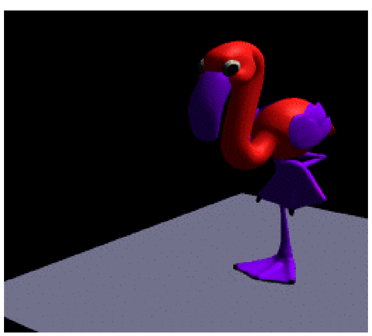
CIS 781
Shadows

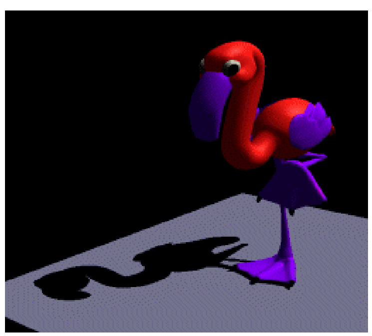
What is a Shadow?

From Webster's dictionary:

- *Shad-ow (noun): partial darkness or obscurity within a part of space from which rays from a source of light are cut off by an interposed opaque body*

Simplest Example : Projection to a Plane

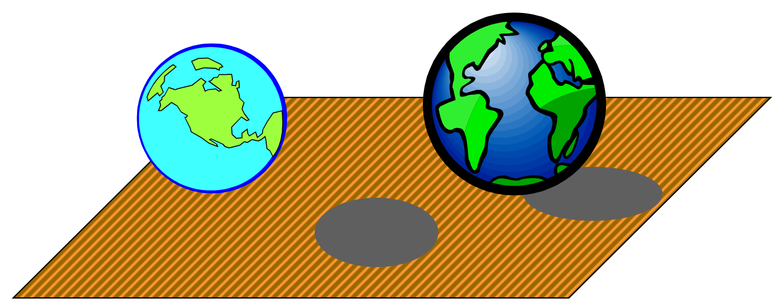




Cue to object-object relationship,
the bird isn't floating

Importance of Shadows

- Provides additional positional or depth cue.

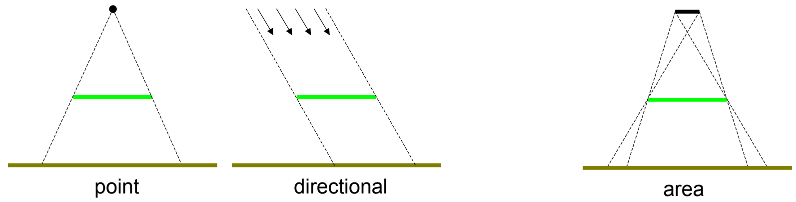


Issues To Address

- Two main problems to solve
  - Determine if a visible point is in shadow
    - Shadows are view-independent
  - How to illuminate the point?
    - Consider only local illumination
    - A decrease in diffuse light

Issues To Address

- Light Sources
  - Point or Directional ("Hard Shadows")



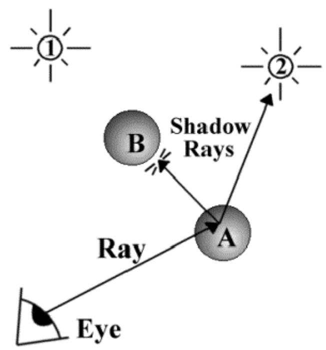
  - Area ("Soft Shadows", *umbra, penumbra*), more difficult problem

Issues To Address

- Number of light sources
- Size of the scene
- Static vs. Dynamic scene
- Self-shadowing
- Opaque vs. Transparent objects

Simple Approach: Raytracing

- Cast ray to light (*shadow feeler*)
- Surface point in shadow if shadow feeler hits an occluder object.
- Raytracing is slow, can we use OpenGL???

