Vulkan Lab 4: Lighting Fundamentals

EXERCISE 1:BASIC SCALING TRANSFORMATION

Goal: Update the application to support vertex normals and a new UBO for lighting data.

Solution: I added normal vectors to each vertex so the GPU knows which direction each face is pointing. Lighting depends on these normals, so every face of the cube needs its own set of vertices, even if the positions are shared. This means the cube now uses 36 separate vertices instead of reusing corners. I also updated the uniform buffer so I can send the light position and camera position to the shader each frame. Because the vertices are no longer shared, I removed the index buffer and now draw the cube using only the vertex buffer. These changes give the shaders all the information they need to start calculating lighting on the cube.

- Vertex Structure Update:

```
struct Vertex {
    glm::vec3 pos;
    glm::vec3 color;
    glm::vec3 normal;      // <- Add normal vector
```

- Uniform Buffer Object Update:

```
struct UniformBufferObject {
    alignas(16) glm::mat4 model;
    alignas(16) glm::mat4 view;
    alignas(16) glm::mat4 proj;
    alignas(16) glm::vec3 lightPos;     // <- New light position
    alignas(16) glm::vec3 eyePos;       // <- New eye position
};
```

- Cube Vertex Data Update:

```
std::vector<Vertex> cubeVertices = {
    // Front (+Z)
    {{-0.5f, -0.5f,  0.5f}, {1,0,0}, {0,0, 1}},
    {{ 0.5f, -0.5f,  0.5f}, {1,0,0}, {0,0, 1}},
    {{ 0.5f,  0.5f,  0.5f}, {1,0,0}, {0,0, 1}},
    {{ 0.5f,  0.5f,  0.5f}, {1,0,0}, {0,0, 1}},
    {{-0.5f,  0.5f,  0.5f}, {1,0,0}, {0,0, 1}},
    {{-0.5f, -0.5f,  0.5f}, {1,0,0}, {0,0, 1}},

    // Back (-Z)
    {{ 0.5f, -0.5f, -0.5f}, {0,1,0}, {0,0,-1}},
```

```
    {{-0.5f, -0.5f, -0.5f}, {0,1,0}, {0,0,-1}},
    {{-0.5f,  0.5f, -0.5f}, {0,1,0}, {0,0,-1}},
    {{-0.5f,  0.5f, -0.5f}, {0,1,0}, {0,0,-1}},
    {{ 0.5f,  0.5f, -0.5f}, {0,1,0}, {0,0,-1}},
    {{ 0.5f, -0.5f, -0.5f}, {0,1,0}, {0,0,-1}},

    // Left (-X)
    {{-0.5f, -0.5f, -0.5f}, {0,0,1}, {-1,0,0}},
    {{-0.5f, -0.5f,  0.5f}, {0,0,1}, {-1,0,0}},
    {{-0.5f,  0.5f,  0.5f}, {0,0,1}, {-1,0,0}},
    {{-0.5f,  0.5f,  0.5f}, {0,0,1}, {-1,0,0}},
    {{-0.5f,  0.5f, -0.5f}, {0,0,1}, {-1,0,0}},
    {{-0.5f, -0.5f, -0.5f}, {0,0,1}, {-1,0,0}},

    // Right (+X)
    {{ 0.5f, -0.5f,  0.5f}, {1,1,0}, {1,0,0}},
    {{ 0.5f, -0.5f, -0.5f}, {1,1,0}, {1,0,0}},
    {{ 0.5f,  0.5f, -0.5f}, {1,1,0}, {1,0,0}},
    {{ 0.5f,  0.5f, -0.5f}, {1,1,0}, {1,0,0}},
    {{ 0.5f,  0.5f,  0.5f}, {1,1,0}, {1,0,0}},
    {{ 0.5f, -0.5f,  0.5f}, {1,1,0}, {1,0,0}},

    // Top (+Y)
    {{-0.5f,  0.5f,  0.5f}, {1,0,1}, {0,1,0}},
    {{ 0.5f,  0.5f,  0.5f}, {1,0,1}, {0,1,0}},
    {{ 0.5f,  0.5f, -0.5f}, {1,0,1}, {0,1,0}},
    {{ 0.5f,  0.5f, -0.5f}, {1,0,1}, {0,1,0}},
    {{-0.5f,  0.5f, -0.5f}, {1,0,1}, {0,1,0}},
    {{-0.5f,  0.5f,  0.5f}, {1,0,1}, {0,1,0}},

    // Bottom (-Y)
    {{-0.5f, -0.5f, -0.5f}, {0,1,1}, {0,-1,0}},
    {{ 0.5f, -0.5f, -0.5f}, {0,1,1}, {0,-1,0}},
    {{ 0.5f, -0.5f,  0.5f}, {0,1,1}, {0,-1,0}},
    {{ 0.5f, -0.5f,  0.5f}, {0,1,1}, {0,-1,0}},
    {{-0.5f, -0.5f,  0.5f}, {0,1,1}, {0,-1,0}},
    {{-0.5f, -0.5f, -0.5f}, {0,1,1}, {0,-1,0}},
};
```

- Drawing without indices:

```
vkCmdDraw(commandBuffer, static_cast<uint32_t>(vertices.size()), 1, 0, 0);
```

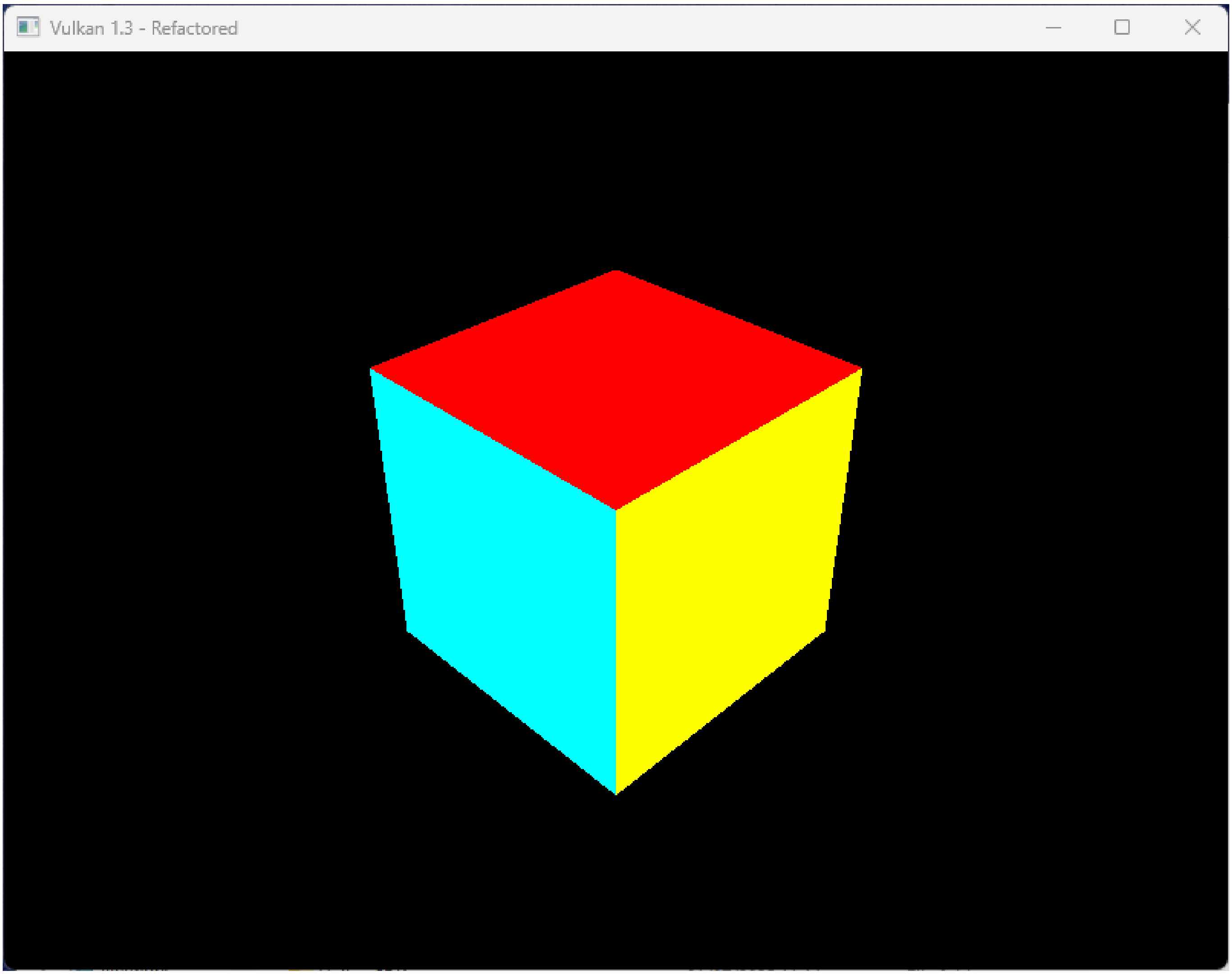
```
void HelloTriangleApplication::updateUniformBuffer(uint32_t currentImage) {
    static auto startTime = std::chrono::high_resolution_clock::now();
    auto currentTime = std::chrono::high_resolution_clock::now();
    float time = std::chrono::duration<float>(currentTime - startTime).count();

    UniformBufferObject ubo{};
```

```
    ubo.model = glm::rotate(glm::mat4(1.0f), glm::radians(90.0f), glm::vec3(0.0f,
0.0f, 1.0f));
    ubo.view = glm::lookAt(glm::vec3(2.0f, 2.0f, 2.0f), glm::vec3(0.0f, 0.0f,
0.0f), glm::vec3(0.0f, 0.0f, 1.0f));
    ubo.proj = glm::perspective(glm::radians(45.0f), swapChainExtent.width /
(float)swapChainExtent.height, 0.1f, 10.0f);
    ubo.proj[1][1] *= -1;

    ubo.lightPos = glm::vec3(1.0f, 1.0f, 1.0f); // <- New light position
    ubo.eyePos = glm::vec3(2.0f, 2.0f, 2.0f); // <- New eye position

    memcpy(uniformBuffersMapped[currentImage], &ubo, sizeof(ubo));
}
```

