DCGI

KATEDRA POČÍTAČOVÉ GRAFIKY A INTERAKCE

Shadows

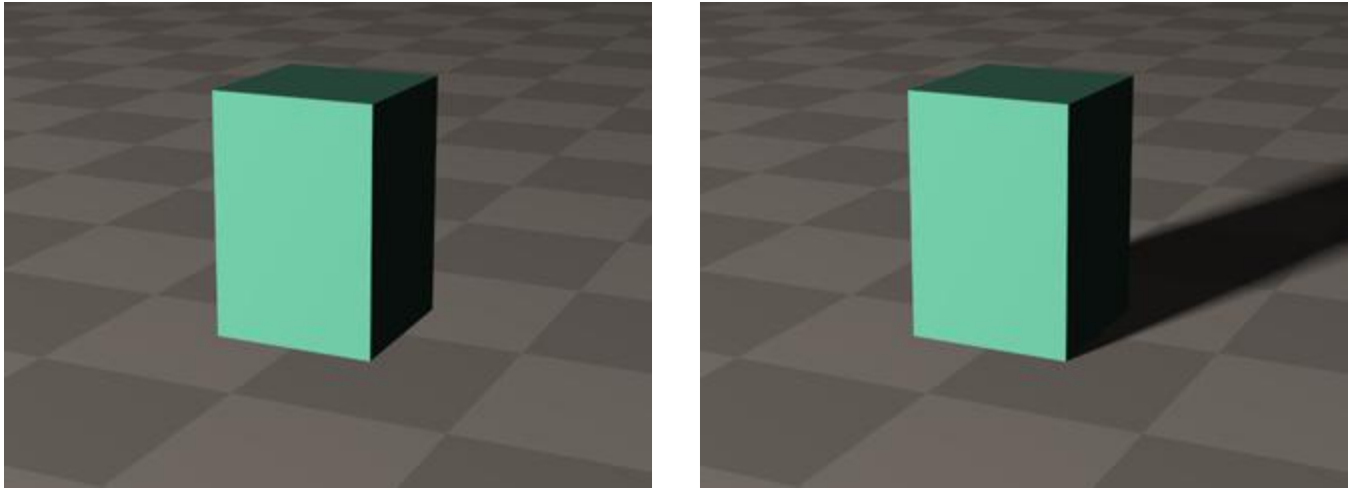
Jiří Bittner, Michael Wimmer

Outline

- Motivation & Terminology — MPG 12
- Approximate & projection shadows — MPG 12.1
- Shadow maps — MPG 12.3
- Shadow volumes — MPG 12.2
- Summary

What for?

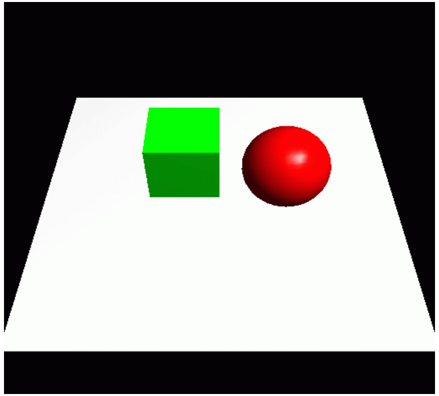
Shadows tell us about the relative locations and motions of objects

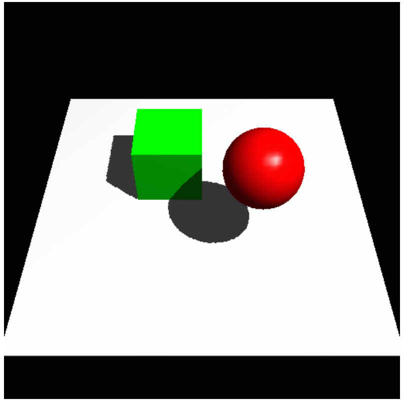


What for?

Shadows tell us about the relative locations and motion of objects

And about light positions





What for?

Objects look like they are “floating”→ shadows fix that!

What for?

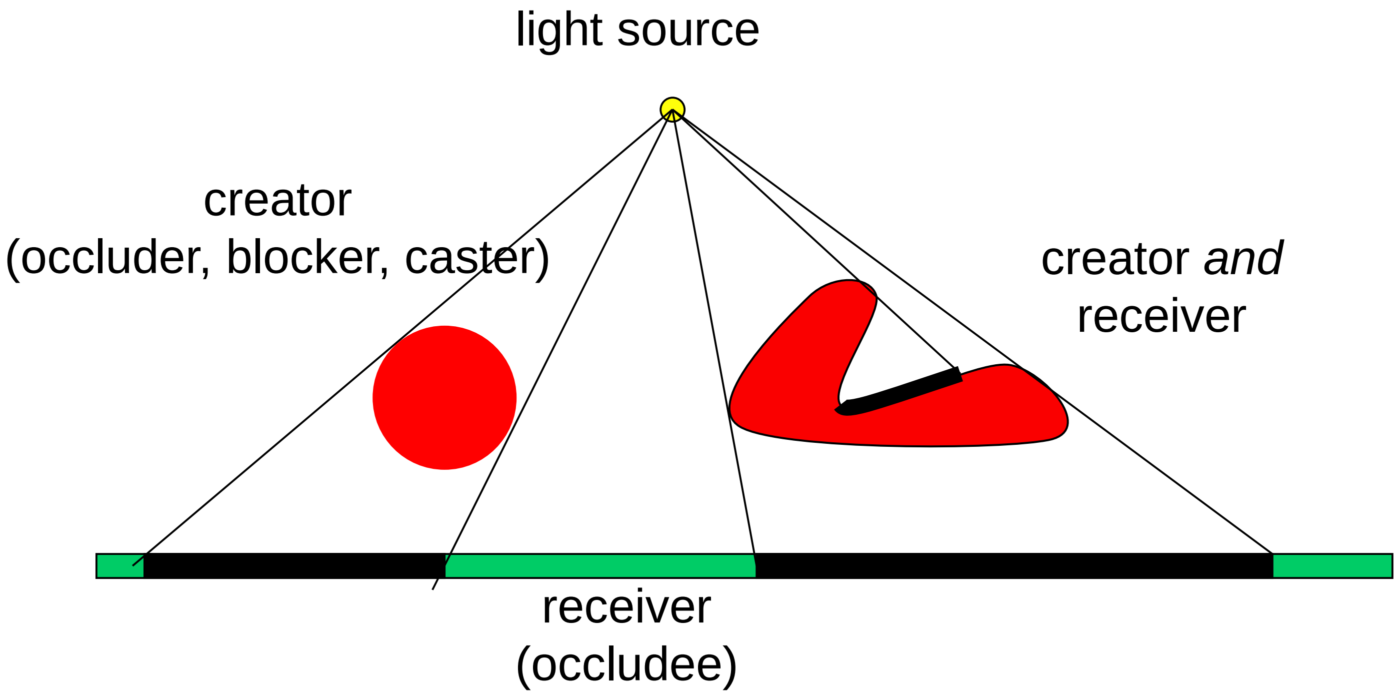
Motivation

- Shadows contribute significantly to realism of rendered images
  - Anchor objects in scene
- **Global** effect → expensive!
- Light source behaves very similar to camera
  - Is a point visible from the light source?
    → shadows are “hidden” regions
  - Shadow is a projection of caster on receiver
    → projection methods

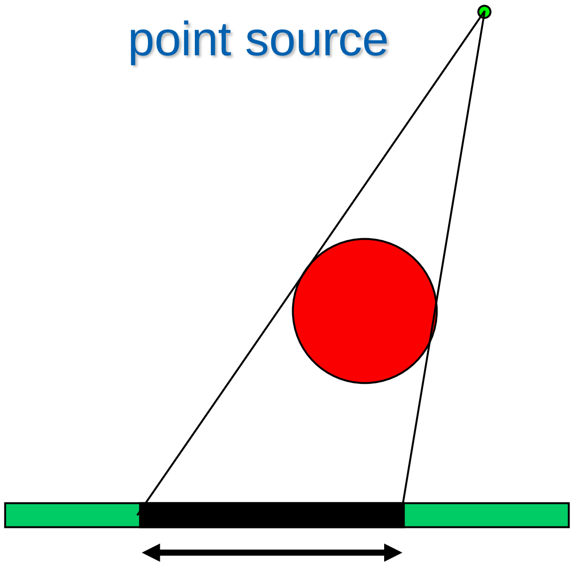
Shadow Algorithms

- Static shadow algorithms (lights + objects)
  - Radiosity, ray tracing → lightmaps
- Approximate shadows
- Projected shadows [Blinn 88]
- Shadow maps [Williams 78]
  - Projective image-space algorithm
- Shadow volumes [Crow 77]
  - Object-space algorithm
- Soft shadow extensions for all above algorithms
  - Still hot research topic (500+ shadow publications)

Shadow Terms



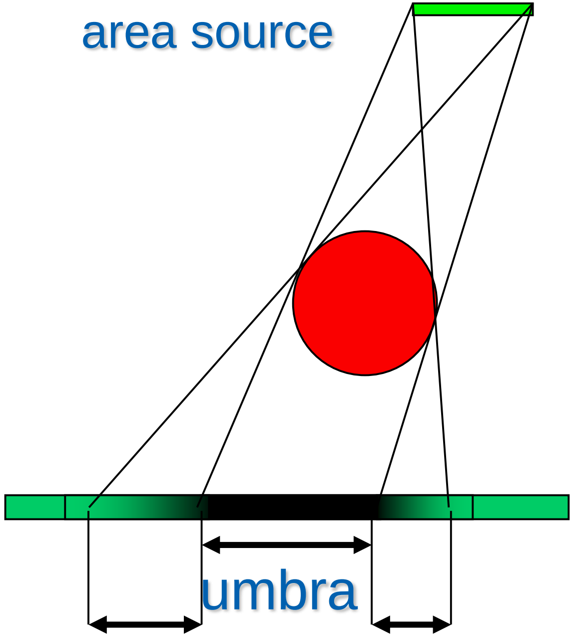
Hard vs. Soft Shadows



+fast

-only good for localized lights (sun, projectors)

+fake soft shadow through filtering



+ very realistic

- very expensive

+ becomes more and more usable

Static Shadows

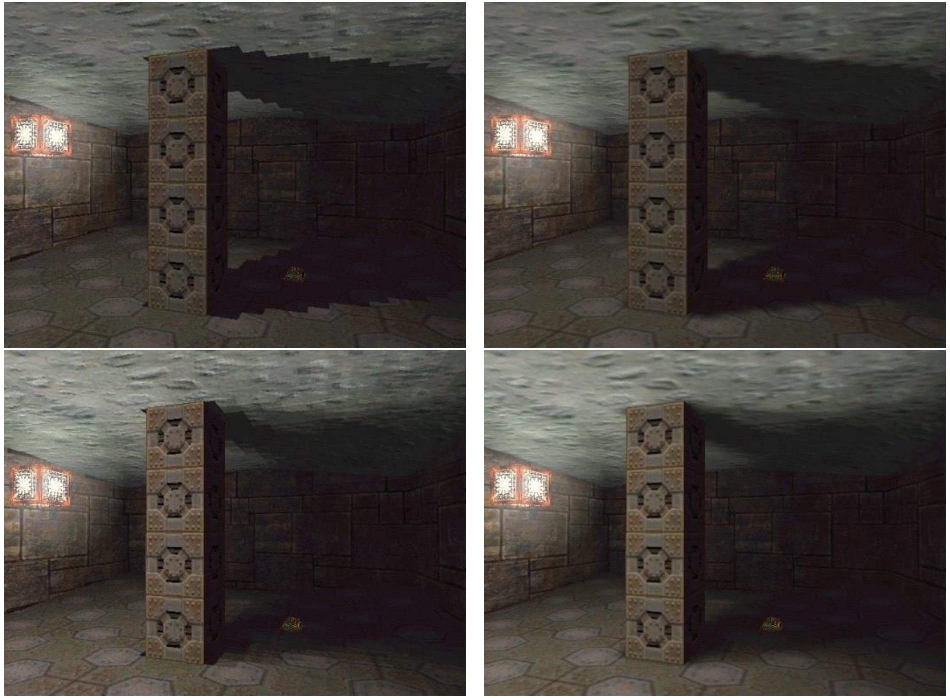
- Glue to surface whatever we want
- Idea: incorporate shadows into light maps
  - For each texel, cast ray to each light source
- “Bake” soft shadows in light maps
  - Not by texture filtering alone, but:
  - Sample area light sources

Static Soft Shadow Example

no filtering | filtering

1 sample

n samples



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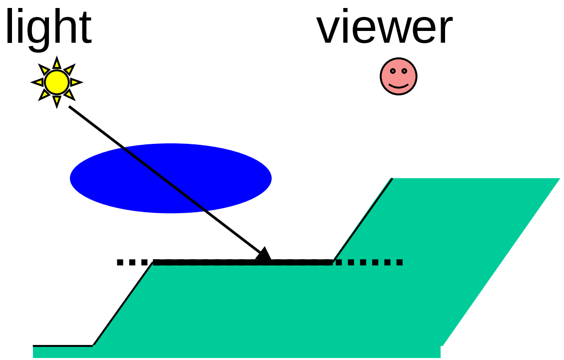
Approximate Shadows

- Handdrawn approximate geometry
  - Perceptual studies suggest: shape not so important
  - Minimal cost

Approximate Shadows

- Dark polygon (maybe with texture)
  - Cast ray from light source through object center
  - Blend polygon into frame buffer at location of hit
  - May apply additional rotation/scale/translation
    - Incorporate distance and receiver orientation
- Problem with z-quantization:

errors!



Approximate Shadows

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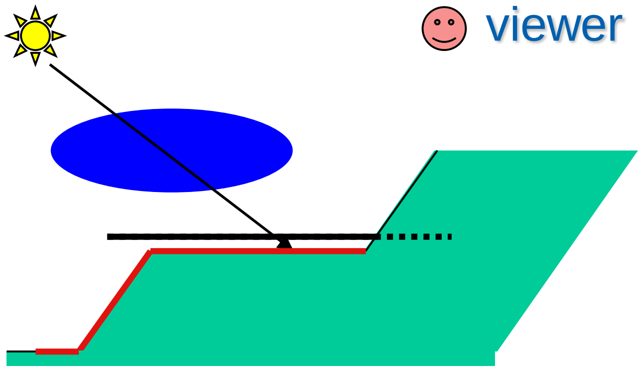

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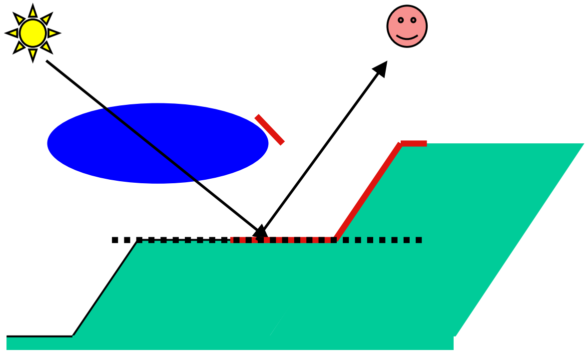
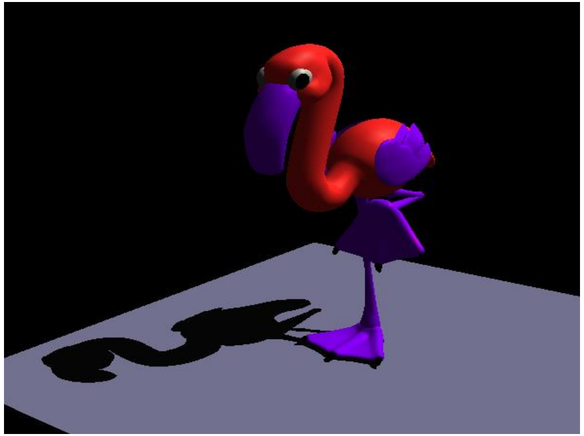