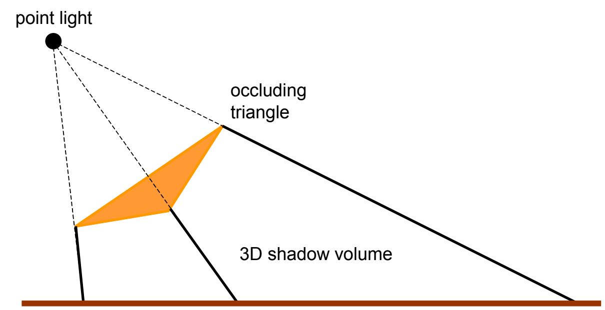


Two Common Shadow Approaches

- Shadow Volumes
- Shadow Map (Shadow Z-Buffer)
  - Projective Textures

Shadow Volumes

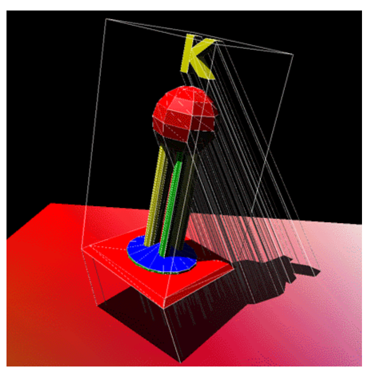
- A volume of space formed by an occluder
- Bounded by the edges of the occluder



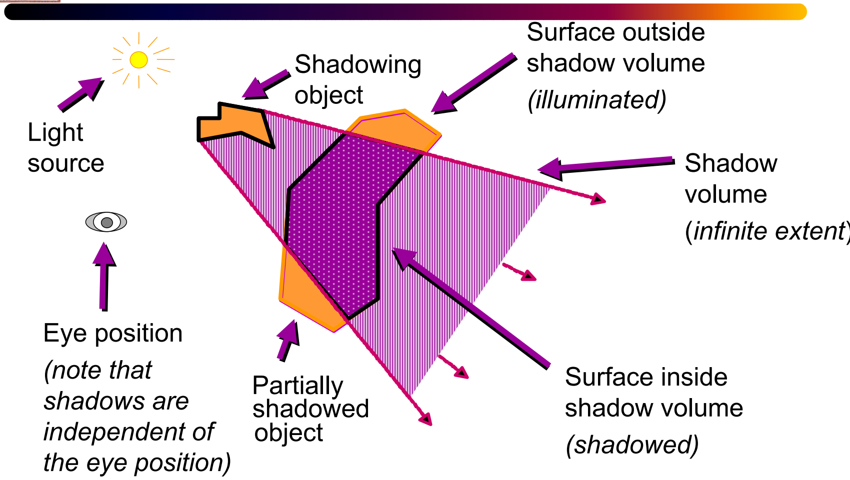
- Notice that the "far" end of the volume goes to infinity
  - Need to cap it

Shadow Volumes

- Compute shadow volume for all visible polygons from the light source
- Add the shadow volume polygons to your scene database
  - Tag them as shadow polygons
  - Assign its associated light source



2D Cutaway of a Shadow Volume



Shadow Volume Advantages

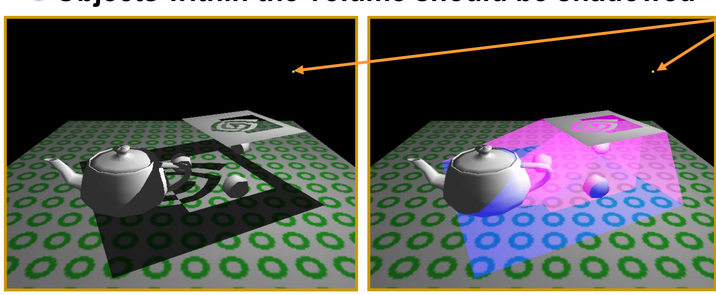
- Omni-directional approach
  - Not just spotlight frustums as with shadow maps
- Automatic self-shadowing
  - Everything can shadow everything, including self
  - Without *shadow acne* artifacts as with shadow maps
- Window-space shadow determination
  - Shadows accurate to a pixel (Object method)
  - Or sub-pixel if multisampling is available
- Required stencil buffer broadly supported today
  - OpenGL support since version 1.0 (1991)
  - Direct3D support since DX6 (1998)

Shadow Volume Disadvantages

- Ideal light sources only
  - Limited to local point and directional lights
  - No area light sources for soft shadows
- Requires polygonal models with connectivity
  - Models must be closed (2-manifold)
  - Models must be free of non-planar polygons
- Silhouette computations are required
  - Can burden CPU
  - Particularly for dynamic scenes
- Inherently multi-pass algorithm
- Consumes lots of GPU fill rate

