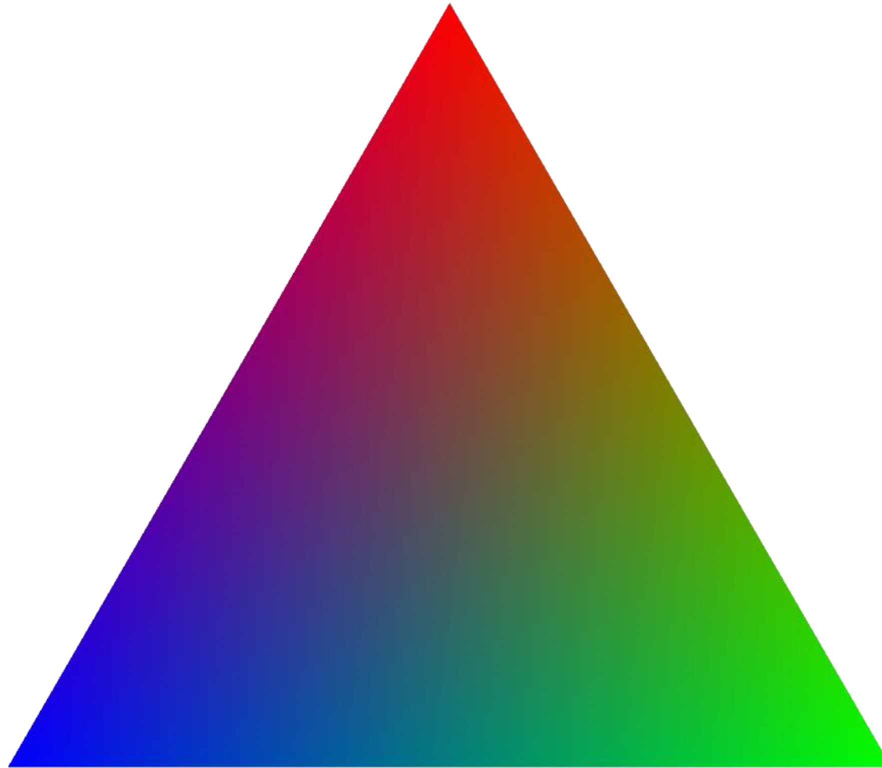
Caveat About Today's Lecture

- Today's focus is on **OpenGL**
  - **The** cross-platform graphics API for Indie games
  - **Vulkan** will eventually 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



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Triangles Can Be Textured

Triangles Can Be Both

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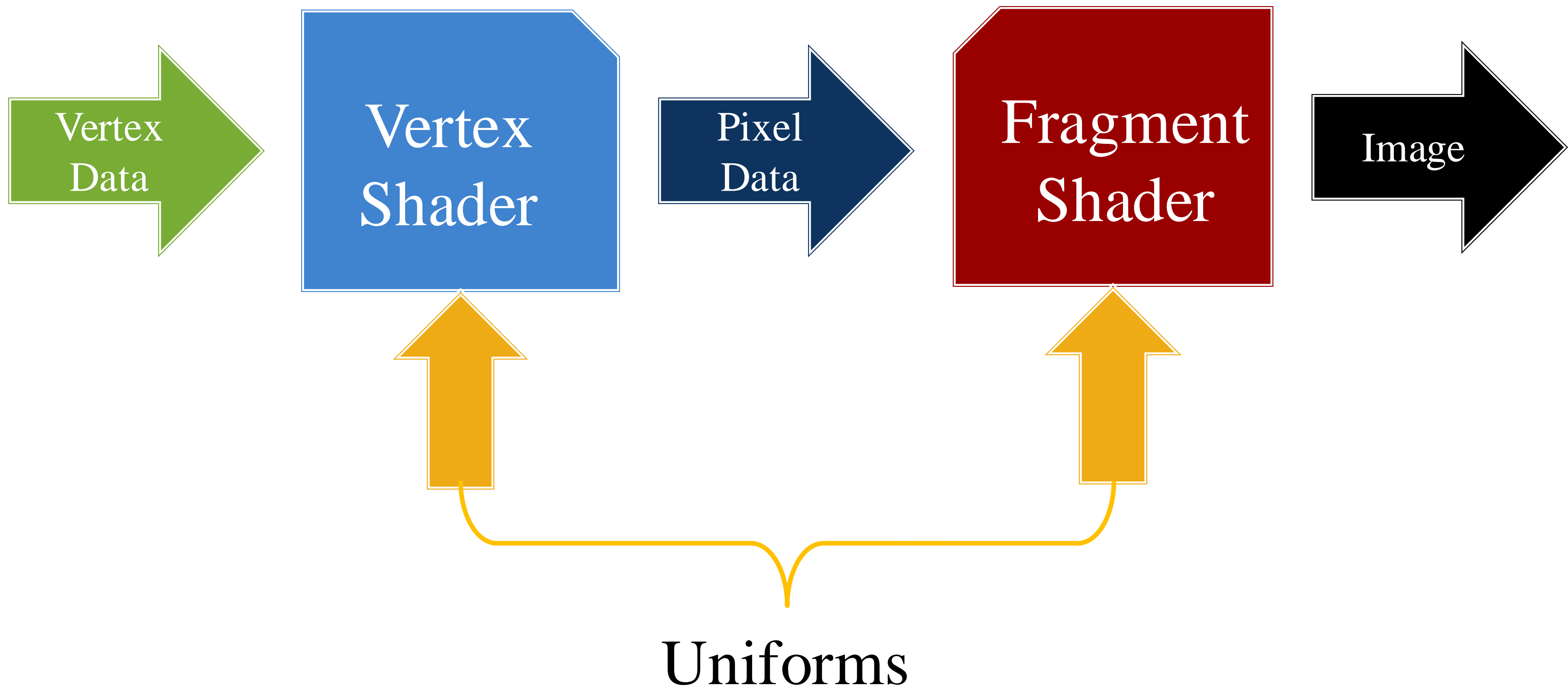
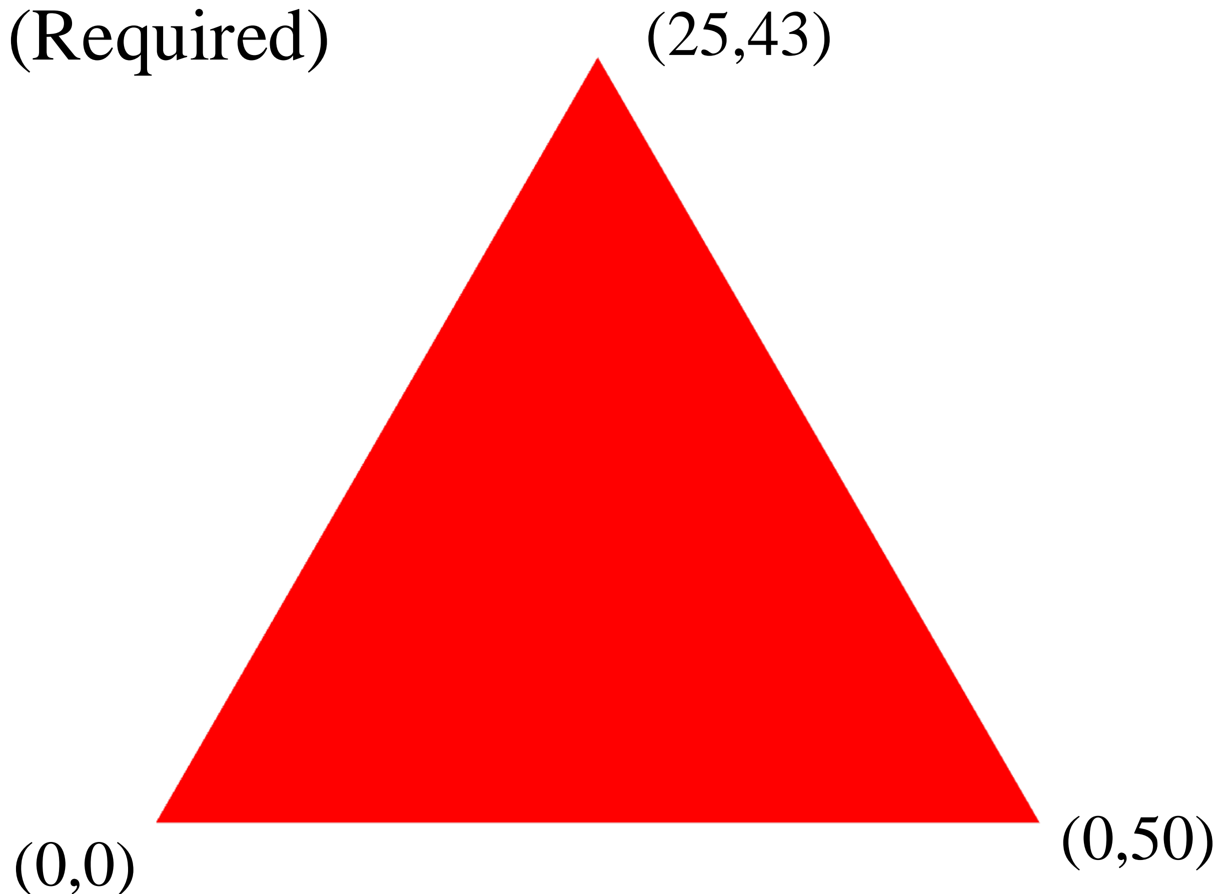
A Sprite is (Often) Two Triangles

