Tutorial 04: Writing a Post-Processing Pass

> 💡 **Tip:** It's recommended using the 04_postprocessing.html version of this tutorial as copying code works best there regarding padding and formatting.

> ⚠ **Build issues?** See Troubleshooting Build Failures at the end of this tutorial for help reading build errors from the terminal.

Welcome to the post-processing tutorial! In this guide, you'll learn how to create a render pass that applies screen-space effects to rendered images. You'll implement the **vignette post-processing effect** — a simple but effective screen-edge darkening technique — and integrate it into the engine's rendering pipeline.

What you'll learn:

- Engine render pass architecture and lifecycle
- Multi-pass rendering (scene → post-process → composite)
- Shader registry and pipeline manager patterns
- Bind group caching for efficient resource reuse
- Fullscreen triangle rendering technique
- Integrating new passes into the renderer pipeline

Important Note: This tutorial implements **one hardcoded post-processing effect (vignette)** added to the engine. This is NOT a general-purpose configurable post-processing system. To add more effects (bloom, tone mapping, color grading), you would need to create additional shader and pass classes. A future tutorial could cover building a flexible post-processing framework.

What you'll build:

- Implement `PostProcessingPass` methods one by one
- Integrate into `Renderer::renderToTexture()` to apply vignette after debug rendering
- Add proper initialization and cleanup in `Renderer`

What's provided:

- `PostProcessingPass.h` - Complete header with all method signatures (already implemented)
- `PostProcessingPass.cpp` - Skeleton ready for your implementation
- `postprocess_vignette.wgsl` - Vignette shader (in `resources/`)
- Shader registration - Already set up in `ShaderRegistry.cpp`
- Renderer integration points - Already marked with tutorial comments

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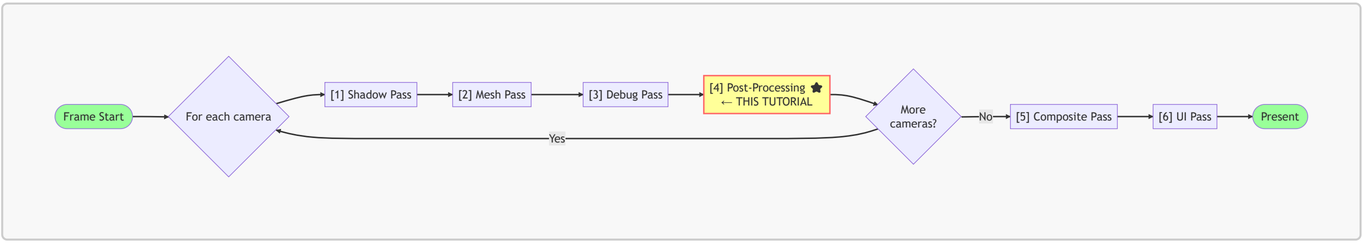
Understanding the Architecture

Steps 1-4 (Shadow, Mesh, Debug, PostProcessing) are **per-camera operations**. If multiple cameras are specified, each one will have:

- Its own shadow maps
- Its own scene render
- Its own debug overlays

- Its own post-processing

Frame Rendering Pipeline:



Then **Composite Pass** (step 5) combines all camera results together and renders to the final surface.

Why Post-Process After Debug Pass?

If we placed it before debug pass, wireframes and gizmos would not receive the vignette effect. By placing it after debug pass, all rendered content (scene + debug overlays) gets processed together.

Pattern Overview:

All render passes in this engine follow the same lifecycle:

```
// Step 1: Create pass
auto pass = std::make_unique<PostProcessingPass>(context);

// Step 2: Initialize (one-time setup)
pass->initialize();  // Get shader, create sampler, create pipeline

// Step 3: Per-frame render
pass->setInputTexture(inputTex);            // Configure input
pass->setRenderPassContext(context);        // Configure output
pass->render(frameCache);                   // Execute on GPU

// Step 4: Cleanup (on shutdown/resize)
pass->cleanup();
```

Step 1: PostProcessingPass::initialize()

This method performs one-time setup: loading the shader and creating the rendering pipeline.

