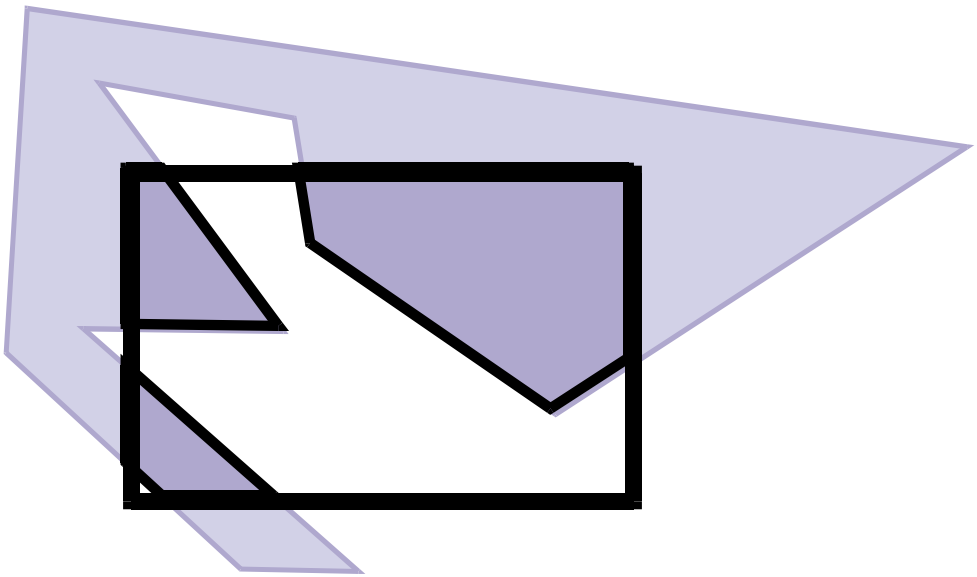
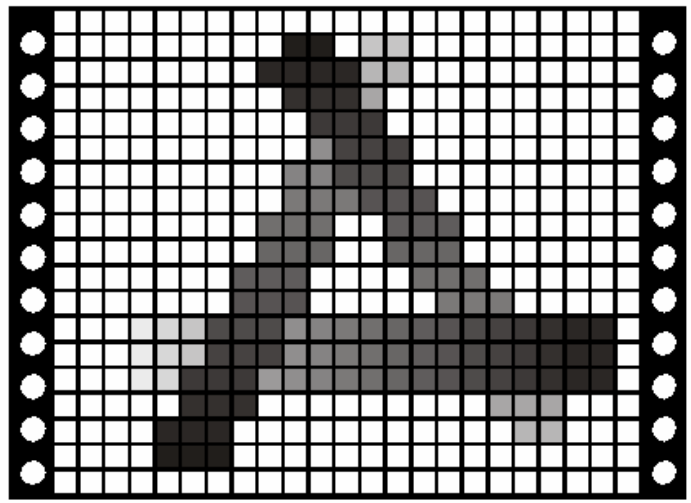
Real-Time Shadows

Last Time?

- The graphics pipeline
- Clipping & rasterization of polygons
- Visibility — the depth buffer (z-buffer)





Schedule

- Quiz 2: Thursday November 20th, in class (two weeks from Thursday)
- Project Presentations (to staff): December 1st - 5th (~ 4 weeks)
- Project Report due: Tuesday December 9th (5 weeks from today)

Questions?

Today

- Why are Shadows Important?
- Shadows & Soft Shadows in Ray Tracing
- Planar Shadows
- Shadow Maps
- Shadow Volumes

Why are Shadows Important?

- Depth cue
- Scene Lighting
- Realism
- Contact points

Image removed due to copyright considerations.

Shadows as a Depth Cue

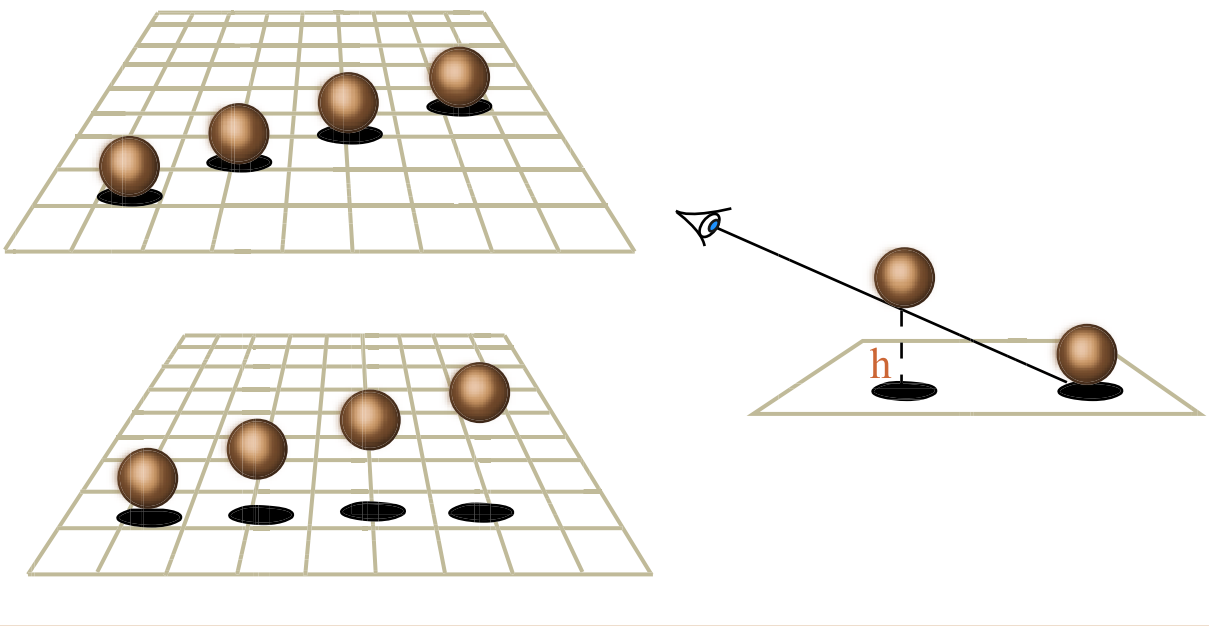
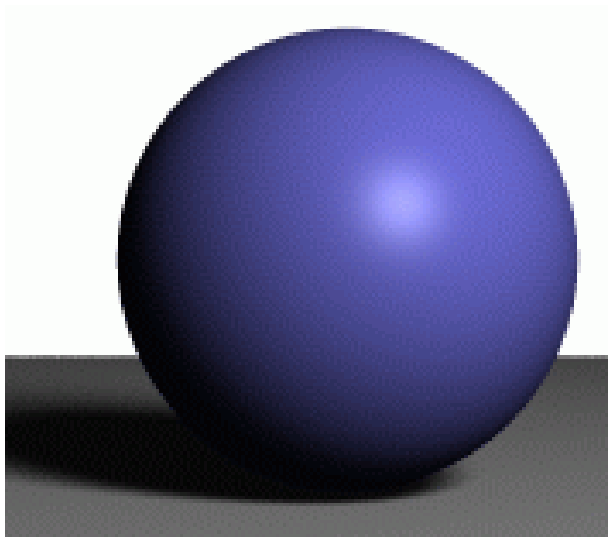
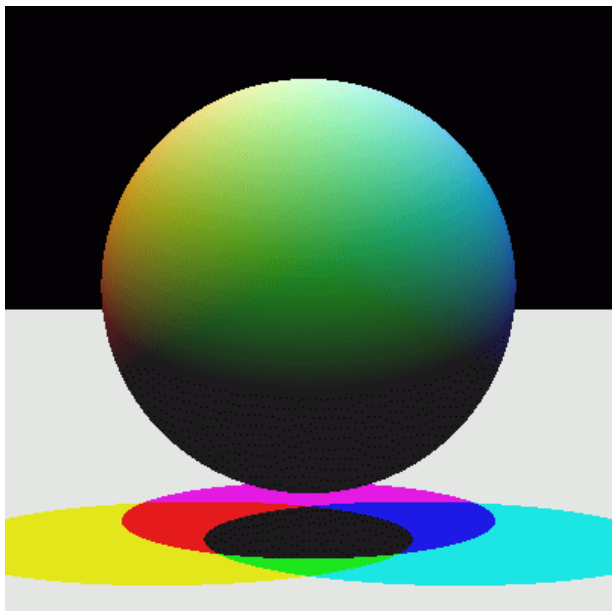


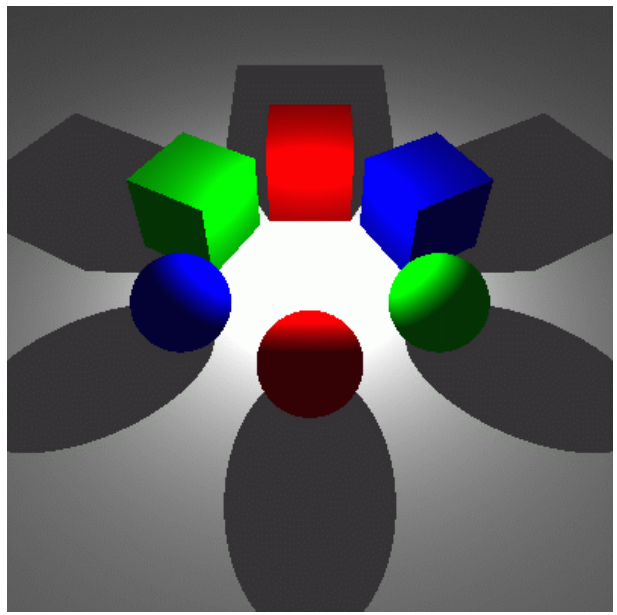
Image adapted from:
Palmer, Stephen E. *Vision Science: Photons to Phenomenology*. MIT Press. May 1999. ISBN: 0-262-16183-4.

For Intuition about Scene Lighting

- Position of the light (e.g. sundial)
- Hard shadows vs. soft shadows
- Colored lights
- Directional light vs. point light





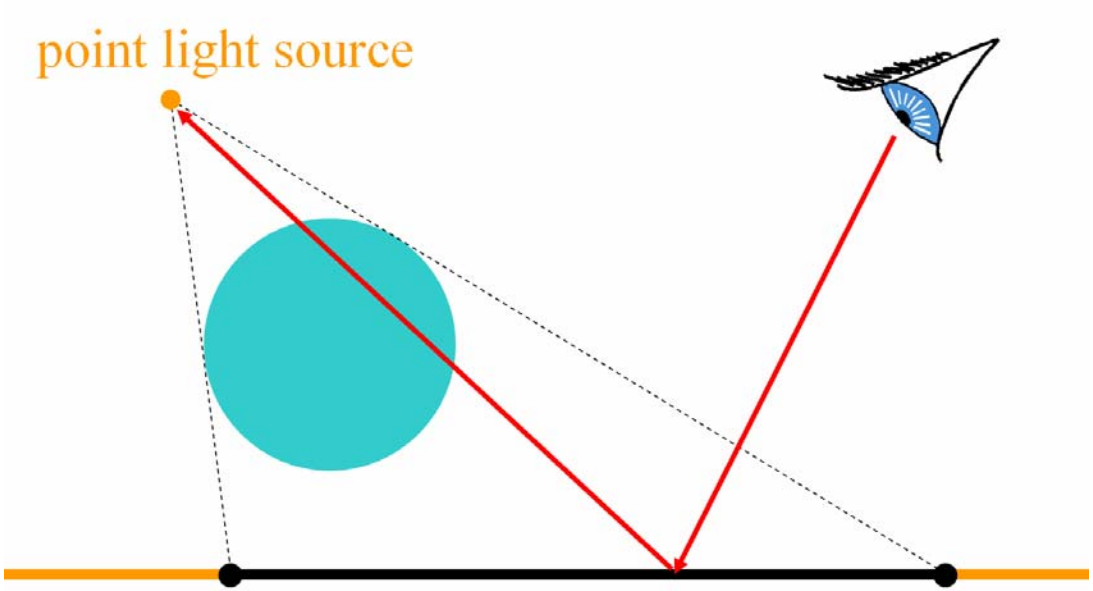


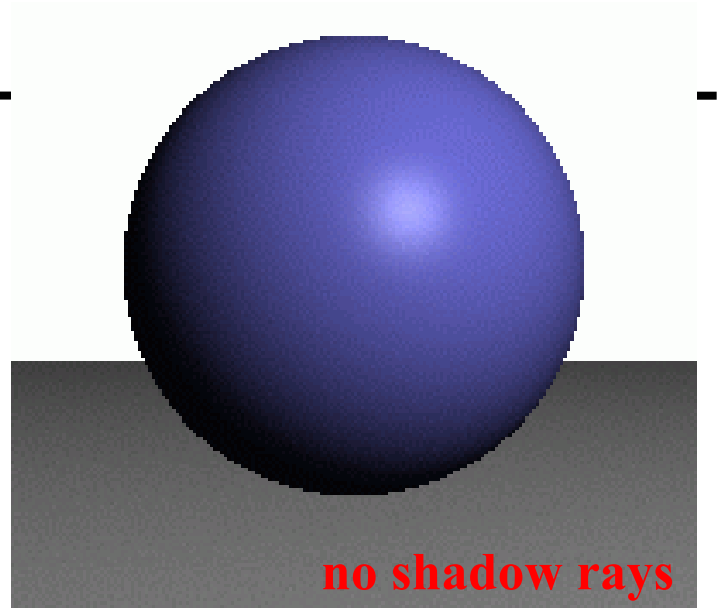
Today

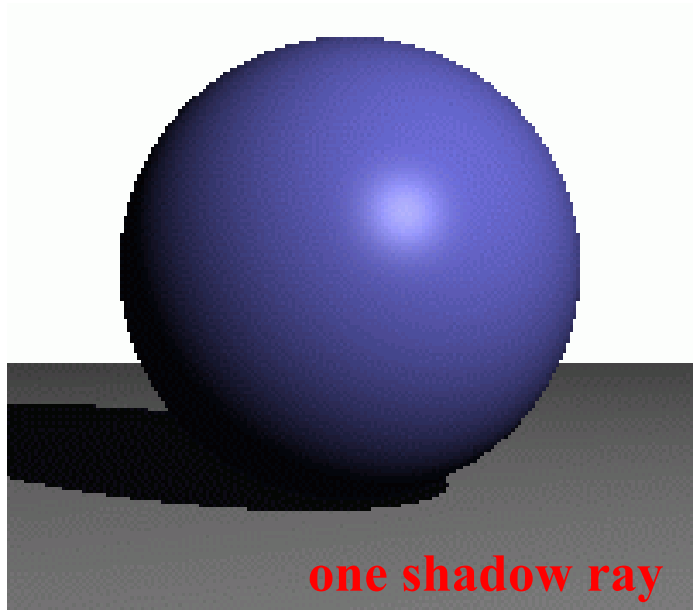
- Why are Shadows Important?
- Shadows & Soft Shadows in Ray Tracing
- Planar Shadows
- Shadow Maps
- Shadow Volumes