Triangles are Drawn with Shaders



Vertex Data Defines the Triangle

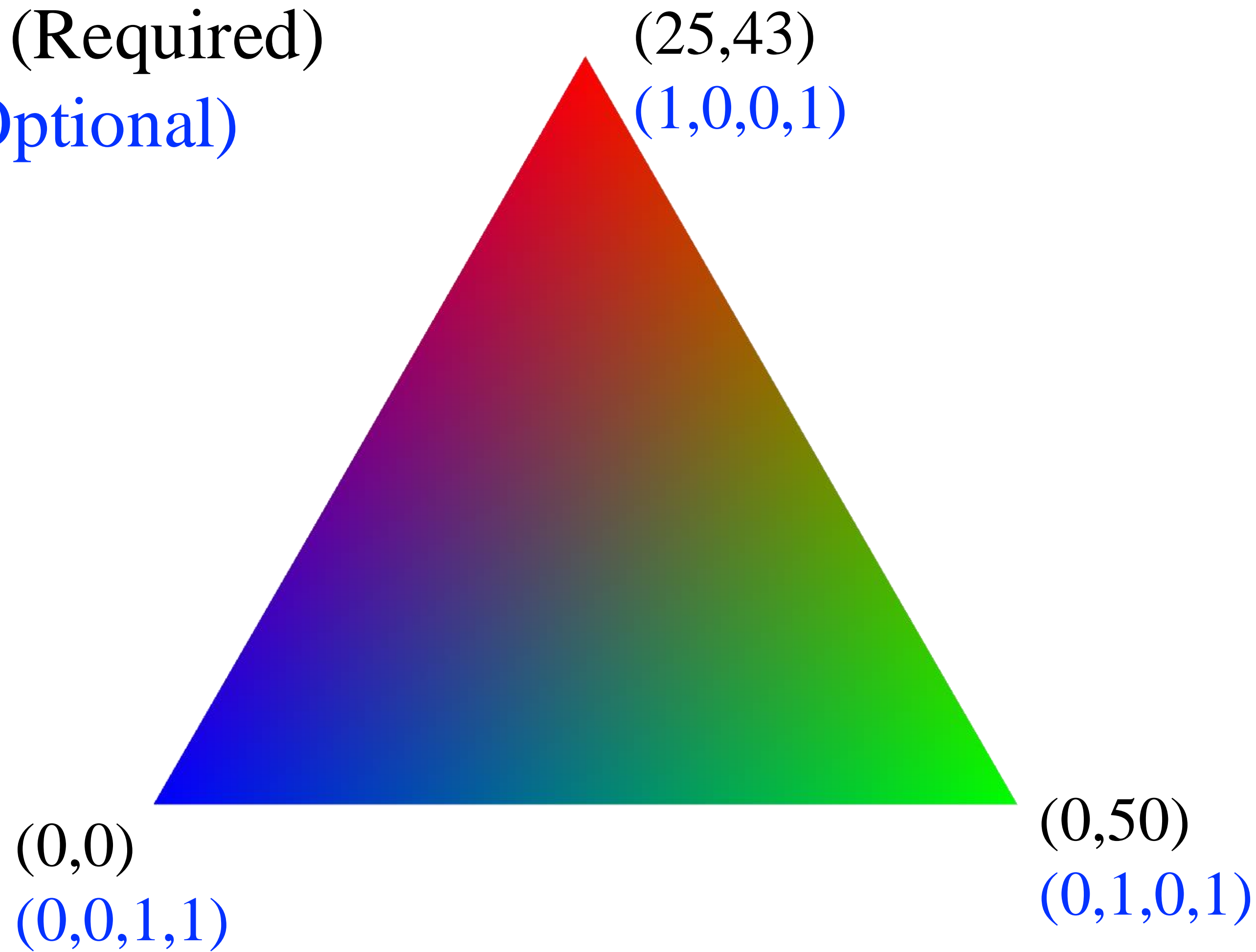
Position (Required)