- Vertex Shader Update:

```
layout(binding = 0) uniform UniformBufferObject {
    mat4 model;
    mat4 view;
    mat4 proj;
    vec3 lightPos;
    vec3 eyePos;
} ubo;

layout(location=0) in vec3 inPosition;
layout(location=1) in vec3 inColor;
layout(location=2) in vec3 inNormal;

layout(location=0) out vec3 fragColor;
layout(location=1) out vec3 fragWorldPos;
layout(location=2) out vec3 fragWorldNormal;

void main() {
    vec4 worldPosition = ubo.model * vec4(inPosition, 1.0);
    fragWorldPos = worldPosition.xyz;
    mat3 normalMatrix = transpose(inverse(mat3(ubo.model)));
    fragWorldNormal = normalize(normalMatrix * inNormal);
    fragColor = inColor;
    gl_Position = ubo.proj * ubo.view * worldPosition;
}
```

Output:



Reflection: This exercise helped me understand that lighting does not work properly unless the geometry data is set up correctly first. I saw how important normals are for shading because they tell the GPU how light should hit the surface. I also learned how a uniform buffer is used to pass important information like the light and camera position from the CPU to the GPU. This made me more aware that real-time rendering depends on good data flow between the application and the shaders.

EXERCISE 2: PER-VERTEX DIFFUSE LIGHTING

Goal: Implement a basic ambient and diffuse lighting model directly in the vertex shader.

Solution: To implement per-vertex ambient and diffuse lighting, I used the normals and lighting data introduced in Exercise 1 and moved the lighting calculations into the vertex shader. The lab-provided code snippet was incomplete because it did not include the required gl_Position assignment and incorrectly multiplied the light color twice in the diffuse term. I corrected these issues by computing world-space position, applying the proper inverse-transpose operation to transform normals, calculating ambient and diffuse lighting once, and then writing the final lit color to the fragColor output. The fragment shader remains a simple pass-through. Since the cube already uses 36 vertices with per-face normals, no changes to the C++ pipeline were required for this exercise. The result meets the goal of Exercise 2: to perform lighting at the vertex stage and observe the faceted shading effect.

- Pipeline Shader Stage Update:

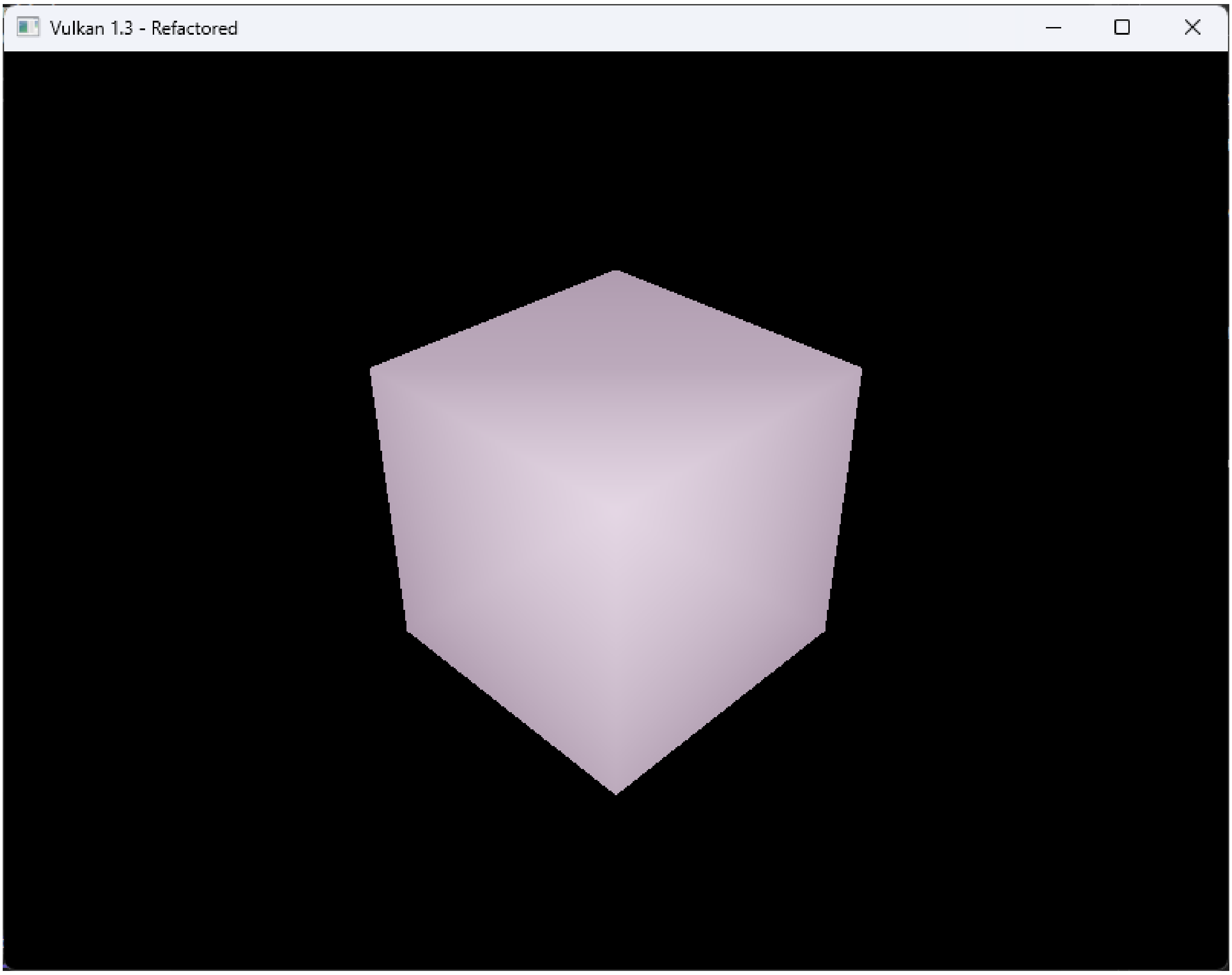
```
uboLayoutBinding.stageFlags = VK_SHADER_STAGE_VERTEX_BIT;
```

- Drawing Command (no change from Exercise 1):

```
vkCmdDraw(commandBuffer, static_cast<uint16_t>(vertices.size()), 1, 0, 0);
```

```
#version 450

layout(binding = 0) uniform UniformBufferObject {
    mat4 model;
    mat4 view;
    mat4 proj;
    vec3 lightPos;
    vec3 eyePos;
} ubo;

layout(location = 0) in vec3 inPosition;
layout(location = 1) in vec3 inColor;
layout(location = 2) in vec3 inNormal;

layout(location = 0) out vec3 fragColor;

void main() {
    // World-space transforms
    vec3 worldPos    = (ubo.model * vec4(inPosition, 1.0)).xyz;
    vec3 worldNormal = mat3(transpose(inverse(ubo.model))) * inNormal;
    vec3 norm        = normalize(worldNormal);

    // Light and material
    vec3 lightColor      = vec3(1.0, 1.0, 1.0);
    vec3 ambientMaterial = vec3(0.2, 0.1, 0.2);
    vec3 diffMaterial    = vec3(1.0, 1.0, 1.0);

    // Diffuse
    vec3 lightDir = normalize(ubo.lightPos - worldPos);
    float diff    = max(dot(norm, lightDir), 0.0);
    vec3 diffuse  = diff * lightColor;

    // Final per-vertex color: ambient + diffuse
    fragColor = ambientMaterial * lightColor + diffMaterial * diffuse;

    // Position
    gl_Position = ubo.proj * ubo.view * vec4(worldPos, 1.0);
}
```

Output:



Reflection: This step showed me that lighting quality depends not only on shader formulas but also on correct spaces and data flow. Using the inverse-transpose for normals avoided skewed lighting when the model rotates, and performing the lighting in the vertex stage produced the expected faceted look because colors are interpolated across triangles. I also saw why we kept the richer UBO from Exercise 1: it already carries the transforms and light parameters needed here. With this foundation in place, I�m ready to move the lighting math to the fragment stage in the next exercise for smoother results.