Visualizing Shadow Volumes in 3D

- **Occluders and light source cast out a shadow volume**
  - **Objects within the volume should be shadowed**

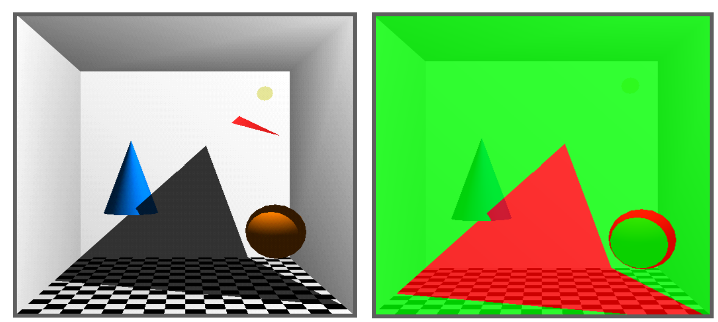


Scene with shadows from an NVIDIA logo casting a shadow volume

Visualization of the shadow volume

Visualizing the Stencil Buffer Counts

Shadowed scene **Stencil buffer contents**



Stencil counts beyond 1 are possible for multiple or complex occluders.

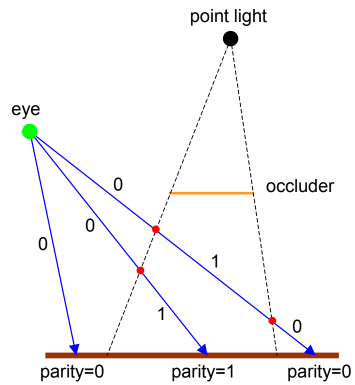
red = stencil value of 1
green = stencil value of 0

GLUT *shadowvol* example credit: Tom McReynolds

Shadow Volumes

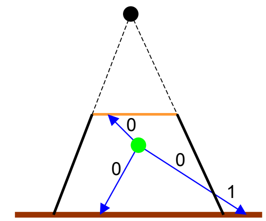
When is a surface point inside shadow?

- Use a parity test similar to a "ray inside-outside" test
- Initially set parity to 0 and shoot ray from eye to P
  - Invert parity when ray crosses shadow volume boundary
  - parity = 0, not in shadow, parity = 1, in shadow

