

Basic Shadow and Reflection Techniques in Real-Time

Shadow Maps and Shadow Volumes

Ulf Assarsson

Why shadows?

- More realism and atmosphere



Doom Eternal – shadow maps

Another example



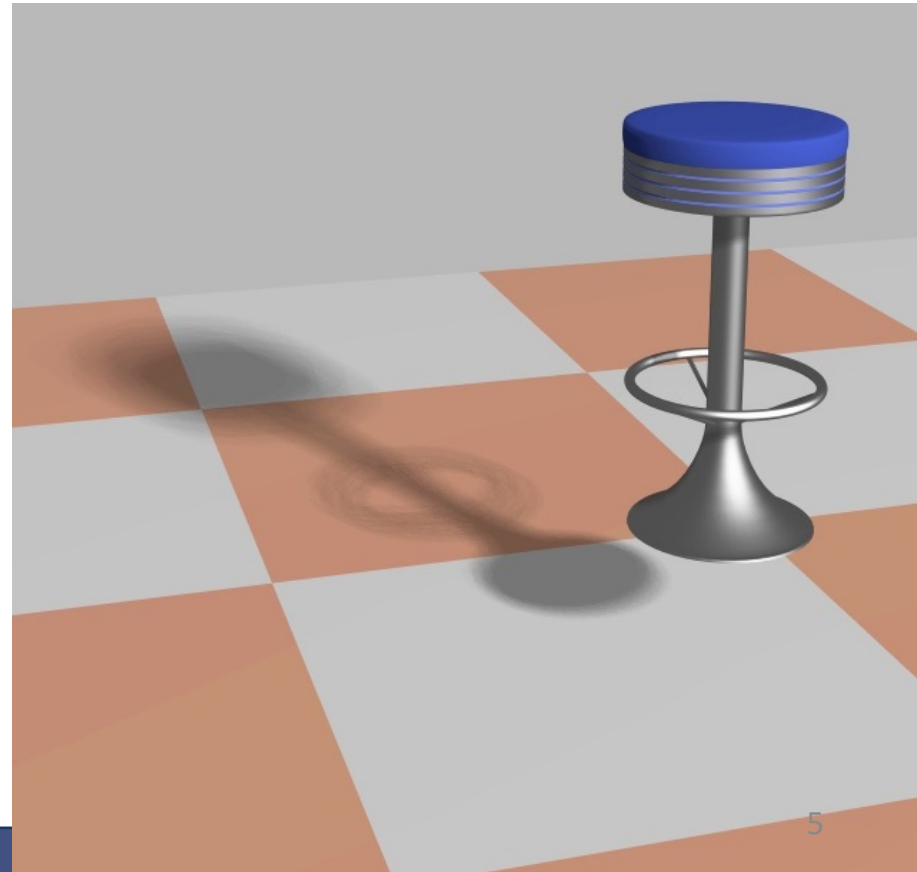
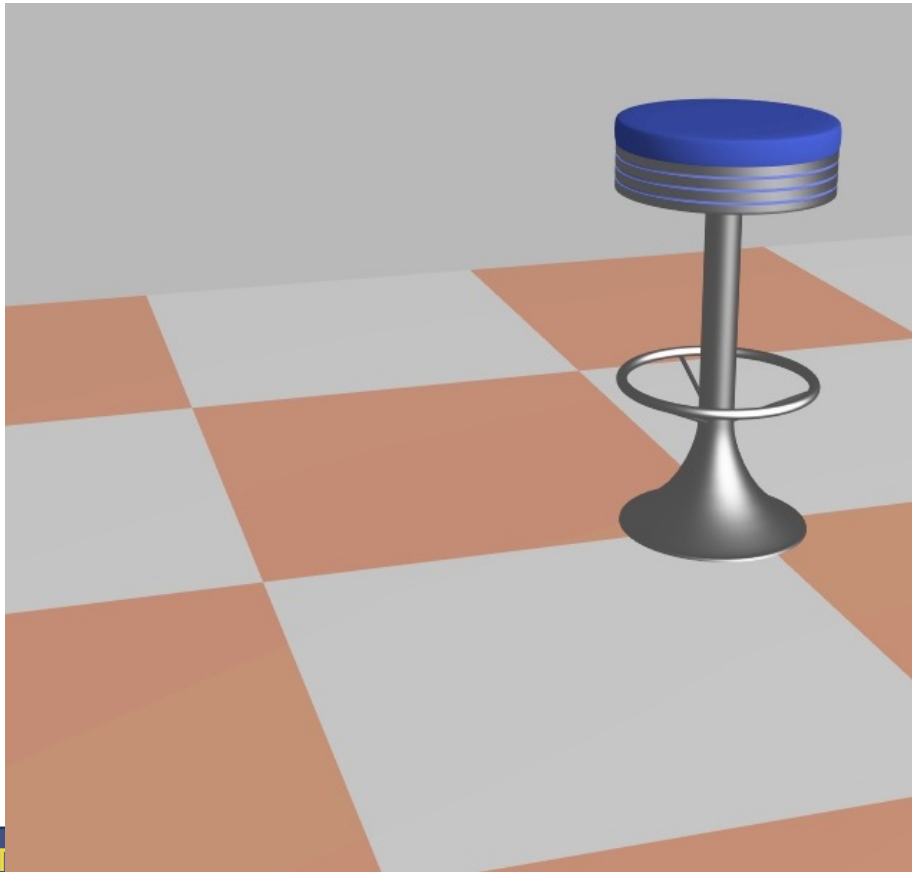


The Kitchen - Jaime Vives Piqueres - POVCOMP 2004

4

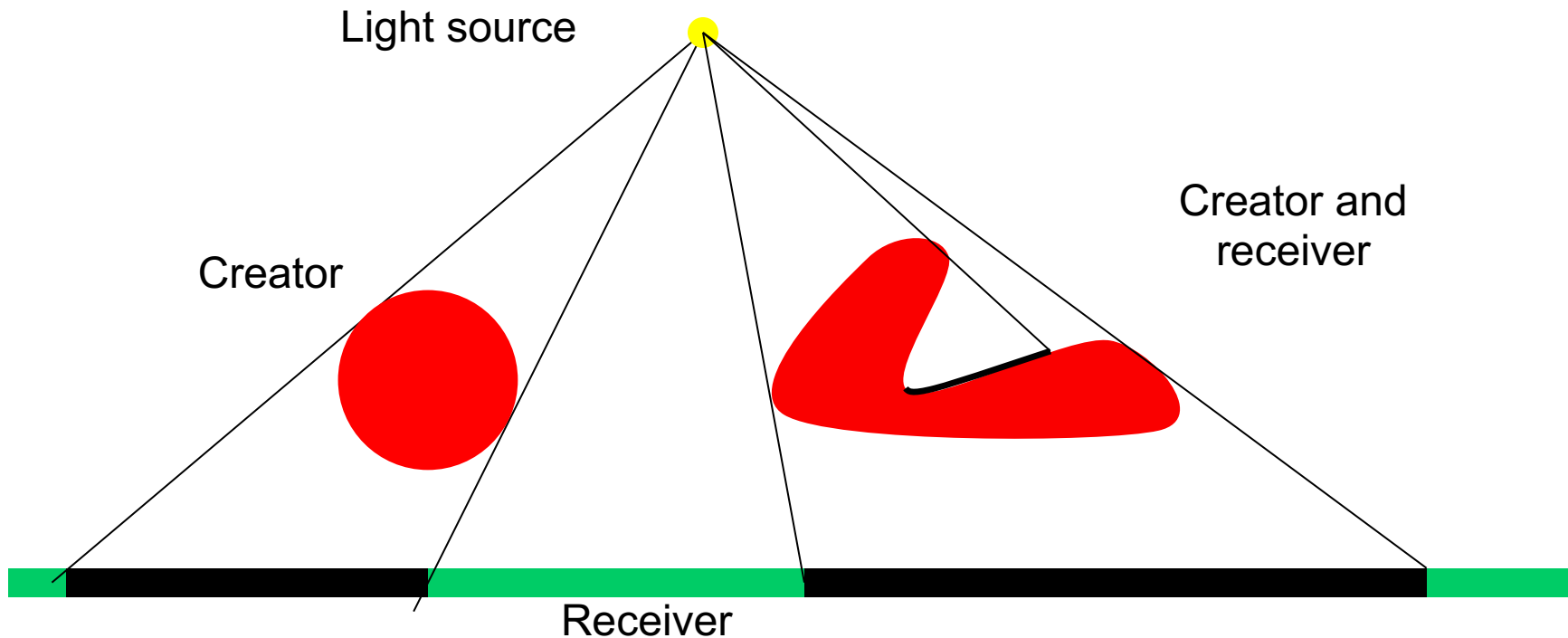
Why shadows?

- More clues about spatial relationships
- Orientation & gameplay



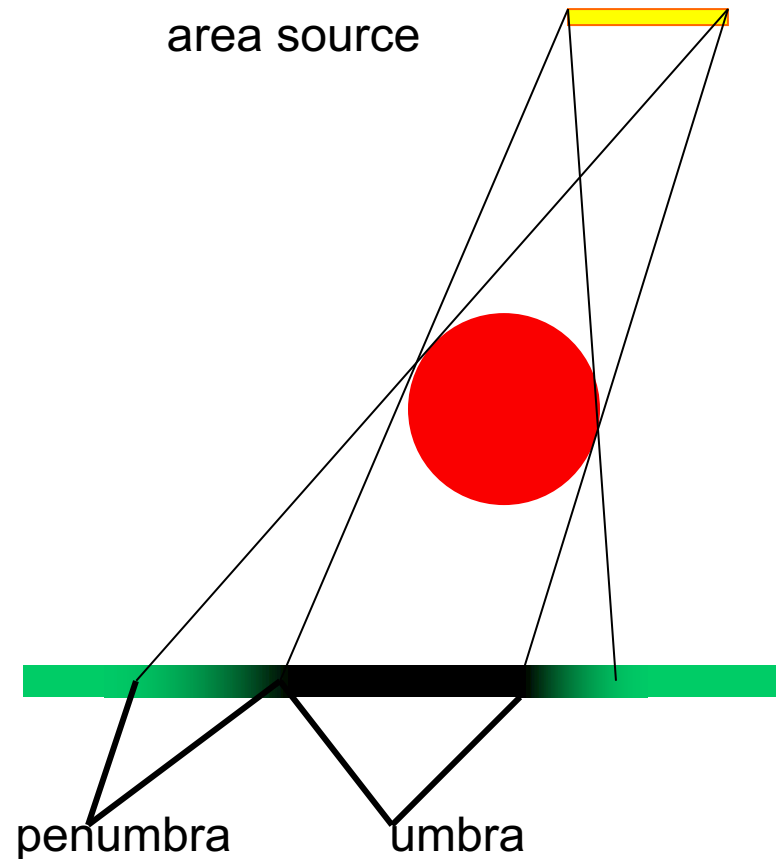
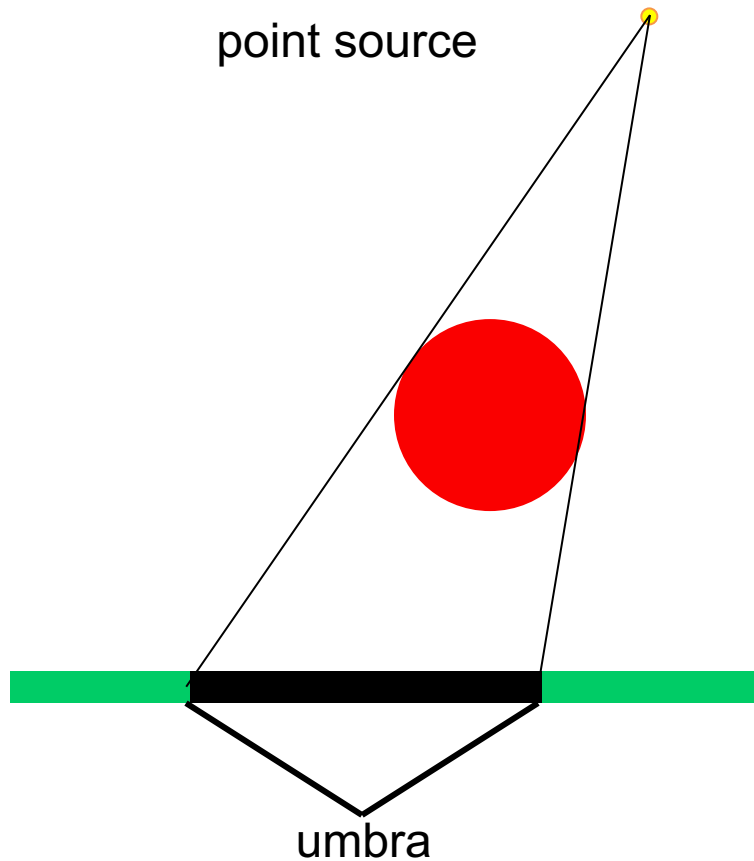
Definitions

- Light sources
- Shadow creators and receivers

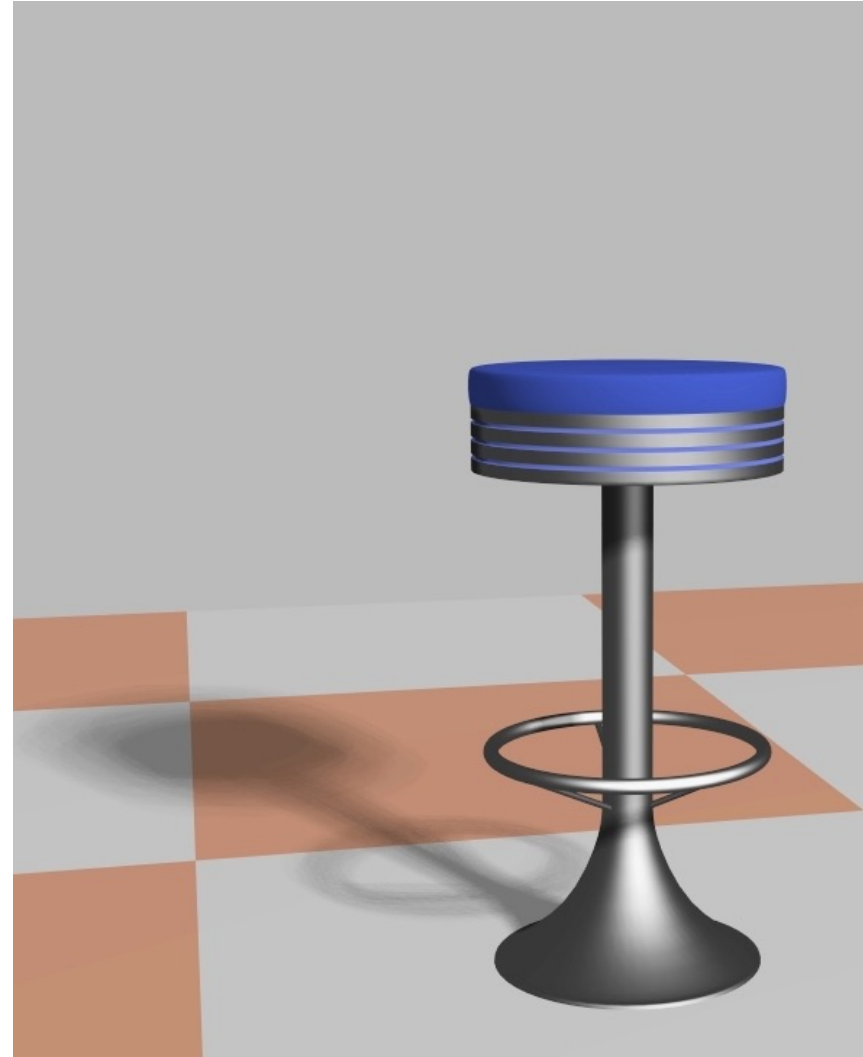
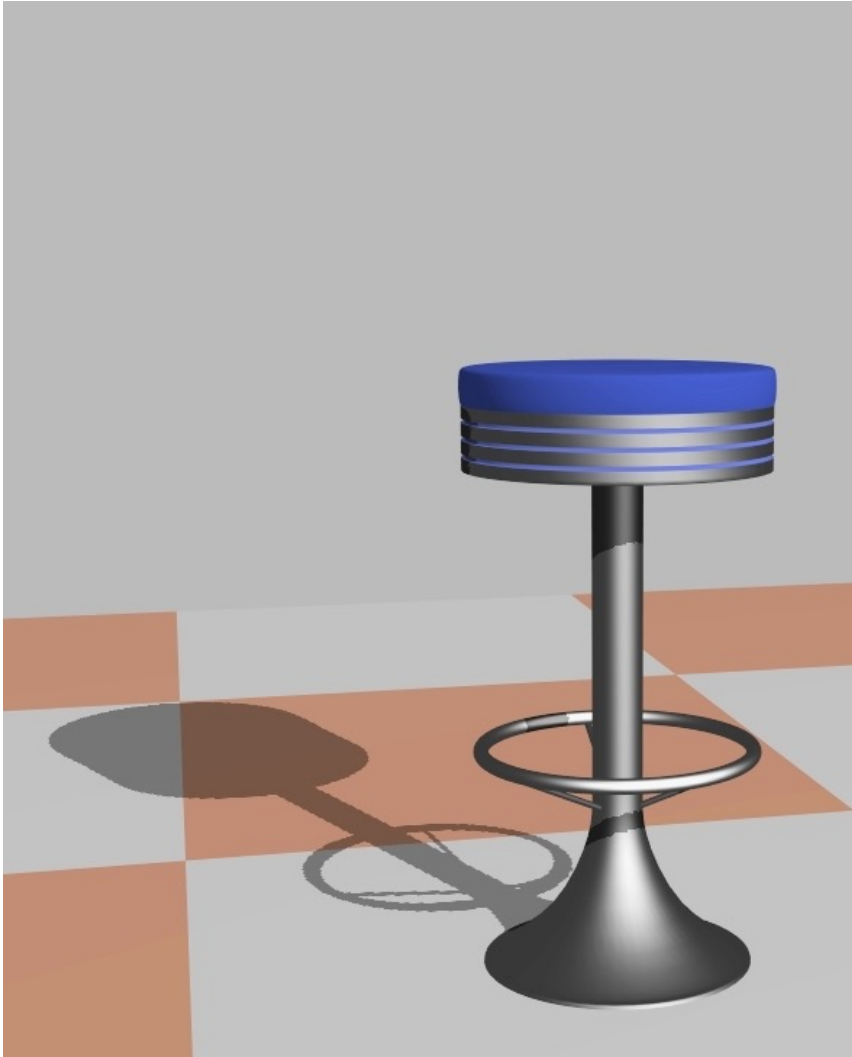


Definitions

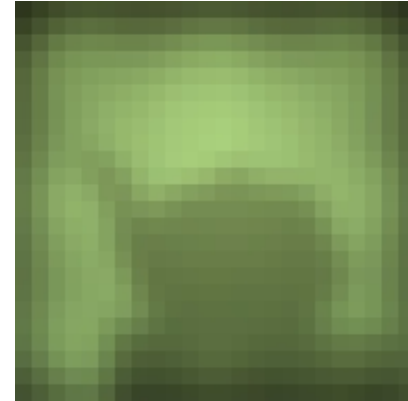
- Light source types



Example: hard vs soft shadows



Store precomputed shadows in textures



Images courtesy of Kasper Høy Nielsen.

