# CSE 167: Introduction to Computer Graphics Lecture #16: Shadows

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# Announcements

- Important dates:
  - Final project outline due November 23rd
    - Email to me at `jschulze@ucsd.edu`
  - Final project presentations: Friday December 2nd, 1-3pm
  - Final Exam: December 9th, 3-6pm
- TA Evaluation for Gregory Long and Jorge Schwarzhaupt

# Lecture Overview

- Ambient Occlusion
- Shadow Mapping

# Screen Space Ambient Occlusion

- Screen Space Ambient Occlusion = SSAO
- Rendering technique for approximating ambient occlusion in real time
- Developed by Vladimir Kajalin while working at Crytek
- First use in 2007 PC game Crysis

SSAO component

# SSAO Demo

- Video

# SSAO Algorithm

- Copy frame buffer to texture
- Pixel shader samples depth values around current pixel and tries to compute amount of occlusion
- Occlusion depends on depth difference between sampled point and current point
- SSAO shader code from Crysis available on-line

# SSAO Discussion

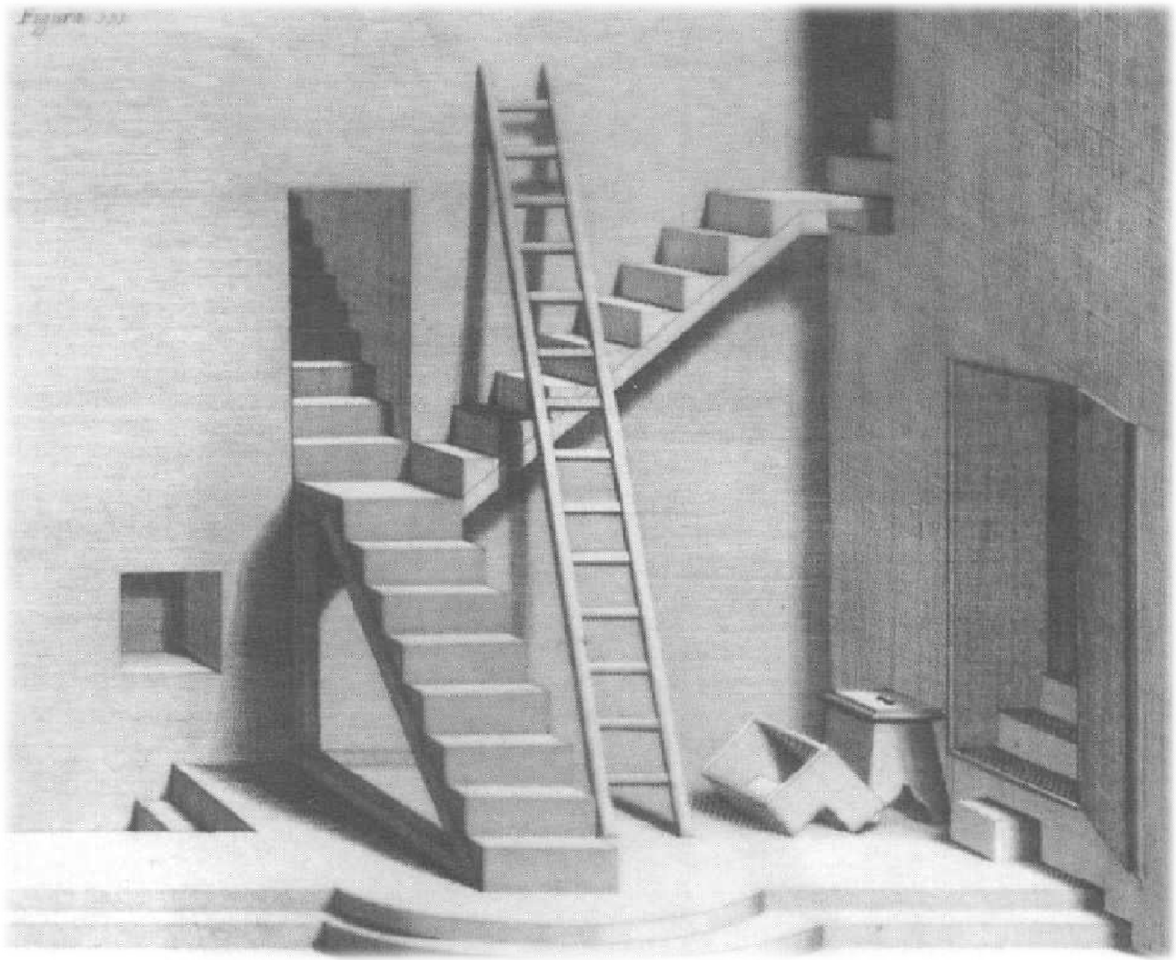
- Advantages:
  - Independent from scene complexity.
  - No pre-processing, no memory allocation in RAM
  - Works with dynamic scenes
  - Works in the same way for every pixel
  - No CPU usage: executed completely on GPU
- Disadvantages:
  - Local and view-dependent (dependent on adjacent texel depths)
  - Hard to correctly smooth/blur out noise without interfering with depth discontinuities, such as object edges

# Lecture Overview

- Ambient Occlusion
- Shadow Mapping

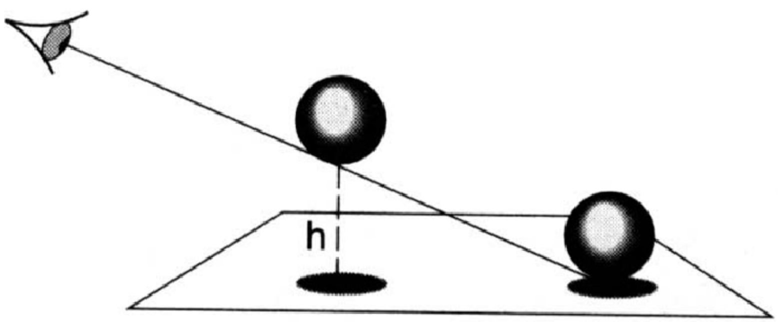
# Why Are Shadows Important?

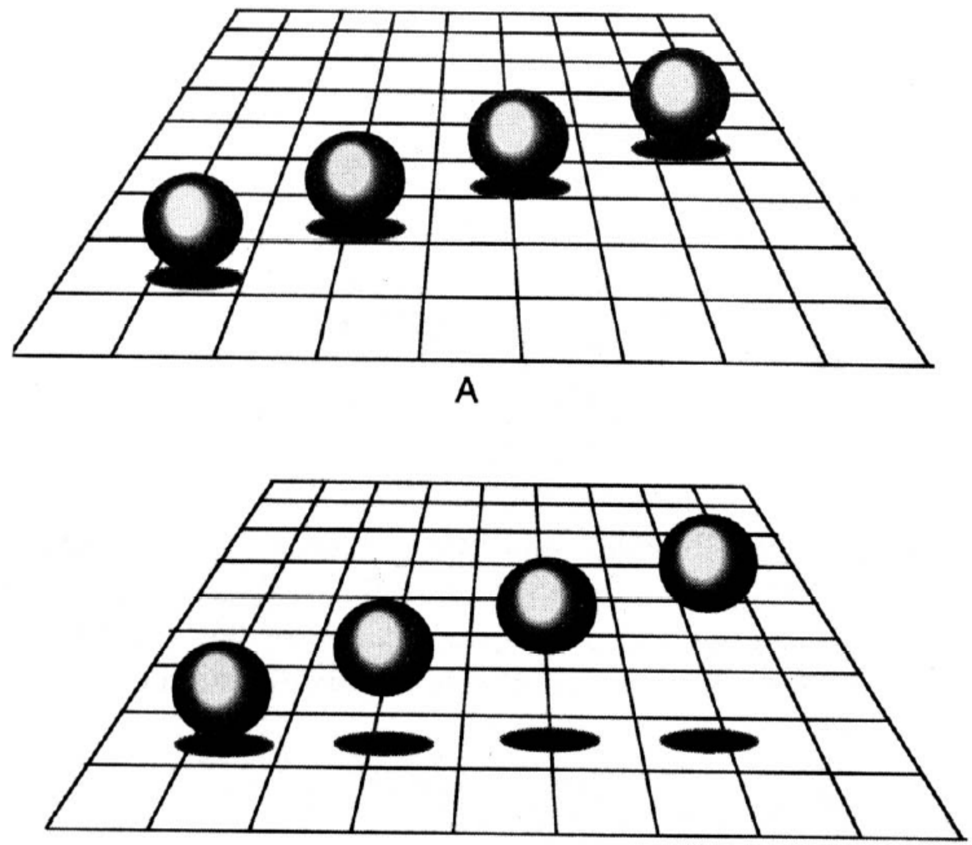
- Give additional cues on scene lighting