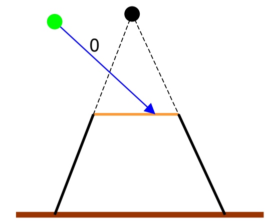


Problems With Parity Test

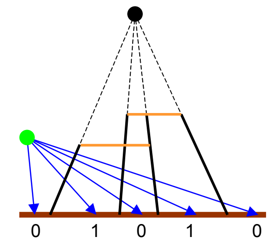
Eye inside of shadow volume



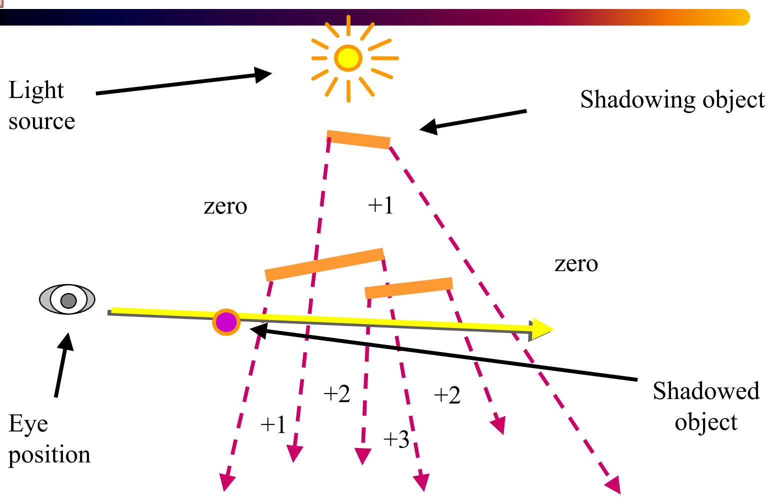
Self-shadowing of visible occluders



Multiple overlapping shadow volumes

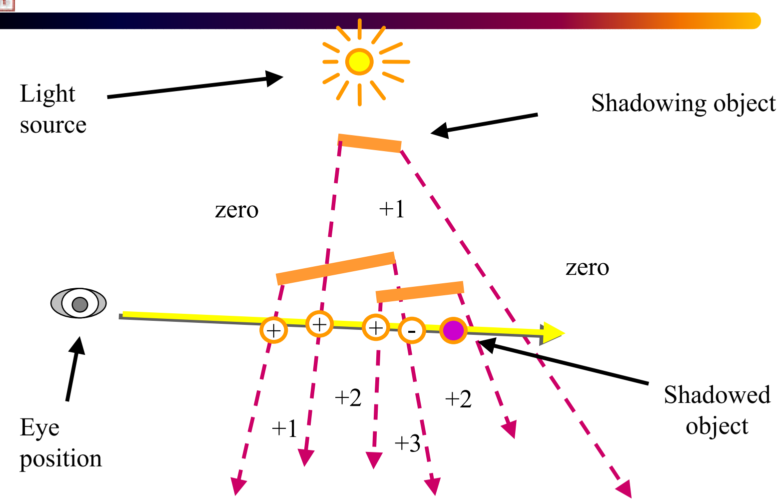


Better Solution : Counter



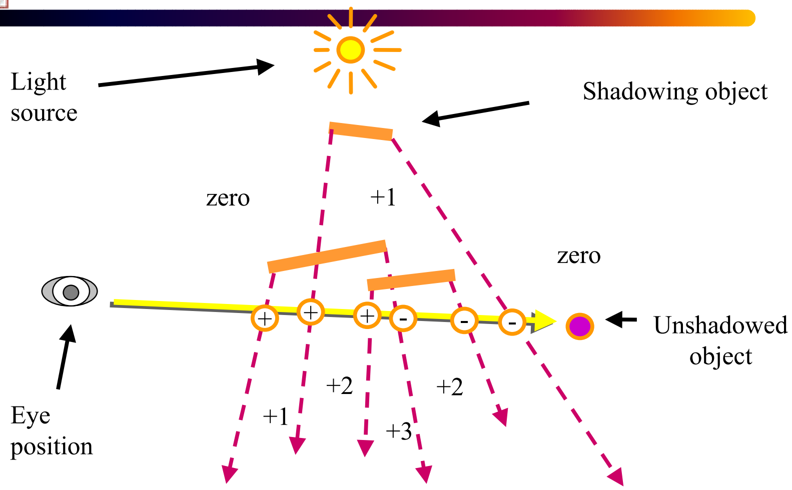
Shadow Volume Count = 0

Better Solution : Counter



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

Better Solution : Counter

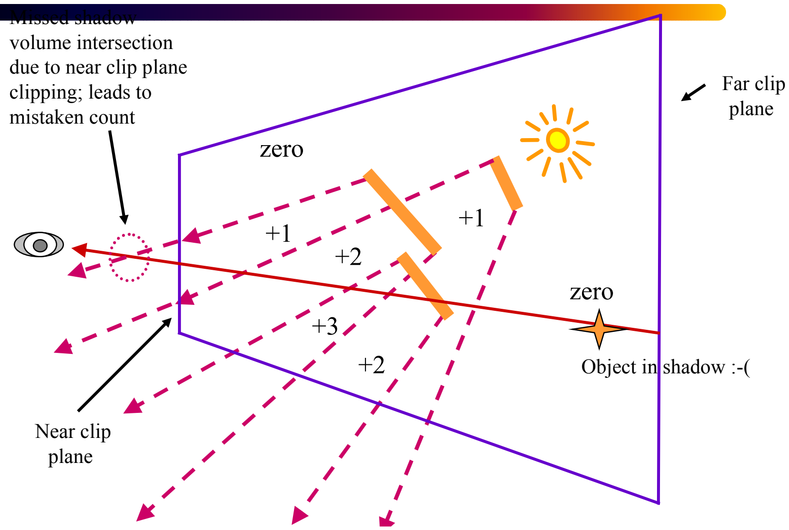


Shadow Volume Count = +1+1+1-1-1-1 = 0

Graphics Hardware Approach Using The Stencil Buffer

- *Zpass approach*
  - Render visible scene to depth buffer
  - Turn off depth and color, turn on stencil
  - Init. stencil buffer given viewpoint
  - Draw shadow volume twice using face culling
    - 1st pass: render *front* faces and *increment* when depth test passes
    - 2nd pass: render *back* faces and *decrement* when depth test passes
- stencil pixels != 0 in shadow, = 0 are lit