Ways of thinking about shadows

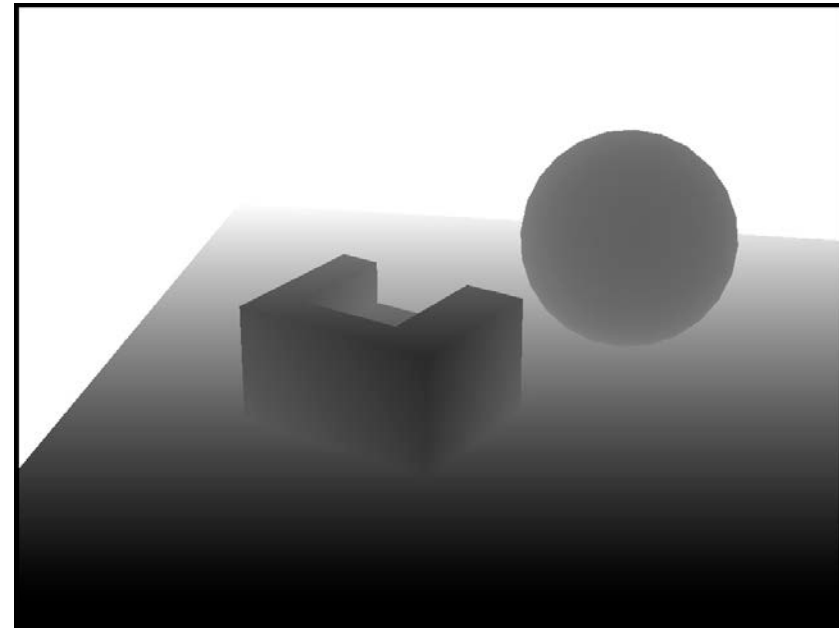
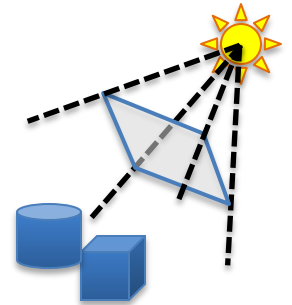
- As separate objects (like Peter Pan's shadow)
- As volumes of space that are dark
 - Shadow Volumes [Franklin Crow 77]
- As places not seen by a light source looking at the scene
 - Shadow Maps [Lance Williams 78]

Shadow Maps

Basic Algorithm – the simple explanation:

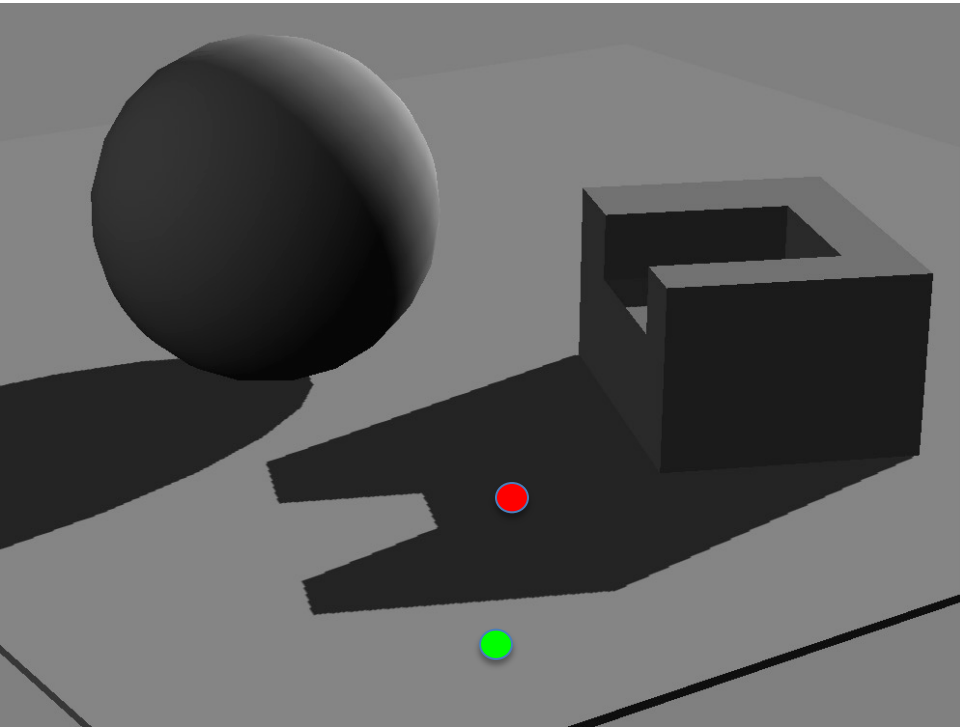
Idea:

- Render image from light source
 - Represents geometry in light
- Render from camera
 - Test if rendered point is visible in the light's view
 - If so -> point in light
 - Else -> point in shadow



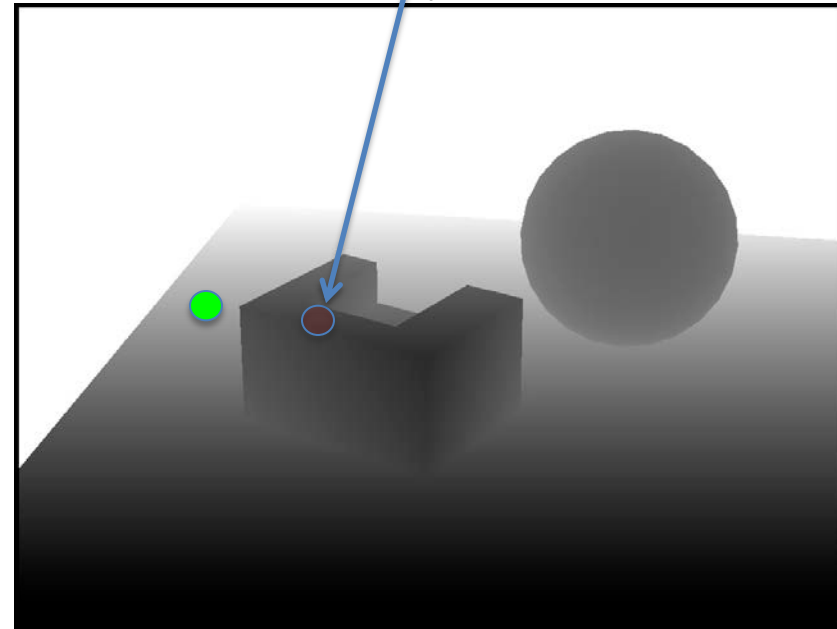
Shadow Map (light's view)

Shadow Maps



Camera's view

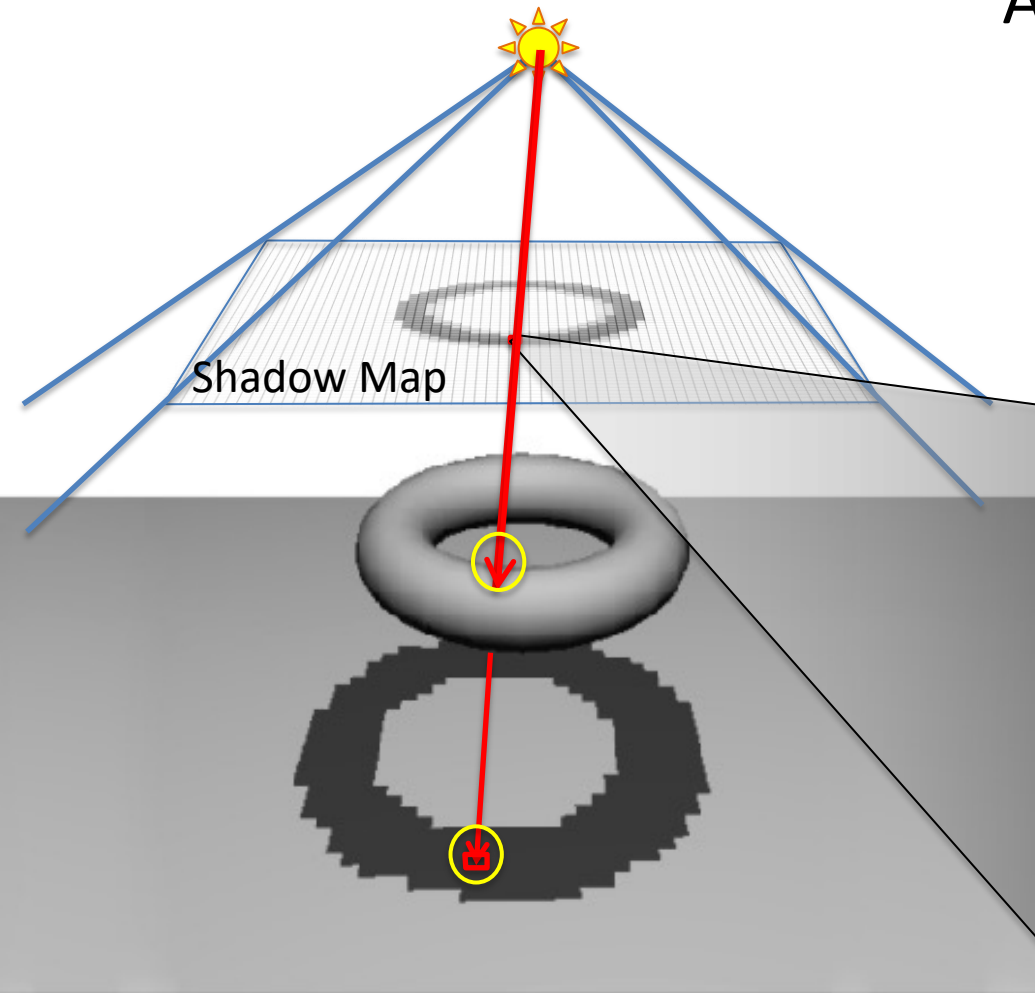
Point not
represented in
shadow map (point is
behind box)



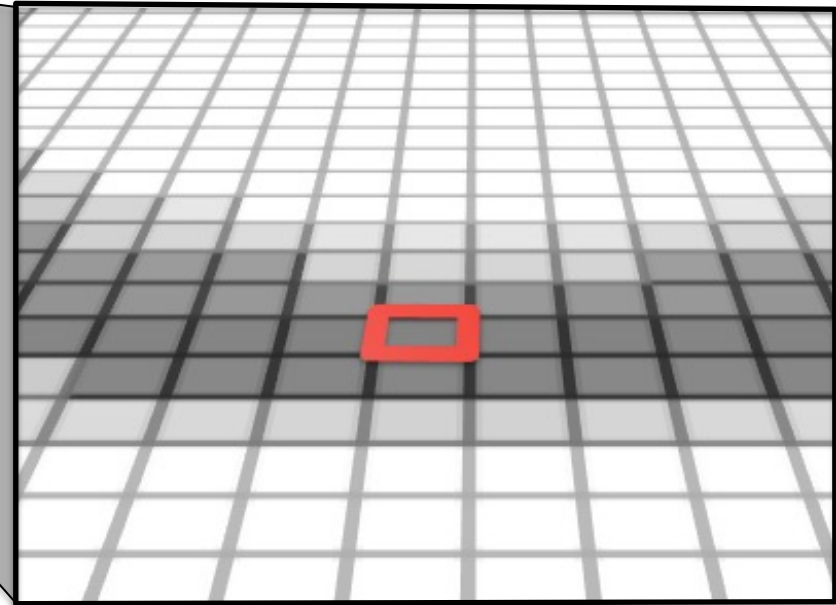
Light's view
(Shadow Map)

Depth Comparison

Render depth image from light



A fragment is in shadow if its depth is greater than the corresponding depth value in the shadow map



Camera's view

Shadow Maps

- Pros

- Very efficient: “This is as fast as it gets”

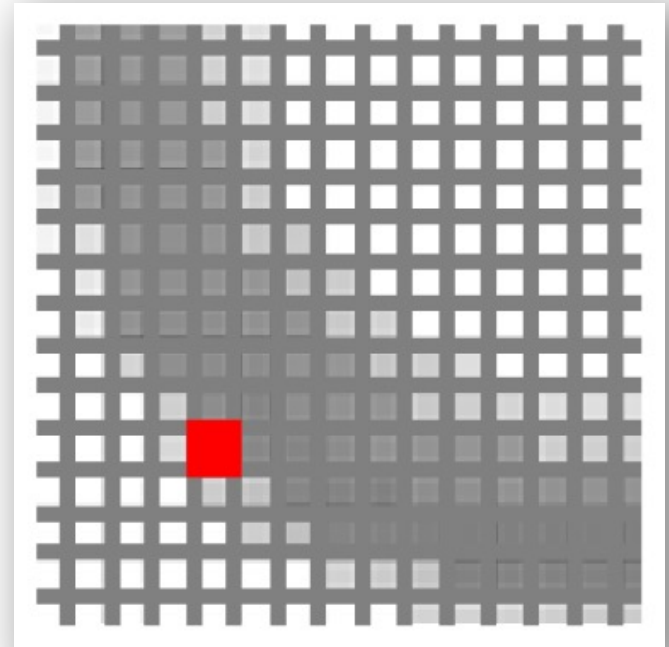
- Cons...

Shadow Maps - Problems

- Low Shadow Map resolution results in jagged shadows



from viewpoint



from light

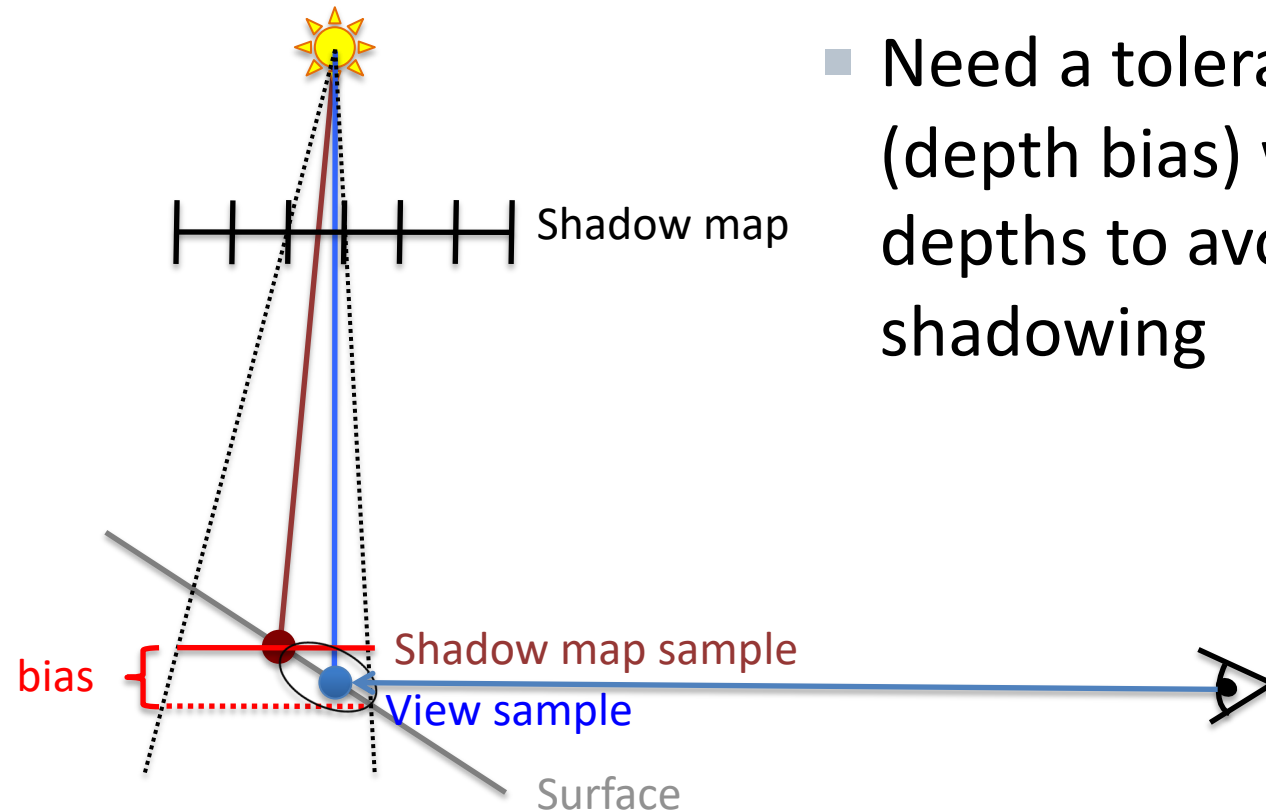
Shadow Maps - Problems

In addition:

- A tolerance threshold (bias) needs to be tuned for each scene for the depth comparison

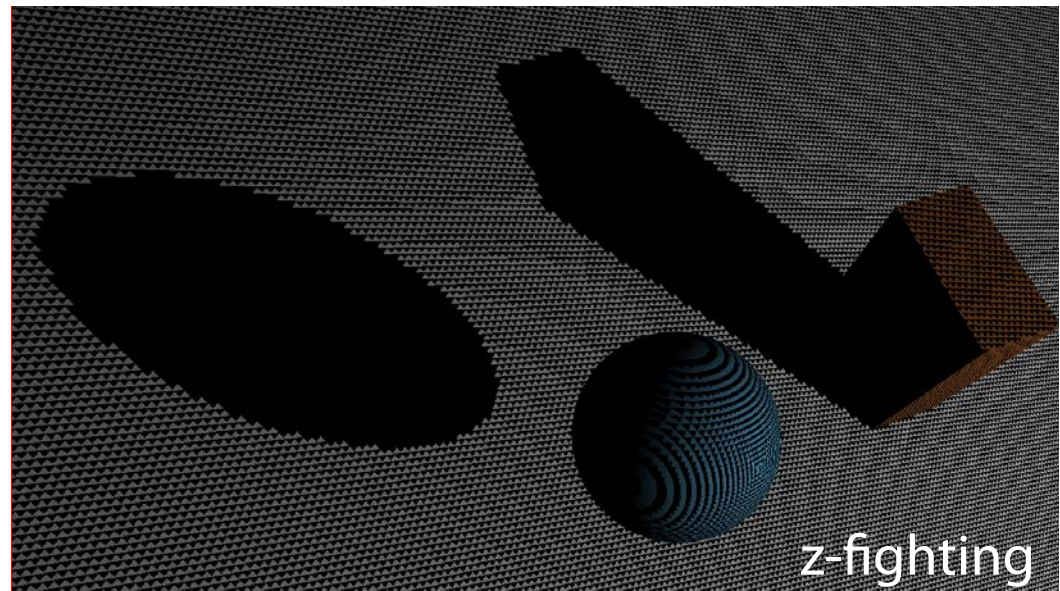
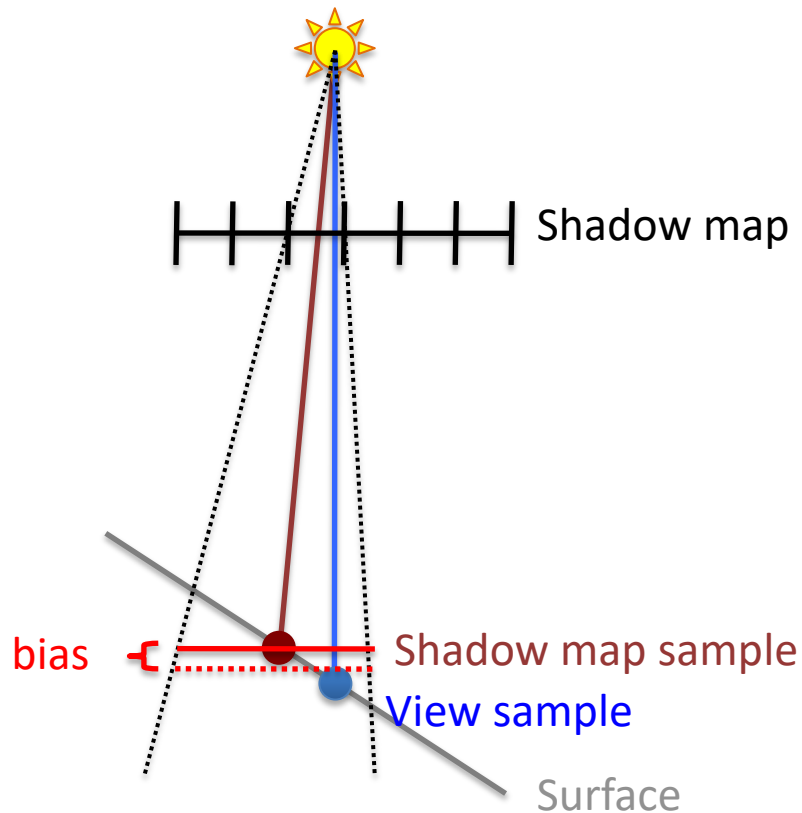
Bias