# Why Are Shadows Important?

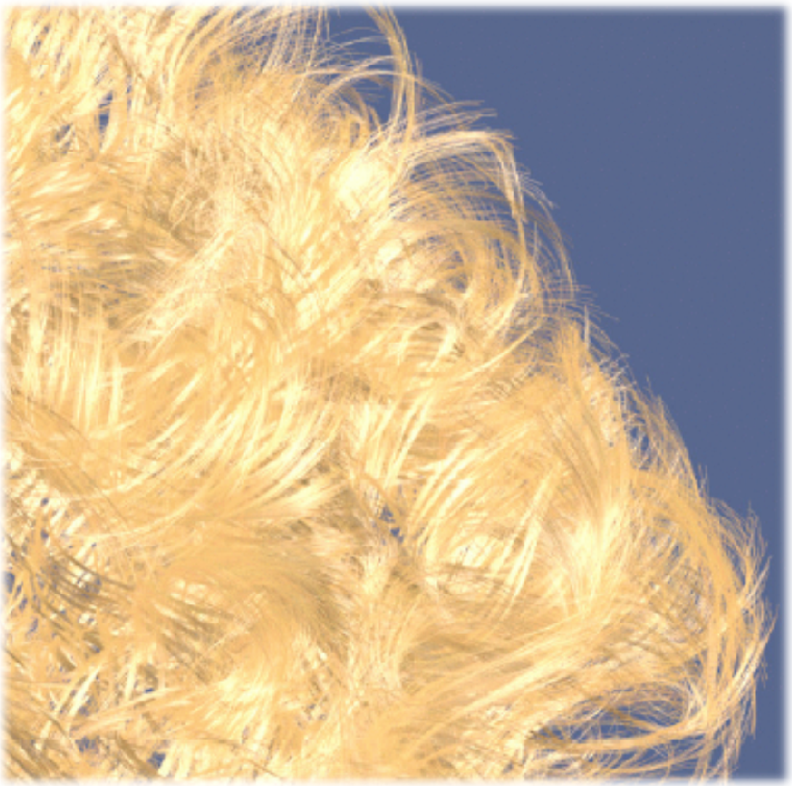
- Contact points
- Depth cues



# Why Are Shadows Important?

- Realism

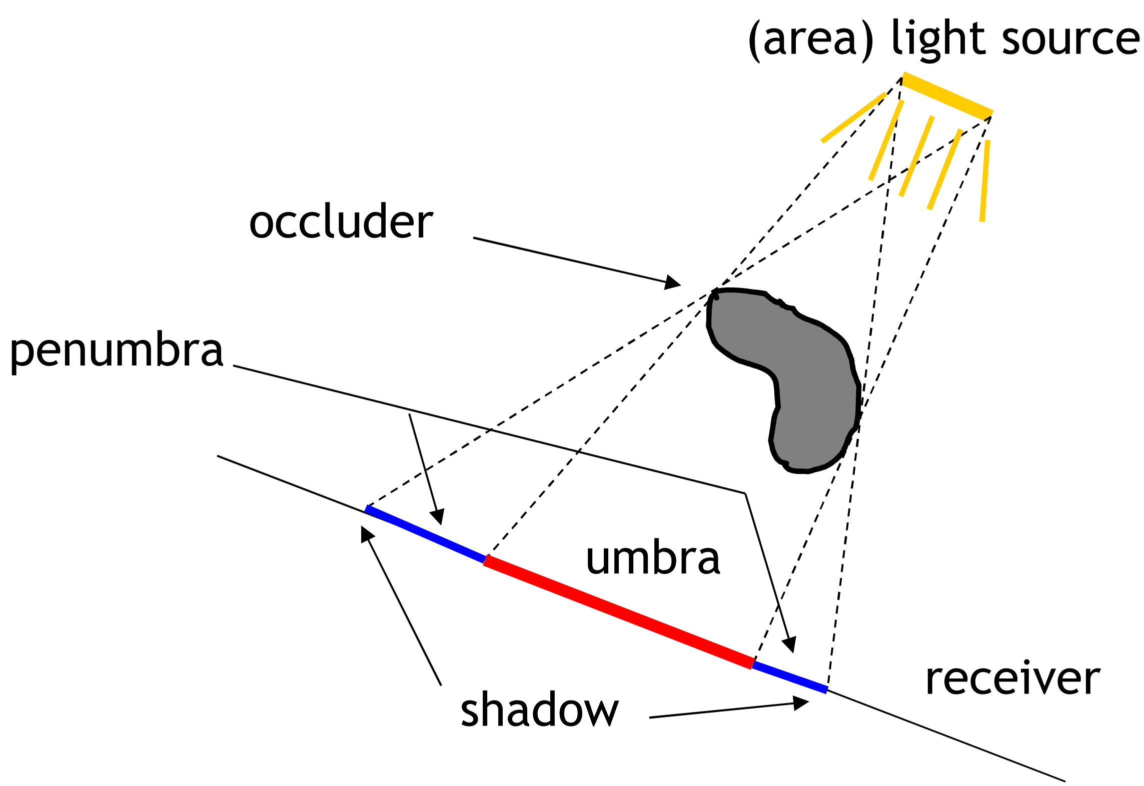


Without self-shadowing

With self-shadowing

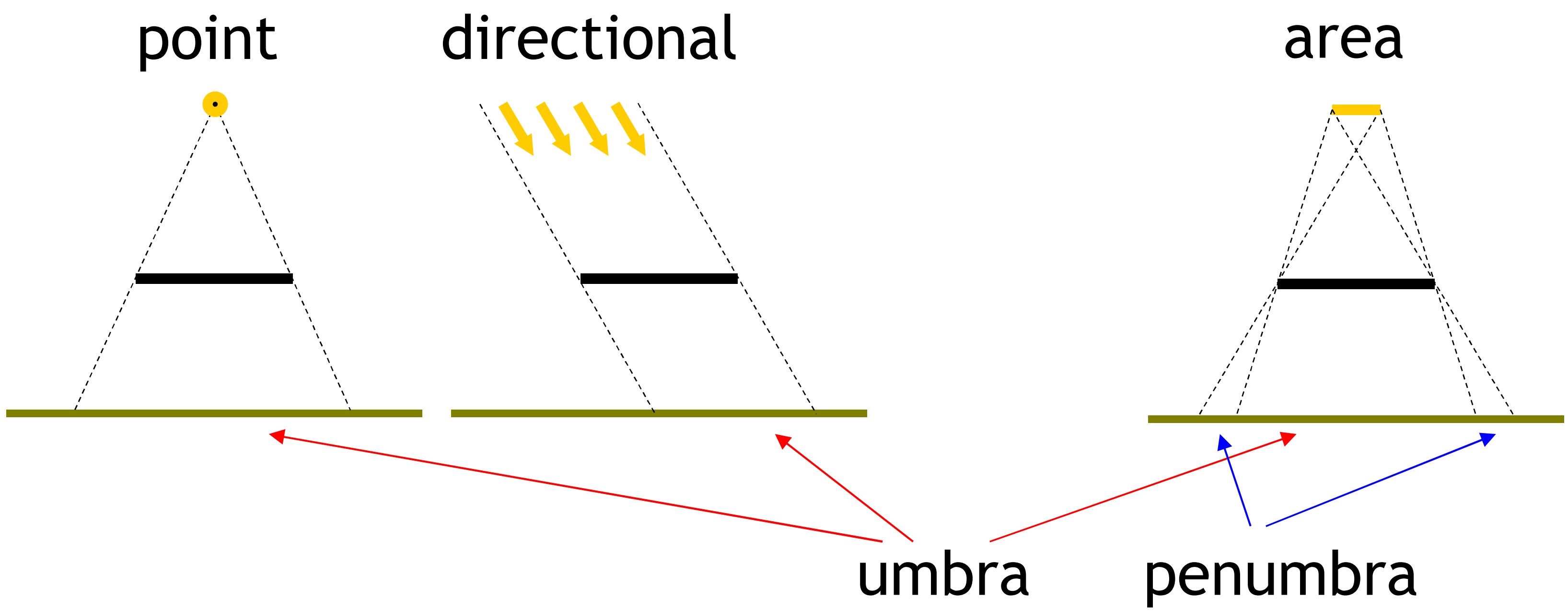
# Terminology

- Umbra: fully shadowed region
- Penumbra: partially shadowed region



# Hard and Soft Shadows

- Point and directional lights lead to hard shadows, no penumbra
- Area light sources lead to soft shadows, with penumbra



# Hard and Soft Shadows

Hard shadow from point light source

Soft shadow from area light source

# Shadows for Interactive Rendering

- In this course: hard shadows only
  - Soft shadows hard to compute in interactive graphics
- Two most popular techniques:
  - Shadow mapping
  - Shadow volumes
- Many variations, subtleties
- Active research area

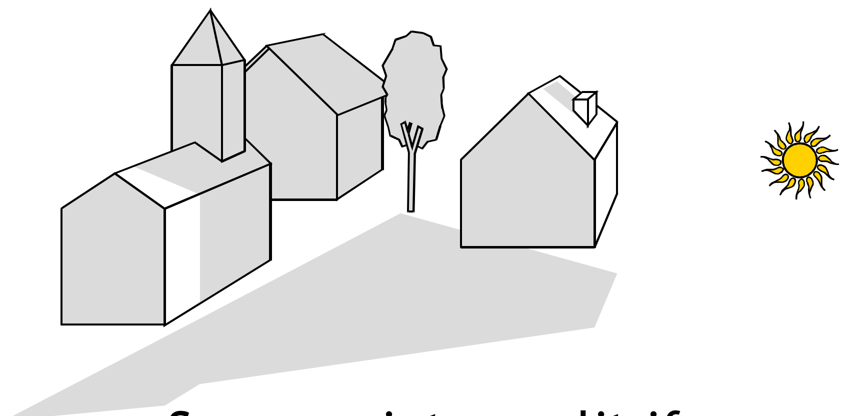
# Lecture Overview

- Shadows
- Shadow mapping

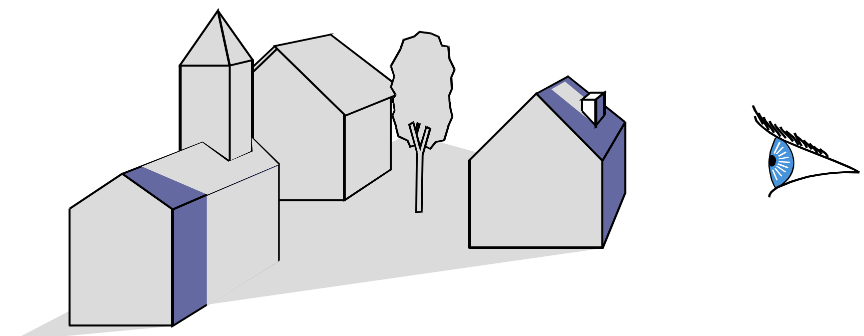
# Shadow Mapping

## Main Idea

- A scene point is lit by the light source if visible from the light source
- Determine visibility from light source by placing a camera at the light source position and rendering the scene from there



Scene points are lit if visible from light source

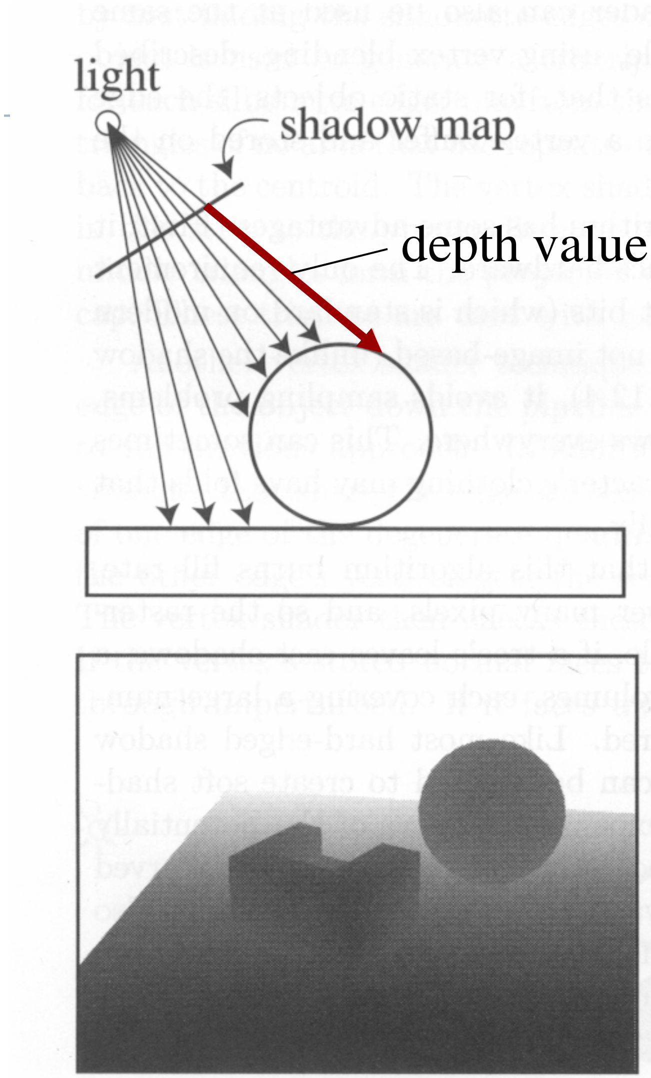


Determine visibility from light source by placing camera at light source position

# Two Pass Algorithm

**First Pass**

- Render scene by placing camera at light source position
- Store depth image (*shadow map*)

