# Shadows

## CS425: Computer Graphics I

**Fabio Miranda**

https://fmiranda.me

# Overview

- Shadow projection
- Shadow Mapping
- Shadow Volume
- Shadow Accumulation

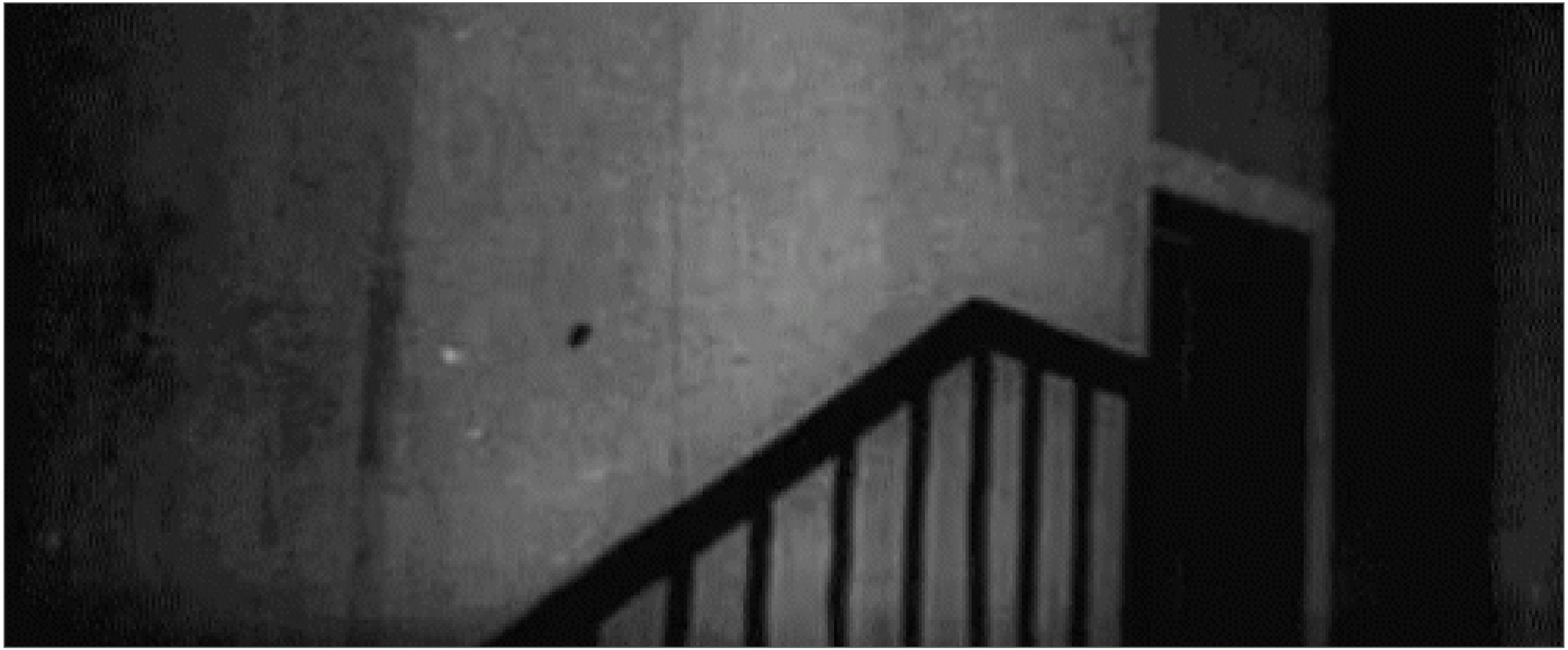
# Shadows

# Shadows

# Shadows

# Shadows

# Shadows

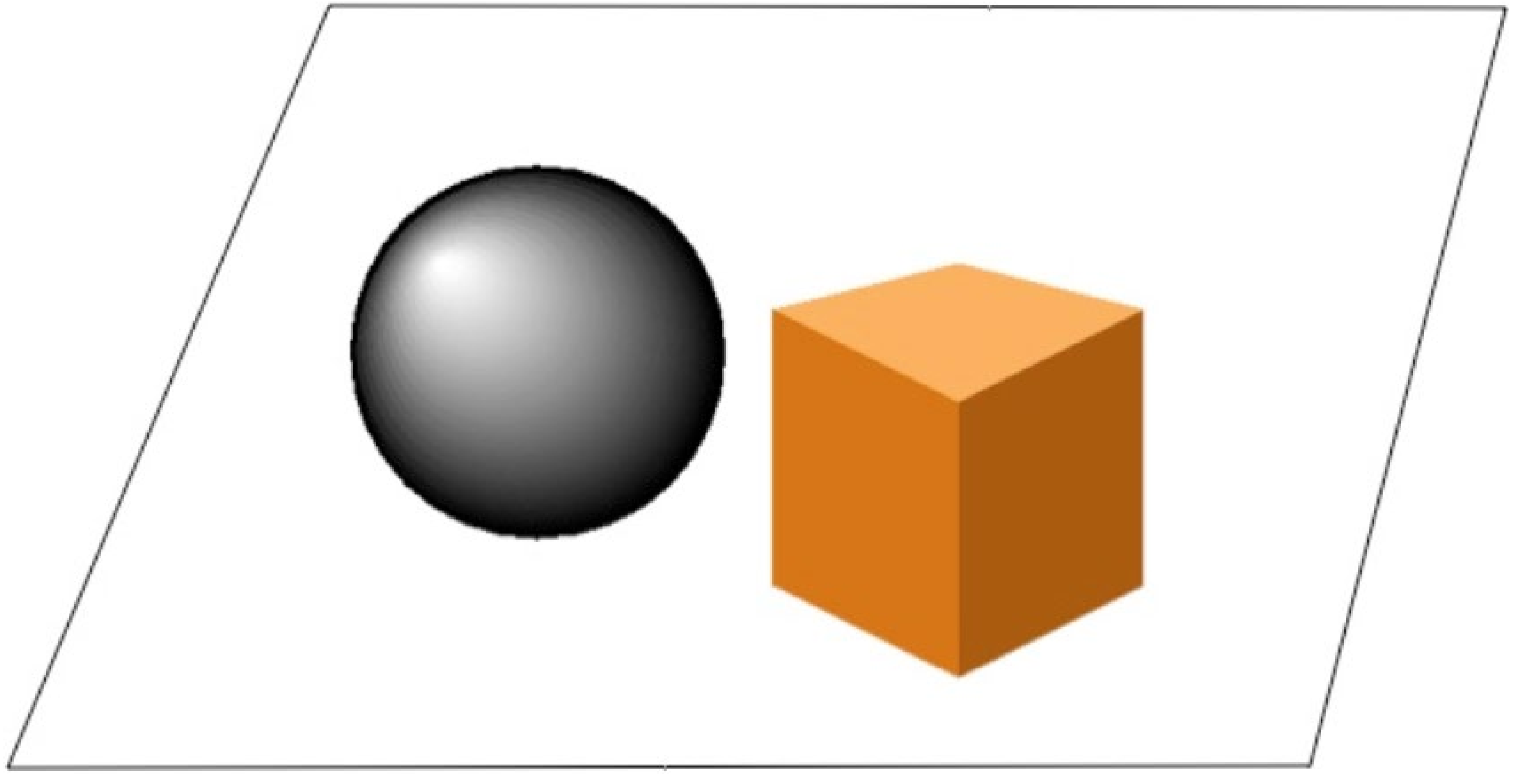


# Shadows

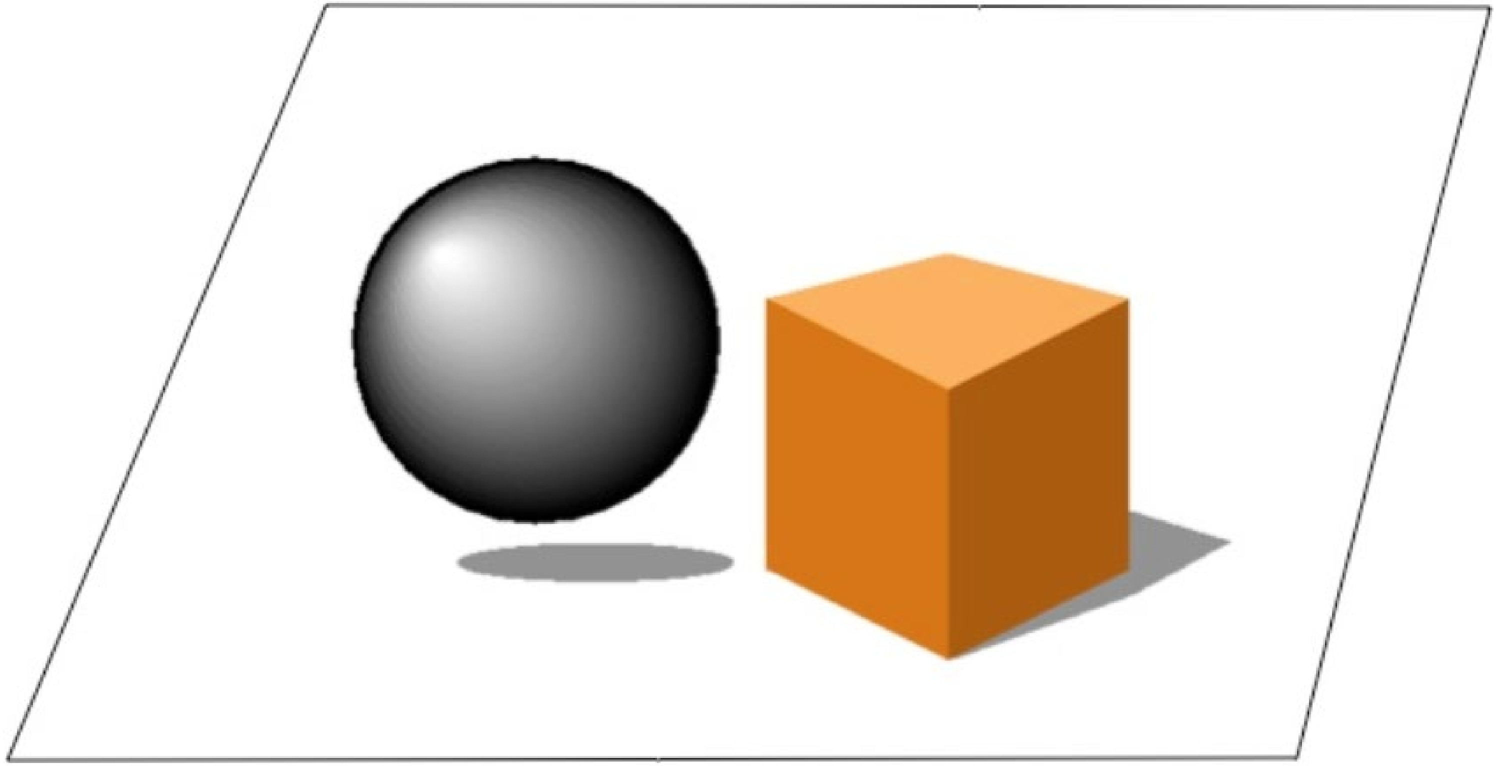
# Importance of shadows

- Add realism to the scene.
- Shape, volume of the object.
- Position of light source.
- Depth perception.

