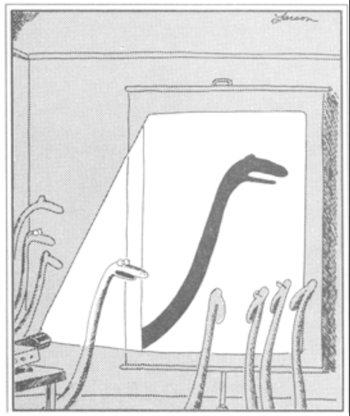
# Real-Time Shadows



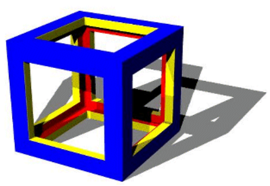
"Now this is…this is…well, I guess it's another snake."

## Last Time?



## Today

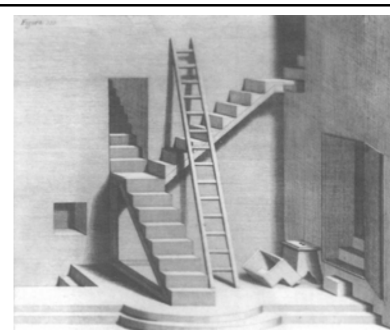
- Why are Shadows Important?
- Shadows & Soft Shadows in Ray Tracing
- Planar Shadows
- Projective Texture Shadows
- Shadow Maps
- Shadow Volumes





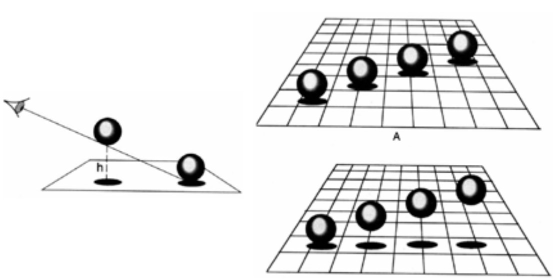
## Why are Shadows Important?

- Depth cue
- Scene Lighting
- Realism
- Contact points





## Shadows as a Depth Cue






## For Intuition about Scene Lighting

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

## Shadows as the Origin of Painting



## Shadows and Art

- Only in Western pictures (here Caravaggio)



## Today

- Why are Shadows Important?
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- Planar Shadows
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- Shadow Maps
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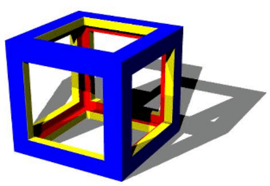
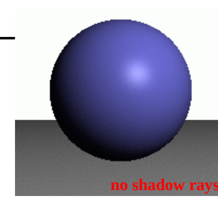
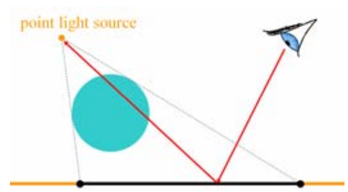


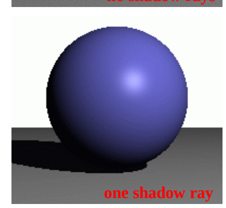


## Shadows

- One shadow ray per intersection per point light source



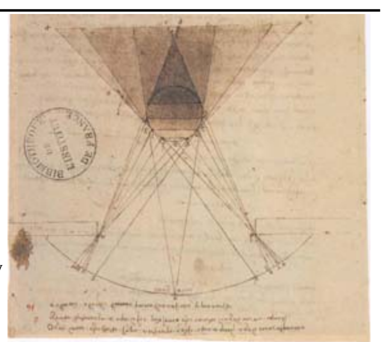






## Soft Shadows

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

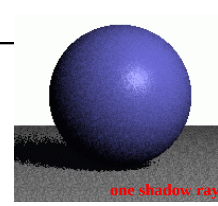


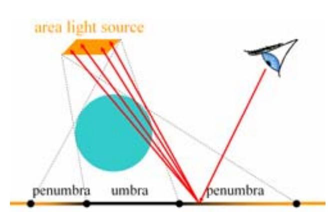
XVI. Léonard de Vinci (1452-1519). Lumière d'une fenêtre sur une sphère ombreuse avec (en partant du haut) ombre intermédiaire, primitive, dérivée et (sur la surface, en bas) portée. Plume et lavis sur pointe de métal sur papier. 24 x 38 cm. Paris, Bibliothèque de l'Institut de France (ms. 2185; B.N. 2038, f° 14 r°).