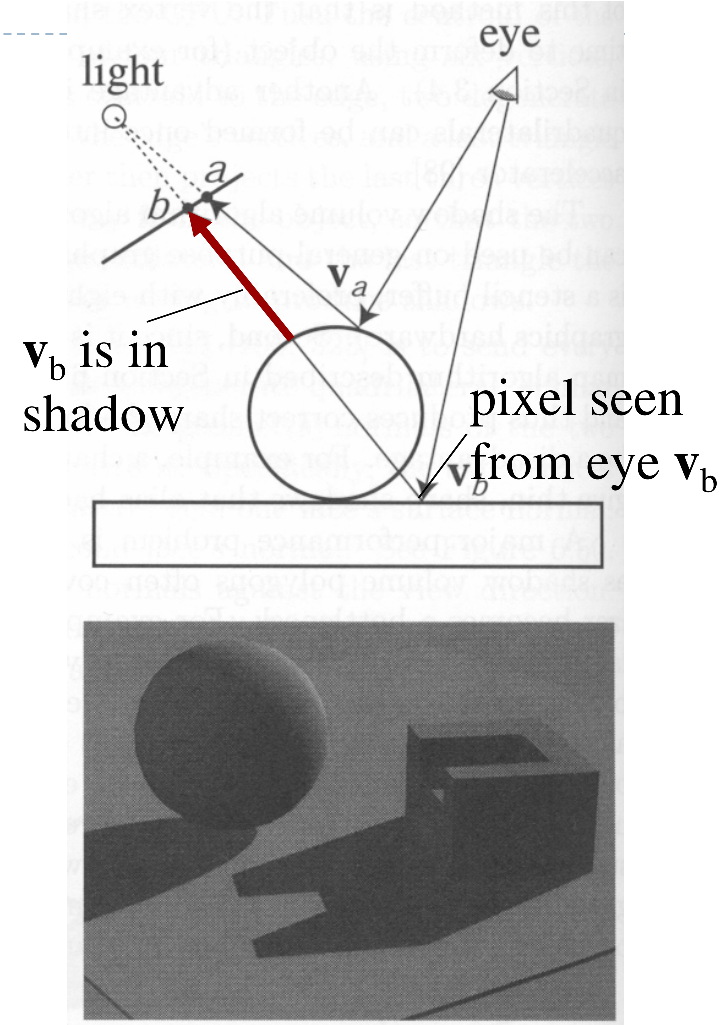



Depth image as seen from light source

# Two Pass Algorithm

## Second Pass

- Render scene from camera position
- At each pixel, compare distance to light source with value in shadow map
  - If distance is larger, pixel is in shadow
  - If distance is smaller or equal, pixel is lit