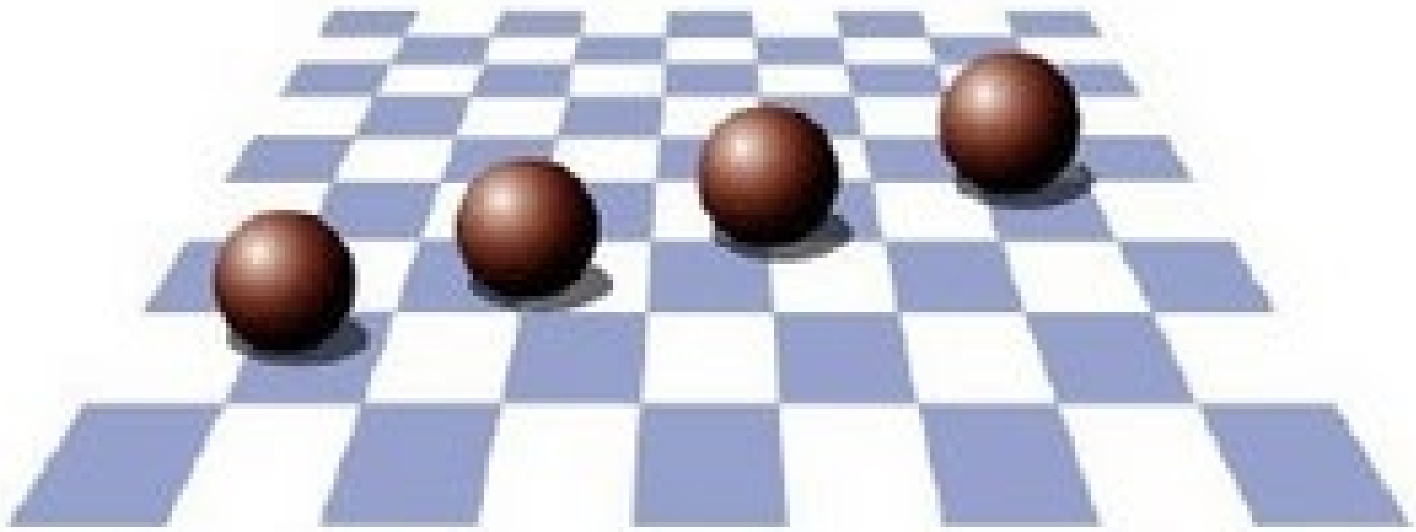
# Importance of shadows



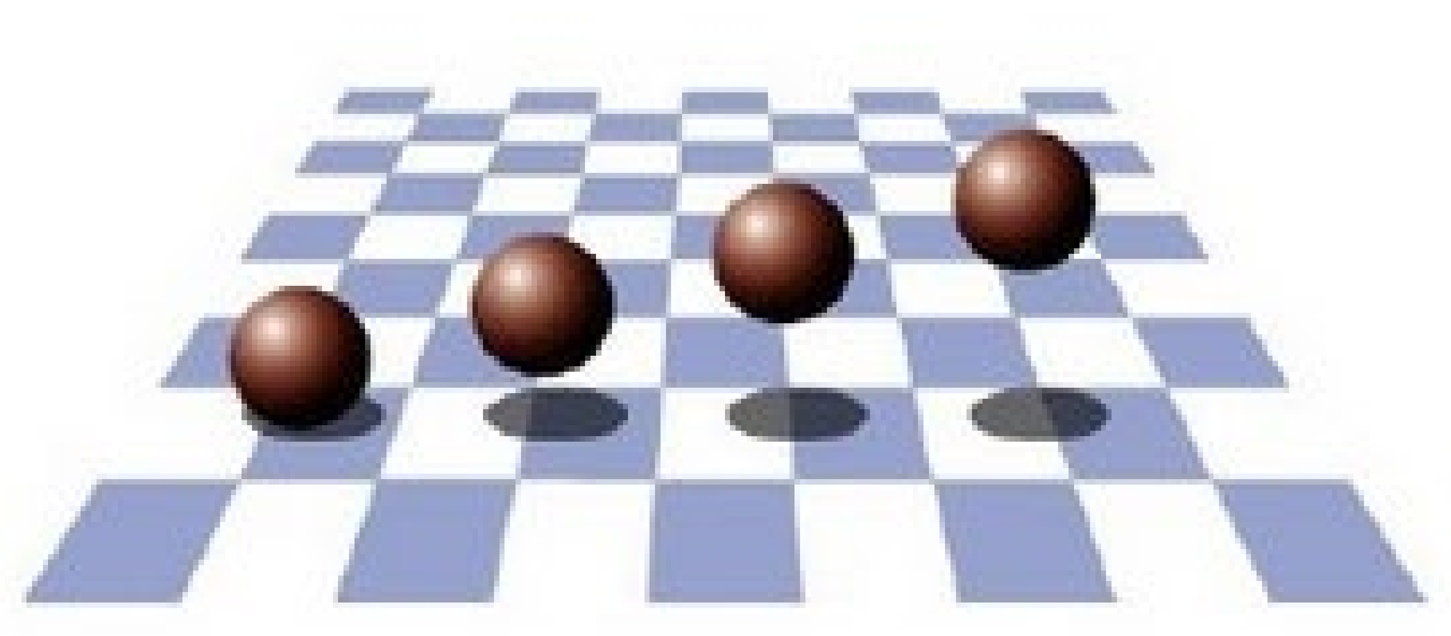
# Importance of shadows



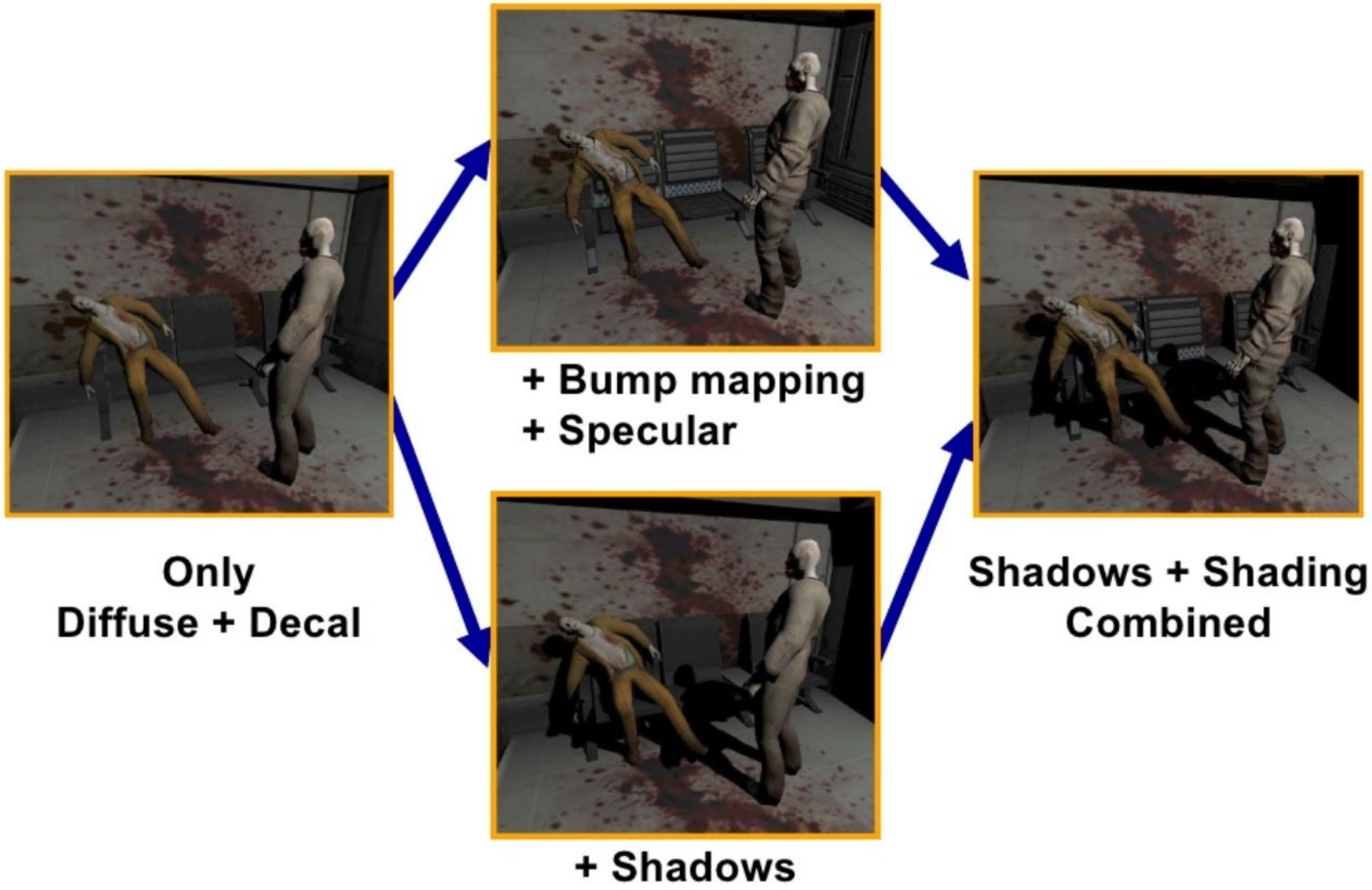
# Importance of shadows



# Importance of shadows



# Shading and shadows



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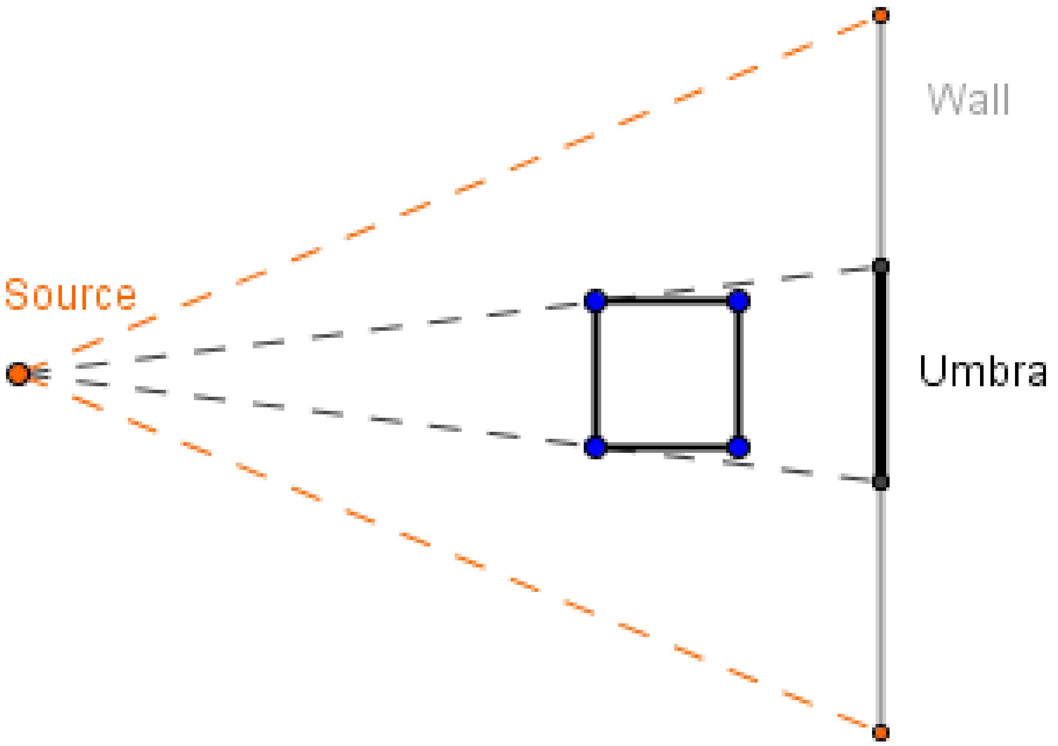
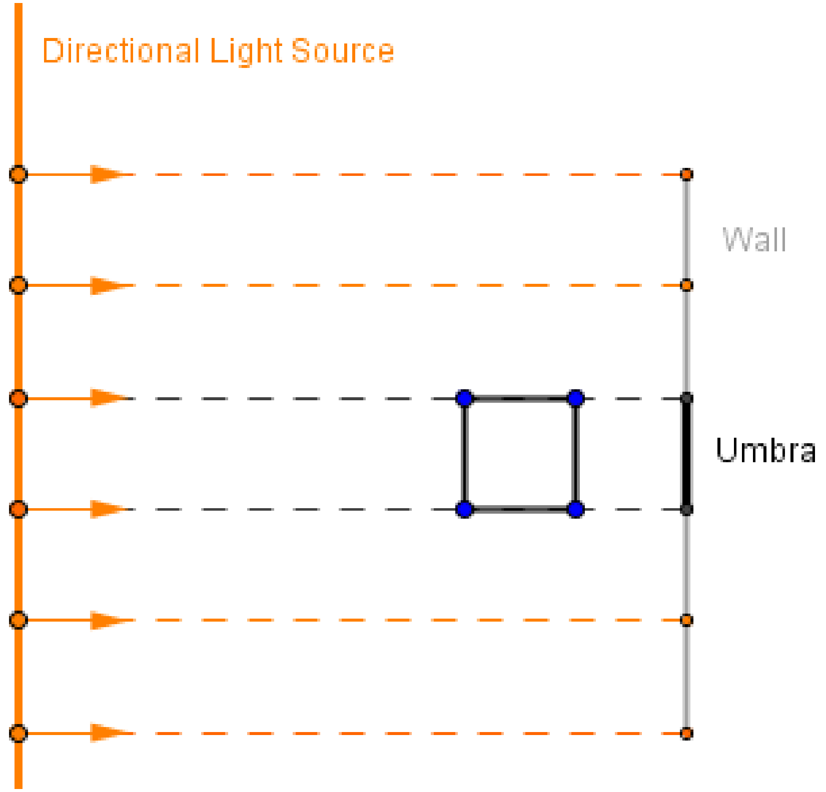
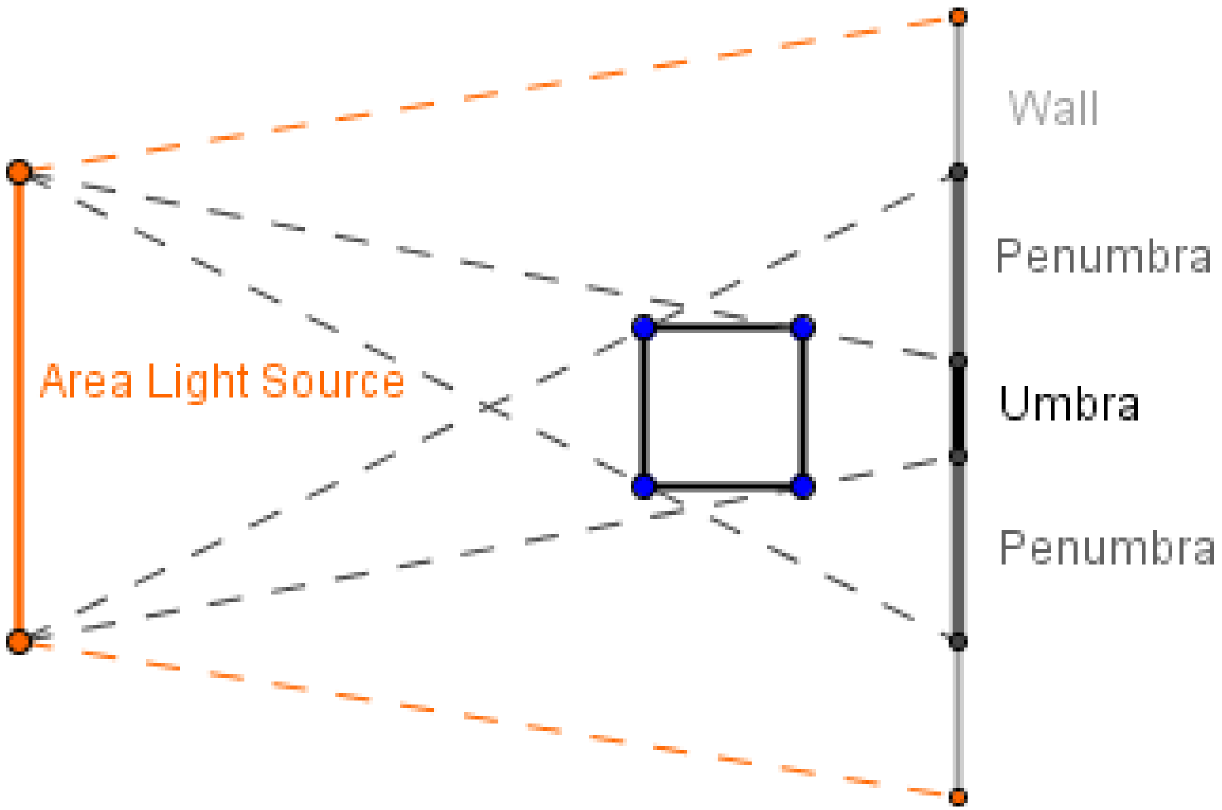
# Shadow components



