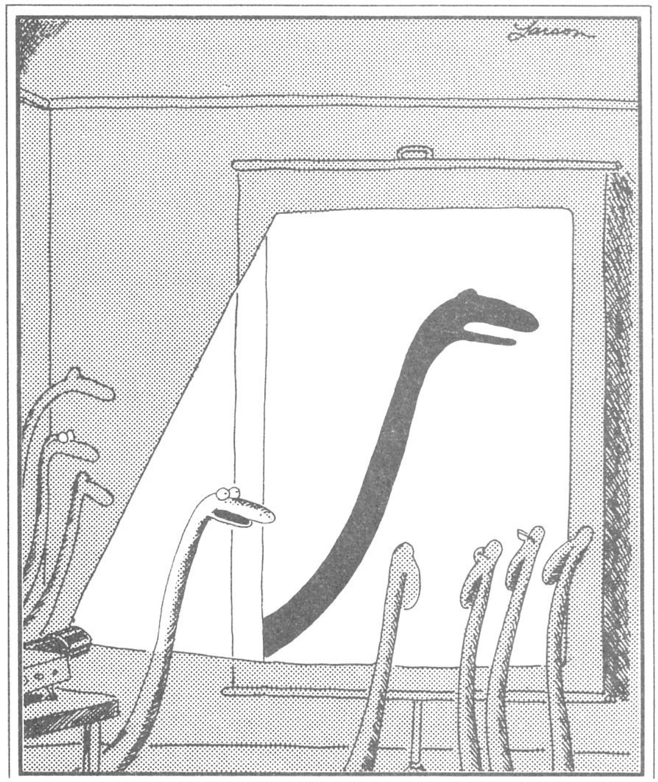
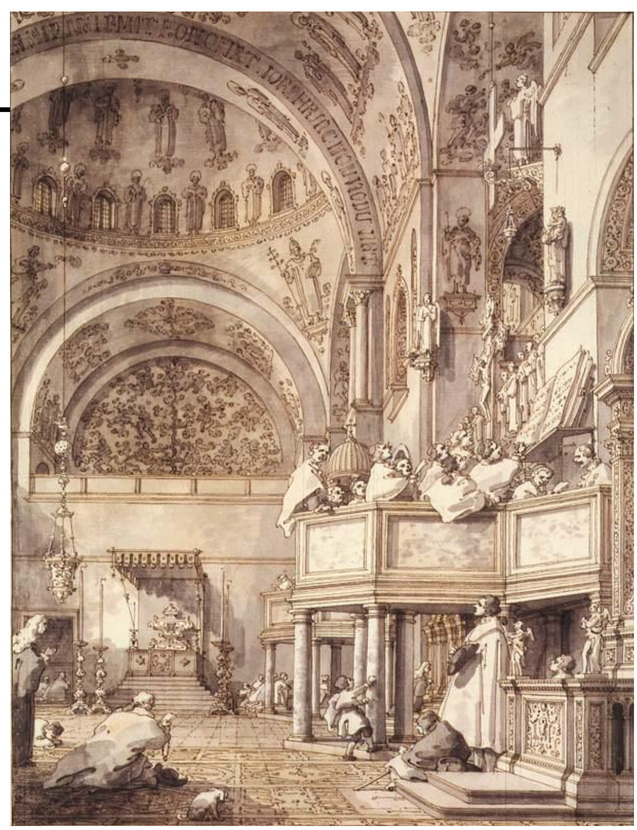
Real-Time Shadows



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

San Marco - The Crossing and North Transept, with Musicians Singing

Giovanni Antonio Canal, il Canaletto
1766



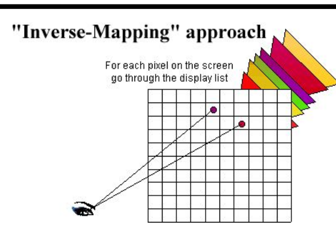
Last Drawing of Canaletto
Cameron McNall, 2000

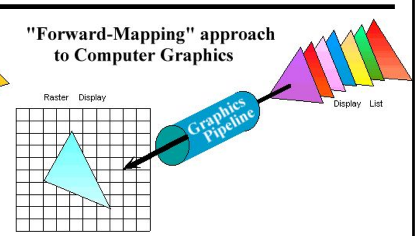
The Presentation of the Doge in San Marco
Giovanni Antonio Canal, il Canaletto 1766

The Coronation of the Doge on the Scala dei Giganti, Giovanni Antonio Canal, Canaletto, 1763-1766

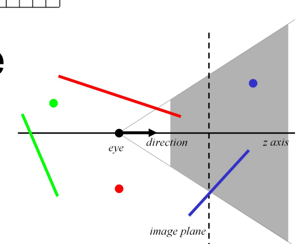
Last Time

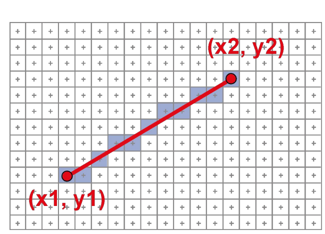
- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

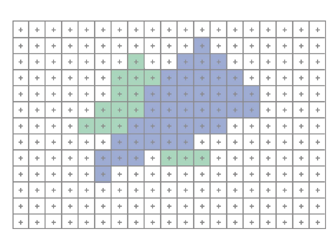




- Graphics Pipeline
- Clipping
- Rasterization

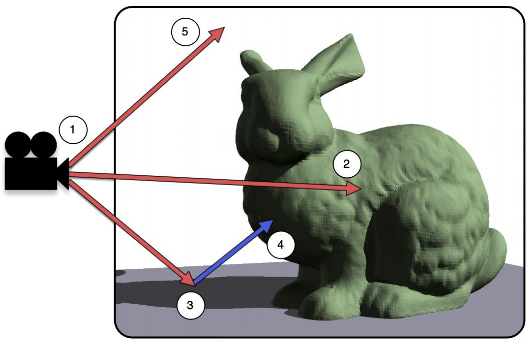


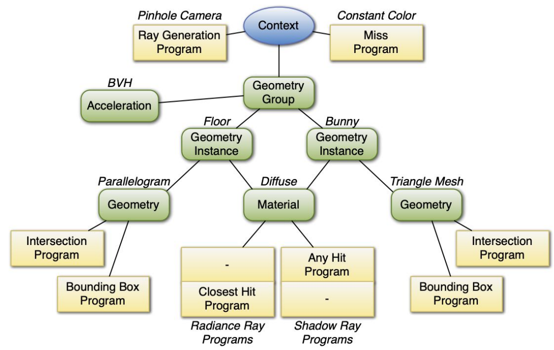




Reading for Today:

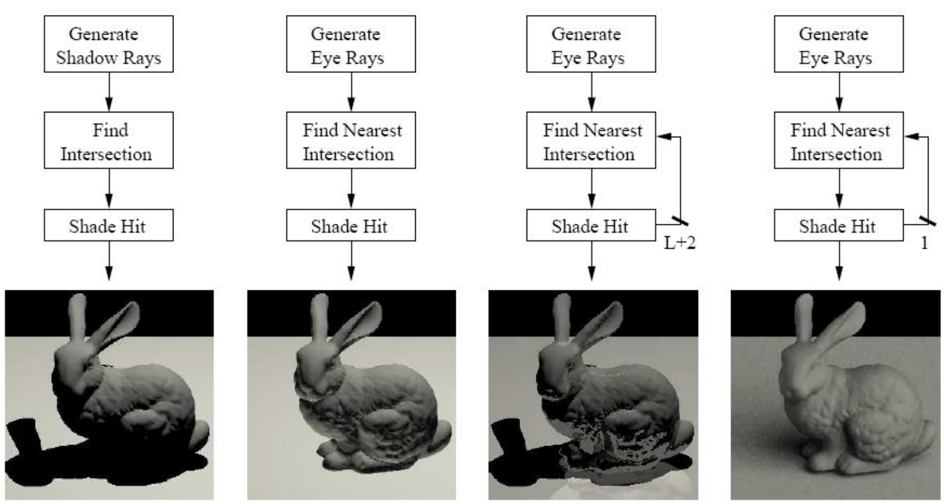
- "OptiX: A General Purpose Ray Tracing Engine", Parker, Bigler, Dietrich, Friedrich, Hoberock, Luebke, McAllister, McGuire, Morley, Robison, Stitch, ACM Transactions on Graphics 2010