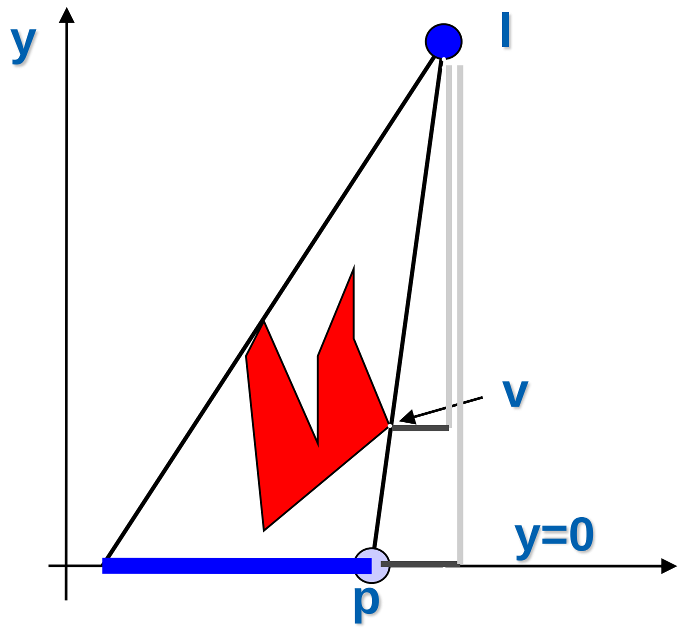
Projection Shadows (Blinn 88)

- Shadows for selected large ***planar*** receivers
  - Ground plane
  - Walls
- Projective geometry: flatten 3D model onto plane
  - and "darken" using framebuffer blend



Projection for Ground Plane

- Use similar-triangles



$$\frac{p_x - l_x}{v_x - l_x} = \frac{l_y}{l_y - v_y}$$

$$p_x = \frac{l_y v_x - l_x v_y}{l_y - v_y}$$

$$p_z = \frac{l_y v_z - l_z v_y}{l_y - v_y}$$

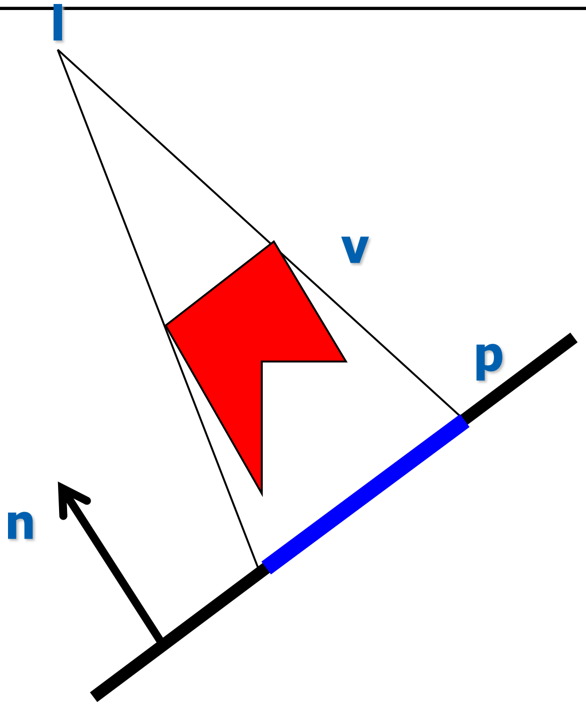
$$p_y = 0$$

Projection Matrix

- Projective 4x4 matrix:

$$M = \begin{pmatrix} l_y & -l_x & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -l_z & l_y & 0 \\ 0 & -1 & 0 & l_y \end{pmatrix}$$

- Arbitrary plane:
  - Intersect line **p** = **l** – α (**v** – **l**)
  - with plane **n x** + d = 0
  - Express result as a 4x4 matrix
- Append this matrix to view transform

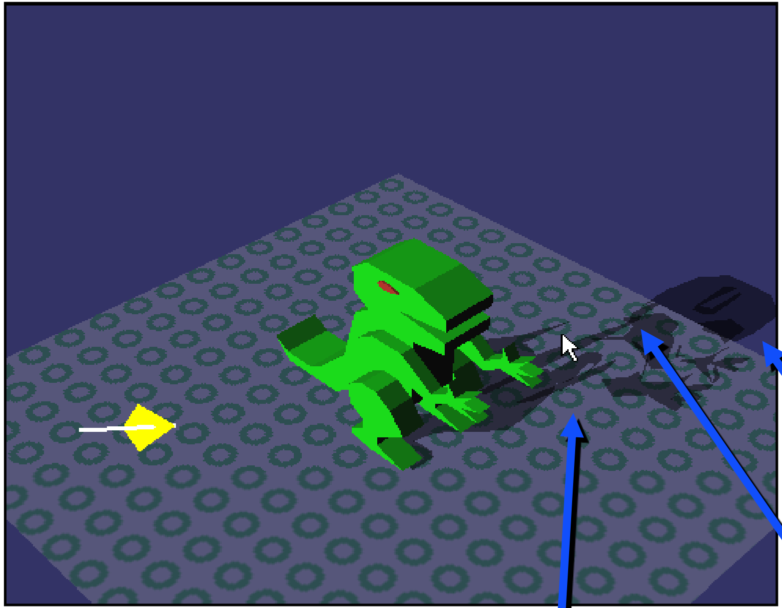


Projection Shadow Algorithm

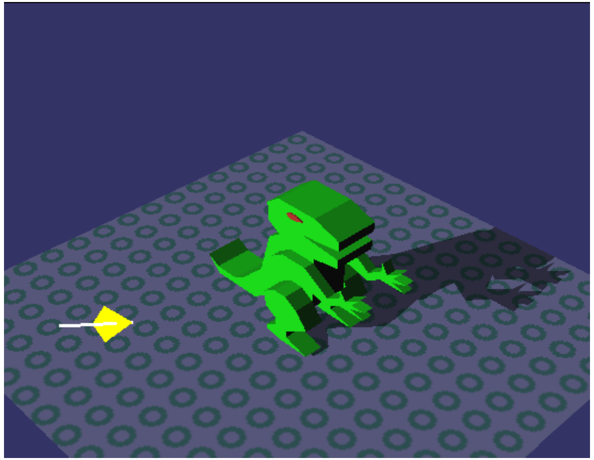
- Render scene (full lighting)
- For each receiver polygon
  - Compute projection matrix M
  - Append to view matrix
  - Render selected shadow caster
    - With framebuffer blending enabled

Projection Shadow Artifacts

Bad



Good



extends off
ground region

Z fighting

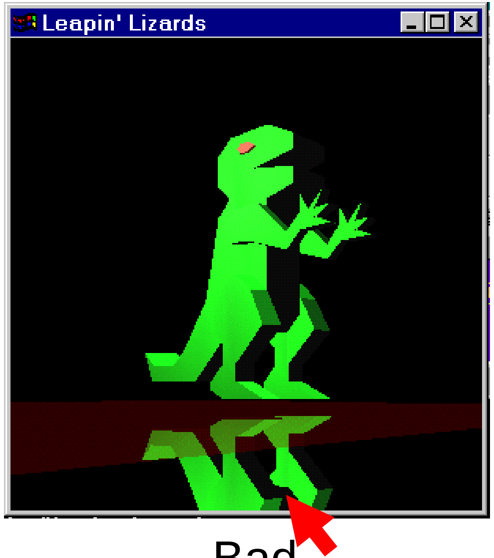
double blending

Stencil Buffer Projection Shadows

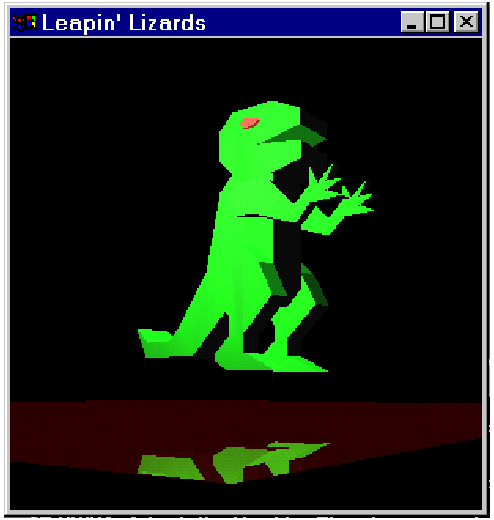
- Stencil can solve all of these problems
  - Separate 8-bit frame buffer for numeric ops
- Stencil buffer algorithm (requires 1 bit):
  - Clear stencil to 0
  - Draw ground polygon last and with
    - `glStencilOp(GL_KEEP, GL_KEEP, GL_ONE);`
  - Draw shadow caster with no depth test but
    - `glStencilFunc(GL_EQUAL, 1, 0xFF); glStencilOp(GL_KEEP, GL_KEEP, GL_ZERO);`
- Every plane pixel is touched at most once

Stencil Buffer Planar Reflections

- Draw object twice, second time with:
  - `glScalef(1, -1, 1)`
- Reflects through floor



Bad



Good, stencil used to limit reflection.

Projection Shadow Summary

- Easy to implement
  - GLQuake first game to implement it
- Only practical for very few, large receivers
- No self shadowing

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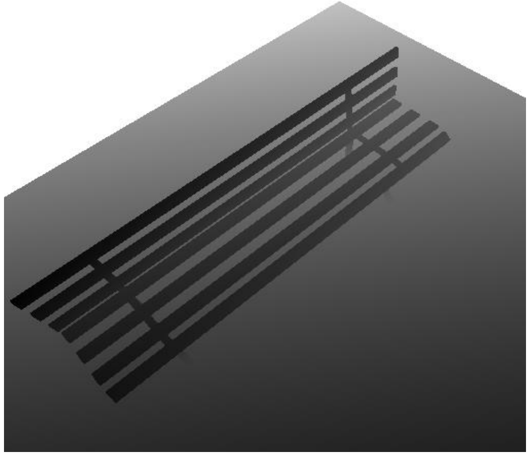
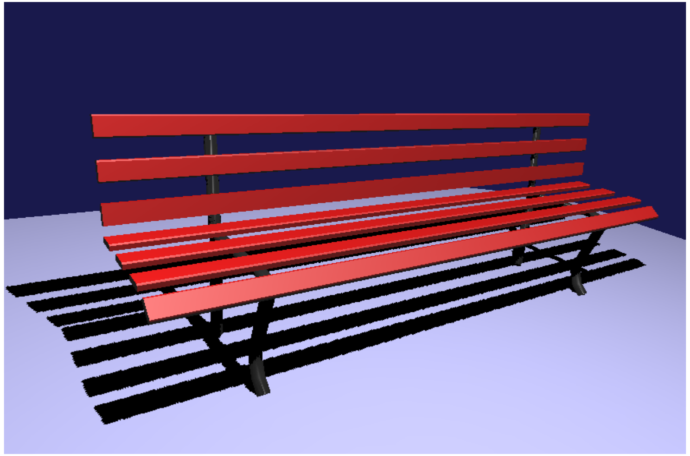
Shadow Maps

- Casting curved shadows on curved surfaces
  - Image-space algorithm, 2 passes

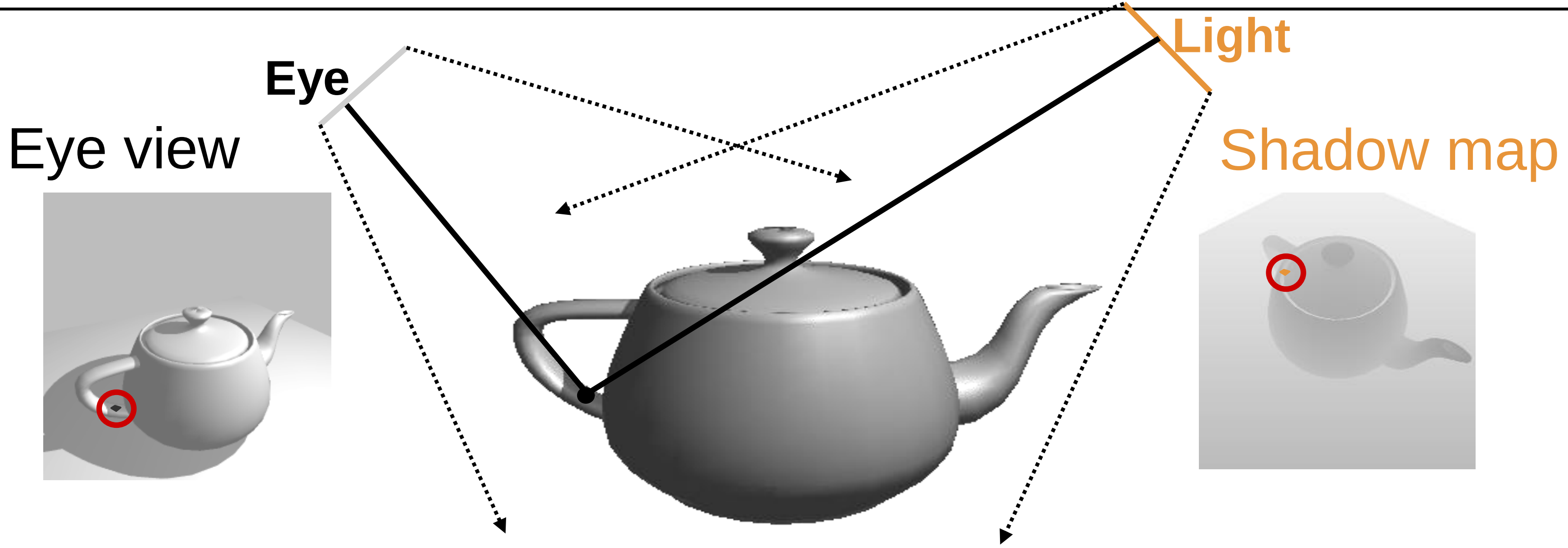


Shadow map

Final scene



Shadow Map Algorithm



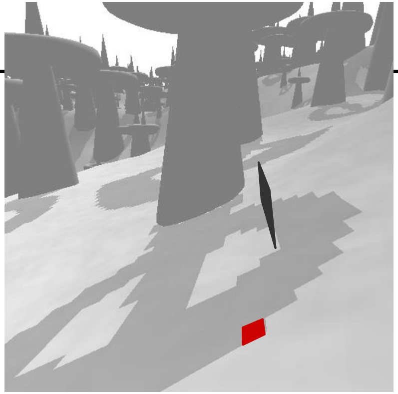
- Render from light; save depth values
- Render from eye
  - Transform all fragments to light space
  - Compare z_{eye} and z_{light} (both in light space!!!)
  - $z_{eye} > z_{light}$ → fragment in shadow

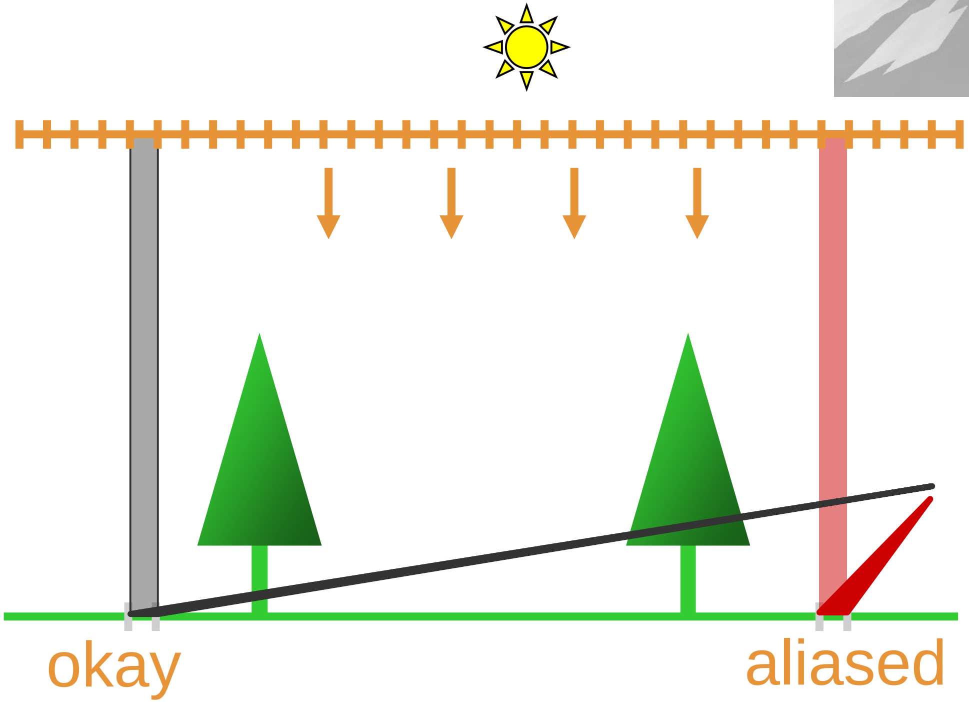
Shadow Maps in Hardware

- Render lightspace depth into texture
- In vertex shader:
  - Calculate texture coordinates as in projective texturing
- In fragment shader:
  - Depth compare