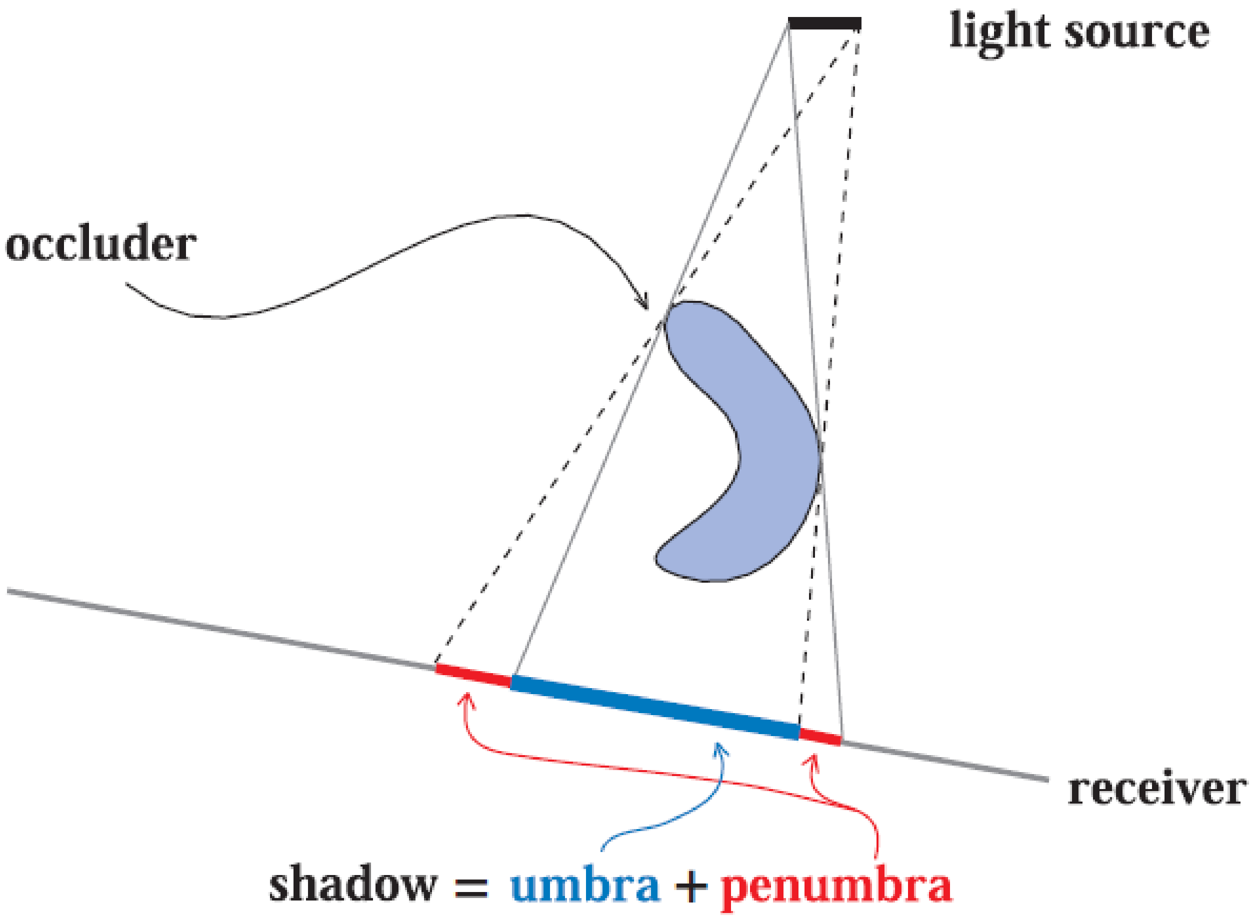
# Shadow components



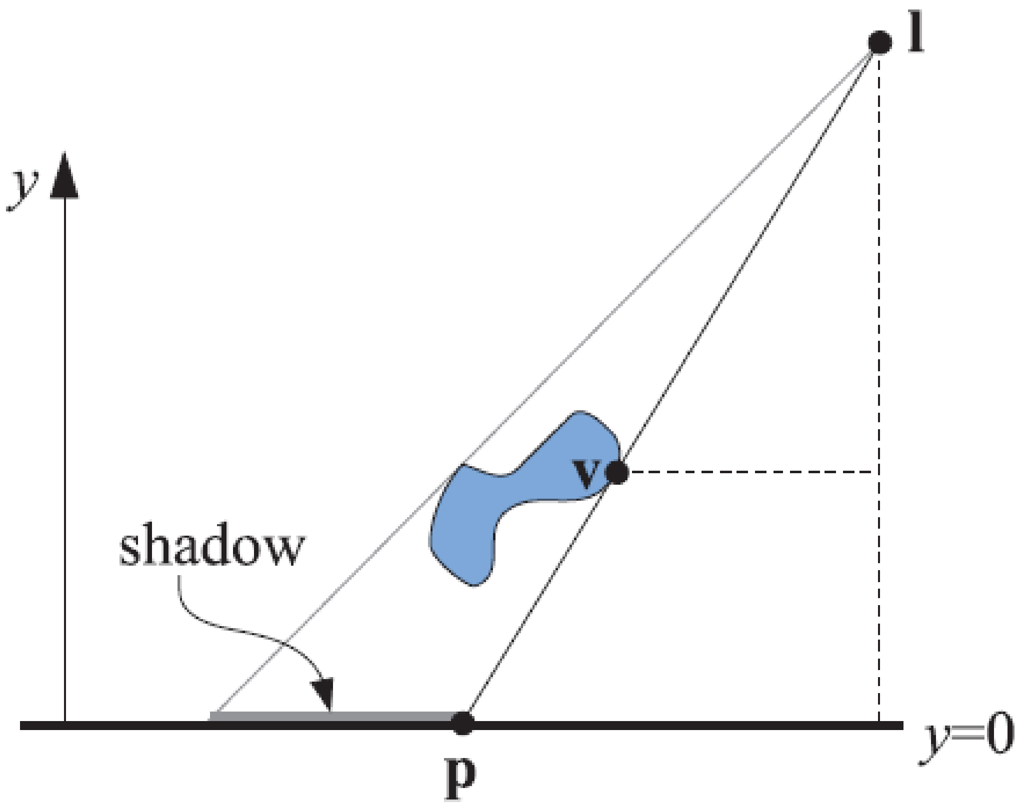
# Shadow components



# Goal

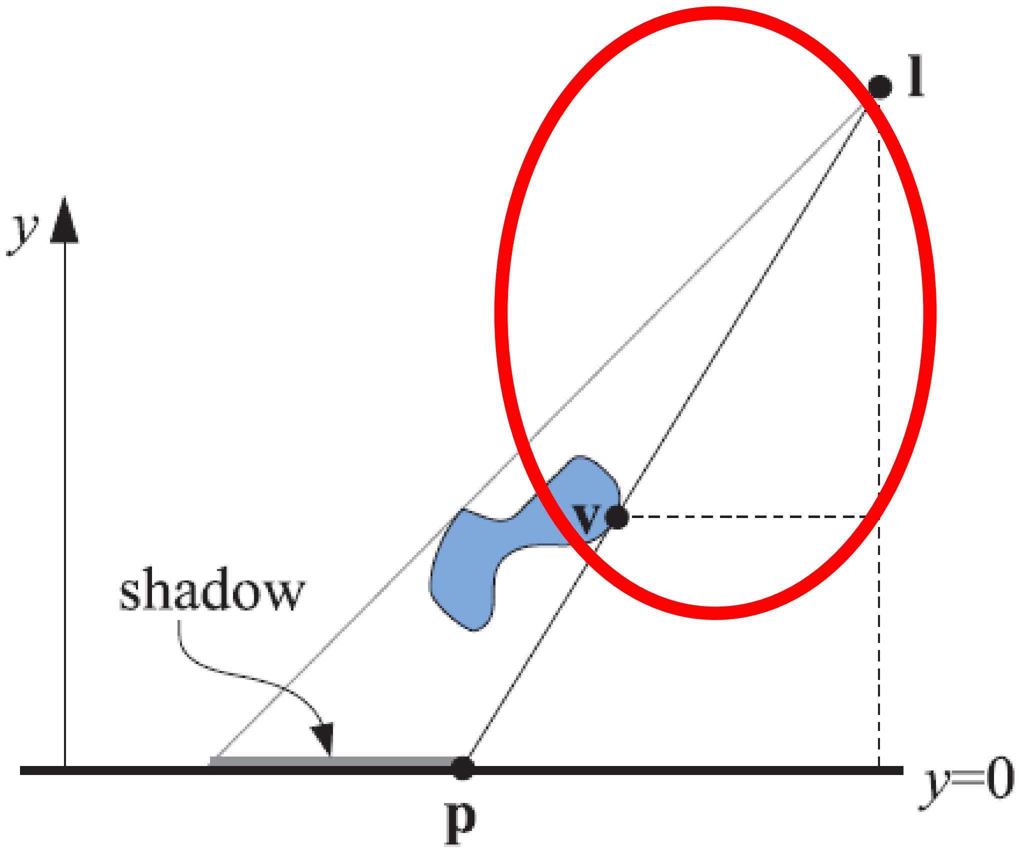


# Planar shadows

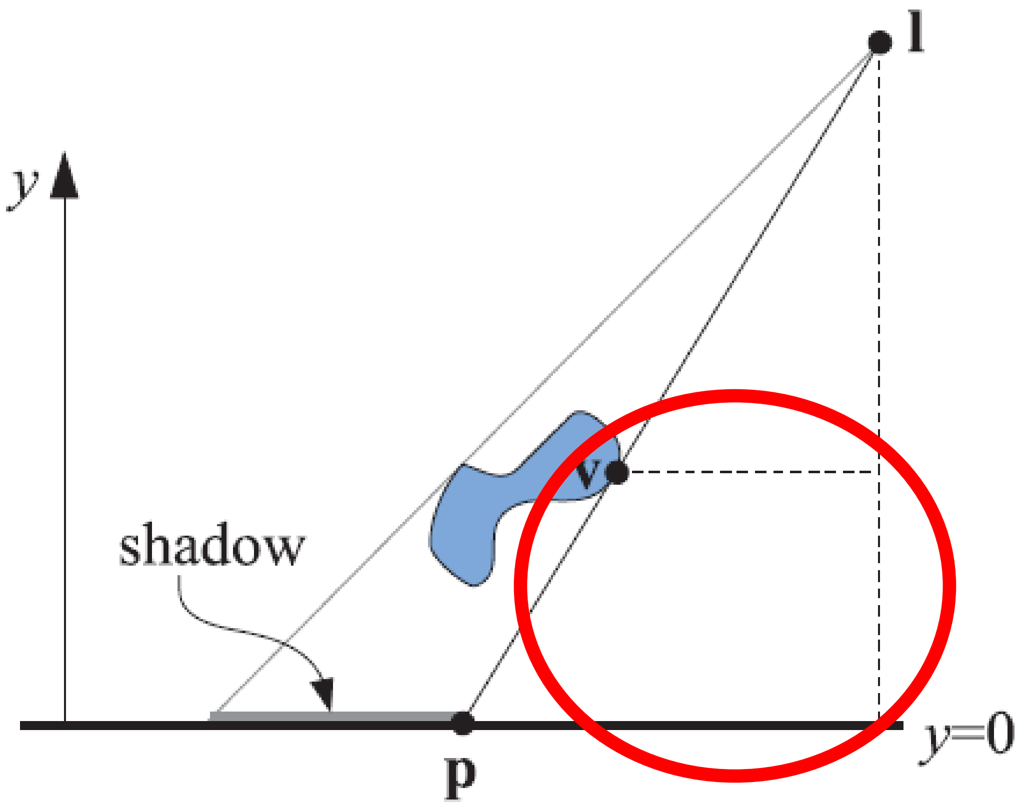



p?