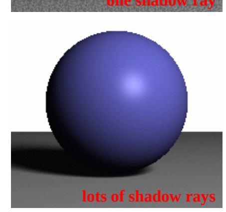


## Soft Shadows

- Multiple shadow rays to sample area light source

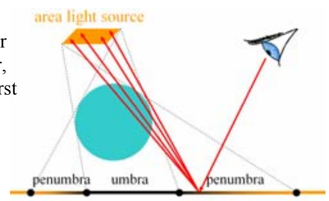


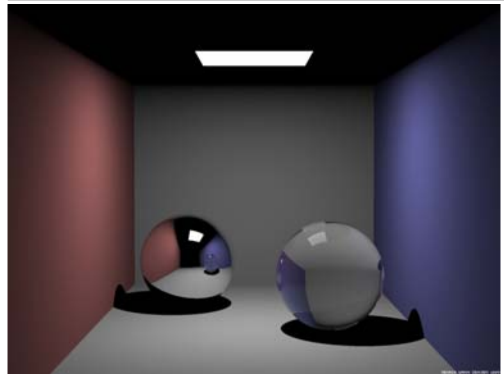
## Shadows in Ray Tracing

- Shoot ray from visible point to light source
- If blocked, discard light contribution
- Optimizations?
  - Stop after you find the first intersection
  - Coherence: remember the previous occluder, and test that object first

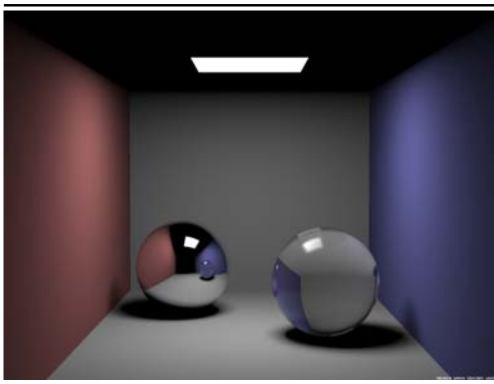





## Traditional Ray Tracing

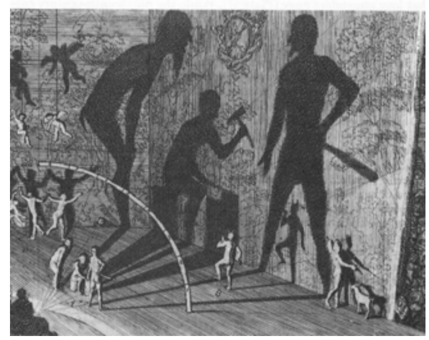


## Ray Tracing + Soft Shadows



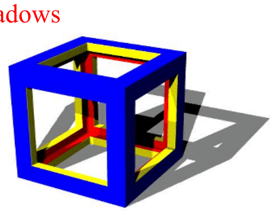
## Questions?

Plate 50 Samuel van Hoogstraten, *Shadow Theatre*. From *Inleyding tot de hooghe schoole der schilderkonst* 1678.



## Today

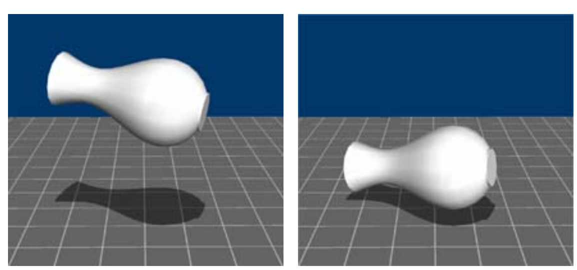
- Why are Shadows Important?
- Shadows & Soft Shadows in Ray Tracing
- Planar Shadows
- Projective Texture Shadows
  - Shadow View Duality
  - Texture Mapping
- Shadow Maps
- Shadow Volumes