EXERCISE 3: PER-FRAGMENTDIFFUSE LIGHTING

Goal: Improve visual quality by moving the lighting logic to the fragment shader, allowing for smoother, more accurate calculations.

Solution: I completed per fragment diffuse lighting by shifting the lighting calculations from the vertex shader to the fragment shader. The vertex shader now transforms each vertex to world space, computes a world space normal using the inverse transpose of the model matrix, and passes only world position and world normal to the fragment stage. I updated the descriptor set layout so the uniform buffer can be read in the fragment stage. I also exposed the normal attribute in the vertex input descriptions and removed the unused index buffer bind since the draw is non indexed. The fragment shader reads the interpolated world position and world normal, builds a unit light direction from the uniform light position, and evaluates ambient plus diffuse to produce the final color per pixel, with no tint from vertex colors. The result is a cube rendered with a single base hue whose faces vary only by brightness according to the light direction.

- Vertex Shader:

```
#version 450

layout(binding = 0) uniform UniformBufferObject {
    mat4 model;
    mat4 view;
    mat4 proj;
    vec3 lightPos;
  //vec3 eyePos;
} ubo;

layout(location = 0) in vec3 inPosition;
layout(location = 1) in vec3 inColor;
layout(location = 2) in vec3 inNormal;

layout(location = 0) out vec3 fragWorldPos;
layout(location = 1) out vec3 fragWorldNormal;

void main() {
    vec4 worldPosition = ubo.model * vec4(inPosition, 1.0);
    fragWorldPos = worldPosition.xyz;

    mat3 normalMatrix = transpose(inverse(mat3(ubo.model)));
    fragWorldNormal = normalize(normalMatrix * inNormal);

    gl_Position = ubo.proj * ubo.view * worldPosition;
}
```

- Fragment Shader:

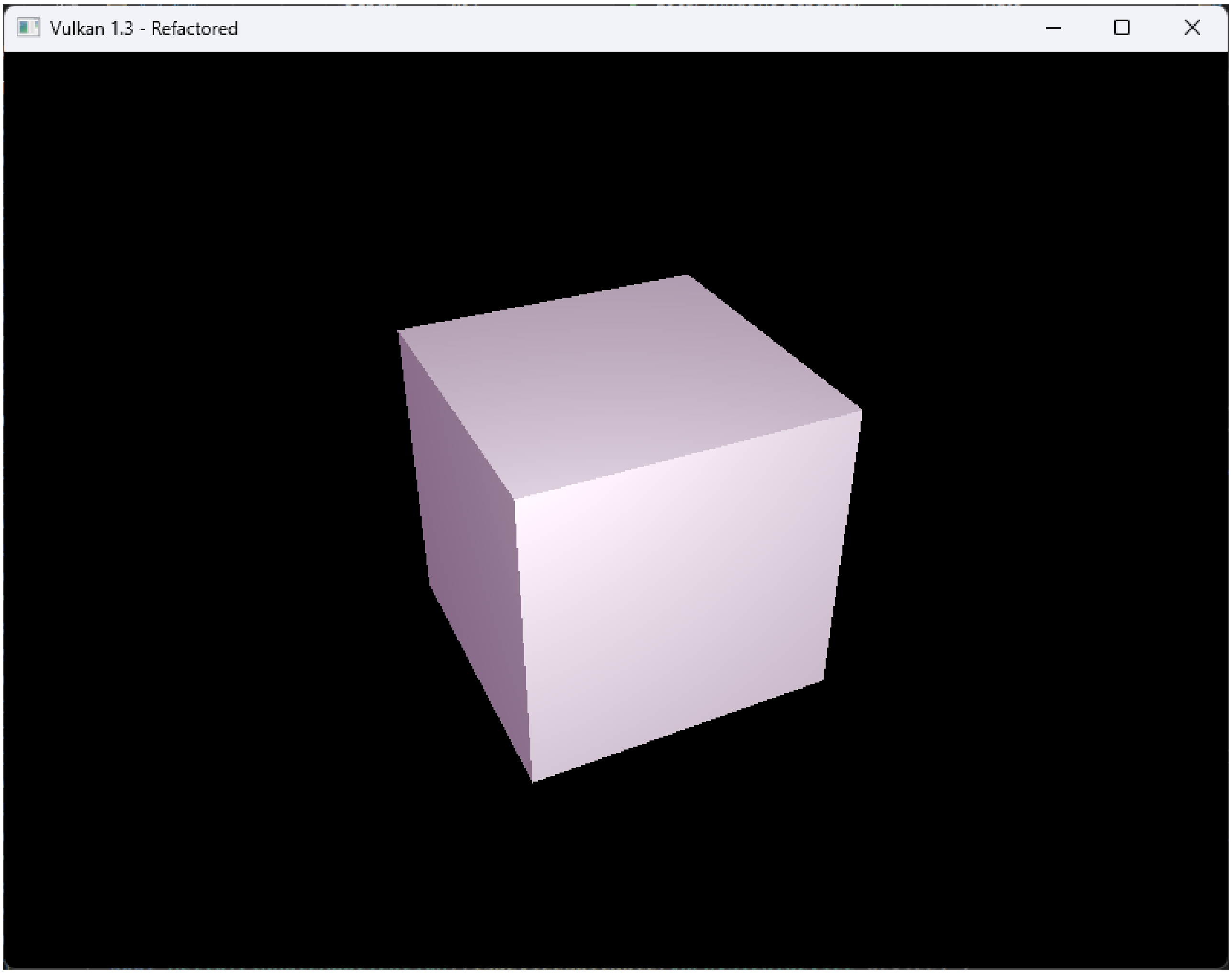
```
#version 450

layout(binding = 0) uniform UniformBufferObject {
    mat4 model;
    mat4 view;
    mat4 proj;
    vec3 lightPos;
  //vec3 eyePos;
} ubo;

layout(location = 0) in vec3 fragWorldPos;
layout(location = 1) in vec3 fragWorldNormal;

layout(location = 0) out vec4 outColor;

void main() {
```