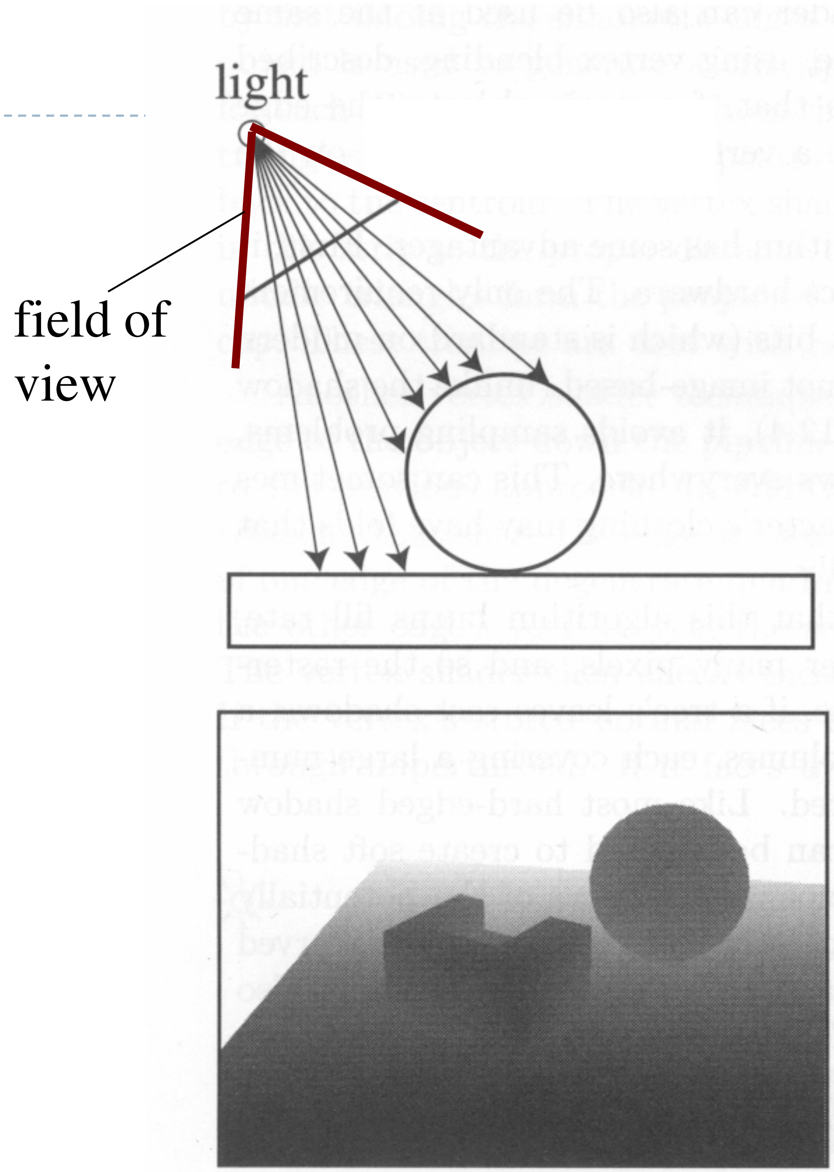

Final image with shadows

# Issues With Shadow Maps

- Limited field of view of shadow map
- Z-fighting
- Sampling problems

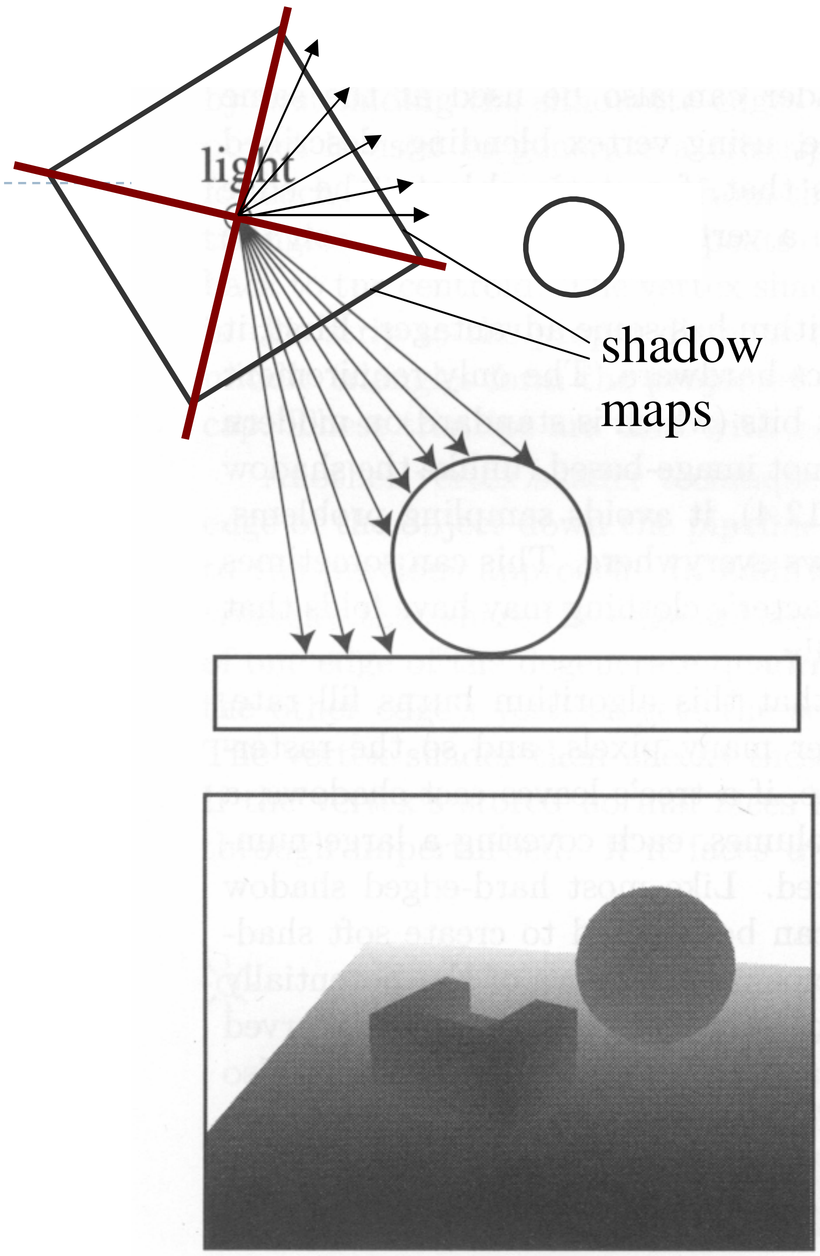
# Limited Field of View

- What if a scene point is outside the field of view of the shadow map?



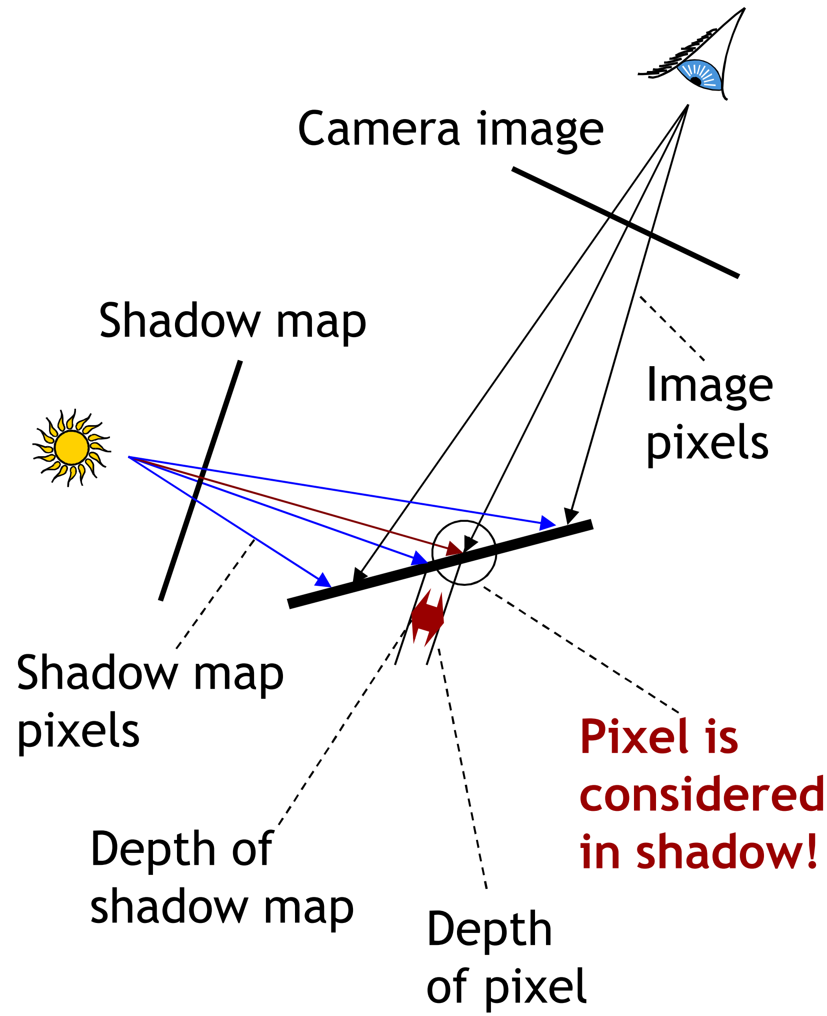
# Limited Field of View

- What if a scene point is outside the field of view of the shadow map?
  → Use six shadow maps, arranged in a cube
- Requires a rendering pass for each shadow map



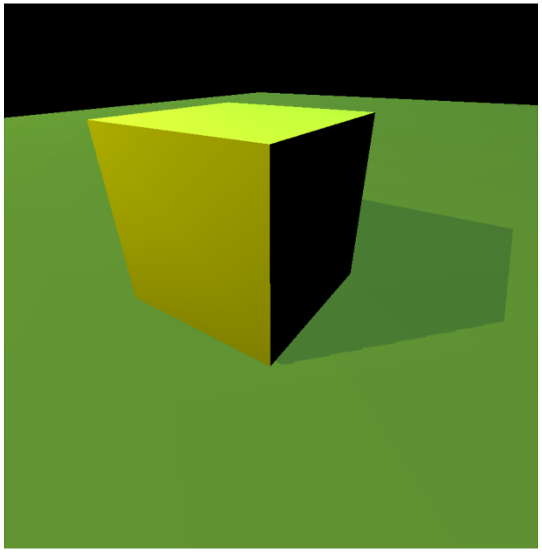
# Z-Fighting

- Depth values for points visible from light source are equal in both rendering passes
- Because of limited resolution, depth of pixel visible from light could be larger than shadow map value
- Need to add bias in first pass to make sure pixels are lit

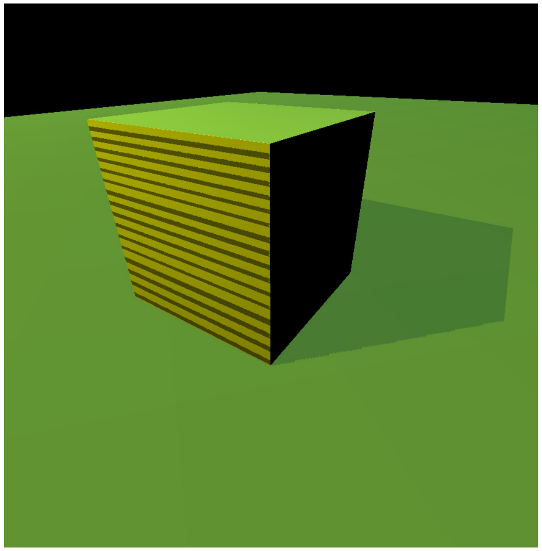


# Solution: Bias

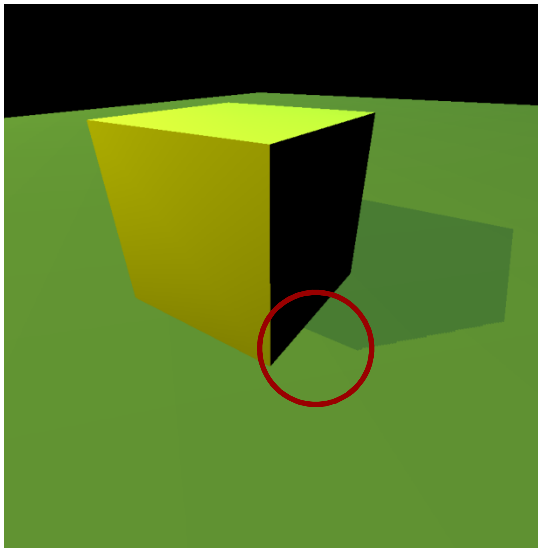
- Add bias when rendering shadow map
  - Move geometry away from light by small amount
- Finding correct amount of bias is tricky