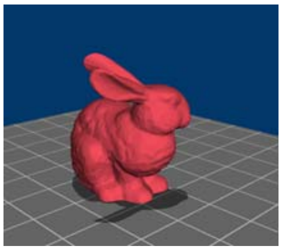
## Cast Shadows on Planar Surfaces

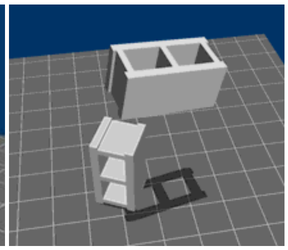
- Draw the object primitives a second time, projected to the ground plane



## Limitations of Planar Shadows

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

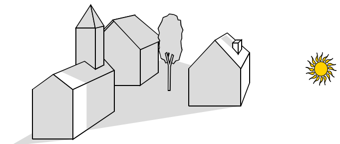




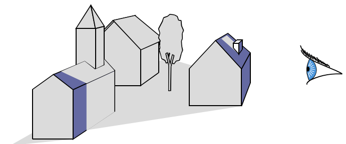


## Shadow/View Duality

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



- Shadow computation similar to view computation





## Texture Mapping

- Don't have to represent everything with geometry



## 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

*Image from light source* *BW image of obstacle* *Final image*

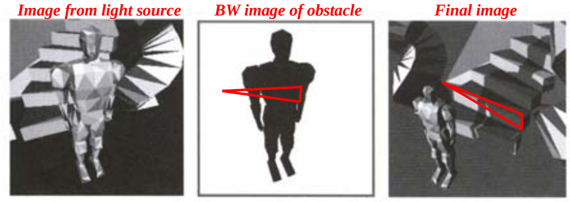


Figure from Moller & Haines "Real Time Rendering"



## Projective Texture Shadow Limitations

- Must specify occluder & receiver
- No self-shadows
- Resolution

Figure from Moller & Haines "Real Time Rendering"



## Questions?

Plate 52 Grandville, *The Shadows (The French Cabinet)* from *La Caricature*, 1830.

## Today

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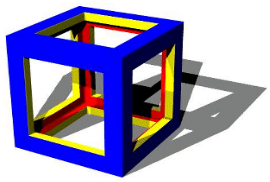
- Shadow Volumes





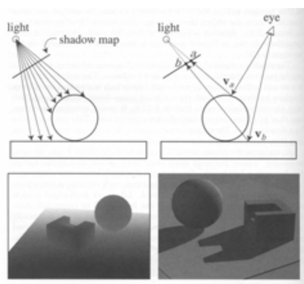
## Shadow Maps

- In Renderman
  - (High-end production software)



## Shadow Mapping

- Texture mapping with depth information
- Requires 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*

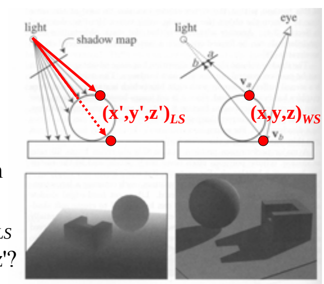



Foley et al. "Computer Graphics Principles and Practice"



## 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'?

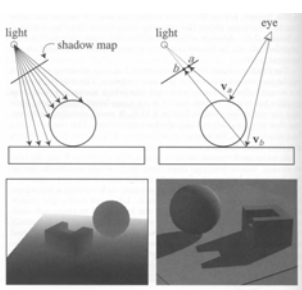



Foley et al. "Computer Graphics Principles and Practice"



## Limitations of Shadow Maps

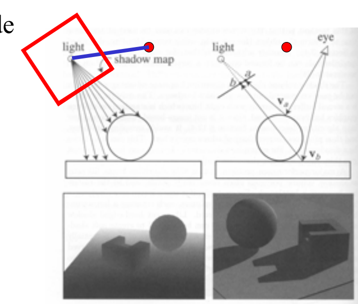
1. Field of View
2. Bias (Epsilon)
3. Aliasing





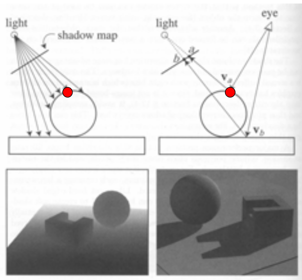

## 1. Field of View Problem

- 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)