Overview:

- Get the vignette shader from the shader registry
- Retrieve a sampler from the sampler factory
- Lazy pipeline creation (happens in render())

What to understand:

1. **Sampler Reuse** - We get a pre-made sampler (`getClampLinearSampler()`) instead of creating one. This is more efficient and reuses GPU resources.
2. **Shader Registry Pattern** - Instead of loading shaders directly, we use `shaderRegistry().getShader()`. This allows:
   - Centralized shader management
   - Hot-reloading support (shaders can be updated without recompiling)
   - Bind group layout information already parsed from shader
3. **Lazy Pipeline Creation** - The pipeline is created in `render()`, not `initialize()`. This allows:
   - Different output formats for different render targets
   - Pipeline recreation if shader reloads
   - Pattern used by `MeshPass` and `CompositePass`

Your Task:

Open `src/engine/rendering/PostProcessingPass.cpp` and implement the `initialize()` method:

```
bool PostProcessingPass::initialize()
{
    spdlog::info("Initializing PostProcessingPass");

    // Tutorial 4 - Step 1: Get vignette shader from registry
    // The shader contains:
    // - Vertex shader (vs_main): Generates fullscreen triangle
    // - Fragment shader (fs_main): Applies vignette darkening
    // - Bind Group 0: Sampler + input texture
    m_shaderInfo = m_context-
>shaderRegistry().getShader(shader::defaults::VIGNETTE);
    if (!m_shaderInfo || !m_shaderInfo->isValid())
    {
        spdlog::error("Vignette shader not found in registry");
        return false;
    }

    // Get a sampler for texture filtering (linear interpolation, clamp-to-edge)
    // This is a pre-made sampler shared across the engine
    m_sampler = m_context->samplerFactory().getClampLinearSampler();

    spdlog::info("PostProcessingPass initialized successfully");
    return true;
}
```

Key Points:

- `shader::defaults::VIGNETTE` is a constant defined in `ShaderRegistry.h` with value `"Vignette_Shader"`
- `m_shaderInfo` contains the shader module AND the bind group layout (parsed from `@group(0)` in WGSL)

- `m_sampler` is used in `getOrCreateBindGroup()` later
- The actual pipeline is created in `render()` method (lazy initialization)

Step 2: PostProcessingPass::setInputTexture()

This method stores which texture to read post-processing input from.

Your Task:

```
void PostProcessingPass::setInputTexture(const
std::shared_ptr<webgpu::WebGPUTexture> &texture)
{
    // Tutorial 4 - Step 2: Store the texture to post-process
    // This is the output of MeshPass/DebugPass (the rendered scene)
    // Called before render() to specify what we're processing
    m_inputTexture = texture;
}
```

Why This Matters:

- Each render target (camera) has its own texture
- Before rendering, we need to tell the pass which texture to sample from
- The texture contains the scene after mesh and debug passes

Step 3: PostProcessingPass::setRenderPassContext()

This method stores where post-processing output should be written.

Your Task:

```
void PostProcessingPass::setRenderPassContext(const
std::shared_ptr<webgpu::WebGPURenderPassContext> &renderPassContext)
{
    // Tutorial 4 - Step 3: Store where to render output
    // The render pass context defines:
    // - Color attachment (where to draw)
    // - Clear flags (do we clear before rendering?)
    // - Load/store operations
    m_renderPassContext = renderPassContext;
}
```

How This Works:

The render pass context is created in `Renderer::renderToTexture()` with a descriptor specifying:

- Output texture
- Whether to clear

- Load/store operations

Step 4: PostProcessingPass::render() - Part A (Validation & Setup)

This is the main method called each frame. We'll implement it in two parts.

Part A: Validate inputs and create pipeline

```
void PostProcessingPass::render(FrameCache &frameCache)
{
    // Tutorial 4 - Step 4A: Validate inputs
    if (!m_inputTexture || !m_renderPassContext)
    {
        spdlog::warn("PostProcessingPass: Missing input texture or render pass 
context");
        return;
    }
    // Tutorial 4 - Step 4B: Get or create pipeline
    // The pipeline is created lazily (on first use) because:
    // 1. Output format depends on render pass context (determined at runtime)
    // 2. Shader might be hot-reloaded, needing a new pipeline
    auto pipeline = m_pipeline.lock();  // Try to get weak_ptr
    if (!pipeline)
    {
        // Create new pipeline with, Shader info (loaded in initialize()) and 
Output format from render pass (the texture we're writing to)
        m_pipeline = m_context->pipelineManager().getOrCreatePipeline(
            m_shaderInfo, // Shader info contains shader modules and bind groups
            m_renderPassContext->getColorTexture(0)->getFormat(), // Output format
            wgpu::TextureFormat::Undefined, // No depth needed for post-processing
            Topology::Triangles, // Triangle list topology (for fullscreen 
triangle)
            wgpu::CullMode::None, // No culling (both sides of triangle must be 
visible)
            1 // Sample count
        );
        pipeline = m_pipeline.lock();

        if (!pipeline || !pipeline->isValid())
        {
            spdlog::error("PostProcessingPass: Failed to create pipeline");
            return;
        }
    }
```