Vertex Data Defines the Triangle

Position (Required)

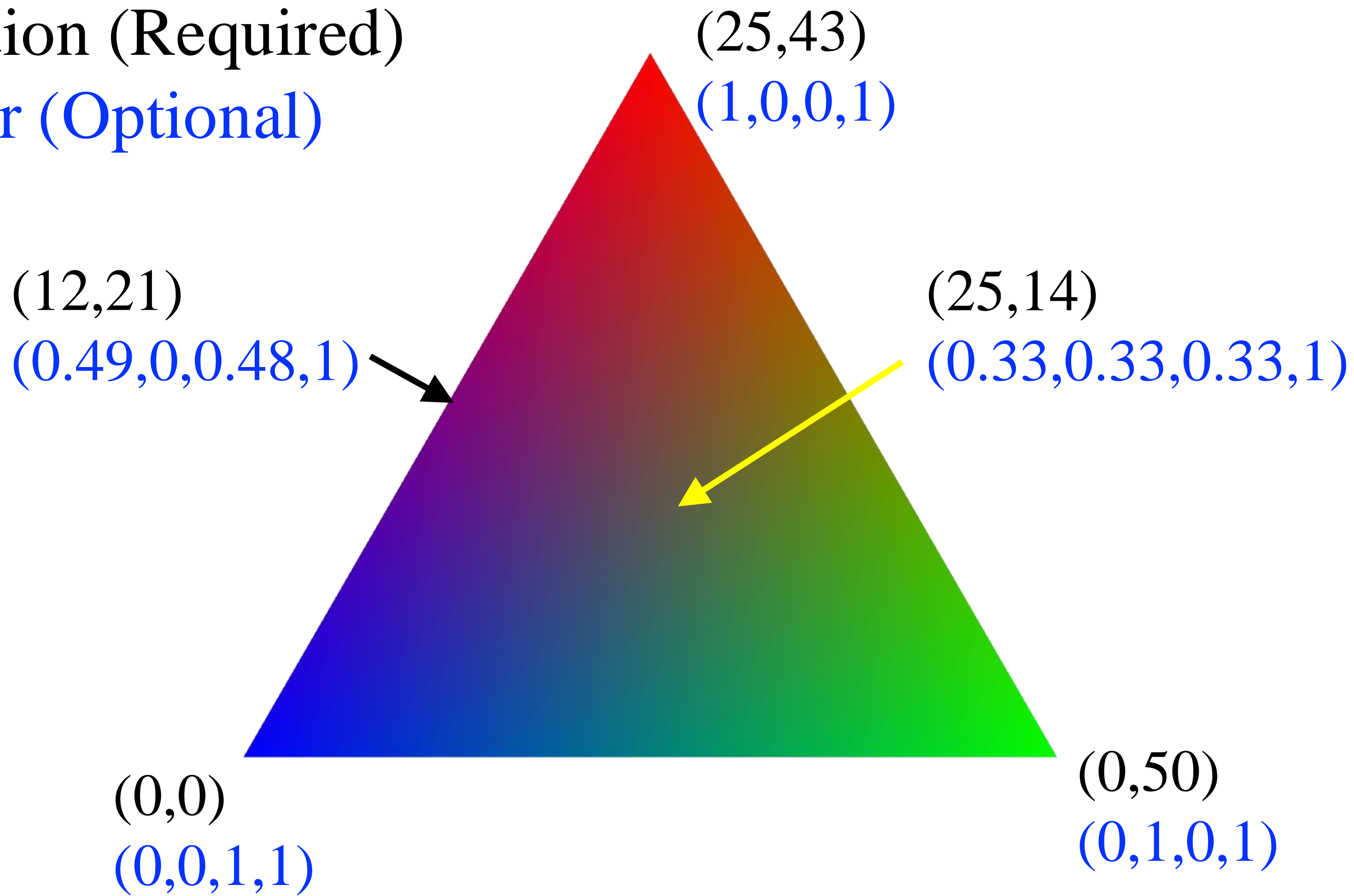
Color (Optional)



Vertex Shader **Interpolates** Pixels

Position (Required)

Color (Optional)



What Does The Fragment Shader Do?

- Vertex shader just produces interpolated values
  - Interpolated vector for position
  - Interpolated color for the pixel
- Fragment shader assigns the "official" color
  - May be the color interpolated by vertex shader
  - May be some variation of this color
- Often applies post-processing effects
  - **Example:** gaussian blur
  - Sometimes the more complicated of the two