- Need a tolerance threshold (depth bias) when comparing depths to avoid surface self shadowing



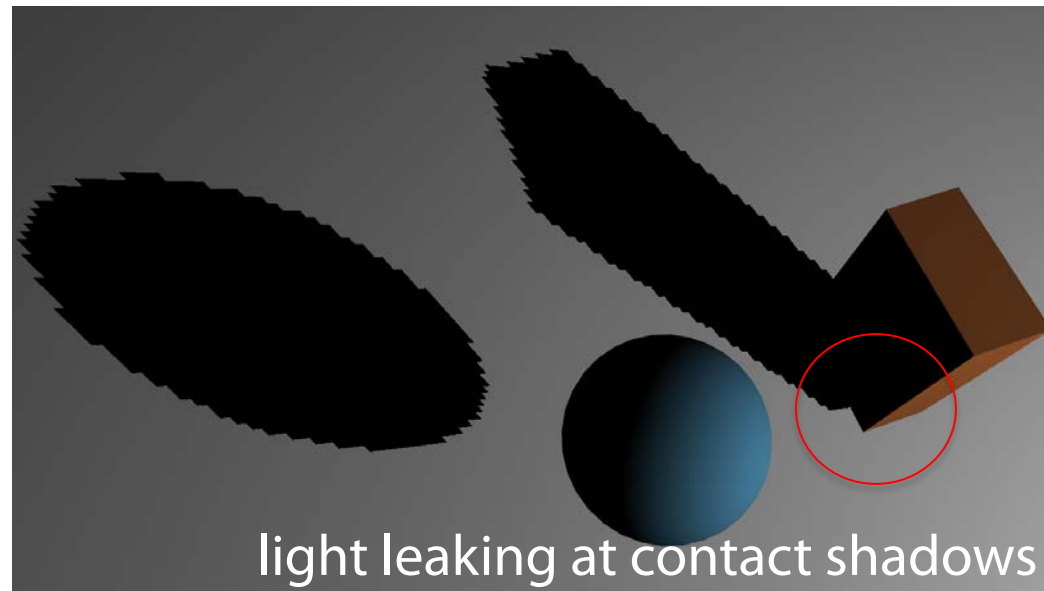
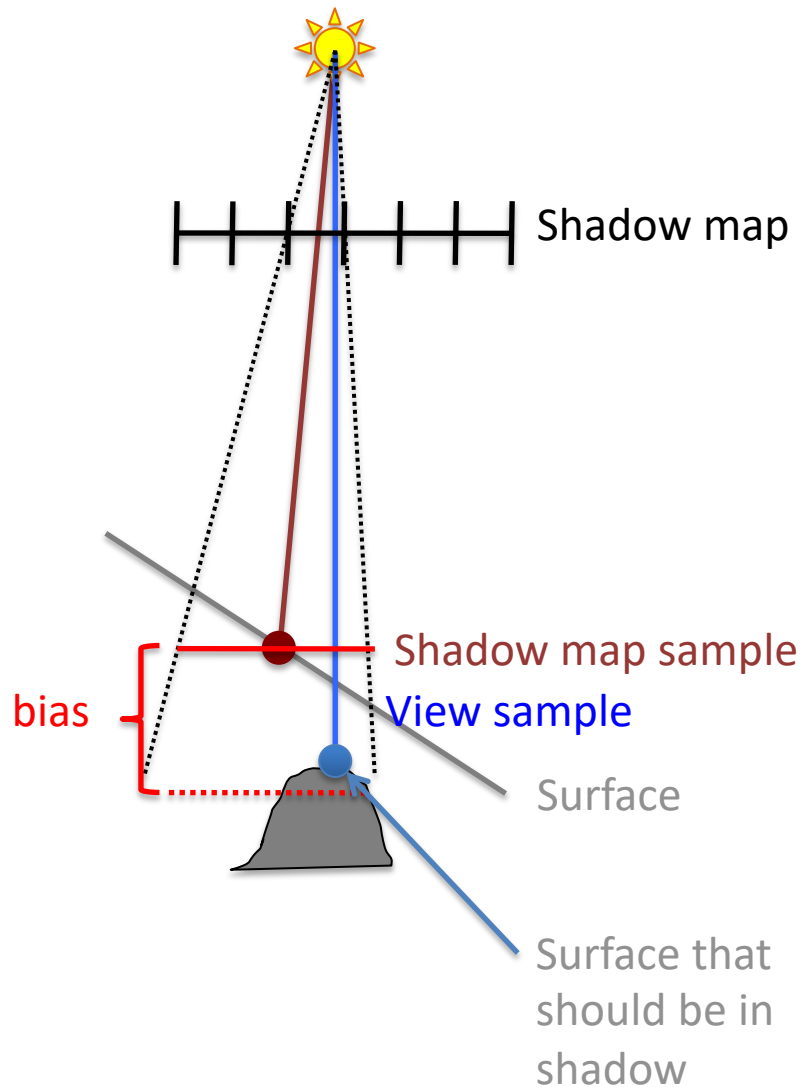
Bias

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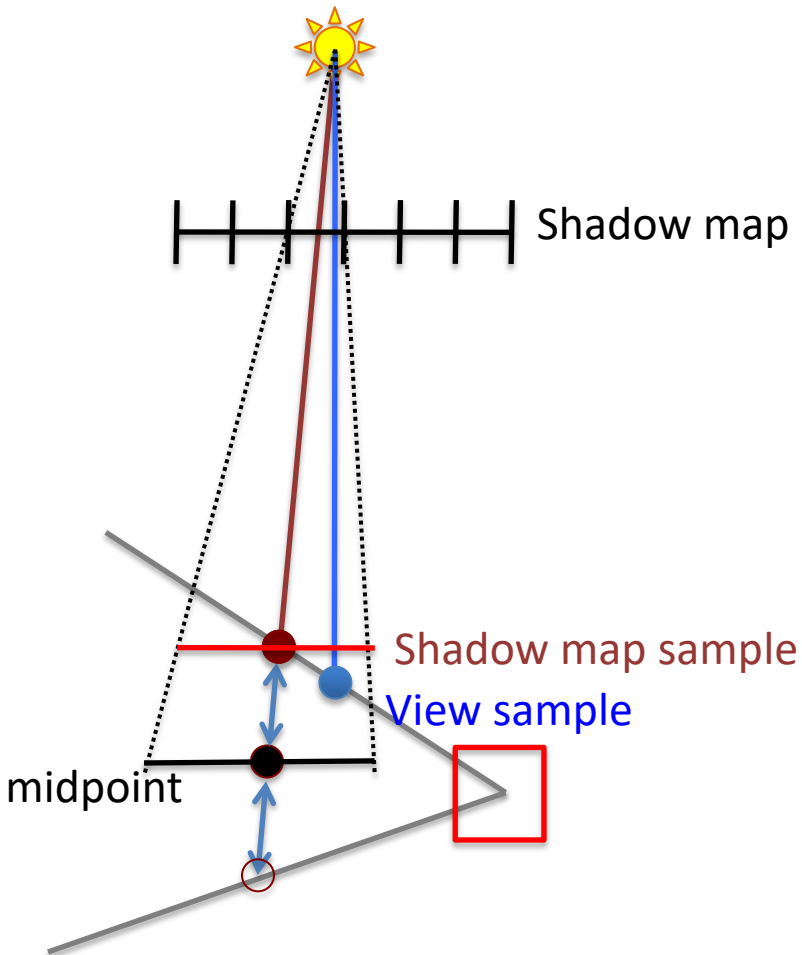


Bias

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Ameliorating the Bias

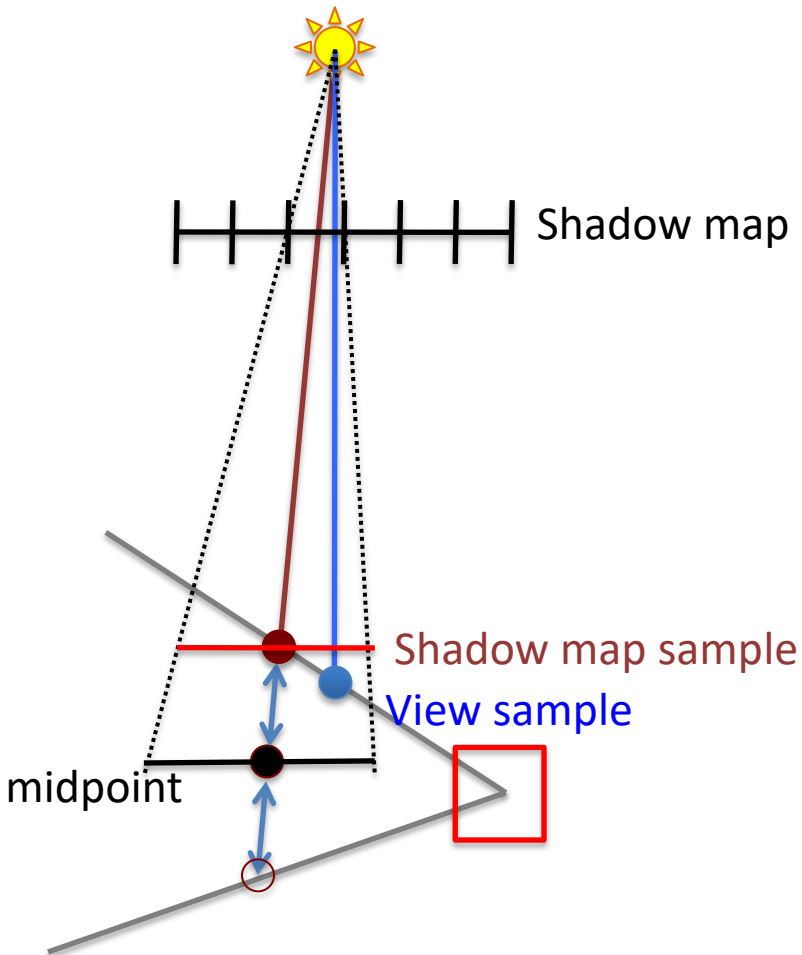


- Midpoint Shadow Maps [Woo 92]

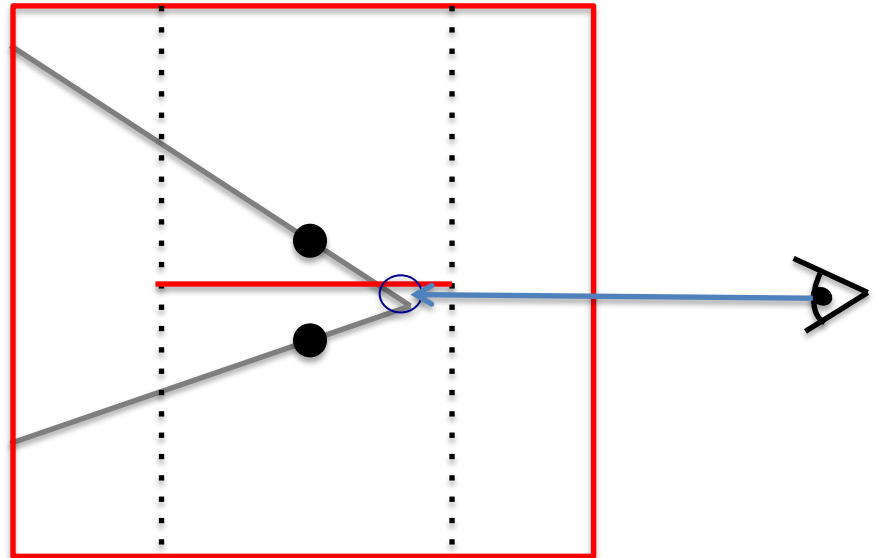
Further methods:

- Second Depth Shadow Mapping [Wang and Molnar94]
- Dual Depth Layer [Weiskopf and Ertl 04]
- Neither solves the problem completely but both improve a lot!
- Needs depth peeling of 1st & 2nd layer.

Ameliorating the Bias



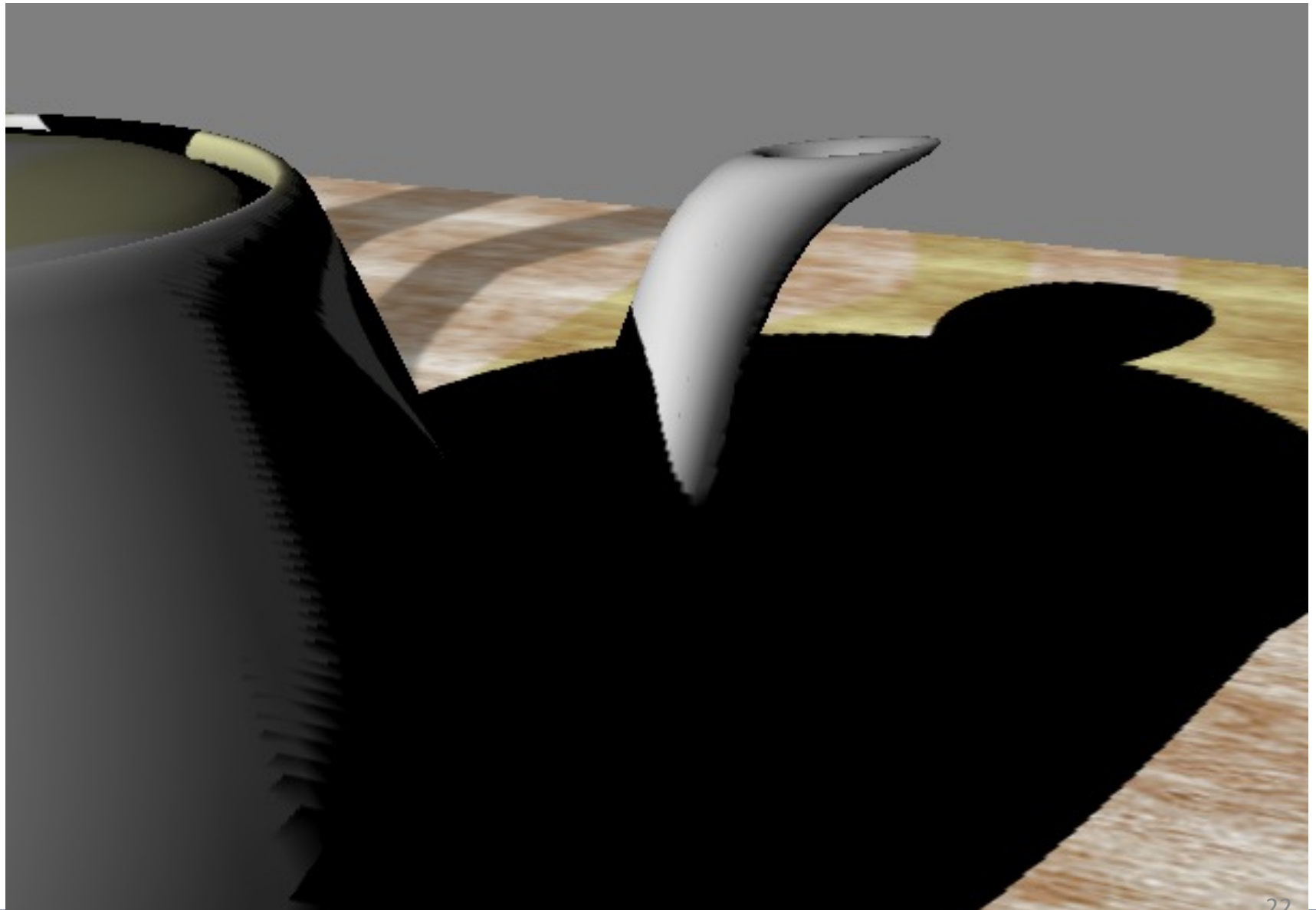
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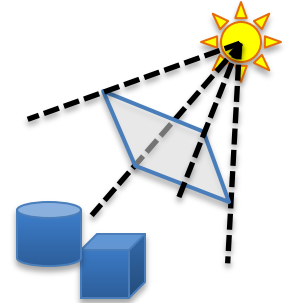
Further methods:

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Shadow Maps

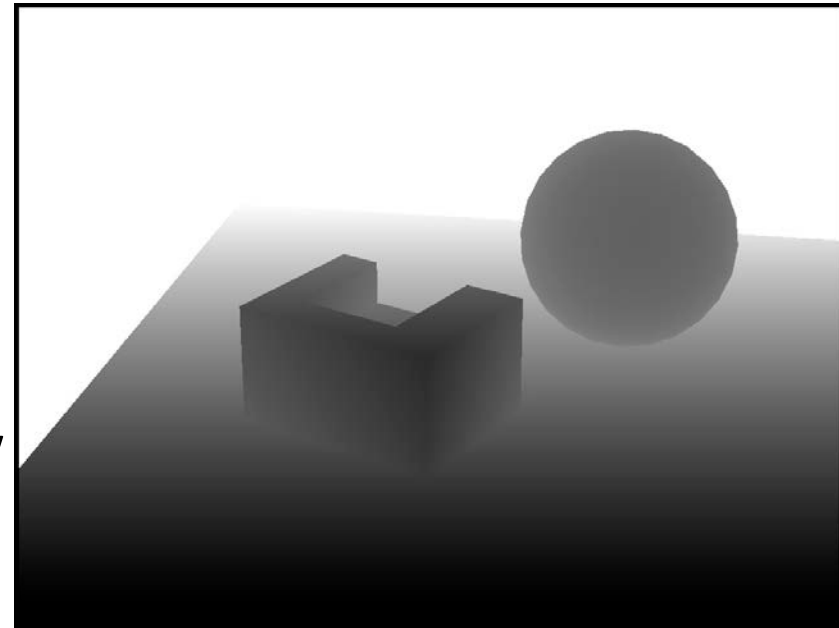


Shadow Maps - Summary



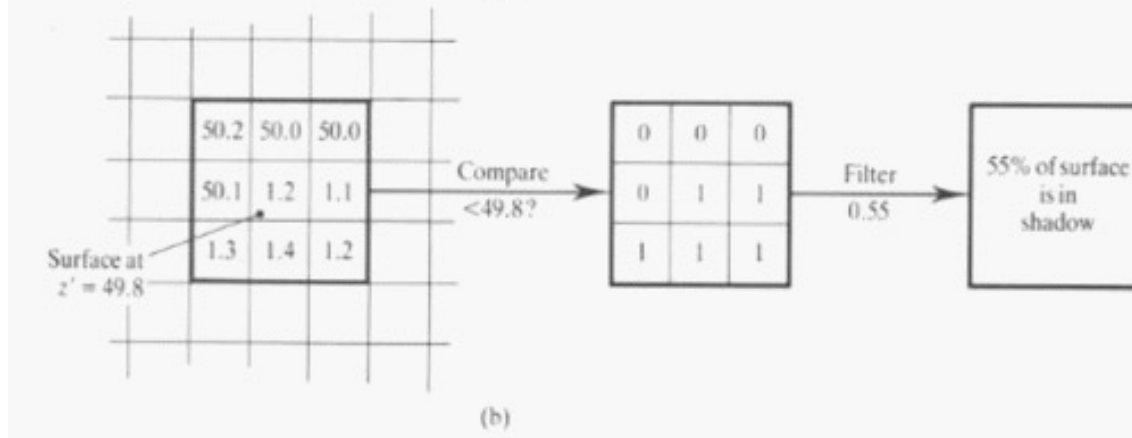
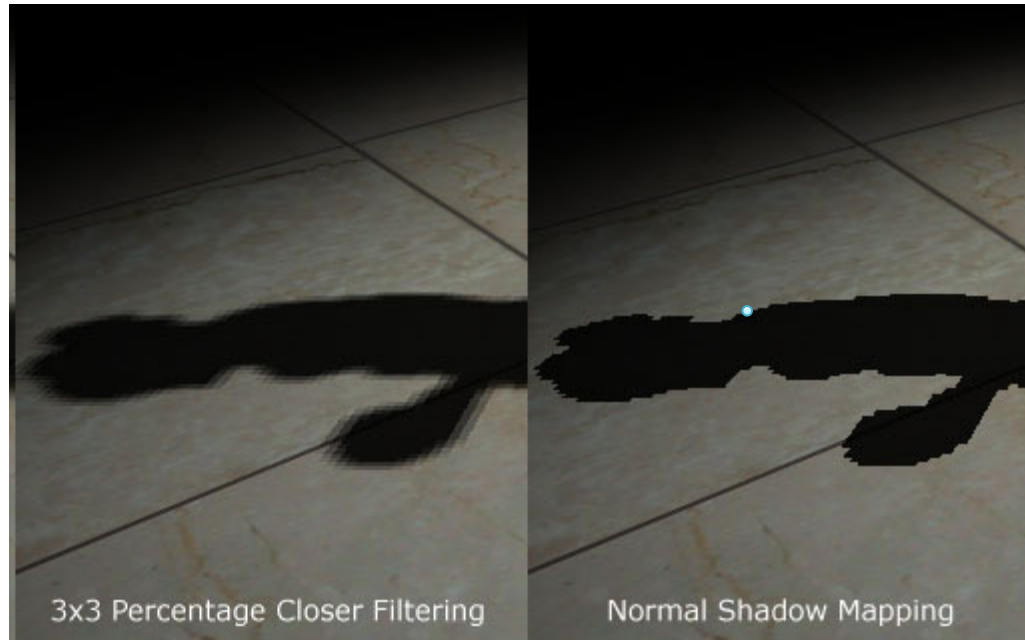
Shadow Map Algorithm:

- Render a z-buffer from the light source
 - Represents geometry in light
- Render from camera
 - For every fragment:
 - transform its 3D-pos into shadow map (light space)
 - If depth greater-> point in shadow
 - Else -> point in light
 - Use a bias at the comparison



Shadow Map (=depth buffer)

Percentage Closer Filtering



Cascaded Shadow Maps

- You need high SM resolution close to the camera and can use lower further away. So create a separate SMs per depth region of the view frustum, with higher spatial resolution closer to camera.

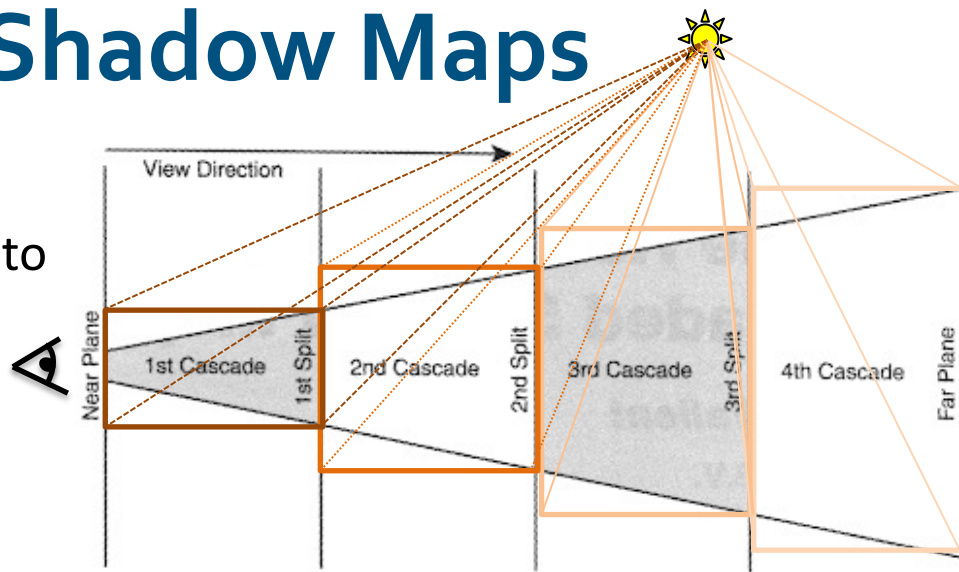
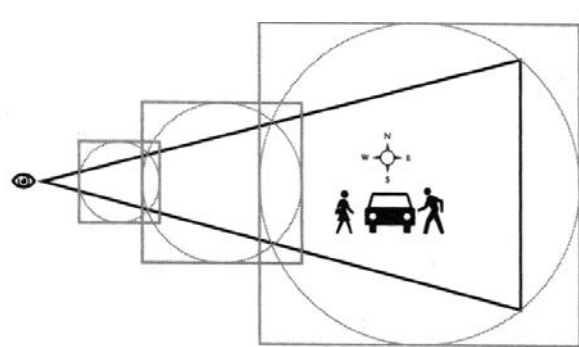
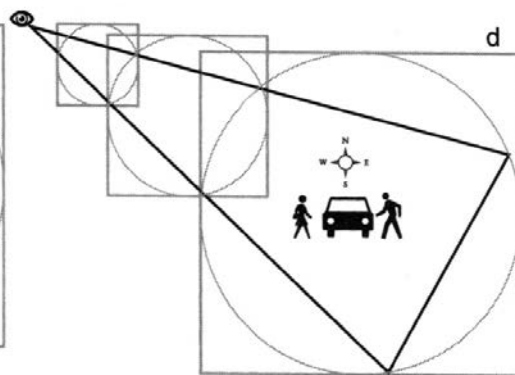


FIGURE 4.1.1 2D visualization of view frustum split (uniformly) into separate cascade frustums.

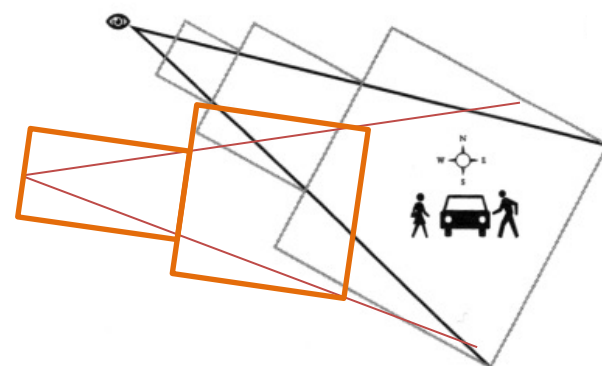
- Optionally:



To hide discrete resolution changes, let SMs overlap a bit and blend result from both at overlap.



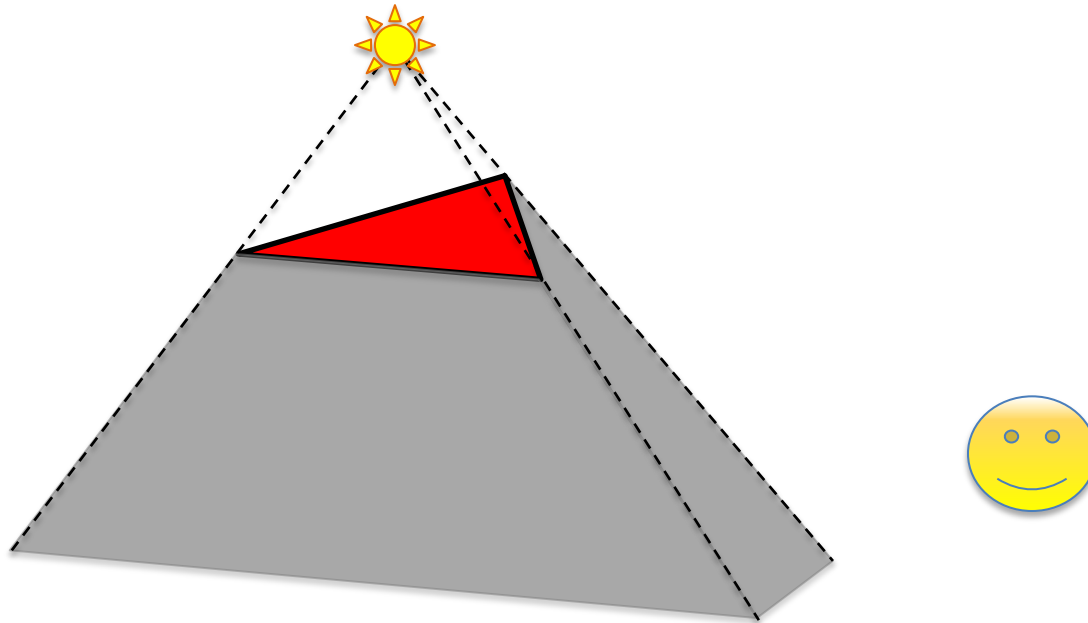
Aligned SMs allow reuse between frames for small cam movements...



... as opposed to non-aligned SM (if the scene is static).

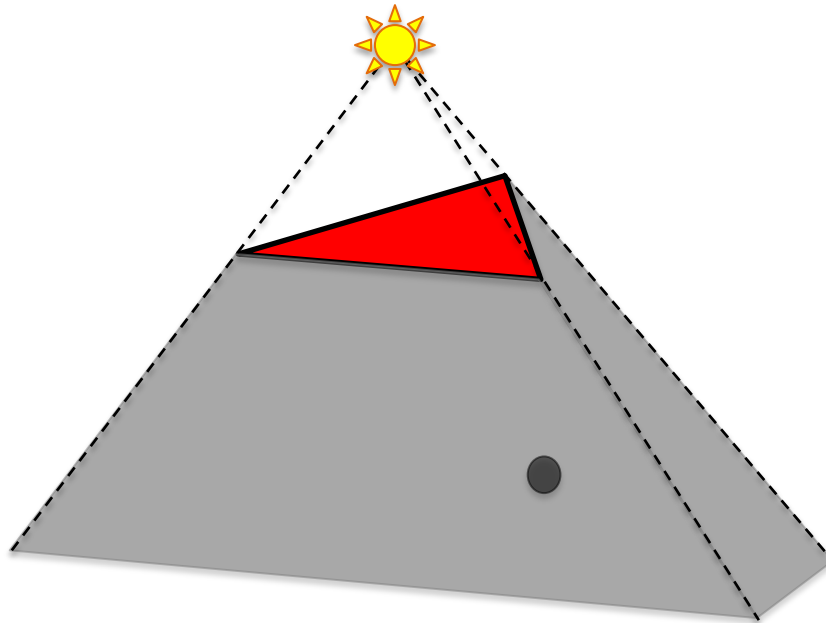
Shadow Volumes

- Concept
 - Create volumes of “space in shadow” from each triangle
 - Each triangle creates 3 quads that extends to infinity



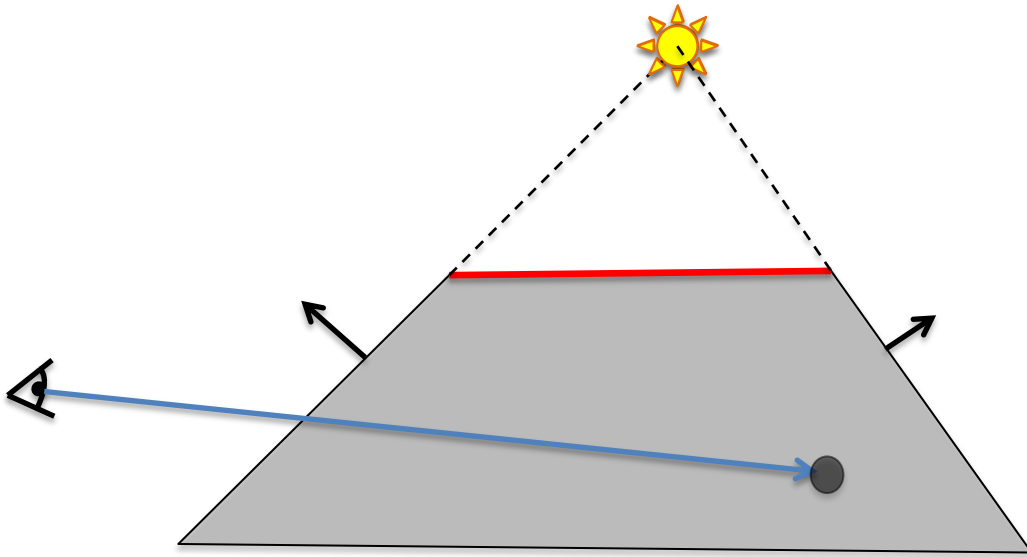
Shadow Volumes

- To test a point, count how many shadow volumes it is located within. One or more means the point is in shadow



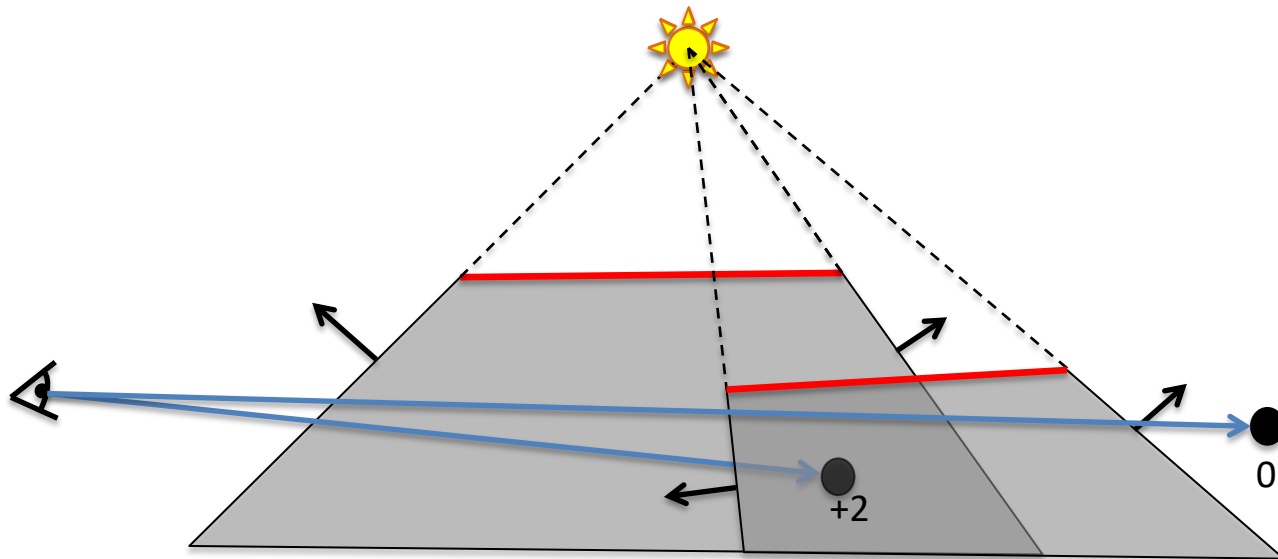
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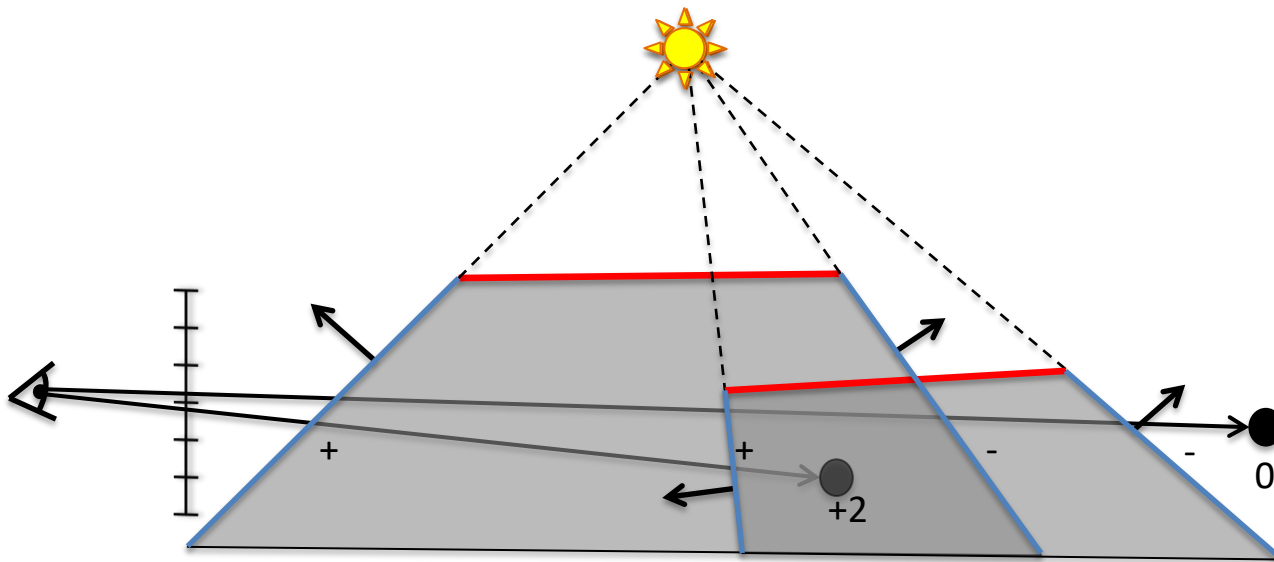
Shadow Volumes