Key Concepts:

1. **Lazy Pipeline Creation** - The pipeline is created on first use, not in initialize()
2. **Weak Pointer** - We use `std::weak_ptr<WebGPUPipeline>` to avoid circular references
3. **Pipeline Manager** - Handles pipeline caching and hot-reload

4. **Output Format** - We match the output texture's format (from render pass context)

Step 5: PostProcessingPass::render() - Part B (Bind Groups & Drawing)

Part B: Create bind group and draw

```
    // Tutorial 4 - Step 4C: Get or create bind group for input texture
    // Bind groups are cached by texture pointer to avoid recreation each frame
    auto bindGroup = getOrCreateBindGroup(m_inputTexture);
    if (!bindGroup)
    {
        spdlog::warn("PostProcessingPass: Failed to create bind group");
        return;
    }

    // Tutorial 4 - Step 4D: Record and submit draw commands
    // Create command encoder (WebGPU's command recording object)
    wgpu::CommandEncoder encoder = m_context-
>createCommandEncoder("PostProcessingPass Encoder");

    // Begin render pass (starts recording commands into this pass)
    wgpu::RenderPassDescriptor renderPassDescriptor = m_renderPassContext-
>getRenderPassDescriptor();
    wgpu::RenderPassEncoder renderPass =
encoder.beginRenderPass(renderPassDescriptor);

    // Set the pipeline (tells GPU which shader to use)
    renderPass.setPipeline(pipeline->getPipeline());

    // Bind the group 0 (texture + sampler for shader to use)
    renderPass.setBindGroup(0, bindGroup->getBindGroup(), 0, nullptr);

    // Draw 3 vertices (fullscreen triangle)
    // Vertices are generated in shader's vs_main using vertex_index
    renderPass.draw(3, 1, 0, 0);

    // End render pass
    renderPass.end();
    renderPass.release();

    // Submit commands to GPU
    wgpu::CommandBufferDescriptor commandBufferDescriptor{};
    commandBufferDescriptor.label = "PostProcessingPass Commands";
    wgpu::CommandBuffer commandBuffer = encoder.finish(commandBufferDescriptor);
    encoder.release();
    m_context->getQueue().submit(commandBuffer);
    commandBuffer.release();
}
```

What Each WebGPU Component Does:

- **Command Encoder** - Records GPU commands into a buffer for later execution
- **Render Pass Descriptor** - Defines color/depth attachments, clear colors, and load/store operations
- **Render Pass Encoder** - Records rendering-specific commands (pipeline, bind groups, draw calls)
- **Pipeline** - Contains shader program, vertex layout, blend mode, and other render state
- **Bind Group** - Groups GPU resources (textures, samplers, buffers) accessible to shader
- **Draw Call** `renderPass.draw(3, 1, 0, 0)` - Process 3 vertices in 1 instance to generate fullscreen triangle

> 📝 **Note:** The engine provides abstractions to simplify this. Here we show the **full WebGPU API** for deeper understanding. Production code typically uses engine abstractions.

Step 6: PostProcessingPass::getOrCreateBindGroup() - Part A (Cache & Layout)

This method creates or reuses bind groups that bind the texture + sampler to shader bindings.