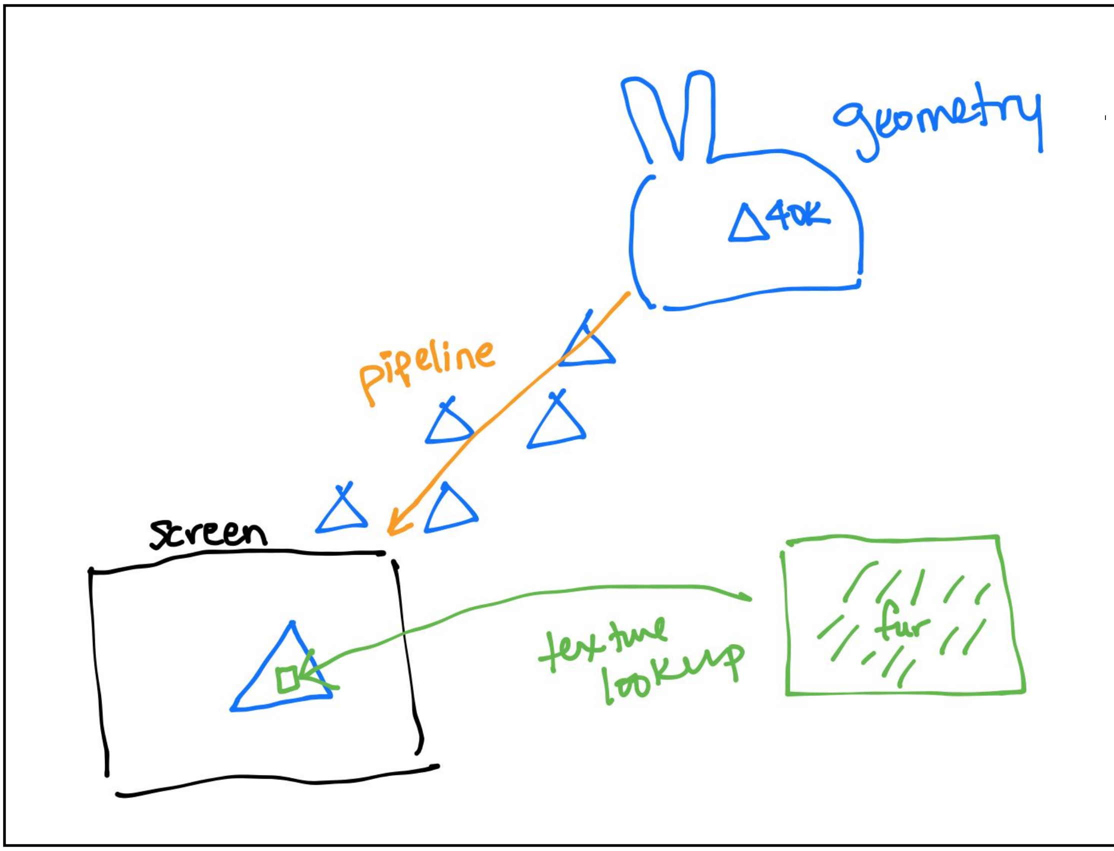


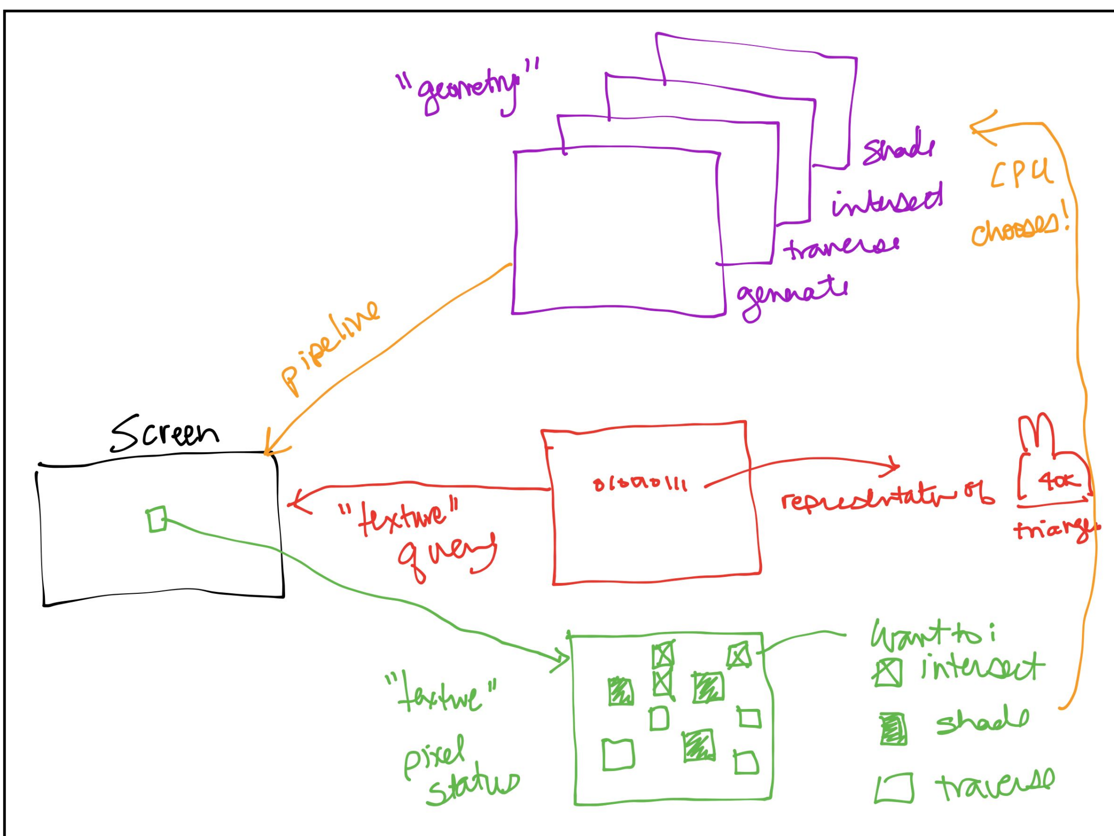
Reading for Today:

- "Ray Tracing on Programmable Graphics Hardware Purcell", Buck, Mark, & Hanrahan SIGGRAPH 2002



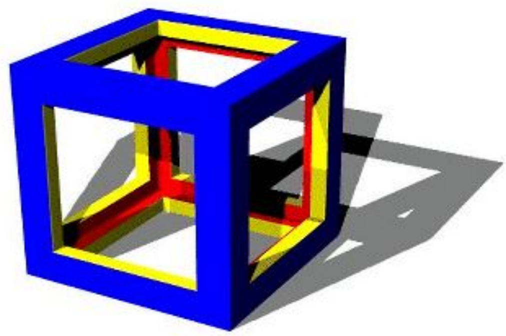
Shadow Caster (a) | Ray Caster (b) | Whitted Ray Tracer (c) | Path Tracer (d)


geometry
Δ40K
pipeline
screen
texture lookup
fur


"geometry"
shade
intersect
traverse
generate
CPU chooses!
pipeline
Screen
01010111
"texture" query
representation of
40K
triangles
"texture" pixel status
Want to:
intersect
shade
traverse

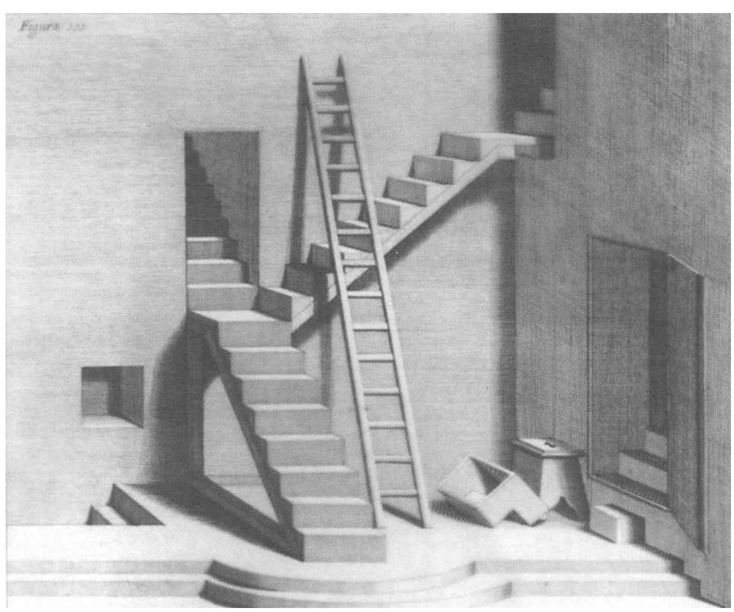
Today

- Why are Shadows Important?
- Planar Shadows
- Projective Texture Shadows
- Shadow Maps
- Shadow Volumes

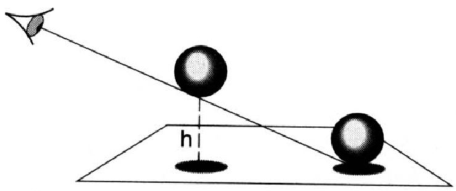


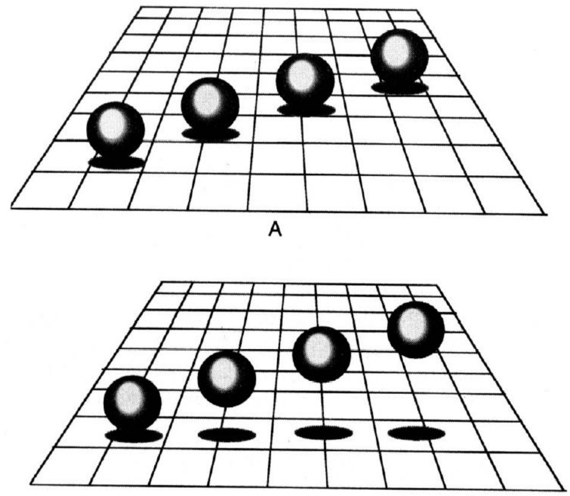
Why are Shadows Important?