Zpass Problem



Zfail Approach

- Render visible scene to depth buffer
- Turn off depth and color, turn on stencil
- Init. stencil buffer given viewpoint
- Draw shadow volume twice using face culling
  - 1st pass: render *back* faces and *increment* when depth test fails
  - 2nd pass: render *front* faces and *decrement* when depth test fails
- stencil pixels != 0 in shadow, = 0 are lit

Clipping Plane Problem

- *Zpass* : Near clipping plane
  - Move near clipping plane closer to eye?
    - Lose depth precision in perspective
- *Zfail* : Far clipping plane
  - Move far clipping plane closer to eye?
    - Set far clipping plane to infinity.
    - See "***Practical & Robust Stenciled Shadow Volumes for Hardware-Accelerated Rendering"*** by Cass Everitt & Mark J. Kilgard, Nvidia

Zfail *versus* Zpass *Comparison (1)*

- **When stencil increment/decrements occur**
  - ***Zpass:* on depth test pass**
  - ***Zfail:* on depth test fail**
- **Increment on**
  - ***Zpass:* front faces**
  - ***Zfail:* back faces**
- **Decrement on**
  - ***Zpass:* front faces**
  - ***Zfail:* back faces**

Zfail *versus* Zpass *Comparison (2)*

- Both cases order passes based stencil operation
  - First, render *increment* pass
  - Second, render *decrement* pass
  - Why?
    - Because standard stencil operations saturate
    - Wrapping stencil operations can avoid this
- Which clip plane creates a problem
  - *Zpass:* near clip plane
  - *Zfail:* far clip plane
- Either way is foiled by view frustum clipping
  - Which clip plane (front or back) changes

Insight!

- If we could avoid *either* near plane *or* far plane view frustum clipping, shadow volume rendering could be robust
- Avoiding near plane clipping
  - Not really possible
  - Objects can always be behind you
  - Moreover, depth precision in a perspective view goes to hell when the near plane is too near the eye
- Avoiding far plane clipping
  - Perspective make it possible to render at infinity
  - Depth precision is terrible at infinity, but we just care about avoiding clipping

Avoiding Far Plane Clipping

- Usual practice for perspective GL projection matrix
  - Use *glFrustum* (or *gluPerspective*)
  - Requires two values for near & far clip planes
    - Near plane's distance from the eye
    - Far plane's distance from the eye
  - Assumes a *finite* far plane distance
- Alternative projection matrix
  - Still requires near plane's distance from the eye
  - But assume far plane is *at infinity*
- What is the limit of the projection matrix when the far plane distance goes to infinity?

Standard glFrustum *Projection Matrix*

$$\mathbf{P} = \begin{bmatrix} \frac{2\times Near}{Right-Left} & 0 & \frac{Right+Left}{Right-Left} & 0 \\ 0 & \frac{2\times Near}{Top-Bottom} & \frac{Top+Bottom}{Top-Bottom} & 0 \\ 0 & 0 & -\frac{Far+Near}{Far-Near} & -\frac{2\times Far\times Near}{Far-Near} \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

- **Only third row depends on *Far* and *Near***

Limit of glFrustum *Projection Matrix*

$$\lim_{Far\to\infty} \mathbf{P} = \mathbf{P}_{\mathbf{inf}} = \begin{bmatrix} \frac{2\times Near}{Right-Left} & 0 & \frac{Right+Left}{Right-Left} & 0 \\ 0 & \frac{2\times Near}{Top-Bottom} & \frac{Top+Bottom}{Top-Bottom} & 0 \\ 0 & 0 & -1 & -2\times Near \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

- **First, second, and fourth rows are the same as in P**
- **But third row *no longer* depends on *Far***
  - **Effectively, *Far* equals ∞**