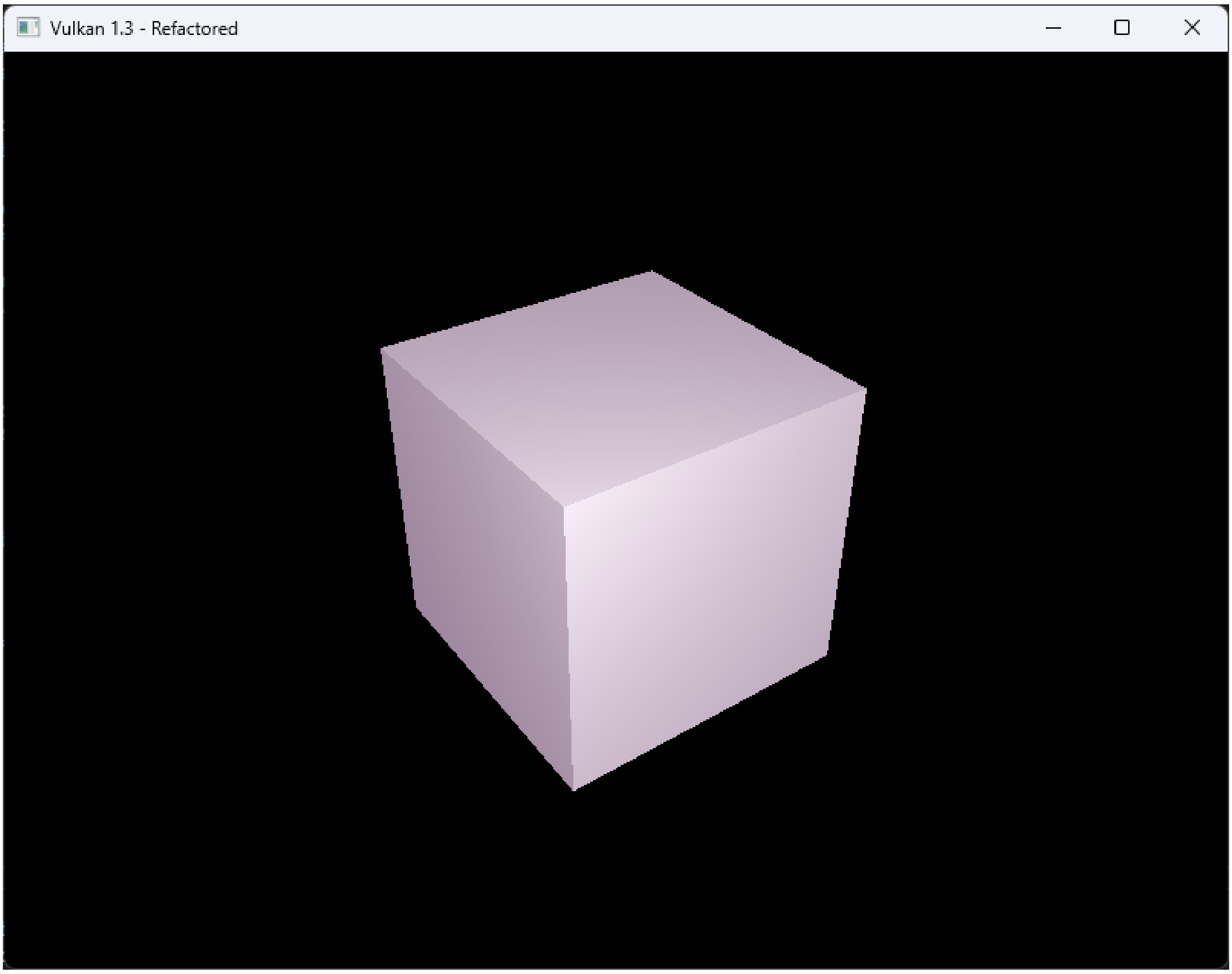
```
    vec3 lightColor      = vec3(1.0);
    vec3 ambientMaterial = vec3(0.2, 0.1, 0.2);
    vec3 diffMaterial    = vec3(1.0);

    vec3 n = normalize(fragWorldNormal);
    vec3 l = normalize(ubo.lightPos - fragWorldPos);

    float diff   = max(dot(n, l), 0.0);
    vec3 diffuse = diff * lightColor;

    vec3 color = ambientMaterial * lightColor + diffMaterial * diffuse;
    outColor = vec4(color, 1.0);
}
```

```
static std::array<VkVertexInputAttributeDescription, 3> getAttributeDescriptions()
{
    std::array<VkVertexInputAttributeDescription, 3> attributeDescriptions{};
    attributeDescriptions[0] = { 0, 0, VK_FORMAT_R32G32B32_SFLOAT,
offsetof(Vertex, pos)    };
    attributeDescriptions[1] = { 1, 0, VK_FORMAT_R32G32B32_SFLOAT,
offsetof(Vertex, color)  };
    attributeDescriptions[2] = { 2, 0, VK_FORMAT_R32G32B32_SFLOAT,
offsetof(Vertex, normal) };
    return attributeDescriptions;
}
```

```
uboLayoutBinding.stageFlags = VK_SHADER_STAGE_VERTEX_BIT |
VK_SHADER_STAGE_FRAGMENT_BIT;
```

Output:

- 70 degrees view:


- 80 degrees view:
  

Reflection: This exercise made the benefit of pixel shading very clear. In the previous exercise the lighting was calculated per vertex and then interpolated, which produced a faceted and slightly flat appearance across the cube's faces. After moving the lighting to the fragment shader, the normals and positions are interpolated first and the lighting is evaluated at every pixel, which produces smoother shading and a more natural falloff of light across surfaces. I also reinforced two practical Vulkan details that matter for correctness and debugging. First, stage visibility must include the fragment stage when a shader reads the uniform buffer there. Second, the pipeline must advertise every vertex attribute actually used by the shaders, including normals, and state should not bind resources that are not used, such as an index buffer when drawing non indexed geometry.

EXERCISE 4:ADDING PER-VERTEX SPECULAR LIGHTING

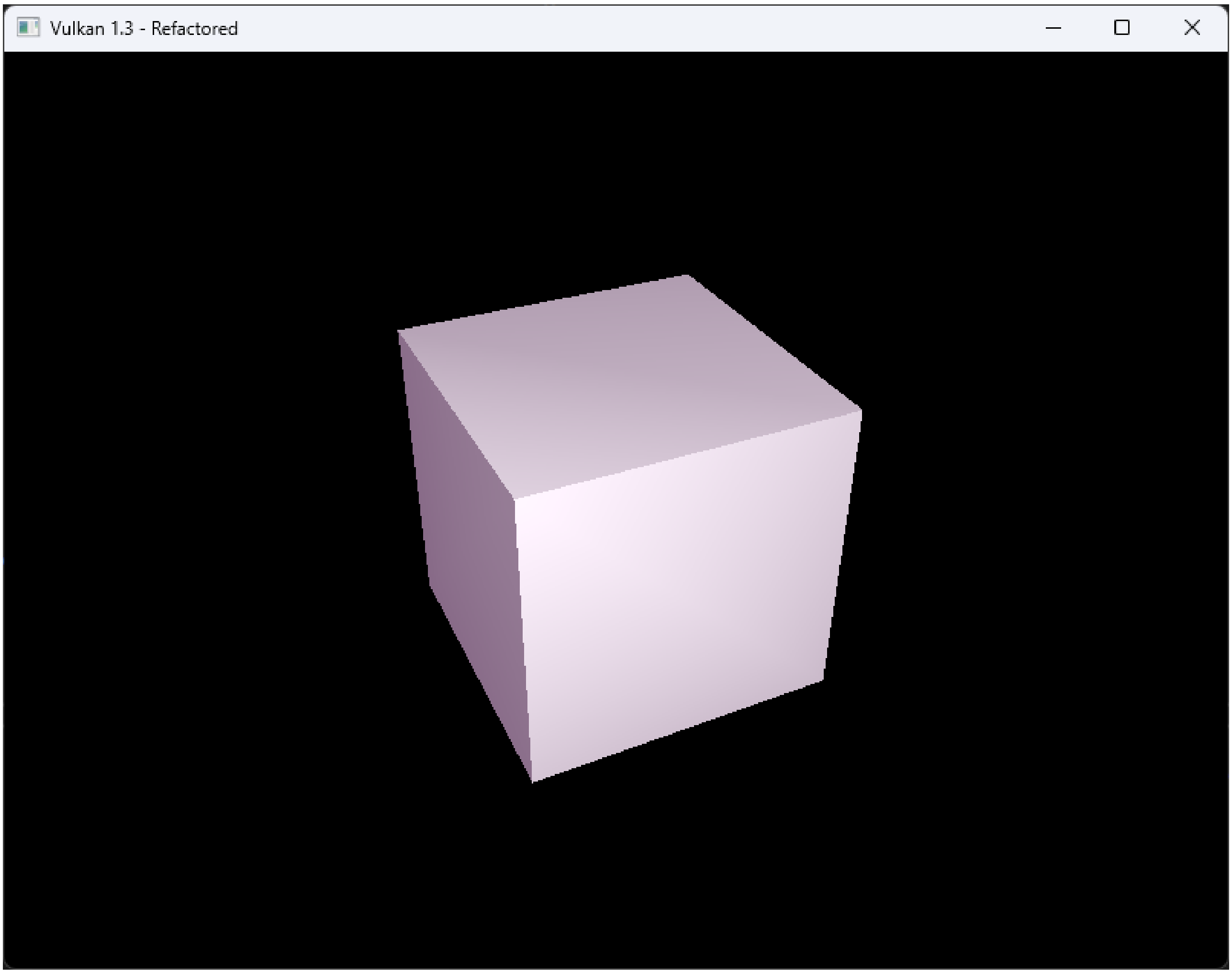
Goal: : Complete the reflection model implemented in Exercise 2 by adding specular highlights to the vertex shader.

Solution: In this exercise I completed the Phong reflection model by adding a specular component to the vertex shader. This extended the lighting calculations from Exercise 2, where only ambient and diffuse were used. I transformed the vertex position and normal to world space, calculated the light direction and diffuse term, then computed the view direction using the eye position from the uniform buffer. I generated the reflection vector using the GLSL reflect function and applied the shininess exponent so the highlight intensity falls off correctly. The final lighting result is the sum of ambient, diffuse, and specular components and it is written to fragColor. The fragment shader remained unchanged, simply outputting the interpolated vertex colour. This correctly implements per vertex specular lighting as defined in the exercise requirements.