A Very Simple Shader

Vertex Shader

```
// Positions
in vec4 aPosi
```

Input

```
// Colors
in  vec4 aCo
out vec4 outColor;

uniform mat4 uCamera;

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

Input

Fragment Shader

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

// Color resu
vertex shader
in vec4 outColor;

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

Input

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Input

Input

Output

Output

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```

Output

Input

Pass-through

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out vec4 out
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Output

Fragment Shader

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Output

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Input

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 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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Will the camera ever change?

Images Have Texture Coordinates

(0,0) (1,0)

(0,1) (1,1)

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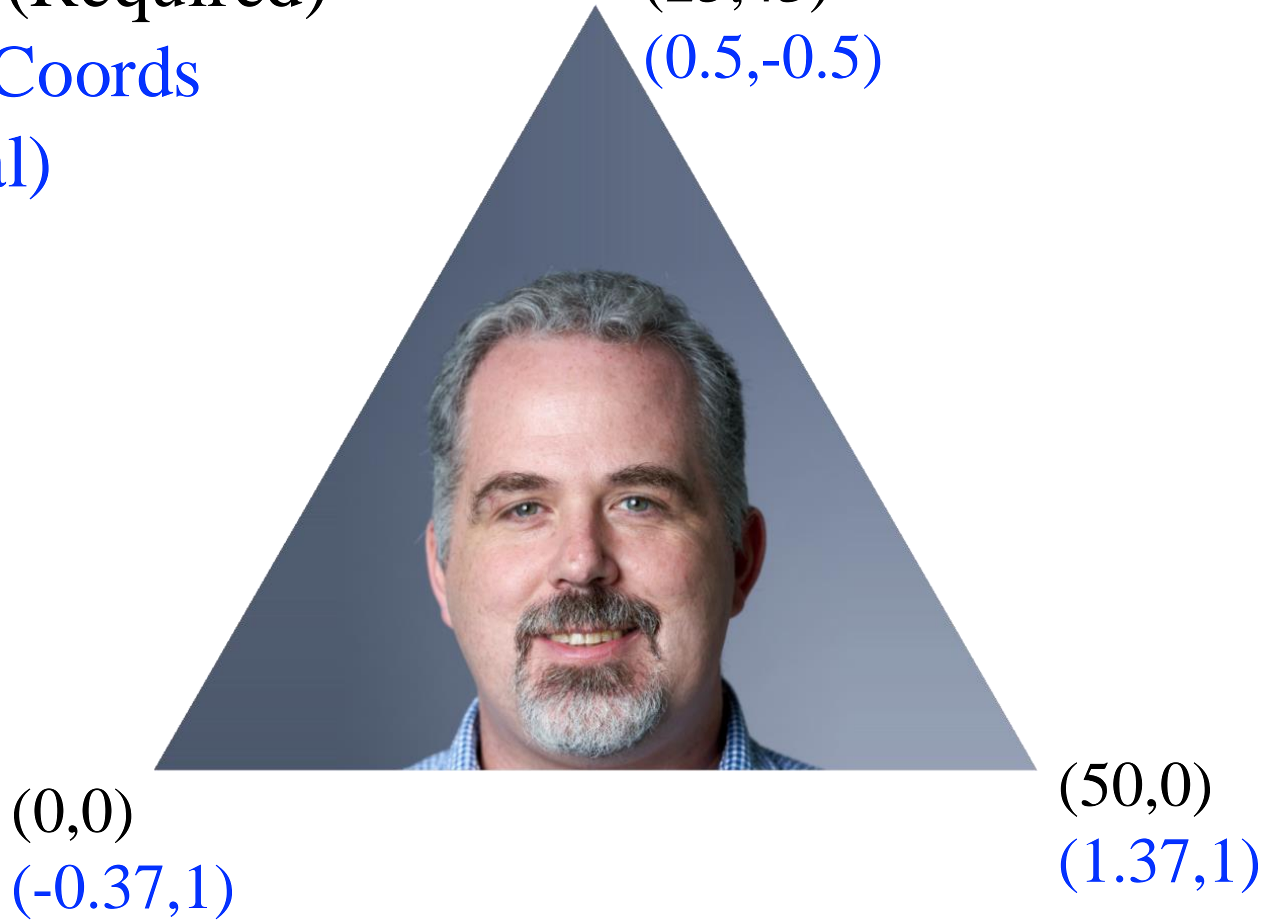
Vertex Data Can Include Texture Data

Position (Required)

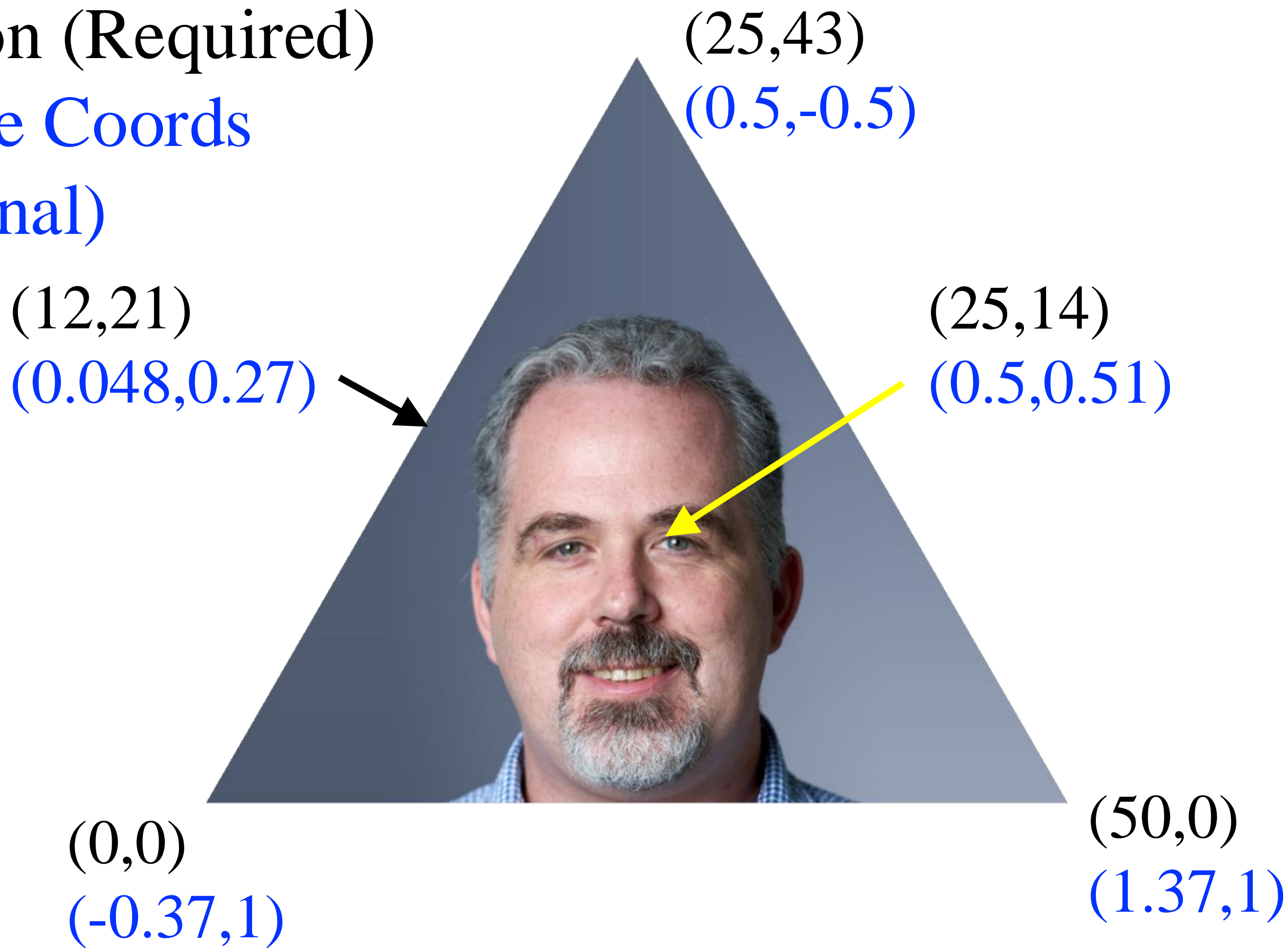
Texture Coords (Optional)



Vertex Shader **Interpolates** Pixels

Position (Required)

Texture Coords (Optional)



A Texture Shader

Vertex Shader

```
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// Texture Coords
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out vec4 outCoord;

uniform mat4 uCamera;

// Interpolate position and coords
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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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texture + coord = color

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Changing the texture *stalls* the stream