Part A: Check cache and get layout

```
std::shared_ptr<webgpu::WebGPUBindGroup> PostProcessingPass::getOrCreateBindGroup(
    const std::shared_ptr<webgpu::WebGPUTexture> &texture,
    int layerIndex
)
{
    // Tutorial 4 - Step 6A: Validate input
    if (!texture)
        return nullptr;

    // Tutorial 4 - Step 6B: Create cache key
    // We cache bind groups by texture pointer + layer index
    // This avoids recreating the same bind group multiple times per frame
    auto cacheKey = std::make_pair(reinterpret_cast<uint64_t>(texture.get()),
layerIndex);

    // Tutorial 4 - Step 6C: Check if bind group already cached
    auto it = m_bindGroupCache.find(cacheKey);
    if (it != m_bindGroupCache.end())
        return it->second;  // Reuse cached bind group

    // Tutorial 4 - Step 6D: Get bind group layout from shader
    // The shader info was loaded in initialize()
    // The layout describes what resources Group 0 expects:
    // - Binding 0: sampler (for texture filtering)
    // - Binding 1: texture (the input scene)
    auto bindGroupLayout = m_shaderInfo->getBindGroupLayout(0);
    if (!bindGroupLayout)
        return nullptr;
```

Why Caching?

Without caching, we'd create a new bind group every frame for the same texture, wasting GPU memory and CPU time. By caching, we only create it once per unique texture.

Step 7: PostProcessingPass::getOrCreateBindGroup() - Part B (Create & Cache)

Part B: Create new bind group

```
    // Tutorial 4 - Step 7E: Create bind group entries matching shader layout
    // The shader defines:
    // @group(0) @binding(0) var inputSampler: sampler;
    // @group(0) @binding(1) var inputTexture: texture_2d<f32>;

    // We create entries in the same order:
    std::vector<wgpu::BindGroupEntry> entries = {
        WGPUBindGroupEntry{nullptr, 0, nullptr, 0, 0, m_sampler, nullptr},
        // binding=0, sampler resource

        WGPUBindGroupEntry{nullptr, 1, nullptr, 0, 0, nullptr, texture-
>getTextureView(layerIndex)},
        // binding=1, texture resource
    };

    // Tutorial 4 - Step 7F: Create WebGPU bind group descriptor
    wgpu::BindGroupDescriptor desc = {};
    desc.layout = bindGroupLayout->getLayout();
    desc.entryCount = static_cast<uint32_t>(entries.size());
    desc.entries = entries.data();

    // Tutorial 4 - Step 7G: Create raw WebGPU bind group
    auto bindGroupRaw = m_context->getDevice().createBindGroup(desc);

    // Tutorial 4 - Step 7H: Wrap in engine's bind group object
    // WebGPUBindGroup is a wrapper that tracks resources and provides utilities
    auto bindGroup = std::make_shared<webgpu::WebGPUBindGroup>(
        bindGroupRaw,
        bindGroupLayout,
        std::vector<std::shared_ptr<webgpu::WebGPUBuffer>>{}  // No buffers in
this bind group
    );

    // Tutorial 4 - Step 7I: Cache for future use
    m_bindGroupCache[cacheKey] = bindGroup;
    return bindGroup;
}
```

Binding Details:

The WGPUBindGroupEntry structure is initialized as:

```
WGPUBindGroupEntry{
    nullptr,            // nextInChain (for extensions)
    binding_index,      // which @binding(N) this is for
    nullptr,            // buffer (null since this is for sampler/texture)
    0,                  // offset (unused for sampler/texture)
    0,                  // size (unused for sampler/texture)
    sampler_or_null,    // sampler resource (if this binding is a sampler)
    textureview_or_null// texture resource (if this binding is a texture)
}
```

Step 8: PostProcessingPass::cleanup()

This method releases cached resources.

Your Task:

```
void PostProcessingPass::cleanup()
{
    // Tutorial 4 - Step 6: Release bind group cache
    // Called on shutdown or window resize
    // The pipeline and sampler are managed by pipeline manager and sampler
factory
    // We only need to clear bind group cache
    m_bindGroupCache.clear();
}
```

Why Only Clear Cache?

- `m_shaderInfo` - Managed by shader registry
- `m_sampler` - Managed by sampler factory (shared resource)
- `m_pipeline` - Managed by pipeline manager (weak_ptr, auto-cleans)
- `m_inputTexture` - Managed by caller (Renderer)
- `m_renderPassContext` - Managed by caller (Renderer)
- `m_bindGroupCache` - **We** own this, so we must clean it

Step 9: Renderer::initialize() - Add PostProcessingPass Setup

Now integrate the pass into the renderer.