Verifying P_{inf} Will Not Clip Infinitely Far Away Vertices (1)

- What is the most distant possible vertex in front of the eye?
  - Ok to use homogeneous coordinates
  - OpenGL convention looks down the negative Z axis
  - So most distant vertex is (0,0,-D,0) where D>0
- Transform (0,0,-D,0) to window space
  - Is such a vertex clipped by P_{inf}?
  - No, it is not clipped, as explained on the next slide

Verifying P_{inf} Will Not Clip Infinitely Far Away Vertices (2)

- Transform eye-space (0,0,-D,0) to clip-space

$$\begin{bmatrix} x_c \\ y_c \\ -D \\ -D \end{bmatrix} = \begin{bmatrix} x_c \\ y_c \\ z_c \\ w_c \end{bmatrix} = \begin{bmatrix} \frac{2\times Near}{Right-Left} & 0 & \frac{Right+Left}{Right-Left} & 0 \\ 0 & \frac{2\times Near}{Top-Bottom} & \frac{Top+Bottom}{Top-Bottom} & 0 \\ 0 & 0 & -1 & -2\times Near \\ 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -D \\ 0 \end{bmatrix}$$

- **Then, assuming glDepthRange(0,1), transform clip-space position to window-space position**

$$z_w = 0.5\times\frac{z_c}{w_c}+0.5 = 0.5\times\frac{-D}{-D}+0.5 = 1$$

- **So ∞ *in front of eye* transforms to the maximum window-space Z value, but is still within the valid depth range (i.e., not clipped)**

Is P_{inf} Bad for Depth Buffer Precision?

- Naïve question
  - Wouldn't moving the far clip plane to infinity waste depth buffer precision? Seems plausible, but
- Answer: Not really
  - Minimal depth buffer precision is wasted in practice
  - This is due to projective nature of perspective
- Say *Near* is 1.0 and *Far* is 100.0 (typical situation)
  - P would transform eye-space infinity to only 1.01 in window space
  - Only a 1% compression of the depth range is required to render infinity without clipping
  - Moving near closer would hurt precision

P_{inf} Depth Precision Scale Factor

- Using Pinf with *Near* instead of P with *Near* and *Far* compresses (scales) the depth precision by

$$\frac{(Far-Near)}{Far}$$

- The compression of depth precision is uniform, but the depth precision itself is already non-uniform on eye-space interval [*Near*,*Far*] due to perspective
  - So the discrete loss of precision is more towards the far clip plane
- Normally, *Far* >> *Near* so the scale factor is usually less than but still nearly 1.0
  - So the compression effect is minor

Robust Stenciled Shadow Volumes

Without Near (or Far) Plane Capping

- Use *Zfail* Stenciling Approach
  - Must render geometry to close shadow volume extrusion on the model and at infinity (explained later)
- Use the P_{inf} Projection Matrix
  - No worries about far plane clipping
  - Losses some depth buffer precision (but not much)
- Draw the infinite vertices of the shadow volume using homogeneous coordinates (w=0)

Rendering Closed, but Infinite, Shadow Volumes

- To be robust, the shadow volume geometry must be closed, even at infinity
- Three sets of polygons close the shadow volume
  1. *Possible silhouette edges* extruded to infinity away from the light
  2. All of the occluder's back-facing (w.r.t. the light) triangles projected away from the light to infinity
  3. All of the occluder's front-facing (w.r.t. the light) triangles
- We assume the object vertices and light position are homogeneous coordinates, i.e. (x,y,z,w)
  – Where $w \geq 0$

1st Set of Shadow Volume Polygons

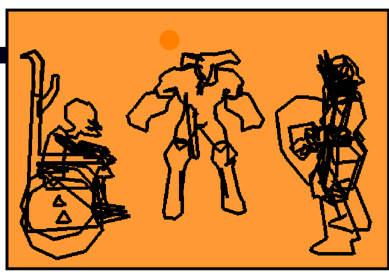
- Assuming
  – A and B are vertices of an occluder model's possible silhouette edge
  – And L is the light position
- For all A and B on silhouette edges of the occluder model, render the quad

$$\langle B_x, B_y, B_z, B_w \rangle$$
$$\langle A_x, A_y, A_z, A_w \rangle$$
$$\langle A_x L_w - L_x A_w, A_y L_w - L_y A_w, A_z L_w - L_z A_w, 0 \rangle$$
$$\langle B_x L_w - L_x B_w, B_y L_w - L_y B_w, B_z L_w - L_z B_w, 0 \rangle$$