Problem: Perspective Aliasing

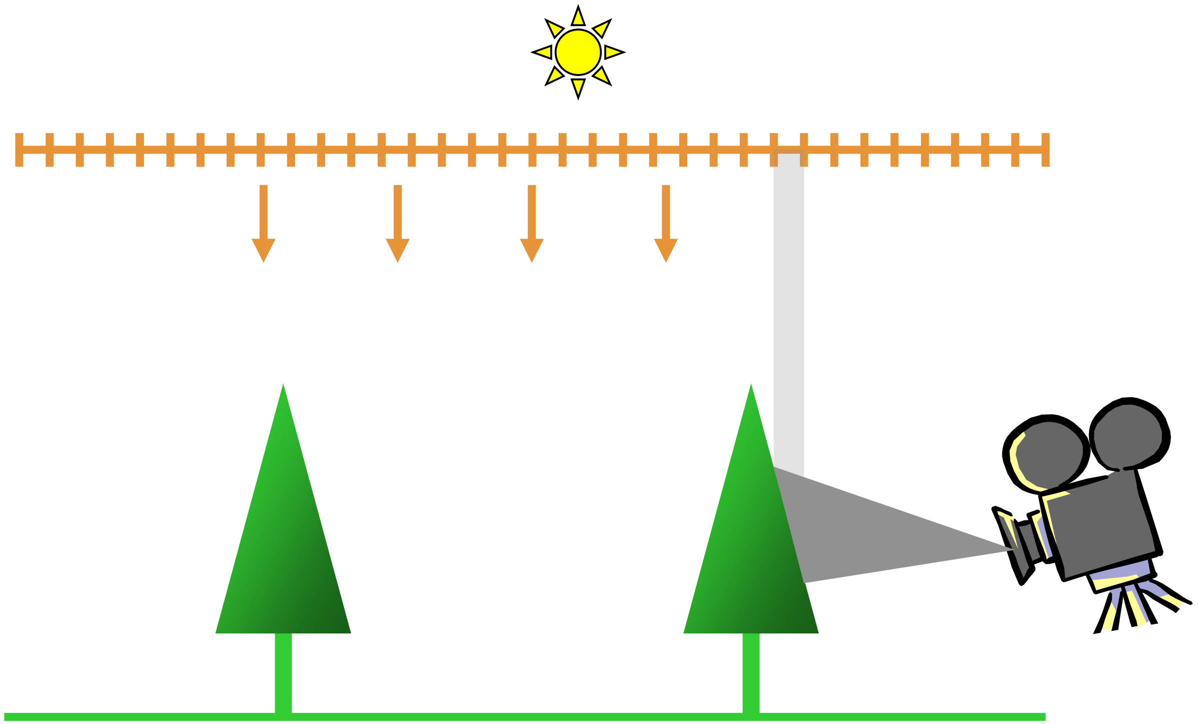
- Sufficient resolution far from eye
- Insufficient resolution near eye



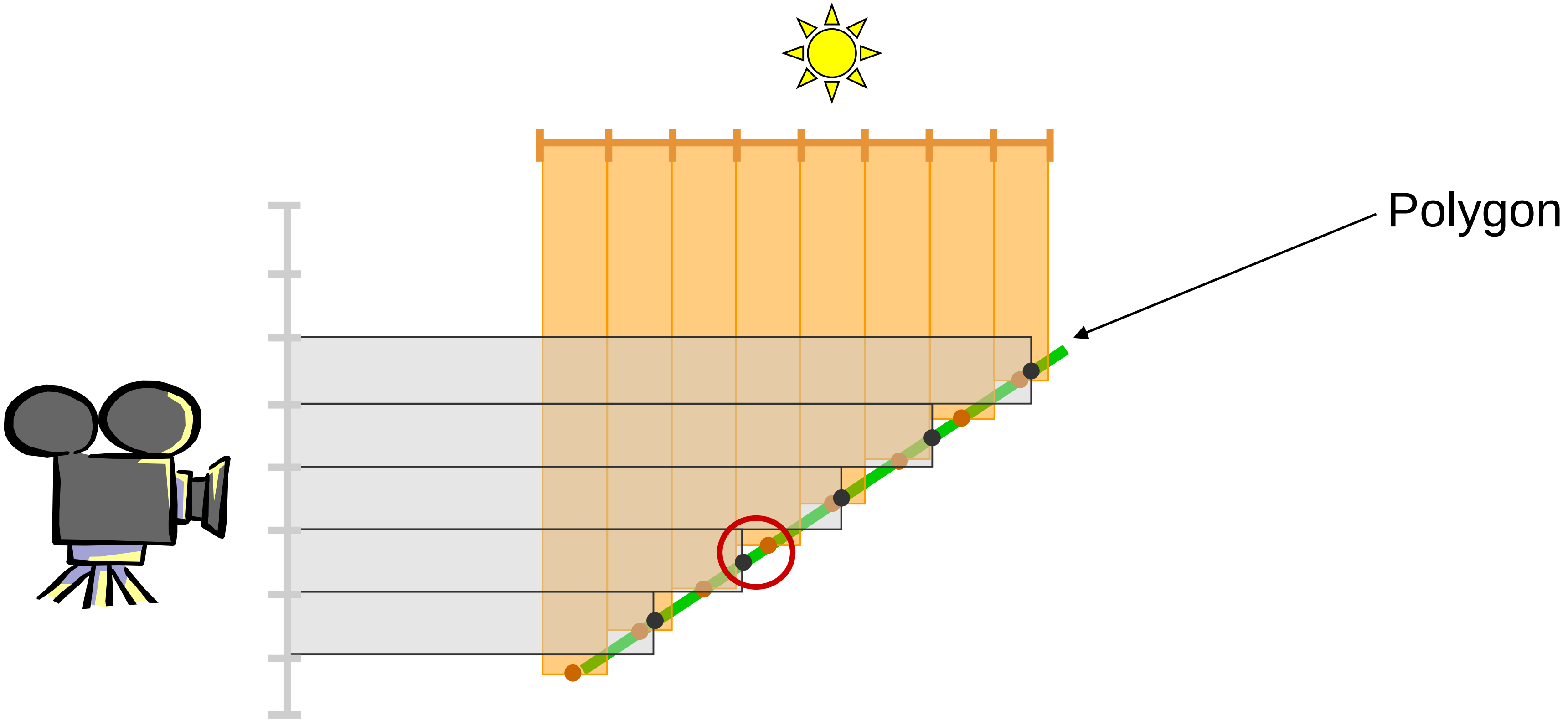


Problem: Projection Aliasing

Shadow receiver ~ **orthogonal** to Shadow Map - viewplane



Problem: Incorrect Self-Shadowing



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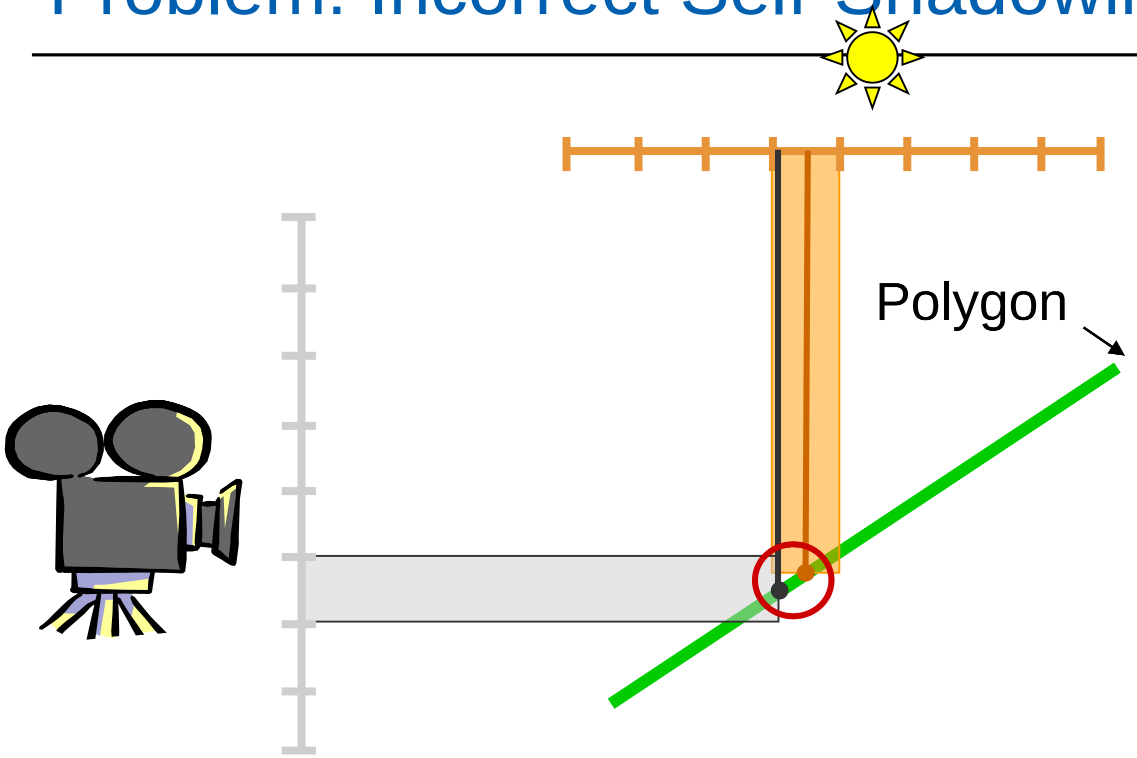
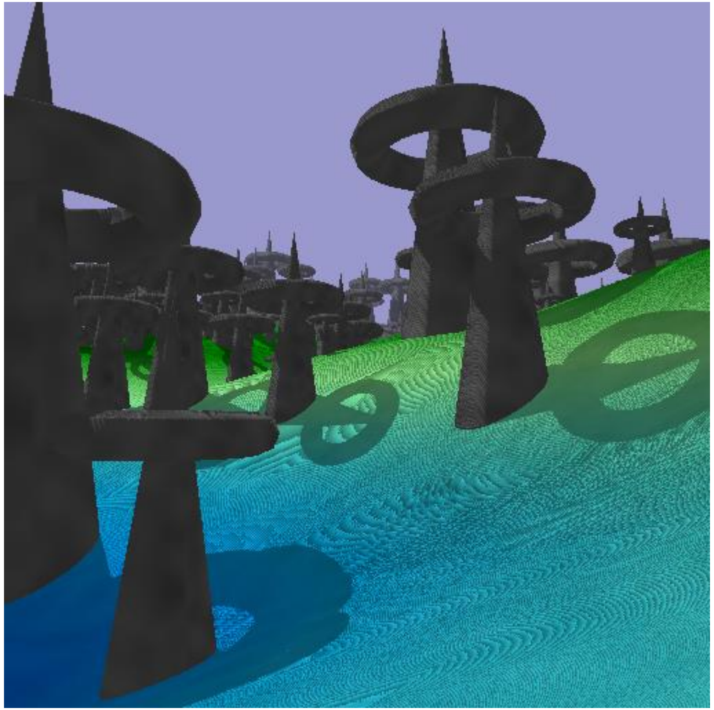
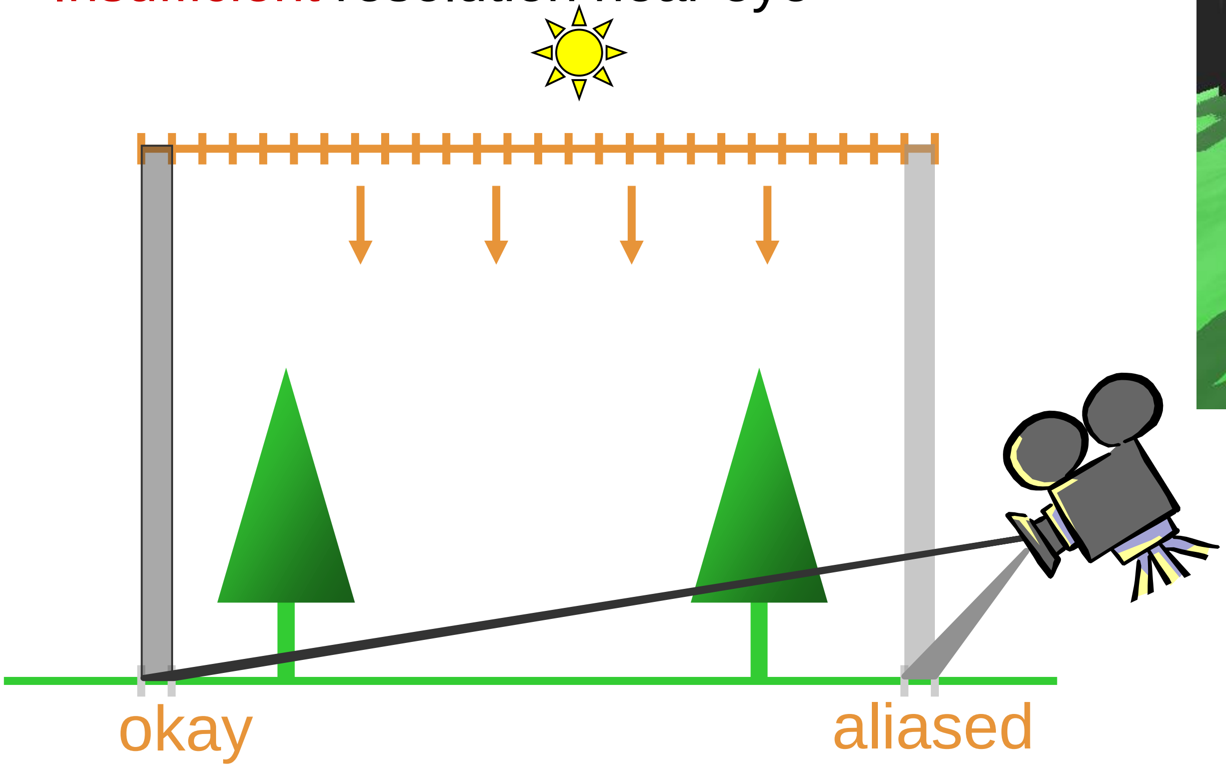