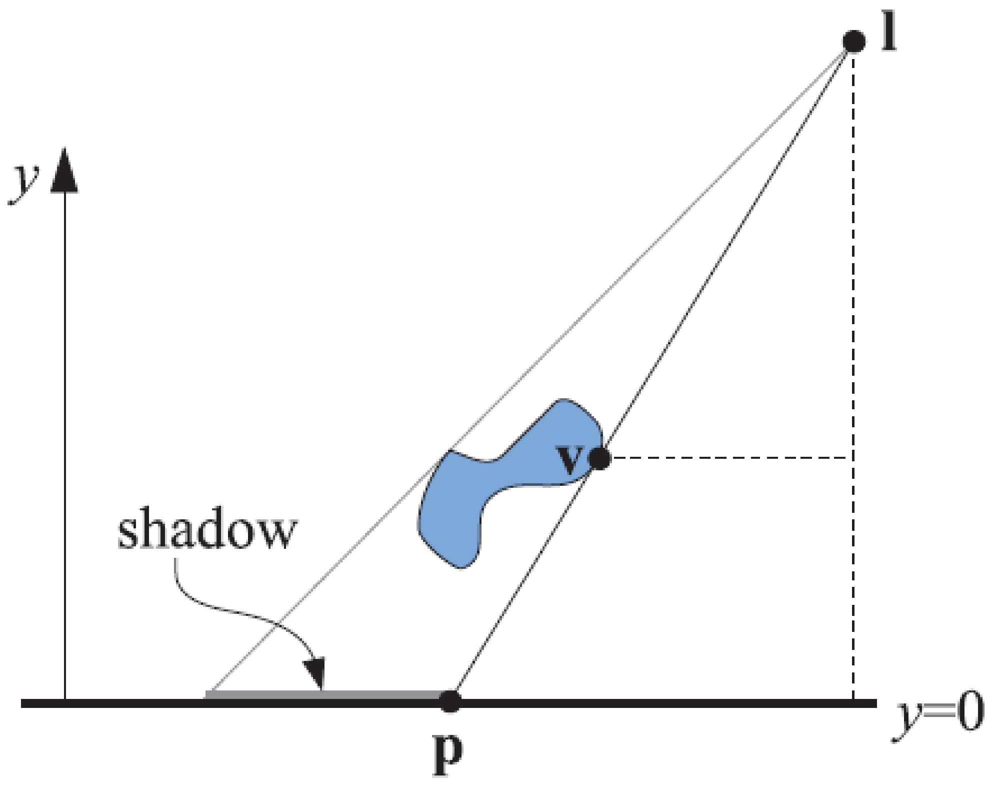
# Planar shadows



# Planar shadows



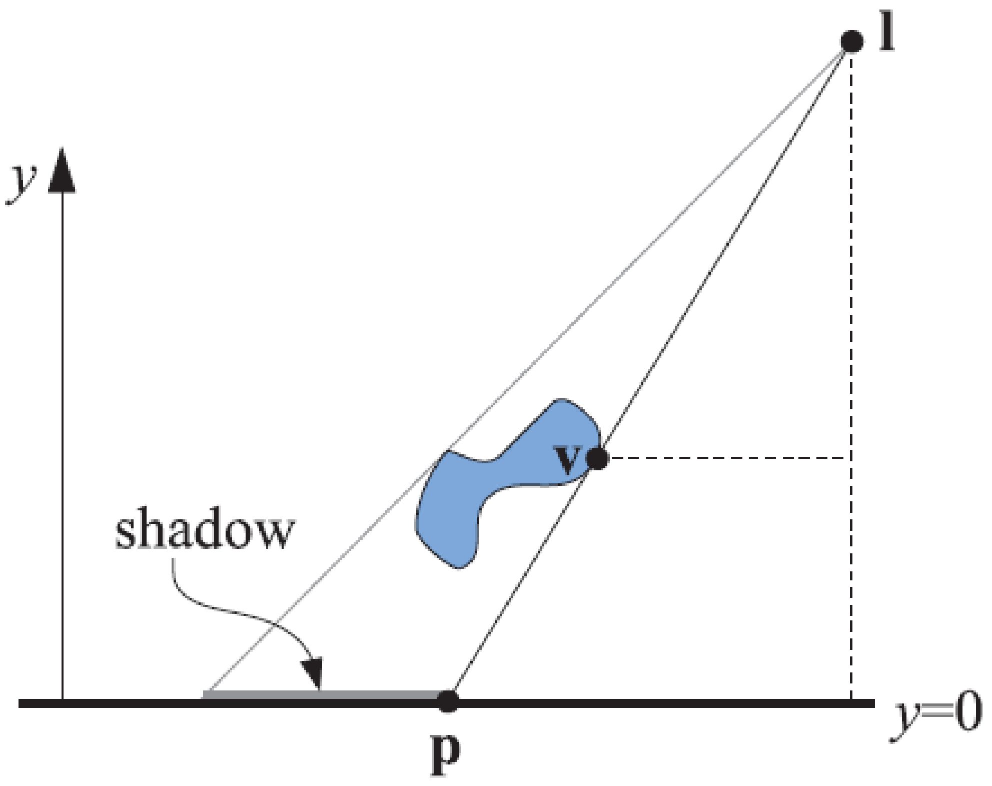
# Planar shadows




$$\frac{p_x - l_x}{v_x - l_x} = \frac{l_y}{l_y - v_y}$$

$$p_x = \frac{l_y v_x - l_x v_y}{l_y - v_y}$$

# Planar shadows



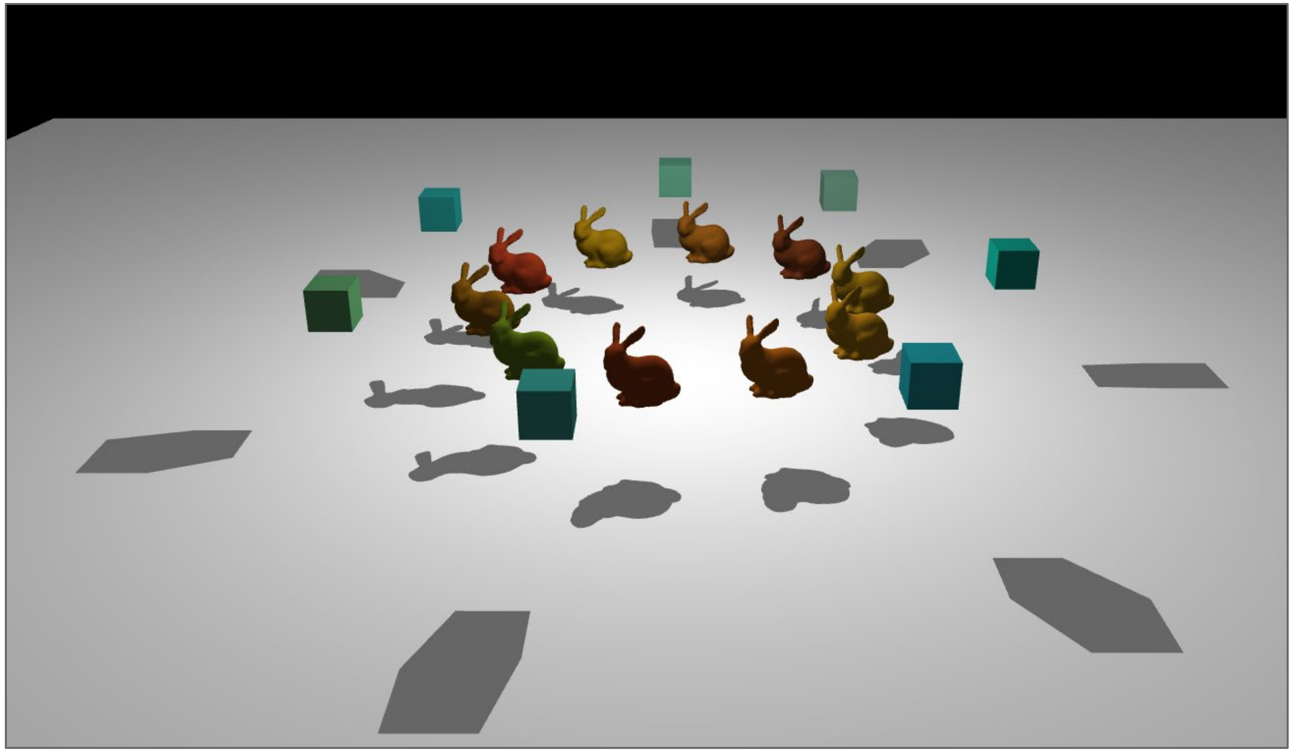

$$\mathbf{M}\mathbf{v} = \mathbf{p}$$

$$\mathbf{M} = \begin{bmatrix} l_y & -l_x & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -l_z & l_y & 0 \\ 0 & -1 & 0 & l_y \end{bmatrix}$$

# Planar shadow: steps

- Render receiving plane
- Render occluder, projecting with matrix M
- Render occluder

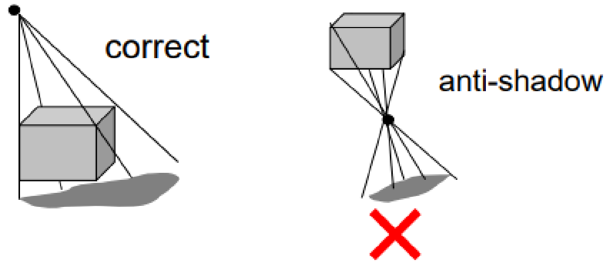
# Planar shadows: example



https://erkaman.github.io/planar_proj_shadows/planar_proj_shadows.html

# Planar Shadows: Shortcomings

- Z-fighting:
  - Precision problem between receiving plane and occlude.
  - Use polygon offset (glPolygonOffset).
- Restricted to planar objects.
- Anti-shadows.



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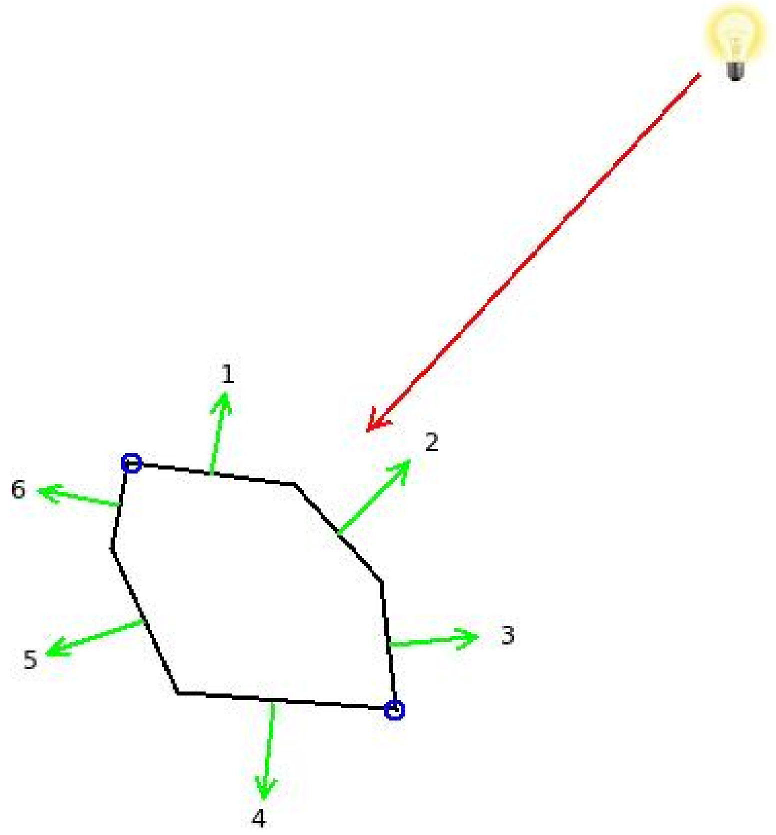
# Shadow volume

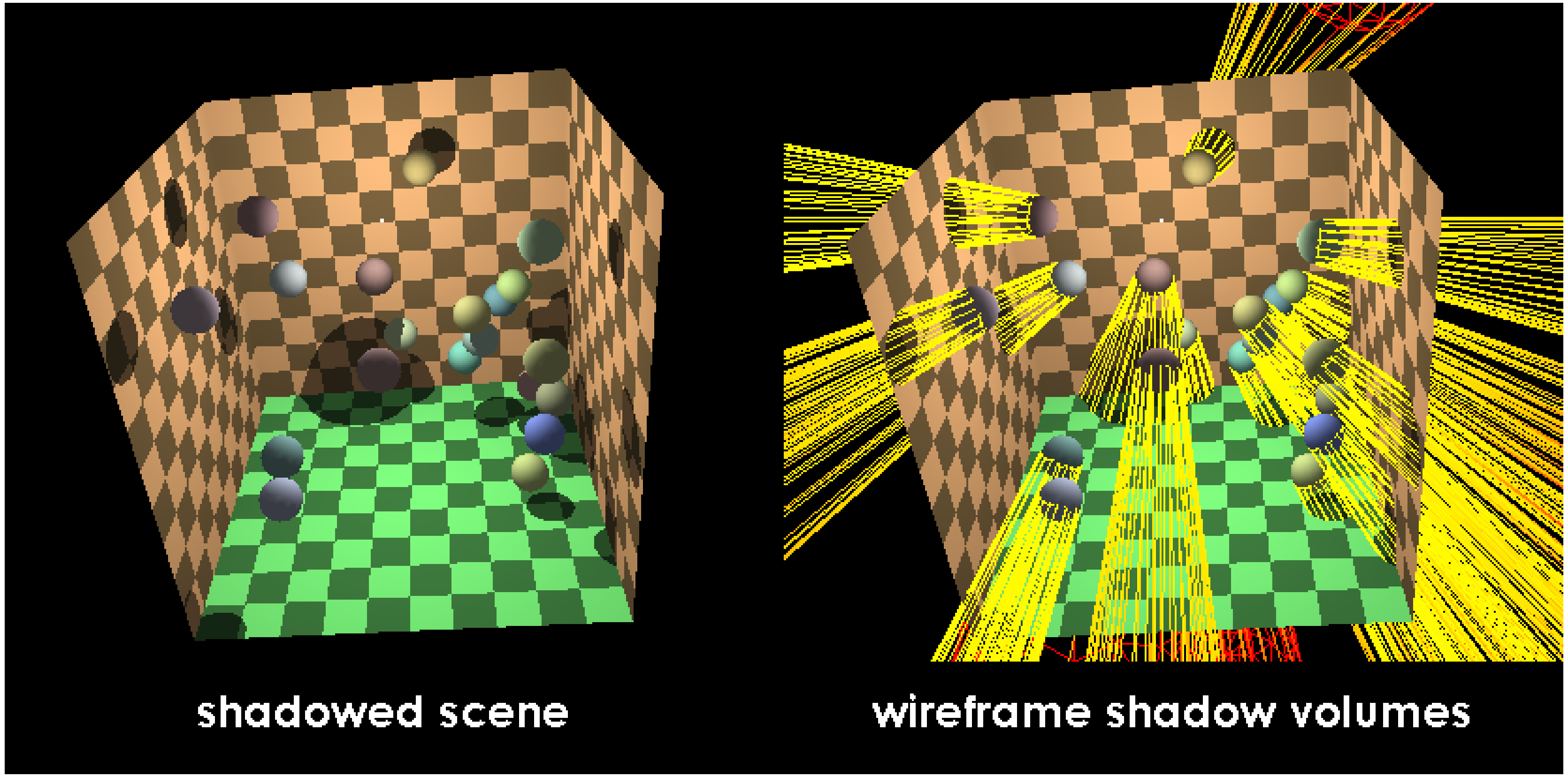
# Silhouette detection




Silhouette:

- If one neighboring edge is facing the light, the other not.

# Silhouette detection



# Silhouette detection

How to find the edges?

Geometry shader

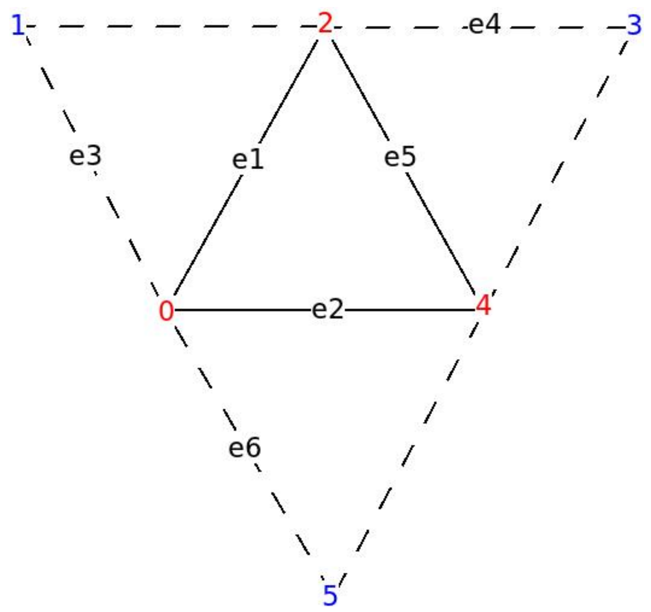
```
#version 330

layout (location = 0) in vec3 Position;
layout (location = 1) in vec2 TexCoord;
layout (location = 2) in vec3 Normal;

out vec3 WorldPos0;

uniform mat4 gWVP;
uniform mat4 gWorld;

void main()
{
    vec4 PosL = vec4(Position, 1.0);
    gl_Position = gWVP * PosL;
    WorldPos0 = (gWorld * PosL).xyz;
}
```

Vertex Shader

# Silhouette detection

How to find the edges?