Correct bias



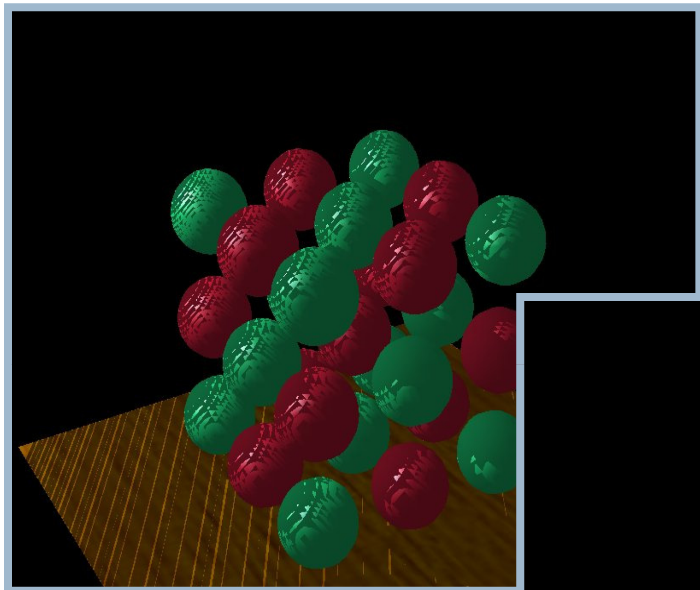
Not enough bias



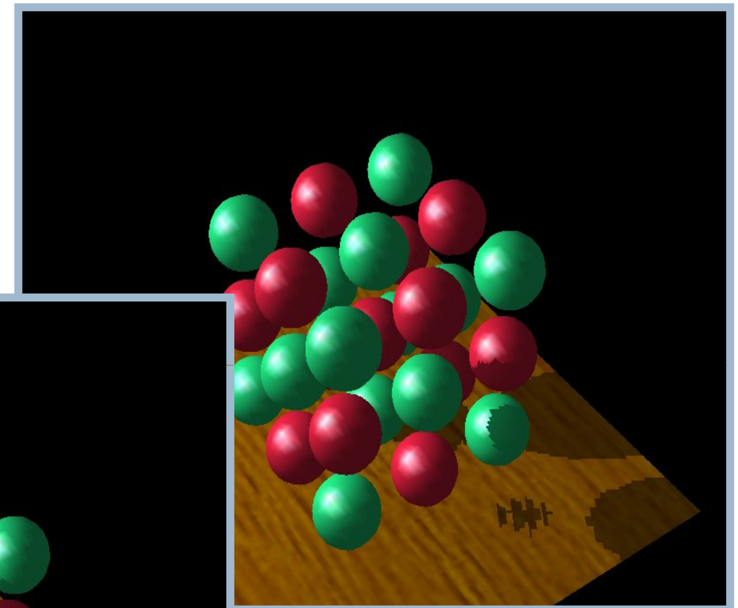
Too much bias

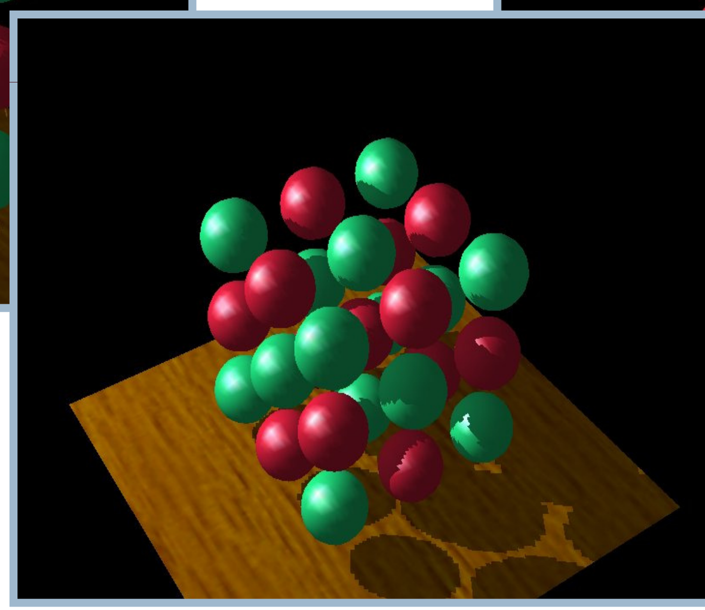
# Bias Adjustment

Not enough



Too much

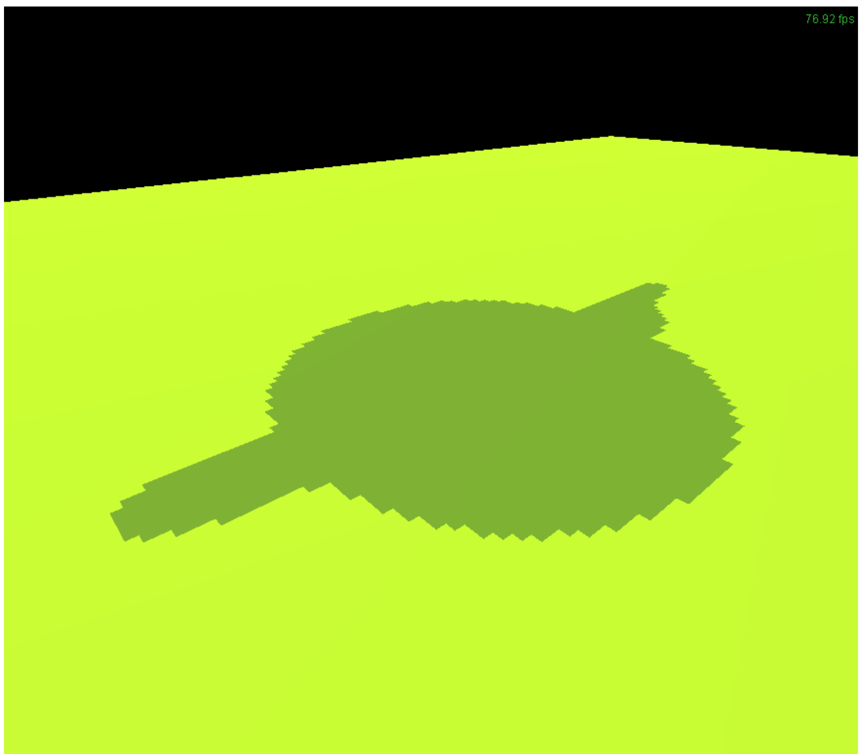




Just right

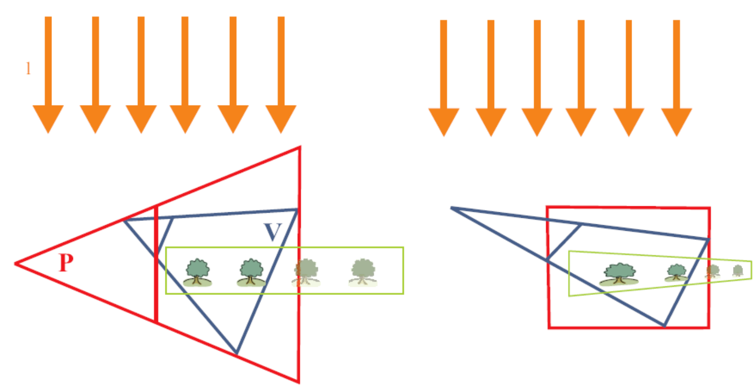
# Sampling Problems

- Shadow map pixel may project to many image pixels
  → Stair-stepping artifacts



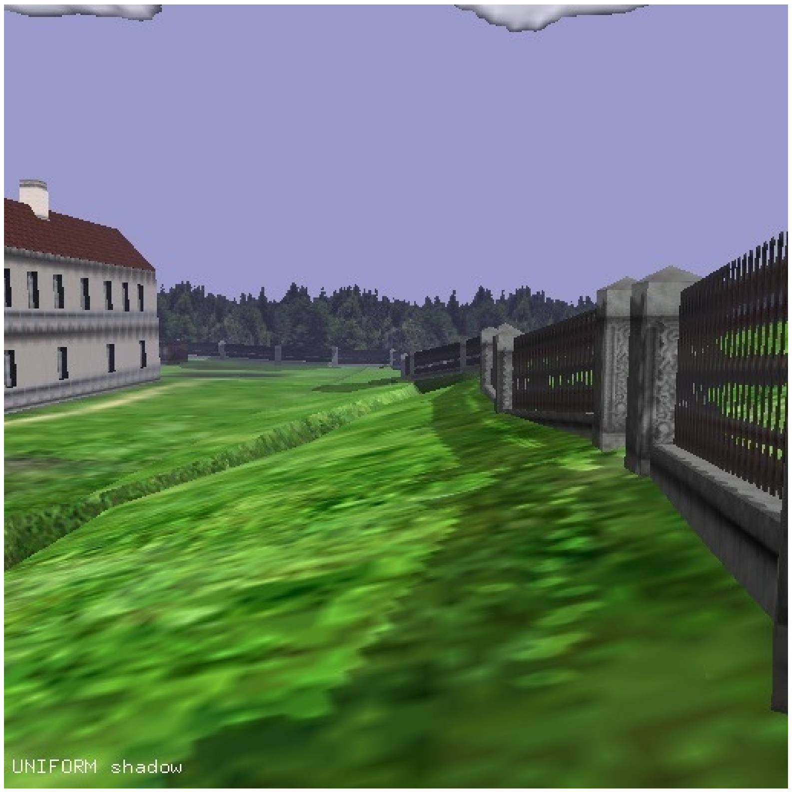

# Solutions

- Increase resolution of shadow map
  - Not always sufficient
- Split shadow map into several tiles
- Tweak projection for shadow map rendering
  - Light space perspective shadow maps (LiSPSM) http://www.cg.tuwien.ac.at/research/vr/lispsm/

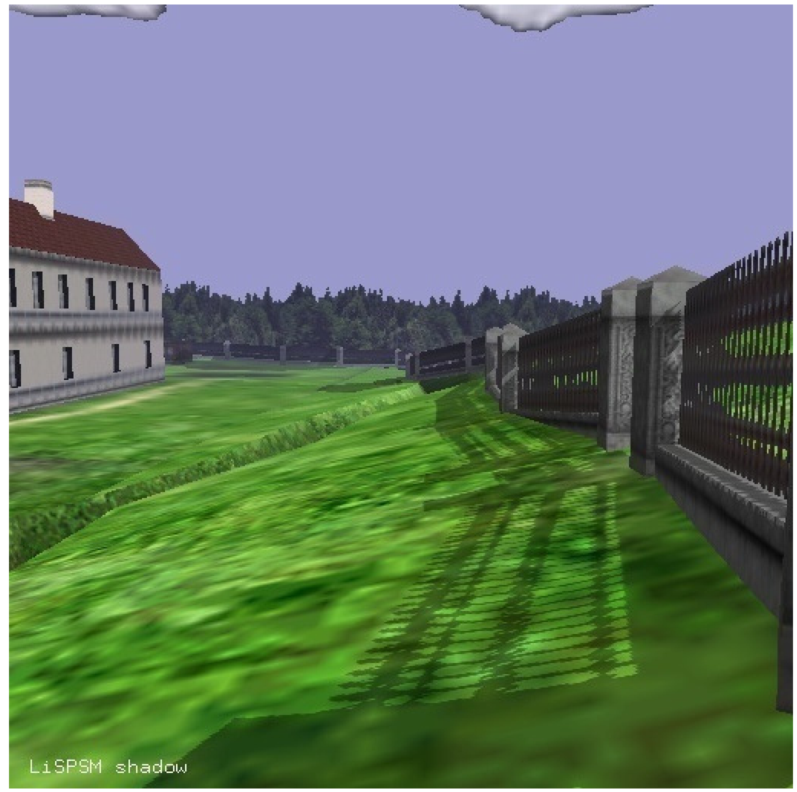