Shadows

- One shadow ray per intersection per point light source







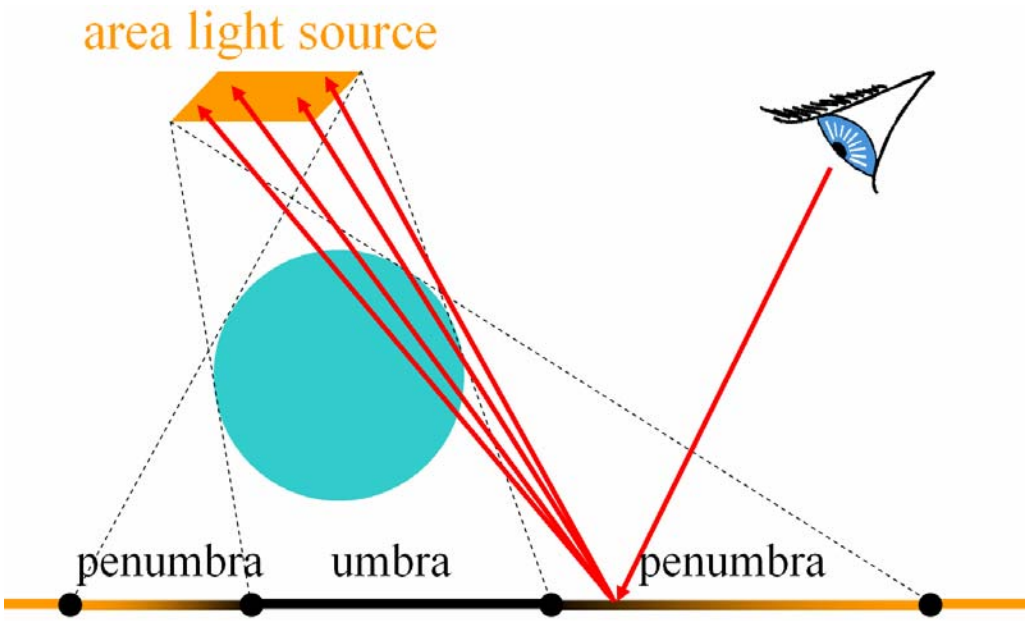
Soft Shadows

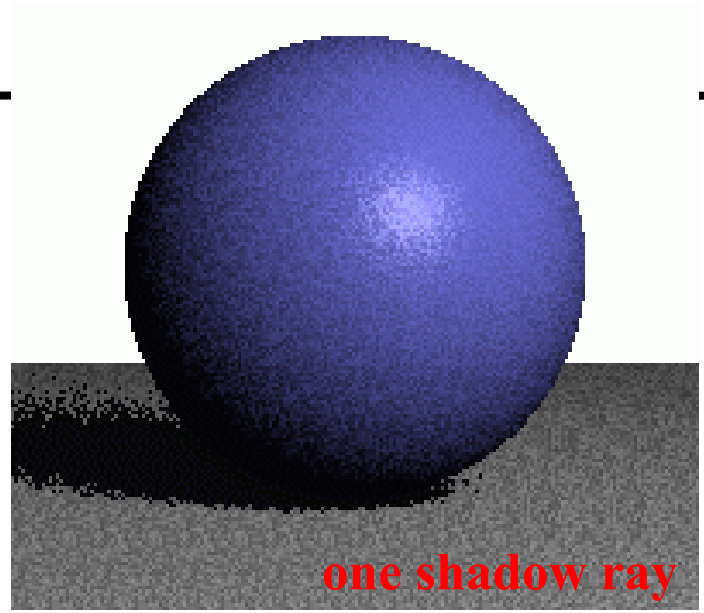
- Caused by extended light sources
- Umbra
  - source completely occluded
- Penumbra
  - Source partially occluded
- Fully lit

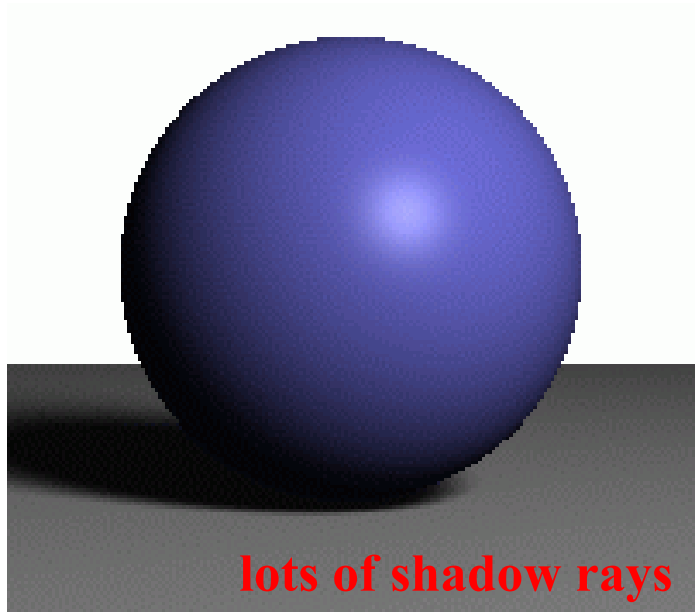
Image removed due to copyright considerations.

Soft Shadows

- Multiple shadow rays to sample area light source

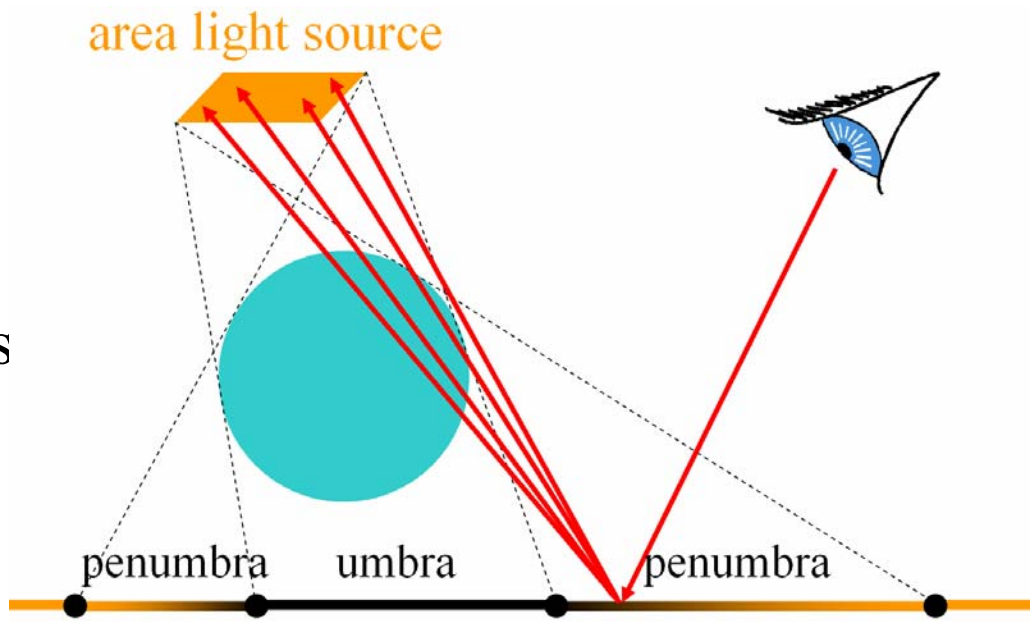




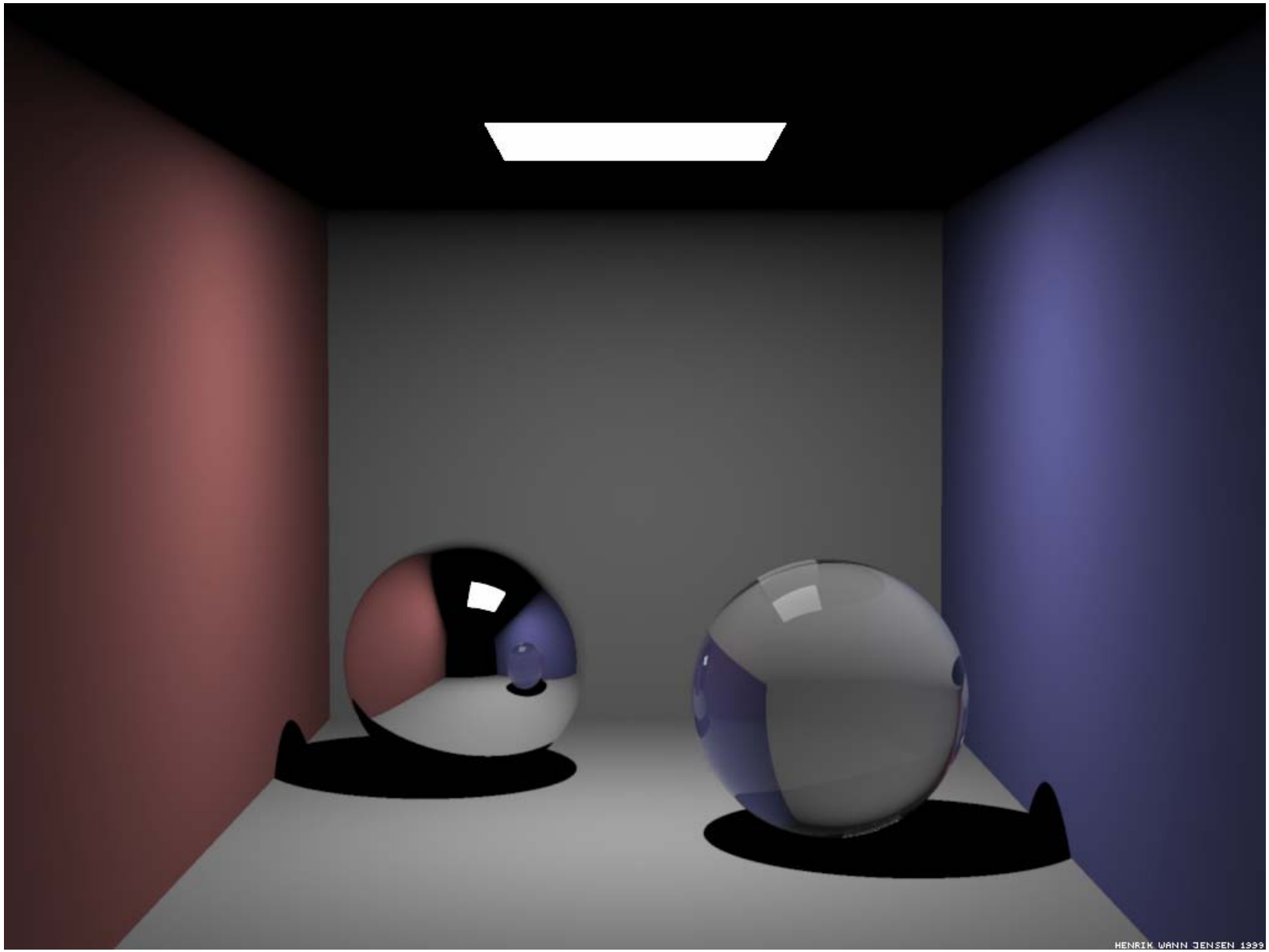


Shadows in Ray Tracing

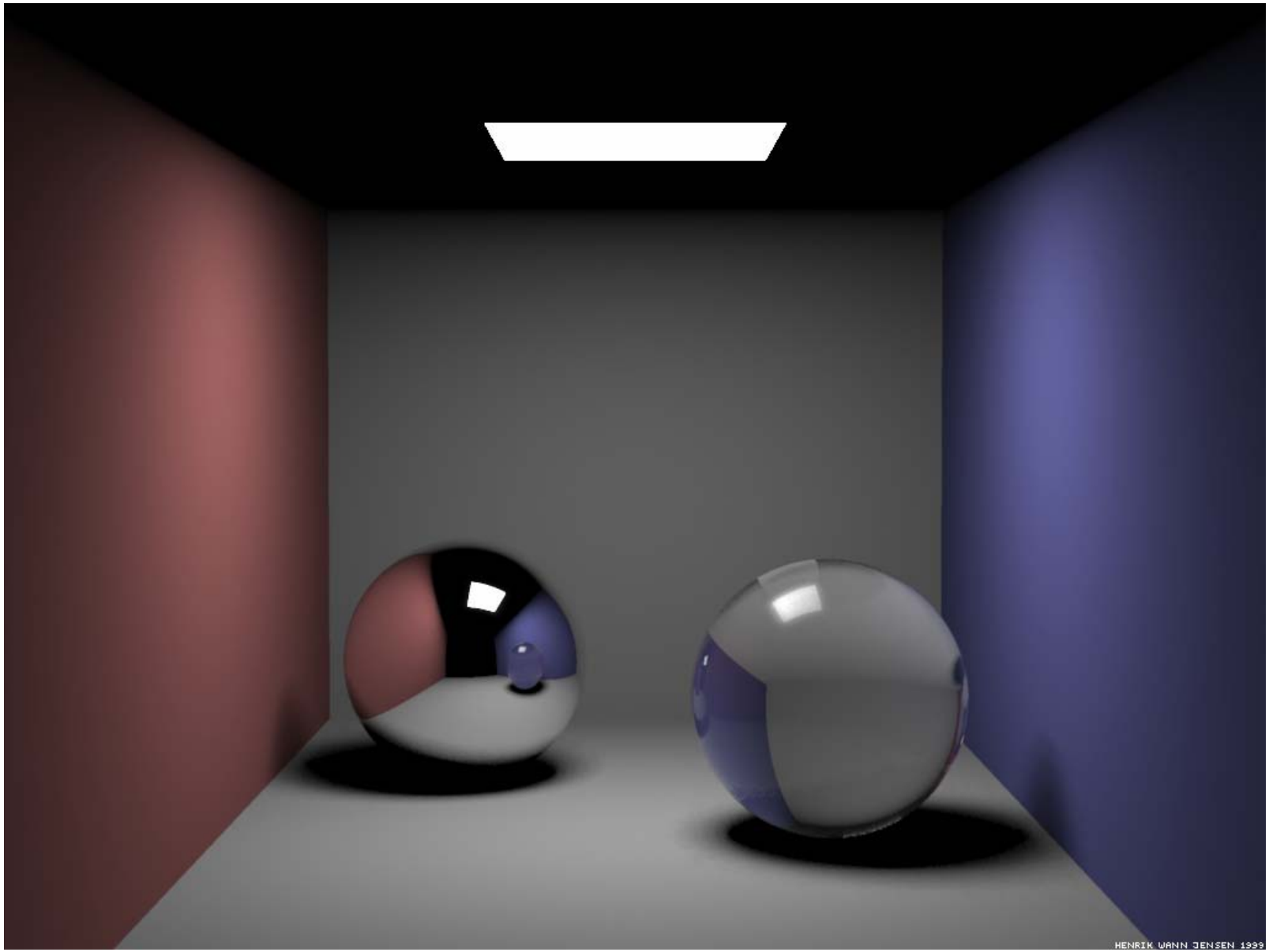
- Shoot ray from visible point to light source
- If blocked, discard light contribution
- Optimization?
  - Stop after first intersection (don't worry about tmin)
  - Coherence: remember the previous occluder, and test that object firs