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Shadow Volumes - concept

- A counter per pixel
- If we go through more frontfacing than backfacing polygons, then the point is in shadow



Shadow volume algorithm uses stencil buffer

- Stencil what?
- Is just another buffer (often 8 bits per pixel)
- When rendering to it, we can add, subtract, etc
- Then, the resulting image can be used to mask off subsequent rendering

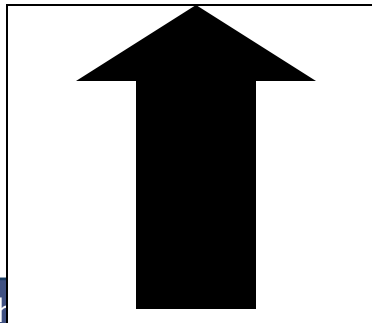
To create stencil values:

```
glStencilFunc(GL_ALWAYS, 0, ~0);  
glStencilOp(GL_KEEP, GL_KEEP, GL_INCR):
```

To use stencil buffer as mask:

```
glStencilFunc(GL_GREATER, 0, ~0);  
glStencilOp(GL_KEEP, GL_KEEP, GL_KEEP):
```

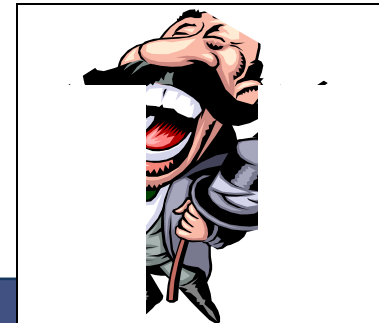
Stencil
Buffer
Mask



Rendered
image

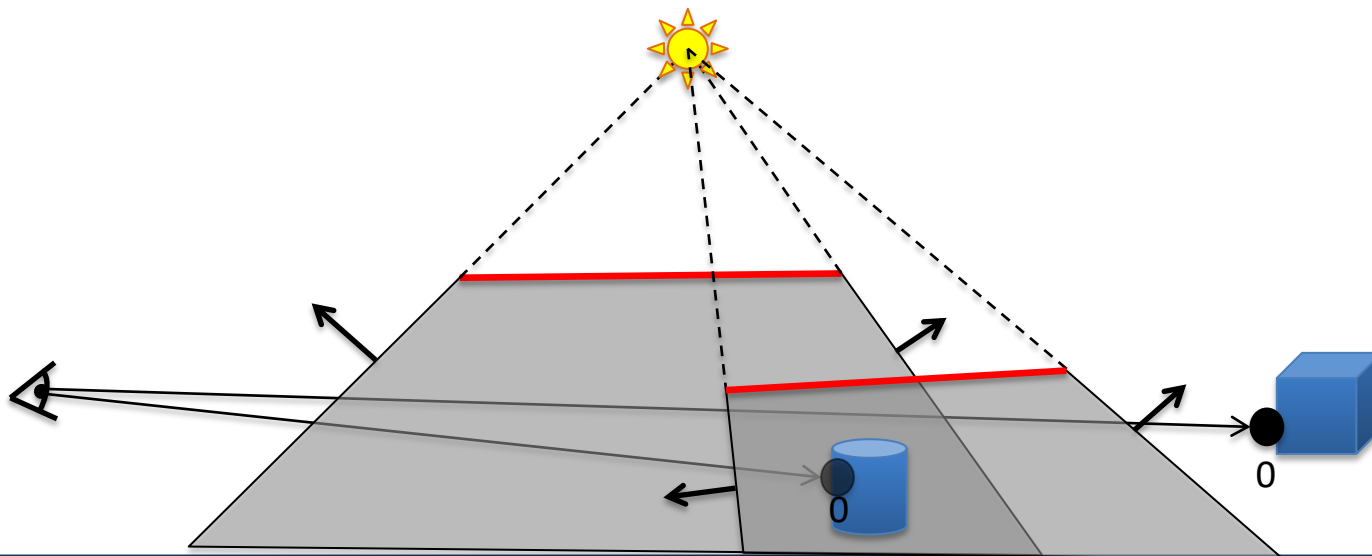


result



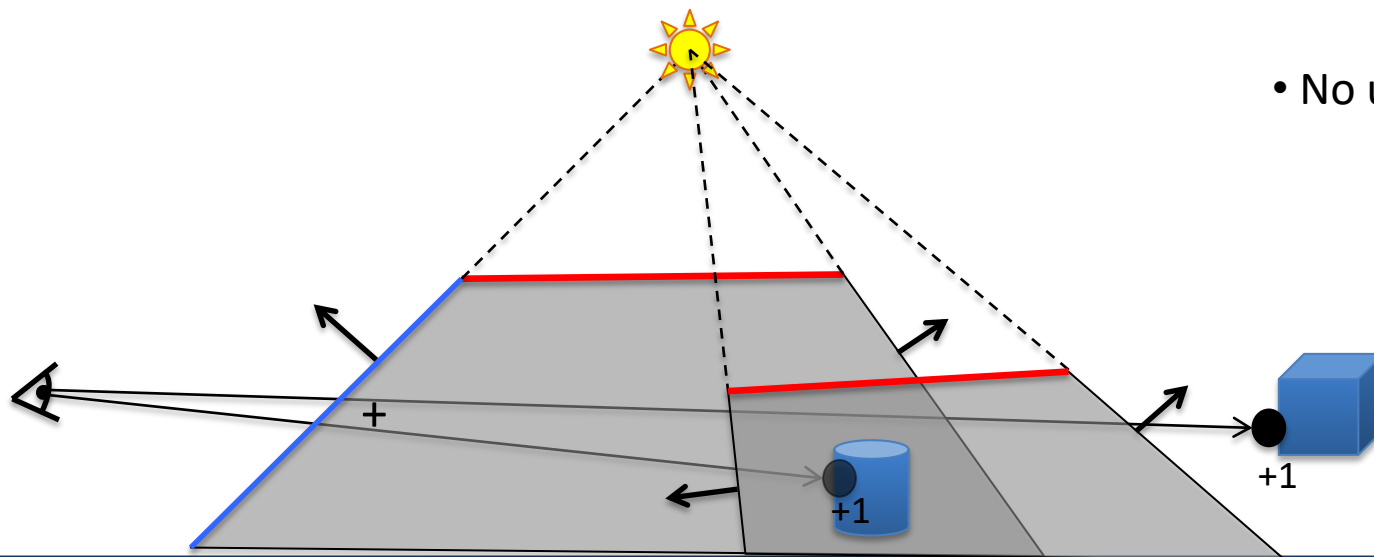
Shadow Volumes - concept

- Perform counting with the stencil buffer
 - Render front facing shadow quads to the stencil buffer
 - Inc stencil value, since those represents entering shadow volume
 - Render back facing shadow quads to the stencil buffer
 - Dec stencil value, since those represents exiting shadow volume



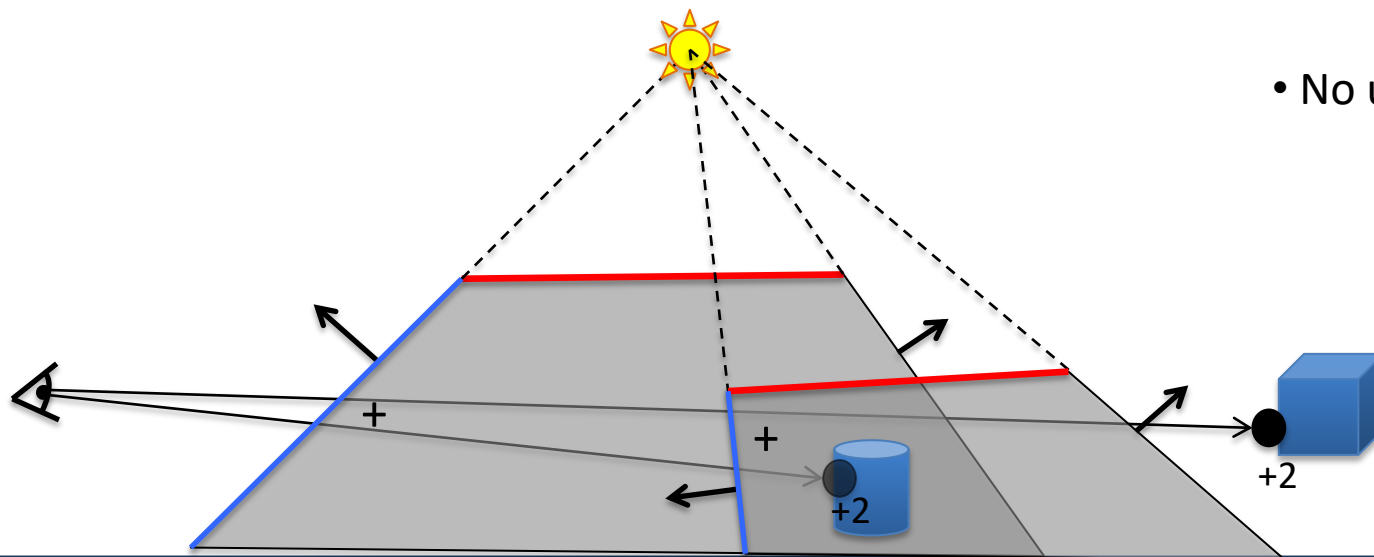
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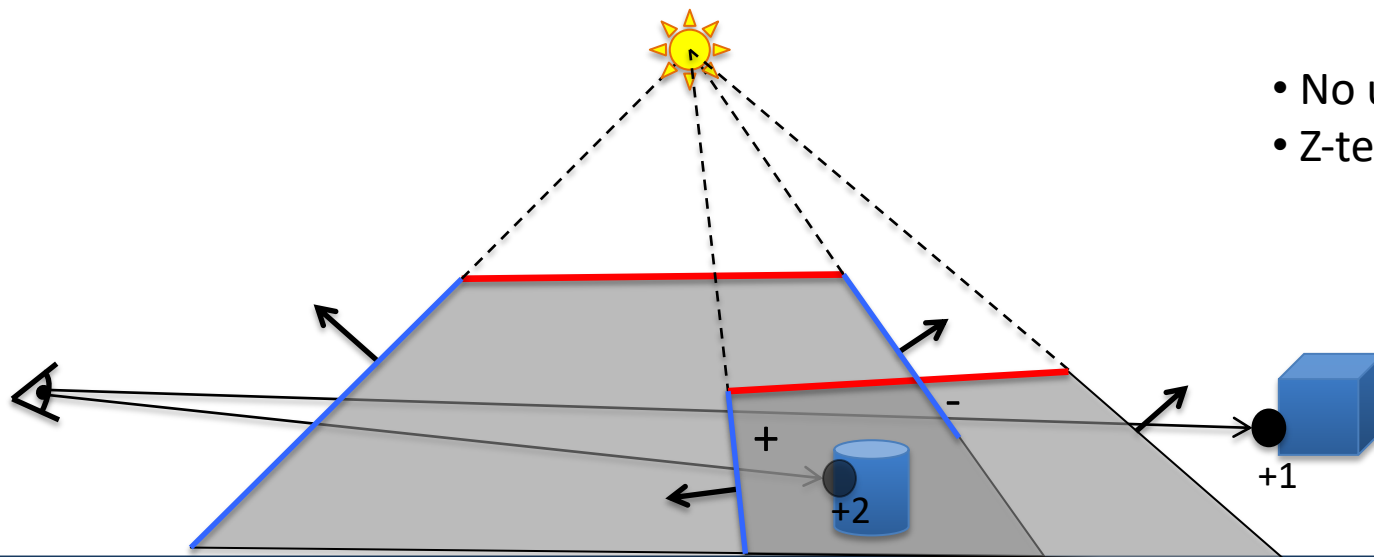
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- No updating of z-buffer

Shadow Volumes - concept

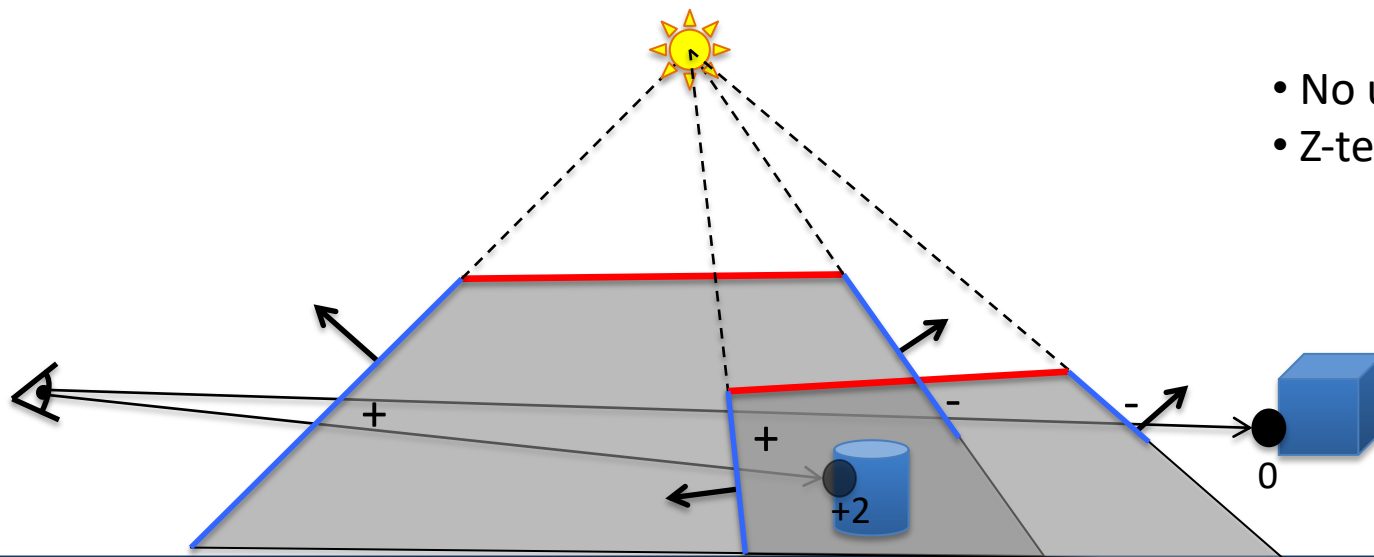
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- No updating of z-buffer
- Z-test is enabled as usual

Shadow Volumes - concept

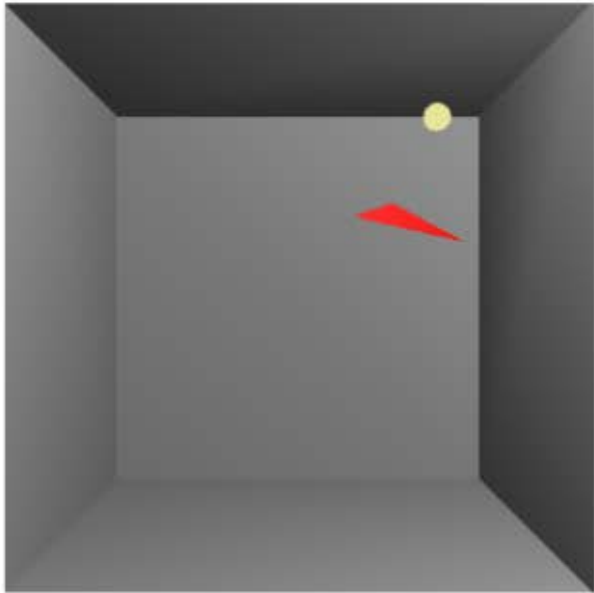
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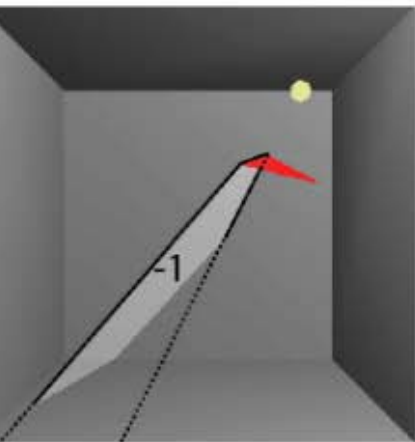
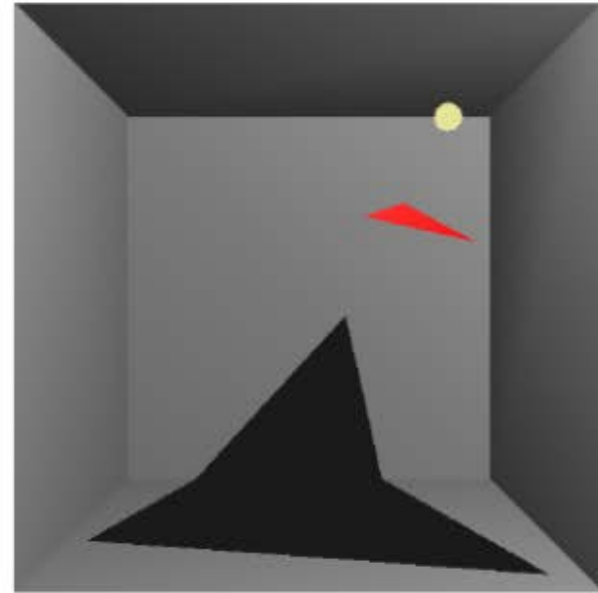
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Z-pass by example: how the stencil buffer is used

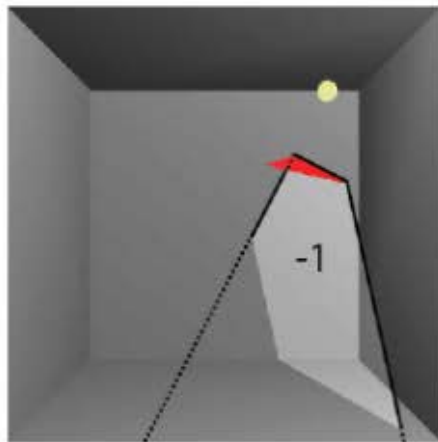
What we have...



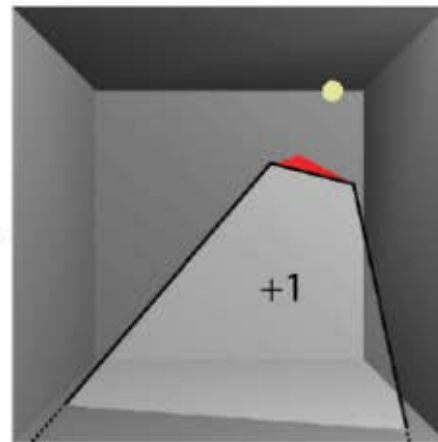
What we want...