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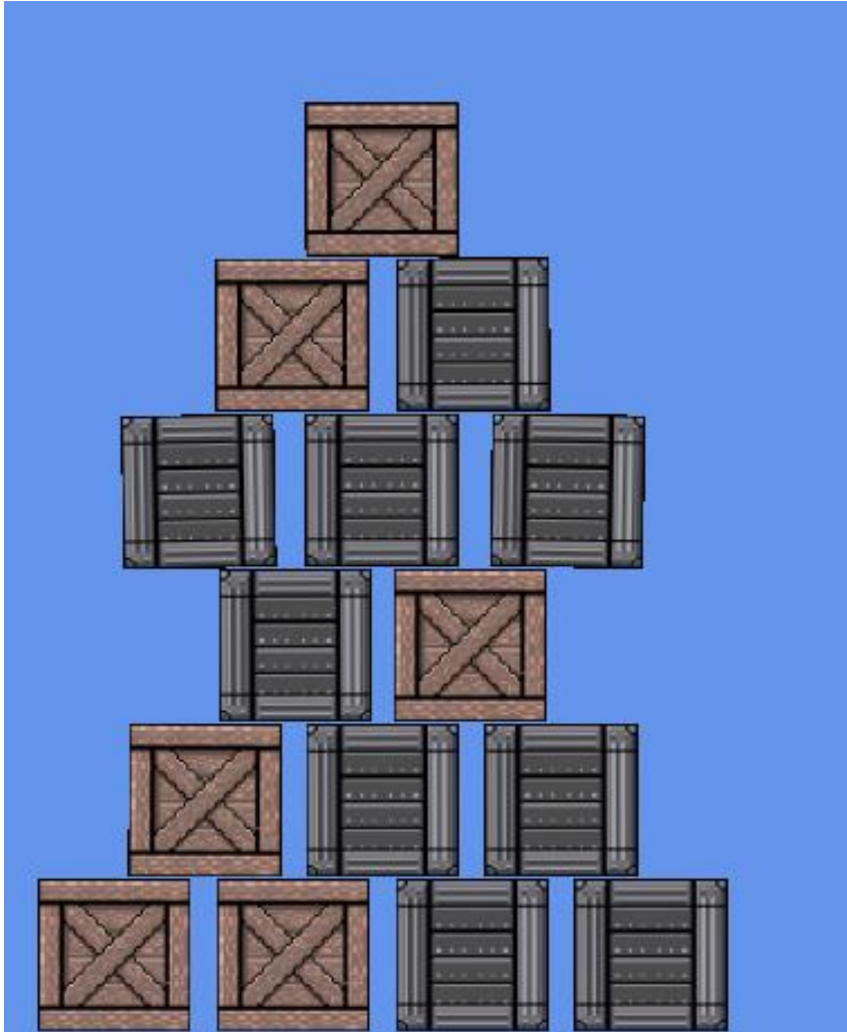
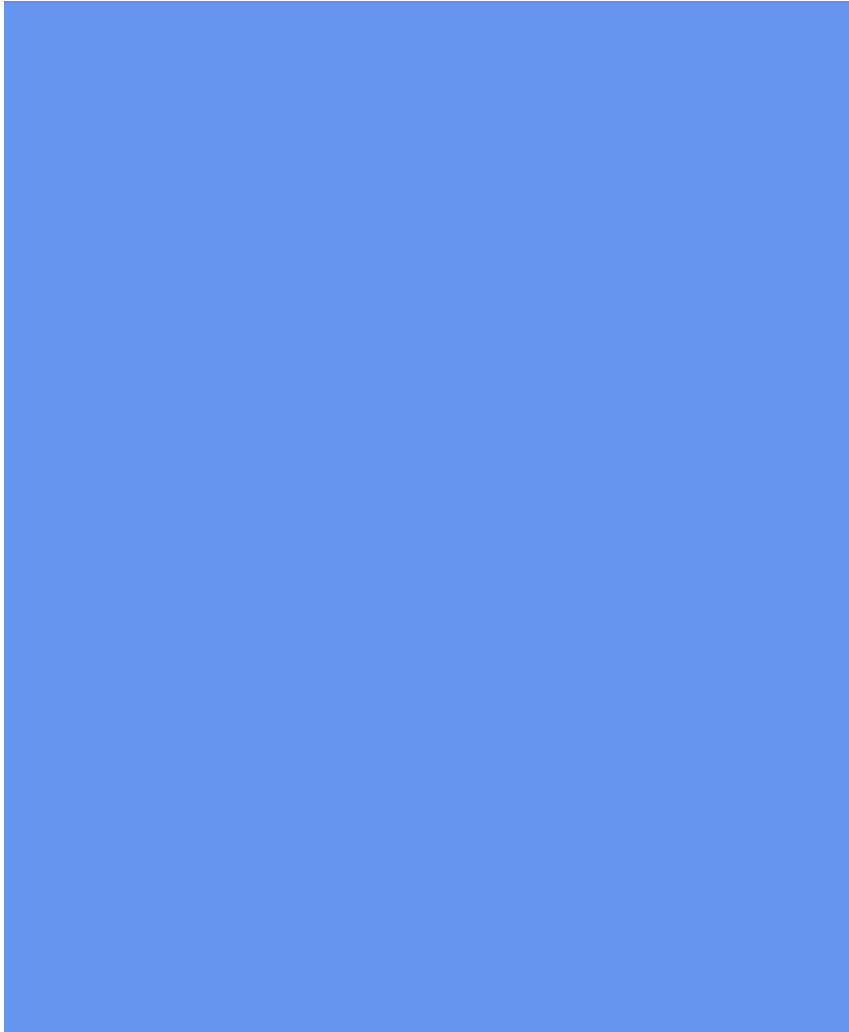
How Does a `SpriteBatch` Work?