Traditional Ray Tracing



Ray Tracing + Soft Shadows

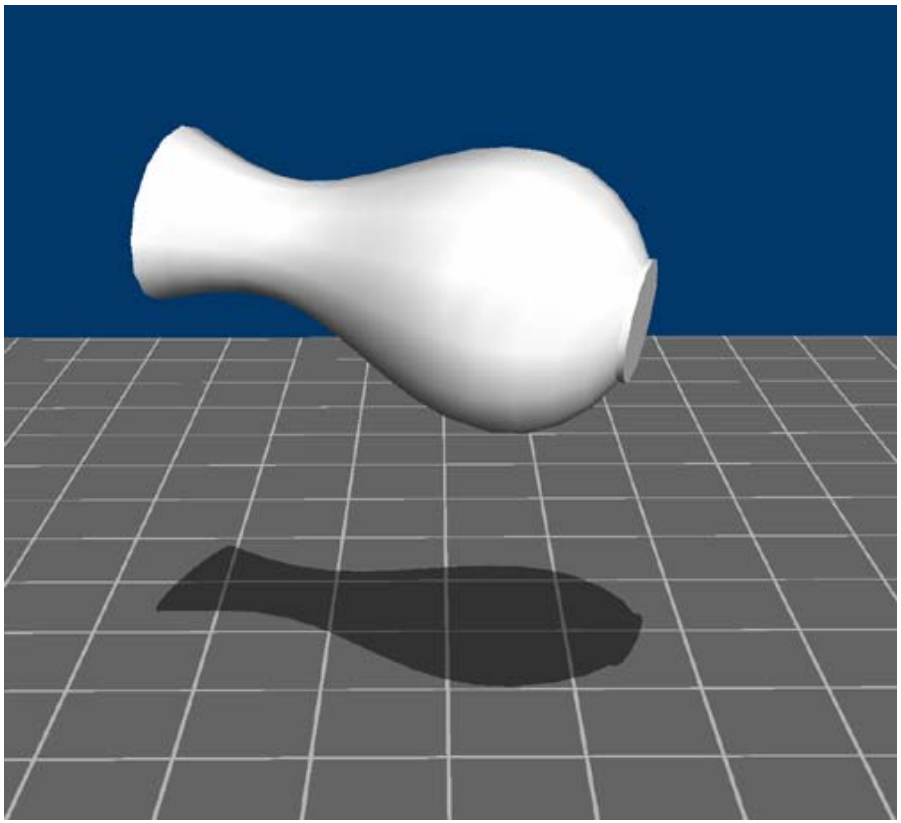


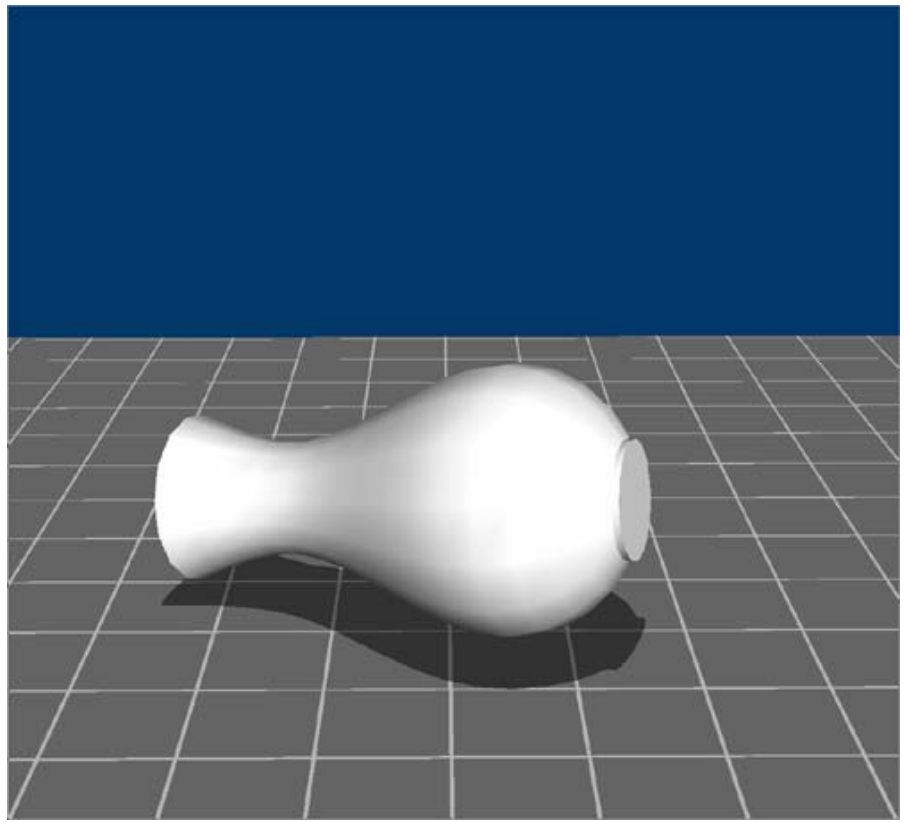
Today

- Why are Shadows Important?
- Shadows & Soft Shadows in Ray Tracing
- Planar Shadows
- Shadow Maps
- Shadow Volumes

Cast Shadows on Planar Surfaces

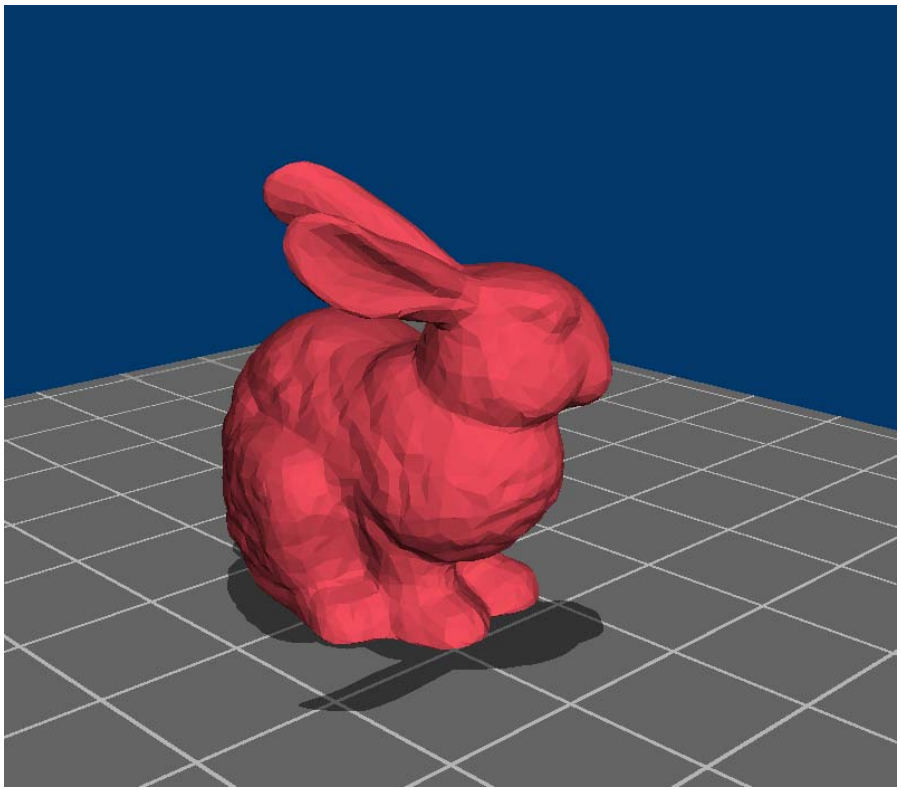
- Draw the object primitives a second time, projected to the ground plane

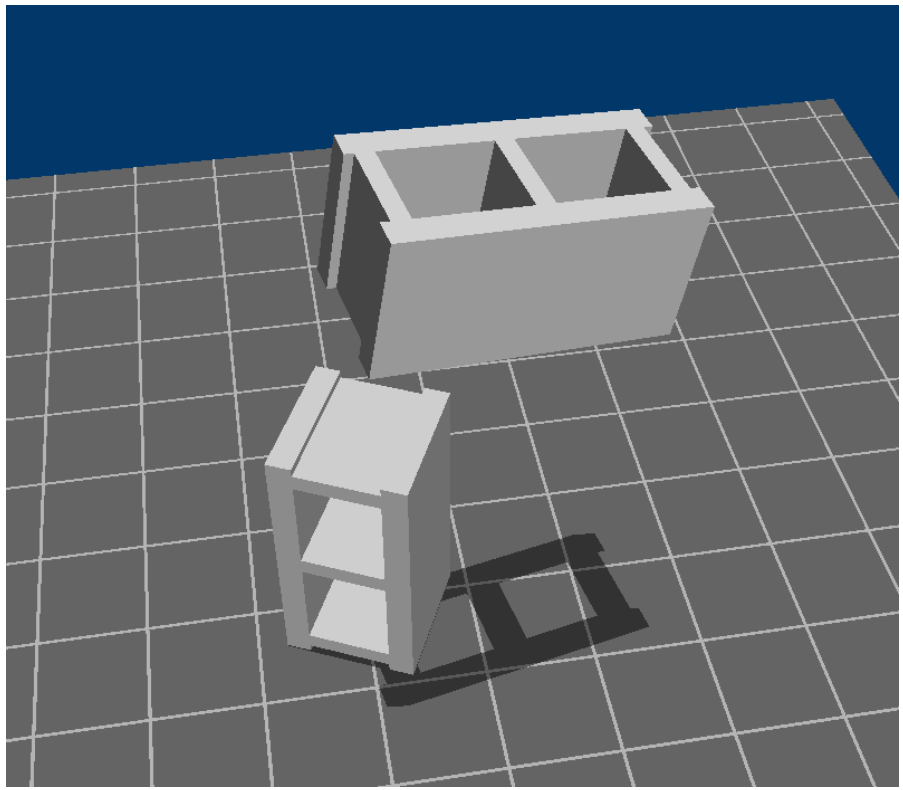




Limitations of Planar Shadows

- Does not produce self-shadows, shadows cast on other objects, shadows on curved surfaces, etc.





Today

- Why are Shadows Important?
- Shadows & Soft Shadows in Ray Tracing
- Planar Shadows
- Shadow Maps
  - Texture Mapping
  - Shadow View Duality
- Shadow Volumes

Texture Mapping

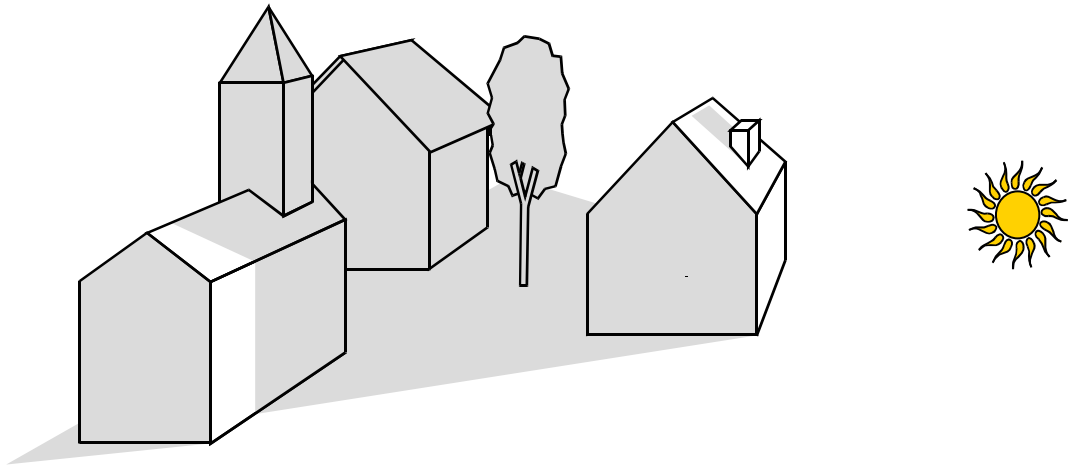
- Don't have to represent everything with geometry

Texture Mapping

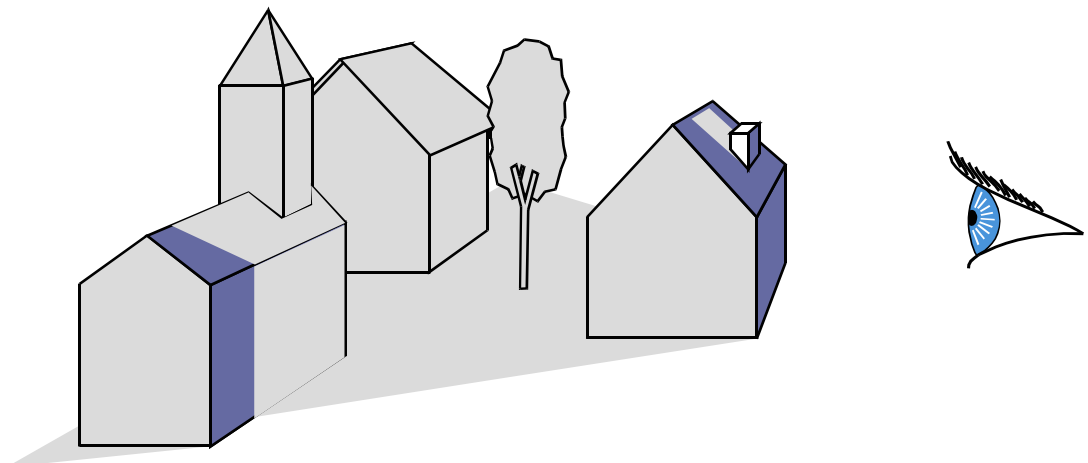
- Like wallpapering or gift-wrapping with stretchy paper
- Curved surfaces require extra stretching or cutting
- More on this in a couple weeks...