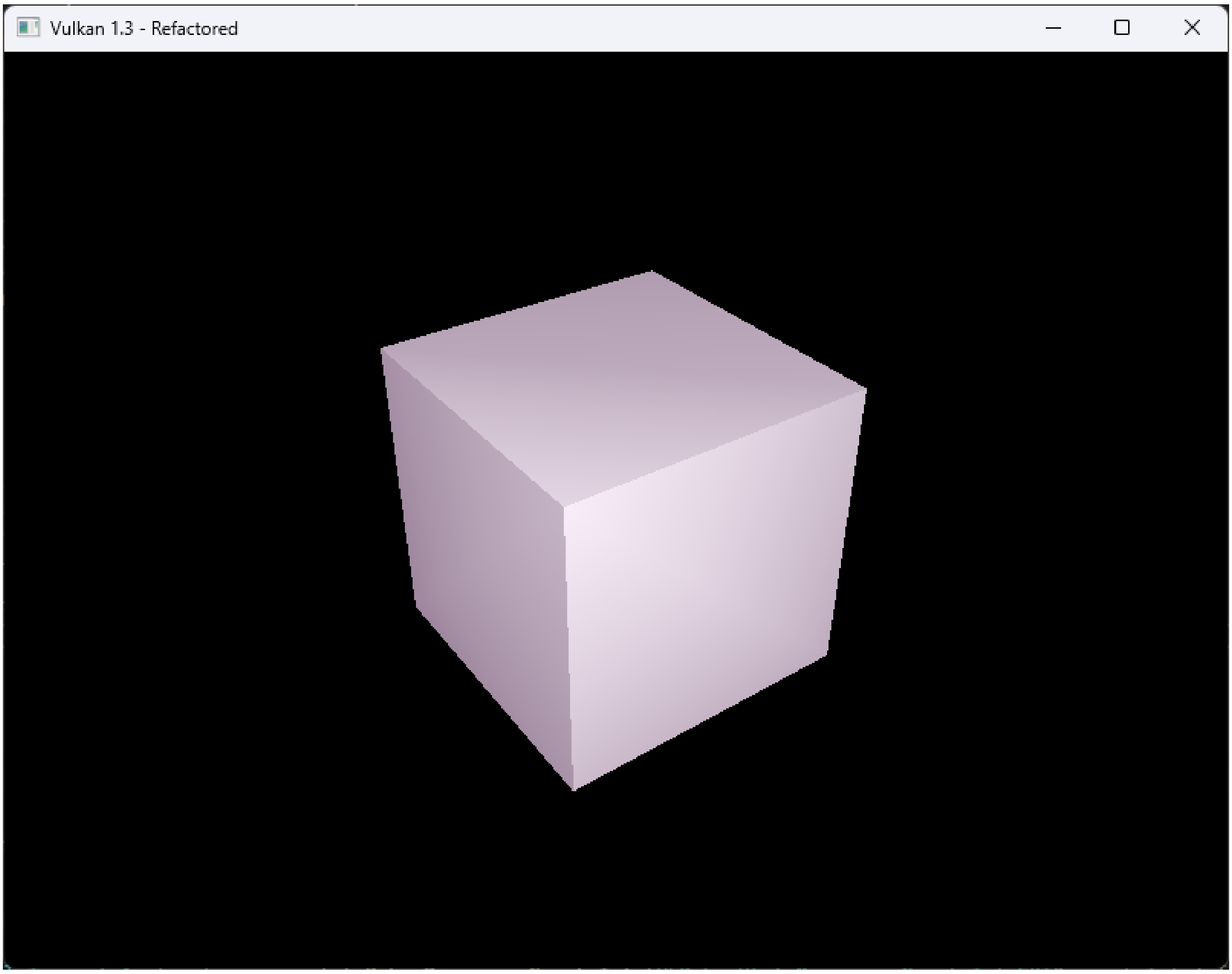
```
#version 450

layout(binding = 0) uniform UniformBufferObject {
    mat4 model;
    mat4 view;
    mat4 proj;
    vec3 lightPos;
    vec3 eyePos;
} ubo;

layout(location=0) in vec3 inPosition;
layout(location=1) in vec3 inColor;
layout(location=2) in vec3 inNormal;

layout(location=0) out vec3 fragColor;

void main() {
    // Transform to world space
    vec3 worldPos = (ubo.model * vec4(inPosition, 1.0)).xyz;
    vec3 worldNormal = mat3(transpose(inverse(ubo.model))) * inNormal;
    vec3 norm = normalize(worldNormal);

    vec3 lightColor = vec3(1.0);
    vec3 ambientMaterial = vec3(0.2, 0.1, 0.2);
    vec3 diffMaterial = vec3(1.0);

    // Diffuse
    vec3 lightDir = normalize(ubo.lightPos - worldPos);
    float diff = max(dot(norm, lightDir), 0.0);
    vec3 diffuse = diff * lightColor;

    // Specular
    vec3 viewDir = normalize(ubo.eyePos - worldPos);
    vec3 reflectDir = normalize(reflect(-lightDir, norm));
    float shininess = 32.0;
    float spec = pow(max(dot(reflectDir, viewDir), 0.0), shininess);
    vec3 specMaterial = vec3(1.0);
    vec3 specular = specMaterial * lightColor * spec;

    // Output lighting result (per-vertex)
    fragColor = ambientMaterial * lightColor + diffMaterial * diffuse + specular;

    gl_Position = ubo.proj * ubo.view * vec4(worldPos, 1.0);
}
```

Output:

- 70 degrees view:



- 80 degrees view:



Reflection: Initially, I could not see the difference between Exercise 3 and Exercise 4, because the specular term was subtle and was being overshadowed by the diffuse lighting. To understand why, I experimented with different light positions, material strengths, and shininess values. Reducing the ambient intensity and increasing the specular material strength made the highlight more visible, while adjusting the light direction ensured that at least one face of the cube reflected light toward the camera. This confirmed that the specular calculation was working correctly but showed how sensitive highlights are to lighting conditions. I also learned that per vertex specular can appear softer or slightly inaccurate because it is interpolated across the triangle surface, but the highlight does move across the cube and responds properly to rotation. These experiments helped me clearly see how the addition of specular lighting enhances realism compared to Exercise 2 and Exercise 3.

EXERCISE 5:ADDING PER-FRAGMENT SPECULAR LIGHTING

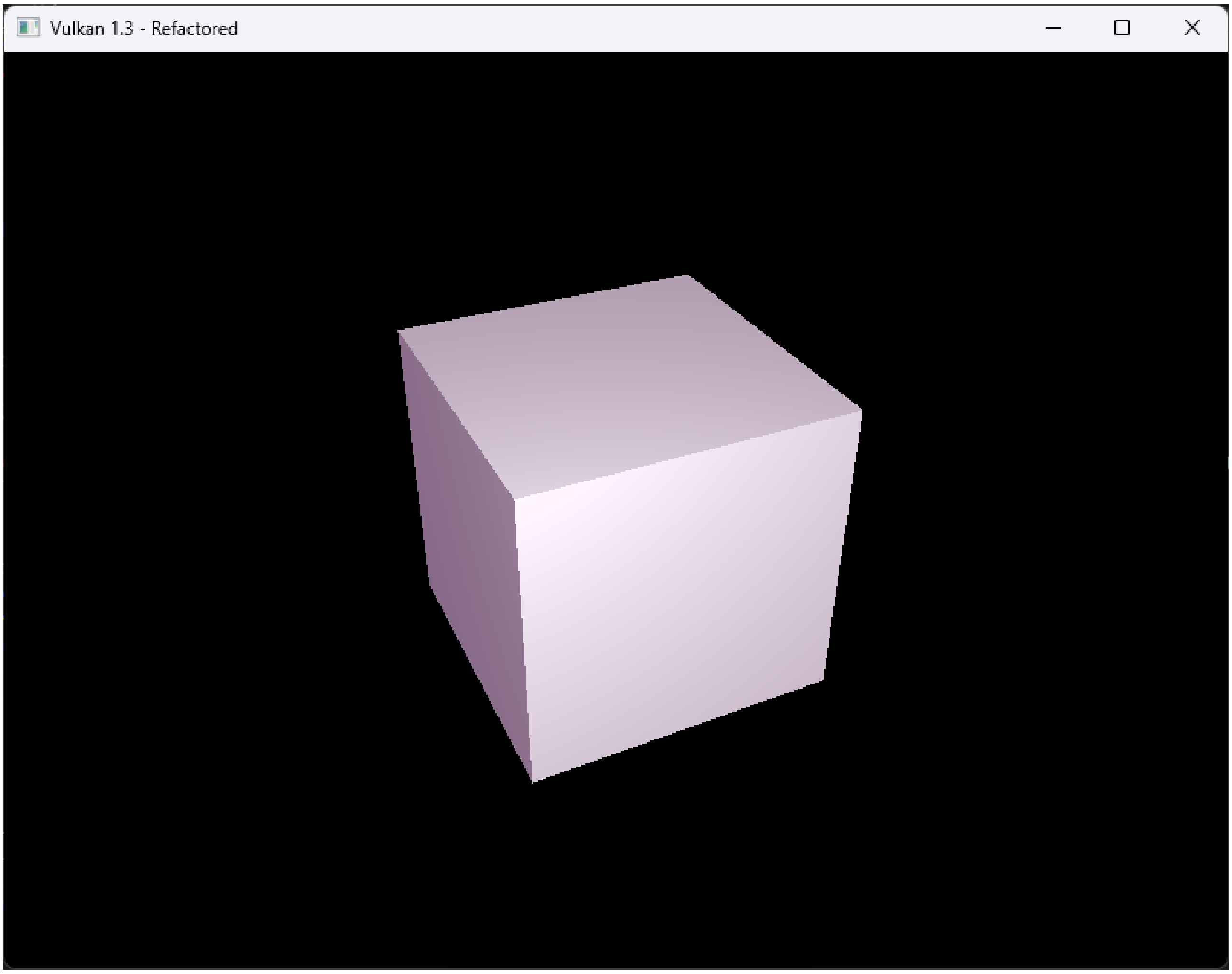
Goal: Complete the reflection model implemented in Exercise 3 by adding specular highlights to the fragment shader.