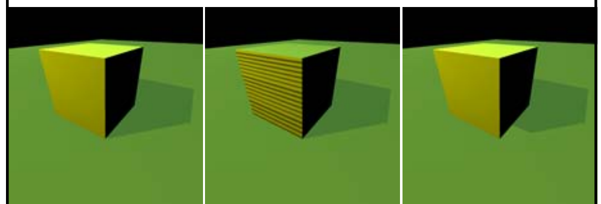





## 2. Bias (Epsilon) for Shadow Maps

ShadowMap(x’,y’) + bias < z’

Choosing a good bias value can be very tricky

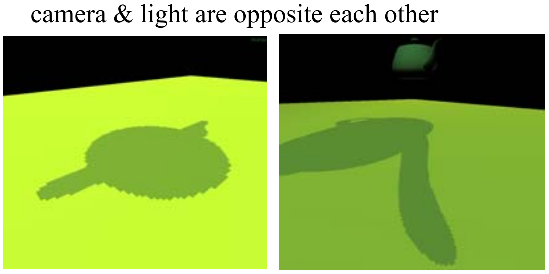


Correct image | Not enough bias | Way too much bias



## 3. Shadow Map Aliasing

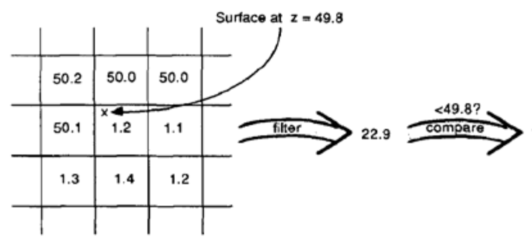
- Under-sampling of the shadow map
- Reprojection aliasing – especially bad when the camera & light are opposite each other





## 3. Shadow Map Filtering

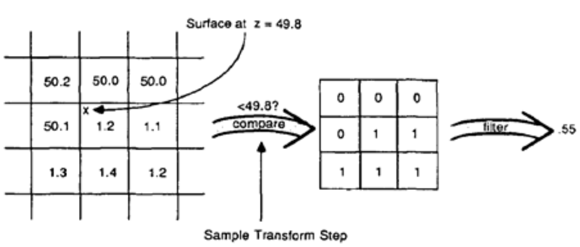
- Should we filter the depth? (weighted average of neighboring depth values)
- No... filtering depth is not meaningful




a) Ordinary texture map filtering. Does not work for depth maps.

## 3. Percentage Closer Filtering

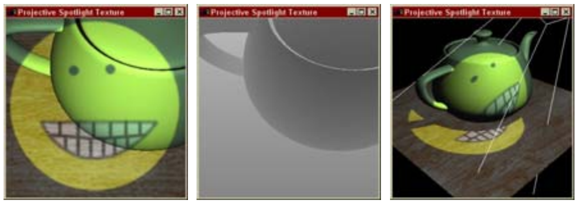
- Instead filter the result of the test (weighted average of comparison results)
- But makes the bias issue more tricky




## 3. 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

Figure 12. Frame from Luxo Jr.

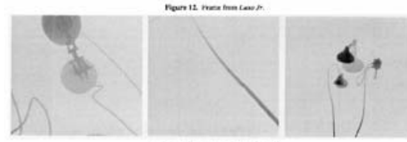
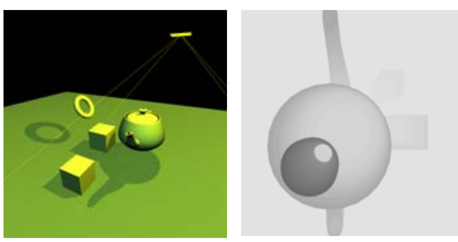


Figure 13. Shadow maps from Luxo Jr.