- Depth cue
- Scene Lighting
- Realism
- Contact points



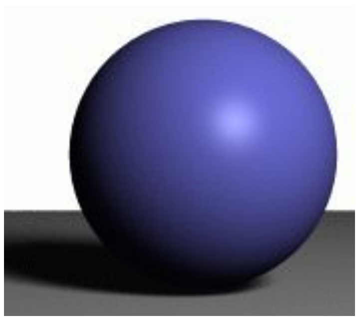
Shadows as a Depth Cue

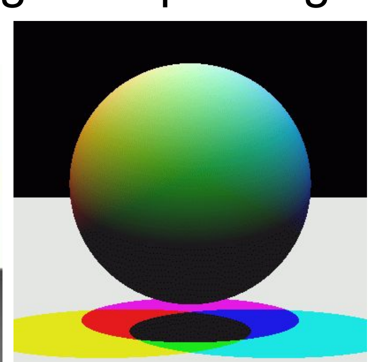


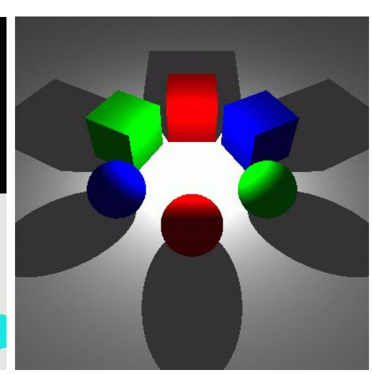


For Intuition about Scene Lighting

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

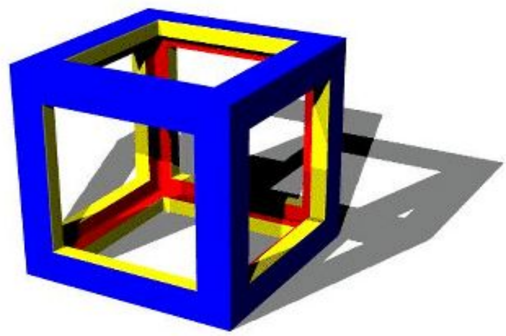






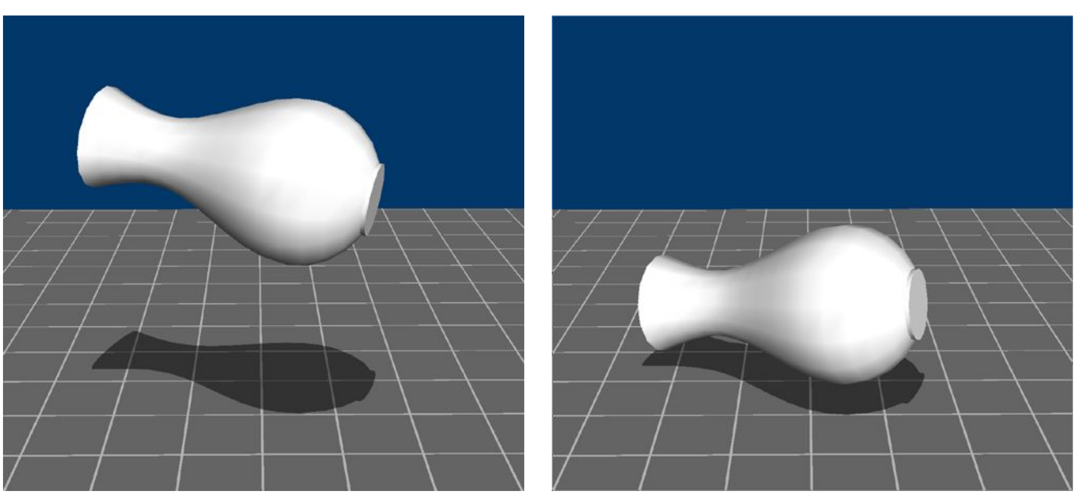
Today

- Why are Shadows Important?
- Planar Shadows
- Projective Texture Shadows
  - Shadow View Duality
  - Texture Mapping
- Shadow Maps
- Shadow Volumes



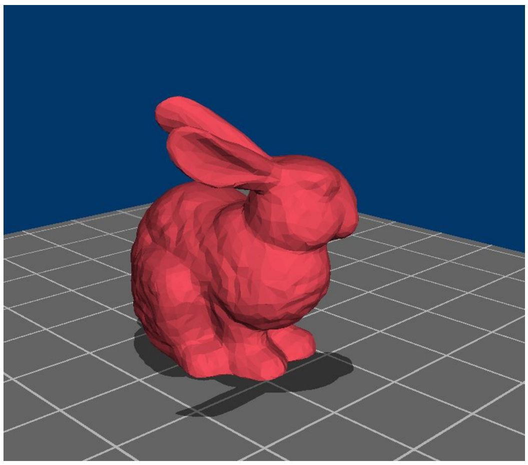
Cast Shadows on Planar Surfaces

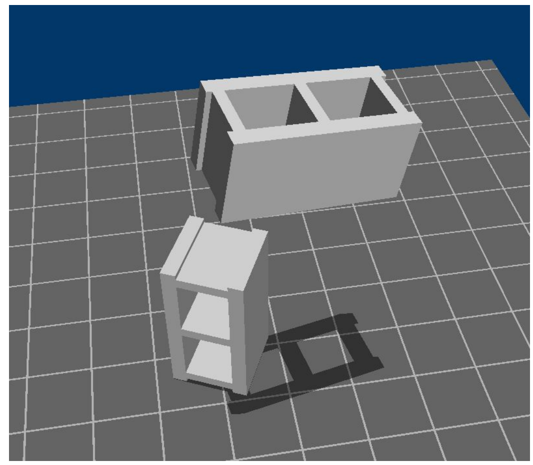
- Draw the object primitives a second time, projected to the ground plane



Limitations of Planar Shadows

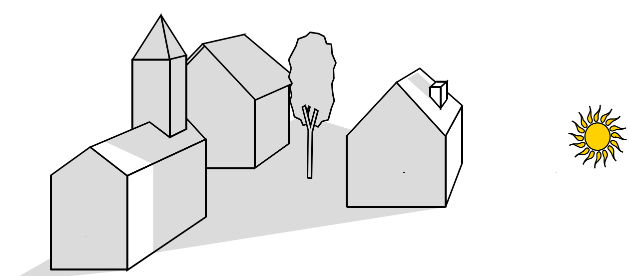
- Does not produce self-shadows, shadows cast on other objects, shadows on curved surfaces, etc.



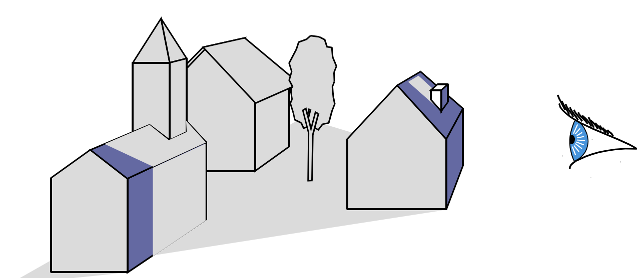


Shadow/View Duality

- 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

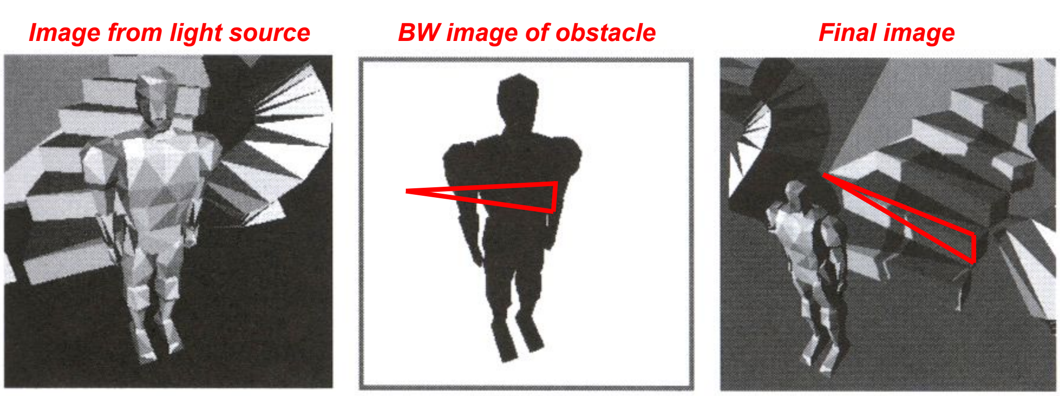


Figure from Moller & Haines “Real Time Rendering”