Geometry shader




```
#version 330

layout (triangles_adjacency) in;
layout (line_strip, max_vertices = 6) out;

in vec3 WorldPos0[];

uniform vec3 gLightPos;

void main()
{
    vec3 e1 = WorldPos0[2] - WorldPos0[0];
    vec3 e2 = WorldPos0[4] - WorldPos0[0];
    vec3 e3 = WorldPos0[1] - WorldPos0[0];
    vec3 e4 = WorldPos0[3] - WorldPos0[2];
    vec3 e5 = WorldPos0[4] - WorldPos0[2];
    vec3 e6 = WorldPos0[5] - WorldPos0[0];

    vec3 Normal = cross(e1,e2);
    vec3 LightDir = gLightPos - WorldPos0[0];

    if (dot(Normal, LightDir) > 0.00001) {

        Normal = cross(e3,e1);

        if (dot(Normal, LightDir) <= 0) {
            // Silhouette!!!
        }

        Normal = cross(e4,e5);
        LightDir = gLightPos - WorldPos0[2];

        if (dot(Normal, LightDir) <=0) {
            // Silhouette!!!
        }

        Normal = cross(e2,e6);
        LightDir = gLightPos - WorldPos0[4];

        if (dot(Normal, LightDir) <= 0) {
            // Silhouette!!!
        }
    }
}
```

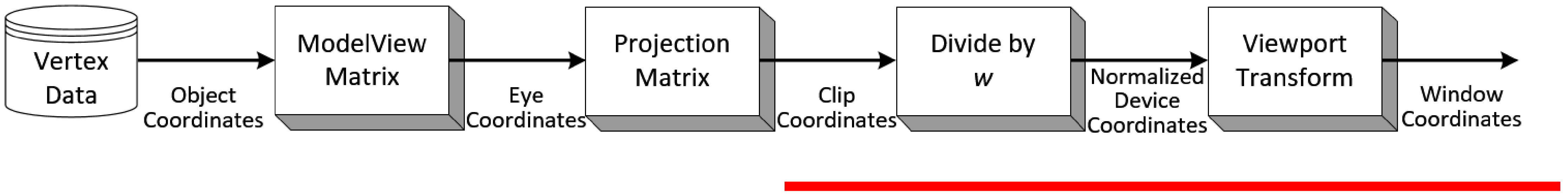
# Projection

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 2 \\ 3 \\ 4 \\ 1 \end{bmatrix} = \begin{bmatrix} 2 \\ 3 \\ 4 \\ 4 \end{bmatrix}$$

$$\frac{(2,3,4)}{4} = (0.5, 0.75, 1)$$

$$\frac{(2,3,4)}{0} = (\infty, \infty, \infty)$$

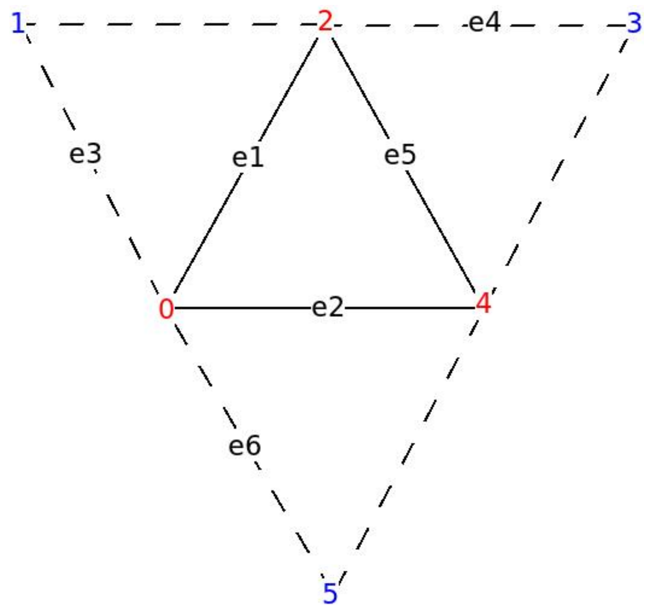
# Projection


Vertex
Data
Object
Coordinates
ModelView
Matrix
Eye
Coordinates
Projection
Matrix
Clip
Coordinates
Divide by
w
Normalized
Device
Coordinates
Viewport
Transform
Window
Coordinates

# Silhouette detection

How to create volume?

Geometry shader




```
// Emit a quad using a triangle strip
void EmitQuad(vec3 StartVertex, vec3 EndVertex)
{
    // Vertex #1: the starting vertex (just a tiny bit below the original edge)
    vec3 LightDir = normalize(StartVertex - gLightPos);
    gl_Position = gWVP * vec4((StartVertex + LightDir * EPSILON), 1.0);
    EmitVertex();

    // Vertex #2: the starting vertex projected to infinity
    gl_Position = gWVP * vec4(LightDir, 0.0);
    EmitVertex();

    // Vertex #3: the ending vertex (just a tiny bit below the original edge)
    LightDir = normalize(EndVertex - gLightPos);
    gl_Position = gWVP * vec4((EndVertex + LightDir * EPSILON), 1.0);
    EmitVertex();

    // Vertex #4: the ending vertex projected to infinity
    gl_Position = gWVP * vec4(LightDir , 0.0);
    EmitVertex();

    EndPrimitive();
}
```

# Projection

Far plane at infinity

$$P = \begin{pmatrix} \frac{1}{aspectRatio \cdot tan(\frac{\alpha}{2})} & 0 & 0 & 0 \\ 0 & \frac{1}{tan(\frac{\alpha}{2})} & 0 & 0 \\ 0 & 0 & \frac{near+far}{near-far} & \frac{-2 \cdot far \cdot near}{near-far} \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

# Projection

Far plane at infinity

$$\lim_{far \to \infty} -\frac{far + near}{far - near} = \lim_{far \to \infty} -\frac{\frac{far}{far} + \frac{near}{far}}{\frac{far}{far} - \frac{near}{far}} = -\frac{1+0}{1-0} = -1$$

$$P = \begin{pmatrix} \frac{1}{aspectRatio \cdot tan(\frac{\alpha}{2})} & 0 & 0 & 0 \\ 0 & \frac{1}{tan(\frac{\alpha}{2})} & 0 & 0 \\ 0 & 0 & \frac{near+far}{near-far} & \frac{-2 \cdot far \cdot near}{near-far} \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

# Projection

Far plane at infinity

$$\lim_{far\to\infty} -\frac{far+near}{far-near} = \lim_{far\to\infty} -\frac{\frac{far}{far}+\frac{near}{far}}{\frac{far}{far}-\frac{near}{far}} = -\frac{1+0}{1-0} = -1$$

$$P = \begin{pmatrix} \frac{1}{aspectRatio \cdot tan(\frac{\alpha}{2})} & 0 & 0 & 0 \\ 0 & \frac{1}{tan(\frac{\alpha}{2})} & 0 & 0 \\ 0 & 0 & \frac{near+far}{near-far} & \frac{-2 \cdot far \cdot near}{near-far} \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

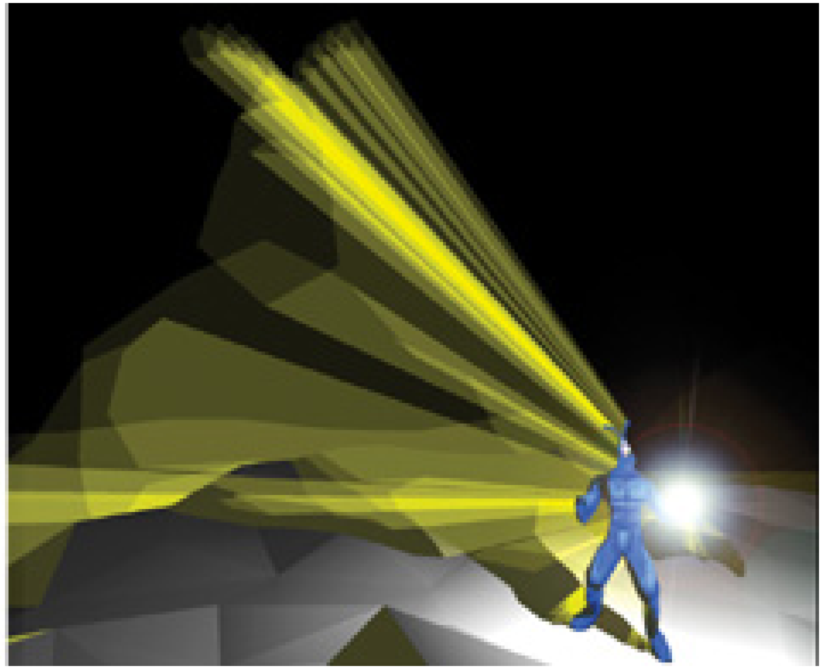
$$\lim_{far\to\infty} -\frac{2 \cdot far \cdot near}{far-near} = \lim_{far\to\infty} -\frac{\frac{2 \cdot far \cdot near}{far}}{\frac{far}{far}-\frac{near}{far}} = -\frac{2 \cdot near}{1-0} = -2 \cdot near$$

# Projection

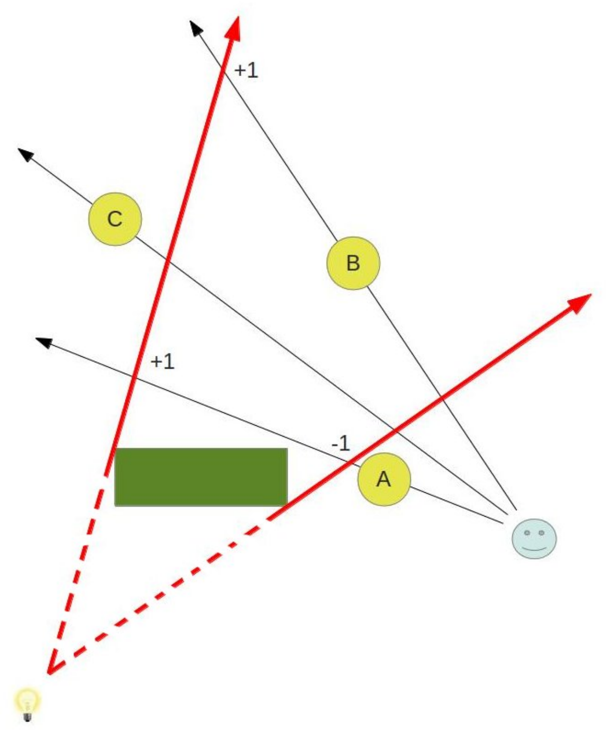
Far plane at infinity

$$P_{inf} = \begin{pmatrix} \frac{1}{aspectRatio \cdot tan(\frac{\alpha}{2})} & 0 & 0 & 0 \\ 0 & \frac{1}{tan(\frac{\alpha}{2})} & 0 & 0 \\ 0 & 0 & -1 & -2 \cdot near \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

# Shadow volume



# Shadow volume




ogldev.org

- Trace rays
  - Ray enters volume
    - Increase counter
  - Ray exists volume
    - Decreases counter
  - Shadow: counter different than zero

**Point *P* is in shadow if and only if there were more entering intersections than exiting intersections along a ray to infinity.**



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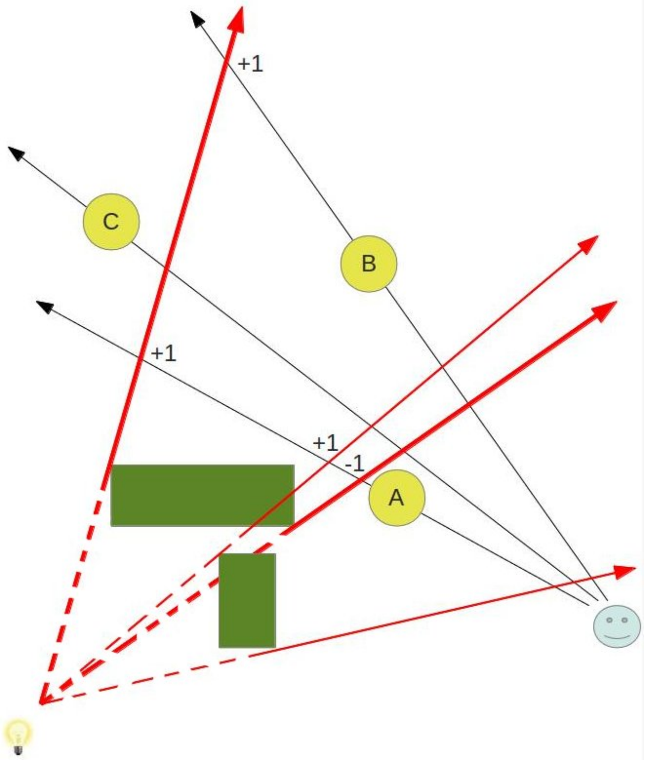
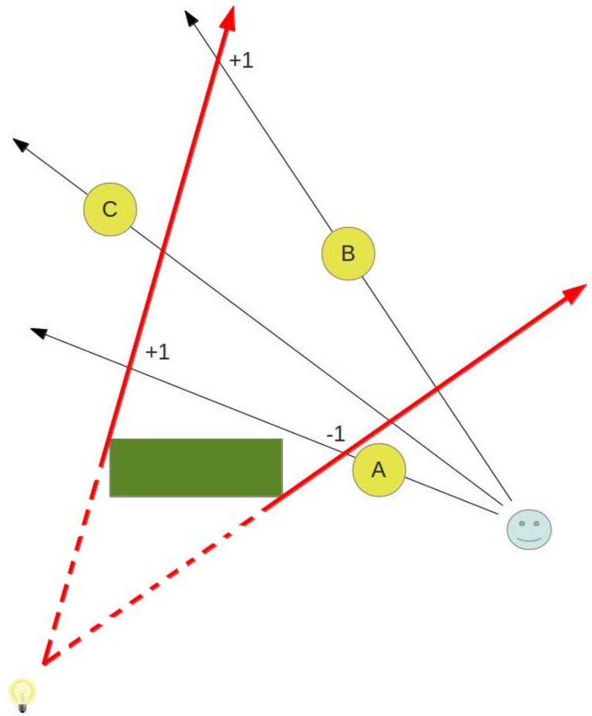
# Shadow volume




- Trace rays
  - Ray enters volume
    - Increase counter
  - Ray exists volume
    - Decreases counter
  - Shadow: counter different than zero

**Point *P* is in shadow if and only if there were more entering intersections than exiting intersections along a ray to infinity.**

# Shadow volume




- For each object, determine its shadow volume
- Render back facing polygons of volumes into stencil buffer
  - Depth test fail: increment
- Render front facing polygons of volume into stencil buffer
  - Depth test fail: decrement

**Point *P* is in shadow if and only if there were more entering intersections than exiting intersections along a ray to infinity.**

# Shadow volume

- Advantages
  - Self-shadowing
  - Everything can shadow everything, including self
- Disadvantages
  - Silhouette computation required
  - Slow on scenes with polygons with large number of triangles

# Shadow maps

- Image-space shadow determination.
- Leverages GPU hardware:
  - Depth buffering  + texture mapping
- Two steps algorithm:
  - First, render scene from light’s point of view.
  - Second, render scene from eye’s point of view.