- `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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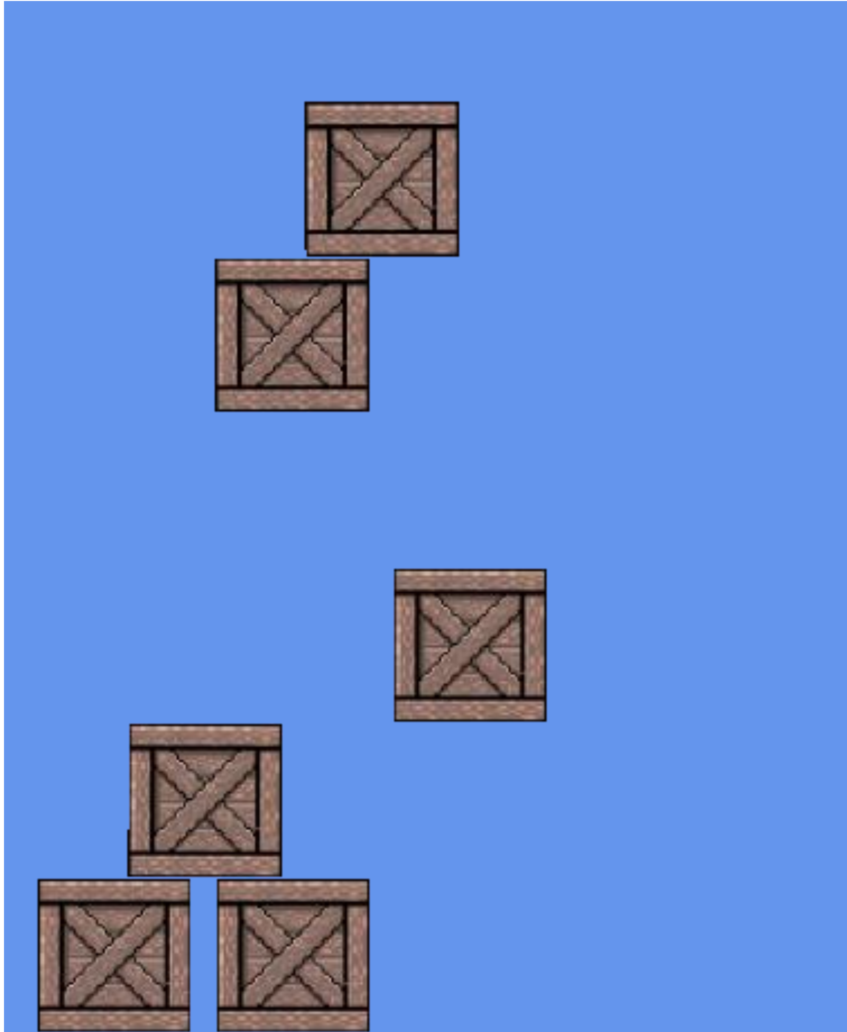

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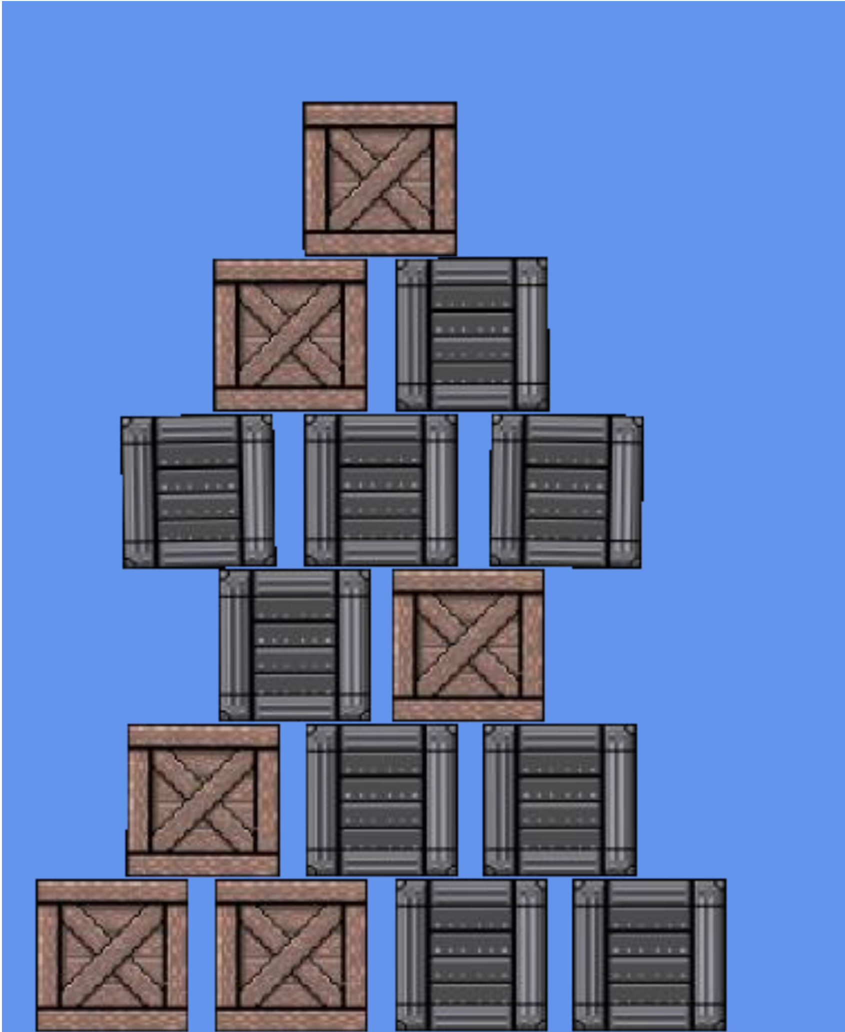

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Optimizing Performance: **Atlases**

- **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

Optimizing Performance: **Atlases**

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Better: Vulkan supports Texture **array** uniforms

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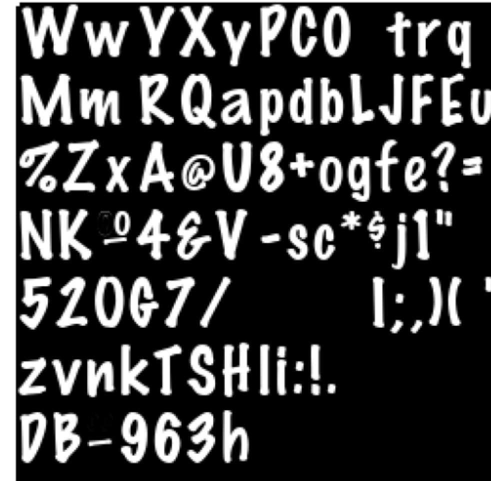
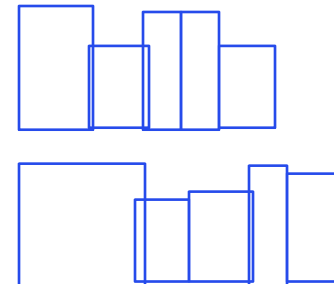
Aside: This is How Fonts Work

- 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)





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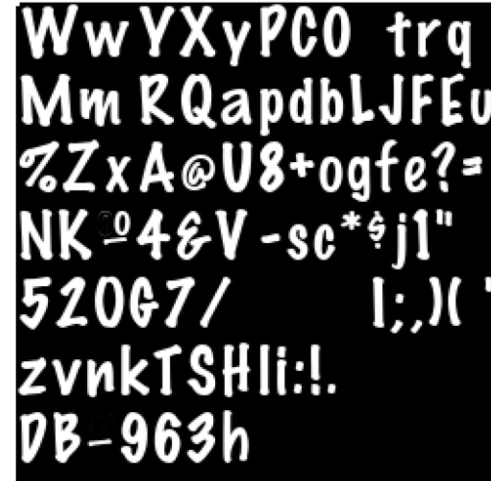