Shadow/View Duality

- A point is lit if it is visible from the light source



- Shadow computation similar to view computation



Fake Shadows using Projective Textures

- Separate obstacle and receiver
- Compute b/w image of obstacle from light
- Use image as projective texture for each receiver

(Images removed due to copyright considerations.)

Figure from Moller & Haines “Real Time Rendering”

Shadow Mapping

- Texture mapping with depth information
- ≥ 2 passes through the pipeline
  - Compute shadow map (depth from light source)
  - Render final image (check shadow map to see if points are in shadow)

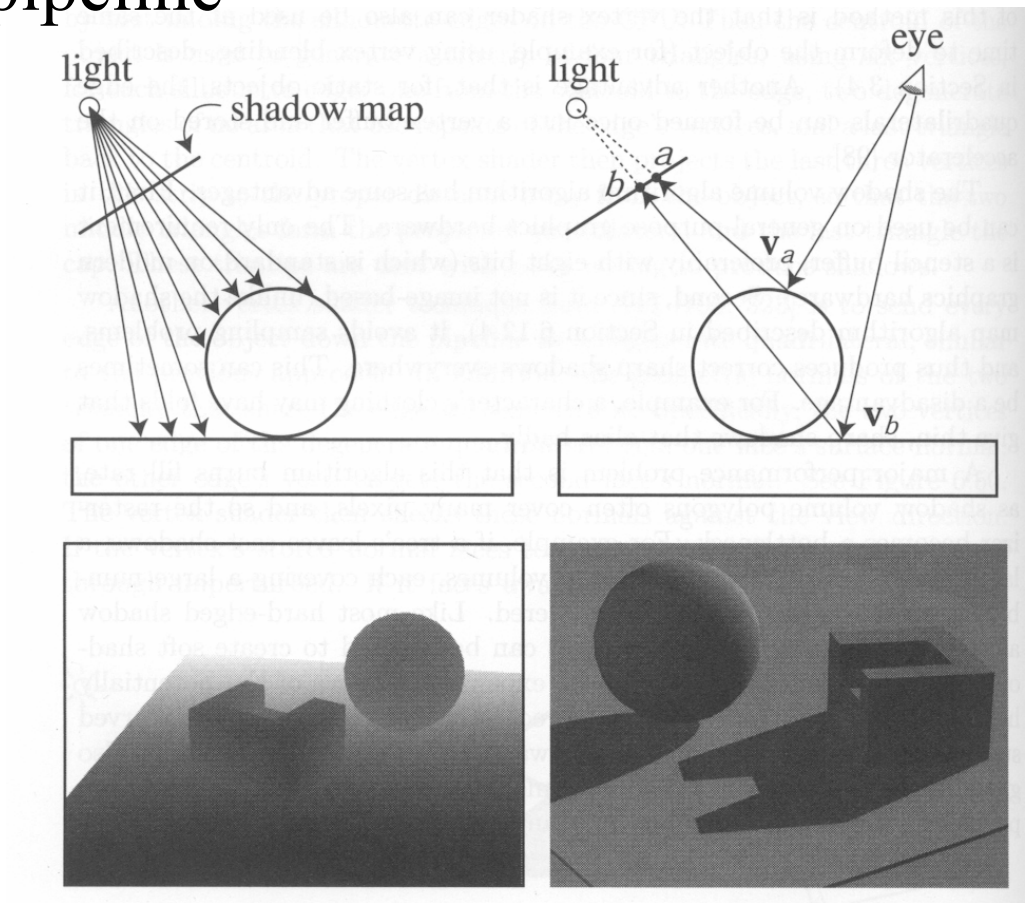
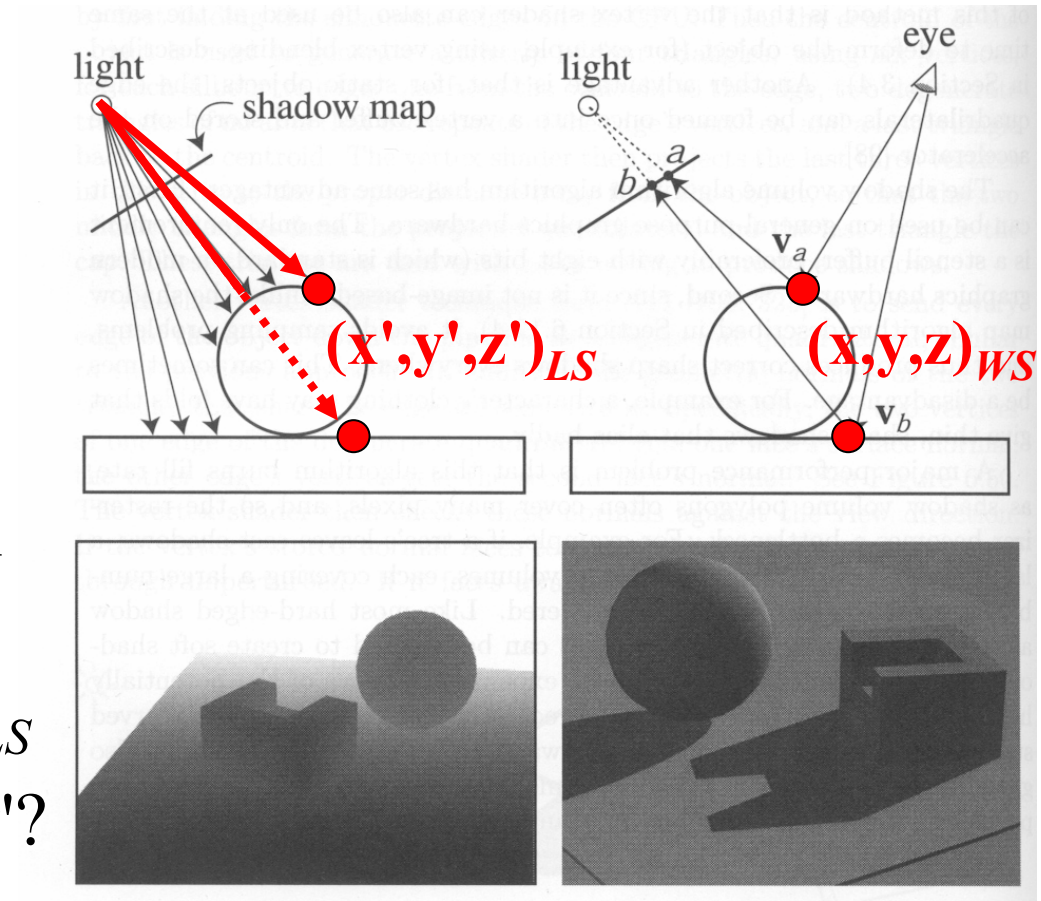


Figure from Foley et al. "Computer Graphics Principles and Practice"

Shadow Map Look Up

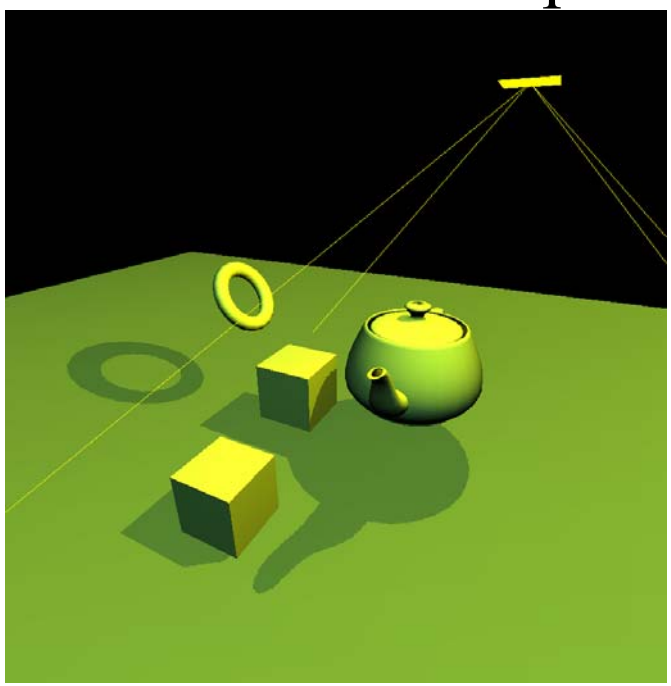
- We have a 3D point $(x,y,z)_{WS}$
- How do we look up the depth from the shadow map?
- Use the 4x4 perspective projection matrix from the light source to get $(x',y',z')_{LS}$
- ShadowMap(x',y') < z'?

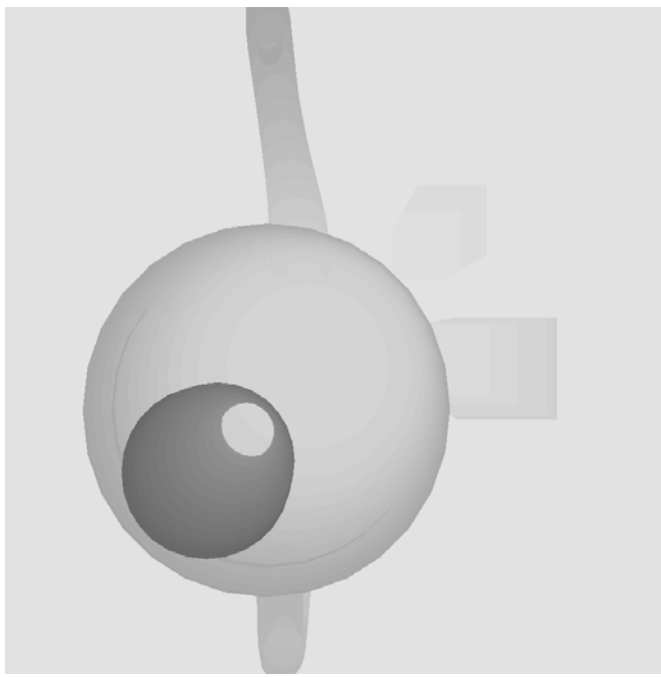


Foley et al. "Computer Graphics Principles and Practice"

Shadow Maps

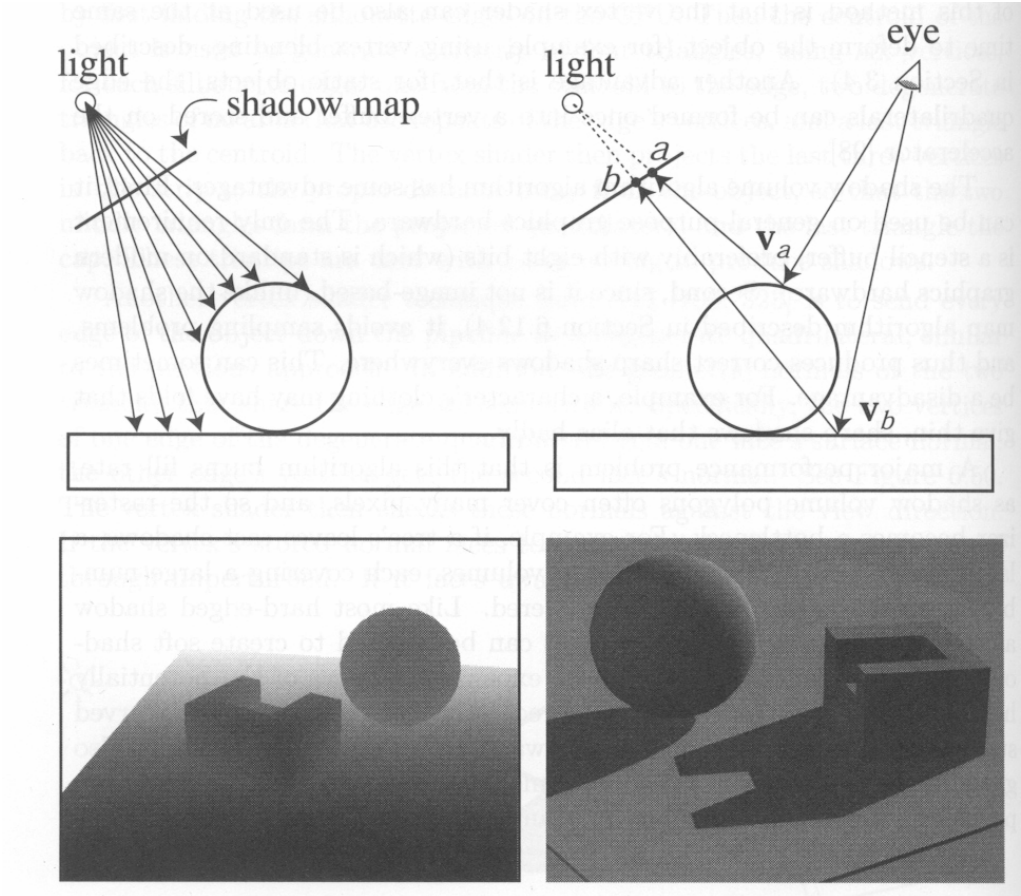
- Can be done in hardware
- Using hardware texture mapping
  - Texture coordinates u,v,w generated using 4x4 matrix
  - Modern hardware permits tests on texture values