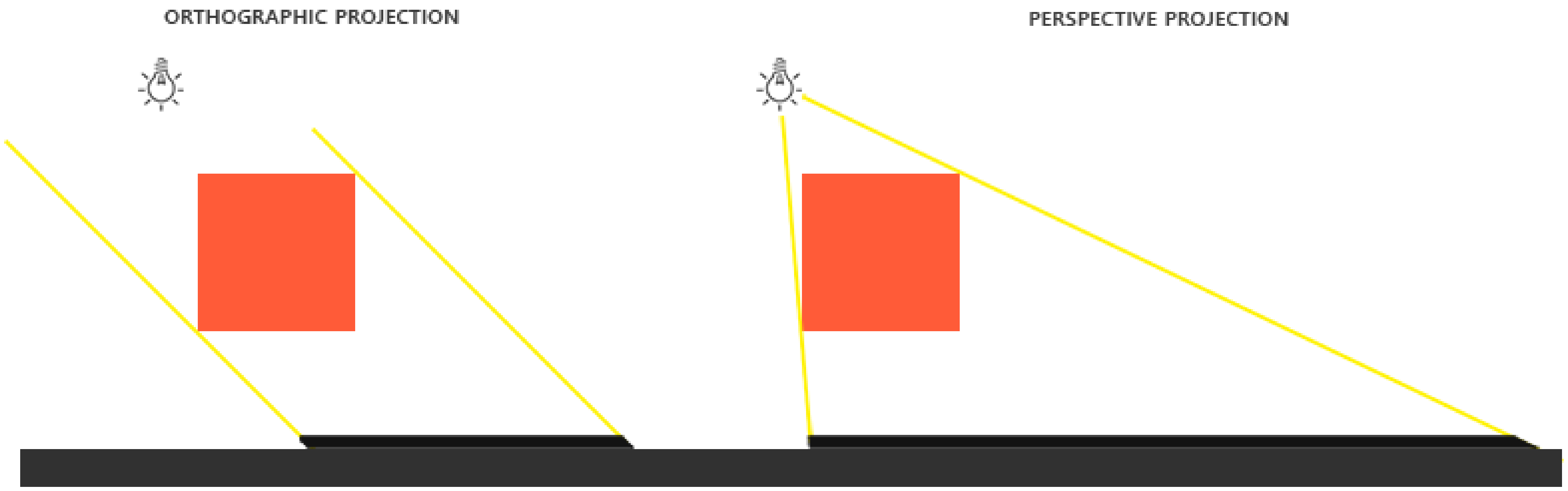
# Shadow maps

- First step:
  - Render from light's point of view:
    - Result stored in a depth buffer, as a shadow map.
    - A 2D function indicating the depth of the closest pixel to the light.
  - Shadow map is used in the second step.

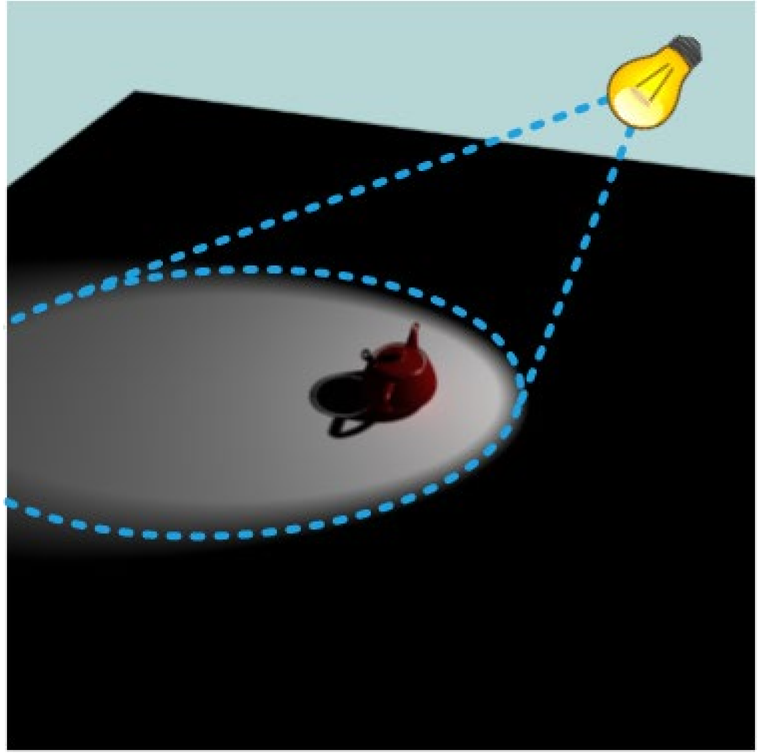
# Shadow maps

- Second step:
  - Render from eye's point of view:
    - For each fragment, determine its position in the light space.
    - Compare depth value at light position with the depth value from shadow map.
  - Two values:
    - A: z value of fragment in light space.
    - B: z value of fragment in shadow map.
    - B>A: shadow
    - A>B: no shadow

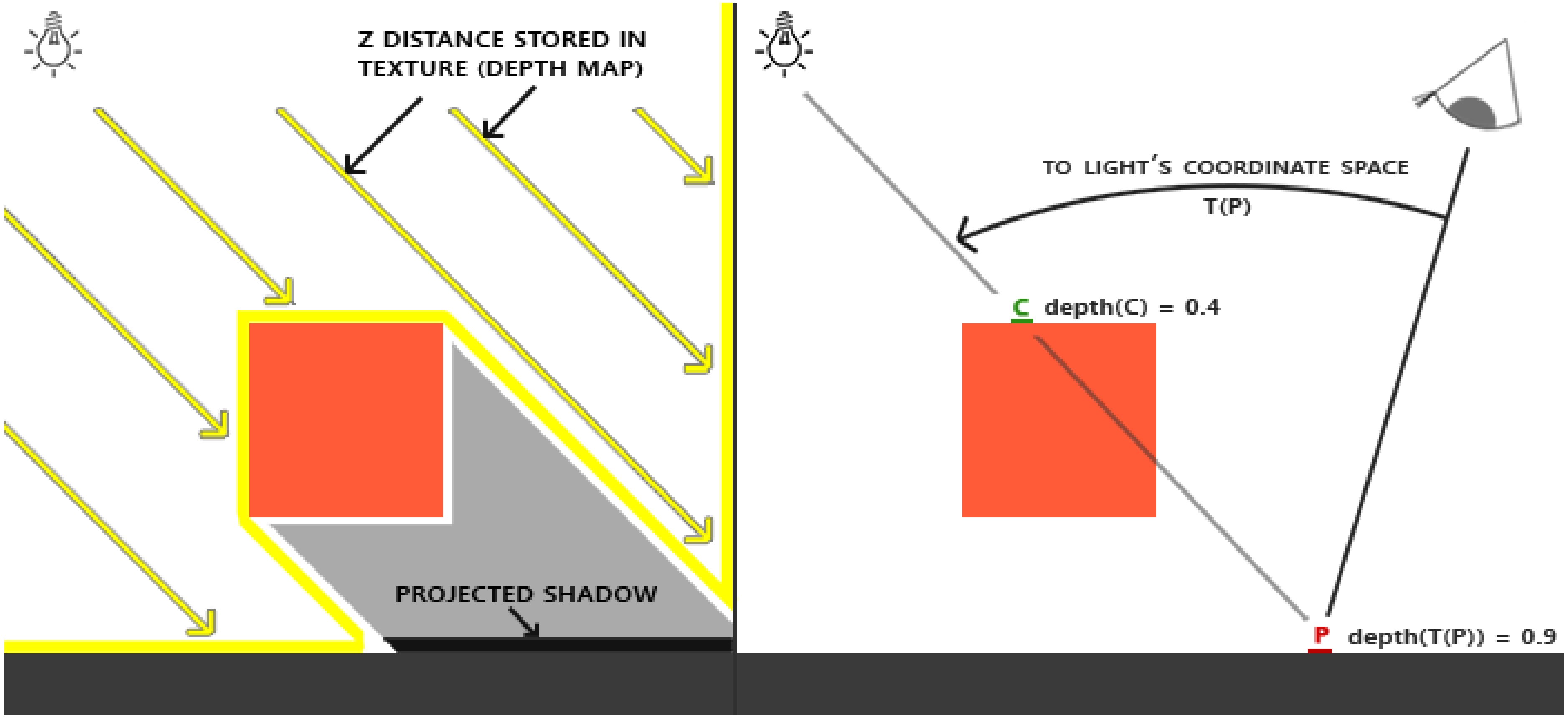
# Shadow maps



# Shadow test



# Shadow test


Z DISTANCE STORED IN
TEXTURE (DEPTH MAP)
PROJECTED SHADOW
TO LIGHT'S COORDINATE SPACE
T(P)
C depth(C) = 0.4
P depth(T(P)) = 0.9

# Shadow maps + GL

1. Creating shadow map framebuffer for rendering shadow map:

```
unsigned int depthMapFBO;
glGenFramebuffers(1, &depthMapFBO);
```

2. Creating shadow map texture with size 1024

```
const unsigned int SHADOW_WIDTH = 1024, SHADOW_HEIGHT = 1024;

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_REPEAT);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT);
```

Snippets from: https://learnopengl.com/

# Shadow maps + GL

3. Attach texture to framebuffer

```
unsigned int depthMapFBO;
glGenFramebuffers(1, &depthMapFBO);
```

```
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 maps + GL

4. Render scene twice

```
// 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();
```

# Shadow maps + GL

## 4. Shadow test: vertex shader

```glsl
#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);
}
```

# Shadow maps + GL

4. Shadow test: fragment shader

```
float ShadowCalculation(vec4 fragPosLightSpace)
{
    // perform perspective divide
    vec3 projCoords = fragPosLightSpace.xyz / fragPosLightSpace.w;
    [...]
}
```