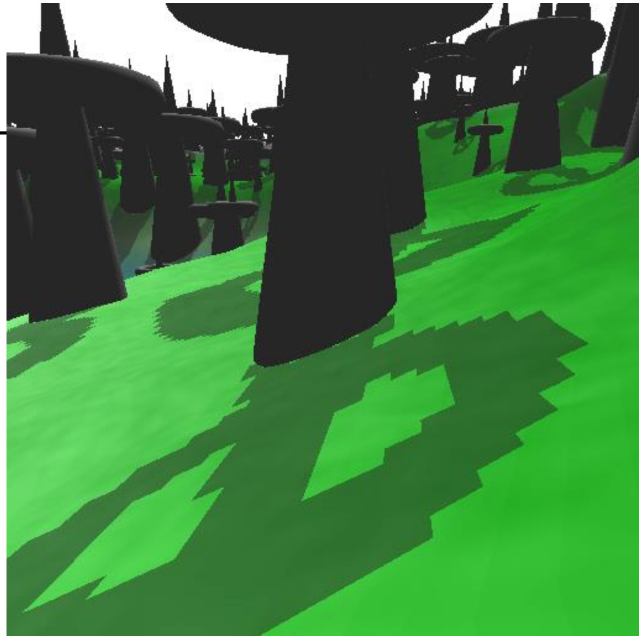


$z_{eye} > z_{light}$ ➡ Incorrect Self-shadowing

Solution for Perspective Aliasing

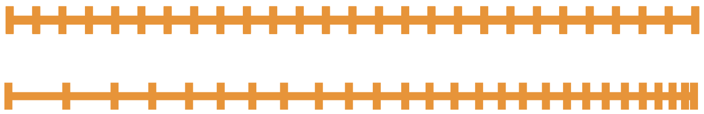
- Insufficient resolution near eye





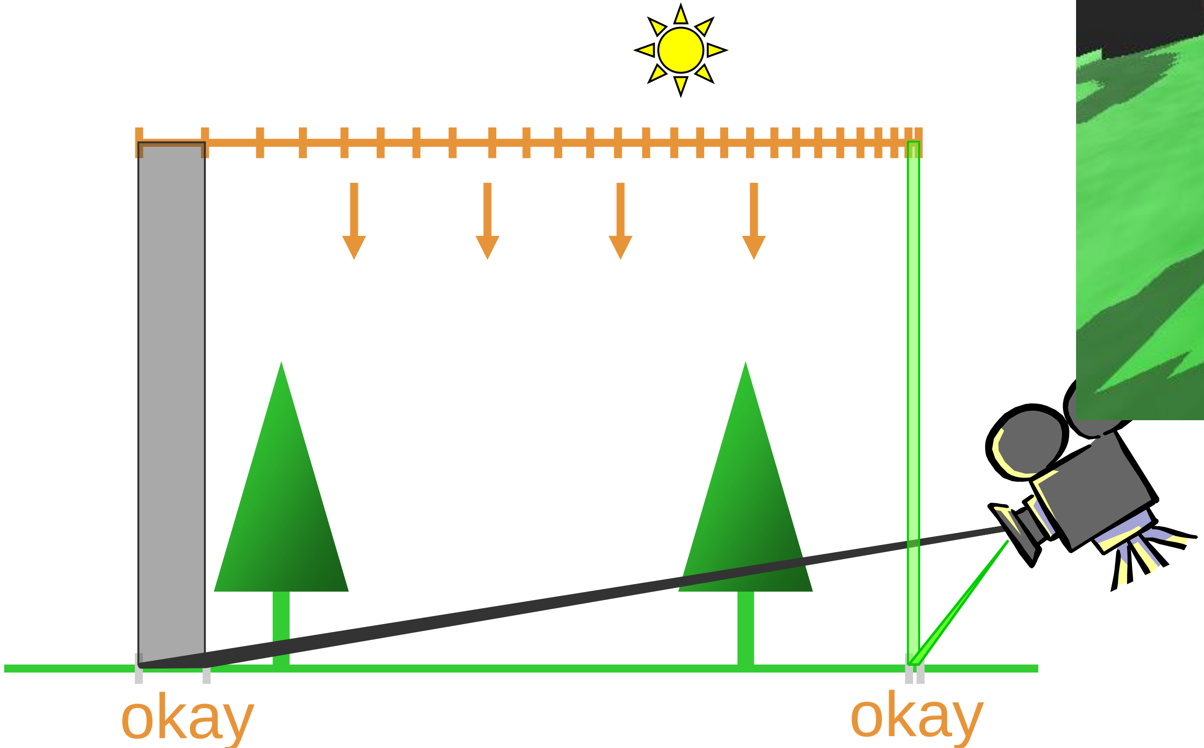
Solution for Perspective Aliasing

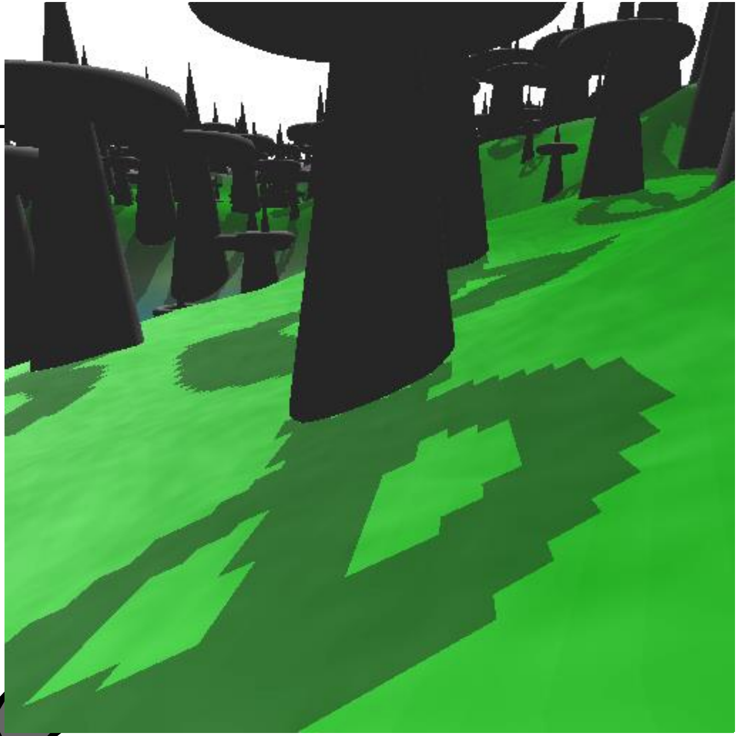
- Insufficient resolution near eye
- **Redistribute** values in shadow map



Solution for Perspective Aliasing

- **Sufficient** resolution near eye
- **Redistribute** values in shadow map

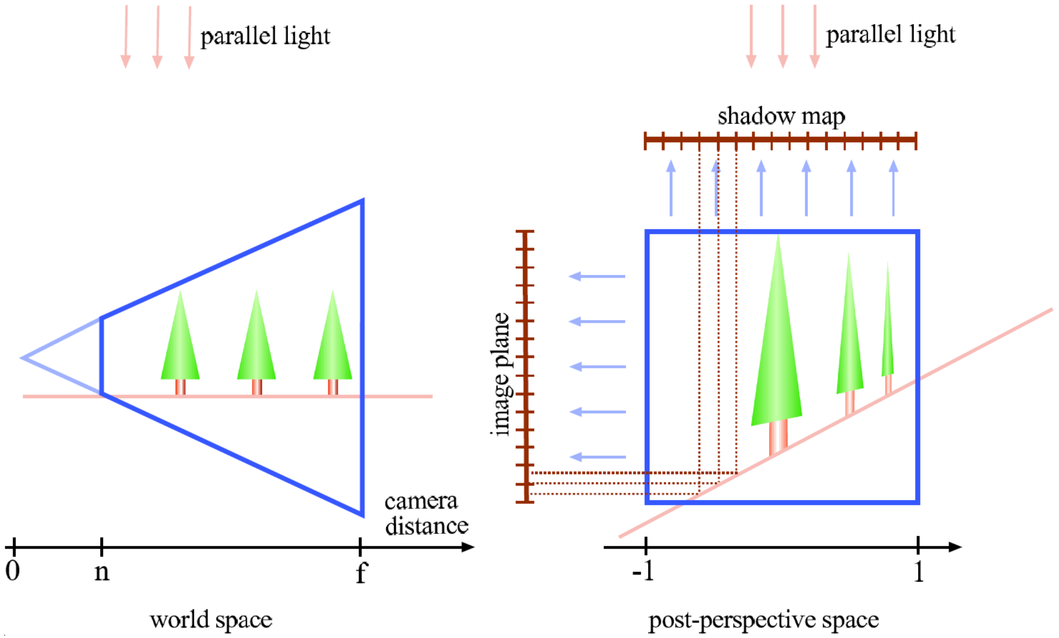




Solution for Perspective Aliasing

- Use warping for light pass (and lookups)

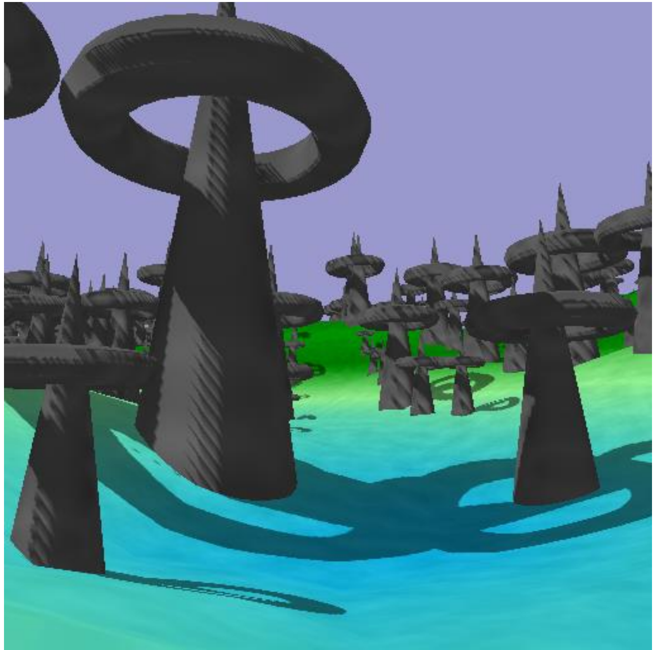
Solution for Perspective Aliasing

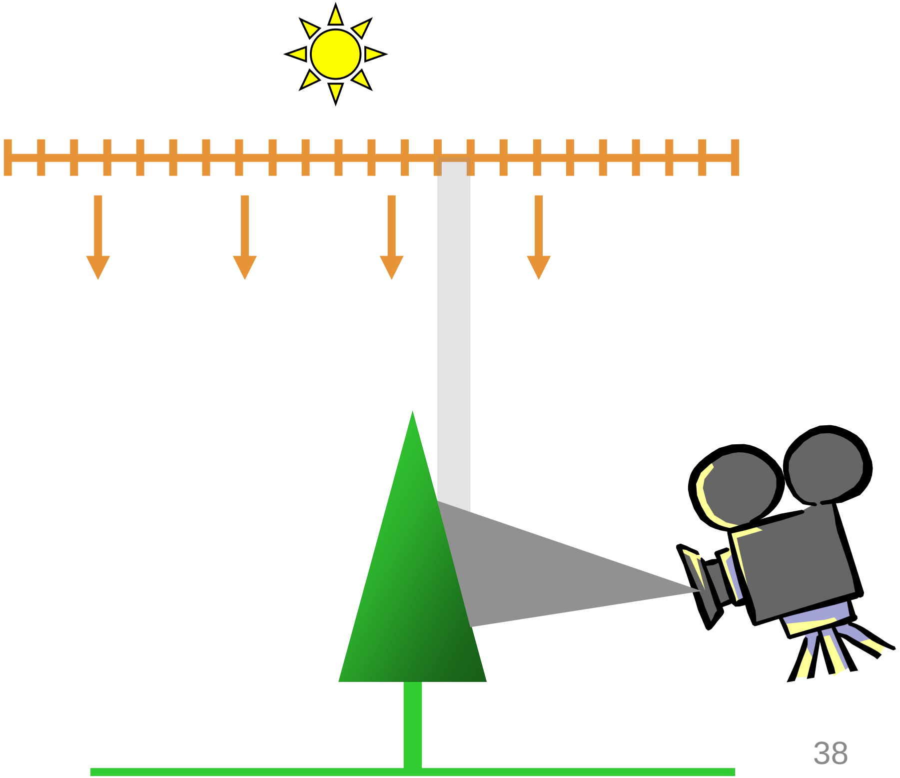


- Stamminger, Drettakis - Perspective Shadow Maps
- Wimmer et al. – Light space perspective shadow maps

Solution for Projection Aliasing

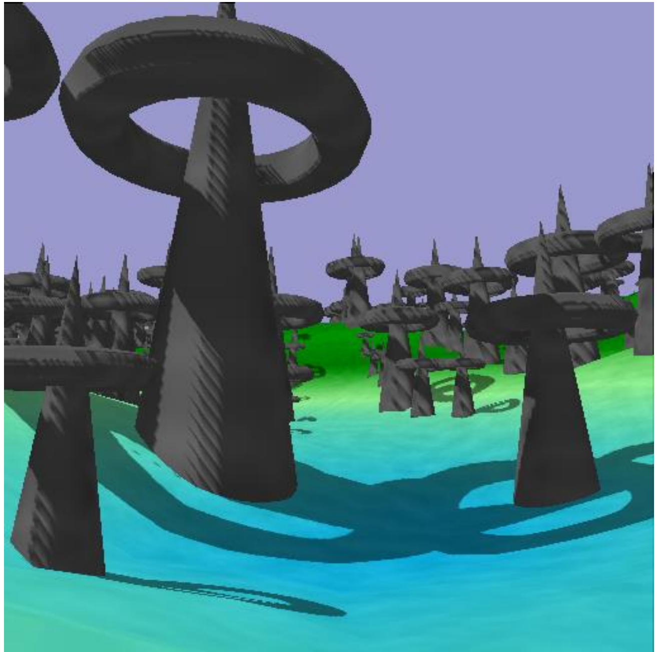
- Shadow receiver ~ **orthogonal** to Shadow Map plane
- Redistribution does not work
- **But...**

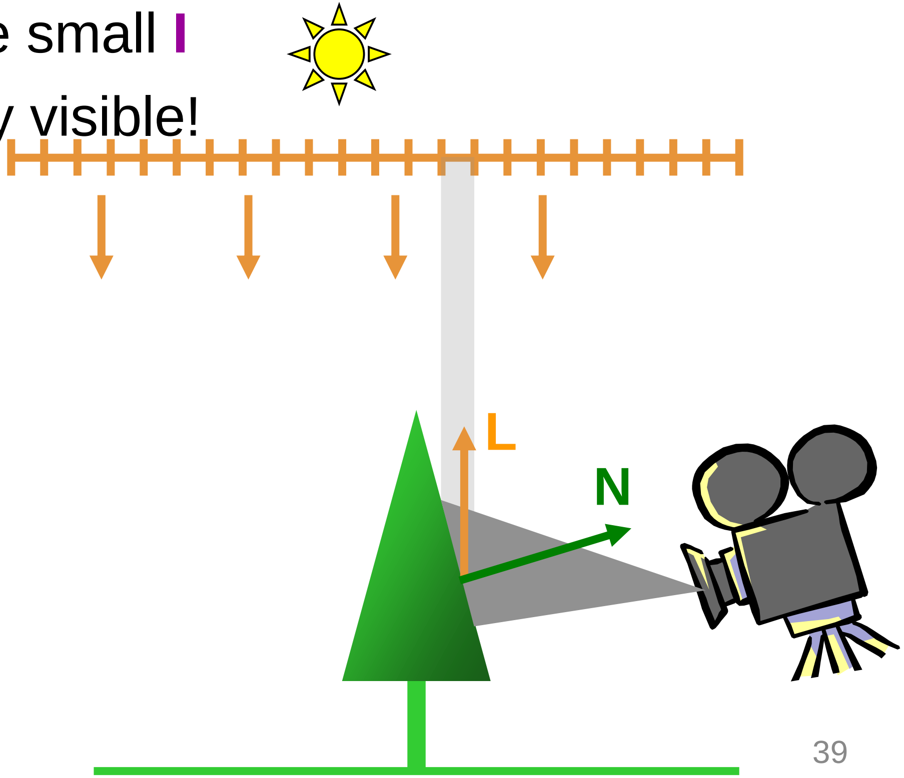




Solution for Projection Aliasing

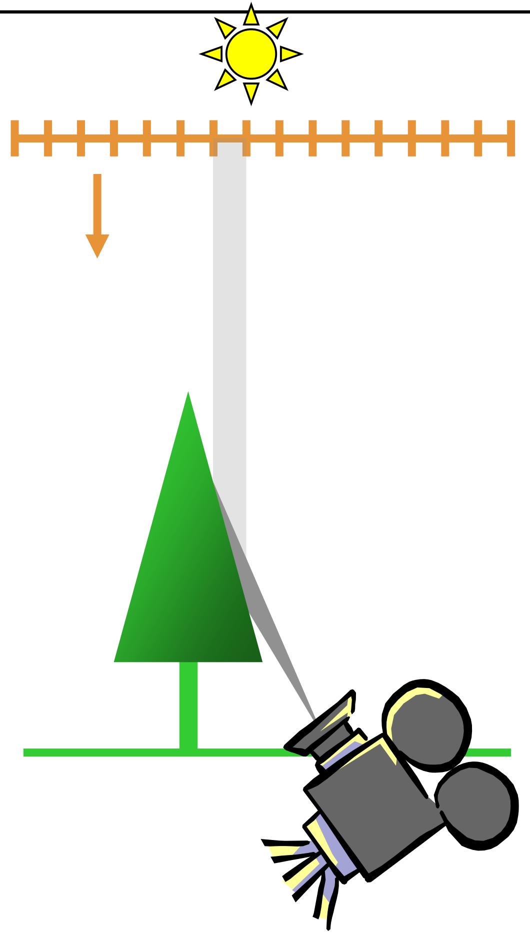
- Diffuse lighting: **I** = I_L *max*(*dot*(L, **N**), 0)
- Almost orthogonal receivers have small **I**
- Dark ➡ artifacts not very visible!