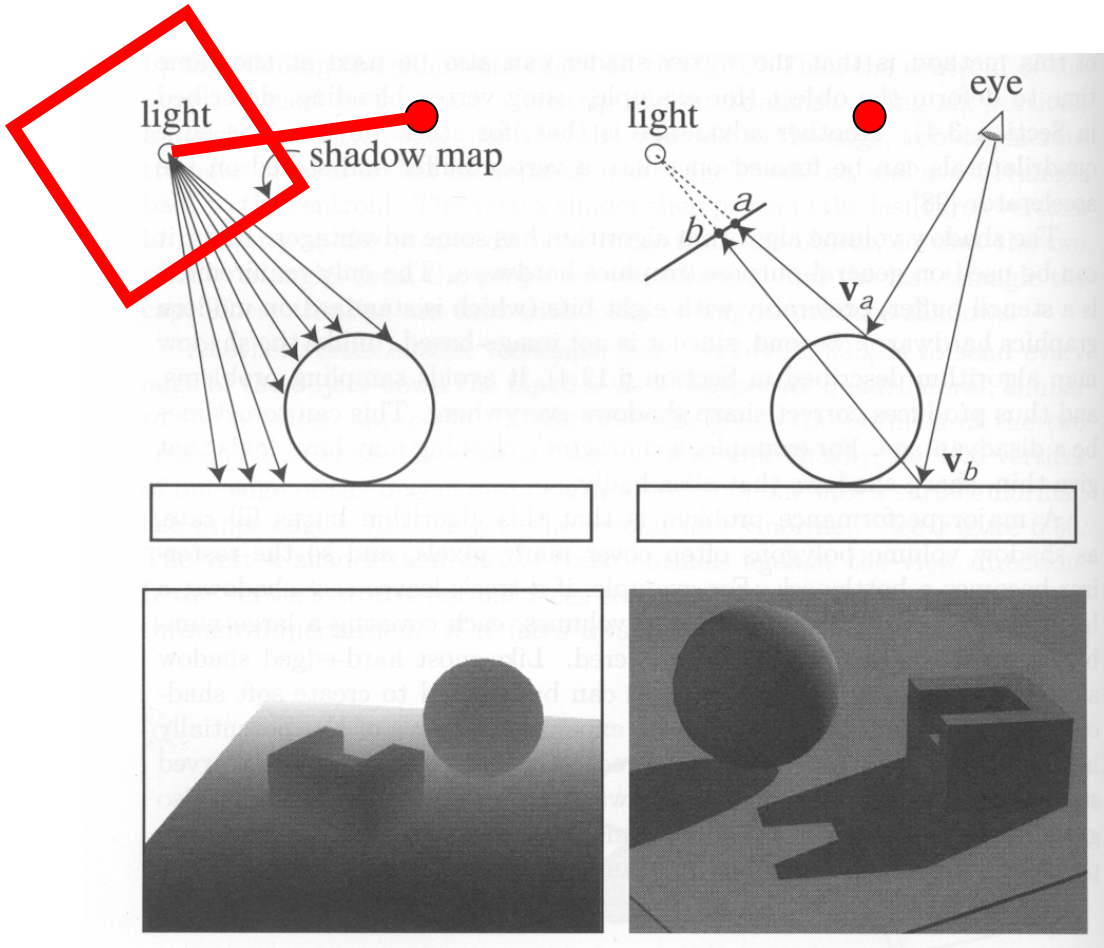
Limitations of Shadow Maps

1. Field of View
2. Bias (Epsilon)
3. Aliasing



1. Field of View Problem

- What if point to shadow is outside field of view of shadow map?
  - Use cubical shadow map
  - Use only spot lights!

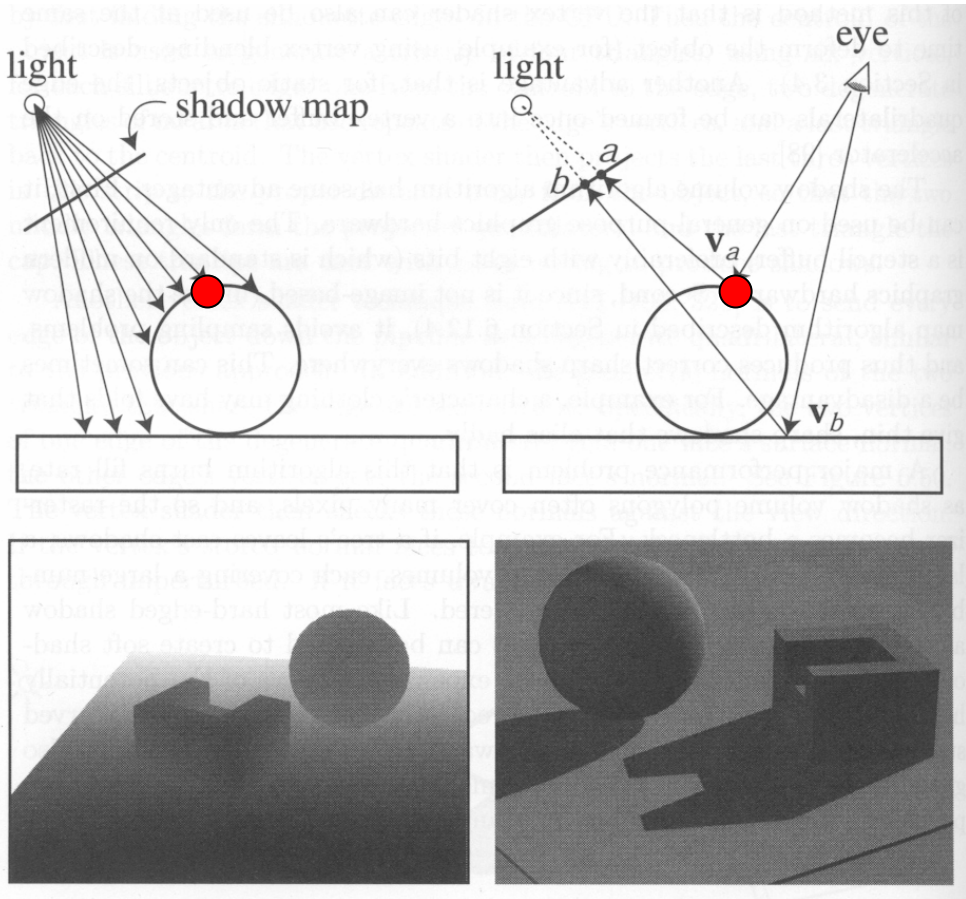


2. The Bias (Epsilon) Nightmare

- For a point visible from the light source

  ShadowMap(x',y') ≈ z'

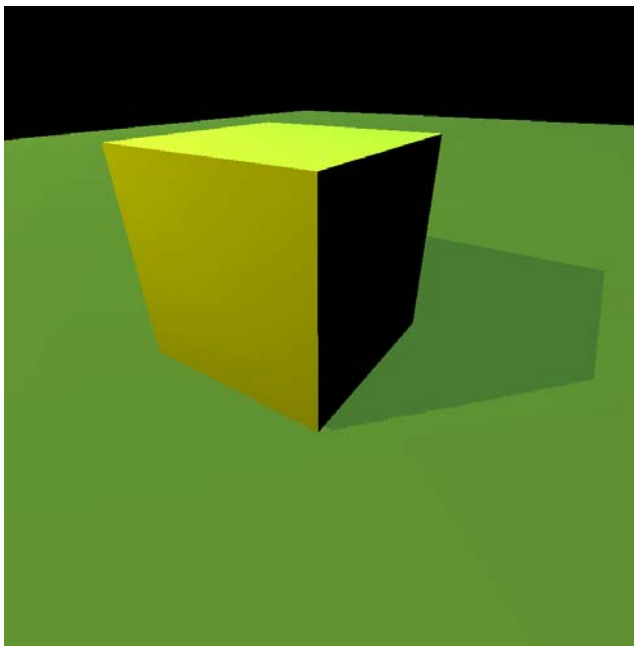
- How can we avoid erroneous self-shadowing?
  - Add bias (epsilon)



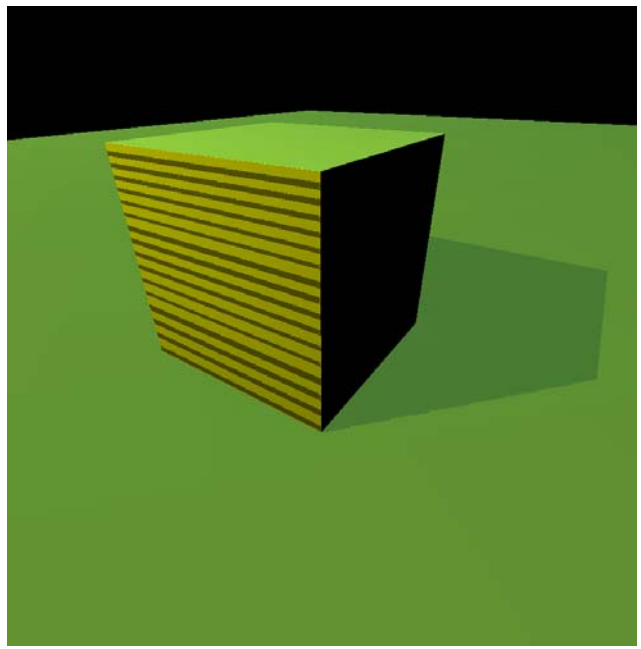
2. Bias (Epsilon) for Shadow Maps

ShadowMap(x',y') + bias < z'

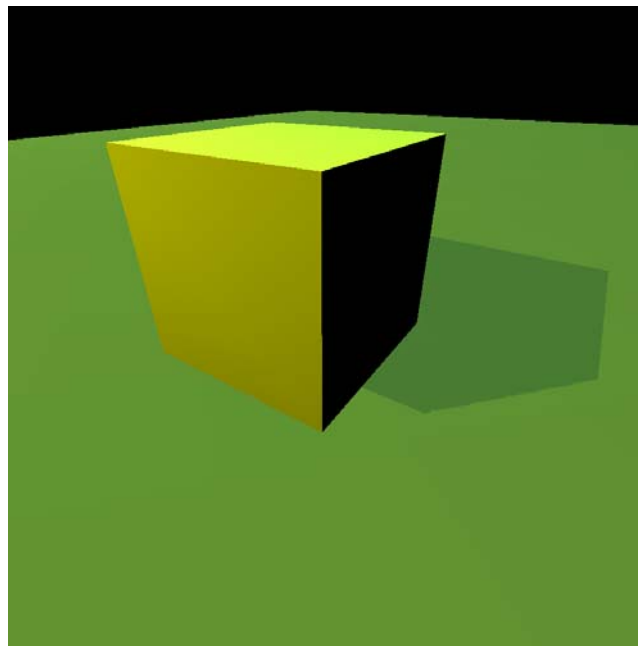
Choosing a good bias value can be very tricky