Your Task:

Open `src/engine/rendering/Renderer.cpp` and find the initialize() method. Look for the comment: `// Tutorial 4 - Step 9`

Add this code:

```
    // Tutorial 4 - Step 9: Initialize PostProcessingPass
    m_postProcessingPass = std::make_unique<PostProcessingPass>(m_context);
    if (!m_postProcessingPass->initialize())
    {
        spdlog::error("Failed to initialize PostProcessingPass");
        return false;
    }
```

What's Happening:

During initialization, we create the PostProcessingPass object and call its `initialize()` method. This one-time setup:

- Loads the vignette shader from the shader registry
- Gets a pre-made sampler for texture filtering
- Prepares the pass for rendering (actual rendering happens in the render phase, not initialization)

Step 10: Prepare Post-Processing Texture

Before we can render to a post-process texture, we need to create it.

Location: In `Renderer::renderToTexture()`, find the comment: `// Tutorial 4 - Step 10:`

Your Task:

After the depth buffer setup (and before the Culling step), add this code to create the post-processing texture:

```
    // Tutorial 4 - Step 10: Prepare post-processing texture
    // Post-processing texture is an intermediate render target for effects like
bloom, tone mapping, etc.
    // Use negative ID to differentiate post-process textures from main render
targets
    if (!m_postProcessTextures[renderTargetId])
    {
        m_postProcessTextures[renderTargetId] = m_context-
>textureFactory().createRenderTarget(
            -renderTargetId - 1,
            renderFromTexture->getWidth(),
            renderFromTexture->getHeight(),
            renderFromTexture->getFormat() // match format of main render target
        );
    }
```

What This Does:

- Creates an intermediate texture with the same dimensions and format as the main render target
- Uses negative ID (`-renderTargetId - 1`) to distinguish post-process textures from main render targets
- Only creates the texture once; reuses it for subsequent frames

---

Step 11: Renderer::renderToTexture() - Call PostProcessingPass

This is where post-processing actually executes each frame.

Location: Find this comment in `renderToTexture()`: `// Tutorial 4 - Step 11:`

Your Task:

Add this code after the Debug Pass section:

```
    // Tutorial 4 - Step 11: Apply vignette effect
    // Texture swapping: MeshPass/DebugPass output → input for post-processing
    // Output: Post-processed image (stored in m_postProcessTextures for
CompositePass)
    renderFromTexture = renderToTexture; // Post-processing reads from the main
render target
    renderToTexture = m_postProcessTextures[renderTargetId];
    auto postProcessingContext = m_context->renderPassFactory().create(
        renderToTexture,  // Color attachment (post-process output)
        nullptr,          // No depth attachment (use existing depth)
        ClearFlags::None, // Don't clear anything
        renderTarget.backgroundColor
    );

    m_postProcessingPass->setCameraId(renderTargetId);
    m_postProcessingPass->setInputTexture(renderFromTexture);
    m_postProcessingPass->setRenderPassContext(postProcessingContext);
    m_postProcessingPass->render(m_frameCache);
```

How It Works:

1. **Texture Swapping:**
   - `renderFromTexture = renderToTexture` - Save the current render target (scene + debug)
   - `renderToTexture = m_postProcessTextures[renderTargetId]` - Switch output to an intermediate post-process texture
2. **Rendering:**
   - Create a render pass that outputs to the post-process texture
   - `setInputTexture(renderFromTexture)` - Tell post-processing to READ from the scene texture
   - `setRenderPassContext(postProcessingContext)` - Tell post-processing to WRITE to the intermediate texture
   - `render()` - Execute the vignette shader
3. **Result:**
   - Input: Scene + debug overlays (from MeshPass + DebugPass)
   - Processing: Vignette shader darkens the edges
   - Output: Post-processed image in `m_postProcessTextures[renderTargetId]`

    - Next step: CompositePass will use this post-processed texture

Why Separate Textures?

Using intermediate textures allows:

- Read and write to different textures (required by WebGPU)
- Chain multiple post-processing effects
- Keep original scene data for debugging
- Proper texture synchronization between passes

Step 12: Renderer::onResize() - Handle Post-Processing Texture Resize

When the window is resized, all textures need to be updated to match the new dimensions.