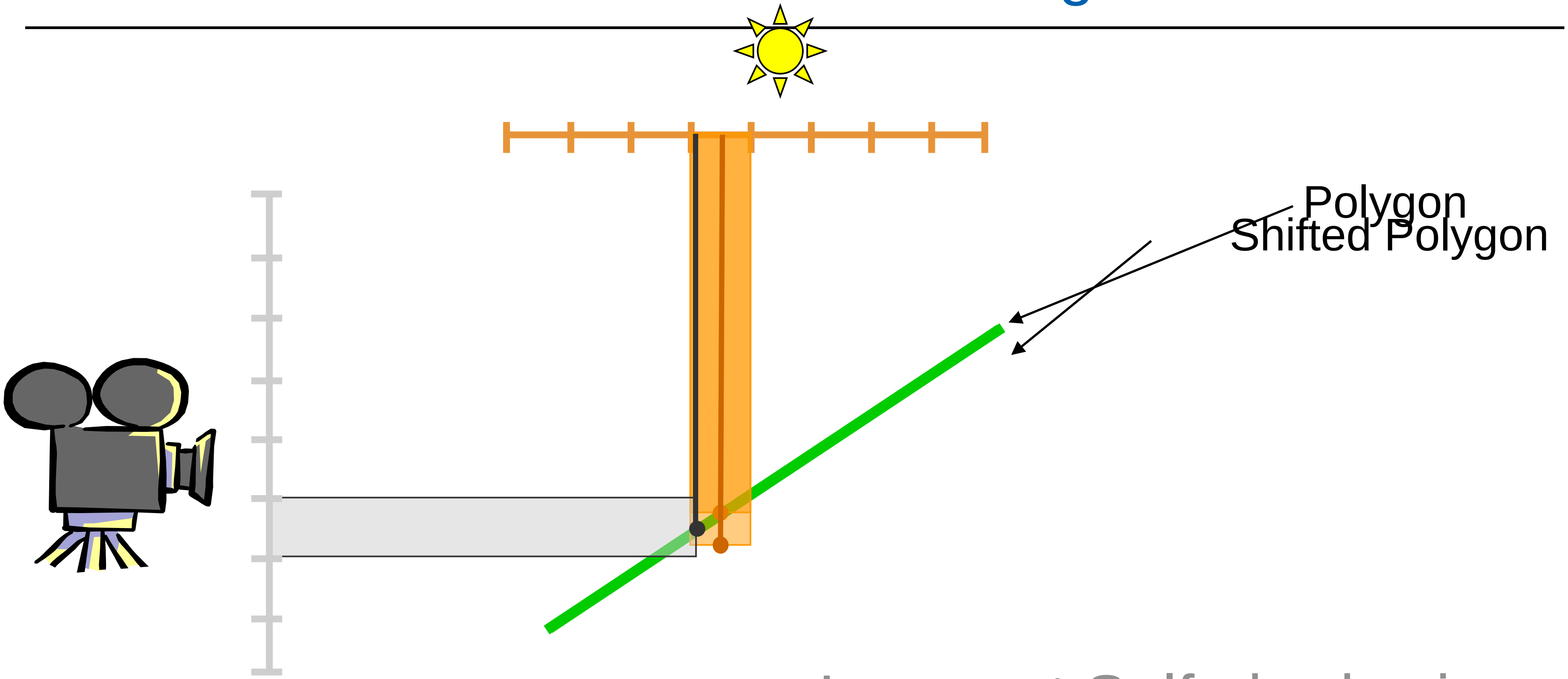


Solution for Projection Aliasing

- Recommendations
  - Small **ambient** term
  - **Diffuse term** hides artifacts
  - **Specular term** not problematic
    - Light and view direction almost identical
    - Shadow Map resolution sufficient



Solution for Incorrect Self-Shadowing

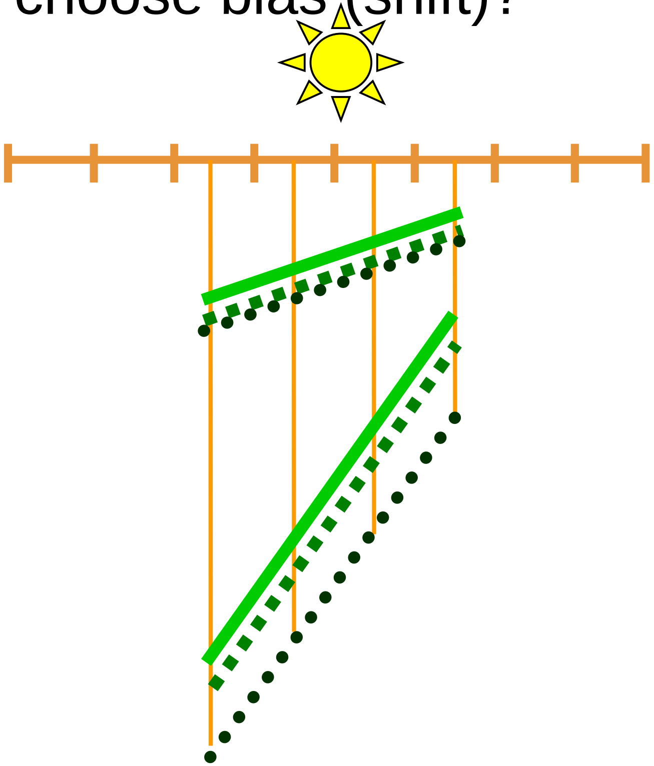


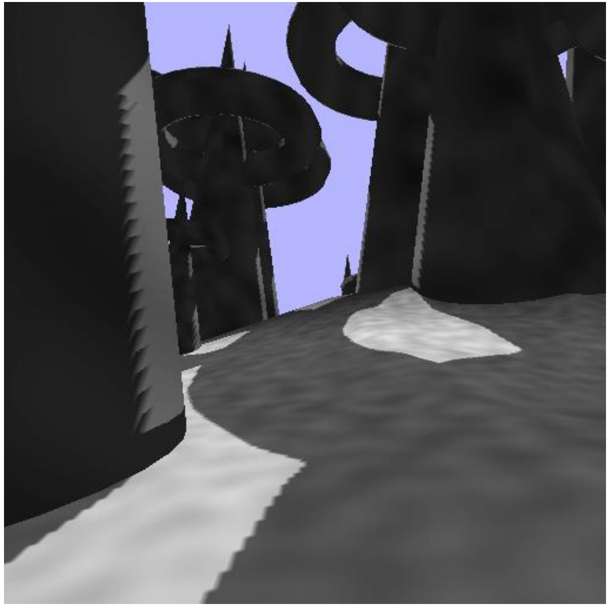
$z_{eye} > z_{light}$ ➡ Incorrect Self-shadowing

$z_{eye} < z_{light}$ ➡ No Self-shadowing

Solution for Incorrect Self-Shadowing

- How to choose bias (shift)?





No Bias

Constant Bias

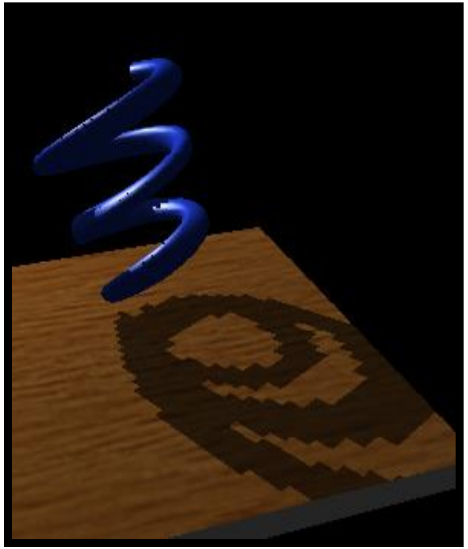
Slope-Scale Bias

Problem: Aliasing Artifacts

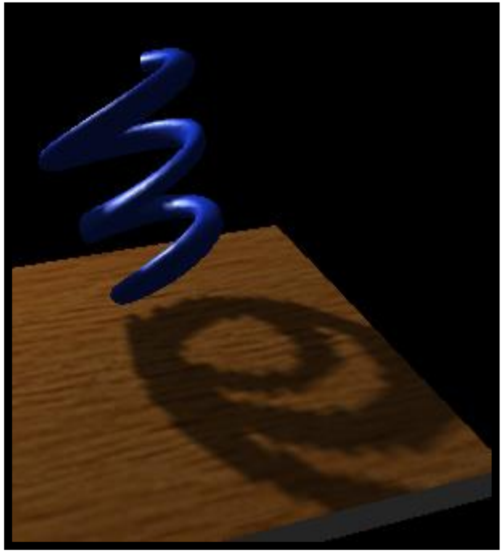
- Resolution mismatch image/shadow map!
  - Use perspective shadow maps
- Use “percentage closer” filtering
  - Normal color filtering cannot be used
  - Filter lookup result, not depth map values!
  - 2x2 PCF in hardware for NVIDIA

Shadow Map Filtering

NEAREST



LINEAR PCF



Shadow Map Summary

- Advantages
  - Fast – only one additional pass
  - Independent of scene complexity (no additional shadow polygons!)
  - Self shadowing (but beware bias)
  - Can sometimes reuse depth map
- Disadvantages
  - Problematic for omnidirectional lights
  - Biasing tweak (light leaks, surface acne)
  - Jagged edges (aliasing)

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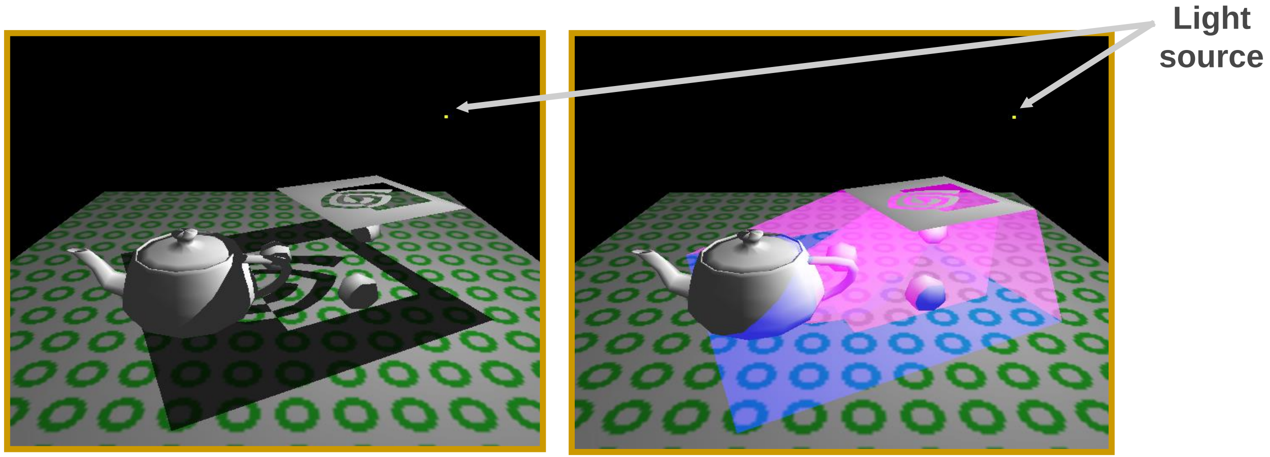
Shadow Volumes (Crow 1977)

- Occluders and light source cast out a 3D shadow volume
  - Shadow through new geometry
  - Results in Pixel correct shadows



Shadowed scene

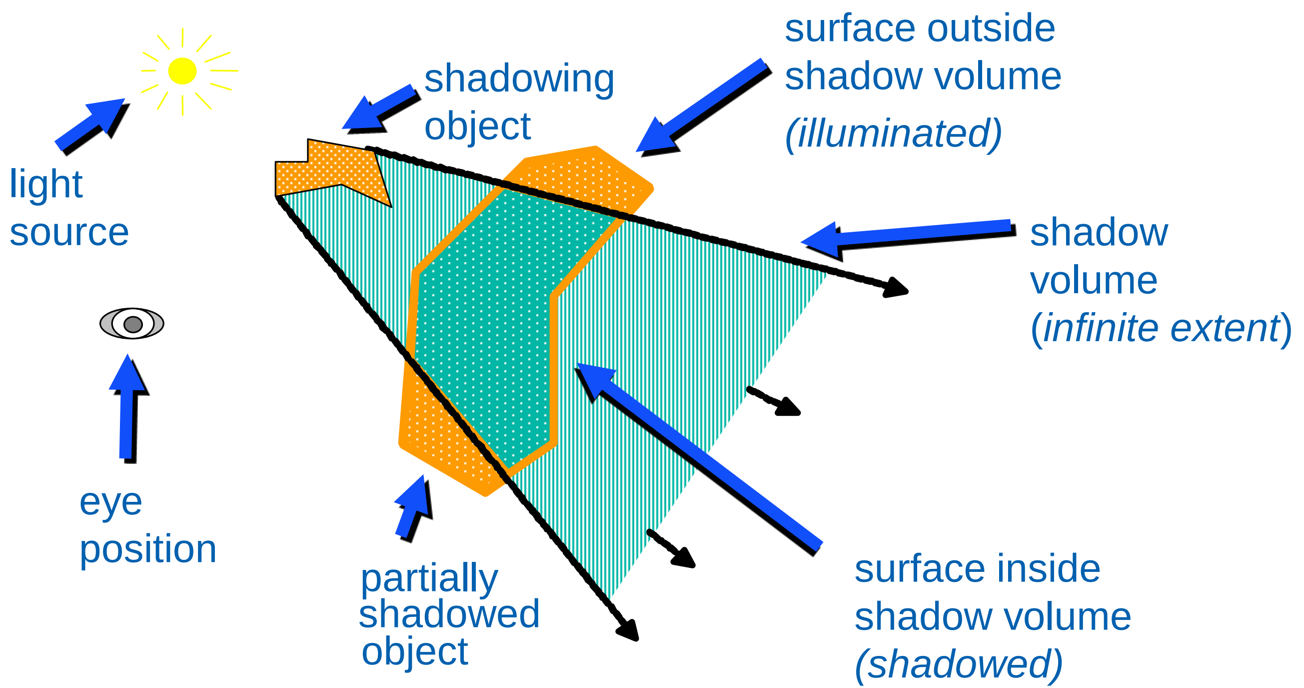
Visualization of shadow volume

Shadow Volumes (Crow 1977)