Projective Texture Shadow Limitations

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

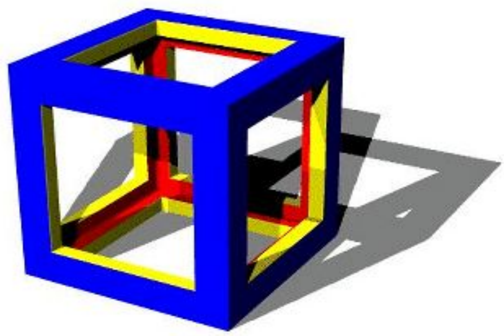
Figure from Moller & Haines “Real Time Rendering”

Questions?

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

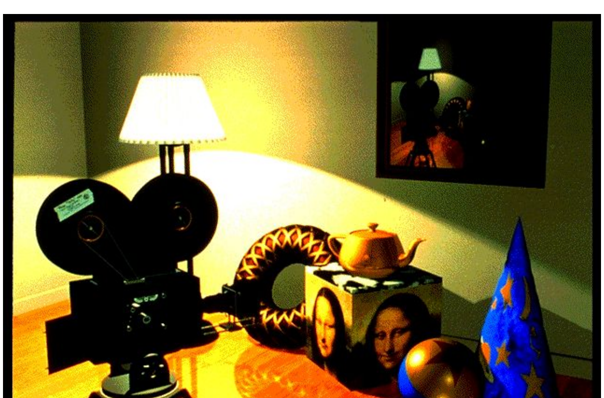
Today

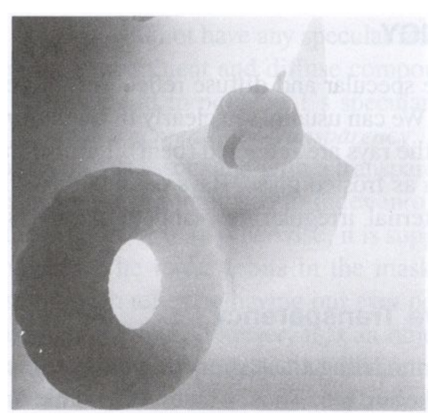
- Why are Shadows Important?
- Planar Shadows
- Projective Texture Shadows
- Shadow Maps
- Shadow Volumes



Shadow Maps

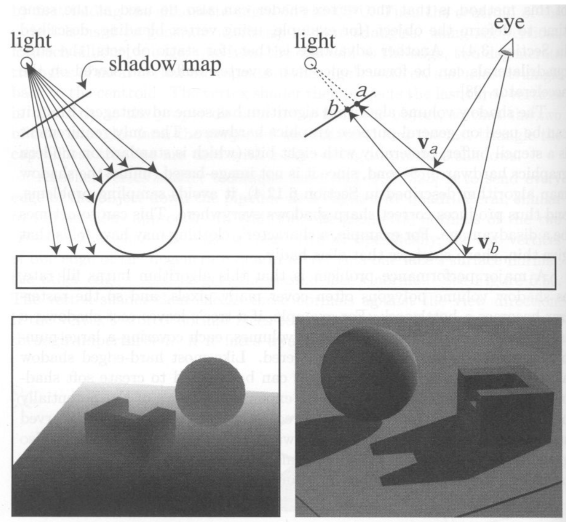
- In Renderman
  - (High-end production software)





Shadow Mapping

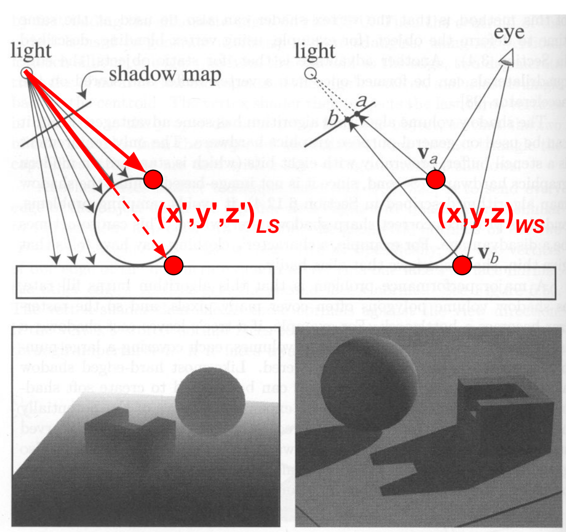
- Texture mapping with depth information
- Requires 2 passes through the pipeline:
  - Compute shadow map (depth from light source)
  - Render final image, *check shadow map to see if points are in shadow*



Foley et al. "Computer Graphics Principles and Practice"

Shadow Map Look Up

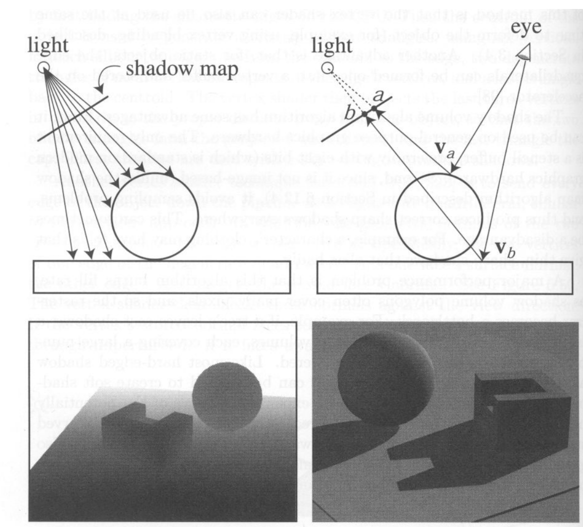
- We have a 3D point $(x,y,z)_{WS}$
- How do we look up the depth from the shadow map?
- Use the 4x4 perspective projection matrix from the light source to get $(x',y',z')_{LS}$
- ShadowMap(x',y') < z'?



Foley et al. "Computer Graphics Principles and Practice"

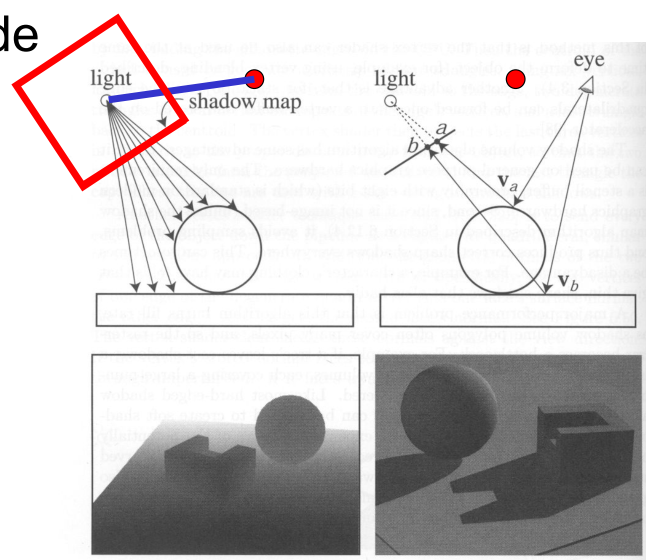
Limitations of Shadow Maps

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!