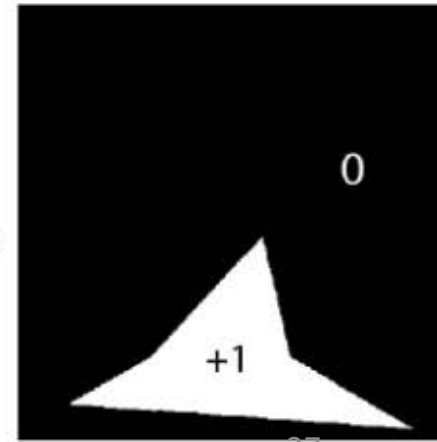
+



+



=

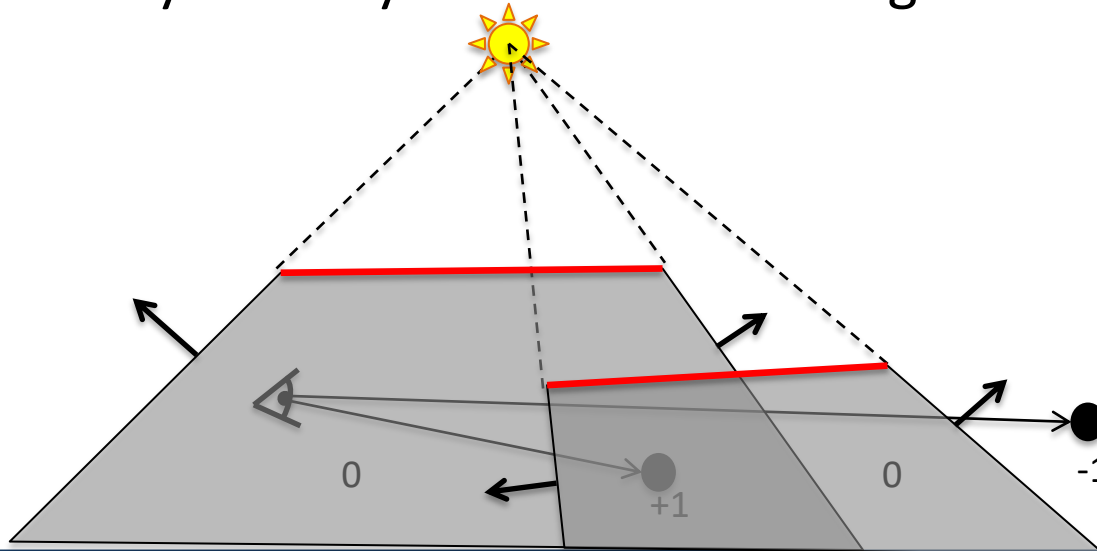


Shadow Volumes with the Stencil Buffer

- A three pass process:
 - **1st pass:** Render *ambient* lighting
 - **2nd pass:**
 - Draw to stencil buffer only
 - Turn off updating of z-buffer and writing to color buffer but still use standard depth test
 - Set stencil operation to
 - » *incrementing* stencil buffer count for *frontfacing* shadow volume quads, and
 - » *decrementing* stencil buffer count for *backfacing* shadow volume quads
 - use **glStencilOpSeparate(...)**
 - **3rd pass:** Render *diffuse and specular* where stencil buffer is 0.

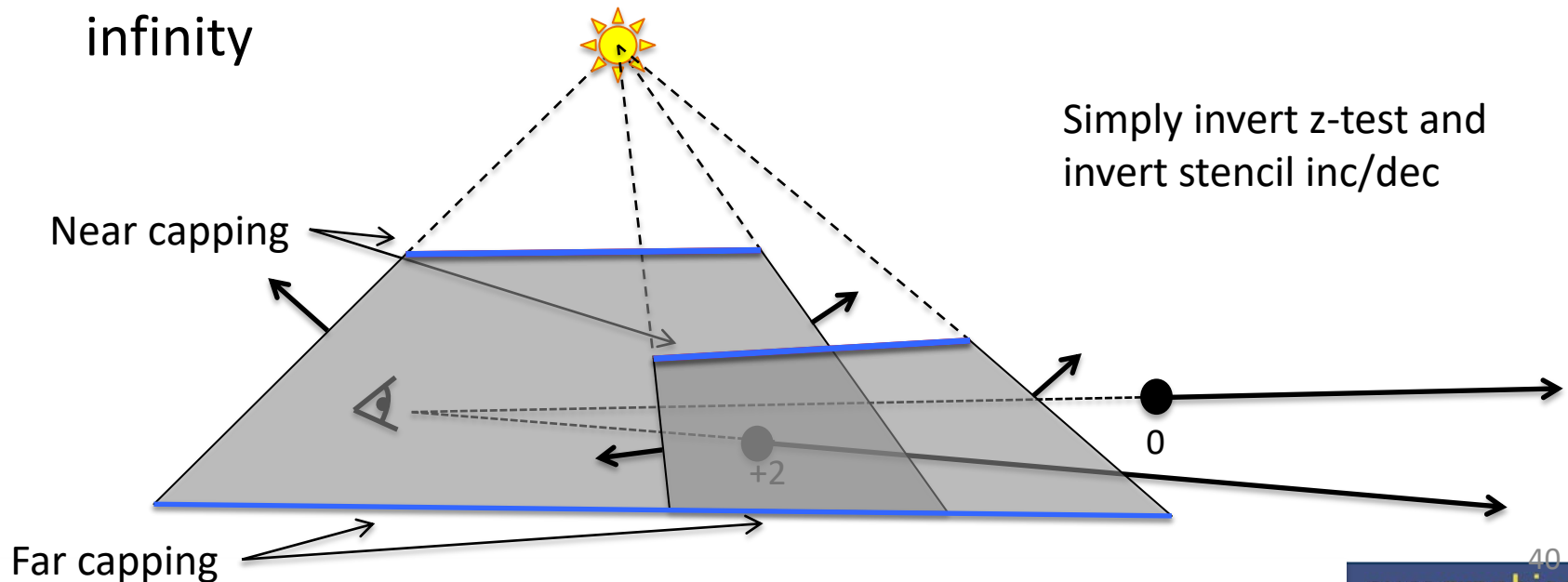
Eye Location Problem

- If the eye is located inside one or more shadow volumes, then the count will be wrong
- Solution:
 - Offset stencil buffer with the #shadow volumes that the eye is located within
 - Or modify the way we do the counting...

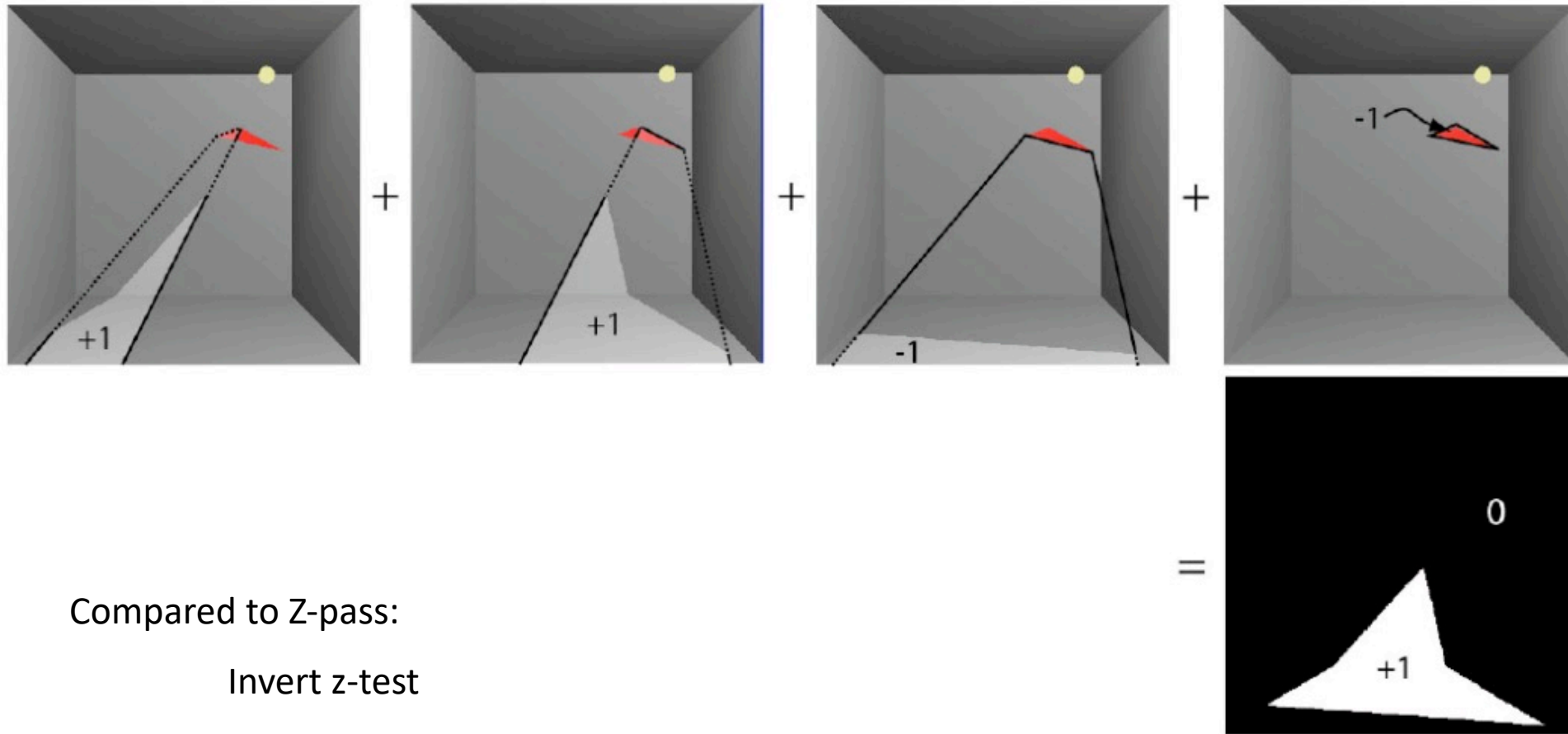


The Z-fail Algorithm

- By [Carmack00] and [Bilodeau and Songy 99]
 - “Carmacks Reverse”
- Count to infinity instead of to the eye
 - We can choose any reference location for the counting
 - A point in light avoids any offset
 - Infinity is always in light – if we cap the shadow volumes at infinity



Z-fail by example



Compared to Z-pass:

Invert z-test

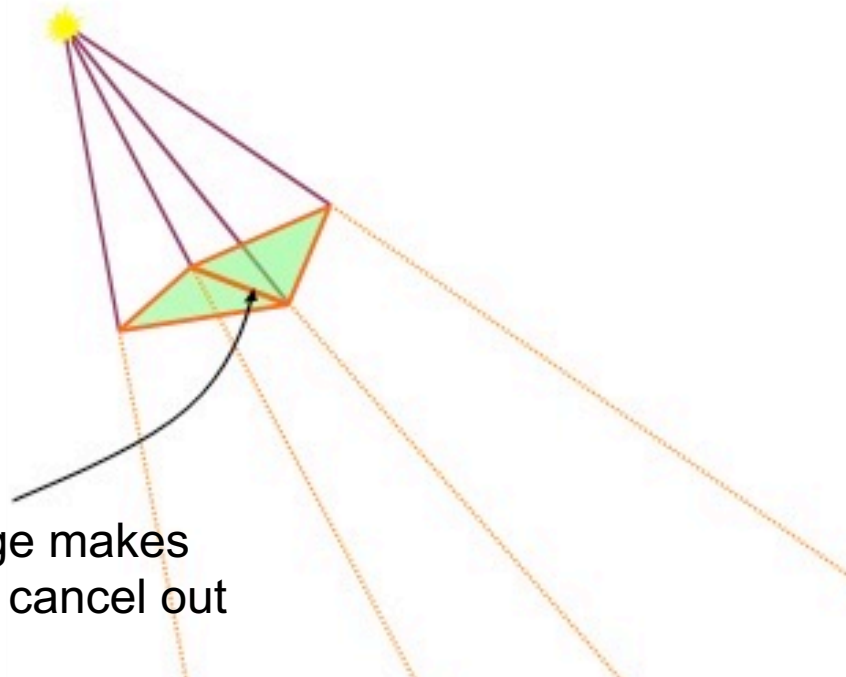
Invert stencil inc/dec

I.e., count to infinity instead of from eye.

Shadow Volumes from Silhouette Edges

Merging shadow volumes:

- An interior edge (non-silhouette edge as seen from the light position) creates two shadow quads that cancel each other out:

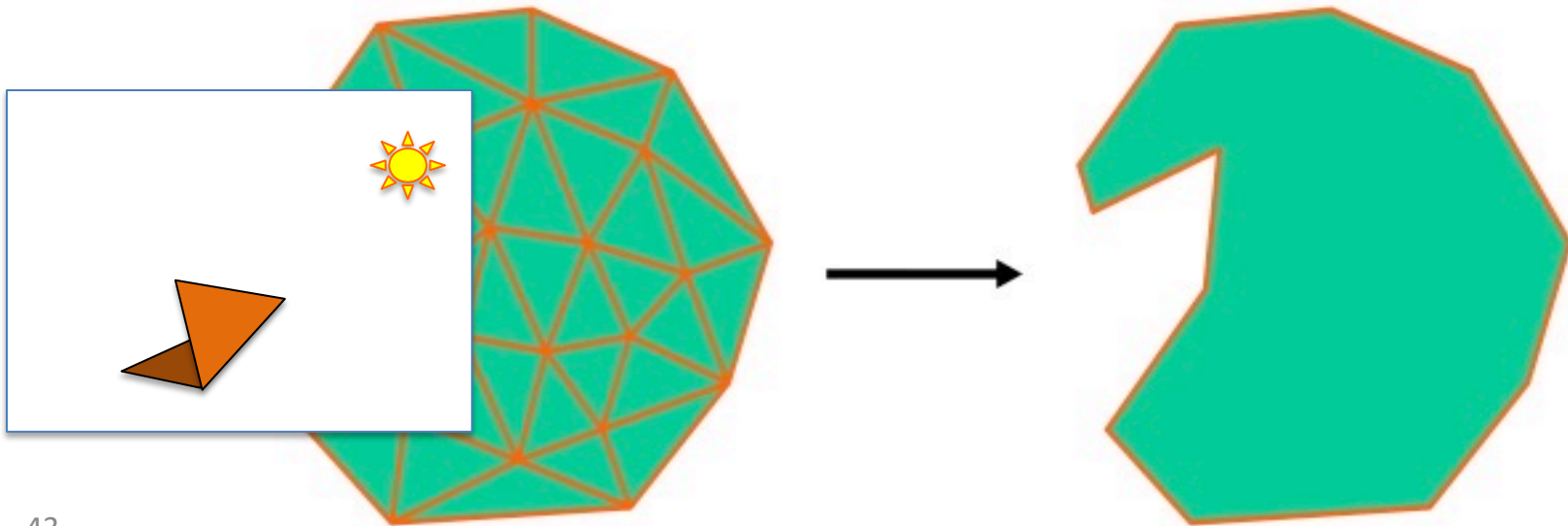


This interior edge makes
two quads, which cancel out

Shadow Volumes from Silhouette Edges

Merging shadow volumes:

- An interior edge (non-silhouette edge as seen from the light position) creates two shadow quads that cancel out each other:
- Thus, popular to create a shadow quad only per silhouette edge as seen from the light source.
 - (Slightly more care needed for non-closed objects...)
 - Avoids rendering of many useless shadow quads



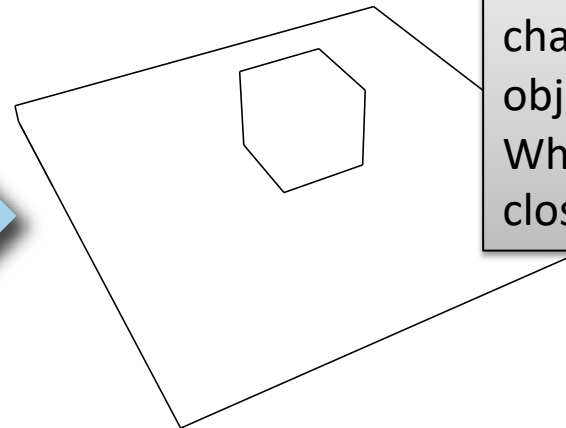
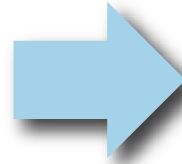
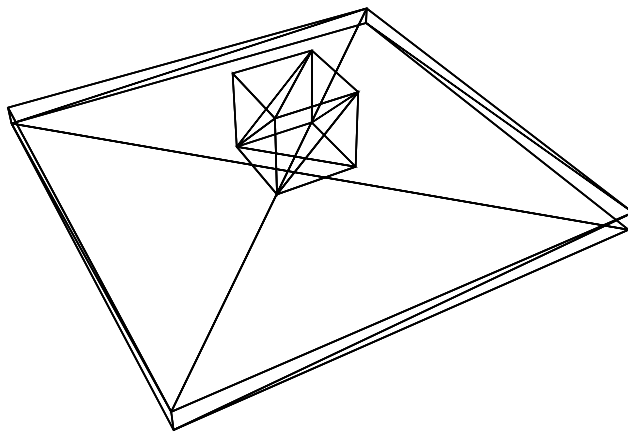
Example of silhouettes from light position



Shadow Volumes from Silhouette Edges

Merging shadow volumes:

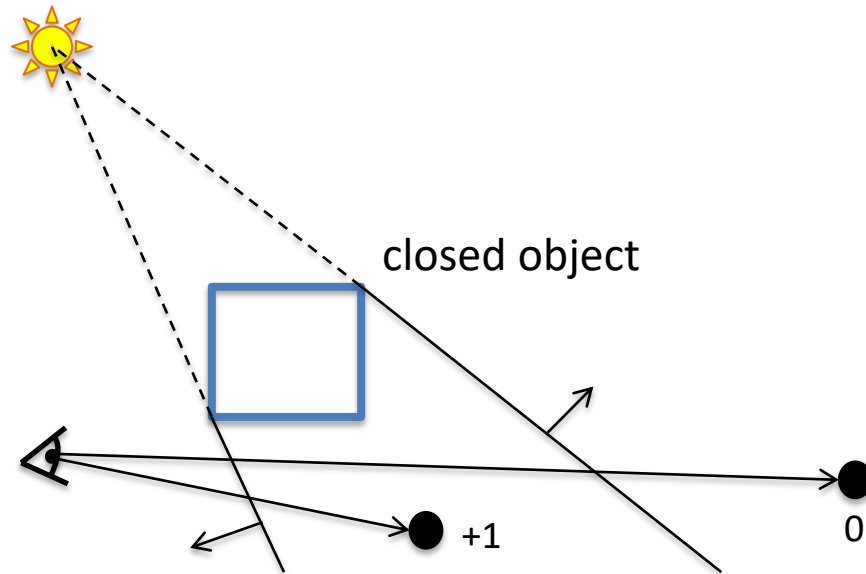
- An interior edge (non-silhouette edge as seen from the light position) creates two shadow quads that cancel out each other:
- Thus, popular to create a shadow quad only per silhouette edge as seen from the light source.
 - (Slightly more care needed for non-closed objects...)
 - Avoids rendering of many useless shadow quads
 - A real example:



This works like a charm for closed objects.
What about non-closed objects?