Location: In `Renderer::onResize()`, this code should already exist:

```
void Renderer::onResize(uint32_t width, uint32_t height)
{
    for (auto &[id, target] : m_renderTargets)
    {
        // ... existing resize code ...

        // Resize post-processing texture
        auto postProcessingTexture = m_postProcessTextures[id];
        if (postProcessingTexture)
            postProcessingTexture->resize(*m_context, viewPortWidth,
viewPortHeight);
    }

    // ... cleanup passes ...

    if (m_postProcessingPass)
        m_postProcessingPass->cleanup();  // Tutorial 4 - Step 12: Clear bind
group cache and reset

    spdlog::info("Renderer resized to {}x{}", width, height);
}
```

What This Does:

- Resizes the post-processing texture to match the new window dimensions
- Calls `cleanup()` on PostProcessingPass to clear the bind group cache
    - The cached bind groups are tied to the old texture dimensions
    - Next frame, new bind groups will be created with the correct dimensions

---

Summary: Complete Flow

Here's what happens each frame:

```
// Frame setup (Renderer::renderFrame)
  └ For each camera:
       └ Renderer::renderToTexture(camera)
            ├ MeshPass::render()           // Renders 3D scene
            │   └ Output: renderTarget.gpuTexture with lit scene
            │
            ├ DebugPass::render()          // Renders wireframes, gizmos
            │   └ Output: Same texture, with debug overlays added
            │
            ├ PostProcessingPass::render() // ← YOU ADDED THIS!
            │   ├ setInputTexture(gpuTexture)
            │   ├ setRenderPassContext(renderPassContext)
            │   └ render() {
            │       - Get pipeline
            │       - Create bind group (texture + sampler)
            │       - Draw 3 vertices (fullscreen triangle)
            │       - Vignette shader darkens edges
            │     }
            │   └ Output: Same texture, but with vignette effect
            │
            └ CompositePass::render()      // Copies to surface
                └ Output: Final image on screen
```

Rebuild and Run

```
# Rebuild and run
scripts\build-example.bat tutorial Debug WGPU
examples/build/tutorial/Windows/Debug/Tutorial.exe
```

VS Code shortcuts:

- Press `F5` to build and run with debugger
- Or open **Run and Debug** panel (`Ctrl+Shift+D`) → select **"Tutorial (Debug)"** → click green play button

Expected Result

You should see: ☑ **Vignette Effect** - Screen edges are darker, center is brighter ☑ **Smooth Falloff** - Gradual transition from center to edges ☑ **Applied to Everything** - Both 3D scene and debug overlays affected ☑ **Screen-Space** - Effect doesn't rotate with camera movement

Visual Test

- **Move camera around** - Vignette stays screen-aligned (doesn't follow camera)
- **Look at bright areas** - Center remains visible despite vignette
- **Look at edges** - Edges are noticeably darker

Understanding the Vignette Shader

The vignette effect happens in `resources/postprocess_vignette.wgsl`:

Shader Structure:

```
// Bind Group 0: Input texture from previous render pass
@group(0) @binding(0) var inputSampler: sampler;
@group(0) @binding(1) var inputTexture: texture_2d<f32>;

// Vertex shader output / Fragment shader input
struct VertexOutput {
    @builtin(position) position: vec4f,
    @location(0) texCoord: vec2f,
}
```

Vertex Shader (`vs_main`):

Generates a fullscreen triangle without vertex buffers using bit manipulation on the vertex index:

```
@vertex
fn vs_main(@builtin(vertex_index) vertexIndex: u32) -> VertexOutput {
    var output: VertexOutput;

    // Bit manipulation to generate triangle coordinates
    // vertexIndex: 0 -> (0, 0), 1 -> (2, 0), 2 -> (0, 2)
    let x = f32((vertexIndex << 1u) & 2u);
    let y = f32(vertexIndex & 2u);

    // Convert to NDC: (0,0) -> (-1,1), (2,0) -> (3,1), (0,2) -> (-1,-3)
    output.position = vec4f(x * 2.0 - 1.0, 1.0 - y * 2.0, 0.0, 1.0);

    // Pass through texture coordinates (0 to 1 range)
    output.texCoord = vec2f(x, y);

    return output;
}
```

This creates a triangle that covers the entire screen:

- Vertex 0: (-1, -1) bottom-left → UV (0, 0)
- Vertex 1: (3, -1) bottom-right → UV (1, 0) [off-screen]
- Vertex 2: (-1, 3) top-left → UV (0, 1) [off-screen]