- Heavily used in Doom3

2D Cutaway of Shadow Volume

- Occluder polygons extruded to semi-infinite volumes



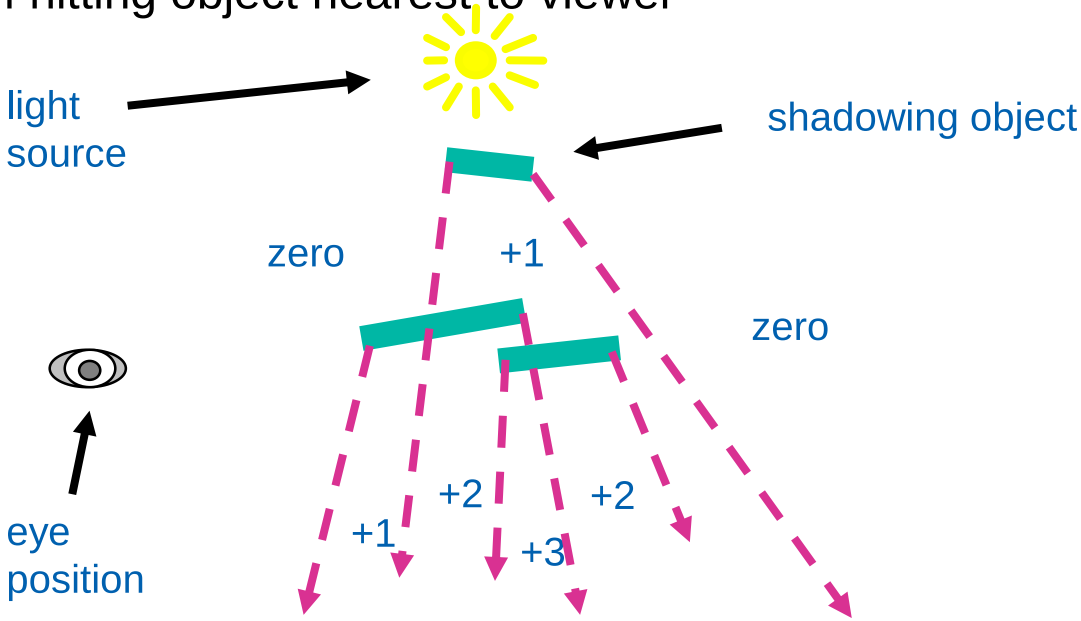
Shadow Volume Algorithm

- 3D point-in-polyhedron inside-outside test
- Principle similar to 2D point-in-polygon test
  - Choose a point known to be outside the volume
  - Count ray intersections from test point to known point with polyhedron faces
    - Front face +1
    - Back face -1
- Known point will distinguish algorithms:
  - Infinity: “Z-fail” algorithm
  - Eye-point: “Z-pass” algorithm

Enter/Leave Approach

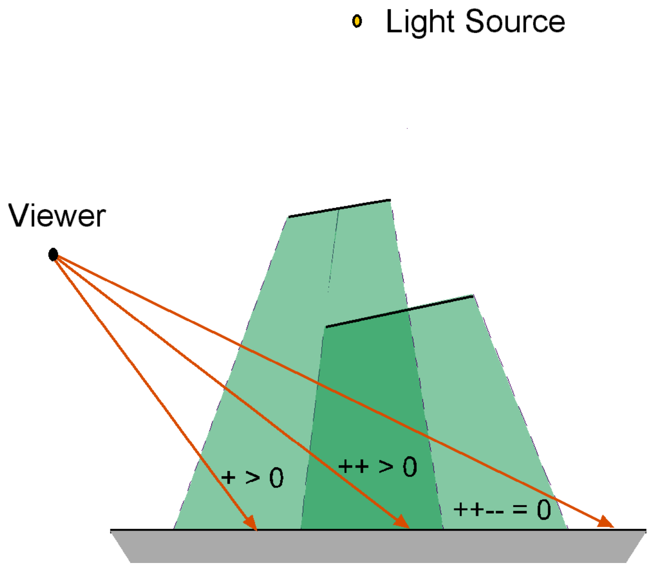
- Increment on enter, decrement on leave
- Simultaneously test all visible pixels

  → Stop when hitting object nearest to viewer

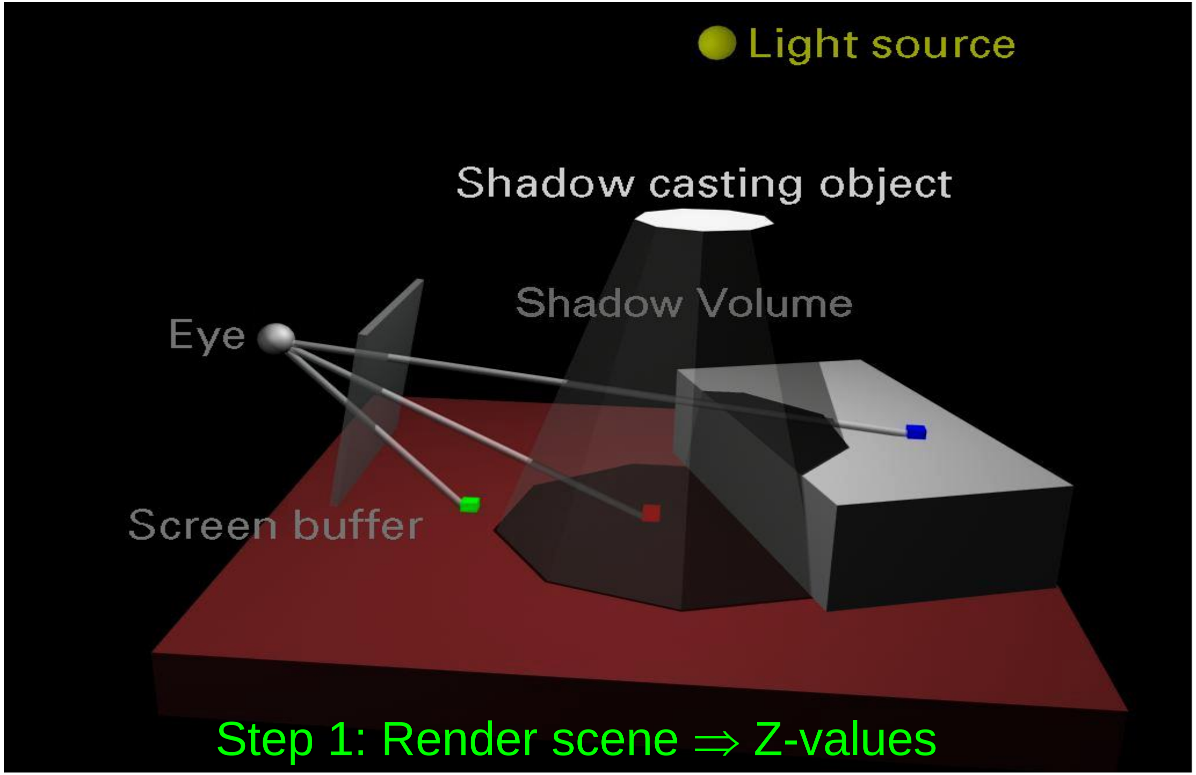


Shadow Volume Algorithm

- Shadow volumes in object precision
  - Calculated by CPU/Vertex Shaders
- Shadow test in image precision
  - Using stencil buffer as counter!



Shadow Volume Algorithm



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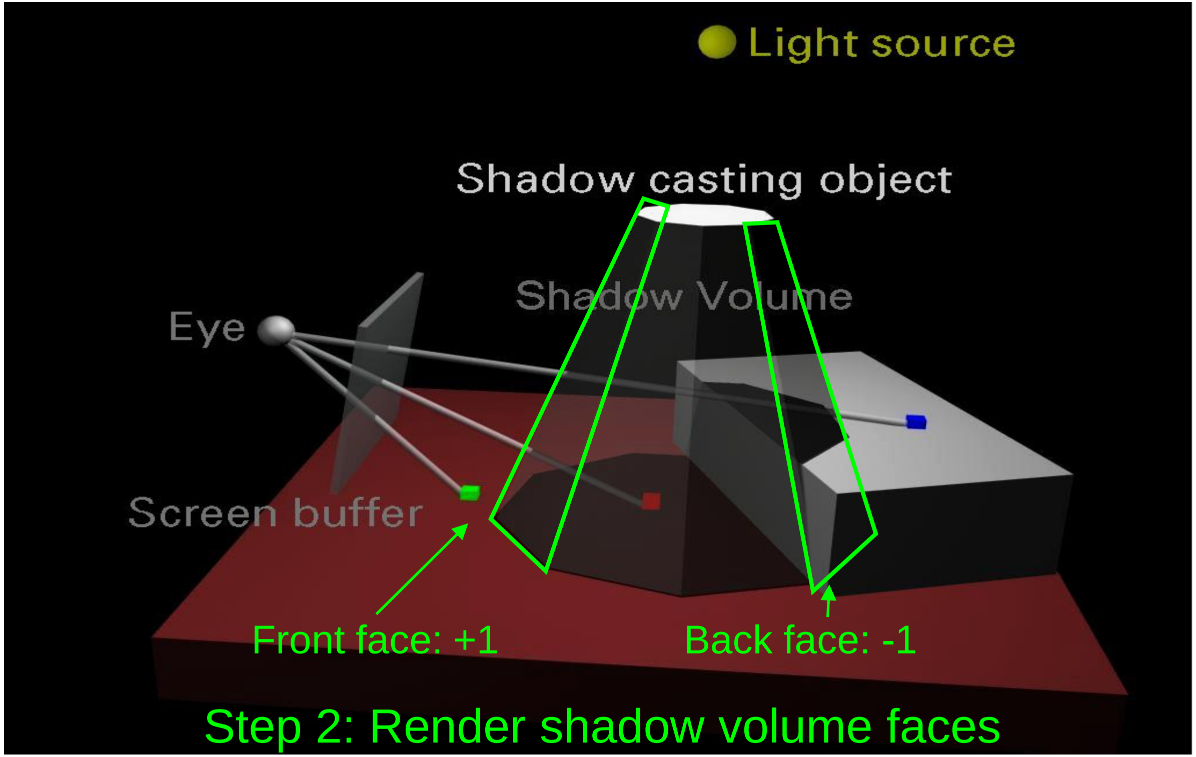

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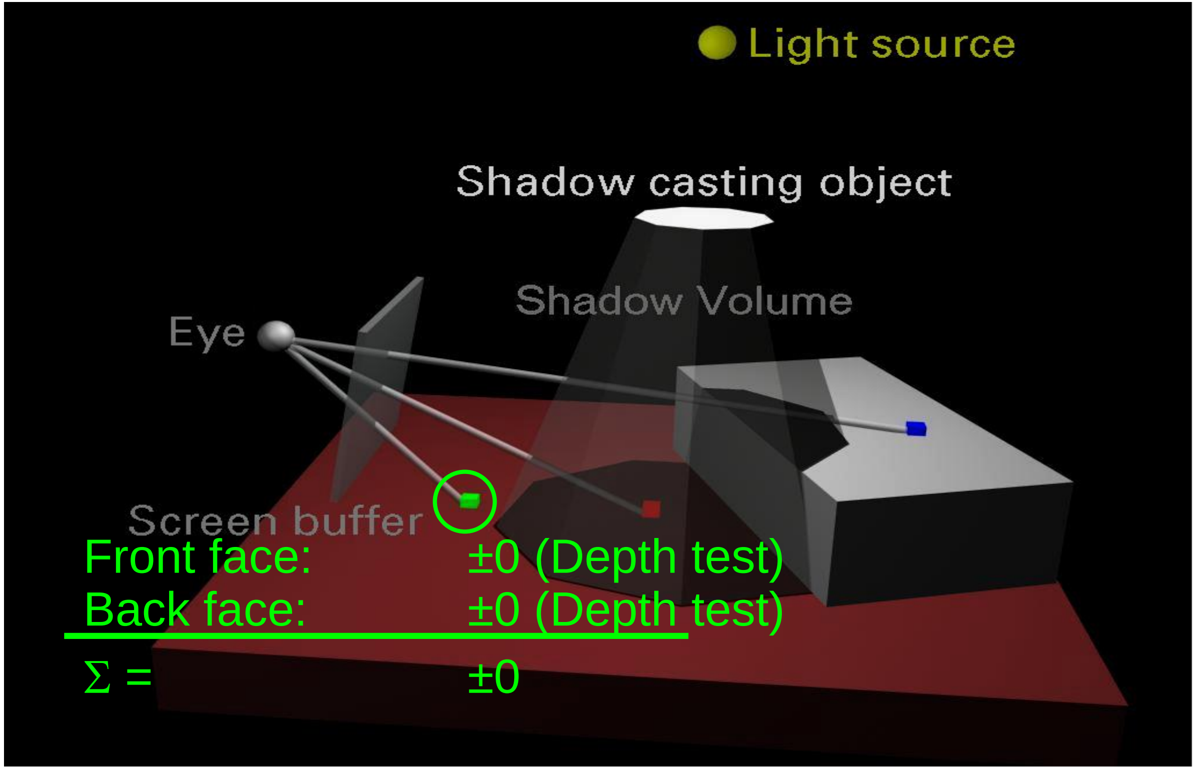
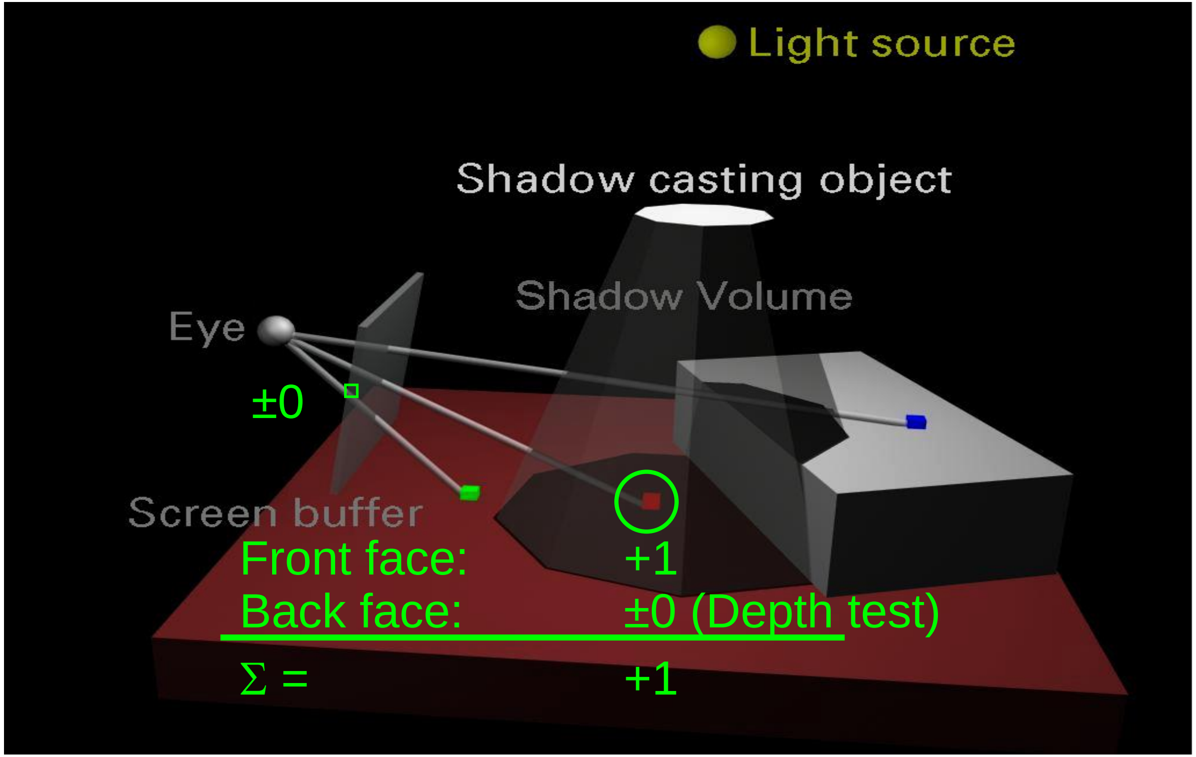