- Combination of splitting and LiSPSM
  - Basis for most serious implementations

# LiSPSM




Basic shadow map




Light space perspective shadow map

# Video

# Shadow Mapping With GLSL

**First Pass**

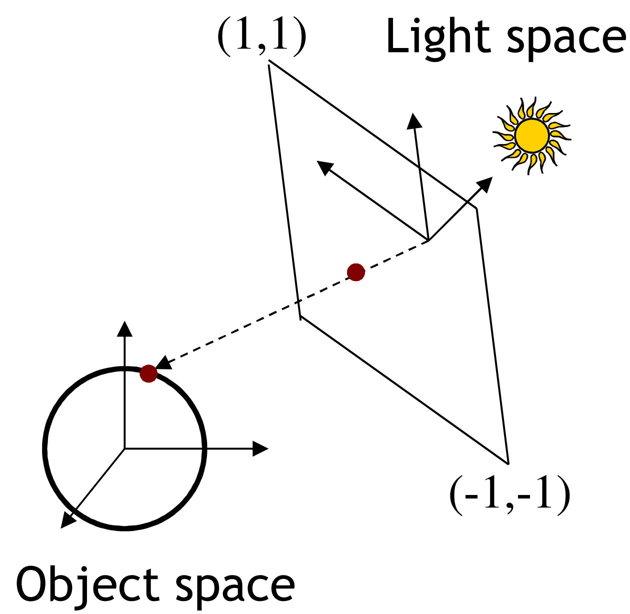
- Render scene by placing camera at light source position
- Compute light view (look at) matrix
  - Similar to computing camera matrix from look-at, up vector
  - Compute its inverse to get world-to-light transform
- Determine view frustum such that scene is completely enclosed
  - Use several view frusta/shadow maps if necessary

# First Pass

- Each vertex point is transformed by

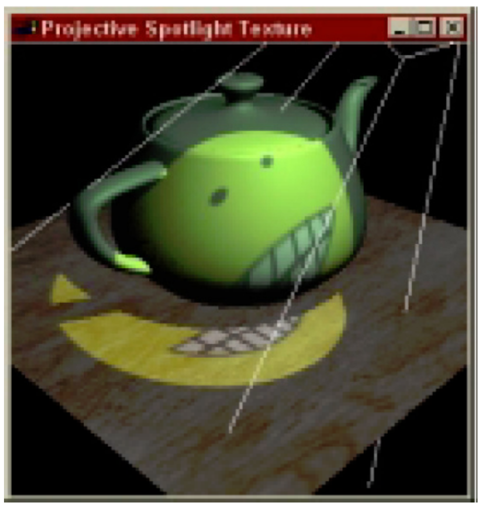
$$\mathbf{P}_{light}\mathbf{V}_{light}\mathbf{M}$$