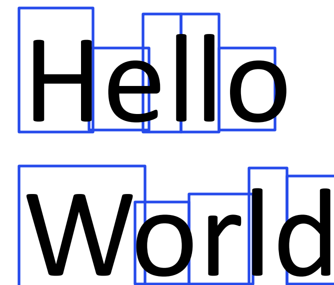

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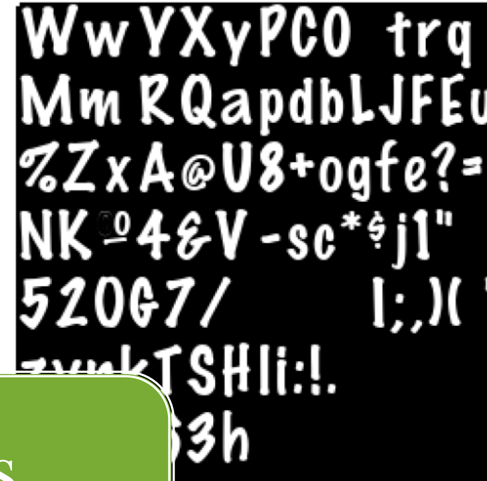
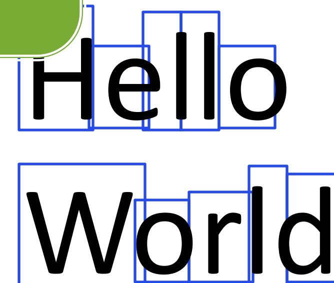


Which glyphs go in the atlas?



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**

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The `SpriteBatch` Shader

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in vec2 outPosition;
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    return clamp((m + feather*0.5) / feather, 0.0, 1.0);
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        result = mix(gdInner,gdOuter,d)*outColor;
    } else {
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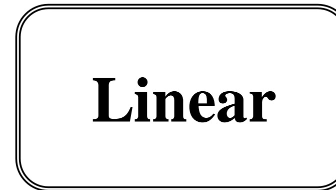
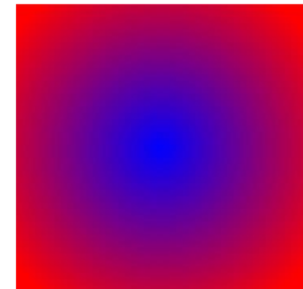
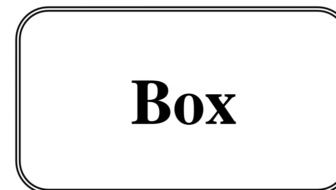
- Provides support for
  - Solid/vertex colors
  - Color gradients (linear, radial)
  - Textures/texture coords
  - Gaussian blur
  - Scissoring/masking
- Not “**user-serviceable**”
  - Do not try to replace this
  - Will break all the UI code
- More on that next time

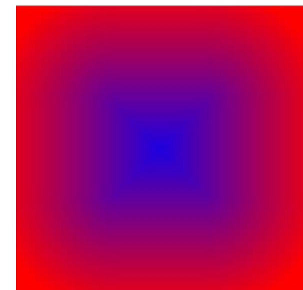
Gradients

- `Gradient` in `cugl::graphics`
    - Only supports two *stops*
    - More colors = more shapes
- Has its own coordinates
    - Defined on unique square
    - Coords define the "stretch"
    - Often same as texture cords
- Primarily nice in UI effects
    - Can be defined in JSON
    - But no Figma support



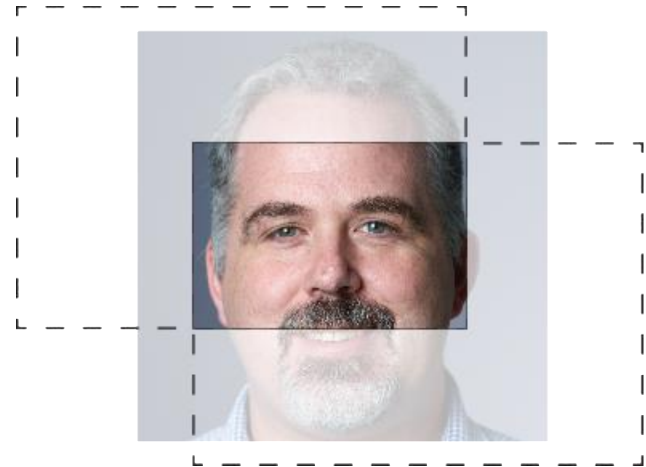






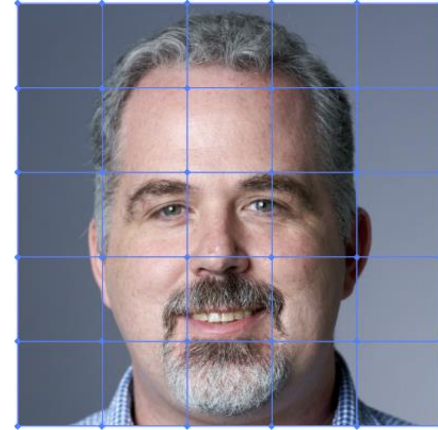
Scissors

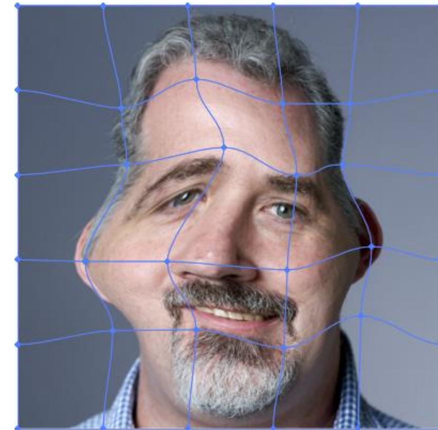
- Mask part of the screen
  - Defined as a rectangle
  - Drops pixels outside rect
- Scissors can be…
  - Rotated, Transformed
  - Intersected
  - But not really *both*
- Used by `ScrollPane`
  - Makes internal "window"
  - Can scroll the contents



What Goes to The Shader?