## Hardware Shadow Maps

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



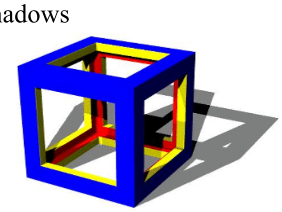


## Questions?



## Today

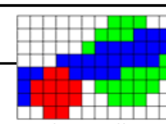
- Why are Shadows Important?
- Shadows & Soft Shadows in Ray Tracing
- Planar Shadows
- Projective Texture Shadows
- Shadow Maps
- Shadow Volumes
  - The Stencil Buffer



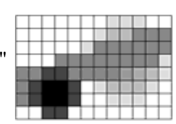


## Stencil Buffer

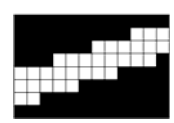
- Tag pixels in one rendering pass to control their update in subsequent rendering passes
  - "For all pixels in the frame buffer" → "For all *tagged* pixels in the frame buffer"
- Can specify different rendering operations for each case:
  - stencil test fails
  - stencil test passes & depth test fails
  - stencil test passes & depth test passes



**frame buffer**



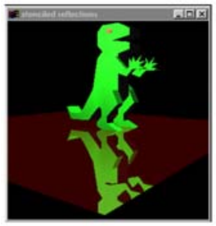
**depth buffer**



**stencil buffer**

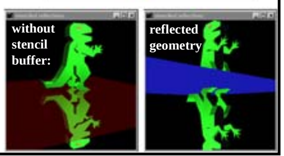
## Stencil Buffer – Real-time Mirror

- Clear frame, depth & stencil buffers
- Draw all non-mirror geometry to frame & depth buffers
- Draw mirror to stencil buffer, where depth buffer passes
- Set depth to infinity, where stencil buffer passes
- Draw reflected geometry to frame & depth buffer, where stencil buffer passes



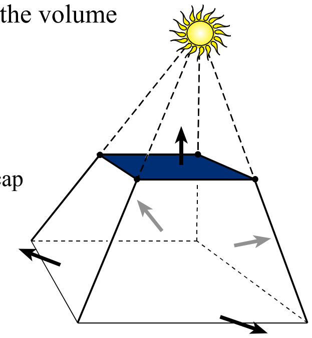
**See NVIDIA's stencil buffer tutorial**
**http://developer.nvidia.com**

also discusses blending, multiple mirrors, objects behind mirror, etc…




## Shadow Volumes

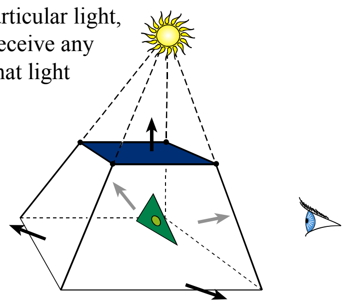
- Explicitly represent the volume of space in shadow
- For each polygon
  - Pyramid with point light as apex
  - Include polygon to cap
- Shadow test similar to clipping





## Shadow Volumes

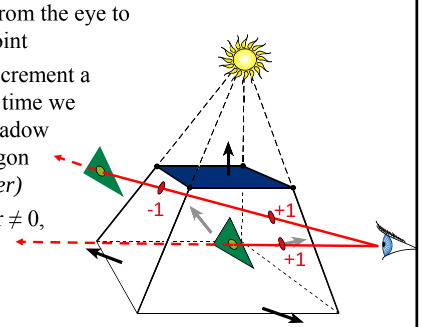
- If a point is inside a shadow volume cast by a particular light, the point does not receive any illumination from that light
- Cost of naive implementation:
  #polygons * #lights





## Shadow Volumes

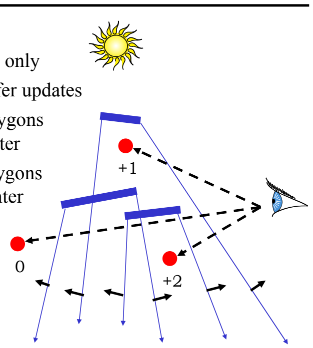
- Shoot a ray from the eye to the visible point
- Increment/decrement a counter each time we intersect a shadow volume polygon *(check z buffer)*
- If the counter ≠ 0, the point is in shadow