Fragment Shader (`fs_main`):

Applies the vignette effect by darkening edges based on distance from center:

```
@fragment
fn fs_main(input: VertexOutput) -> @location(0) vec4f {
    // Sample the rendered scene color
    let sceneColor = textureSample(inputTexture, inputSampler, input.texCoord);

    // Calculate distance from screen center (0.5, 0.5)
    let center = vec2f(0.5, 0.5);
    let dist = distance(input.texCoord, center);

    // Vignette parameters
    let vignetteIntensity = 0.85;  // How dark edges get (0.0 = no effect, 1.0 =
black)
    let vignetteFalloff = 2.0;    // Transition sharpness (higher = sharper edge)

    // Calculate vignette factor (1.0 at center, approaches 0.0 at edges)
    // smoothstep creates a smooth S-curve interpolation
    let vignette = 1.0 - smoothstep(0.0, 1.0, dist * vignetteFalloff);

    // Mix between darkened (1.0 - intensity) and full brightness (1.0)
    let vignetteFactor = mix(1.0 - vignetteIntensity, 1.0, vignette);

    // Apply vignette by multiplying scene color
    let finalColor = sceneColor * vignetteFactor;

    return finalColor;
}
```

How the Vignette Calculation Works:

1. **Distance from Center** - Calculate how far each pixel is from screen center (0.5, 0.5)
2. **Smoothstep Transition** - Use `smoothstep()` to create a smooth falloff curve
3. **Mix Factor** - Interpolate between darkened edges and full brightness
4. **Apply Effect** - Multiply scene color by the vignette factor to darken edges

---

Key Concepts Learned

✅ **Render Pass Lifecycle** - initialize() → render() → cleanup()
✅ **Shader Registry** - Centralized shader management with hot-reload support
✅ **Pipeline Manager** - Lazy pipeline creation with caching
✅ **Bind Group Caching** - Efficient resource reuse across frames
✅ **Fullscreen Triangle** - Procedural vertex generation in shader
✅ **Multi-Pass Rendering** - Reading from previous pass output
✅ **Screen-Space Effects** - Operations in normalized screen coordinates

---

What's Next?

You've implemented a **hardcoded post-processing effect** that's baked into the engine. To extend this:

1. **Add more effects** - Create new shader + new PostProcessingPass-like class for each effect
2. **Multiple passes** - Chain effects (vignette → bloom → tone mapping)
3. **Effect selection** - Allow runtime effect switching via configuration
4. **Framework design** - Build a flexible system supporting arbitrary effects

Future tutorials could cover these advanced topics!

Reference

- Shader source: `resources/postprocess_vignette.wgsl`
- Pass header: `include/engine/rendering/PostProcessingPass.h`
- Pass implementation: `src/engine/rendering/PostProcessingPass.cpp`
- Renderer integration: `src/engine/rendering/Renderer.cpp`
- Shader registration: `src/engine/rendering/ShaderRegistry.cpp`
- Similar passes: `CompositePass.cpp`, `MeshPass.cpp`, `ShadowPass.cpp`

Further Reading

- WebGPU WGSL Specification
- Engine Bind Group System
- Getting Started Guide
- LearnWebGPU Tutorial

Troubleshooting Build Failures

⚠ **Important:** When using `scripts/build.bat`, the task system may report success even if the build actually failed. You **MUST check the terminal output** to see the real result.

What to look for in terminal:

1. Scroll to the **very end** of the terminal output
2. Look for `[SUCCESS] Build completed successfully!` - if this appears, build succeeded
3. If you see `[ERROR] Build failed.` - the build failed regardless of task status

Common issues in post-processing:

- **Shader errors in vignette shader** - Check `.wgsl` for missing semicolons
- **Bind group layout mismatch** - Verify shader layout matches C++ registration
- **Missing pipeline creation** - Ensure `getOrCreatePipeline()` is called before rendering
- **CMake cache issues** - Delete `build/` folder and rebuild clean

Debug Strategy:

1. Open `MeshPass.cpp` in your editor
2. Add a breakpoint in the `render()` method
3. Press `F5` to start debugging with VS Code
4. Check the **Terminal Output** panel - errors will show exact line numbers