Shadow Volume Algorithm



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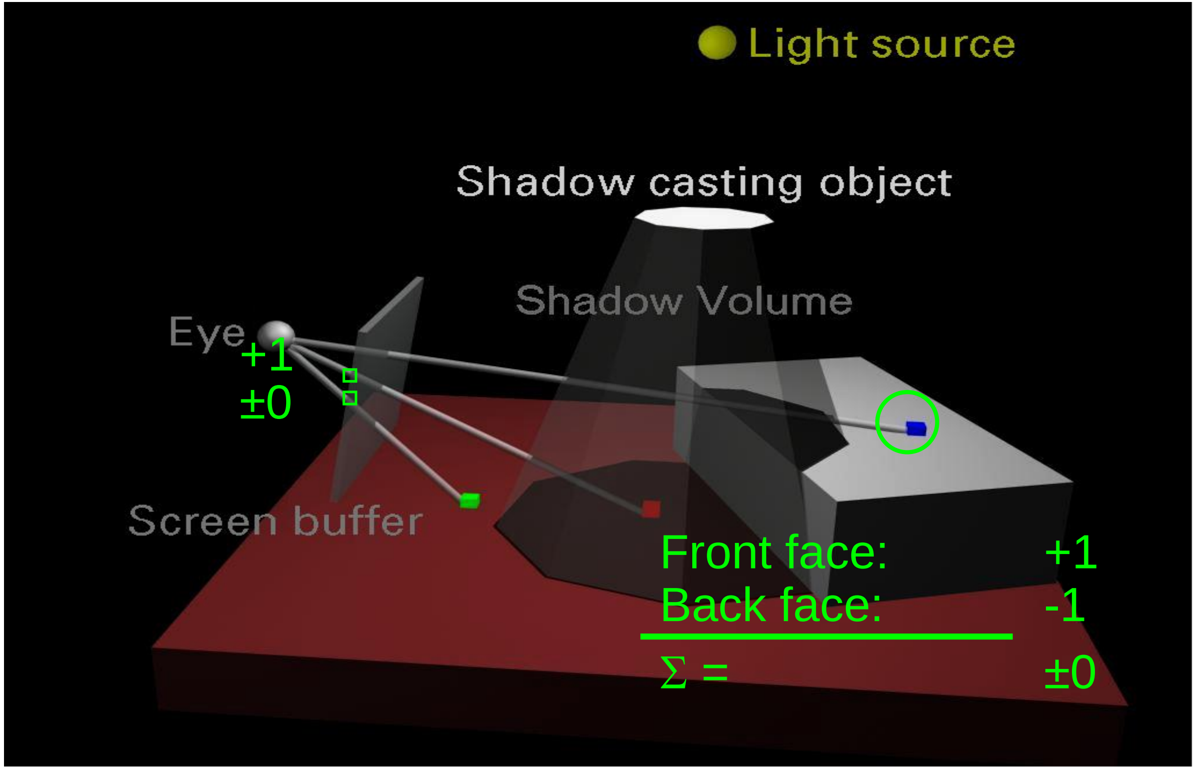
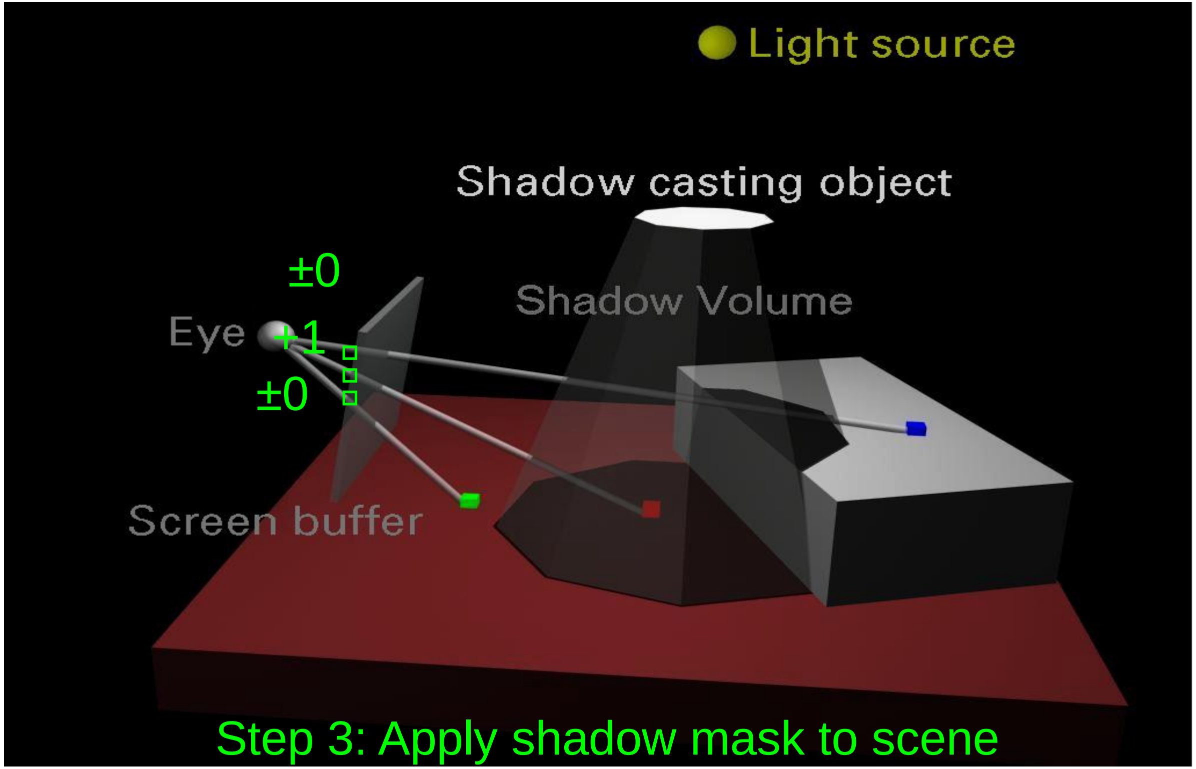


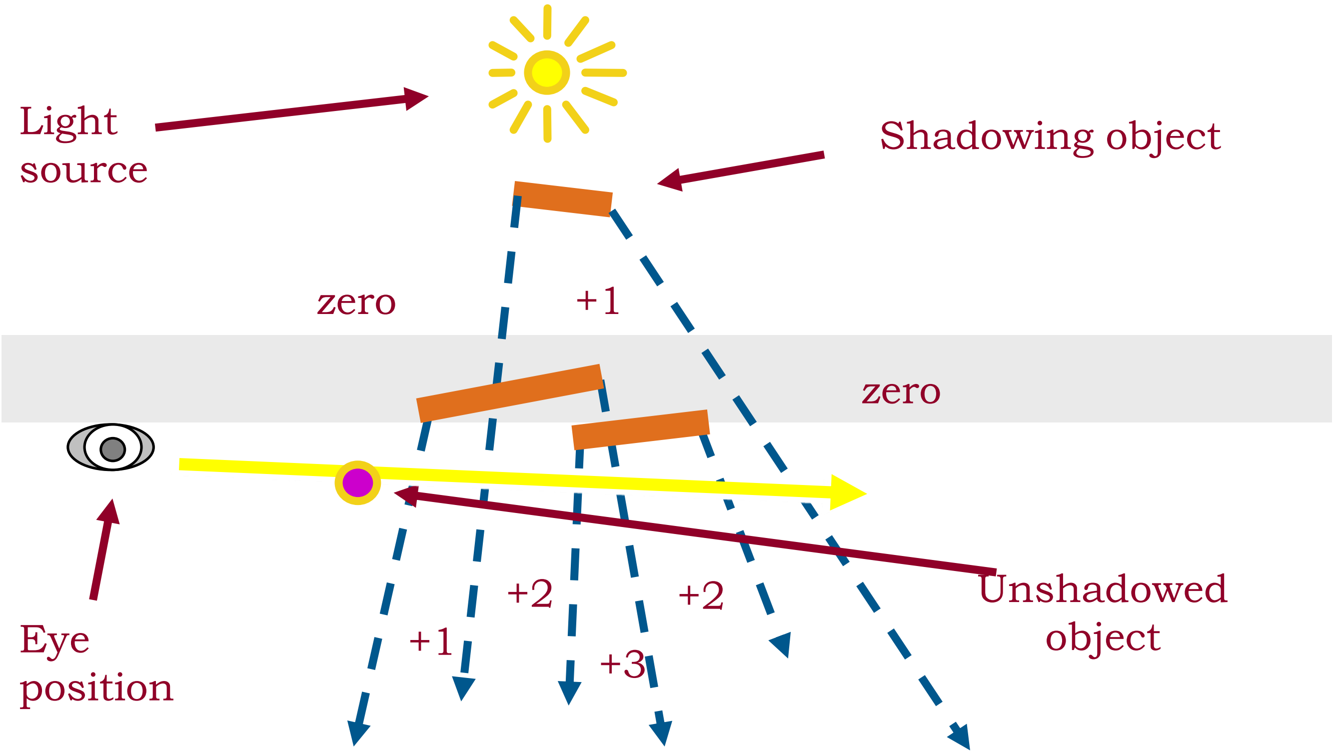
Shadow Volume Algorithm



Shadow Volume Algorithm (Zpass)

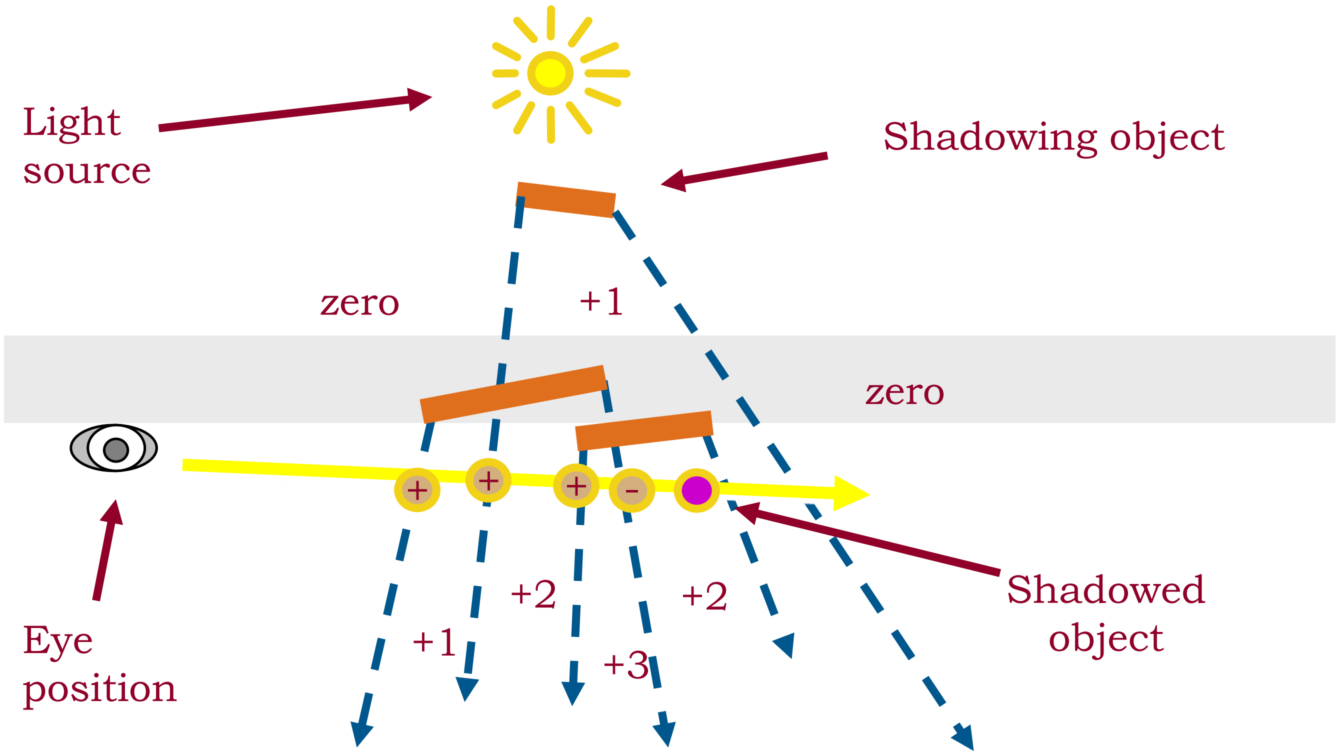
- Render scene to establish z-buffer
  - Can also do ambient illumination
- For each light
  - Clear stencil
  - Draw shadow volume twice using culling
    - Render front faces and increment stencil
    - Render back faces and decrement stencil
  - Illuminate all pixels not in shadow volume
    - Render testing stencil = 0
    - Use additive blend

Zpass Technique (Before Shadow)



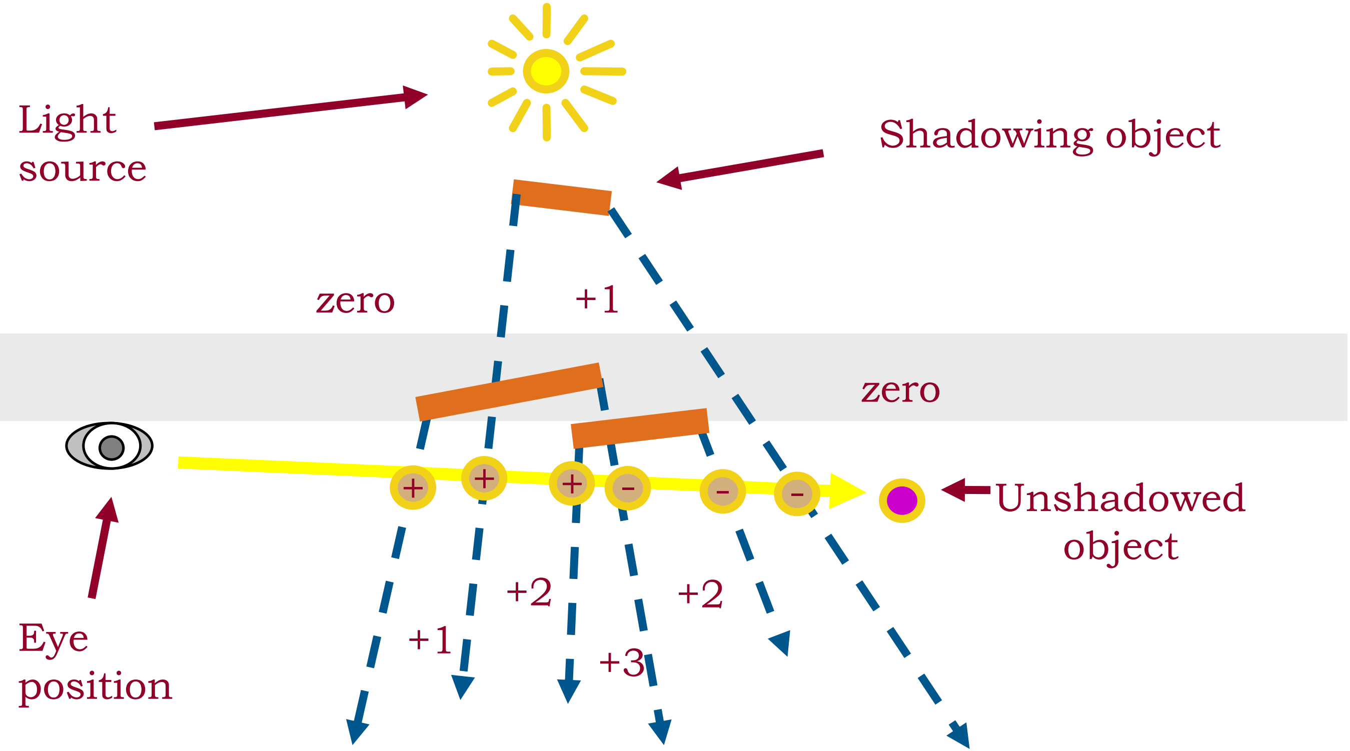
Shadow Volume Count = 0 (no depth tests passes)