Correct image



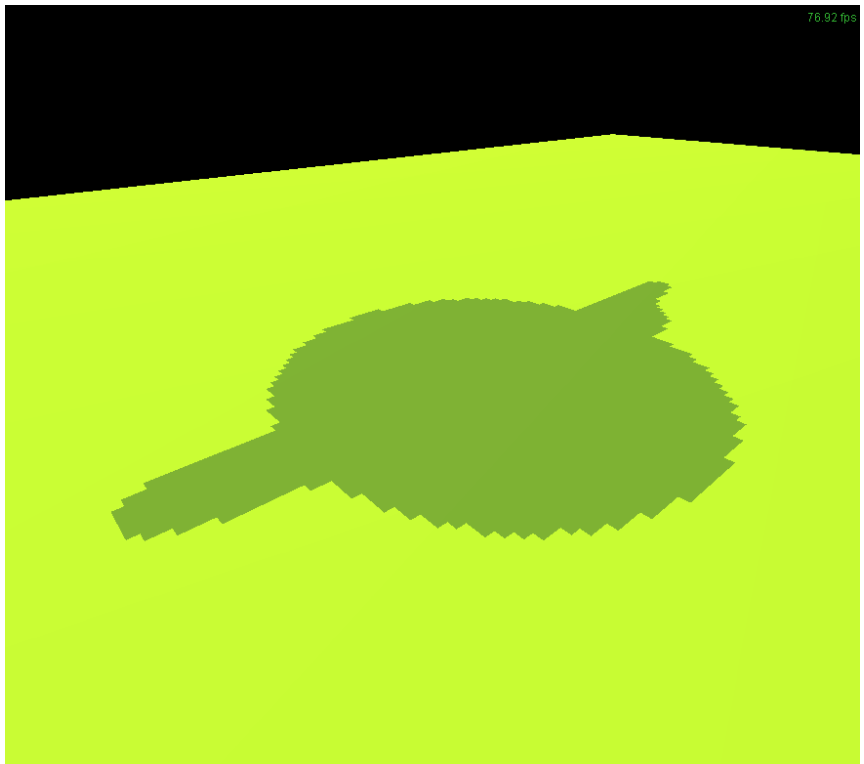
Not enough bias

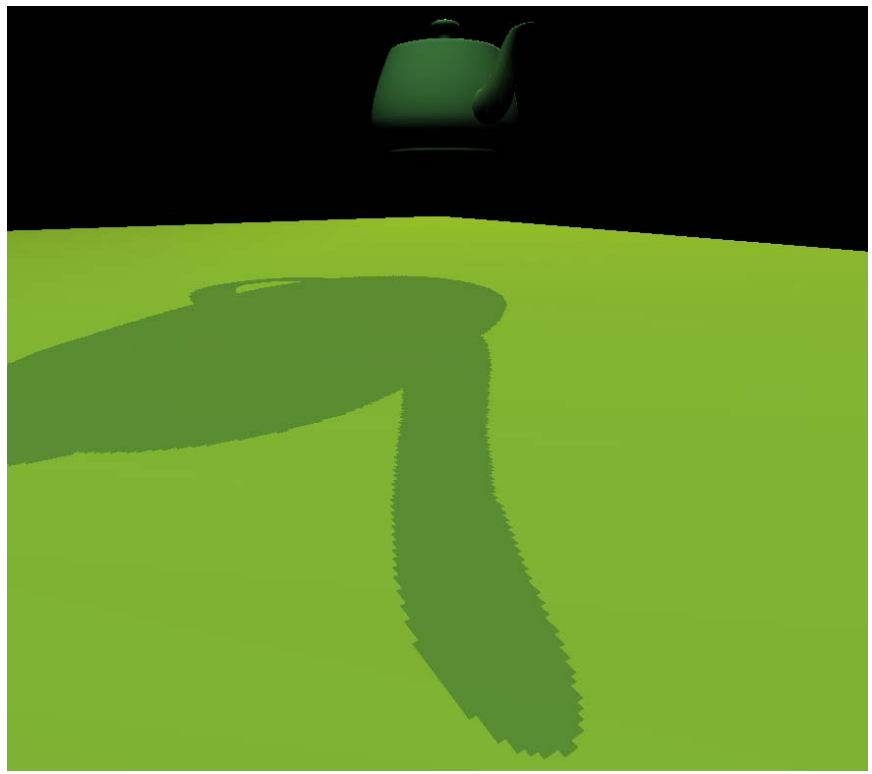


Way too much bias

3. Shadow Map Aliasing

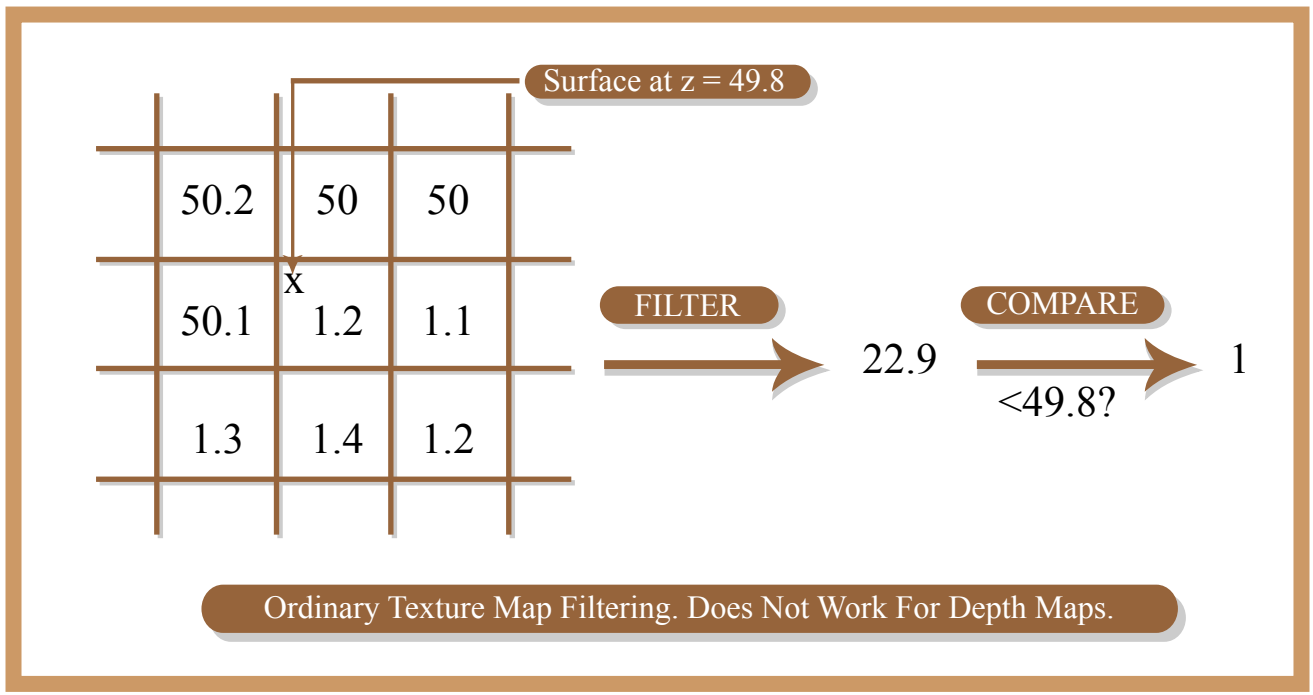
- Under-sampling of the shadow map
- Reprojection aliasing – especially bad when the camera & light are pointing towards each other





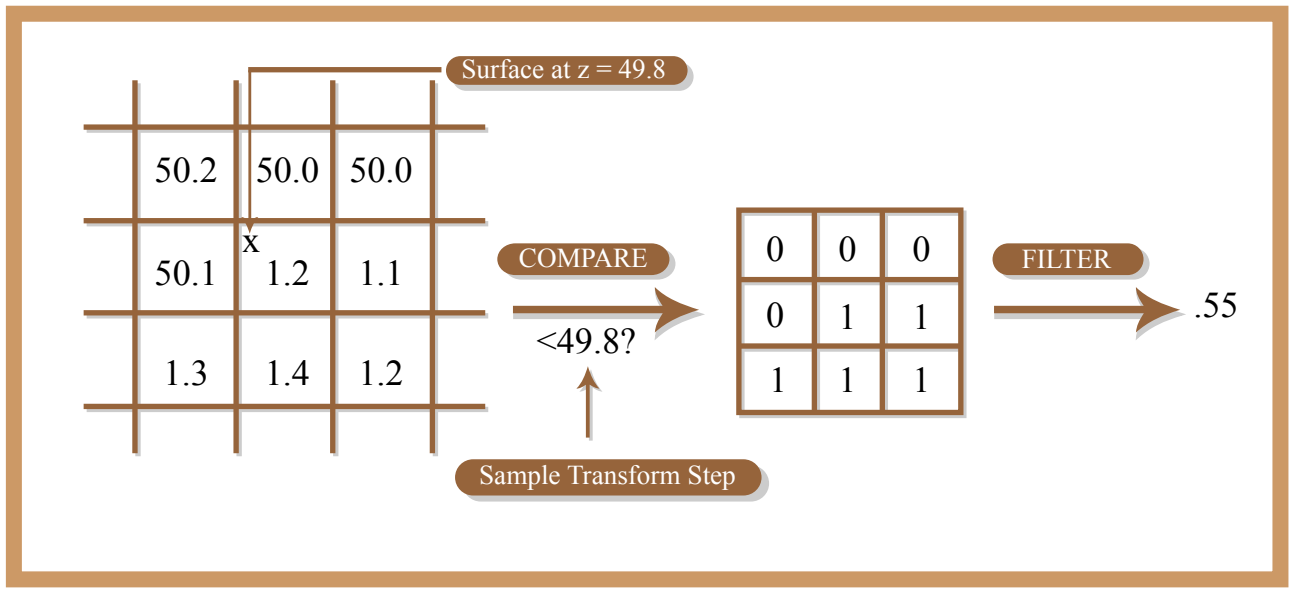
Shadow Map Filtering

- Should we filter the depth? (weighted average of neighboring depth values)
- No... filtering depth is not meaningful



Percentage Closer Filtering

- Instead filter the result of the test (weighted average of comparison results)
- But makes the bias issue more tricky

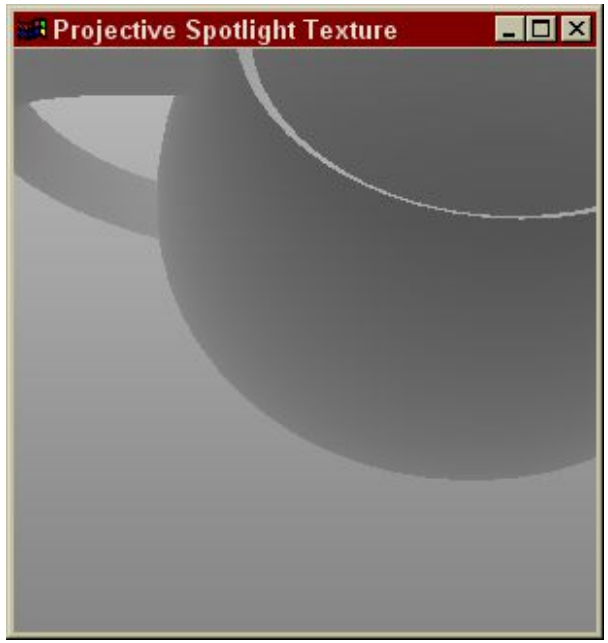


Percentage Closer Filtering

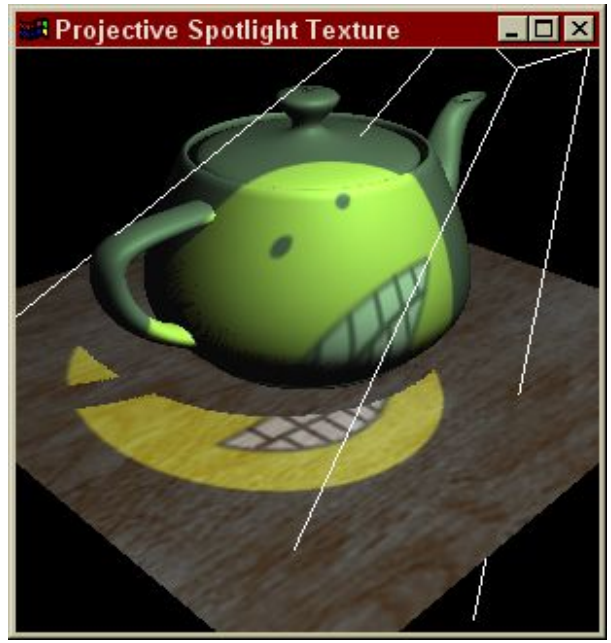
- 5x5 samples
- Nice antialiased shadow
- Using a bigger filter produces fake soft shadows
- Setting bias is tricky

Projective Texturing + Shadow Map

Light's View



Depth/Shadow Map



Eye's View

Images from Cass Everitt et al.,
"Hardware Shadow Mapping"
NVIDIA SDK White Paper

Shadows in Production

- Often use shadow maps
- Ray casting as fallback in case of robustness issues

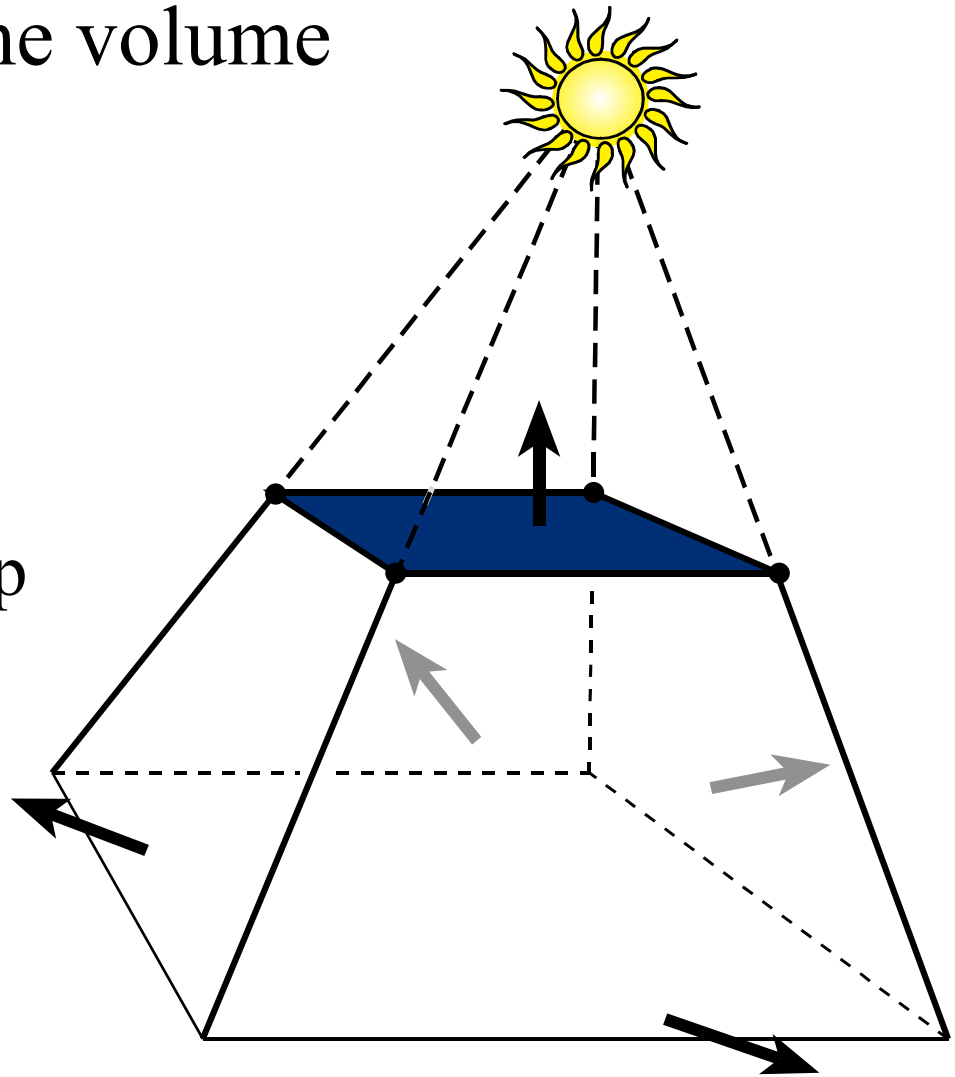
Images removed due to copyright considerations.

Today

- Why are Shadows Important?
- Shadows & Soft Shadows in Ray Tracing
- Planar Shadows
- Shadow Maps
- Shadow Volumes
  - The Stencil Buffer

Shadow Volumes

- Explicitly represent the volume of space in shadow
- For each polygon
  - Pyramid with point light as apex
  - Include polygon to cap
- Shadow test similar to clipping

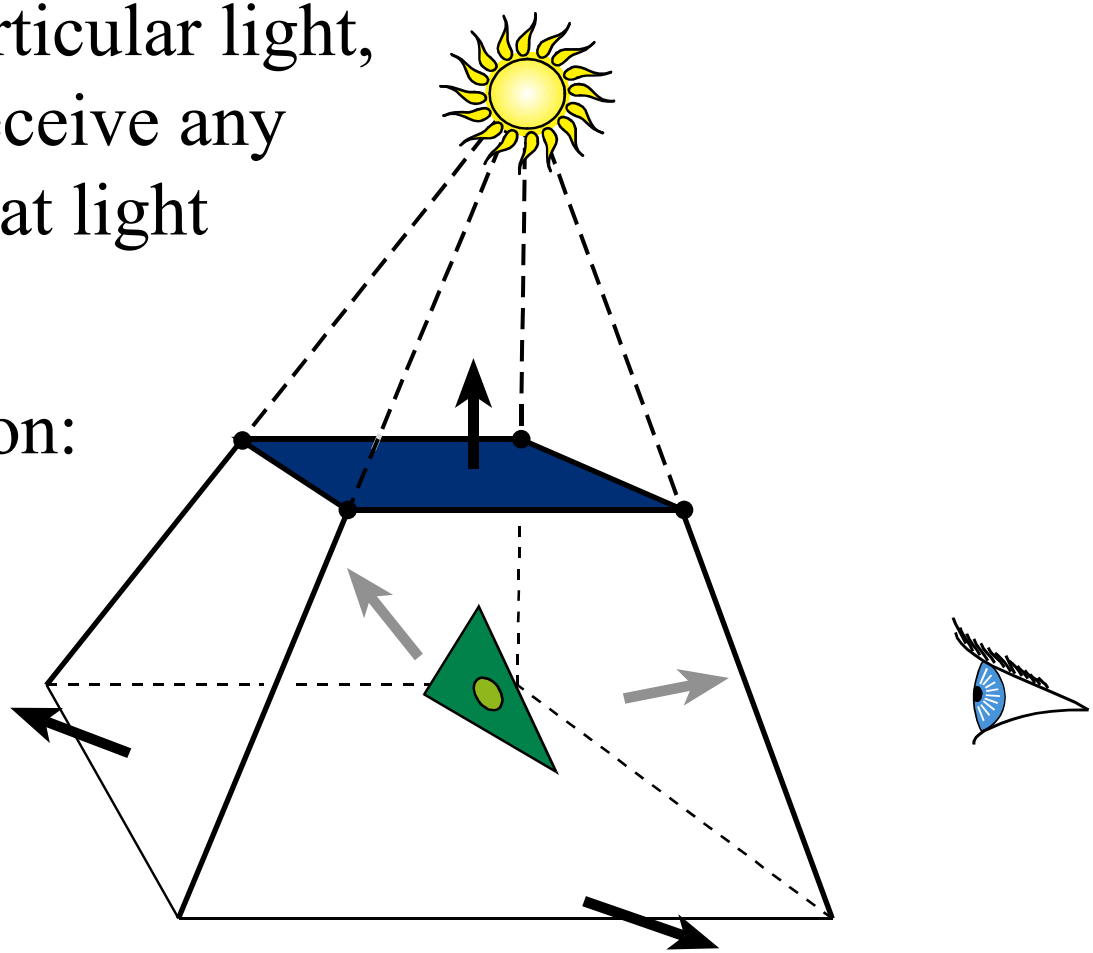


Shadow Volumes

- If a point is inside a shadow volume cast by a particular light, the point does not receive any illumination from that light