Solution: In this exercise I completed the lighting model by moving the specular component from the vertex shader into the fragment shader so the ambient diffuse and specular lighting are now calculated for every pixel. The vertex shader simply transforms each vertex to world space and passes the world position and world normal into the fragment shader. The fragment shader uses these interpolated values to compute the Phong reflection model with the light direction view direction and reflection vector all evaluated per fragment. This produces a more accurate result because the specular effect no longer depends on vertex interpolation. By updating the shader responsibilities in this way the lighting now responds smoothly and correctly across the entire surface which successfully completes the requirements of the exercise.

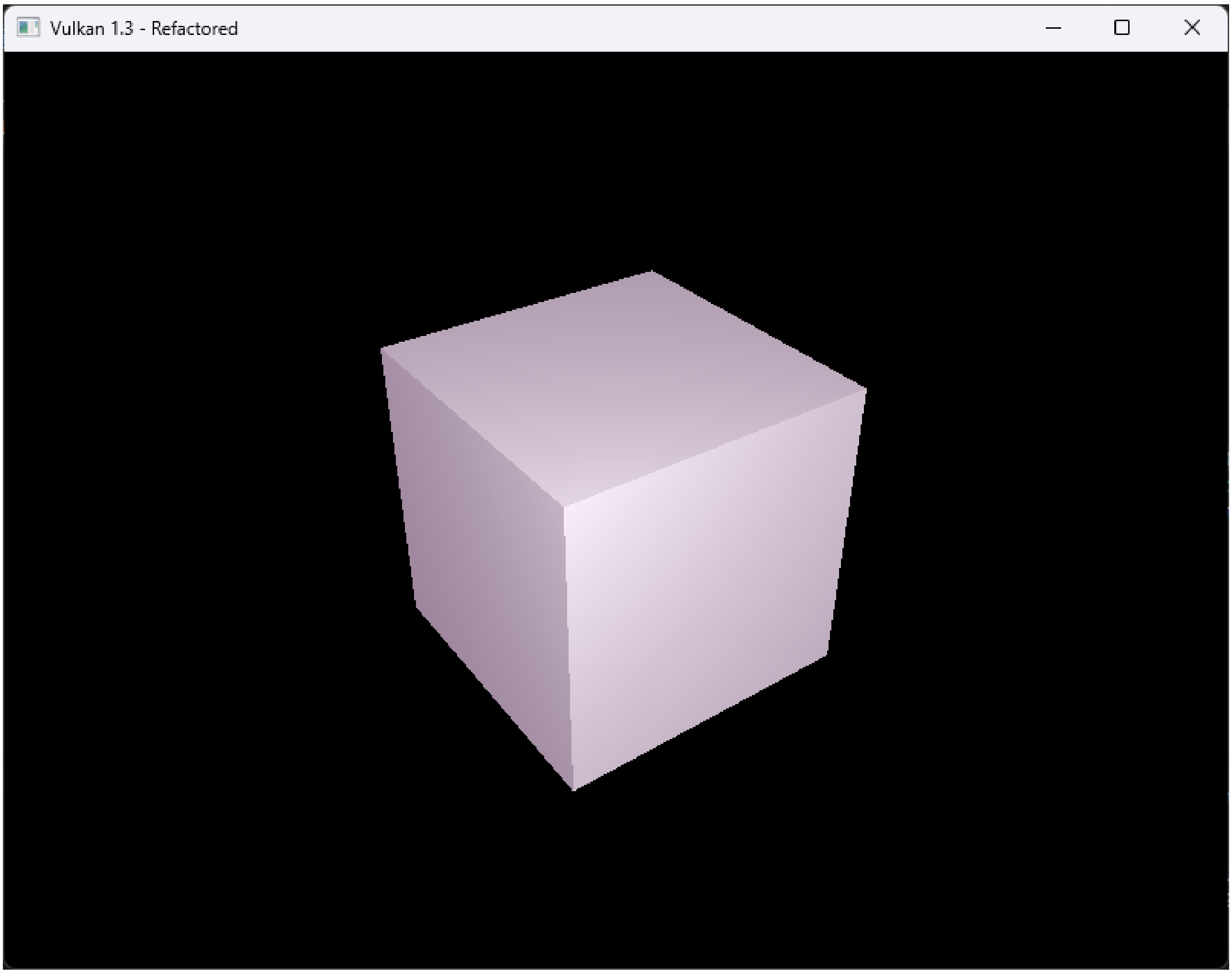
```
#version 450

layout(binding = 0) uniform UniformBufferObject {
    mat4 model;
    mat4 view;
    mat4 proj;
    vec3 lightPos;
    vec3 eyePos;
} ubo;

layout(location = 0) in vec3 fragWorldPos;
layout(location = 1) in vec3 fragWorldNormal;

layout(location = 0) out vec4 outColor;

void main() {
    vec3 lightColor      = vec3(1.0);
    vec3 ambientMaterial = vec3(0.2, 0.1, 0.2);
    vec3 diffMaterial    = vec3(1.0);
    vec3 specMaterial    = vec3(1.0);

    float shininess = 32.0;

    vec3 N = normalize(fragWorldNormal);
    vec3 L = normalize(ubo.lightPos - fragWorldPos);
    vec3 V = normalize(ubo.eyePos - fragWorldPos);
    vec3 R = reflect(-L, N);

    float diff = max(dot(N, L), 0.0);
    vec3 diffuse = diff * lightColor;

    float spec = pow(max(dot(R, V), 0.0), shininess);
    vec3 specular = specMaterial * lightColor * spec;

    vec3 color = ambientMaterial * lightColor
               + diffMaterial * diffuse
               + specular;

    outColor = vec4(color, 1.0);
}
```

Output:

- 70 degrees view:



- 80 degrees view:



- **Reflection:** Moving the specular calculation into the fragment shader resulted in a clear visual improvement. In the previous exercise the highlight appeared soft and sometimes stretched because it was being interpolated across the triangles. After making the change the highlight became sharper and more realistic because it was calculated independently for each pixel. I experimented with different shininess values and light and camera positions to see how the highlight changed based on surface orientation and viewing angle. Through these tests I gained a better understanding of why per fragment lighting is preferred when trying to achieve higher visual quality in real time rendering and how each part of the Phong model contributes to the final appearance.

EXERCISE 6: MULTIPLE LIGHTS AND MATERIALS

Solution: In this exercise, I implemented three cubes with different material properties (gold, jade, and plastic red), lit by two point lights where the static white light remains fixed above the scene and the red light rotates dynamically about the Y-axis by animating its position in the XZ-plane using cosine and sine over time. A Global UBO was used to store the camera matrices and both light properties, while push constants supplied each cube's model matrix and unique material settings (Ka, Kd, Ks, shininess), allowing the same cube geometry to be drawn three times with visibly distinct shading. The fragment shader performs Phong lighting using the two lights, producing ambient, diffuse, and specular contributions per fragment. Small emissive spheres were rendered at each light position as visual indicators (pictures) of the light sources so their placement and motion are clearly visible. Normals were transformed into world space to ensure accurate lighting calculations, and overall this setup fully meets the assignment requirements for multiple materials, two lights, and an animated red light rotating about the Y-axis.

```cpp
struct Vertex {
    glm::vec3 pos;
    glm::vec3 color;   // optional, kept for compatibility
    glm::vec3 normal;

    static VkVertexInputBindingDescription getBindingDescription() {
        VkVertexInputBindingDescription b{};
        b.binding = 0;
        b.stride = sizeof(Vertex);
        b.inputRate = VK_VERTEX_INPUT_RATE_VERTEX;
        return b;
    }
    static std::array<VkVertexInputAttributeDescription, 3>
getAttributeDescriptions() {
        std::array<VkVertexInputAttributeDescription, 3> a{};
        a[0] = { 0, 0, VK_FORMAT_R32G32B32_SFLOAT, offsetof(Vertex, pos) };
        a[1] = { 1, 0, VK_FORMAT_R32G32B32_SFLOAT, offsetof(Vertex, color) };
        a[2] = { 2, 0, VK_FORMAT_R32G32B32_SFLOAT, offsetof(Vertex, normal) };
        return a;
    }
};
```

```cpp
struct GlobalUBO {
    alignas(16) glm::mat4 view;
    alignas(16) glm::mat4 proj;
    alignas(16) glm::vec3 eyePos;      float _pad0{0.f};
    alignas(16) glm::vec3 light1Pos;   float _pad1{0.f};   // static white
    alignas(16) glm::vec3 light1Col;   float _pad2{0.f};
    alignas(16) glm::vec3 light2Pos;   float _pad3{0.f};   // rotating red
    alignas(16) glm::vec3 light2Col;   float _pad4{0.f};
};

struct PushConstants {
    glm::mat4 model;
    glm::vec4 Ka; // ambient
    glm::vec4 Kd; // diffuse
    glm::vec4 Ks; // specular
};
```

```cpp
void HelloTriangleApplication::updateUniformBuffer(uint32_t currentImage) {
    static auto start = std::chrono::high_resolution_clock::now();
    auto now   = std::chrono::high_resolution_clock::now();
    float t    = std::chrono::duration<float>(now - start).count();

    GlobalUBO ubo{};

    // Camera
    glm::vec3 eye(2.4f, 1.4f, 0.8f);
```

```
    glm::vec3 center(0.0f, 0.0f, 0.0f);
    glm::vec3 up(0.0f, 0.0f, 1.0f); // Z-up
    ubo.view = glm::lookAt(eye, center, up);
    ubo.proj = glm::perspective(glm::radians(80.0f),
        swapChainExtent.width / (float)swapChainExtent.height, 0.1f, 20.0f);
    ubo.proj[1][1] *= -1; // Vulkan NDC
    ubo.eyePos = eye;

    // Static white light above origin
    ubo.light1Pos = glm::vec3(0.0f, 0.0f, 1.0f);
    ubo.light1Col = glm::vec3(1.0f, 1.0f, 1.0f);

    // Rotating red light: orbit in XZ plane (rotate around Y-axis)
    const glm::vec3 C = glm::vec3(0.0f, 0.8f, 0.0f);  // orbit center
    const float      R = 2.2f;                         // radius
    const float omega = 0.8f;                          // angular speed
    const float theta = omega * t;

    ubo.light2Pos = C + glm::vec3(R * std::cos(theta), 0.0f, R * std::sin(theta));
    ubo.light2Col = glm::vec3(1.0f, 0.1f, 0.1f);

    // Upload
    memcpy(uniformBuffersMapped[currentImage], &ubo, sizeof(ubo));

    lastUBO = ubo;
}
```