```
projCoords = projCoords * 0.5 + 0.5;
```

```
float closestDepth = texture(shadowMap, projCoords.xy).r;
```

```
float currentDepth = projCoords.z;
float shadow = currentDepth > closestDepth  ? 1.0 : 0.0;
```

# Shadow map result

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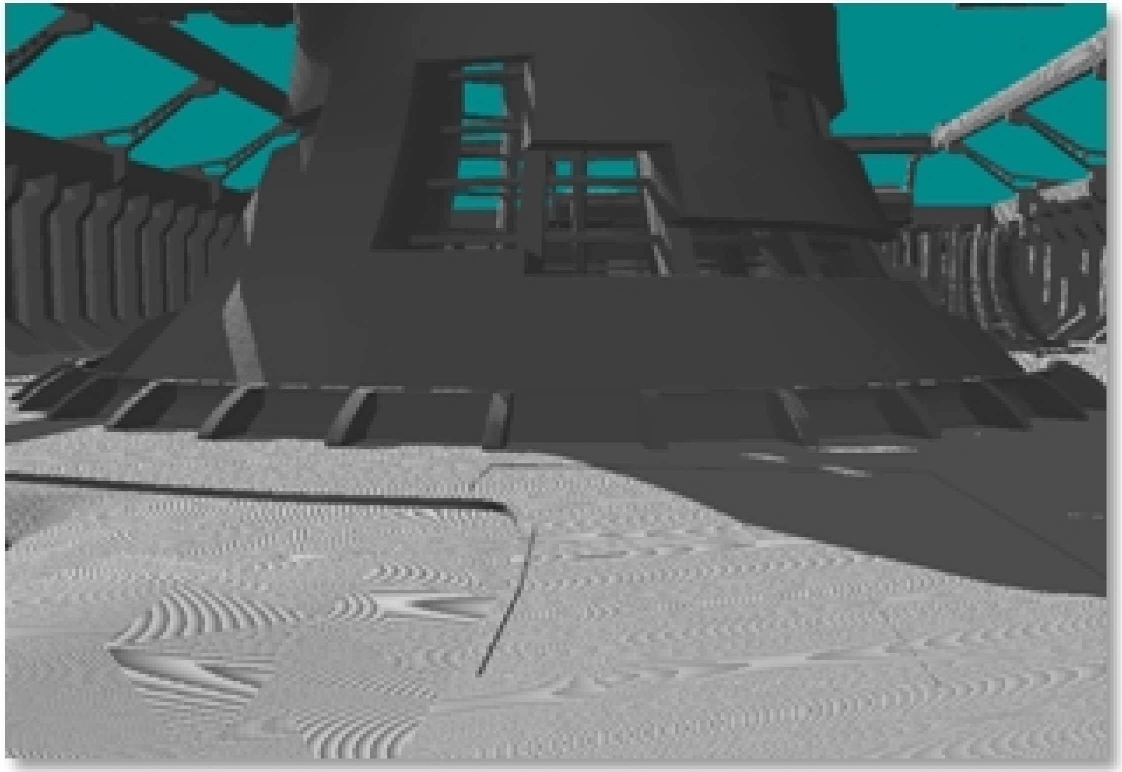
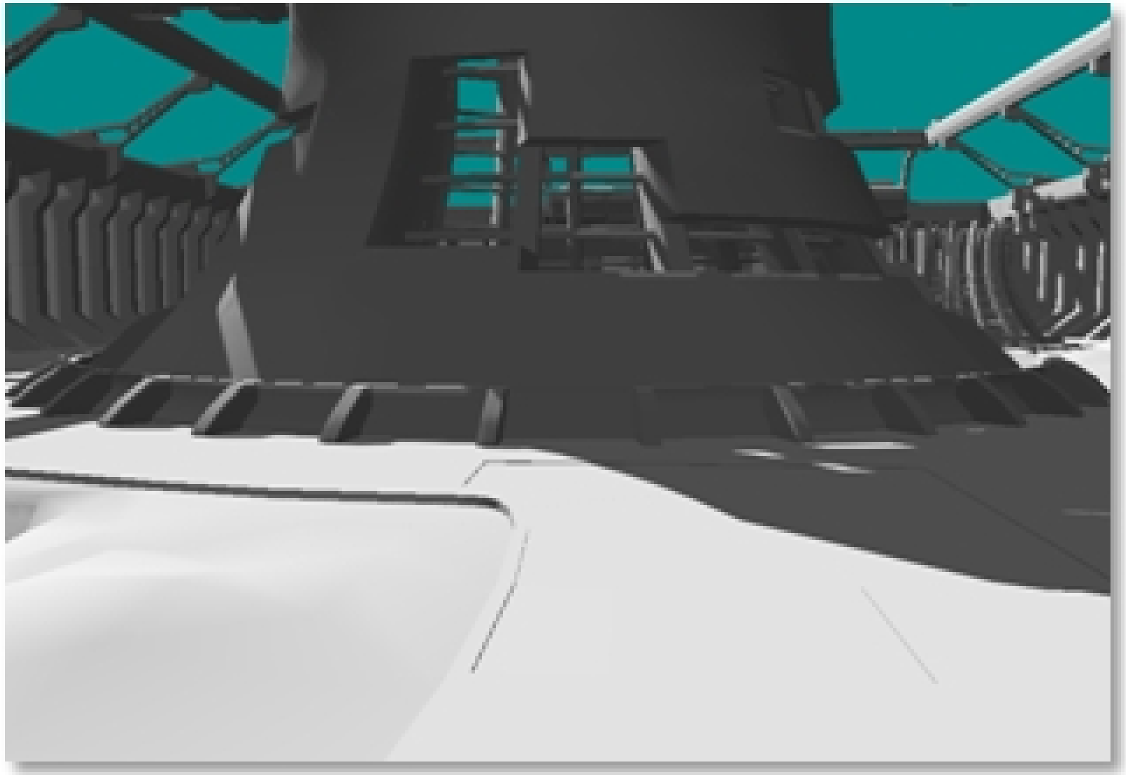
# Shadow maps

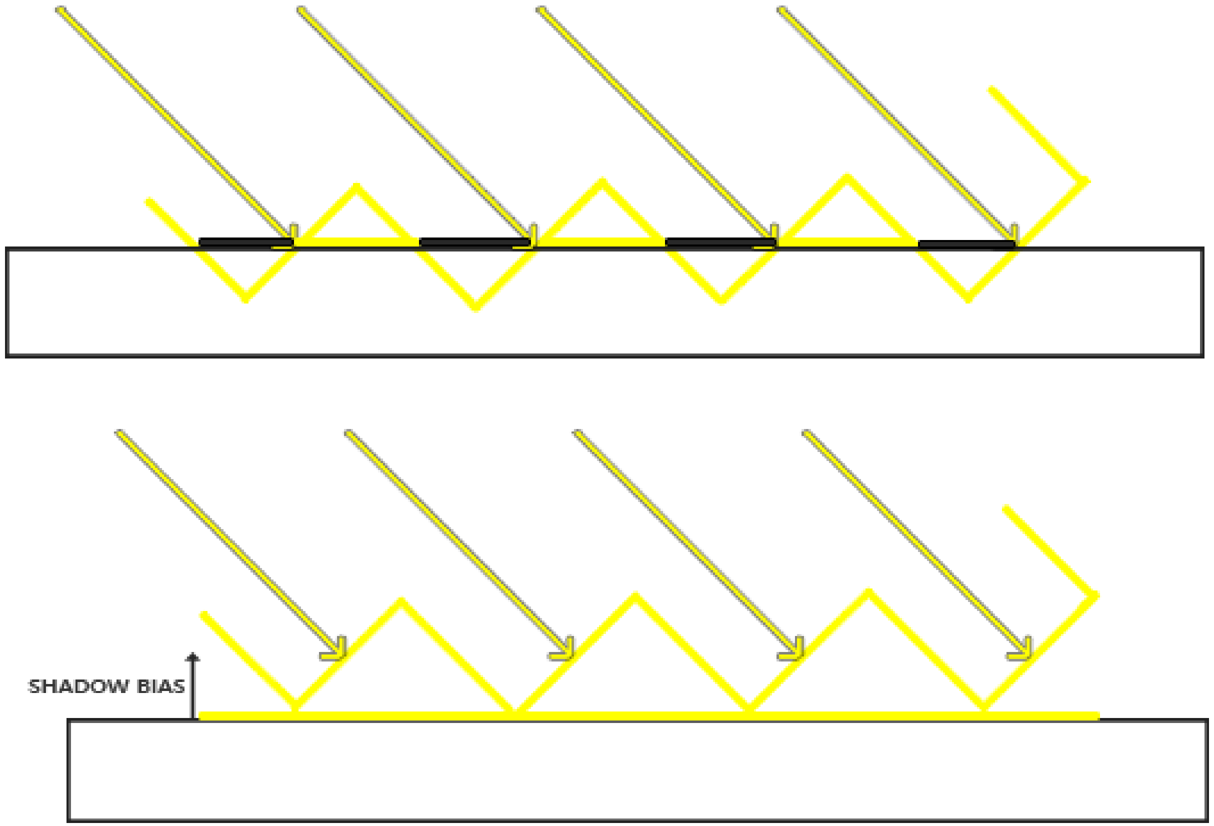
- Advantages:
  - Fast
  - Simple depth map comparison

# Shadow acne





# Shadow acne



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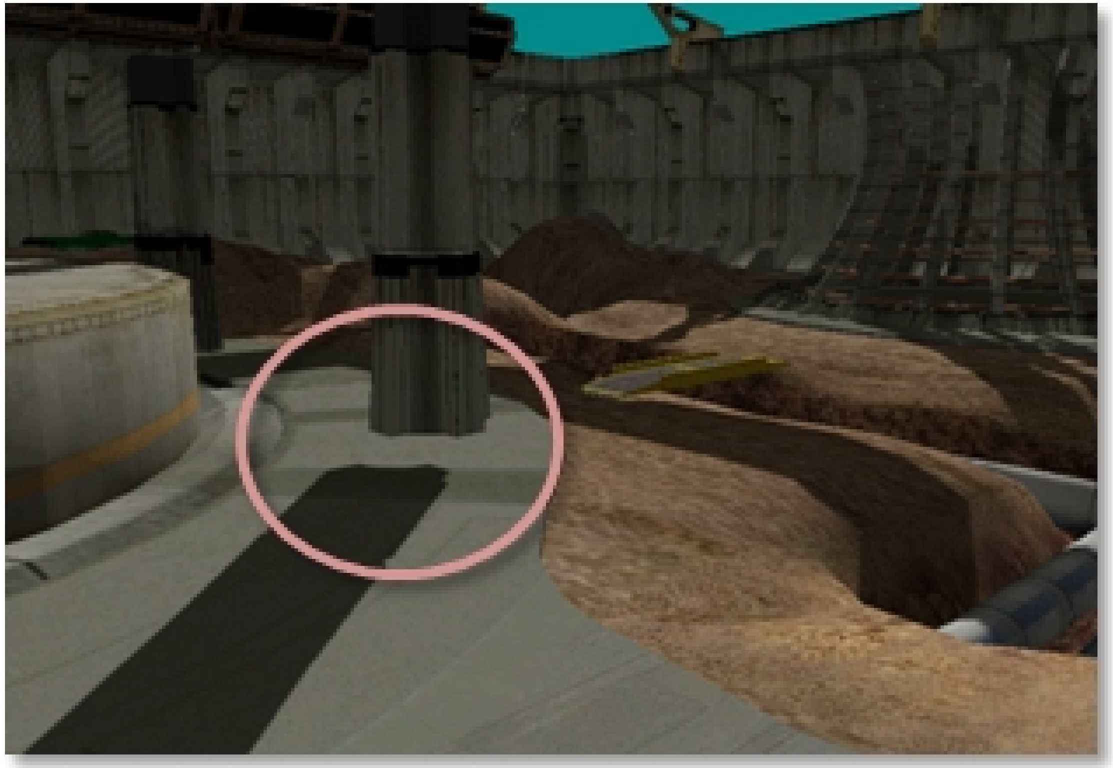
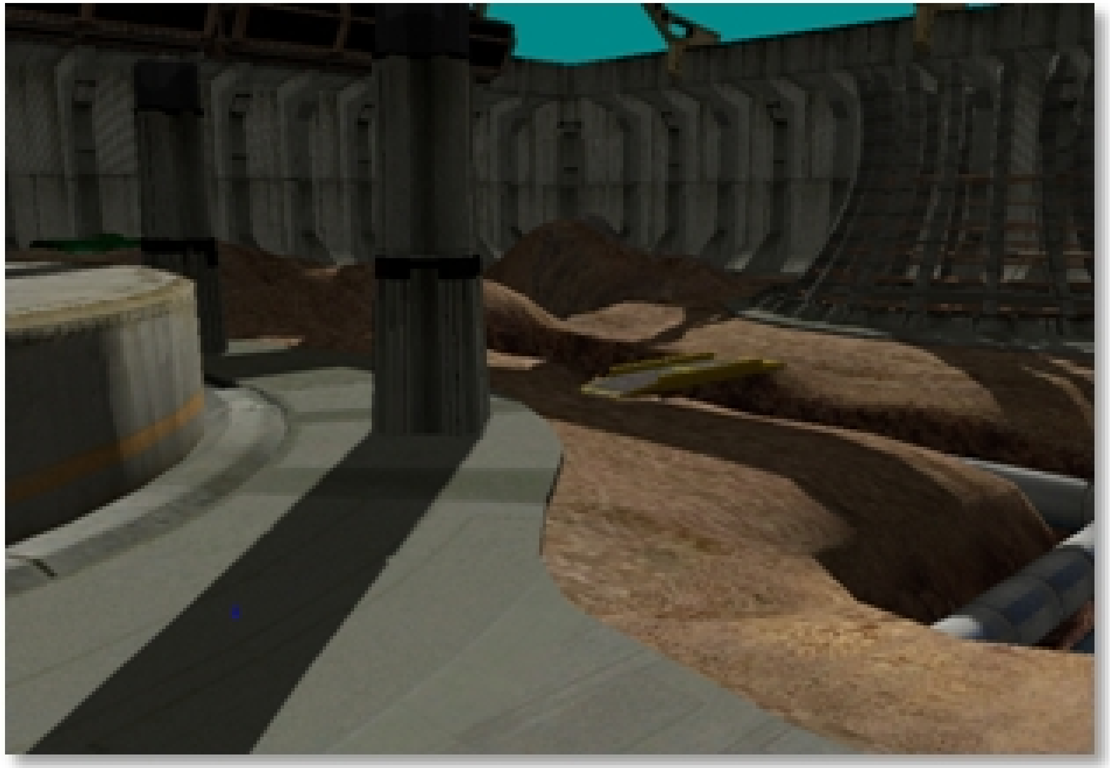
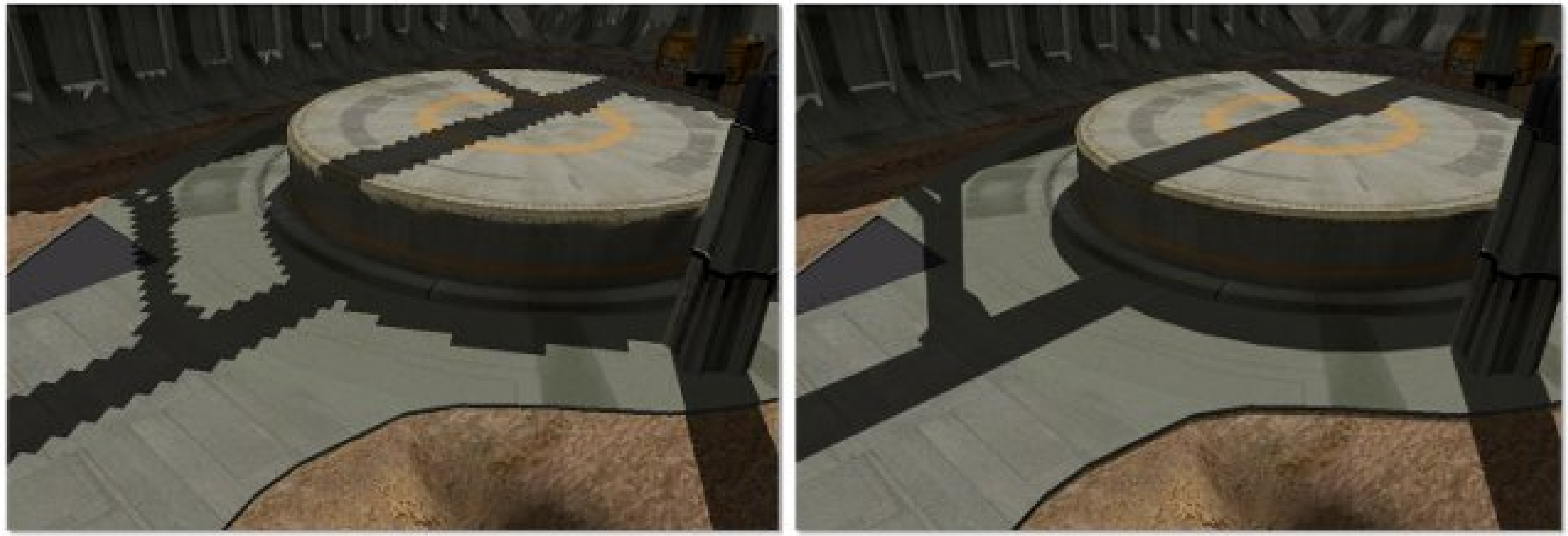
# Peter panning





# Shadow aliasing

- Finite shadow map resolution: pixelized shadows.
- Large scenes require high shadow map resolution, and a tight projection.



# Shadow aliasing

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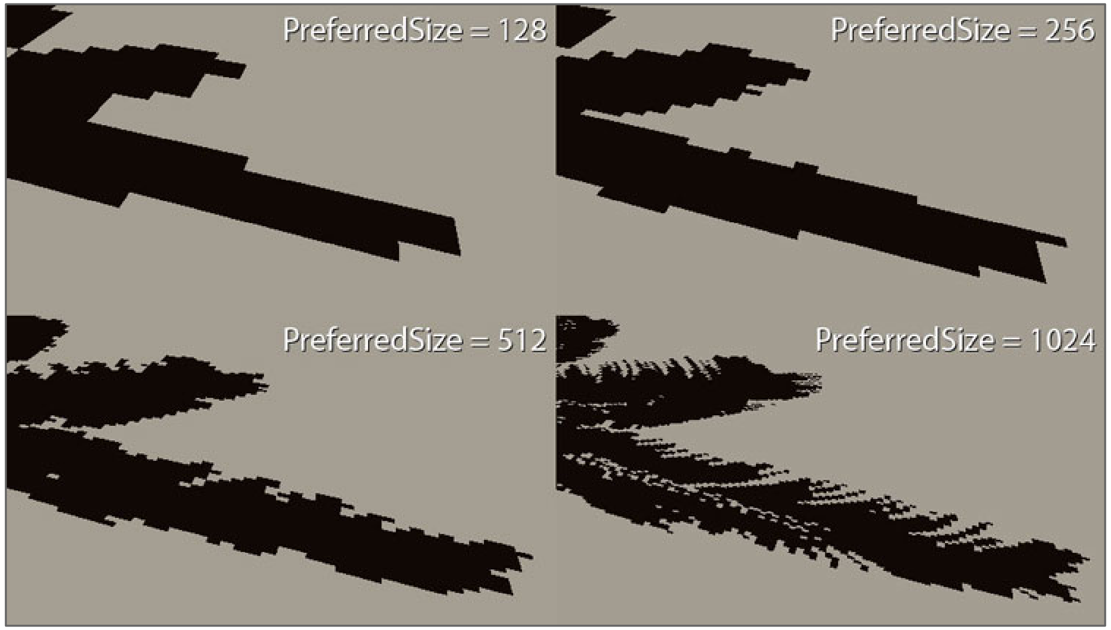
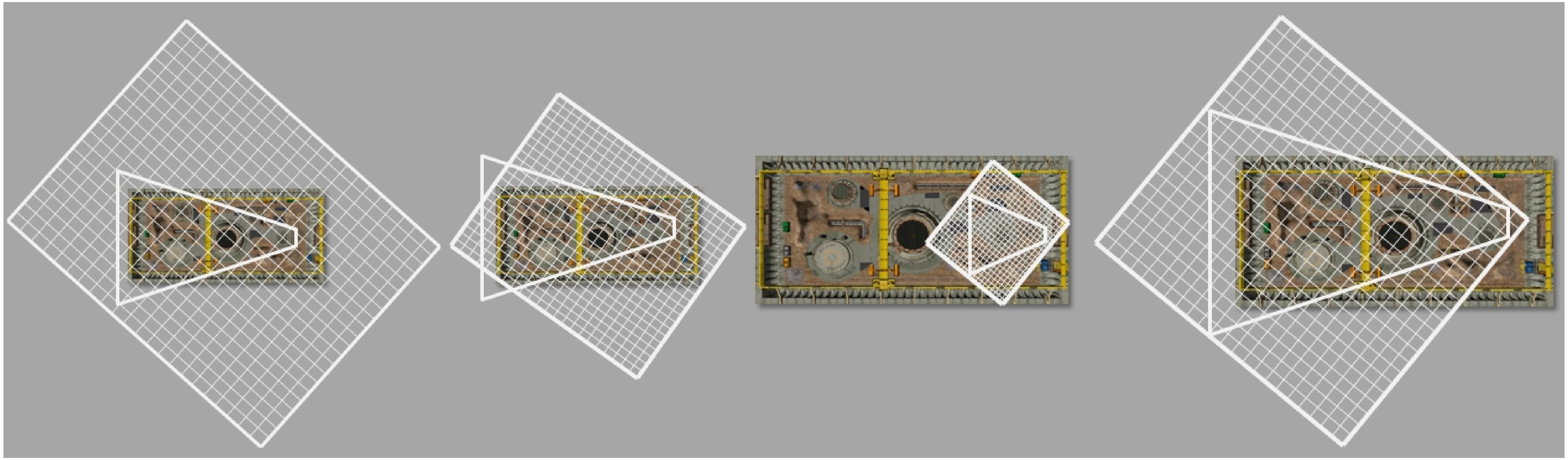



DigitalRune

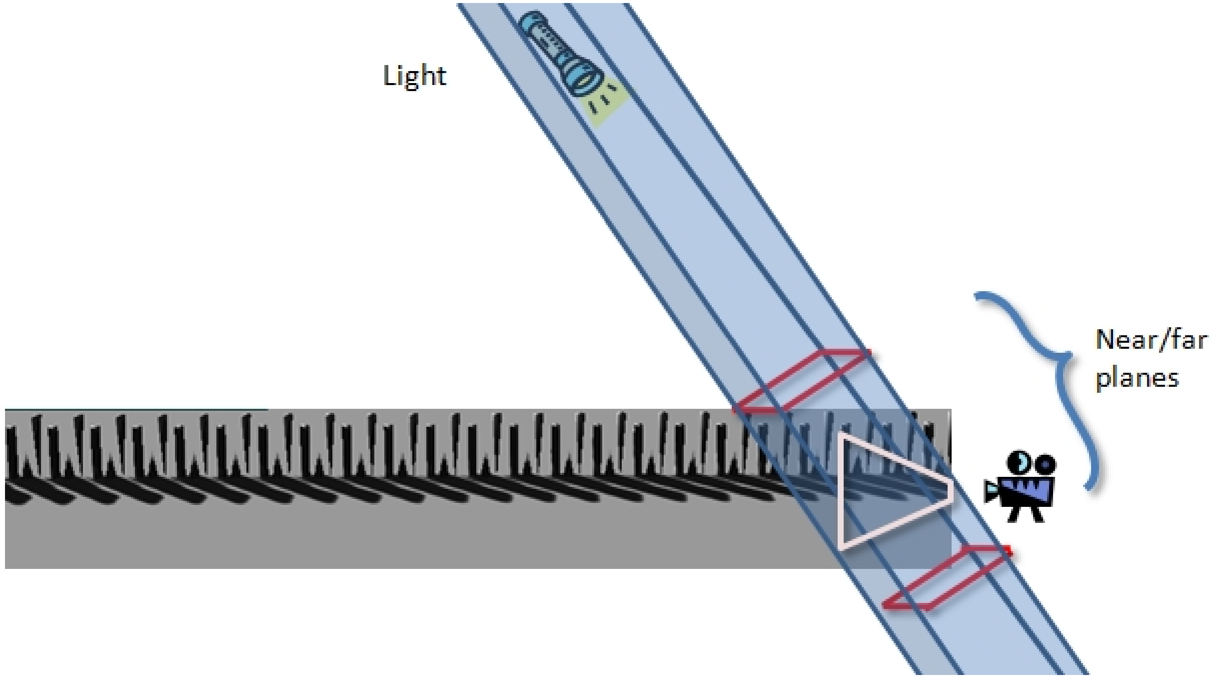
# Shadow aliasing

- Calculate a tight projection. How?



# Computing optimal projection

- Calculate 8 corners of view frustum in light space.
- 6 planes: 4 sides, near, far.
- Clip scene's bounds against 4 side planes.
- Smallest and largest z-values of clipped boundaries represent the near and far plan, respectively.



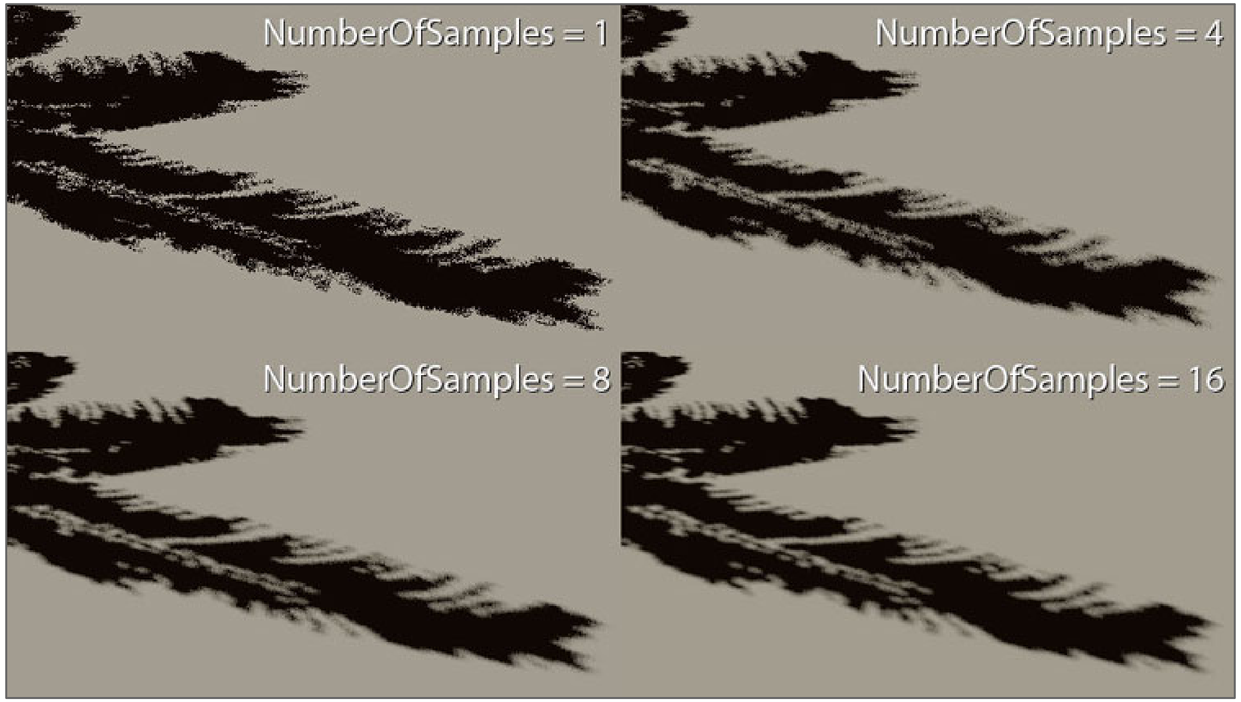
# Shadow aliasing

- Solution: sample from more than once from shadow map