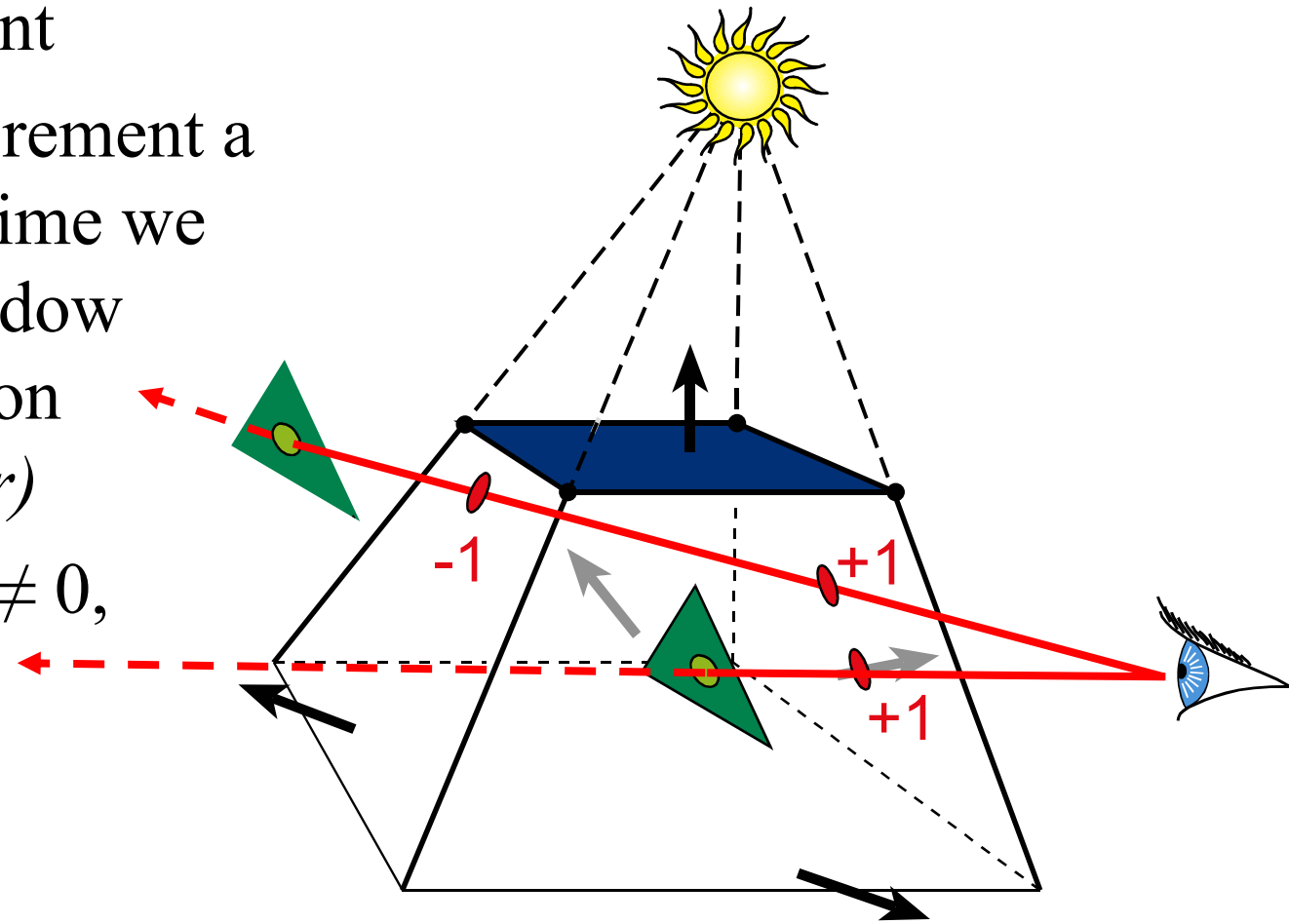
- Naive implementation:

  #polygons * #lights



Shadow Volumes

- Shoot a ray from the eye to the visible point
- Increment/decrement a counter each time we intersect a shadow volume polygon *(check z buffer)*
- If the counter ≠ 0, the point is in shadow



Stencil Buffer

- Tag pixels in one rendering pass to control their update in subsequent rendering passes
- "For all pixels in the frame buffer" →
  "For all *tagged* pixels in the frame buffer"
- Used for real-time mirrors
  (& other reflective surfaces),
  shadows & more!

Stencil Buffer

- Can specify different rendering operations for each of the following stencil tests:
  - stencil test fails
  - stencil test passes & depth test fails
  - stencil test passes & depth test passes

Shadow Volumes w/ the Stencil Buffer

Initialize stencil buffer to 0

Draw scene with ambient light only

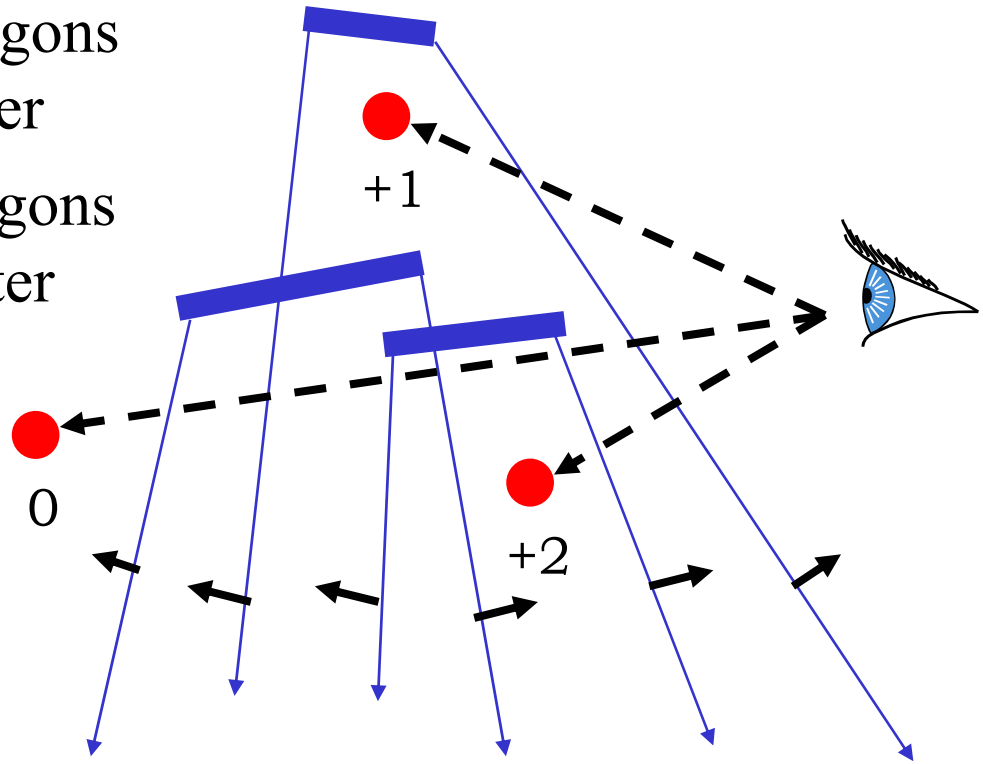
Turn off frame buffer & z-buffer updates

Draw front-facing shadow polygons
    If z-pass → increment counter

Draw back-facing shadow polygons
    If z-pass → decrement counter

Turn on frame buffer updates

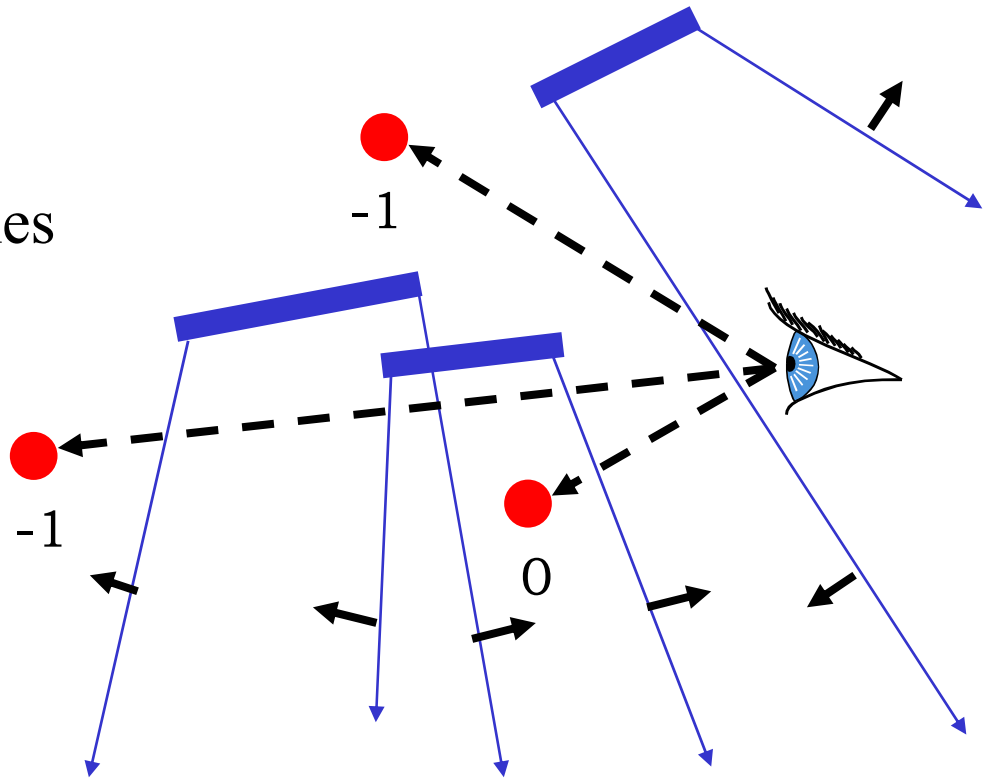
Turn on lighting and
    redraw pixels with
    counter = 0



If the Eye is in Shadow...

- ... then a counter of 0 does not necessarily mean lit

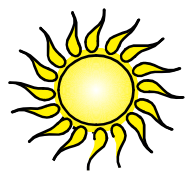
- 3 Possible Solutions:
  1. Explicitly test eye point with respect to all shadow volumes
  2. Clip the shadow volumes to the view frustum
  3. "Z-Fail" shadow volumes