Zpass Technique (In Shadow)



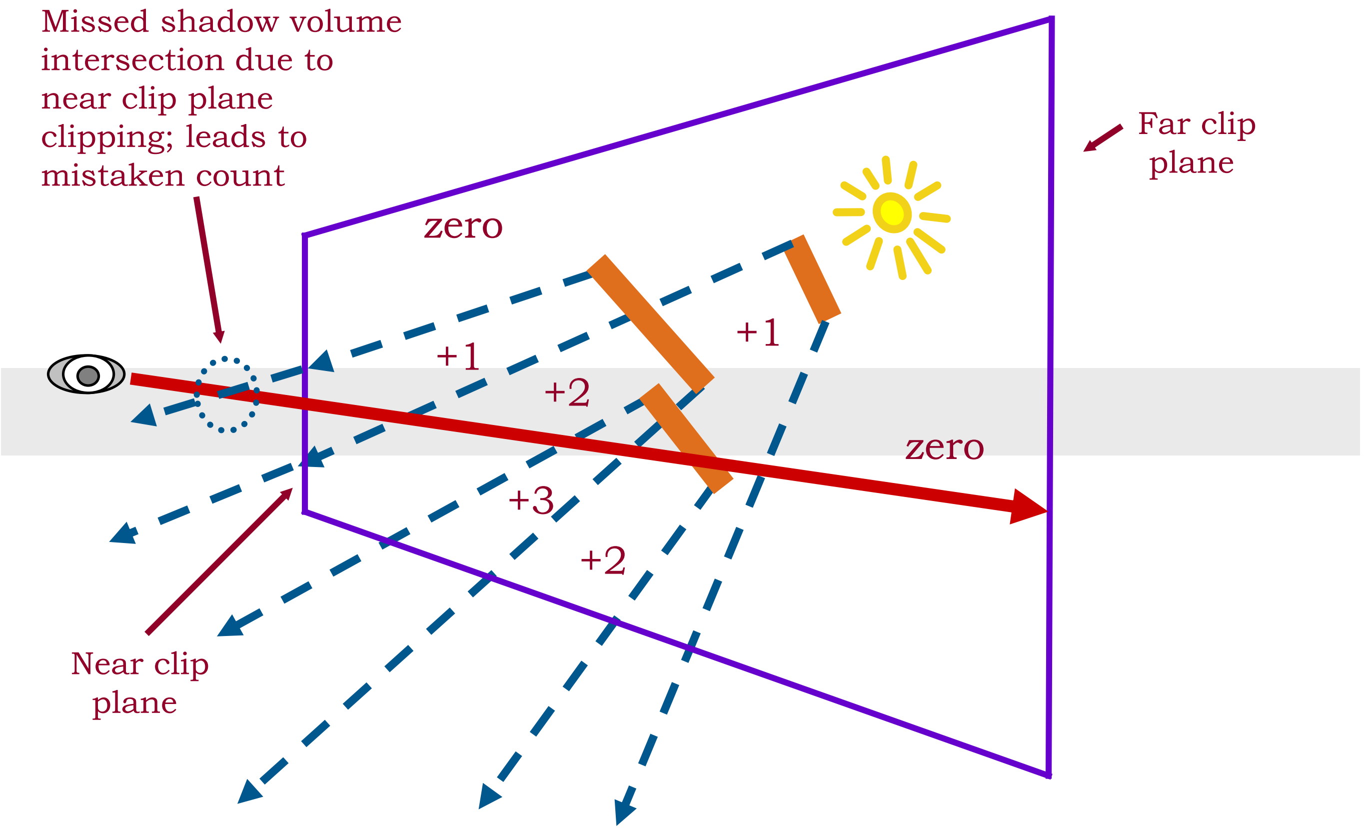
Shadow Volume Count = +1+1+1-1 = 2

Zpass Technique (Behind Shadow)



Shadow Volume Count = +1+1+1-1-1-1 = 0

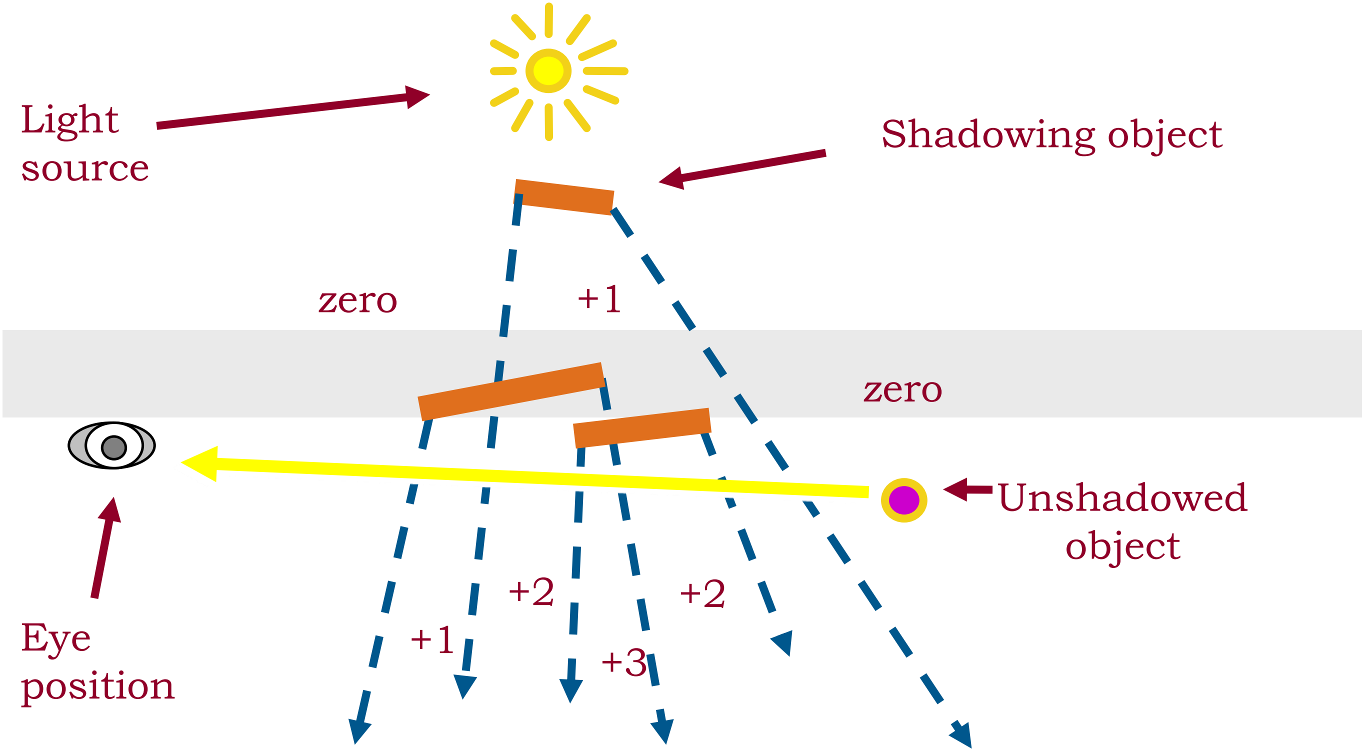
Zpass Near Plane Problem



Alternative: Zfail Technique

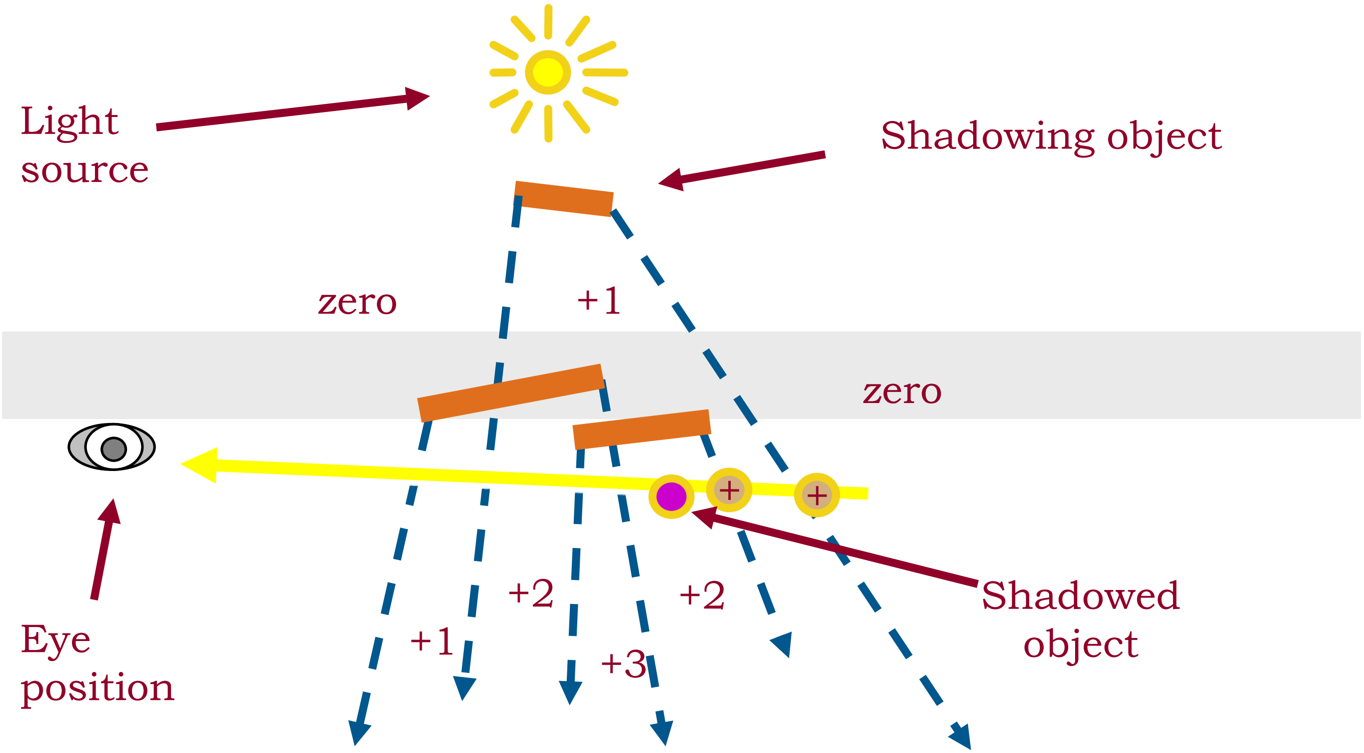
- Zpass near plane problem difficult to solve
  - Have to “cap” shadow volume at near plane
  - Expensive and not robust, many special cases
- Try reversing test order → Zfail technique (also known as Carmack’s reverse)
  - Start from infinity and stop at nearest intersection
    → Render shadow volume fragments only when depth test fails
  - Render back faces first and increment
  - Then front faces and decrement
  - Need to cap shadow volume at infinity or light extent

Zfail, Behind Shadow



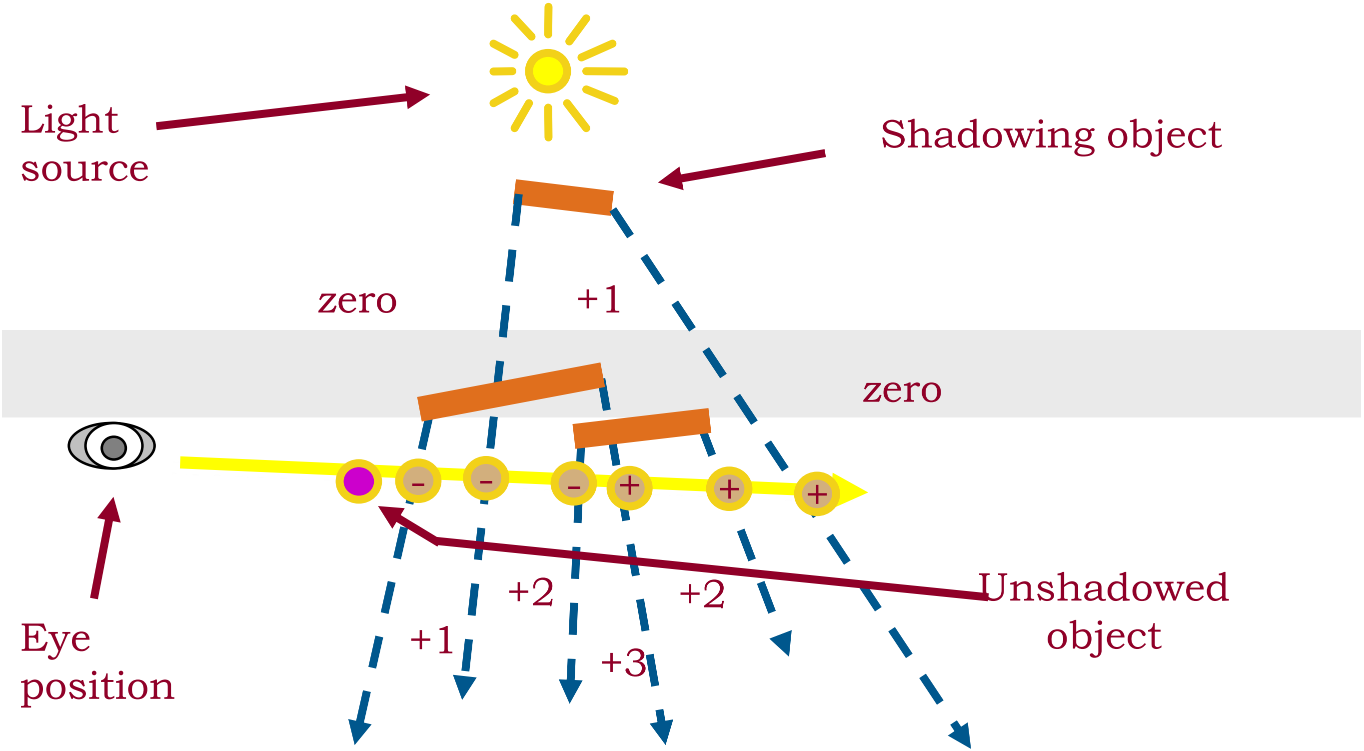
Shadow Volume Count = 0 (zero depth tests fail)

Zfail, in Shadow



Shadow Volume Count = +1+1 = 2

Zfail, before Shadow



Shadow Volume Count = -1-1-1+1+1+1 = 0

Shadow Volumes

- Shadow volume = closed polyhedron
- Actually 3 sets of polygons!
  1. Object polygons facing the light (“light cap”)
  2. Object polygons facing away from the light and projected to infinity (with w = 0) (“dark cap”)
  3. Actual shadow volume polygons (extruded object edges) (“sides”)
     → but which edges?

Computing Actual SV Polygons

- Trivial but bad: one volume per triangle
  - 3 shadow volume polygons per triangle
- Better: find exact silhouette
  - Expensive on CPU
- Even better: **possible silhouette edges**
  - Edge shared by a back-facing and front-facing polygon (with respect to light source!), extended to infinity
  - Actual extrusion can be done by vertex shader

Shadow Volumes Summary

- Advantages
  - Arbitrary receivers
  - Fully dynamic
  - Omnidirectional lights (unlike shadow maps!)
  - Exact shadow boundaries (pixel-accurate)
  - Automatic self shadowing
  - Broad hardware support (stencil)
- Disadvantages
  - Fill-rate intensive
  - Difficult to get right (Zfail vs. Zpass)
  - Silhouette computation required
  - Doesn’t work for arbitrary casters (smoke, fog…)

Conclusions

- Shadows are very important but still difficult

- Many shadow alg. (based on shadow volumes/shadow maps)
  - Variance shadow mapping (VSM)
  - Perspective shadow mapping (PSM)
  - Hierarchical shadow volume
  - Subdivided shadow maps
  - …

Outline

▪ Motivation & Terminology	MPG 12
▪ Approximate & projection shadows	MPG 12.1
▪ Shadow maps	MPG 12.3
▪ Shadow volumes	MPG 12.2
▪ Summary	

DCGI

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Questions?