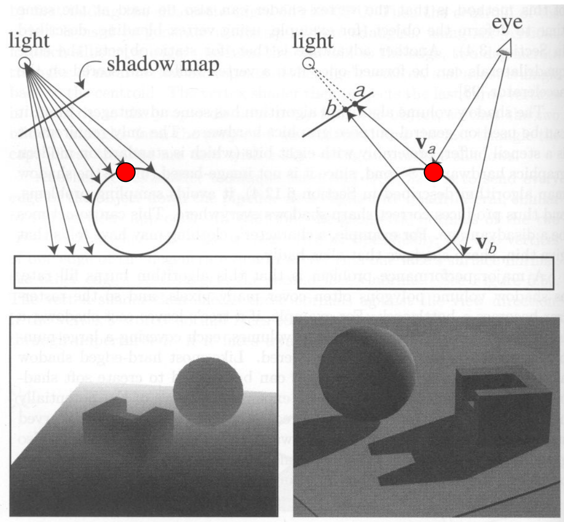


2. The Bias (Epsilon) Nightmare

- For a point visible from the light source

  ShadowMap(x’,y’) ≈ z’

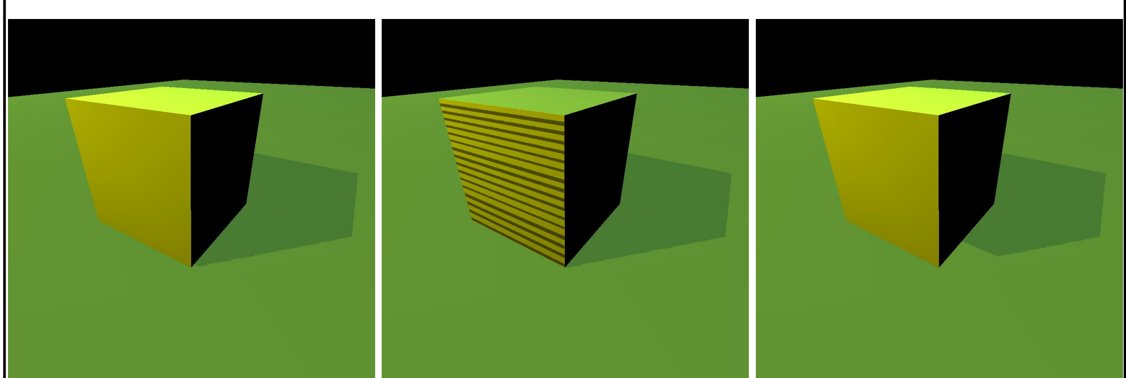
- How can we avoid erroneous self-shadowing?
  – Add bias (epsilon)



2. Bias (Epsilon) for Shadow Maps

ShadowMap(x’,y’) + bias < z’

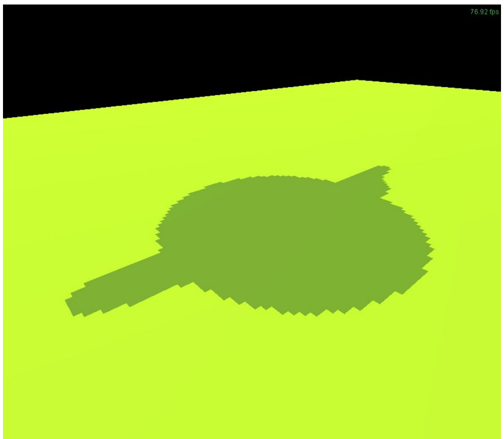
Choosing a good bias value can be very tricky



Correct image | Not enough bias | Way too much bias

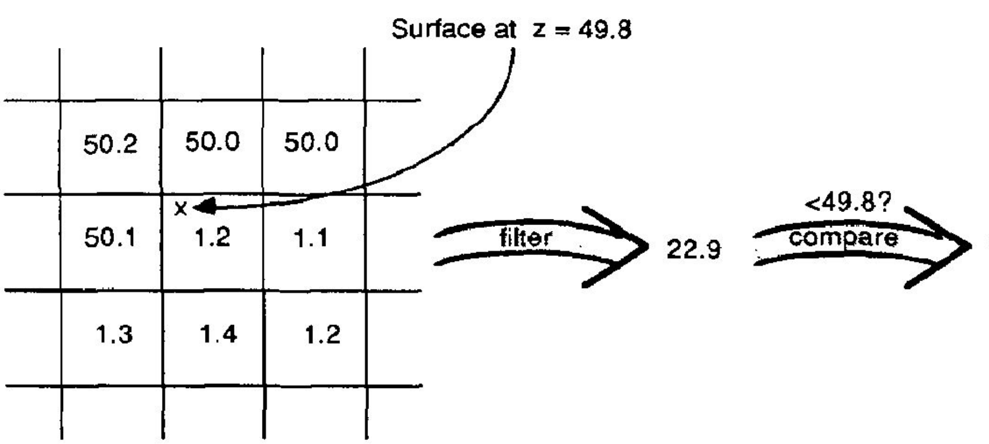
3. Shadow Map Aliasing

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



3. Shadow Map Filtering

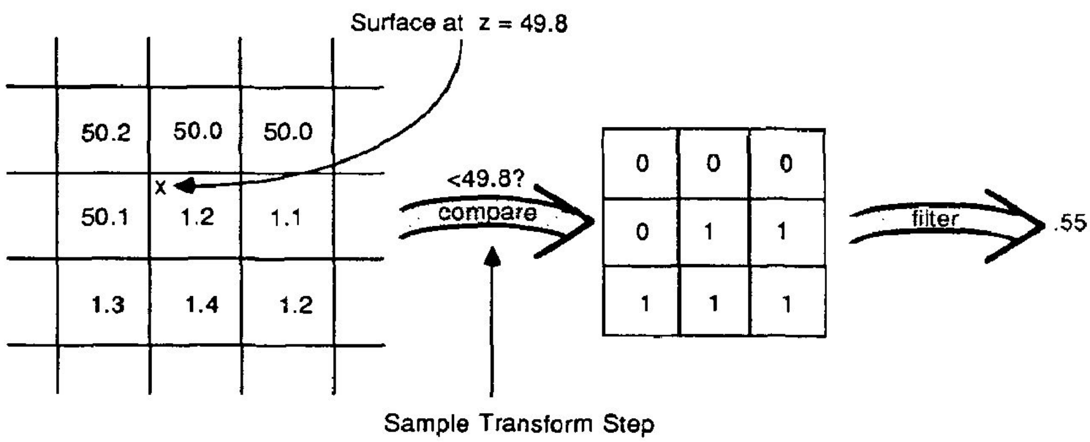
- Should we filter the depth?
  (weighted average of neighboring depth values)
- No... filtering depth is not meaningful



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

3. Percentage Closer Filtering

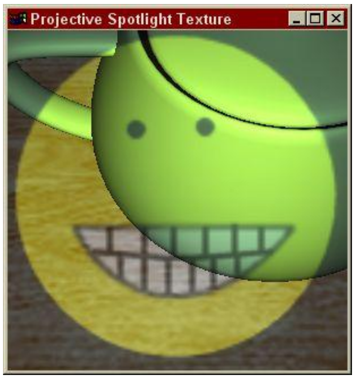
- Instead filter the result of the test (weighted average of comparison results)
- But makes the bias issue more tricky



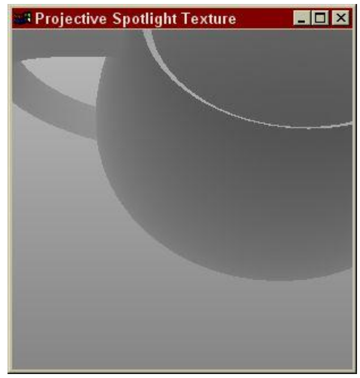
3. Percentage Closer Filtering

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

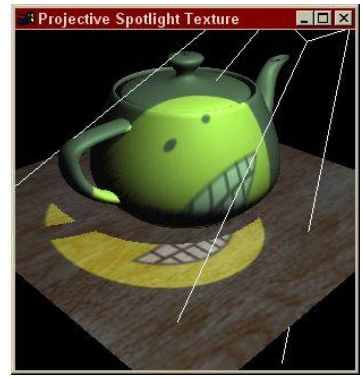
Projective Texturing + Shadow Map



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

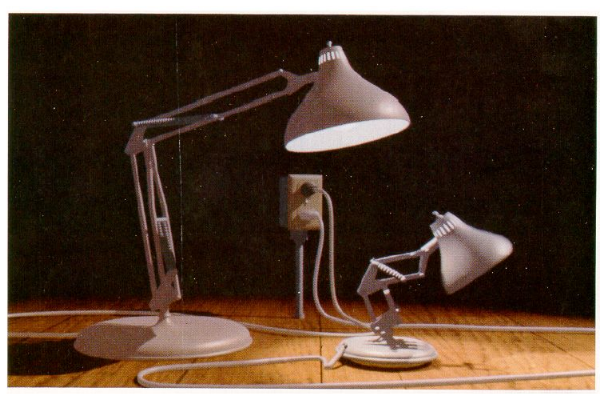


Figure 12. Frame from *Luxo Jr.*

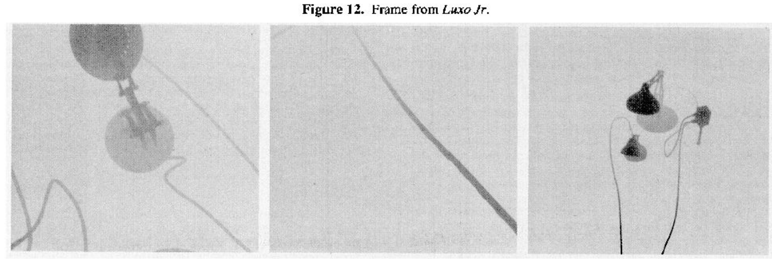
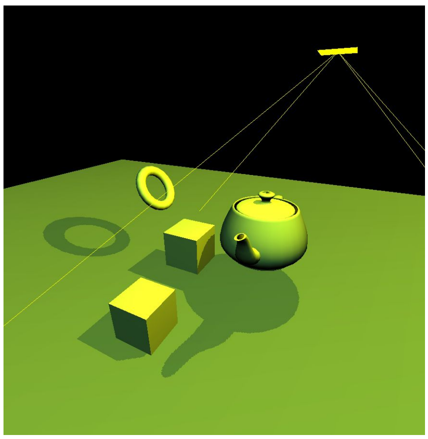