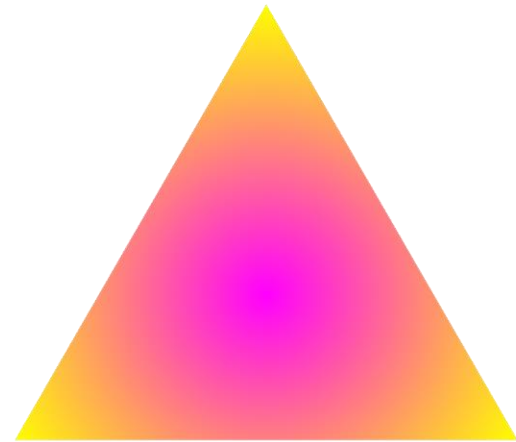
- Templated class `Mesh<T>`
  - Type is a **vertex** class
  - Mesh adds **geometry** info
- CUGL meshes are special
  - Usually an OpenGL buffer
  - But ours is independent!
  - Will carry over to Vulkan
- Vertex must match shader
  - Check each vertex shader `in`
  - Must have attribute for it





The Vertex Class

- 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**: `SpriteVertex`
  - Position (`Vec2`)
  - Color (`unsigned int`)
  - Texture coords (`Vec2`)
  - Gradient coords (`Vec2`)

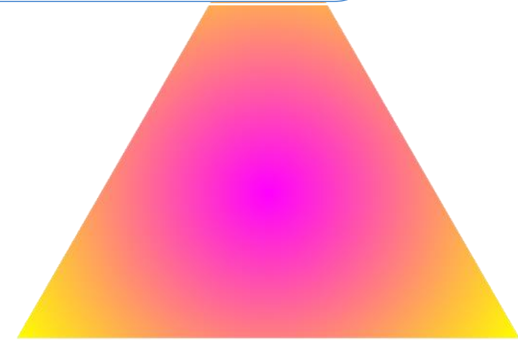


The Vertex Class

- Can be **any class** of your making
  - Should have **position** (`Vec2`, `Vec3`, or `Vec4`)
  - Can have anything else that you want
  - The

- **Exam**
  - Position (`Vec2`)
  - Color (`unsigned int`)
  - Texture coords (`Vec2`)
  - Gradient coords (`Vec2`)

See code demos for other examples



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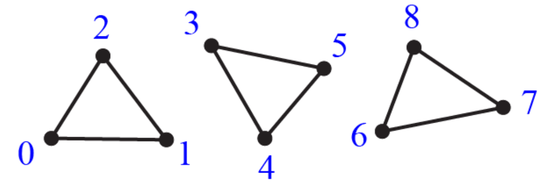
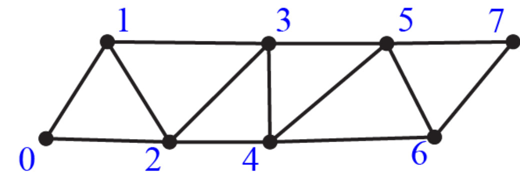
The Mesh Geometry

- 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 most of this for you!
  - Only supports triangle **lists**
  - Also only has positional data
  - But can *initialize* a Mesh

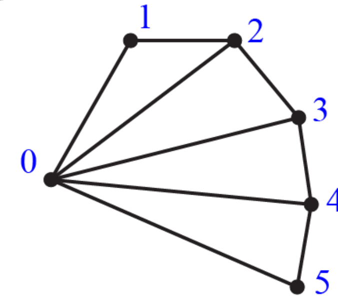
Triangle List



Triangle Strip

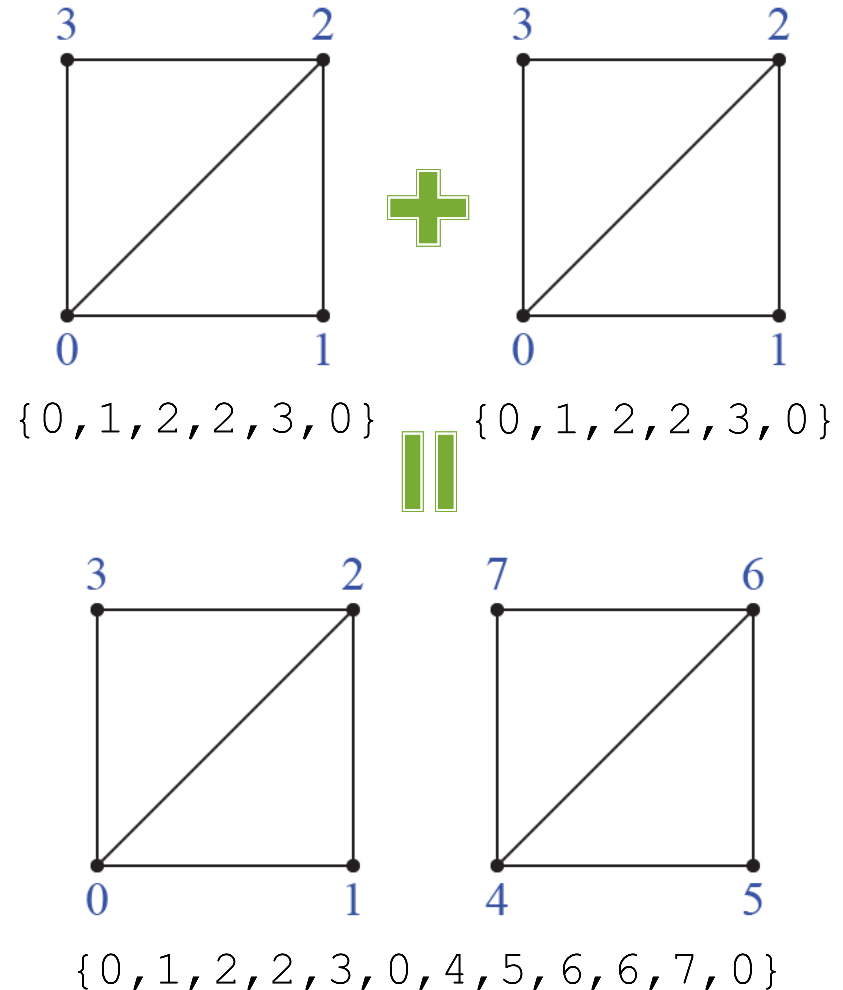


Triangle Fan



Why Triangle Lists?

- Lists are the least compact
  - Lists need 3n indices
  - Strip uses n+2 indices
  - Fan also uses n+2 indices
- But lists are **compositional**
  - Lists can be concatenated
  - Not true for fan/strips
- Needs fewer commands
  - How sprite batch works
  - Just one `Mesh<SpriteVertex>`



Standard Mesh Creation

- Use CUGL tools to **create a geometry**
  - Geometry defines position and triangles
  - End result is (typically) a Poly2 object
  - Just like the geometry lab
- Pass `Poly2` to the **`Mesh<T>` constructor**
  - Your vertex must have a position attribute
  - All other values are set to the default
- Manually **adjust other attributes**
  - Usually just texture and/or color
  - Choices depend on your shader

How Do We Talk to The Shader?

Next Time!

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Summary

- CUGL uses **OpenGLES 3** for rendering
  - Uses shaders to produces triangles on screen
  - `SpriteBatch` (usally) makes all of this easy
- All data sent to graphics card is a **mesh**
  - An array of vertices
  - A geometry on those vertices
  - Like `Poly2` but with more attributes
- **Shaders** render a mesh to the screen
  - Specify data at each vertex
  - Intermediate pixels are interpolated