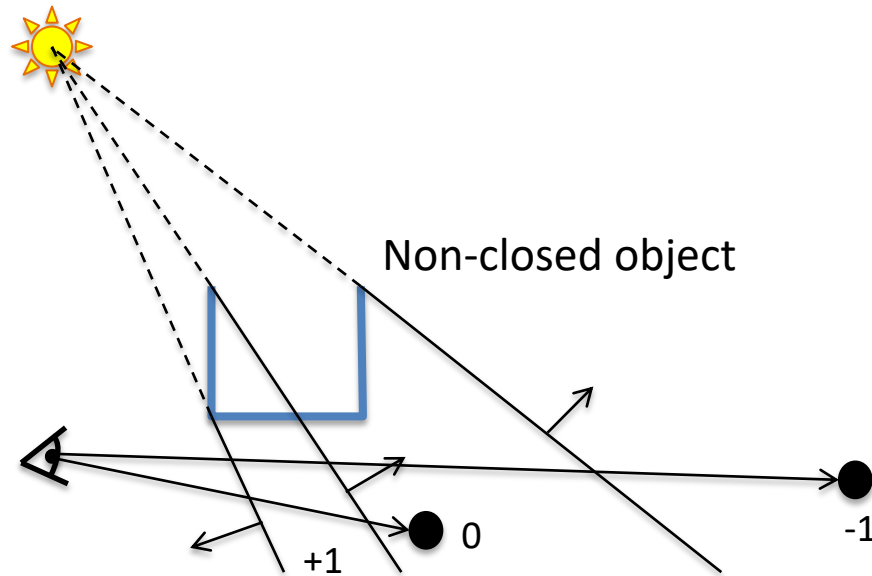
Shadow Volumes from Silhouette Edges

It is a misconception that objects **need** to be closed to remove non-silhouette edges.



Shadow Volumes from Silhouette Edges

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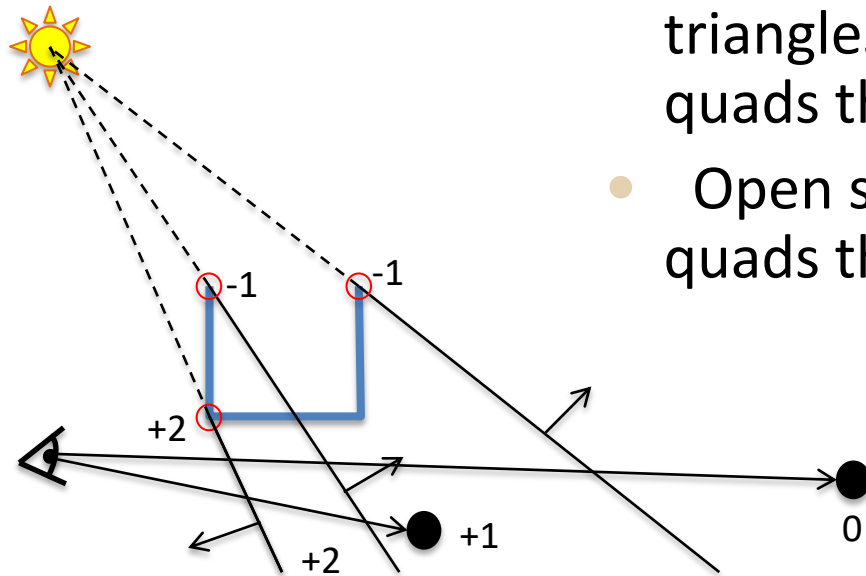
Shadow Volumes from Silhouette Edges

It is a misconception that objects **need** to be closed to remove non-silhouette edges.

Fixed by [Bergeron 86]

Observation:

- Silhouette edges with two adjacent triangles should actually create shadow quads that inc/dec count by 2
- Open silhouette edges create shadow quads that inc/dec count by one

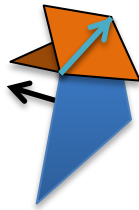


Stencil value >0
means shadow

Works identically
for Z-fail

Shadow Volumes from Silhouette Edges

For general objects with edges that can be shared by many triangles:



Preprocess (or in geometry shader):

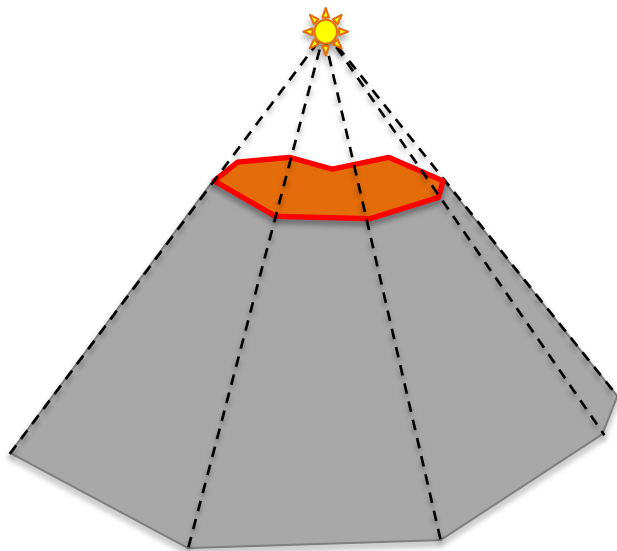
- For each triangle edge e in scene:
 - Choose edge e 's direction
 - Create e 's shadow volume quad
 - Let e have a counter $c_e = 0$
 - For each adjacent triangle, t :
 - Inc/dec c_e depending on if triangle t 's created shadow volume quad would have same/opposite facing of e 's quad.
 - Add quad $\{e, c_e\}$ to list L , if $c_e \neq 0$.

At rendering:

- Render all quads in L , and inc/dec stencil by the quad's c_e depending on if quad is front/back-facing eye.
- For 100% robustness, see our *book Real-Time Shadows*

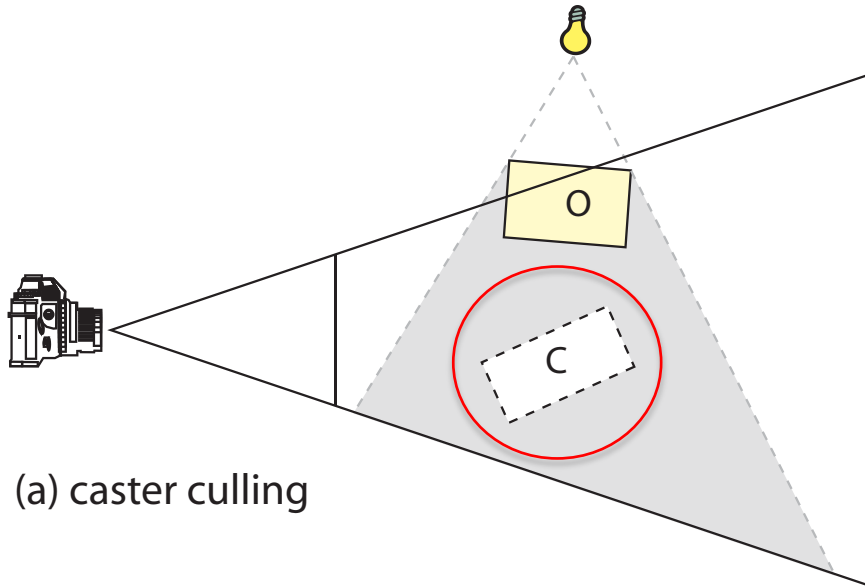
Shadow Volumes - Summary

- Pros:
 - High quality
- Cons:
 - OVERDRAW



Culling and Clamping

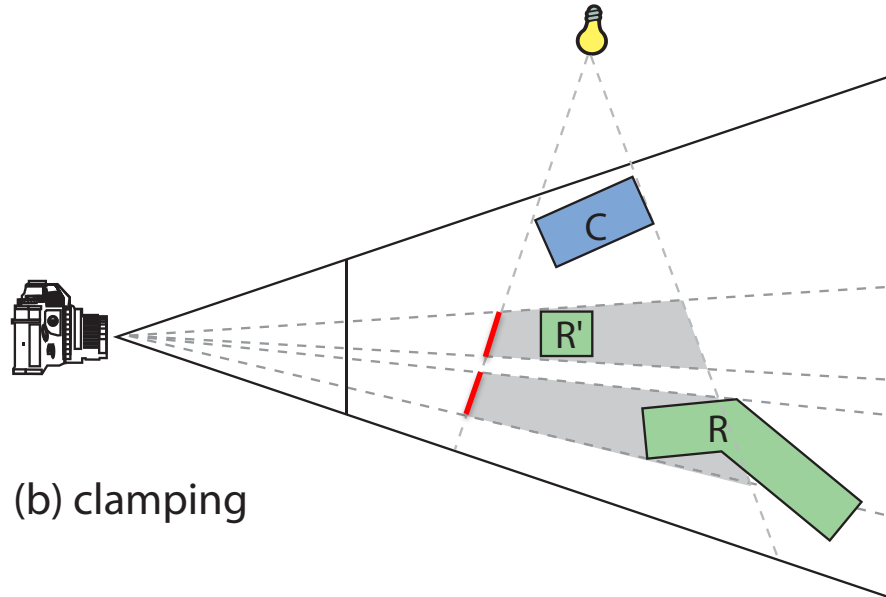
- **Culling of Shadow Volumes** [Lloyd et al. 2004][Stich et al. 2007]
 - **Culling of Shadow Casters** if it is located totally within shadow
 - Tested against a shadow depth map



(a) caster culling

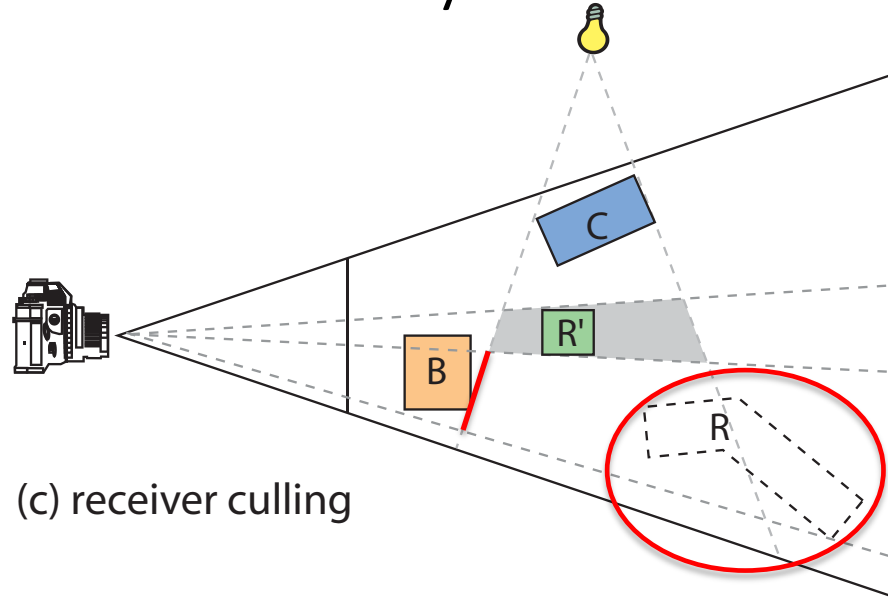
Culling and Clamping

- **Clamping of Shadow Volumes** [Lloyd et al. 2004][Eisemann and Decoret 2006]
 - Idea: Only render parts of shadow quads that affects a shadow receiver
 - Tested against AABB around shadow receivers



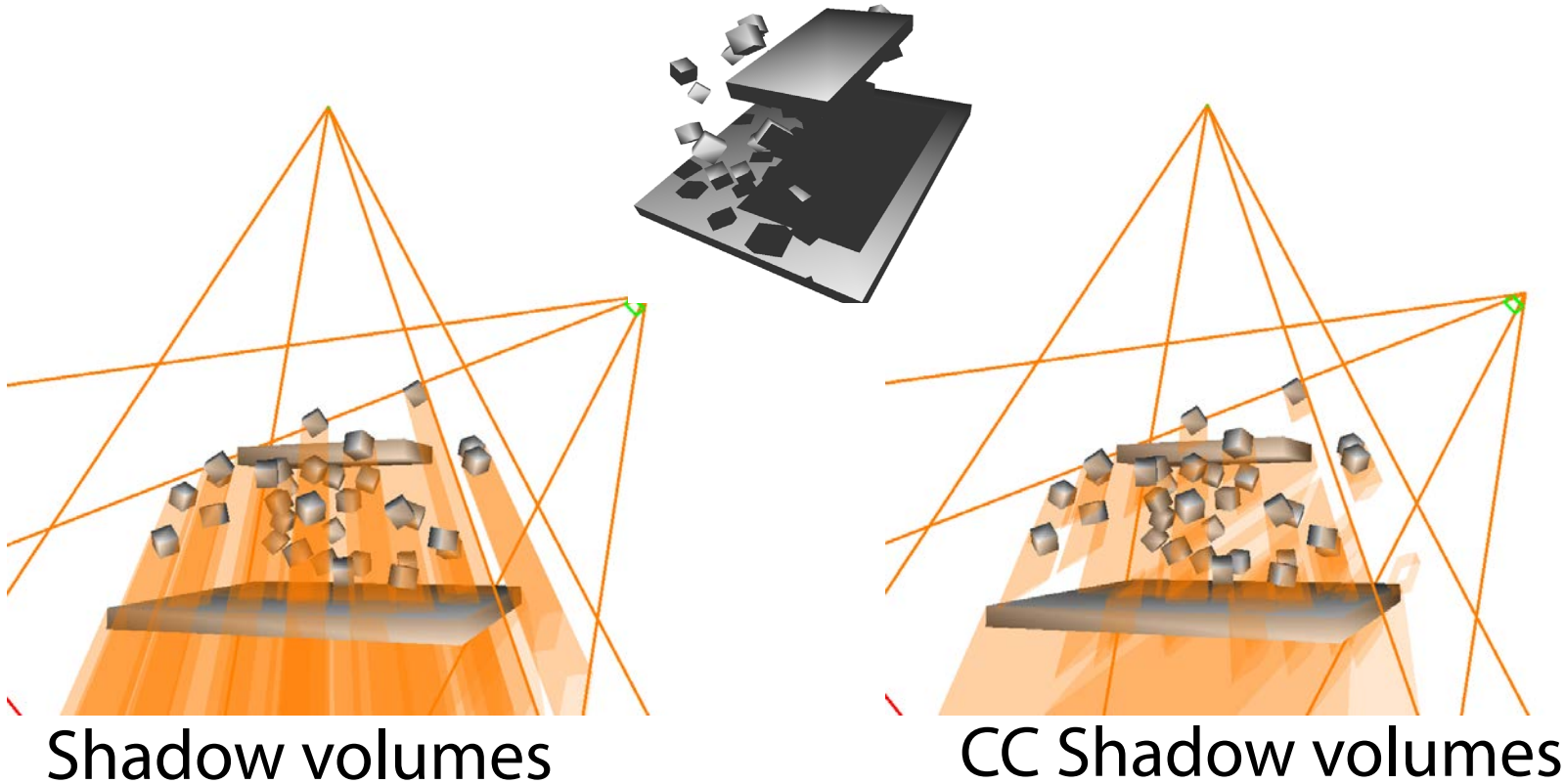
Culling and Clamping

- **Culling of Shadow Volumes** [Lloyd et al. 2004][Eisemann and Decoret 2006]
 - **Receiver Culling**
 - Idea: Cull part of shadow volumes where shadow receivers are not visible from the eye



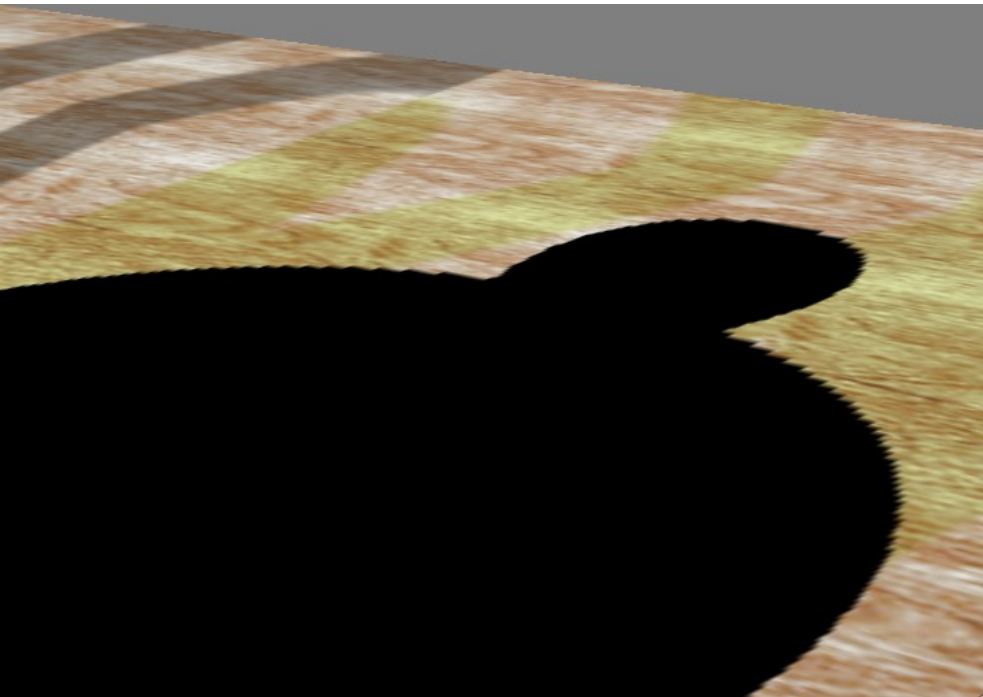
(c) receiver culling

Culling and Clamping



Illustrates reduced depth complexity when using
Culling and Clamping

Shadow Maps vs Shadow Volumes



Shadow Maps

- *Good:* Handles any rasterizable geometry, **constant cost** regardless of complexity, map can sometimes be reused. **Very fast.**
- *Bad:* Frustum limited. **Jagged shadows** if res too low, **biasing** headaches.
 - Solution:
 - 6 SM (cube map), high res., use filtering (huge topic)



Shadow Volumes

- *Good:* shadows are **sharp**. Handles omni-directional lights.
- *Bad:* **3 passes**, shadow polygons must be generated and rendered → lots of polygons & **fill**
 - Solution: culling & clamping (or per-triangle SV using hierarchical shadow buffer)

Shadow Maps vs Shadow Volumes

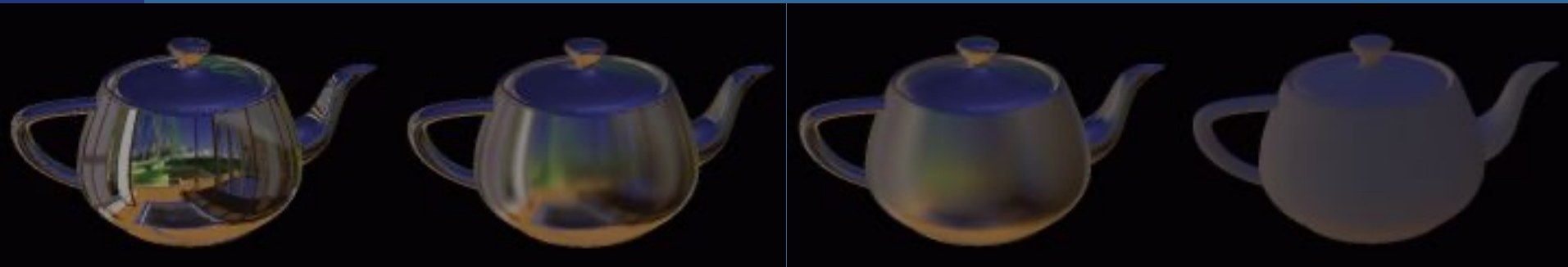
- Shadow volumes: popular in games up to ~2005, e.g.,
 - DOOM 3, 2004.
 - Far Cry (shadow volumes are used indoors, shadow maps - outdoors), 2004.
 - The Chronicles of Riddick: Escape from Butcher Bay. 2004.
 - Spiderman 3 (Activision), 2007.
- Shadow maps are more popular today due to speed and ease of filtering for soft-shadows.
 - E.g., DOOM (5) Eternal, 2020. 4096x8196px 24-bit shadow map.