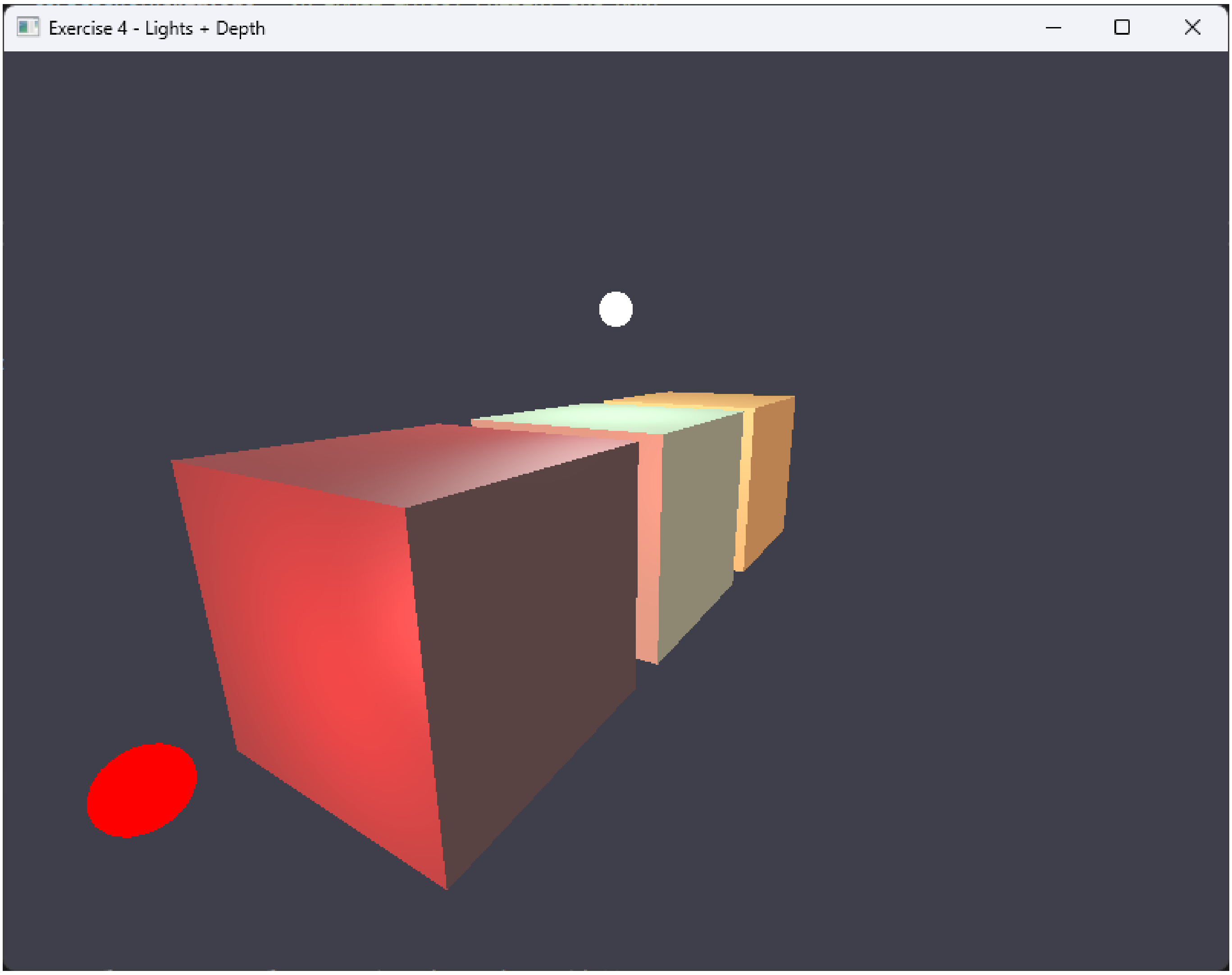
```
#version 460

layout(location = 0) in vec3 inPosition;
layout(location = 1) in vec3 inColor;
layout(location = 2) in vec3 inNormal;

layout(binding = 0) uniform GlobalUBO {
    mat4 view;
    mat4 proj;
    vec3 eyePos; float _pad0;
    vec3 light1Pos; float _pad1;
    vec3 light1Col; float _pad2;
    vec3 light2Pos; float _pad3;
    vec3 light2Col; float _pad4;
} ubo;

layout(push_constant) uniform Push {
    mat4 model;
    vec4 Ka;
    vec4 Kd;
    vec4 Ks; // Ks.w = shininess (if 0, fragment treats as icon/emissive)
} pc;

layout(location = 0) out vec3 vWorldPos;
```

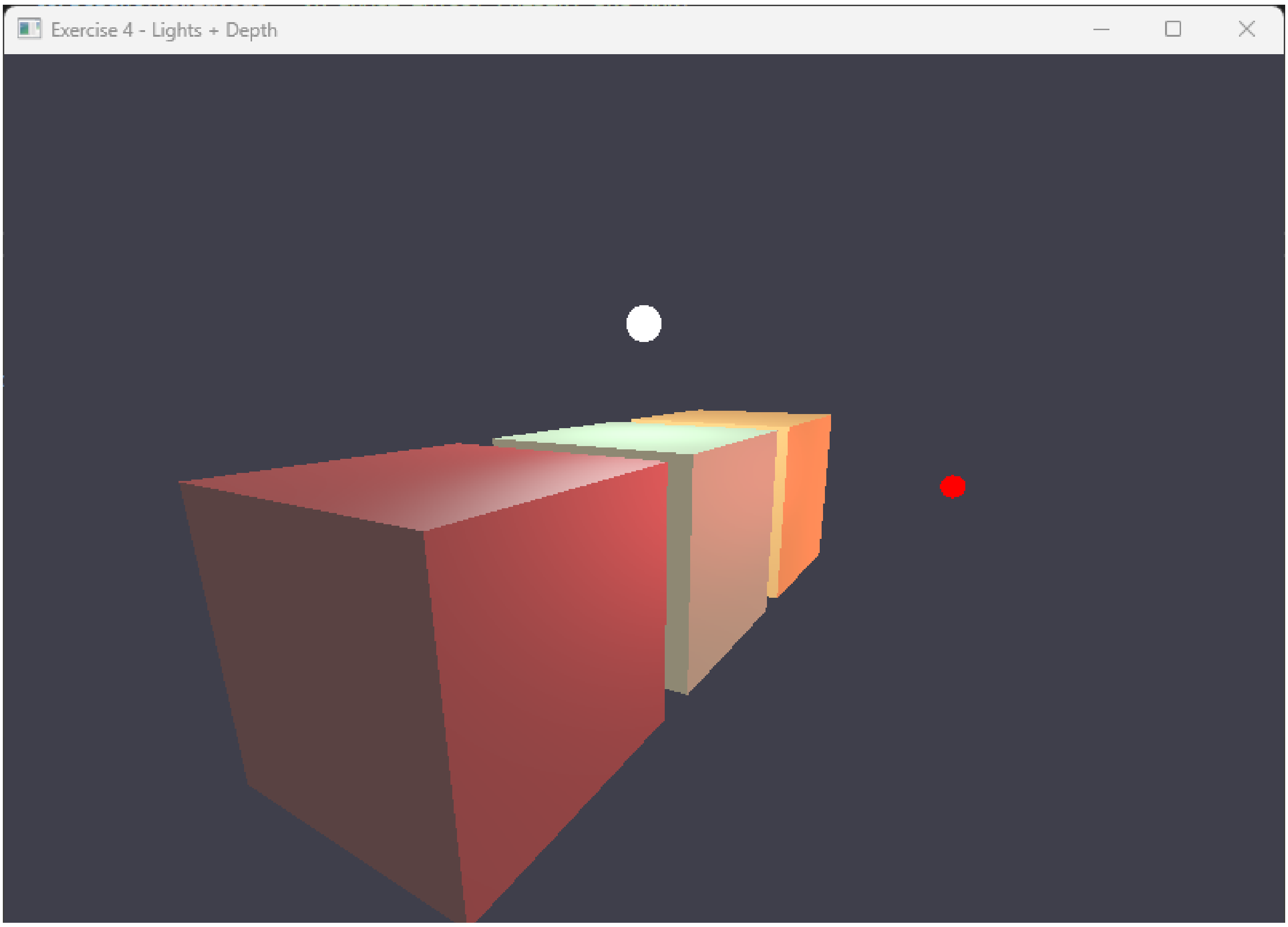
```
layout(location = 1) out vec3 vWorldNormal;

void main() {
    vec4 worldPos = pc.model * vec4(inPosition, 1.0);
    vWorldPos = worldPos.xyz;

    // If you have non-uniform scale, use inverse-transpose of pc.model
    mat3 normalMat = mat3(pc.model);
    vWorldNormal = normalize(normalMat * inNormal);

    gl_Position = ubo.proj * ubo.view * worldPos;
}
```