Figure 13. Shadow maps from *Luxo Jr.*

Hardware Shadow Maps

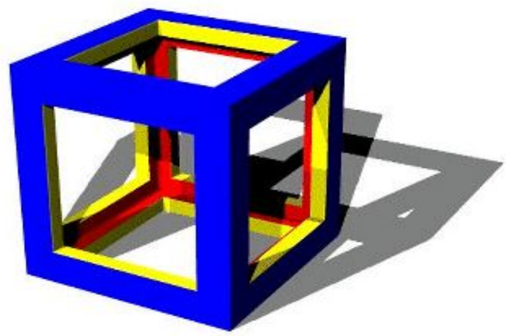
- Can be done with hardware texture mapping
  - Texture coordinates u,v,w generated using 4x4 matrix
  - Modern hardware permits tests on texture values



Questions?

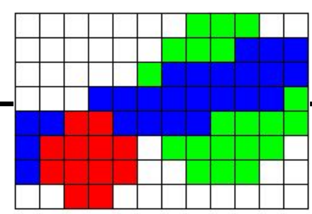
Today

- Why are Shadows Important?
- Planar Shadows
- Projective Texture Shadows
- Shadow Maps
- Shadow Volumes
  - The Stencil Buffer

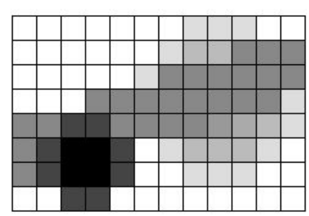


Stencil Buffer

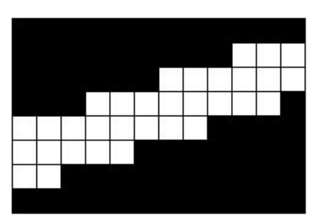
- Tag pixels in one rendering pass to control their update in subsequent rendering passes
  - "For all pixels in the frame buffer" → "For all *tagged* pixels in the frame buffer"
- Can specify different rendering operations for each case:
  - stencil test fails
  - stencil test passes & depth test fails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



frame buffer



depth buffer



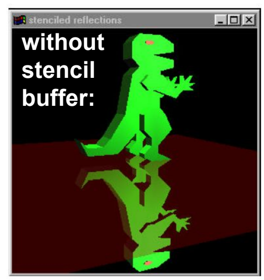
stencil buffer

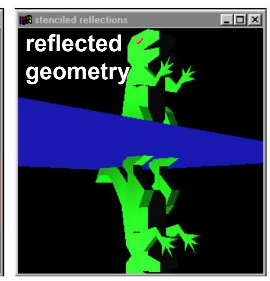
Stencil Buffer – Real-time Mirror

- 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

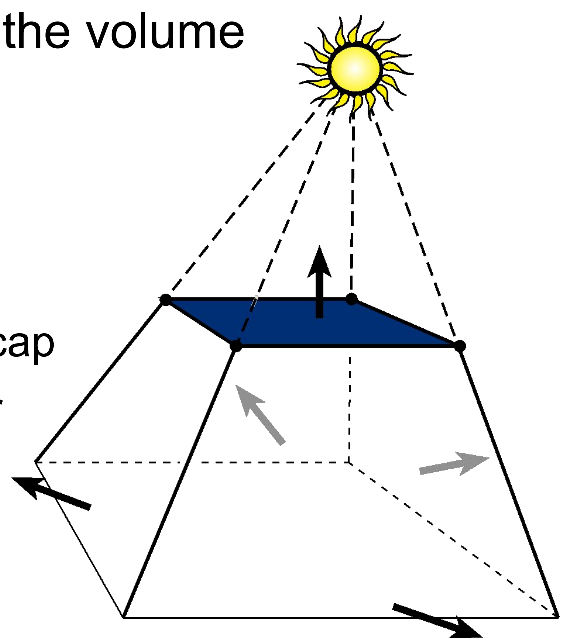
also discusses blending, multiple mirrors, objects behind mirror, etc…





Shadow Volumes

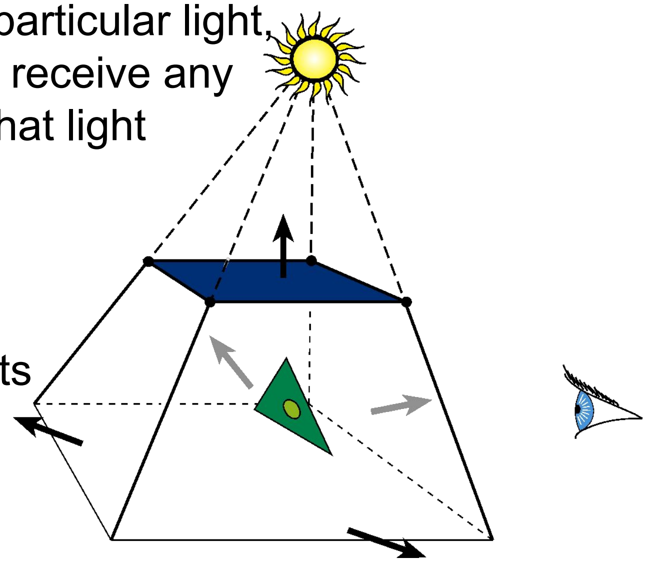
- Explicitly represent the volume of space in shadow
- For each polygon
  - Pyramid with point light as apex
  - Include polygon to cap
- Shadow test similar to clipping



Shadow Volumes

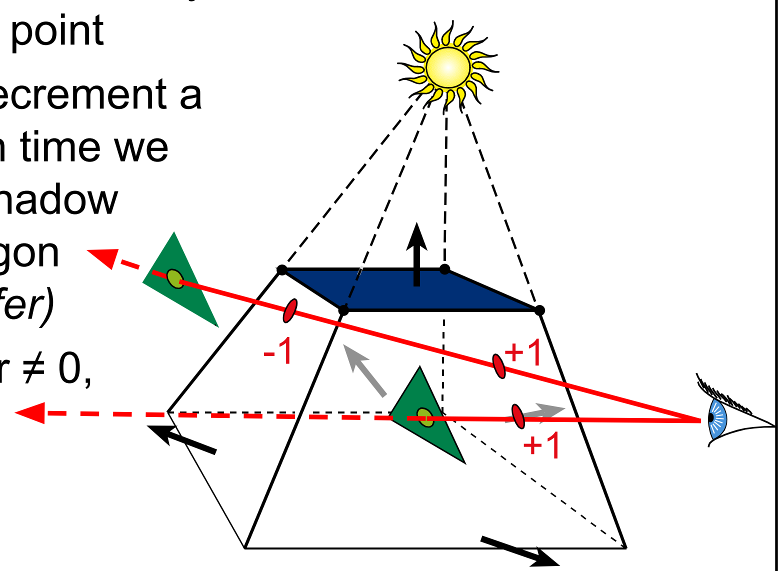
- If a point is inside a shadow volume cast by a particular light, the point does not receive any illumination from that light
- Cost of naive implementation:

  #polygons * #lights



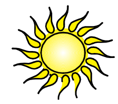
Shadow Volumes

- 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

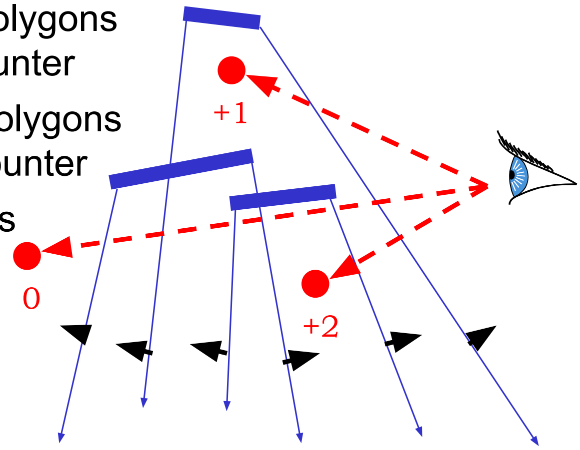
Turn off frame buffer & z-buffer updates