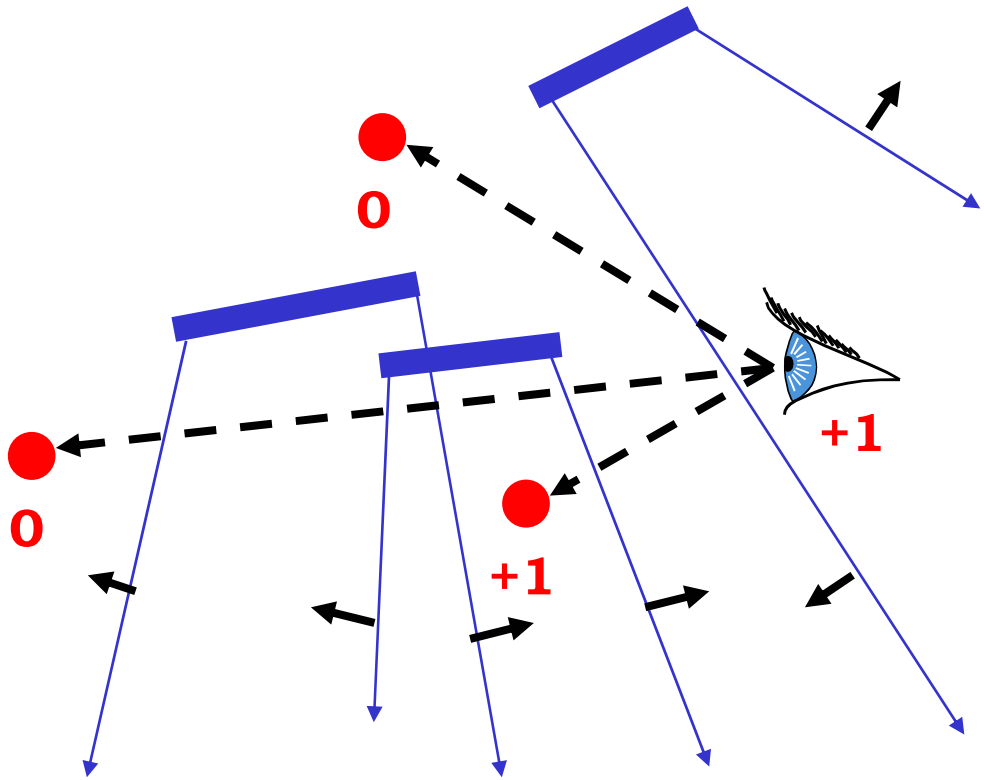


1. Test Eye with Respect to Volumes

- Adjust initial counter value

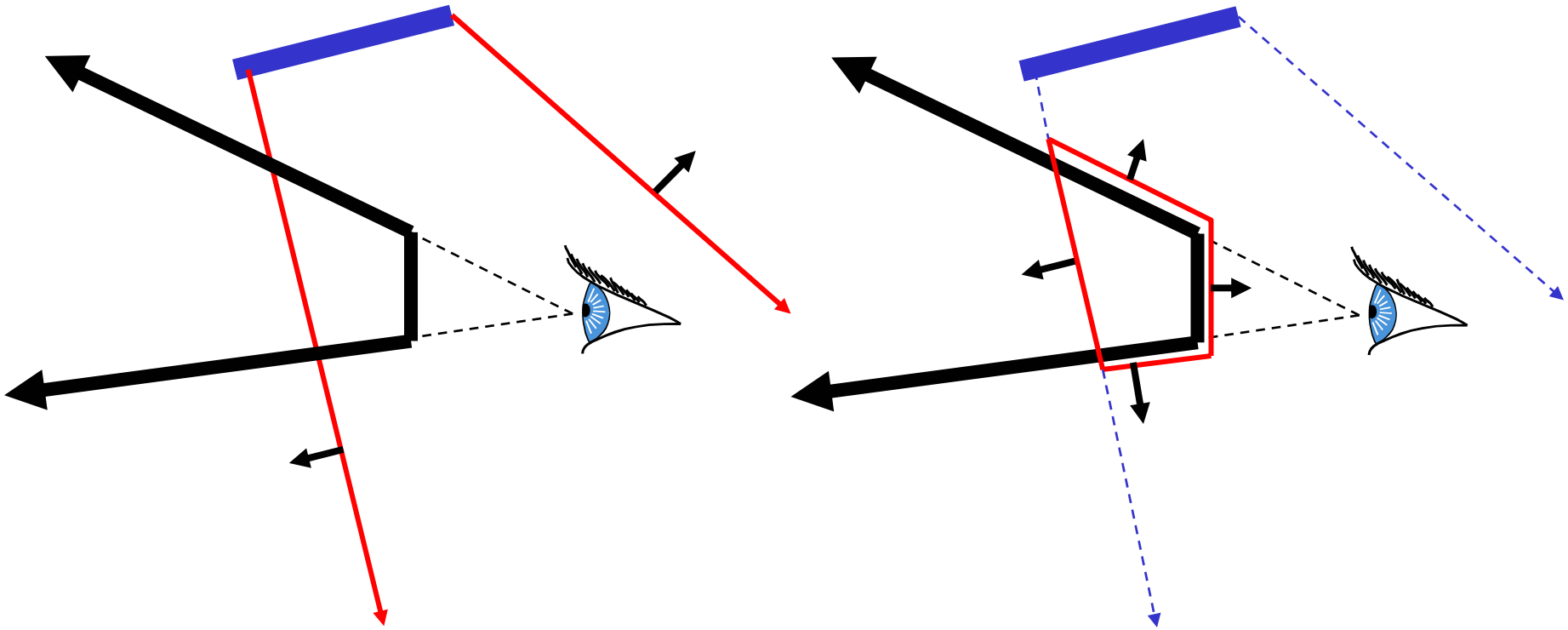
Expensive





2. Clip the Shadow Volumes

- Clip the shadow volumes to the view frustum and include these new polygons
- *Messy CSG*



3. "Z-Fail" Shadow Volumes

Start at infinity

...

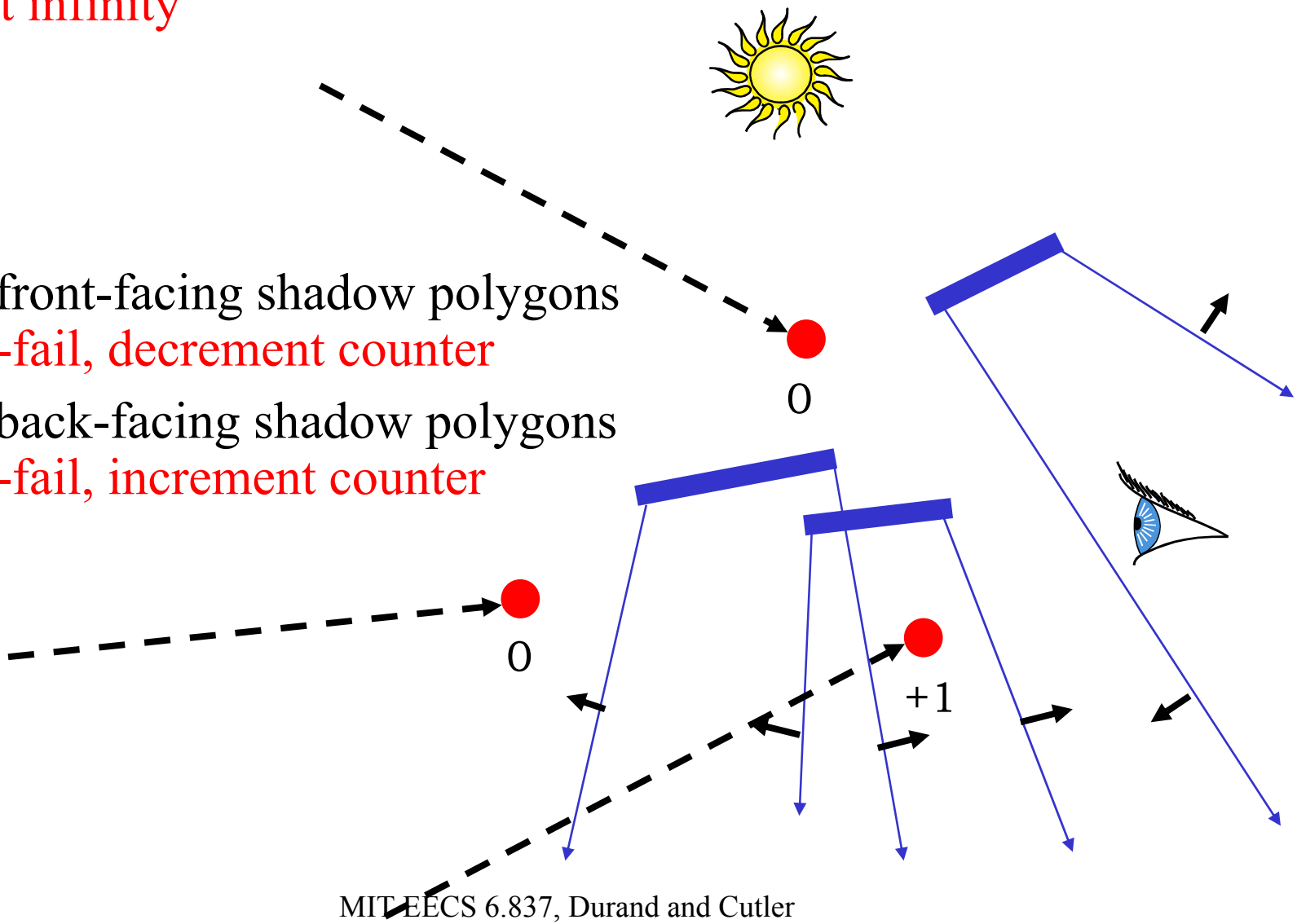
Draw front-facing shadow polygons

If z-fail, decrement counter

Draw back-facing shadow polygons

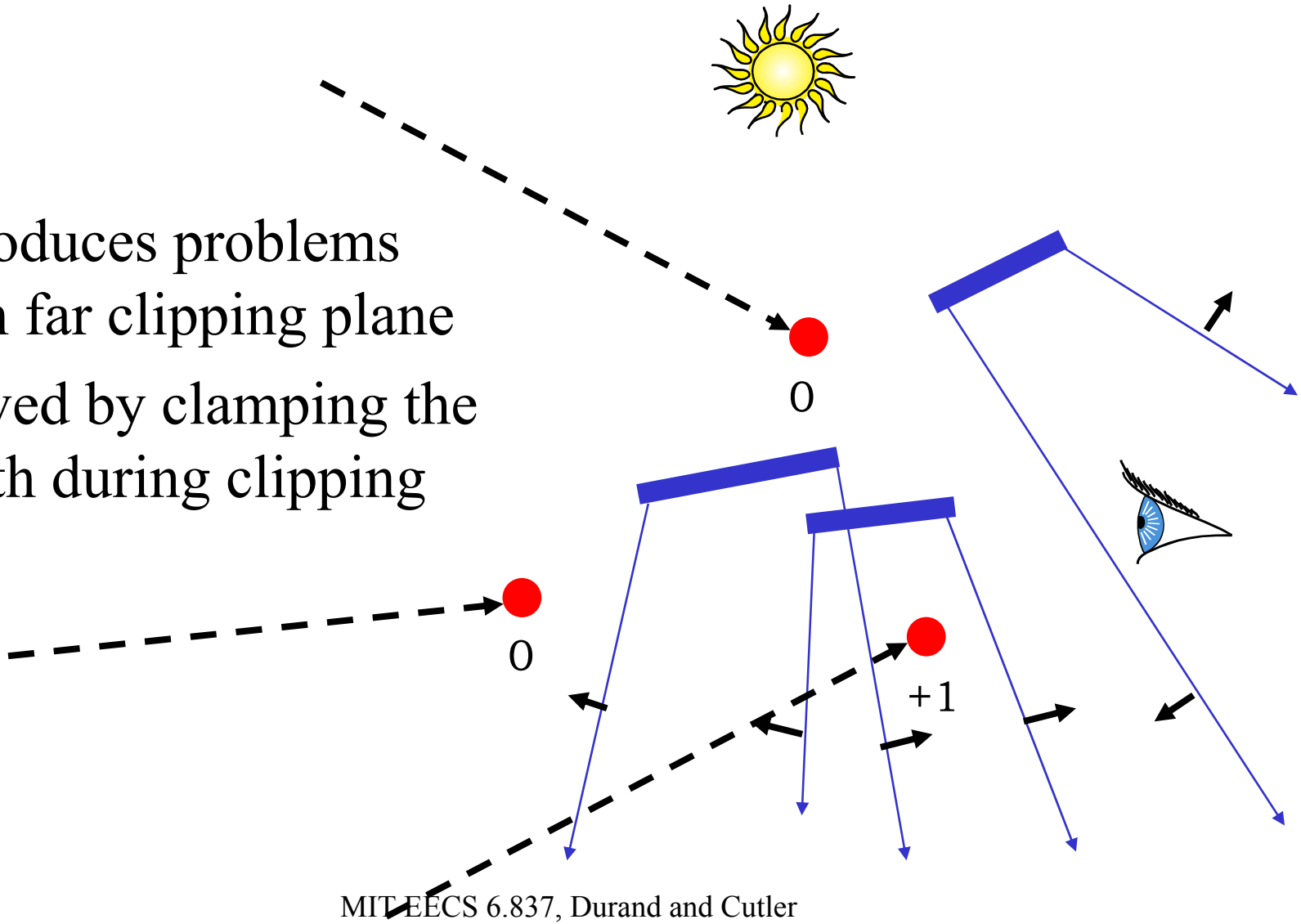
If z-fail, increment counter

...



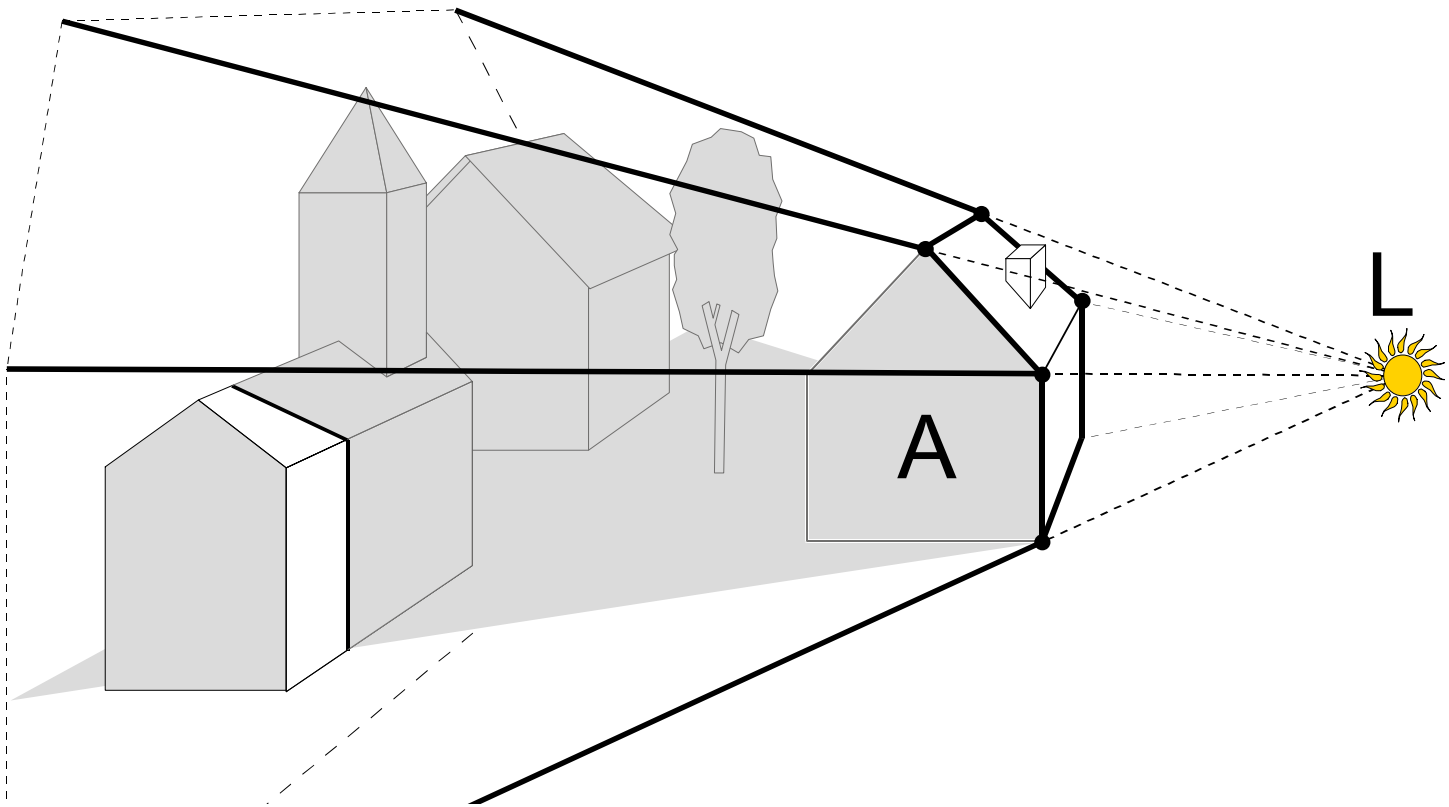
3. "Z-Fail" Shadow Volumes

- Introduces problems with far clipping plane
- Solved by clamping the depth during clipping



Optimizing Shadow Volumes

- Use silhouette edges only (edge where a back-facing & front-facing polygon meet)



Limitations of Shadow Volumes

- Introduces a lot of new geometry
- Expensive to rasterize long skinny triangles
- Limited precision of stencil buffer (counters)
  - for a really complex scene/object, the counter can overflow
- Objects must be watertight to use silhouette trick
- Rasterization of polygons sharing an edge must not overlap & must not have gap

Next Time:

Global Illumination: Radiosity