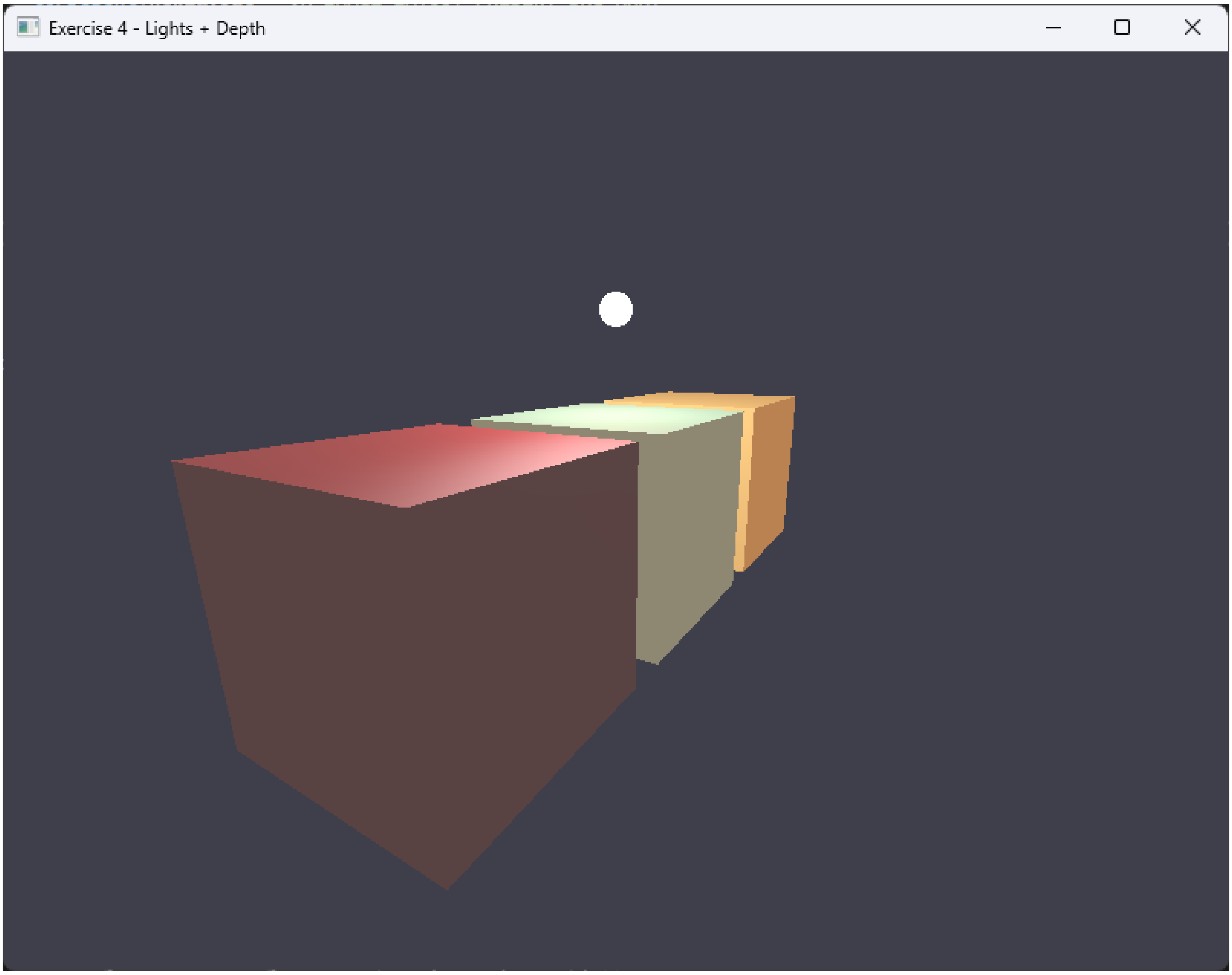
```
#version 460

layout(location = 0) in vec3 vWorldPos;
layout(location = 1) in vec3 vWorldNormal;

layout(location = 0) out vec4 outColor;

layout(binding = 0) uniform GlobalUBO {
    mat4 view;
    mat4 proj;
    vec3 eyePos; float _pad0;
    vec3 light1Pos; float _pad1;
    vec3 light1Col; float _pad2;
    vec3 light2Pos; float _pad3;
    vec3 light2Col; float _pad4;
} ubo;

layout(push_constant) uniform Push {
    mat4 model;
    vec4 Ka;    // ambient
    vec4 Kd;    // diffuse
    vec4 Ks;    // specular
} pc;

vec3 phongLight(vec3 N, vec3 V, vec3 P, vec3 Lpos, vec3 Lcol,
                vec3 Ka, vec3 Kd, vec3 Ks, float shininess)
{
    vec3 L = normalize(Lpos - P);
    vec3 R = reflect(-L, N);

    float NdotL = max(dot(N, L), 0.0);
    float RdotV = max(dot(R, V), 0.0);

    vec3 ambient  = Ka * Lcol;
    vec3 diffuse  = Kd * Lcol * NdotL;
    vec3 specular = Ks * Lcol * pow(RdotV, shininess);
```

```
    return ambient + diffuse + specular;
}

void main() {
    if (pc.Ks.w == 0.0) {
        vec3 emissive = mix(pc.Ka.rgb, pc.Kd.rgb, 0.5);
        outColor = vec4(emissive, 1.0);
        return;
    }

    vec3 N = normalize(vWorldNormal);
    vec3 V = normalize(ubo.eyePos - vWorldPos);

    vec3 Ka = pc.Ka.rgb;
    vec3 Kd = pc.Kd.rgb;
    vec3 Ks = pc.Ks.rgb;
    float shininess = max(pc.Ks.w, 1.0);

    vec3 c1 = phongLight(N, V, vWorldPos, ubo.light1Pos, ubo.light1Col, Ka, Kd,
Ks, shininess);
    vec3 c2 = phongLight(N, V, vWorldPos, ubo.light2Pos, ubo.light2Col, Ka, Kd,
Ks, shininess);

    vec3 color = c1 + c2;
    outColor = vec4(clamp(color, 0.0, 1.0), 1.0);
}
```

Output:


Exercise 4 - Lights + Depth


Exercise 4 - Lights + Depth



Reflection: This task reinforced the importance of correctly interpreting axis-based rotation in 3D graphics, as the light must move in the XZ-plane to genuinely rotate about the Y-axis. I also learned the benefit of separating global and per-object rendering data (lights and camera in a UBO, materials in push constants) as this makes the pipeline more organised and efficient. Performing lighting in world space removed ambiguity around coordinate transforms, leading to more predictable results. Using emissive icons for light sources proved very helpful for debugging and presentation, showing behaviour clearly without additional UI elements. Overall, this exercise strengthened my understanding of real-time lighting, material properties, and animated illumination in Vulkan.

FURTHER EXPLORATION

Solution:

Output:

Reflection: