Shadows

Computer Graphics

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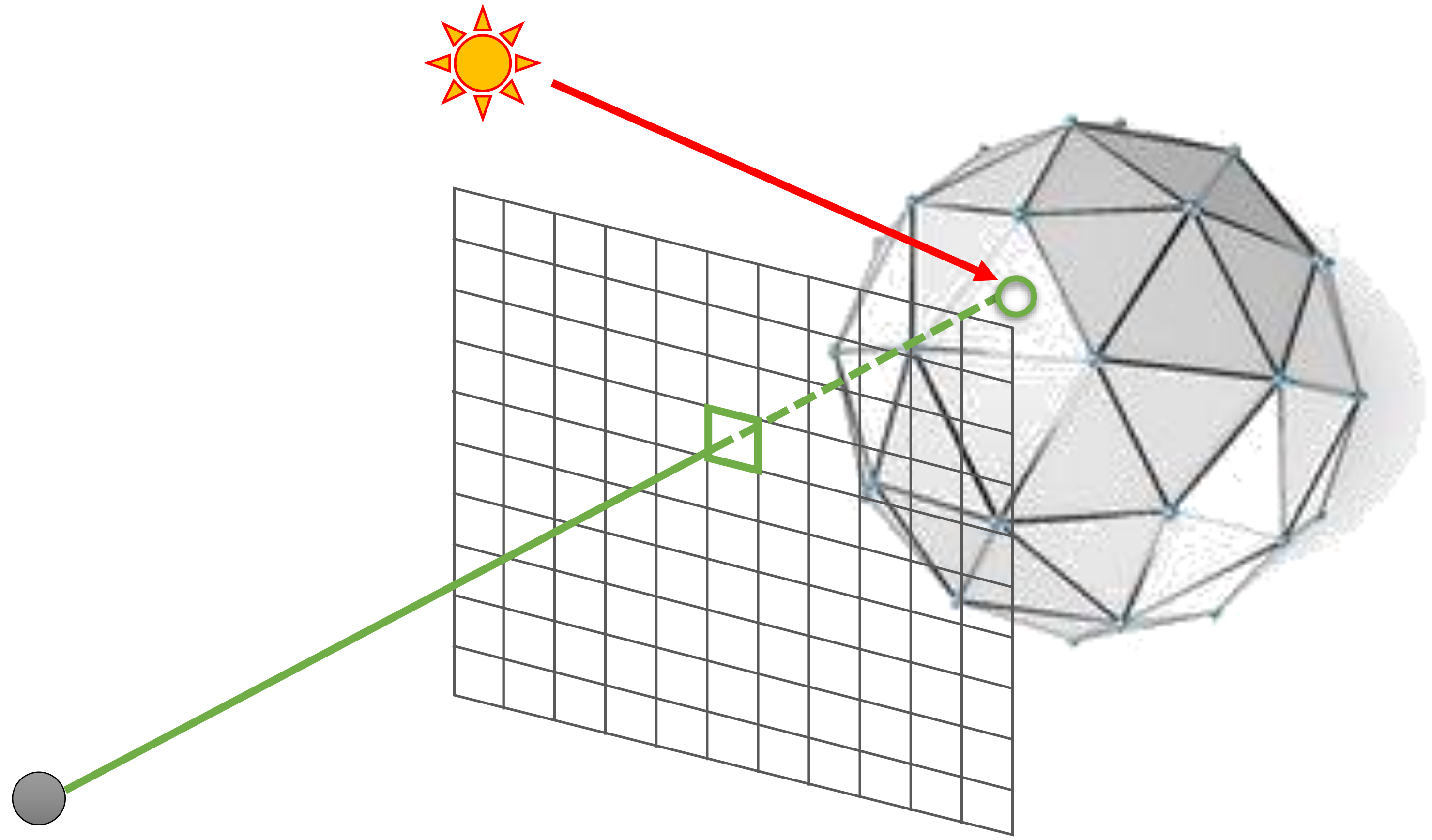
Shadow Map

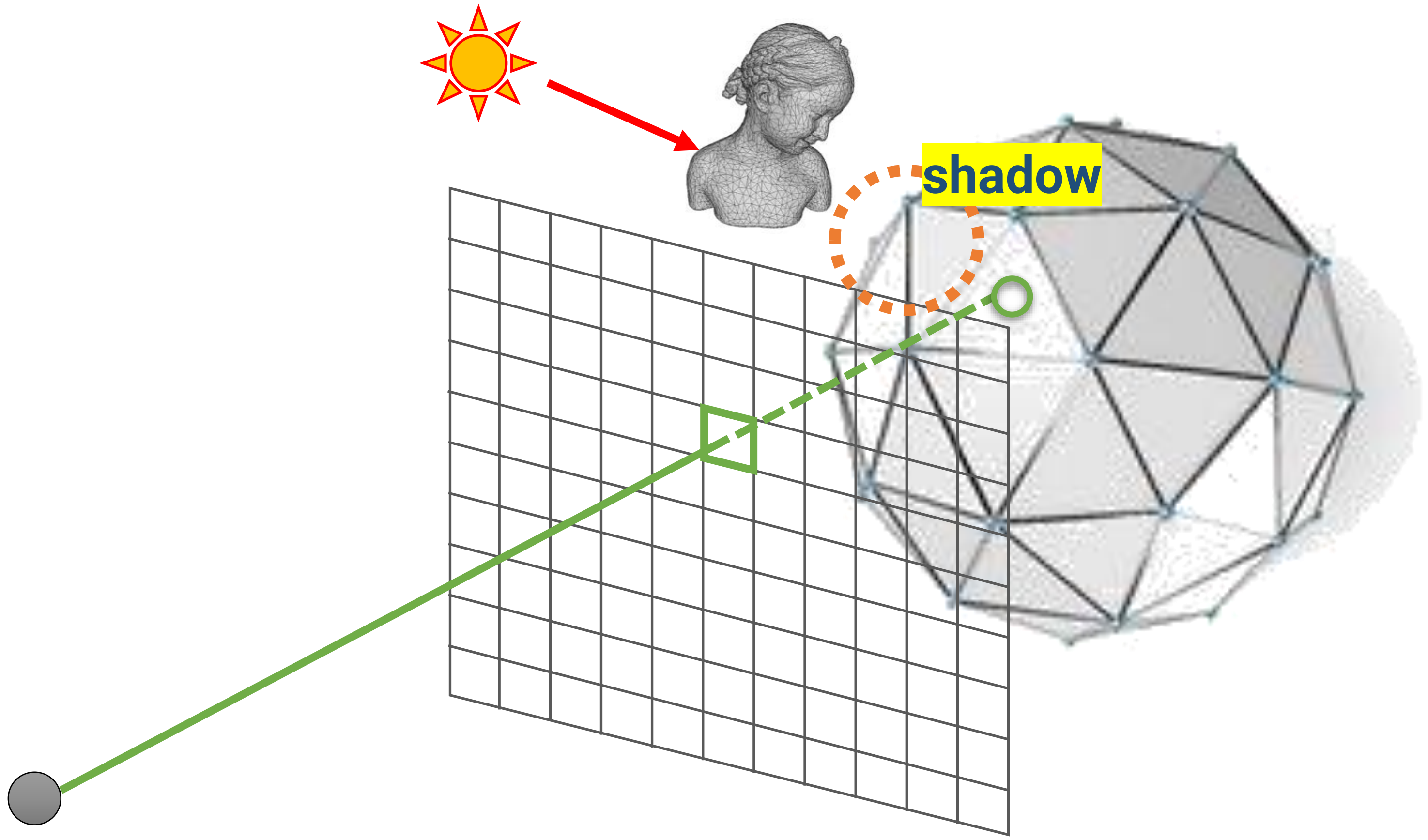
Shadow

- So far, we consider the light to be fully visible to a shading point



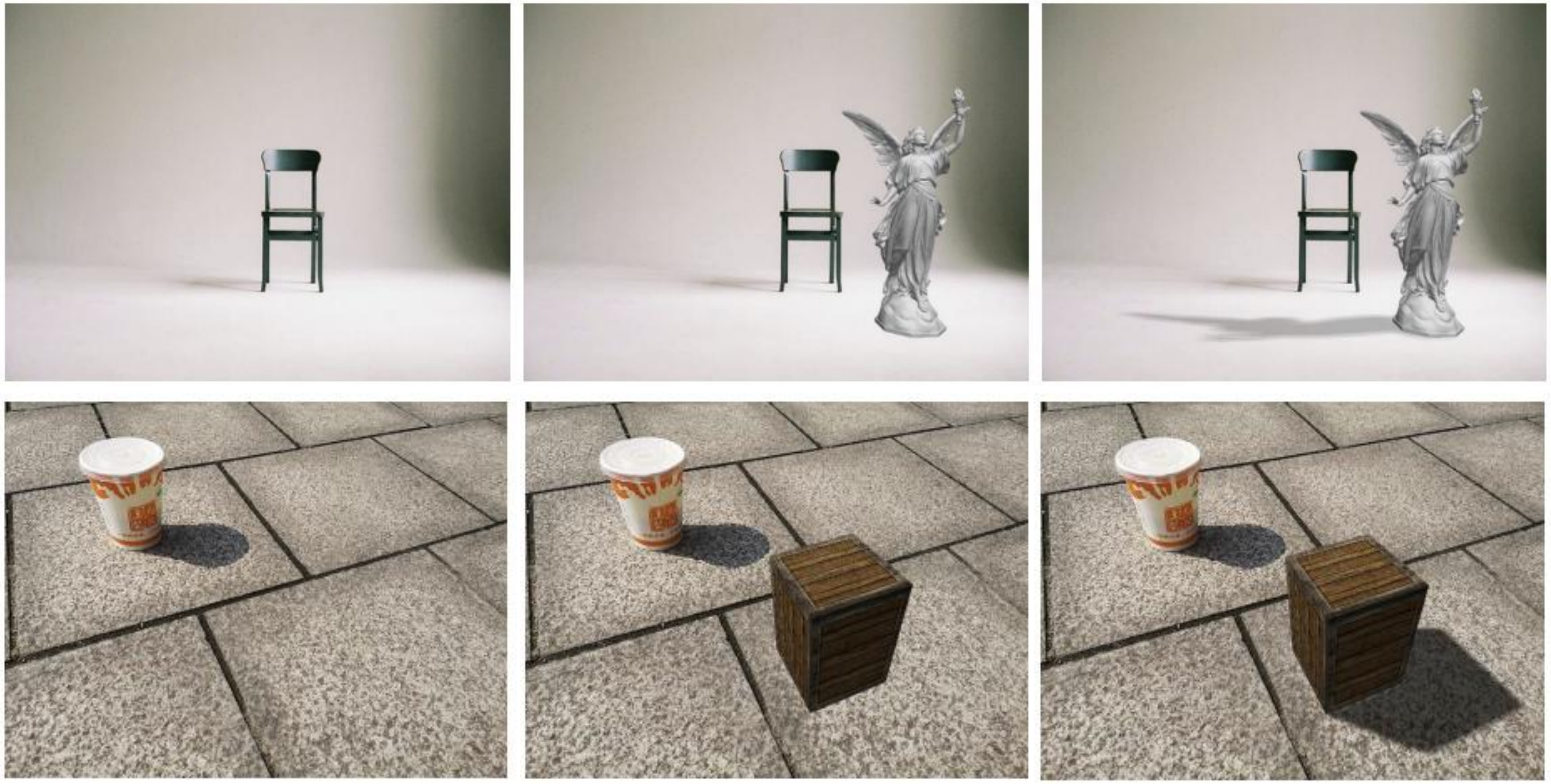
Shadow (cont.)

- It is common that a lighting direction is occluded by some other objects



Shadow (cont.)

- Shadows are very important to provide depth cues



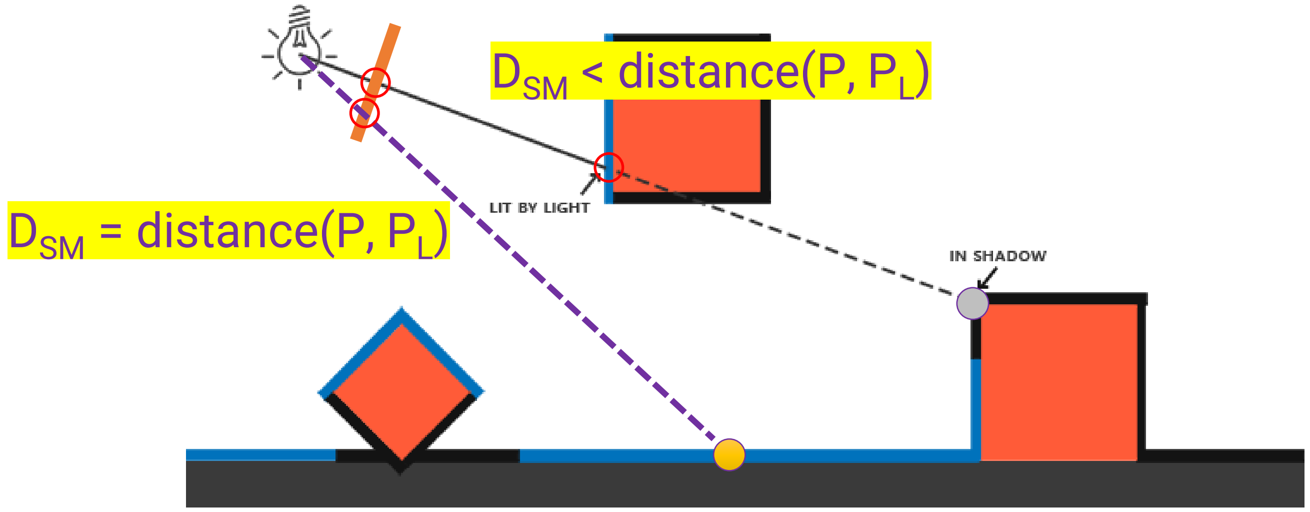
Shadow Map Overview

- Like the case of transparency, rendering shadows is difficult for rasterization because **each polygon only has its own information**
    - It does not know which triangle blocks the light, so it cannot determine the shadow attenuation in its fragment shader

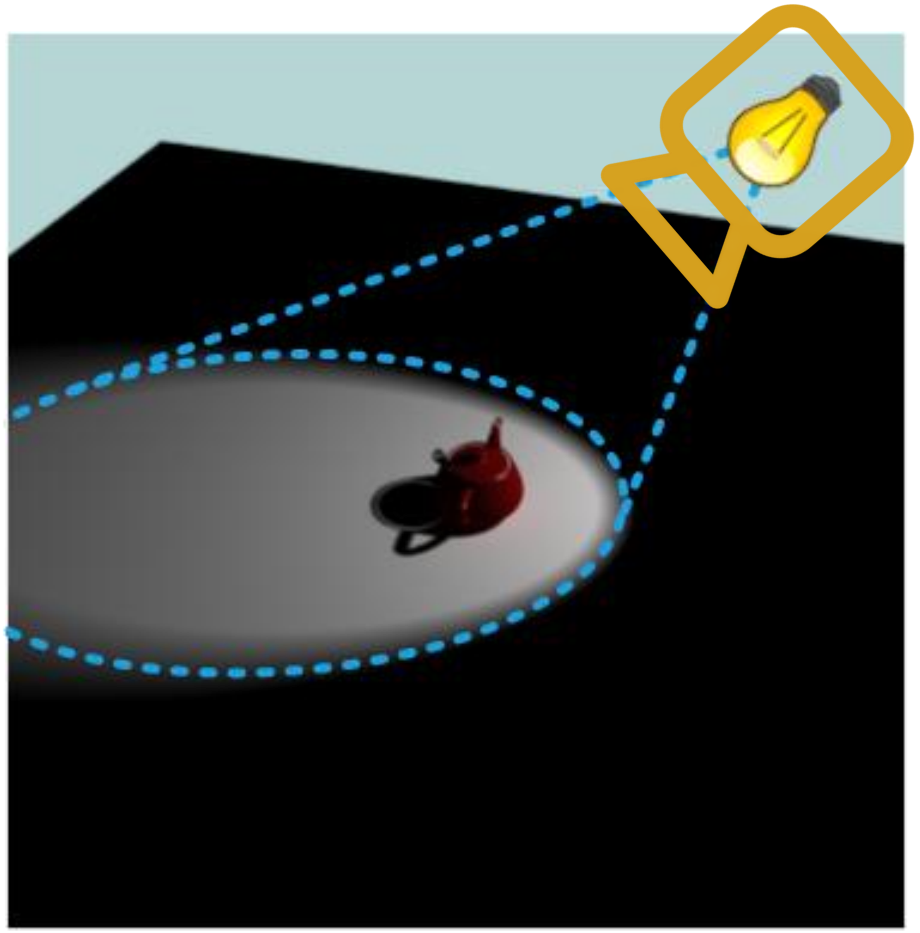
- **Shadow map** is a two-pass rendering technique for simulating shadows using rasterization

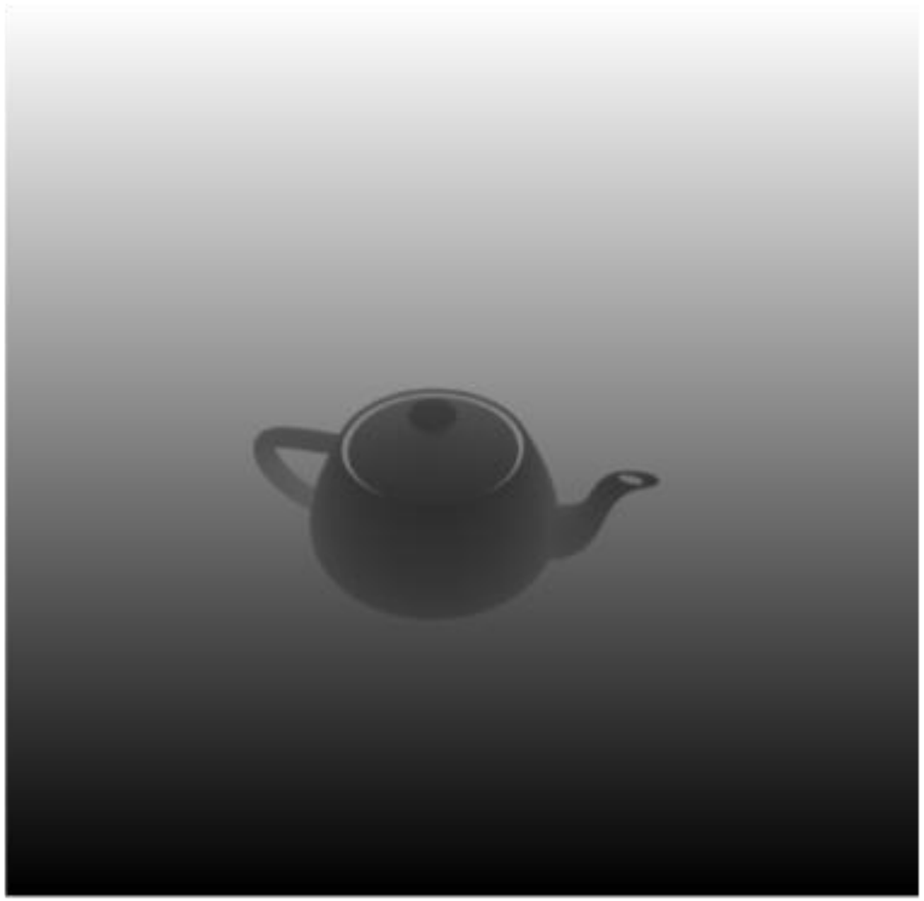
Shadow Map Overview (cont.)

- Major concept
  - **First pass: rendering a depth map from the light position**
    - Record the closest surface from the light and generate a **shadow map**
  - **Second pass: rendering from the camera**
    - During lighting computation, lookup the shadow map to determine the shadow



Shadow Map Overview (cont.)



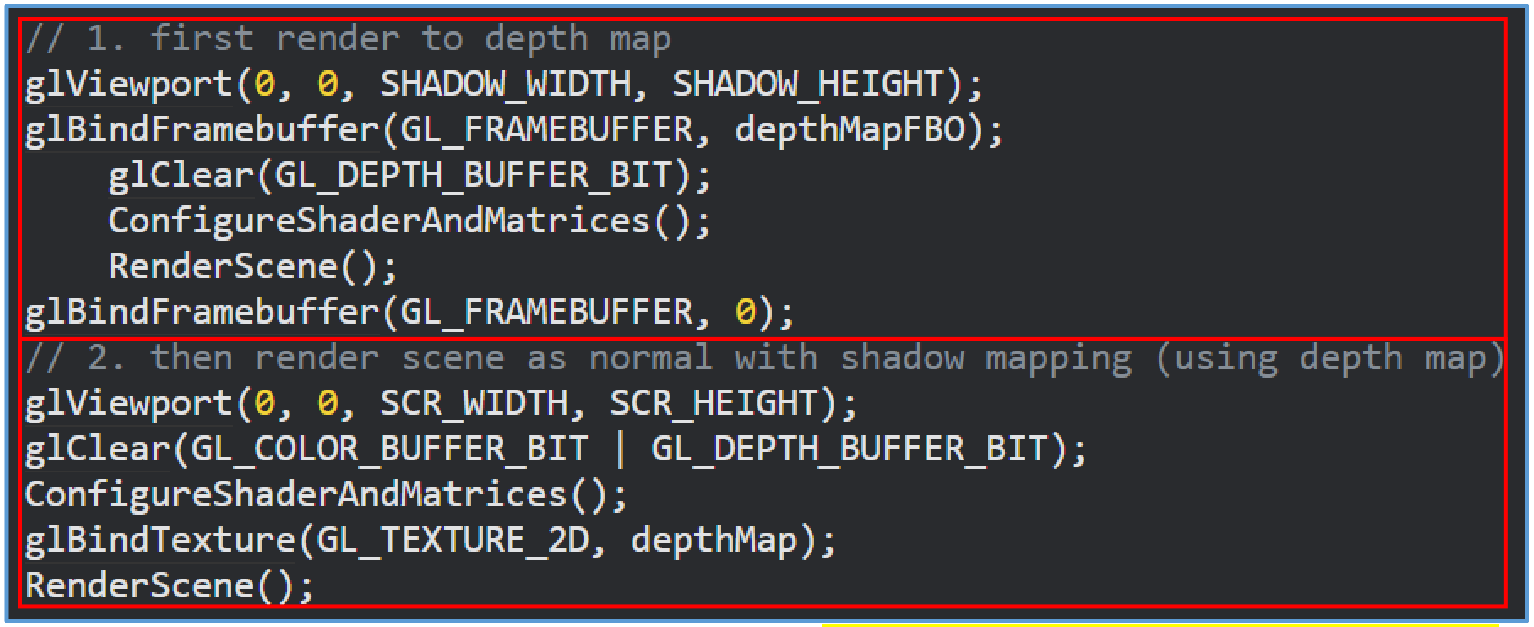


shadow map
(rendering from the light view)

Shadow Map Overview (cont.)

- Major concept
  - https://learnopengl.com/Advanced-Lighting/Shadows/Shadow-Mapping

rendering from the light view

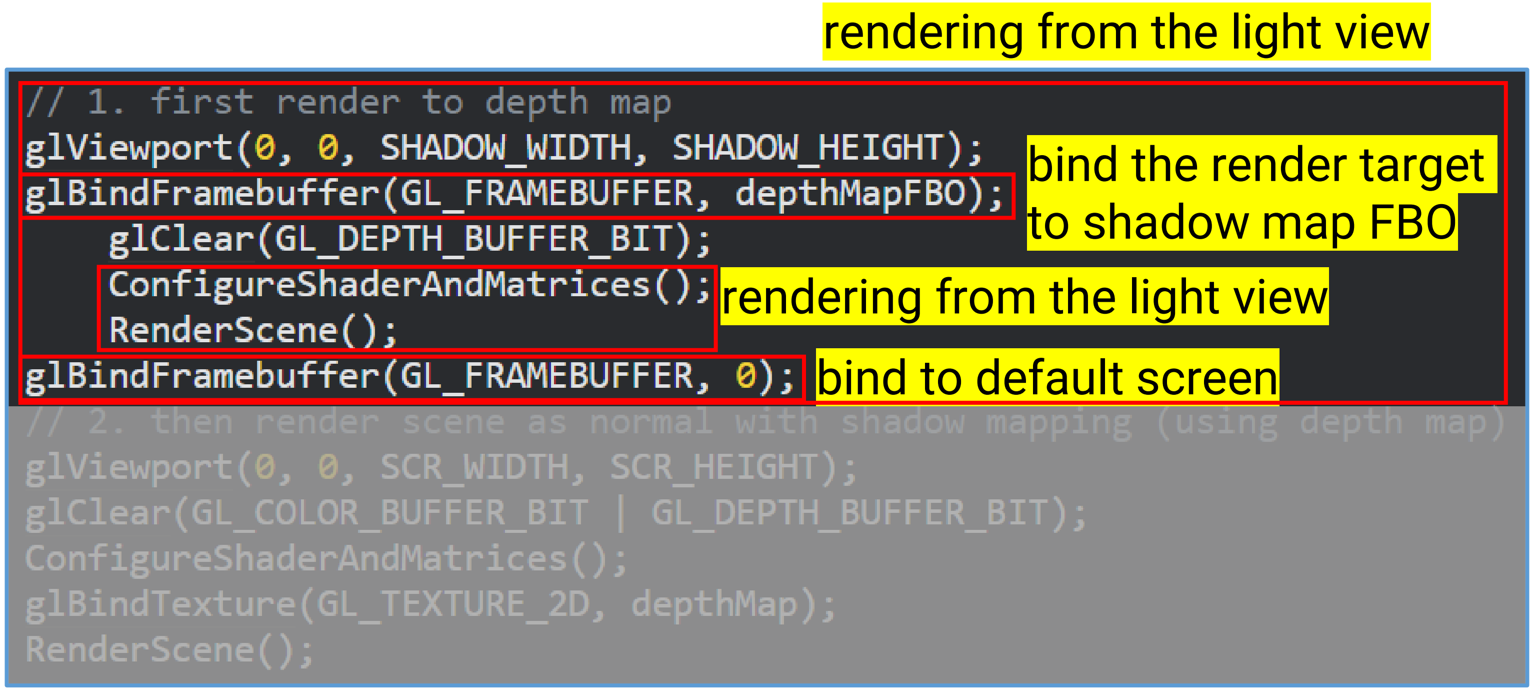


```
// 1. first render to depth map
glViewport(0, 0, SHADOW_WIDTH, SHADOW_HEIGHT);
glBindFramebuffer(GL_FRAMEBUFFER, depthMapFBO);
    glClear(GL_DEPTH_BUFFER_BIT);
    ConfigureShaderAndMatrices();
    RenderScene();
glBindFramebuffer(GL_FRAMEBUFFER, 0);
// 2. then render scene as normal with shadow mapping (using depth map)
glViewport(0, 0, SCR_WIDTH, SCR_HEIGHT);
glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
ConfigureShaderAndMatrices();
glBindTexture(GL_TEXTURE_2D, depthMap);
RenderScene();
```

rendering from the camera view

Shadow Map for Directional Lights

- **First pass: shadow map generation**

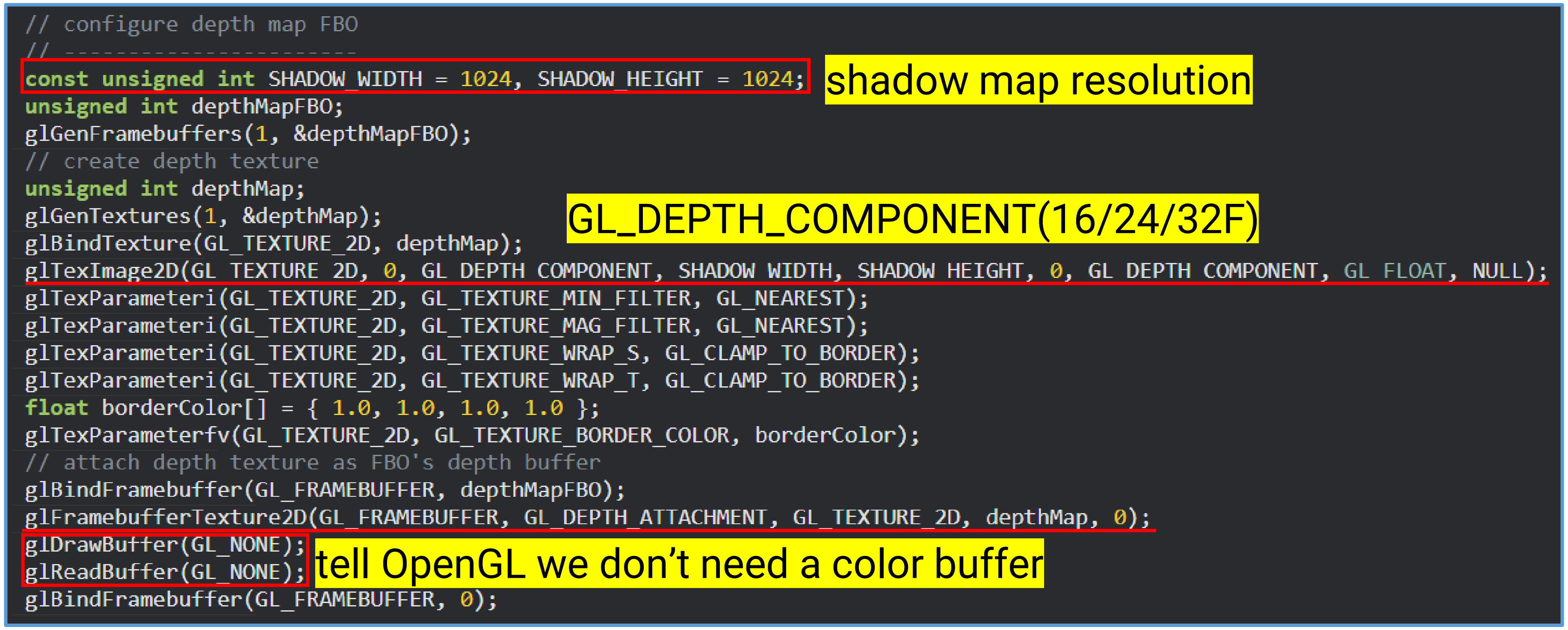


```
// 1. first render to depth map
glViewport(0, 0, SHADOW_WIDTH, SHADOW_HEIGHT);
glBindFramebuffer(GL_FRAMEBUFFER, depthMapFBO);
    glClear(GL_DEPTH_BUFFER_BIT);
    ConfigureShaderAndMatrices();
    RenderScene();
glBindFramebuffer(GL_FRAMEBUFFER, 0);
// 2. then render scene as normal with shadow mapping (using depth map)
glViewport(0, 0, SCR_WIDTH, SCR_HEIGHT);
glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
ConfigureShaderAndMatrices();
glBindTexture(GL_TEXTURE_2D, depthMap);
RenderScene();
```

rendering from the light view
bind the render target to shadow map FBO
rendering from the light view
bind to default screen

Shadow Map for Directional Lights (cont.)

- **First pass: shadow map generation**
  - Create a FBO for the shadow map



```
// configure depth map FBO
// -----------------------
const unsigned int SHADOW_WIDTH = 1024, SHADOW_HEIGHT = 1024;
unsigned int depthMapFBO;
glGenFramebuffers(1, &depthMapFBO);
// create depth texture
unsigned int depthMap;
glGenTextures(1, &depthMap);
glBindTexture(GL_TEXTURE_2D, depthMap);
glTexImage2D(GL_TEXTURE_2D, 0, GL_DEPTH_COMPONENT, SHADOW_WIDTH, SHADOW_HEIGHT, 0, GL_DEPTH_COMPONENT, GL_FLOAT, NULL);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_NEAREST);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_NEAREST);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_CLAMP_TO_BORDER);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_CLAMP_TO_BORDER);
float borderColor[] = { 1.0, 1.0, 1.0, 1.0 };
glTexParameterfv(GL_TEXTURE_2D, GL_TEXTURE_BORDER_COLOR, borderColor);
// attach depth texture as FBO's depth buffer
glBindFramebuffer(GL_FRAMEBUFFER, depthMapFBO);
glFramebufferTexture2D(GL_FRAMEBUFFER, GL_DEPTH_ATTACHMENT, GL_TEXTURE_2D, depthMap, 0);
glDrawBuffer(GL_NONE);
glReadBuffer(GL_NONE);
glBindFramebuffer(GL_FRAMEBUFFER, 0);
```

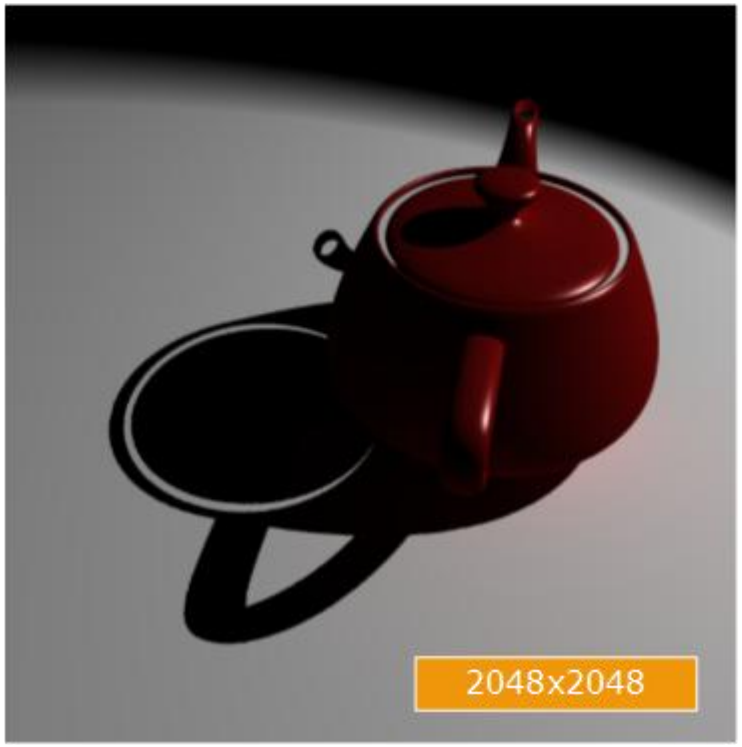
shadow map resolution

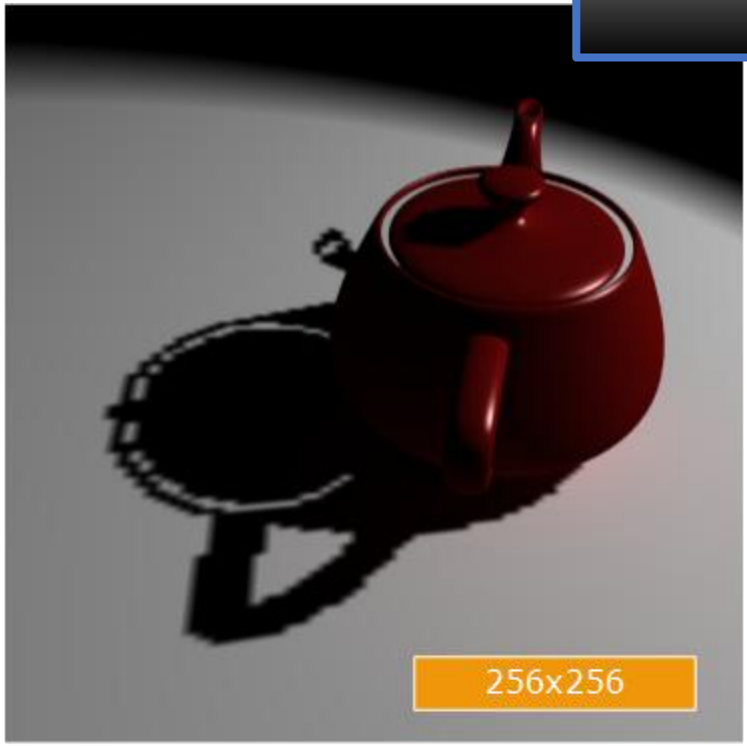
GL_DEPTH_COMPONENT(16/24/32F)

tell OpenGL we don’t need a color buffer

Shadow Map for Directional Lights (cont.)

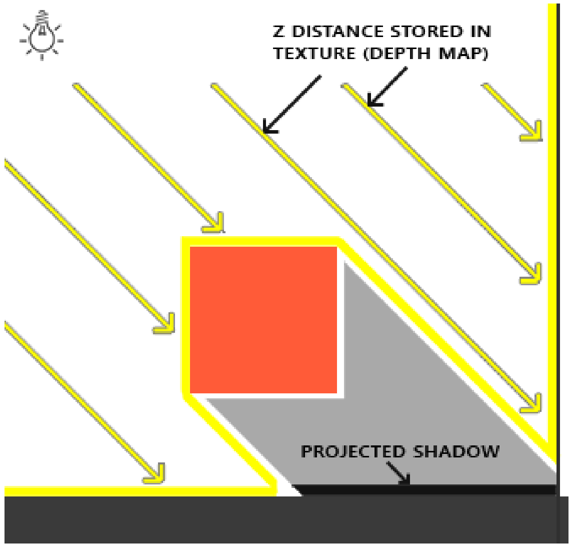
- **First pass: shadow map generation**
  - Choose a proper resolution

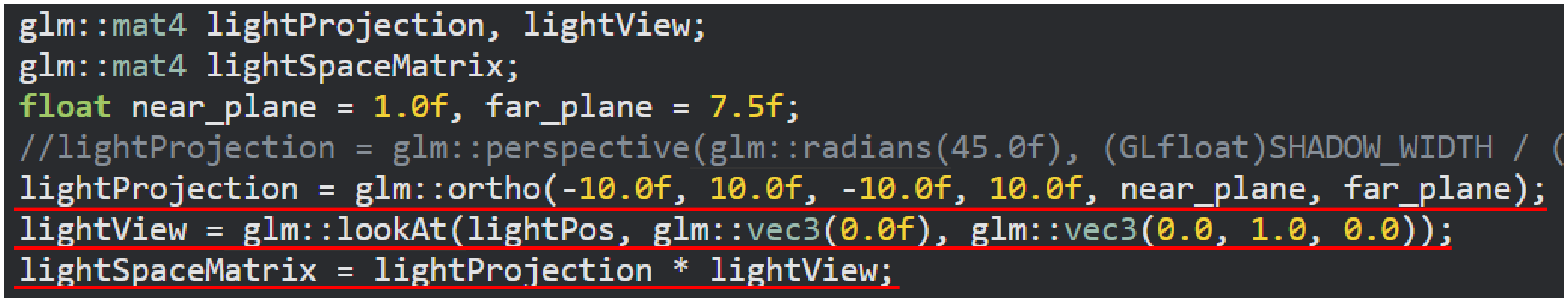




Shadow Map for Directional Lights (cont.)

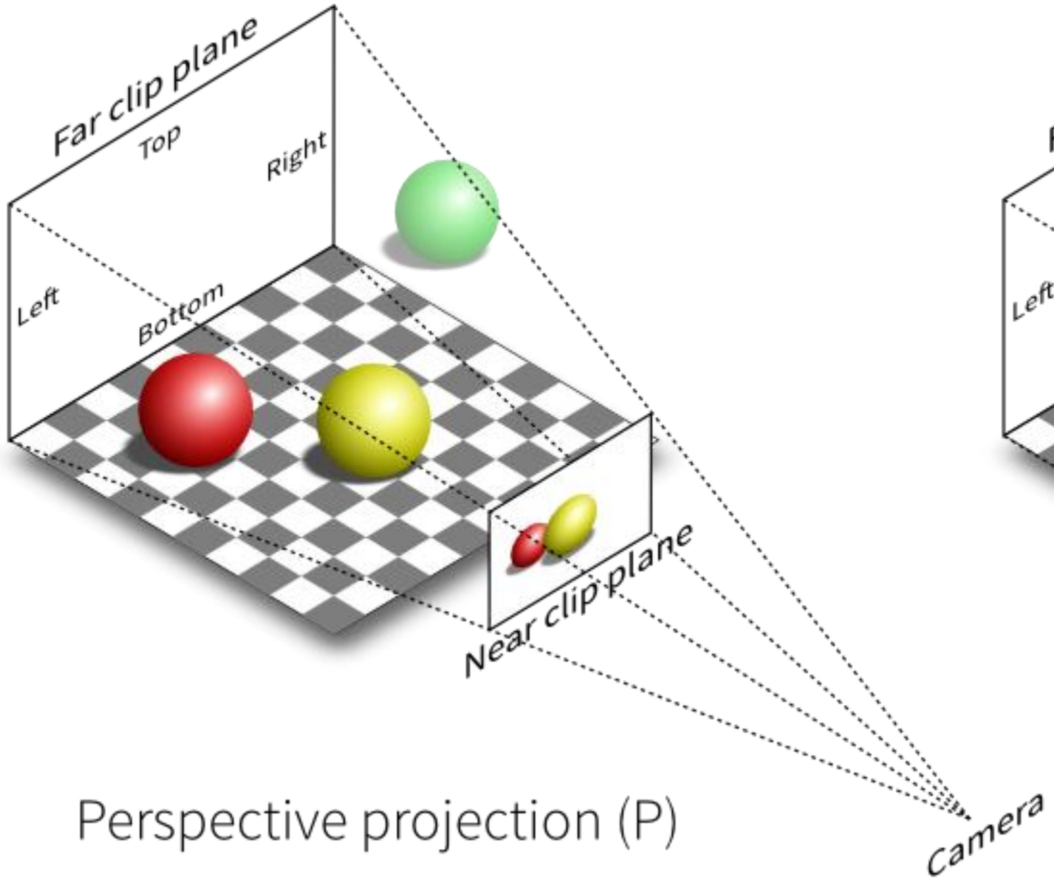
- **First pass: shadow map generation**
  - A directional light does not have a light position
  - We set the camera to a position somewhere **along the lines of the light direction**
  - Use **orthographic projection**



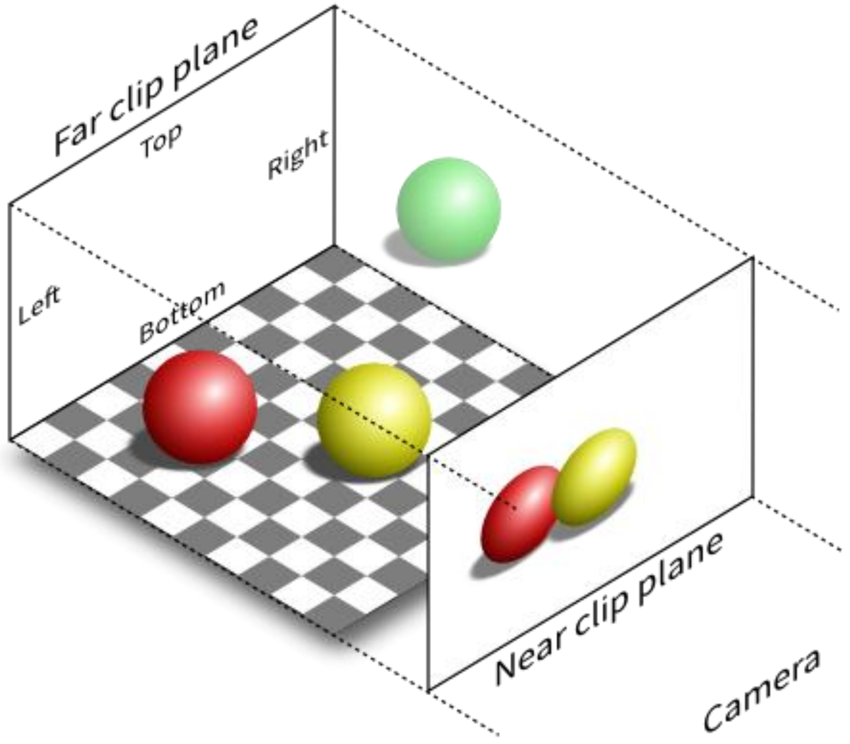


```
glm::mat4 lightProjection, lightView;
glm::mat4 lightSpaceMatrix;
float near_plane = 1.0f, far_plane = 7.5f;
//lightProjection = glm::perspective(glm::radians(45.0f), (GLfloat)SHADOW_WIDTH / (
lightProjection = glm::ortho(-10.0f, 10.0f, -10.0f, 10.0f, near_plane, far_plane);
lightView = glm::lookAt(lightPos, glm::vec3(0.0f), glm::vec3(0.0, 1.0, 0.0));
lightSpaceMatrix = lightProjection * lightView;
```

Recap: Projective Camera Models



Perspective projection (P)



Orthographic projection (O)

Shadow Map for Directional Lights (cont.)

- **First pass: shadow map generation**
  - Vertex Shader

```
#version 330 core
layout (location = 0) in vec3 aPos;

uniform mat4 lightSpaceMatrix;
uniform mat4 model;

void main()
{
    gl_Position = lightSpaceMatrix * model * vec4(aPos, 1.0);
}
```

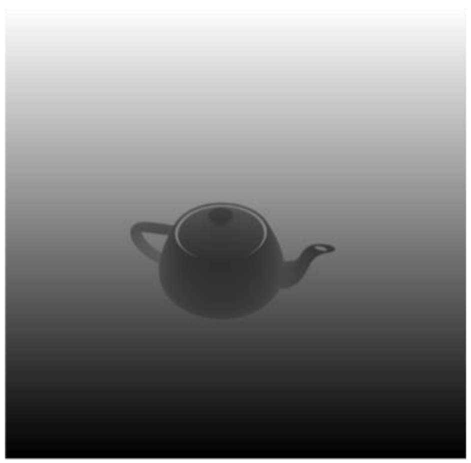
Proj. * View Matrix

Object Space

World Matrix

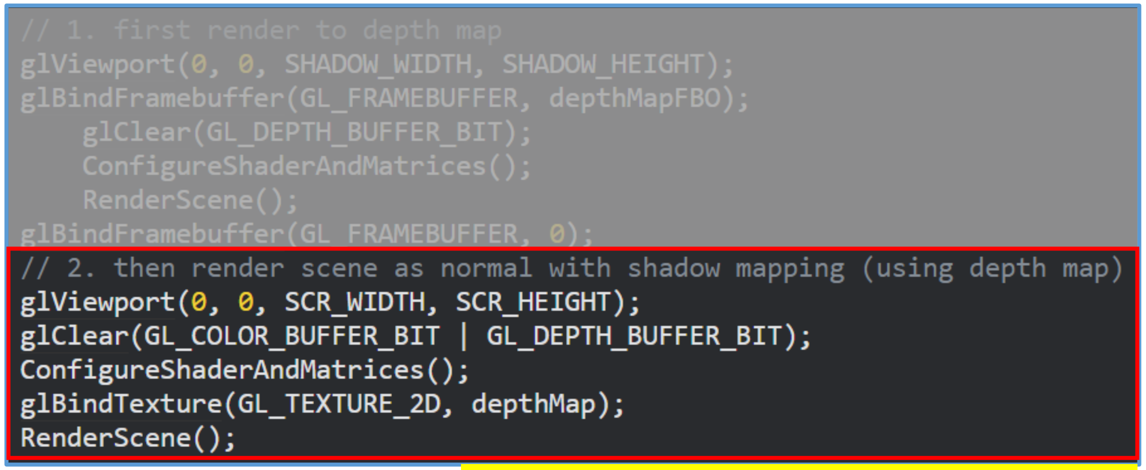
  - Fragment Shader (do nothing)

```
#version 330 core

void main()
{
    // gl_FragDepth = gl_FragCoord.z;
}
```



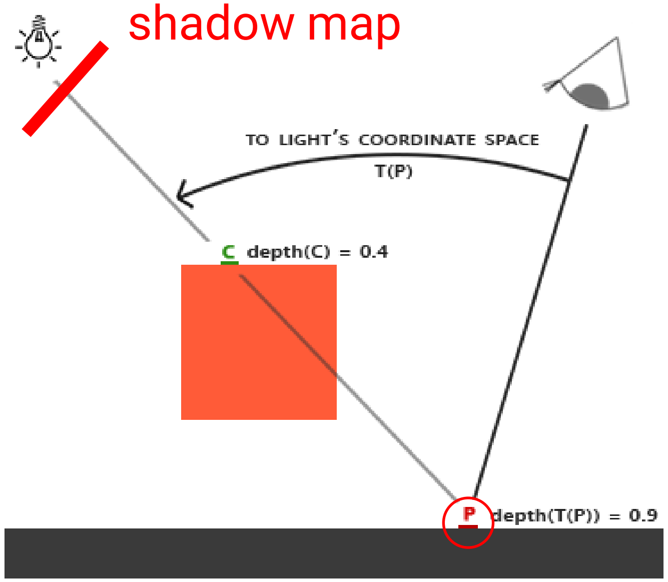
Shadow Map for Directional Lights (cont.)

- **Second pass: normal rendering**
  - Render the scene from the camera
  - Look up the shadow map to determine shadows during lighting computation



```
// 1. first render to depth map
glViewport(0, 0, SHADOW_WIDTH, SHADOW_HEIGHT);
glBindFramebuffer(GL_FRAMEBUFFER, depthMapFBO);
    glClear(GL_DEPTH_BUFFER_BIT);
    ConfigureShaderAndMatrices();
    RenderScene();
glBindFramebuffer(GL_FRAMEBUFFER, 0);
// 2. then render scene as normal with shadow mapping (using depth map)
glViewport(0, 0, SCR_WIDTH, SCR_HEIGHT);
glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
ConfigureShaderAndMatrices();
glBindTexture(GL_TEXTURE_2D, depthMap);
RenderScene();
```

rendering from the camera view



shading point (fragment)

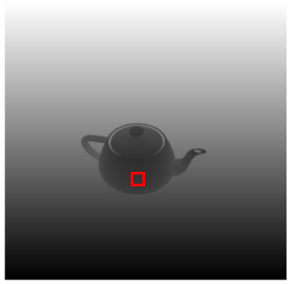
Shadow Map for Directional Lights (cont.)

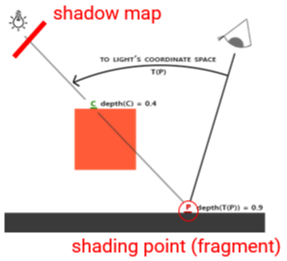
- **Second pass: normal rendering**
  - Vertex Shader

```
#version 330 core
layout (location = 0) in vec3 aPos;
layout (location = 1) in vec3 aNormal;
layout (location = 2) in vec2 aTexCoords;

out VS_OUT {
    vec3 FragPos;
    vec3 Normal;
    vec2 TexCoords;
    vec4 FragPosLightSpace;
} vs_out;

uniform mat4 projection;
uniform mat4 view;
uniform mat4 model;
uniform mat4 lightSpaceMatrix;

void main()
{
    vs_out.FragPos = vec3(model * vec4(aPos, 1.0));
    vs_out.Normal = transpose(inverse(mat3(model))) * aNormal;
    vs_out.TexCoords = aTexCoords;
    vs_out.FragPosLightSpace = lightSpaceMatrix * vec4(vs_out.FragPos, 1.0);
    gl_Position = projection * view * vec4(vs_out.FragPos, 1.0);
}
```

data to be interpolated

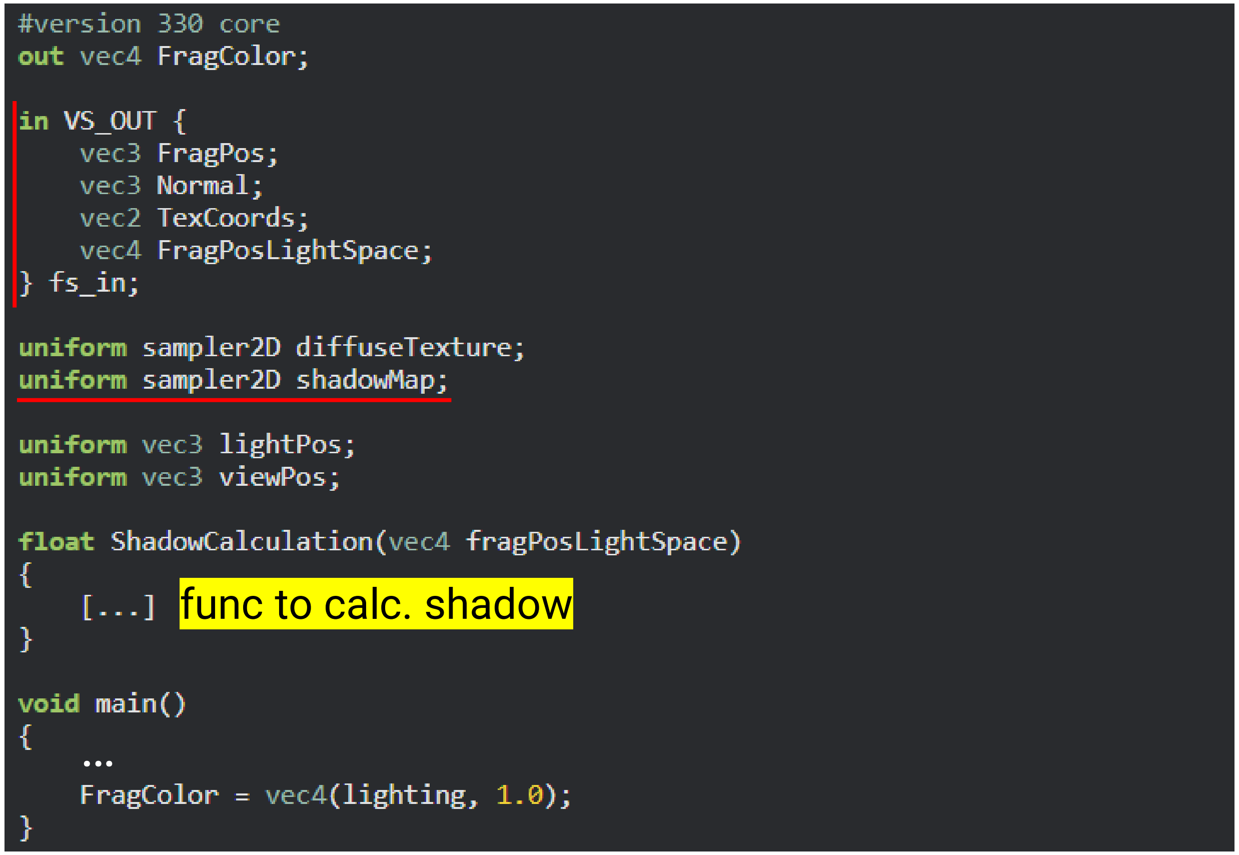
Clip Space coordinate of light space (for looking up the shadow map)





Shadow Map for Directional Lights (cont.)

- **Second pass: normal rendering**
  - Fragment Shader



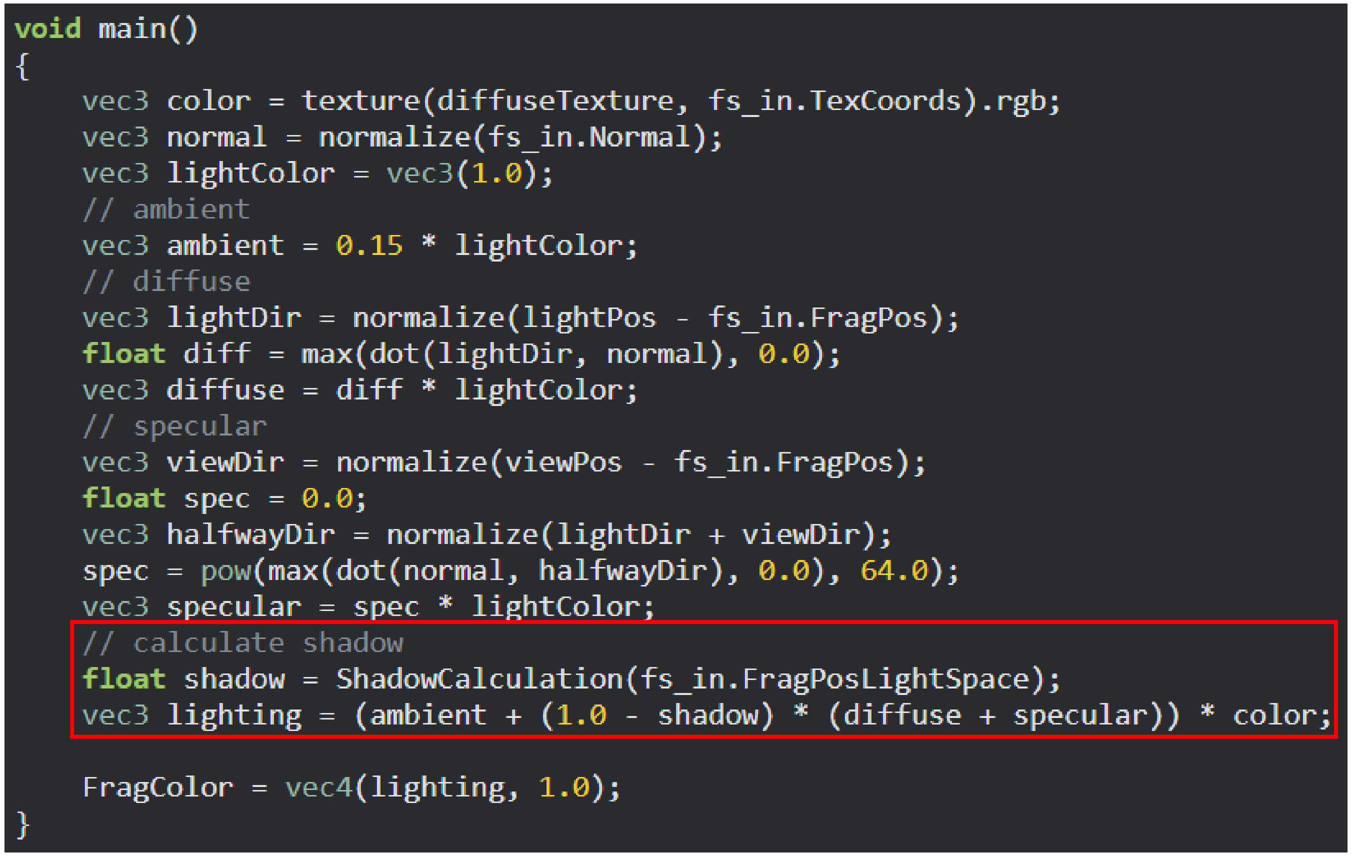
```
#version 330 core
out vec4 FragColor;

in VS_OUT {
    vec3 FragPos;
    vec3 Normal;
    vec2 TexCoords;
    vec4 FragPosLightSpace;
} fs_in;

uniform sampler2D diffuseTexture;
uniform sampler2D shadowMap;

uniform vec3 lightPos;
uniform vec3 viewPos;

float ShadowCalculation(vec4 fragPosLightSpace)
{
    [...]
}

void main()
{
    ...
    FragColor = vec4(lighting, 1.0);
}
```

interpolated data

func to calc. shadow

Shadow Map for Directional Lights (cont.)

- **Second pass: normal rendering**
  - Fragment Shader



```
void main()
{
    vec3 color = texture(diffuseTexture, fs_in.TexCoords).rgb;
    vec3 normal = normalize(fs_in.Normal);
    vec3 lightColor = vec3(1.0);
    // ambient
    vec3 ambient = 0.15 * lightColor;
    // diffuse
    vec3 lightDir = normalize(lightPos - fs_in.FragPos);
    float diff = max(dot(lightDir, normal), 0.0);
    vec3 diffuse = diff * lightColor;
    // specular
    vec3 viewDir = normalize(viewPos - fs_in.FragPos);
    float spec = 0.0;
    vec3 halfwayDir = normalize(lightDir + viewDir);
    spec = pow(max(dot(normal, halfwayDir), 0.0), 64.0);
    vec3 specular = spec * lightColor;
    // calculate shadow
    float shadow = ShadowCalculation(fs_in.FragPosLightSpace);
    vec3 lighting = (ambient + (1.0 - shadow) * (diffuse + specular)) * color;

    FragColor = vec4(lighting, 1.0);
}
```

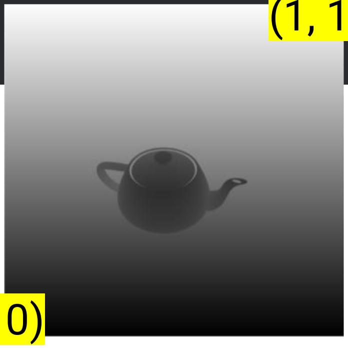
Shadow Map for Directional Lights (cont.)

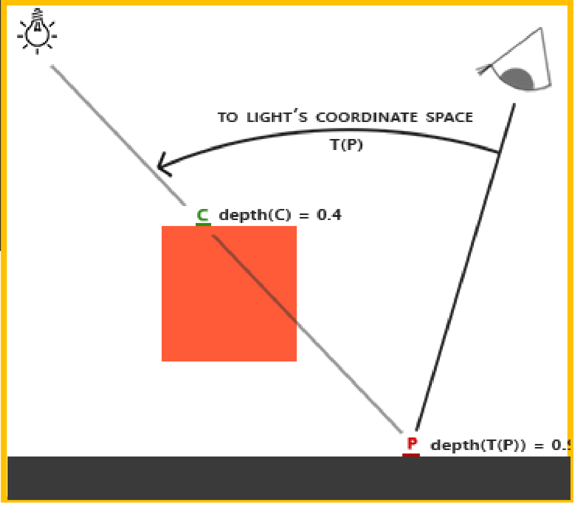
- **Second pass: normal rendering**
  - Fragment Shader

```
float ShadowCalculation(vec4 fragPosLightSpace)
{
    // perform perspective divide
    vec3 projCoords = fragPosLightSpace.xyz / fragPosLightSpace.w;
    // transform to [0,1] range
    projCoords = projCoords * 0.5 + 0.5;
    // get closest depth value from light's perspective (using [0,1] range fragPosLight as coords)
    float closestDepth = texture(shadowMap, projCoords.xy).r;
    // get depth of current fragment from light's perspective
    float currentDepth = projCoords.z;
    // check whether current frag pos is in shadow
    float shadow = currentDepth > closestDepth  ? 1.0 : 0.0;

    return shadow;
}
```

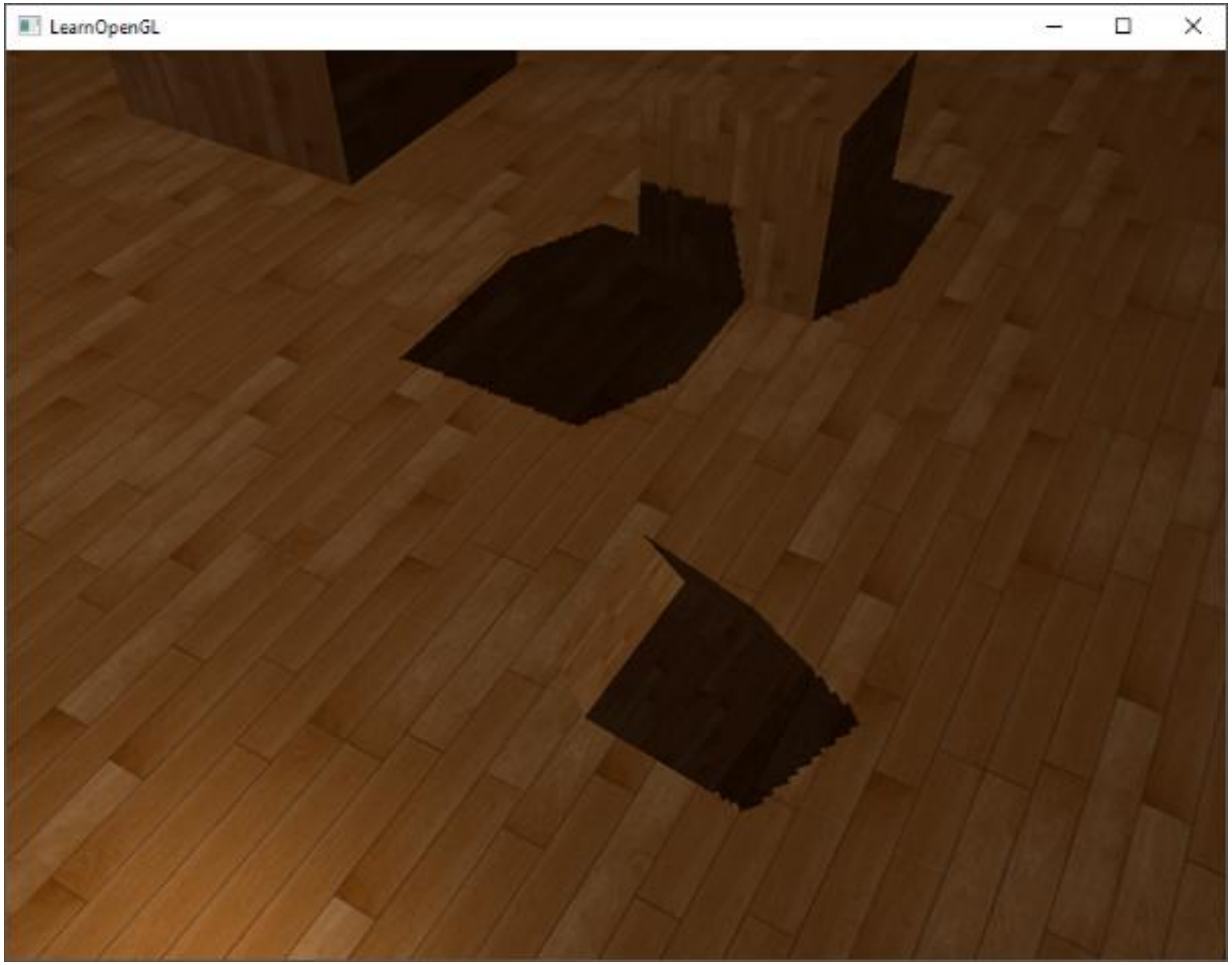
to NDC [-1, 1]

to [0, 1] for looking up the shadow map



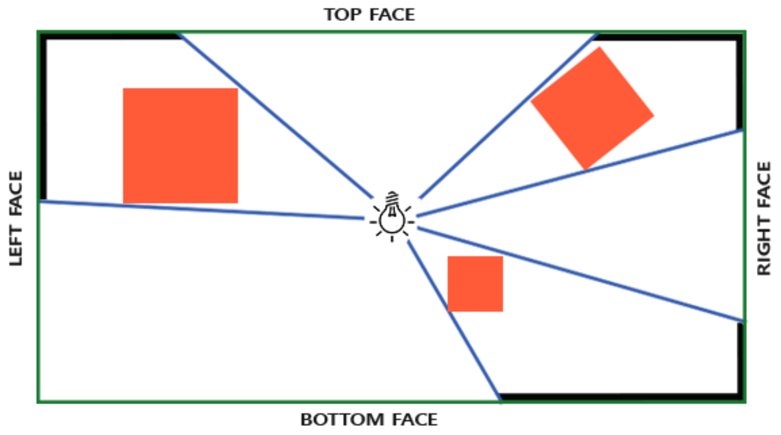


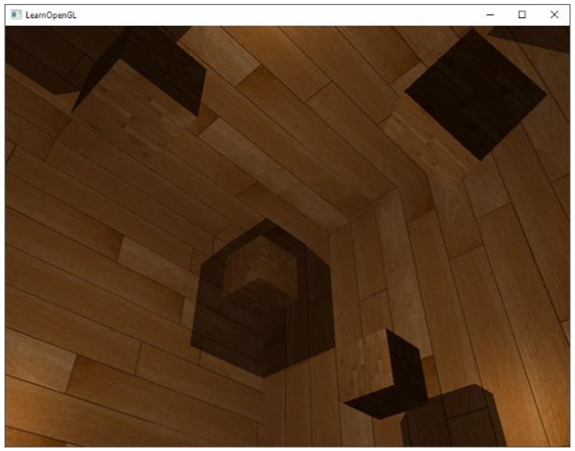
Shadow Map for Directional Lights (cont.)



Shadow Map for Point / Spot Lights

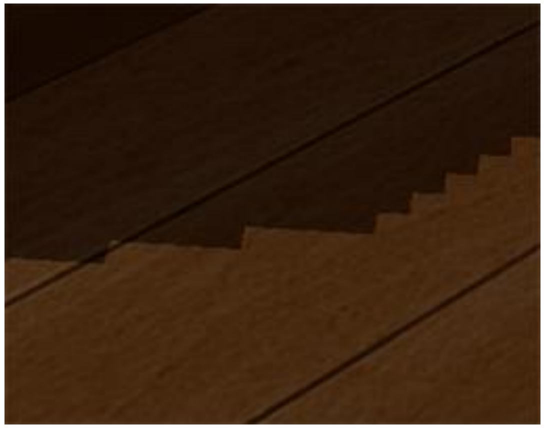
- Generate a shadow map for a **spotlight** is intuitive
  - Locate the camera at the position of the spotlight
  - Use the direction of the spotlight for viewing direction
  - Use **perspective** projection instead of orthogonal projection
- For a point light, you need to render the scene depth into a **cubemap** because the light emits in omni directions
  - https://learnopengl.com/Advanced-Lighting/Shadows/Point-Shadows





Percentage Closer Filtering

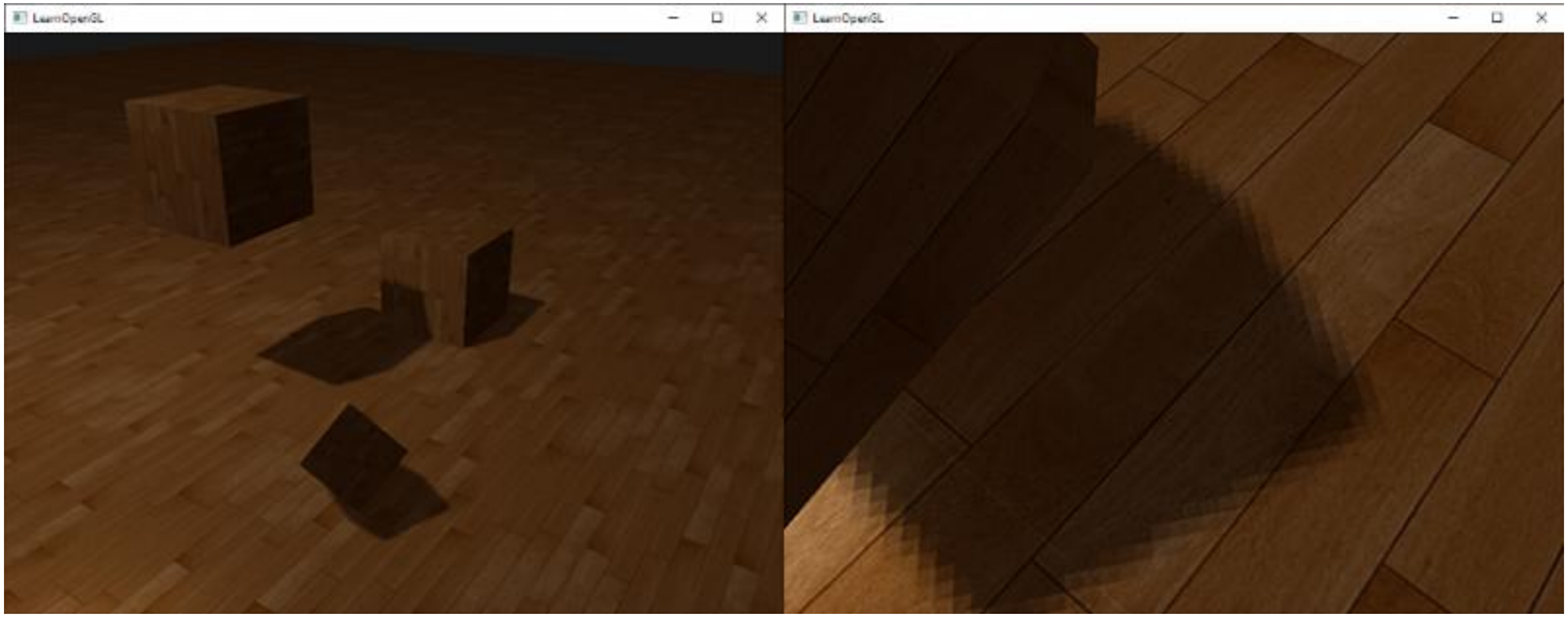
- The shadow map has a fixed (and limited) resolution
- A single lookup of a shadow map often produces jagged blocky edges



- We can reduce these blocky shadows by increasing the depth map resolution, or
- **Sampling more than once** from the depth map, each time with slightly different texture coordinates, and **averaging** the results

Percentage Closer Filtering

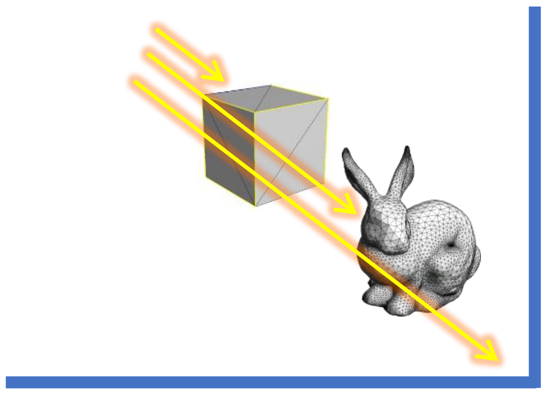
```
float shadow = 0.0;
vec2 texelSize = 1.0 / textureSize(shadowMap, 0);
for(int x = -1; x <= 1; ++x)
{
    for(int y = -1; y <= 1; ++y)
    {
        float pcfDepth = texture(shadowMap, projCoords.xy + vec2(x, y) * texelSize).r;
        shadow += currentDepth - bias > pcfDepth ? 1.0 : 0.0;
    }
}
shadow /= 9.0;
```

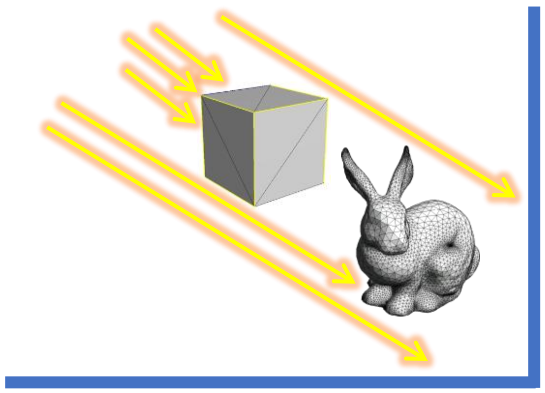


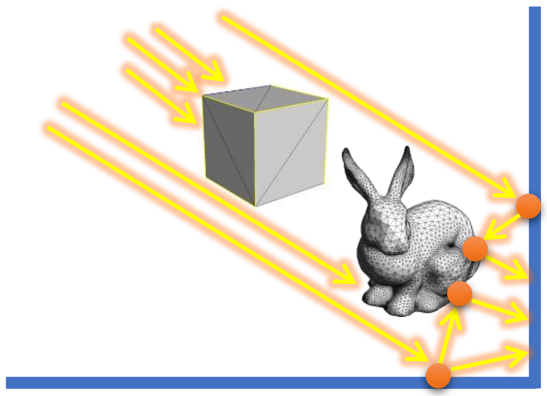
Ambient Occlusion

Recap: Global Illumination

- Global illumination includes multi-bounce lighting
- Very expensive to compute
- In Phong lighting model, a **constant ambient term** is used to account for disregarded illumination
  - However, this produces a “flat”, “non-photo-realistic” appearance

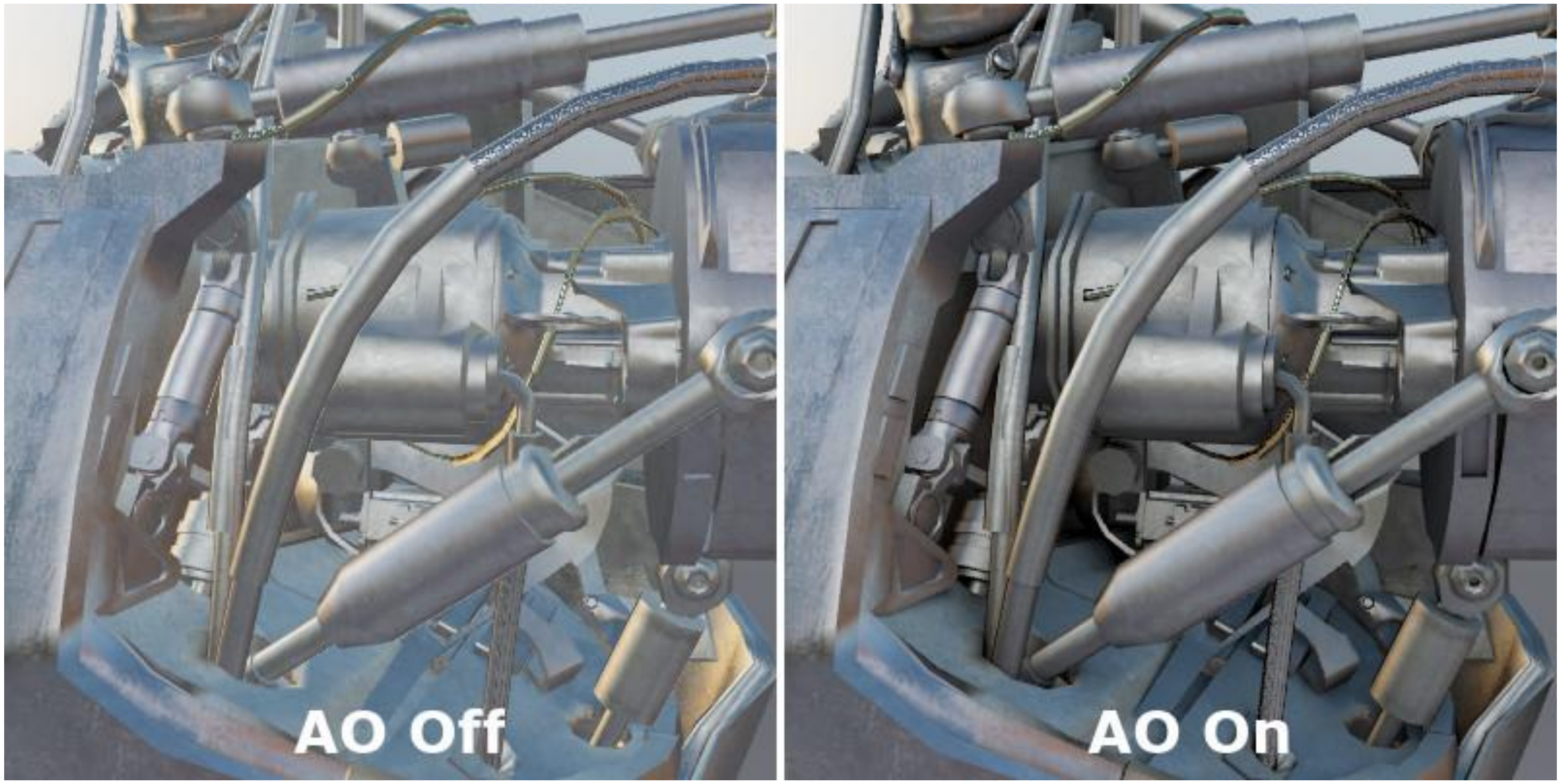

local illumination


direct illumination


global illumination

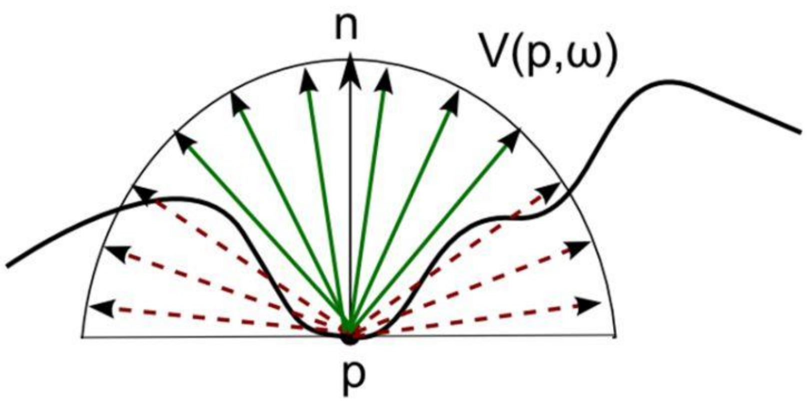
Ambient Occlusion

- Ambient occlusion (AO) is a popular technique to approximate global illumination

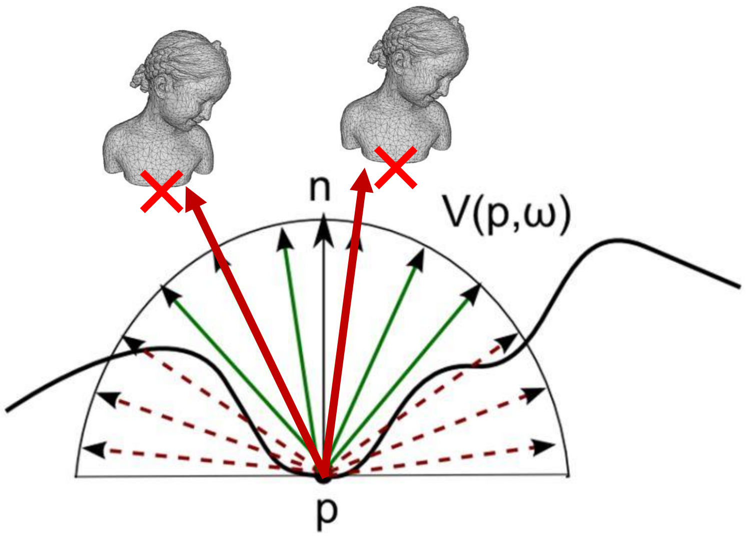


Ambient Occlusion (cont.)

- **Ambient occlusion (AO)** is a popular technique to approximate global illumination
  - Modulate ambient light by the surface's **accessibility**
  - Greatly enhance **depth perception** with a relatively low cost

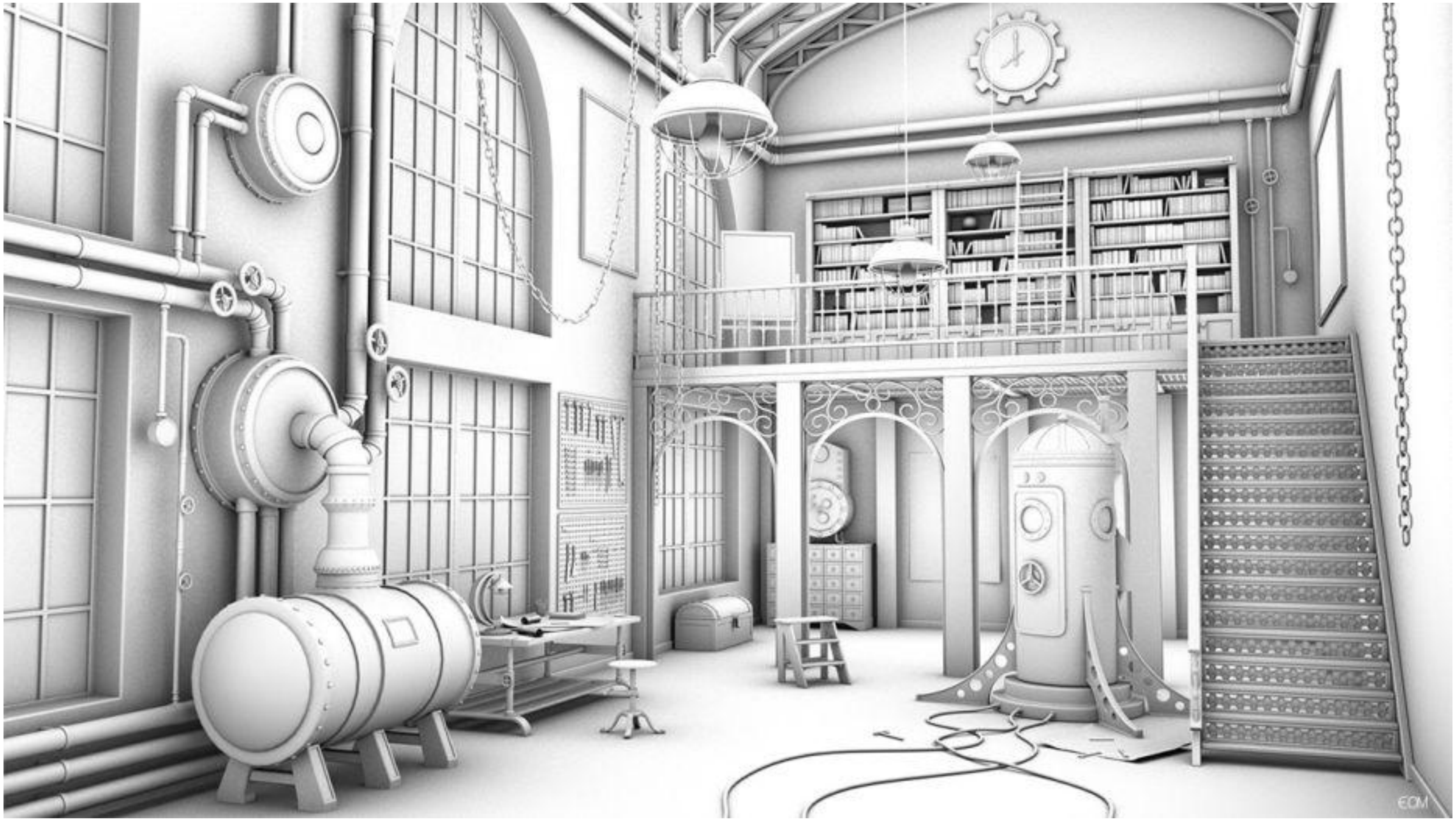


$$AO(\mathbf{p},\mathbf{n}) = \frac{1}{\pi}\int_{\Omega} V(\mathbf{p},\omega)\,\mathbf{n}\cdot\omega\, d\omega,$$

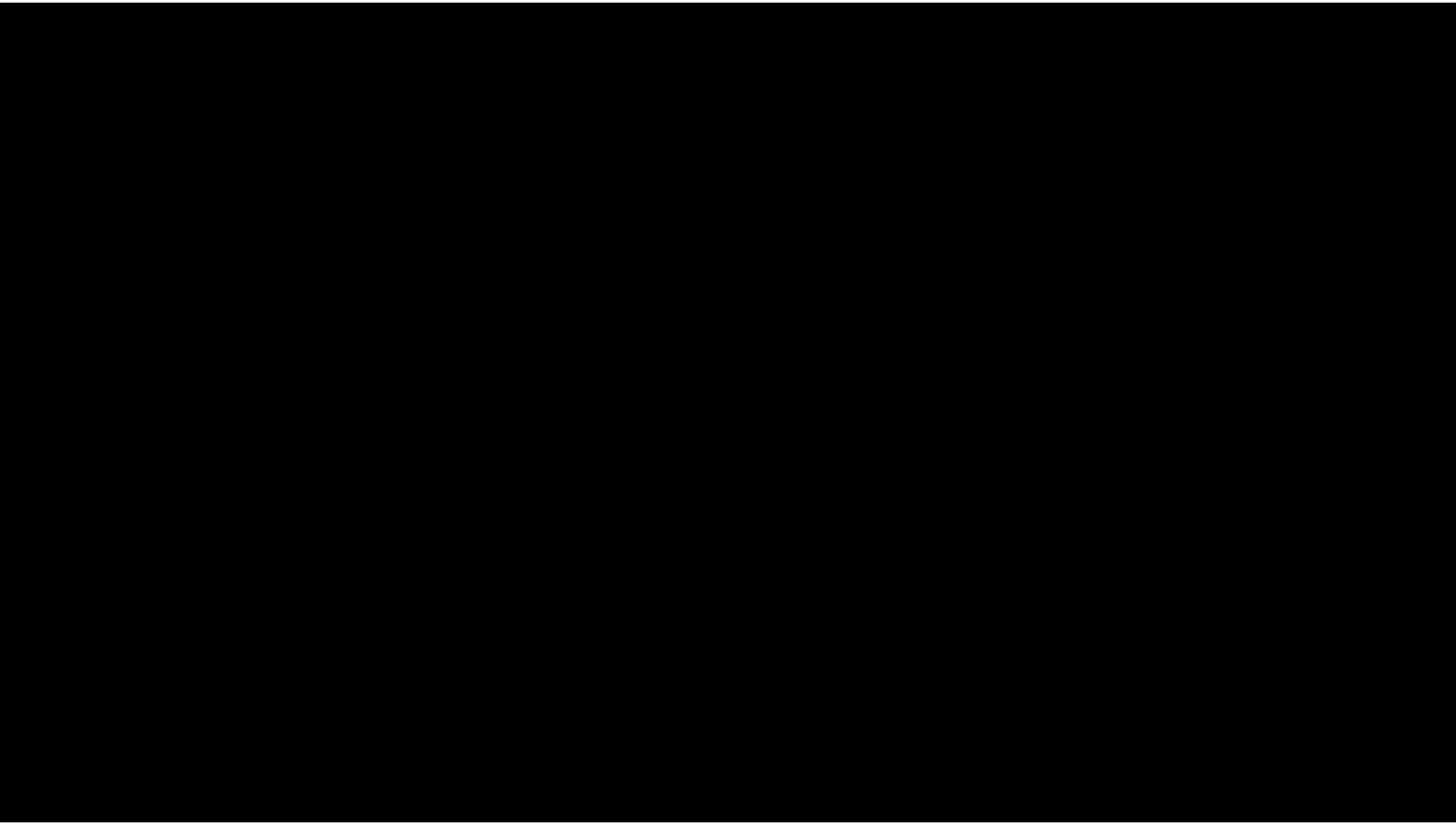


$$AO(\mathbf{p},\mathbf{n}) = \frac{1}{\pi}\int_{\Omega} V(\mathbf{p},\omega)\,\mathbf{n}\cdot\omega\, d\omega,$$

Ambient Occlusion (cont.)

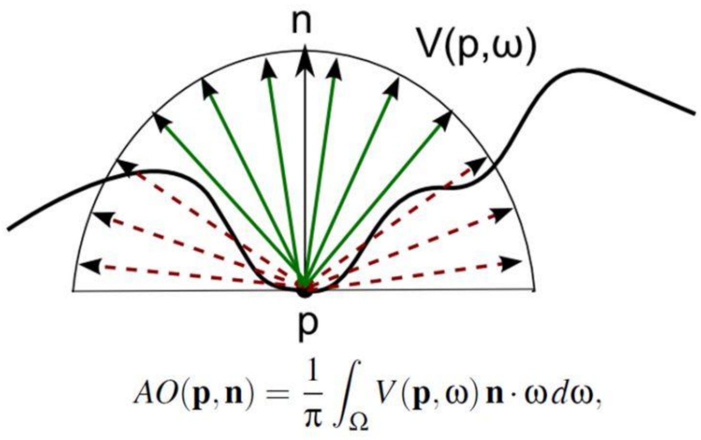


Ambient Occlusion (cont.)

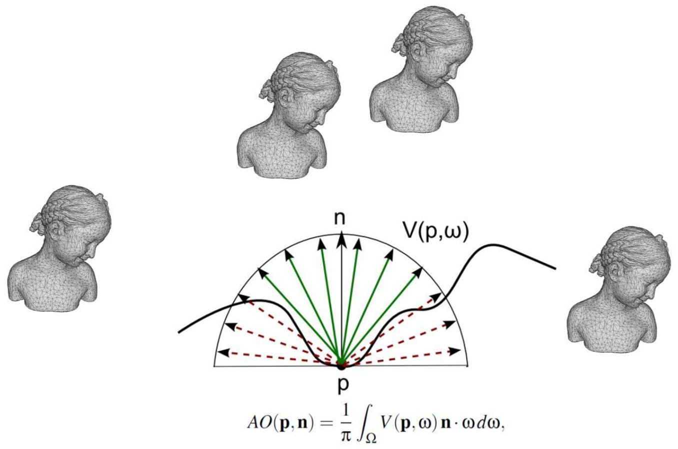


Ambient Occlusion

- To compute AO, you need to know whether the ambient light is occluded in a direction
- In ray tracing, you can **trace rays** to determine the visibility
- For rasterization; however, this is difficult because **each polygon only knows its information** (again!)
  - Performance is also an issue!



$$AO(\mathbf{p},\mathbf{n}) = \frac{1}{\pi}\int_{\Omega} V(\mathbf{p},\omega)\,\mathbf{n}\cdot\omega\, d\omega,$$

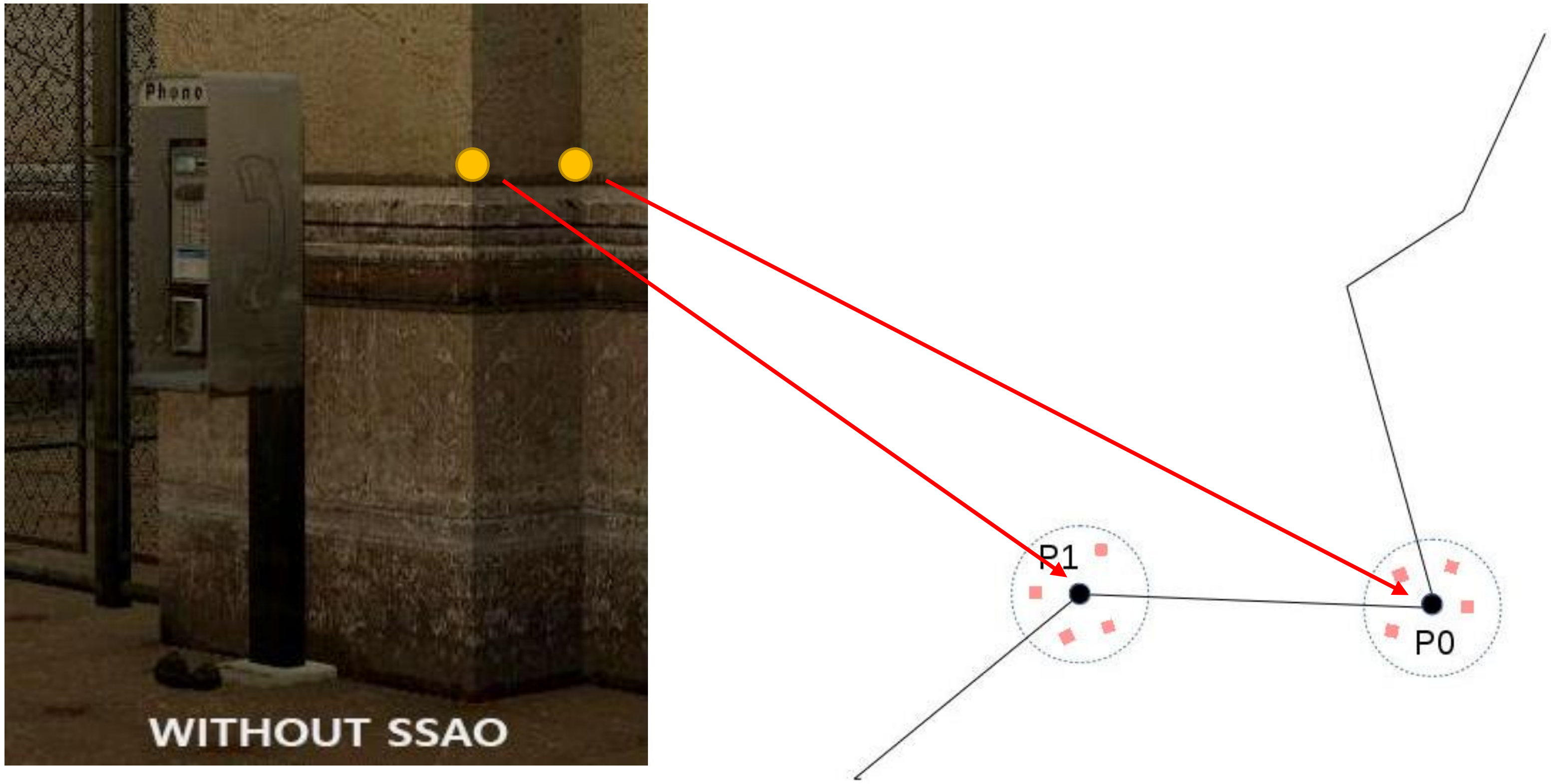

n
V(p,ω)
p
$AO(\mathbf{p},\mathbf{n}) = \frac{1}{\pi}\int_{\Omega} V(\mathbf{p},\omega)\,\mathbf{n}\cdot\omega\, d\omega,$

Screen-space Ambient Occlusion

- Crytek implemented a real-time solution for ***Crysis***
  - Quickly became the yardstick for game graphics
  - Known as screen-space ambient occlusion (**SSAO**)
- Major idea
  - Find nearby occluders in the **depth buffer (screen-space)**

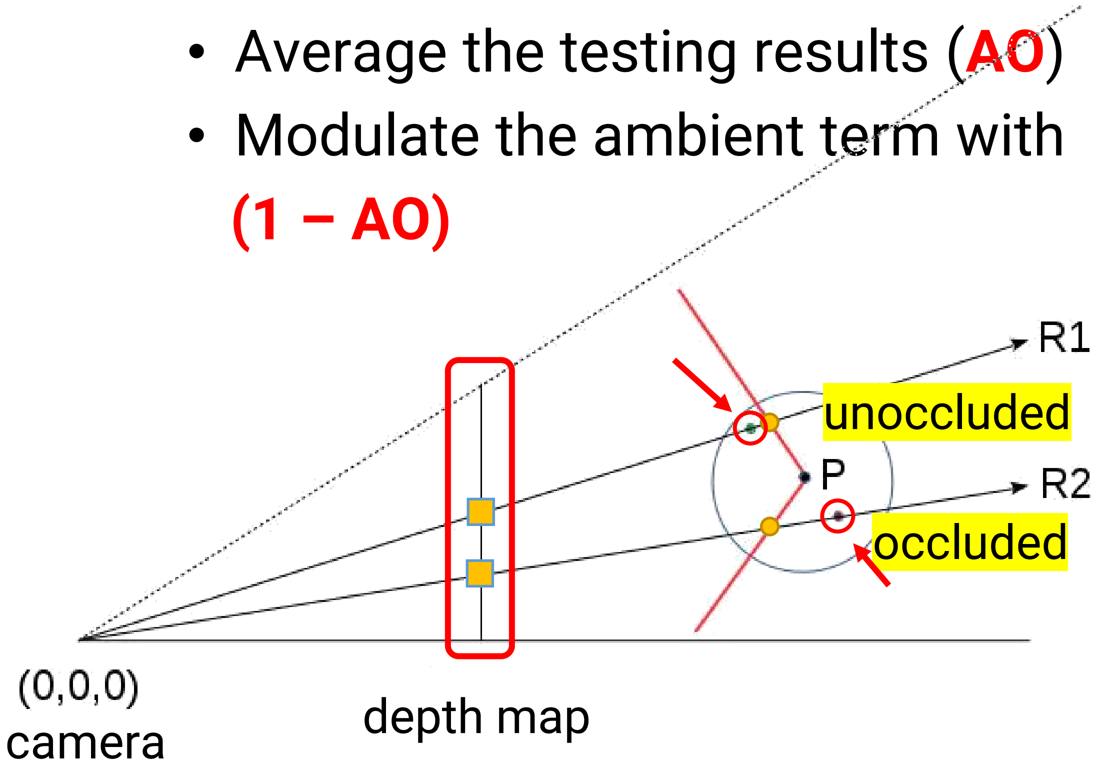
Screen-space Ambient Occlusion (cont.)

- Method
  - Generate samples within a sphere around the shading point (fragment)



Screen-space Ambient Occlusion (cont.)

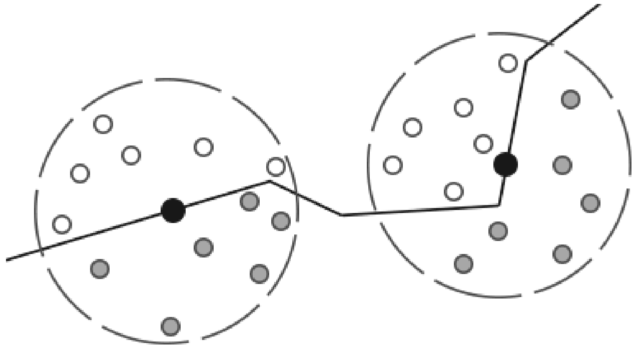
- Method
  - Project the samples back to the depth map from the camera
  - Compare the depth values
  - Average the testing results (**AO**)
  - Modulate the ambient term with **(1 – AO)**

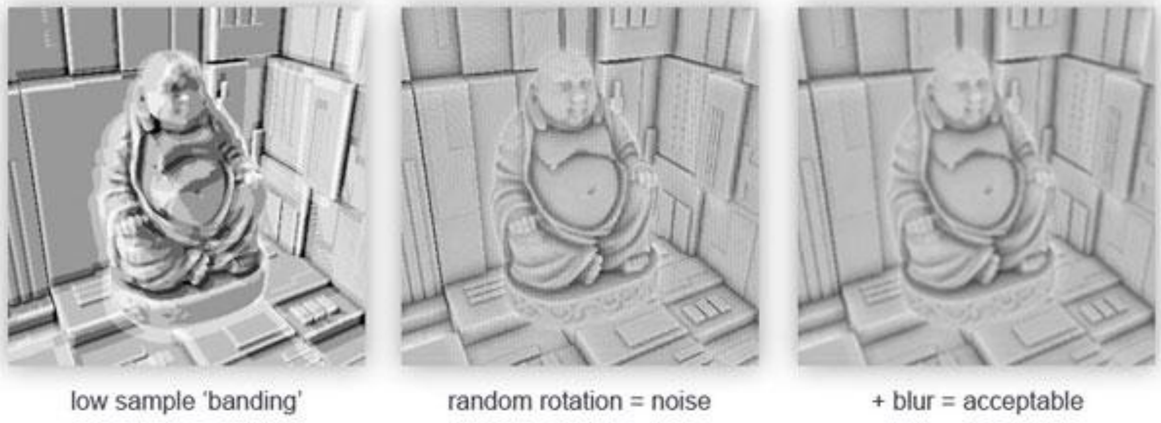


Phone
WITH SSAO

Screen-space Ambient Occlusion (cont.)

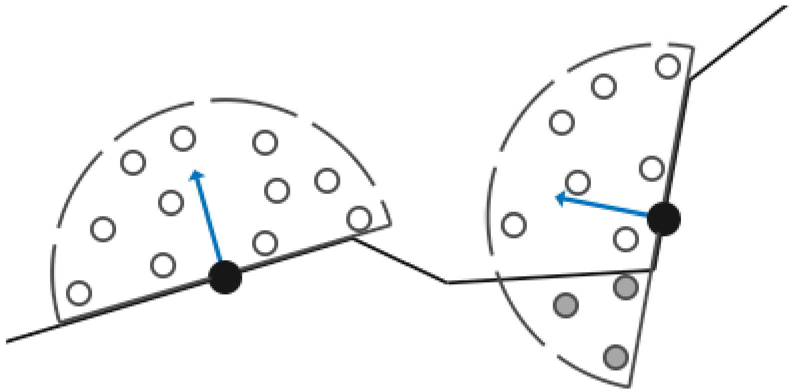
- Strike a balance for the sample count (a compromise between **quality** and **performance**)
- Use some techniques to trade artifacts (banding) with noise, and later removed them by filtering
  - Obtain acceptable results with few samples





Screen-space Ambient Occlusion (cont.)

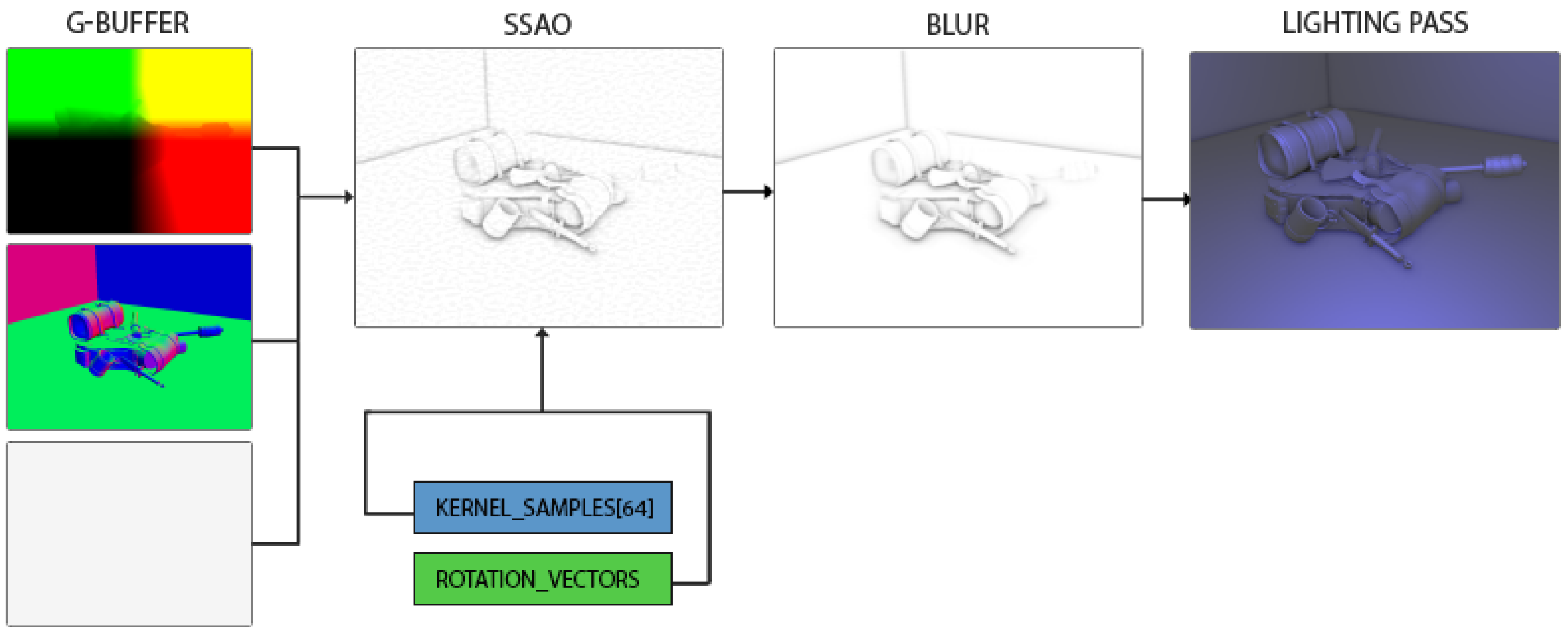
- Problem and improvement
  - Generate samples within a sphere produces results that are too dark
    - Why? Half of the samples are underneath the surface
  - Solution: use **hemisphere** (oriented by **normal**) instead



rotate by the TBN matrix!

Screen-space Ambient Occlusion (cont.)

- An implementation
  - https://learnopengl.com/Advanced-Lighting/SSAO



SSAO in Games

SSAO in Games (cont.)

END OF PRESENTATION
ANY QUESTIONS?