## Shadow Volumes w/ the Stencil Buffer

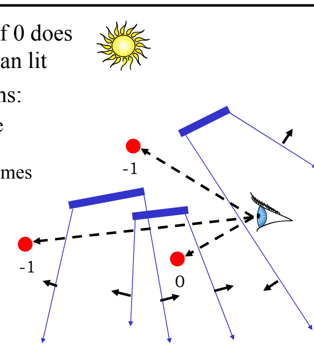
Initialize stencil buffer to 0
Draw scene with ambient light only
Turn off frame buffer & z-buffer updates
Draw front-facing shadow polygons
  If z-pass → increment counter
Draw back-facing shadow polygons
  If z-pass → decrement counter
Turn on frame buffer updates
Turn on lighting and
  redraw pixels with
  counter = 0






## If the Eye is in Shadow...

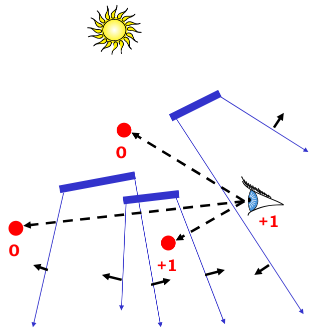
- ... then a counter of 0 does not necessarily mean lit
- 3 Possible Solutions:
  1. Explicitly test eye point with respect to all shadow volumes
  2. Clip the shadow volumes to the view frustum
  3. "Z-Fail" shadow volumes



## 1. Test Eye with Respect to Volumes

- Adjust initial counter value

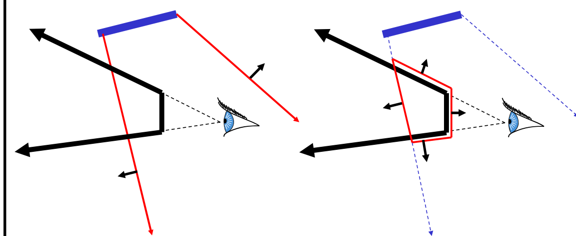
*Expensive*






## 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

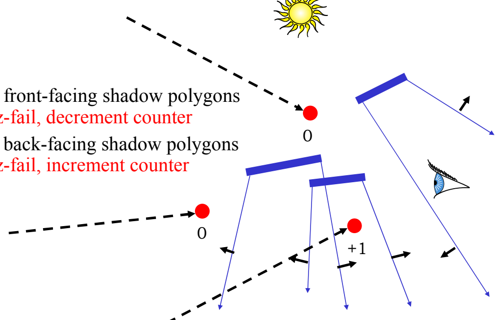
Start at infinity

...

Draw front-facing shadow polygons
    If z-fail, decrement counter

Draw back-facing shadow polygons
    If z-fail, increment counter

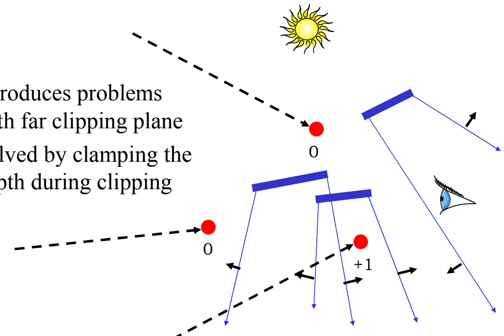
...






## 3. "Z-Fail" Shadow Volumes

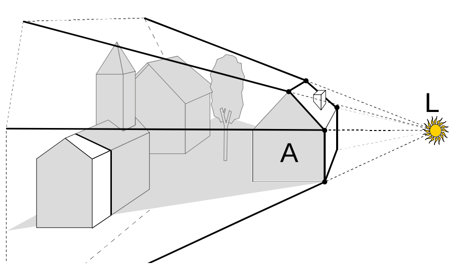
- Introduces problems with far clipping plane
- Solved by clamping the depth during clipping






## 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

# Questions?

- From a previous quiz: Check the boxes to indicate the features & limitations of each technique

| Features / Limitations | Planar Fake Shadows | Projective Texture Shadows | Shadow Maps | Shadow Volumes | Ray Casting Shadows |
|---|---|---|---|---|---|
| Allows objects to cast shadows on themselves (self shadowing) | | | | | |
| Permits shadows on arbitrary surfaces (i.e. curved) | | | | | |
| Renders geometry from the viewpoint of the light | | | | | |
| Generates extra geometric primitives | | | | | |
| Limited resolution of intermediate representation can result in jaggie shadow artifacts | | | | | |