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

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

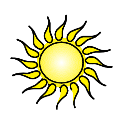
Turn on frame buffer updates

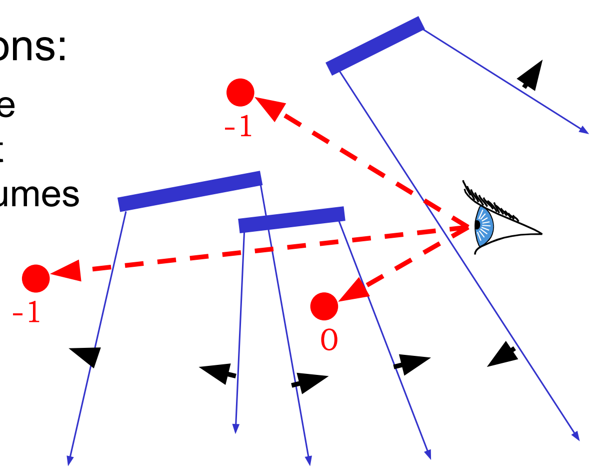
Turn on lighting and
 redraw pixels with
 counter = 0



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

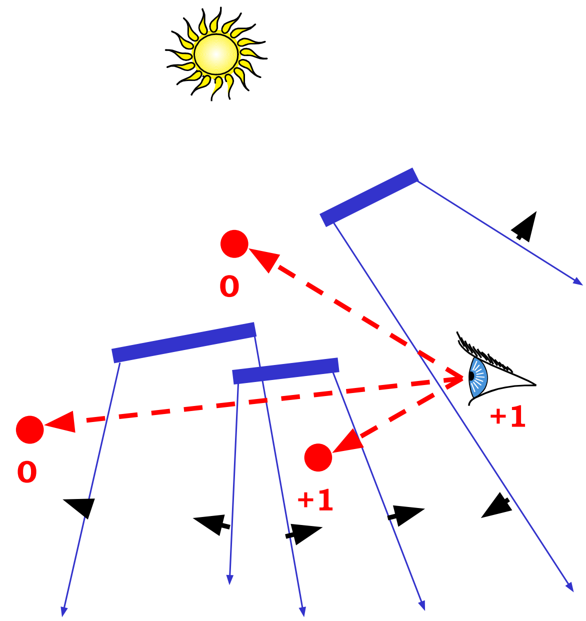




1. Test Eye with Respect to Volumes

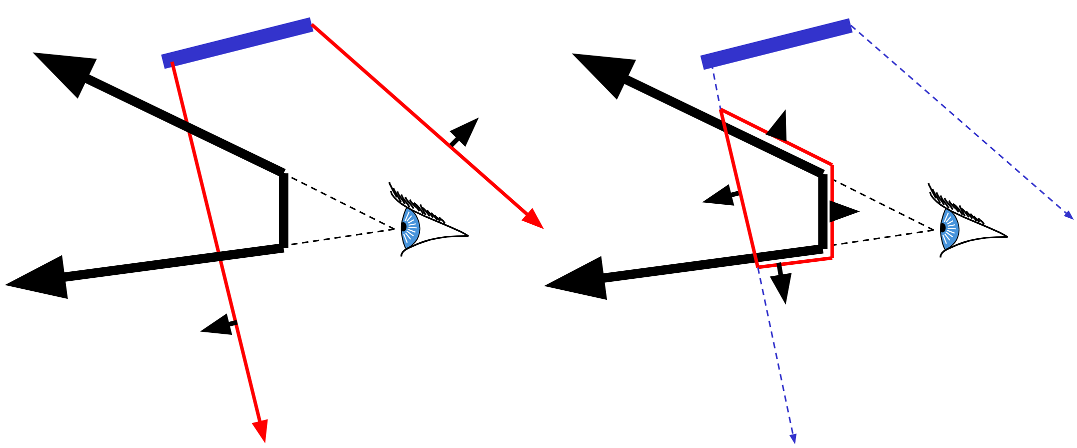
- Adjust initial counter value

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

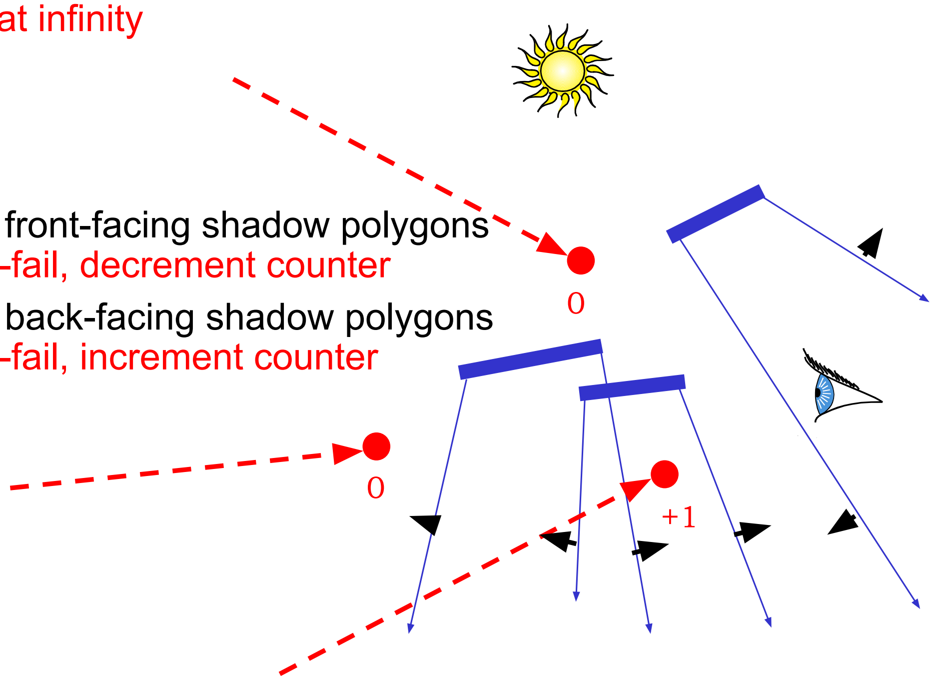
Start at infinity

...

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

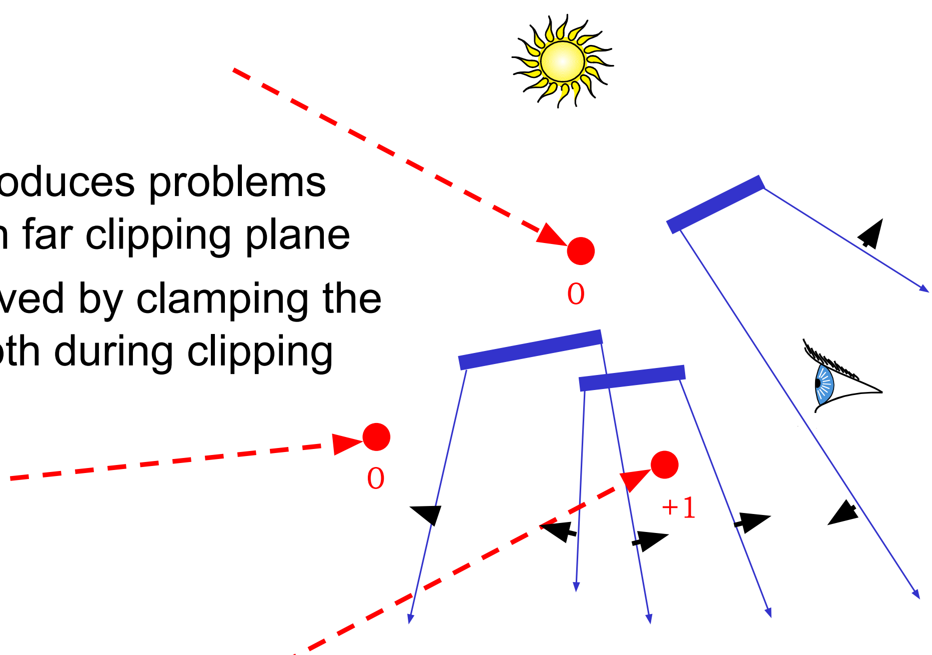
Draw back-facing shadow polygons
    If z-fail, increment counter

...