  - Object-to-world (modeling) matrix $\mathbf{M}$
  - World-to-light space matrix $\mathbf{V}_{light}$
  - Light frustum (projection) matrix $\mathbf{P}_{light}$
- Remember: points within frustum are transformed to unit cube $[-1,1]^3$



# First Pass

- Use glPolygonOffset to apply depth bias
- Store depth image in a texture
  - Use glCopyTexImage with internal format GL_DEPTH_COMPONENT




Final result
with shadows


Scene rendered
from light source


Depth map
from light source

# Second Pass

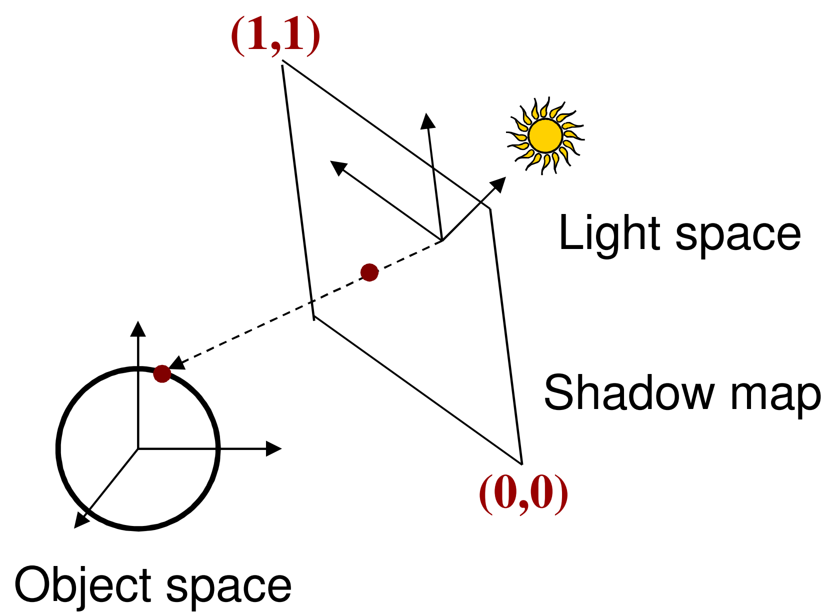
- Render scene from camera
- At each pixel, look up corresponding location in shadow map
- Compare depths with respect to light source

# Shadow Map Look-Up

- Need to transform each point from object space to shadow map
- Shadow map texture coordinates are in $[0,1]^2$
- Transformation from object to shadow map coordinates

$$\mathbf{T} = \begin{bmatrix} 1/2 & 0 & 0 & 1/2 \\ 0 & 1/2 & 0 & 1/2 \\ 0 & 0 & 1/2 & 1/2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \mathbf{P}_{light} \mathbf{V}_{light} \mathbf{M}$$

- $\mathbf{T}$ is called texture matrix
- After perspective projection we have shadow map coordinates



# Shadow Map Look-Up

- Transform each vertex to normalized frustum of light

$$\begin{bmatrix} s \\ t \\ r \\ q \end{bmatrix} = \mathbf{T} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

- Pass s,t,r,q as texture coordinates to rasterizer
- Rasterizer interpolates s,t,r,q to each pixel
- Use projective texturing to look up shadow map
  - This means, the texturing unit automatically computes s/q,t/q,r/q,1
  - s/q,t/q are shadow map coordinates in $[0,1]^2$
  - r/q is depth in light space
- Shadow depth test: compare shadow map at (s/q,t/q) to r/q

# GLSL Specifics

**In application**

- Store matrix **T** in OpenGL texture matrix
- Set using `glMatrixMode(GL_TEXTURE)`

**In vertex shader**

- Access texture matrix through predefined uniform `gl_TextureMatrix`

**In fragment shader**

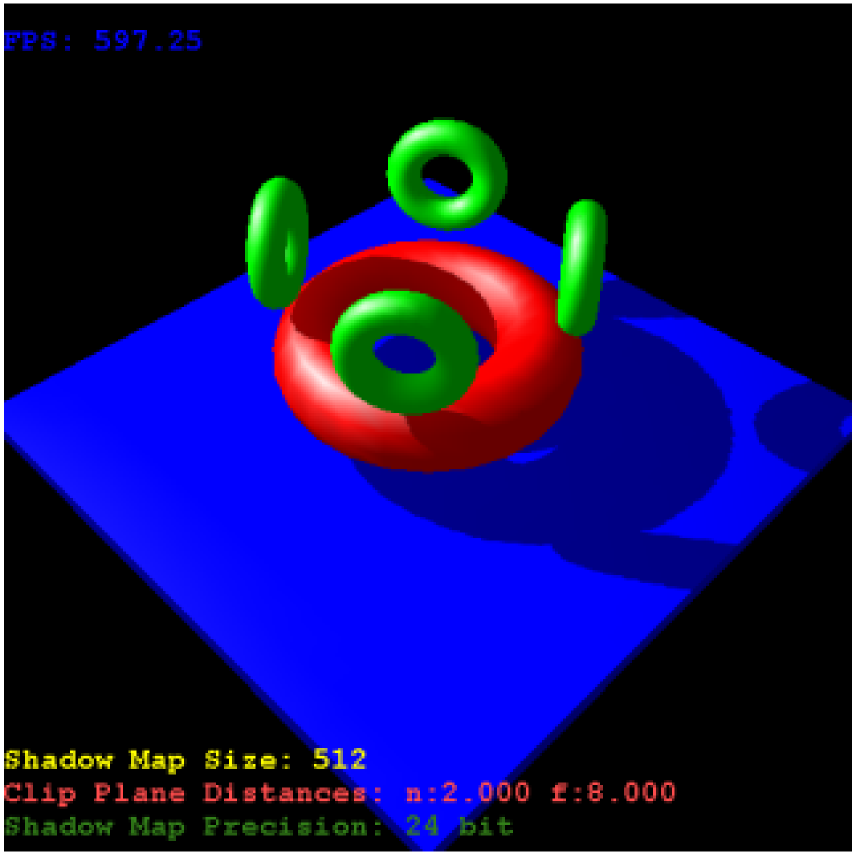
- Declare shadow map as sampler2DShadow
- Look up shadow map using projective texturing with `vec4 texture2DProj(sampler2D, vec4)`

# Implementation Specifics

- When you do a projective texture look up on a `sampler2DShadow`, the depth test is performed automatically
  - Return value is (1,1,1,1) if lit
  - Return value is (0,0,0,1) if shadowed
- Simply multiply result of shading with current light source with this value

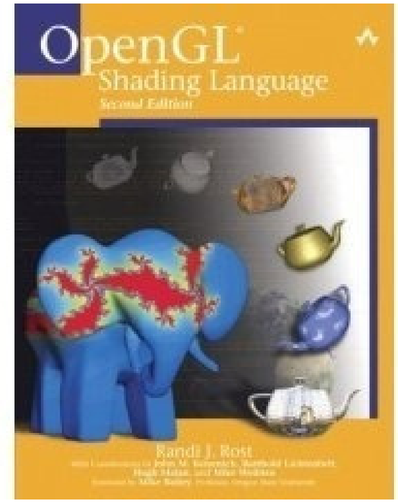
# Demo

- Shadow mapping demo from http://www.paulsprojects.net/opengl/shadowmap/shadowmap.html



# More on Shaders

- OpenGL shading language book
  - "Orange Book"




- Shader Libraries
  - GLSL:
    - http://www.geeks3d.com/geexlab/shader_library.php
  - HLSL:
    - NVidia shader library
    - http://developer.download.nvidia.com/shaderlibrary/webpages/shader_library.html

# Next Lecture

- Procedural Modeling