Reflections

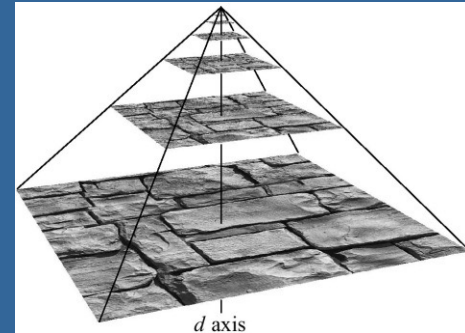


Misc

- Michael Ashikhmin and Abhijeet Ghosh.
Simple blurry reflections with environment maps. Journal of graphics tools, 7(4):3-8, 2002

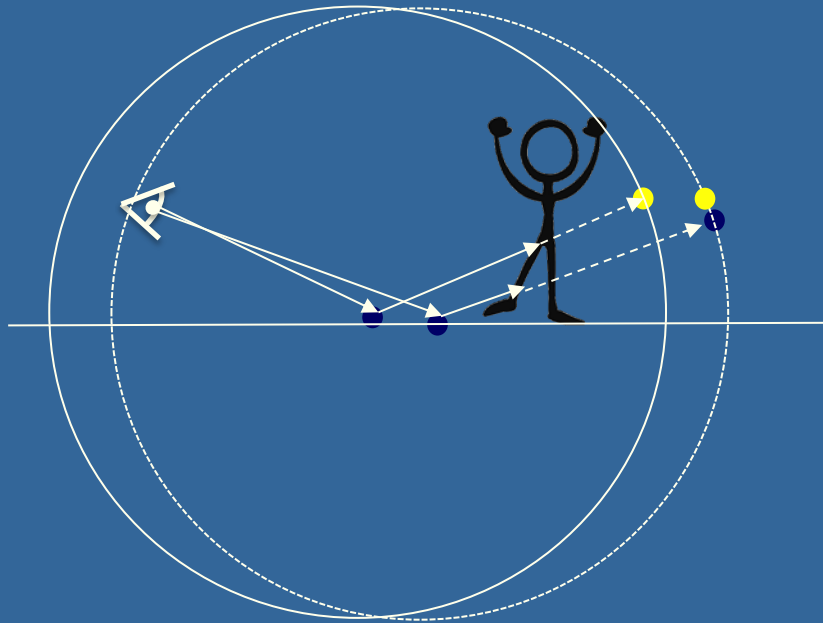


```
glTexParameterf(GL_TEXTURE_CUBE_MAP_ARB,  
GL_TEXTURE_MIN_LOD, lambda);
```



Planar reflections

- We've already done reflections in curved surfaces with environment mapping
- Environment maps does not work well for reflections in planar surfaces:



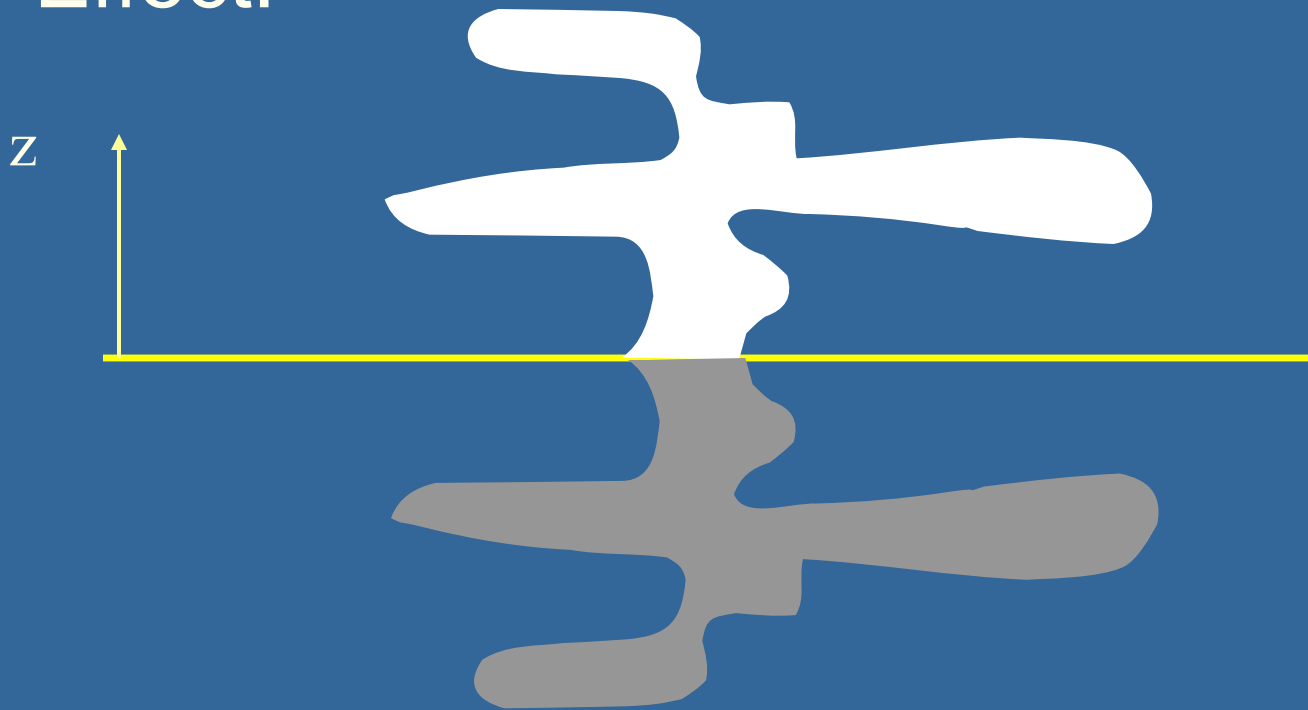
Standard
cube map

Parallax
corrected

- Parallax corrected cube maps fix this, but purely planar reflections are actually easy to get by reflecting the geometry or camera as we will now see...

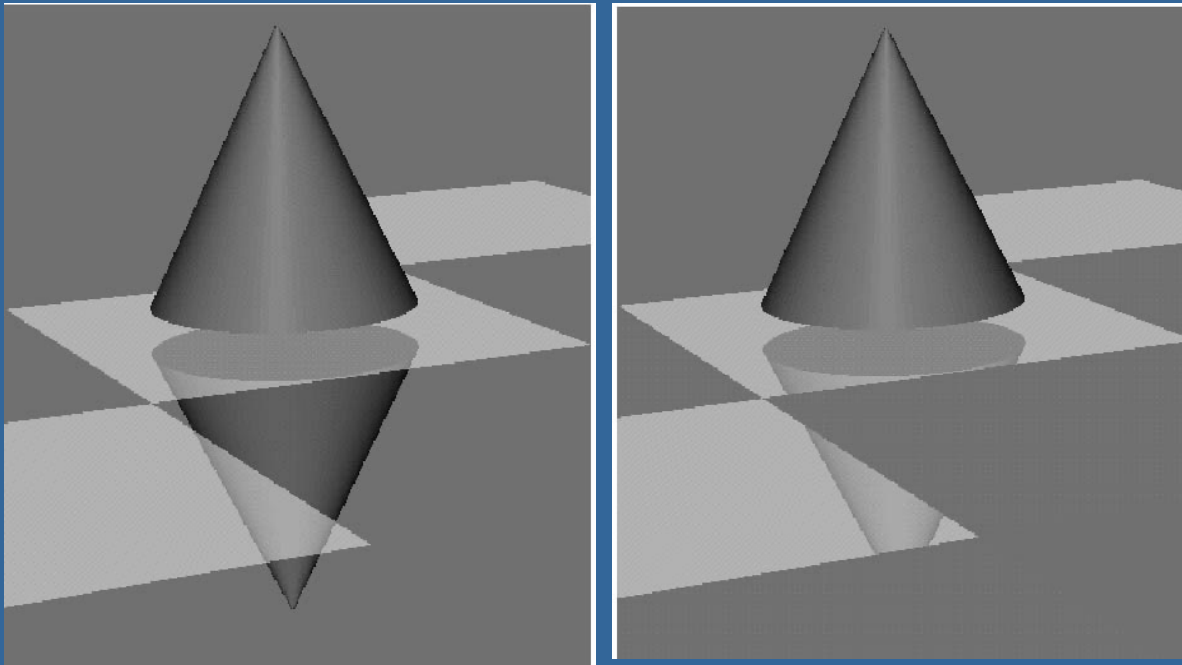
Planar reflections

- Assume plane is $z=0$
- Then apply a scaling matrix $S(1,1,-1)$;
- Effect:

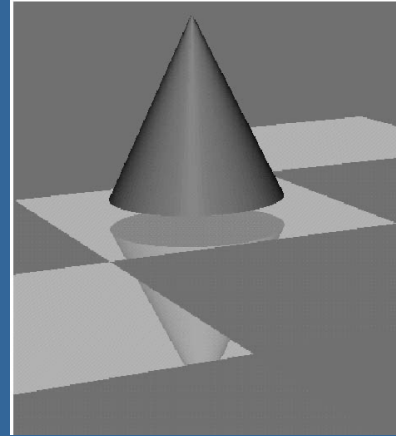


Planar reflections

- Backfacing becomes front facing!
- Lights should be reflected as well
- (May need to clip using stencil buffer)
- See example on clipping:



Planar reflections

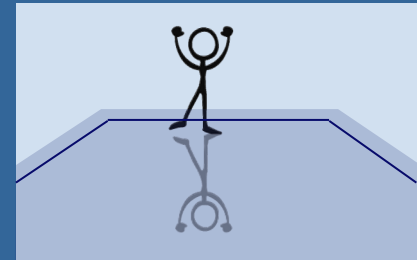
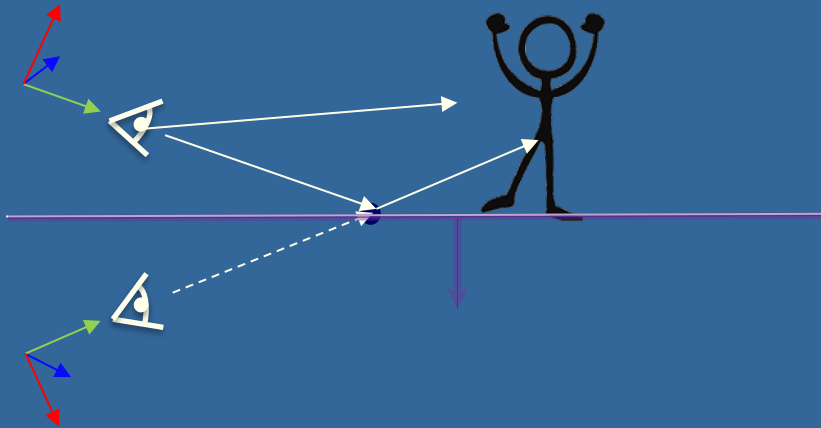


- How should you render?
- 1) the reflective ground plane polygons into the stencil buffer
- 2) the scaled $(1,1,-1)$ model, but mask with stencil buffer
 - Reflect light pos as well
 - Use front face culling
- 3) the ground plane (semi-transparent)
- 4) the unscaled model

Important:

- render scaled $(1,1,-1)$ model
- with reflected light pos.
- using front face culling

Or reflect camera position instead of the object:

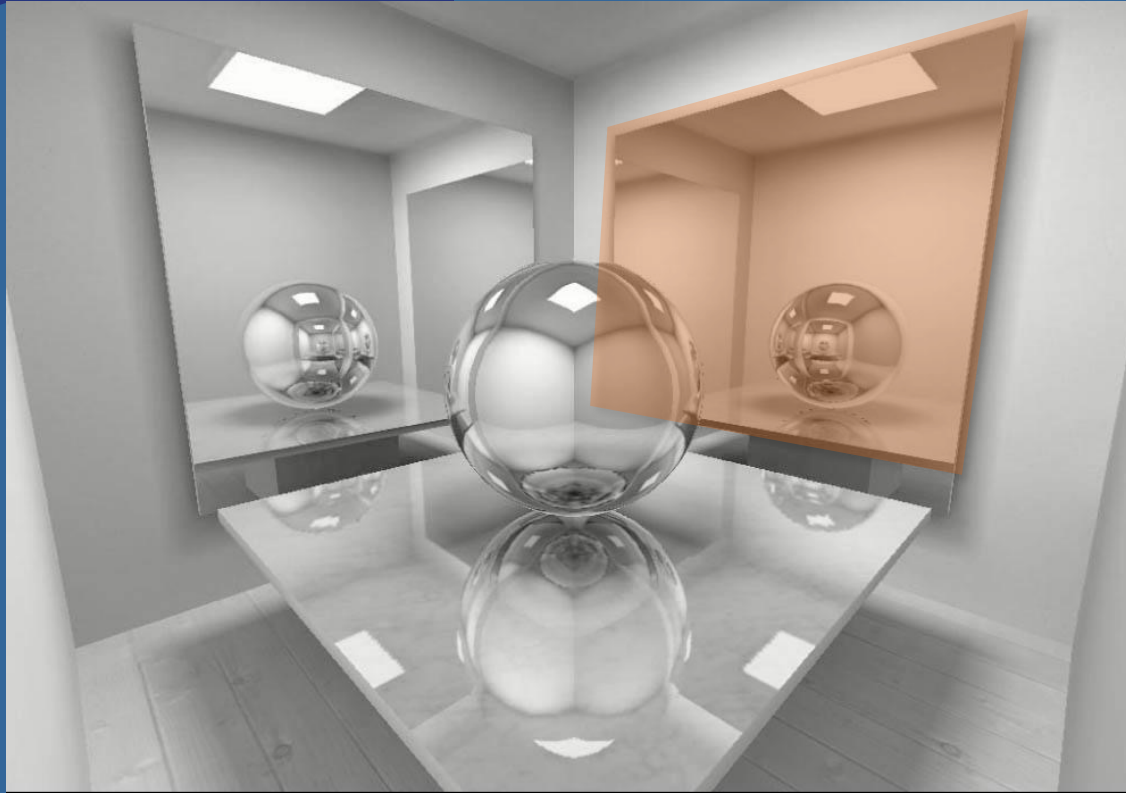


- Render reflection:
 1. Render reflective plane to stencil buffer
 2. Reflect camera (including cam axes)
 3. Set user clip plane in mirror plane to cull anything between mirror and reflected camera
 4. Render scene from reflected camera.
- Render scene as normal from original camera

Final slide

Another example

Image courtesy of Kasper Hoey Nielsen



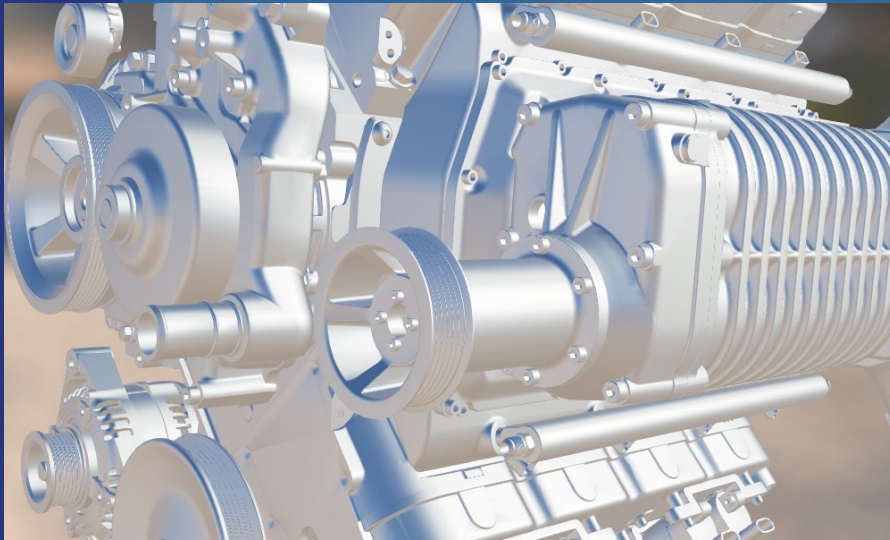
1. Render mirror to stencil buffer
2. Reflect camera (including cam axes)
3. Set user clip plane in mirror plane to cull anything between mirror and reflected camera
4. Render scene to screen.

- Instead of the scale-trick, you can reflect the camera position and direction in the plane
- Then render reflection image from there

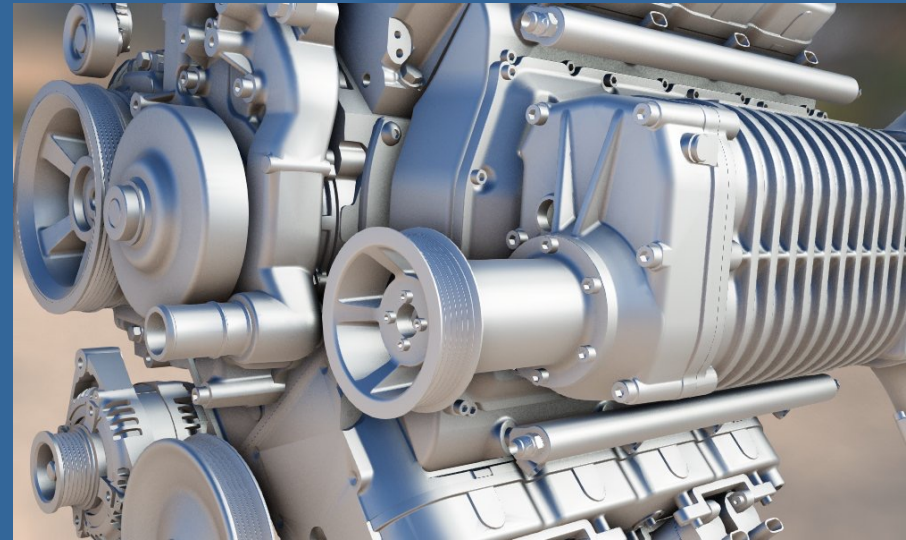
Study Questions

- What is “Planar shadows”
 - Answer: you project the objects’ triangles onto the plane and draw them with dark color.
- Explain shadow maps
- Explain shadow volumes
 - Both z-pass and z-fail
- What are the pros and cons of shadow maps vs. shadow volumes?
- Why are environment maps problematic for planar reflections?
- How can you render planar reflections?

Screen-space Ambient Occlusion



Without SSAO



With SSAO



Use the z buffer to, for each pixel, estimate how much of the hemisphere that is non-blocked for incoming light. (See Labs - Project)