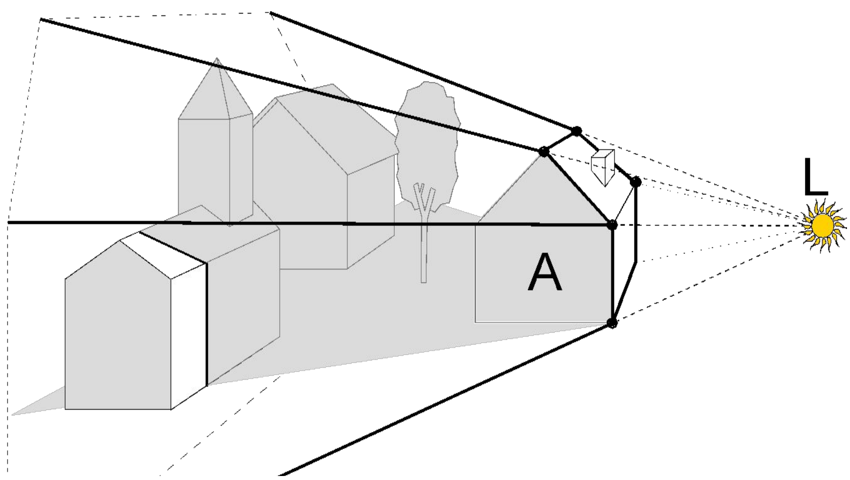
3. "Z-Fail" Shadow Volumes

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



Optimizing Shadow Volumes

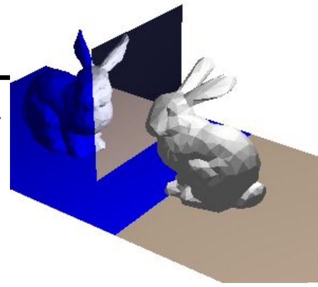
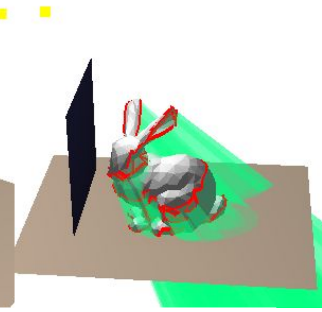
- Use silhouette edges only (edge where a back-facing & front-facing polygon meet)



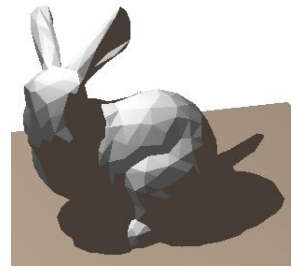
Limitations of Shadow Volumes

- 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

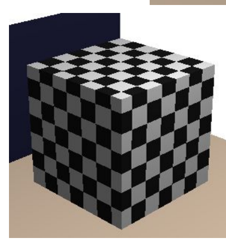
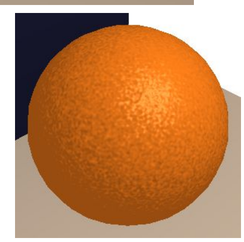
Homework 4

- Create some geometry
  - Reflected object & floor
  - Silhouette edges
  - Shadow polygons
    - Make sure your polygons aren't doubled up
    - Make sure your polygons are oriented consistently

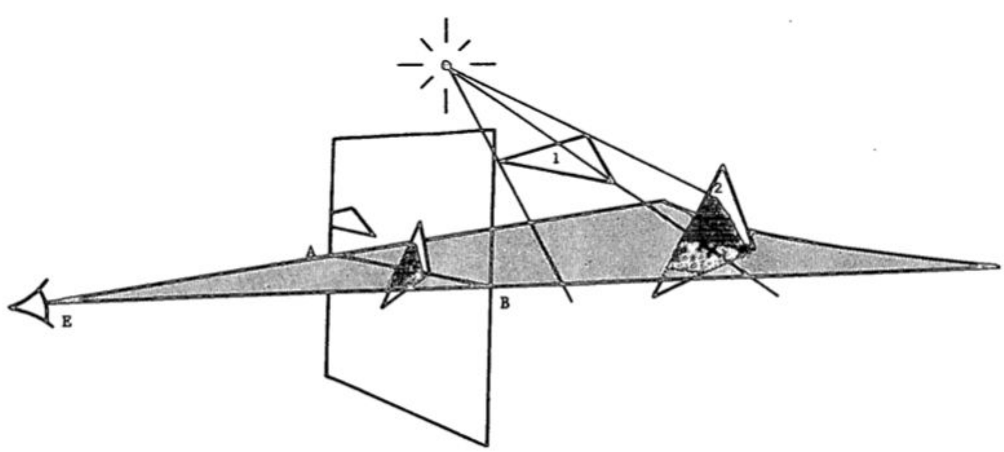


- Mess with the stencil buffer
  - Don't just blindly copy code from the tutorial
  - Use the web to read the man page for each instruction & its parameters
- Be creative with shaders
  - Hopefully everyone can get the examples to compile & run

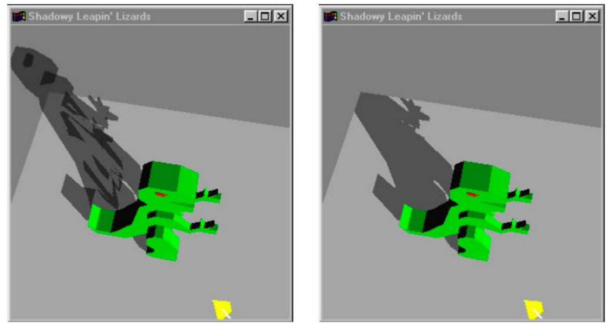
Questions?

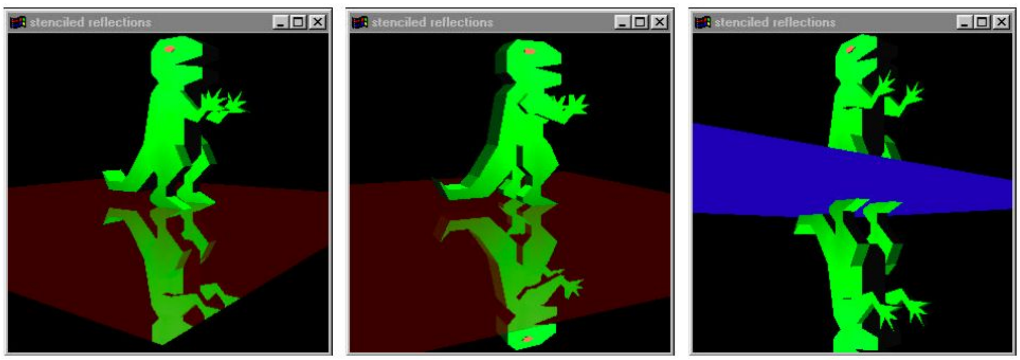
- "Shadow Algorithms for Computer Graphics", Frank Crow, SIGGRAPH 1977



Reading for HW4:

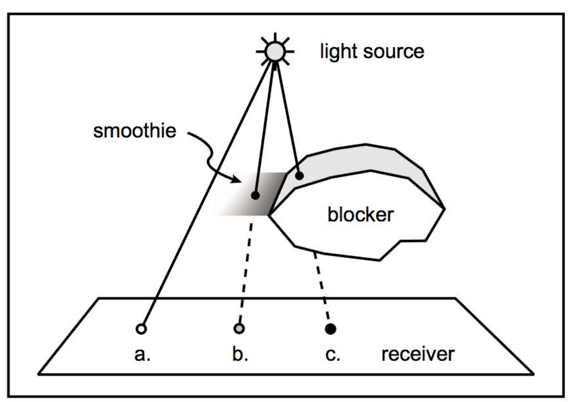
- “Improving Shadows and Reflections via the Stencil Buffer”, Mark Kilgard, NVIDIA

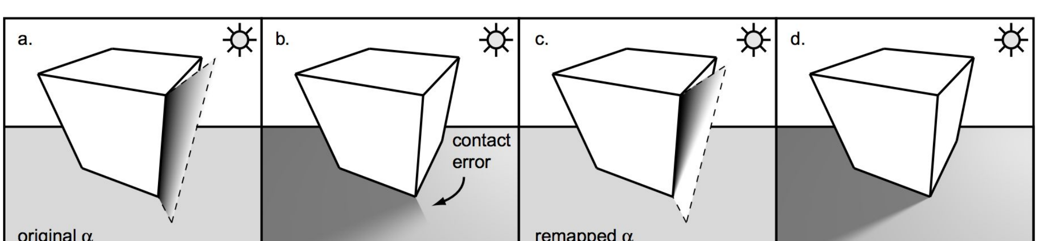




Reading for Next Time: *(pick one)*

- "Rendering Fake Soft Shadows with Smoothies", Chan & Durand, EGSR 2003





Reading for Next Time: *(pick one)*

No shadows	Opacity Shadow Maps	Opacity Shadow Maps	Density Clustering	**Deep Opacity Maps**
–	8 layers	256 layers	4 layers	**3 layers**
(104 fps)	(65 fps)	(0.5 fps)	(37 fps)	**(50 fps)**

- "Deep Opacity Maps",
  Yuksel and Keyser, Eurographics 2008