```
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;
```

# Shadow aliasing

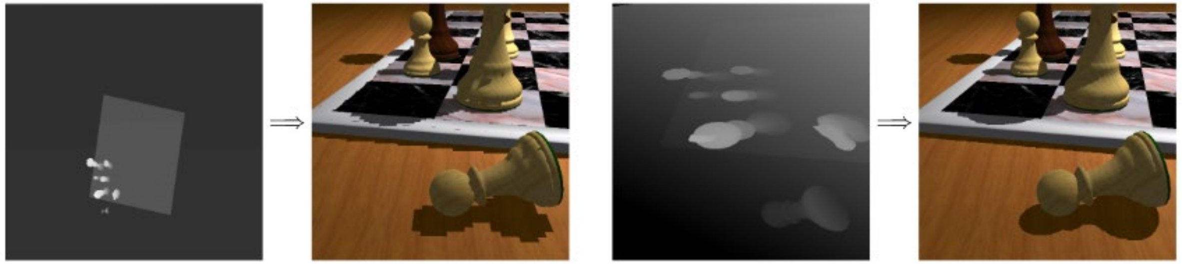
- Solution: sample from more than once from shadow map.




DigitalRune

# Shadow maps

Improving Shadow maps



Perspective Shadow Maps
[Stamminger and Drettakis, 2002]

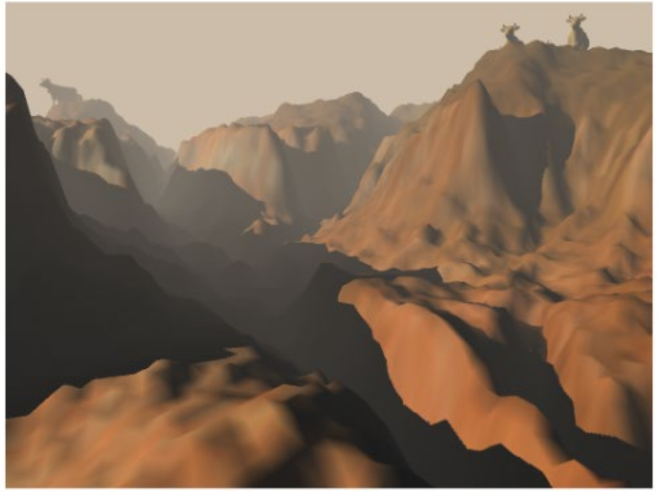


Figure 3-1. Large scale terrain rendering with 4-splits CSM

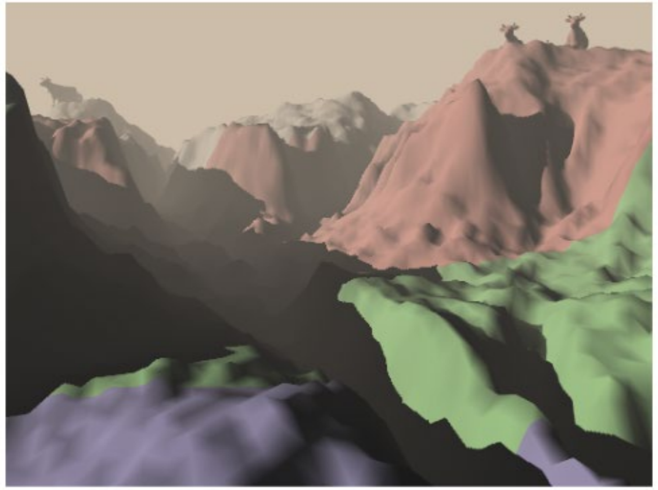


Figure 3-2. Texture look ups from different shadow maps are highlighted

Cascaded Shadow Maps [Dimitrov, 2007]

# Comparison

- Shadow Volumes:
  - Pros: accurate hard shadows
  - Slower, rasterization heavy
- Shadow Maps:
  - Pros: Fast, supports soft shadows
  - Cons: high memory usage, aliasing