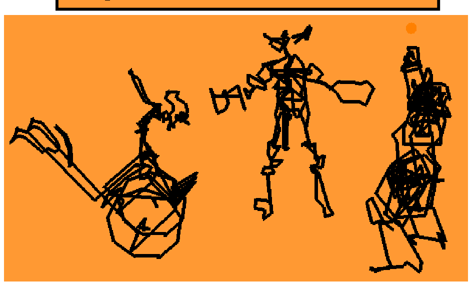
Homogenous vector differences

- What is a possible silhouette edge?
  - One polygon sharing an edge faces toward L
  - Other faces away from L

Examples Silhouette Edges



An object viewed from the same basic direction that the light is shining on the object has an identifiable light-view silhouette



An object's light-view silhouette appears quite jumbled when viewed form a point-of-view that does not correspond well with the light's point-of-view

2nd and 3rd Set of Shadow Volume Polygons

- 2nd set of polygons
  – Assuming A, B, and C are each vertices of occluder model's back-facing triangles w.r.t. light position L

$$\langle A_x L_w - L_x A_w, A_y L_w - L_y A_w, A_z L_w - L_z A_w, 0 \rangle$$
$$\langle B_x L_w - L_x B_w, B_y L_w - L_y B_w, B_z L_w - L_z B_w, 0 \rangle$$
$$\langle C_x L_w - L_x C_w, C_y L_w - L_y C_w, C_z L_w - L_z C_w, 0 \rangle$$

Homogenous vector differences

  - These vertices are effectively directions (w=0)
- 3rd set of polygons
  - Assuming A, B, and C are each vertices of occluder model's front-facing triangles w.r.t. light position L

$$\langle A_x, A_y, A_z, A_w \rangle$$
$$\langle B_x, B_y, B_z, B_w \rangle$$
$$\langle C_x, C_y, C_z, C_w \rangle$$

Requirements for Stenciled Shadow Volumes

1. Models must be composed of triangles only (avoiding non-planar polygons)
2. Models must be closed (2-manifold) and have a consistent winding order
   - Bergeron ['86] approach could be used to handle "open" models if necessary
3. Homogeneous object coordinates are permitted, assuming w≥0
   - If not, (x, y, z, -1) = (-x, -y, -z, 1)
4. Ideal light sources only
   - Directional or positional, assuming w≥0

Requirements for Stenciled Shadow Volumes

5. Connectivity information for occluding models must be available
   - So silhouette edges w.r.t. light positions can be determined at shadow volume construction time
6. Projection matrix must be perspective
   - Not orthographic
   - NV_depth_clamp extension provides orthographic support (more later)
7. Render must guarantee "watertight" rasterization
   - No double hitting pixels at shared polygon edges
   - No missed pixels at shared polygon edges

Requirements for Stenciled Shadow Volumes

8. Enough stencil bits
   - N stencil bits where 2^N is greater than the maximum shadow depth count ever encountered
   - Scene dependent
   - 8-bits is usually quite adequate & what all recent stencil hardware provides
   - Wrapping stencil increment/decrement operations (i.e. OpenGL's EXT_stencil_wrap) permit deeper shadow counts, modulo aliasing with zero
   - Realize that shadow depths > 255 imply too much fill rate for interactive applications

Requirements for Stenciled Shadow Volumes

9. Rendering features provided by OpenGL 1.0 or DirectX 6 (or subsequent versions)
   - Transformation & clipping of homogenous positions
   - Front- and back-face culling
   - Masking color and depth buffer writes
   - Depth buffering (i.e. conventional Z-buffering)
   - Stencil-testing support

In practice, these are quite reasonable requirements for nearly any polygonal-based 3D game or application

Examples

Scene with shadows. Yellow light is embedded in the green three-holed object. P_{inf} is used for all the following scenes.

Same scene visualizing the shadow volumes.

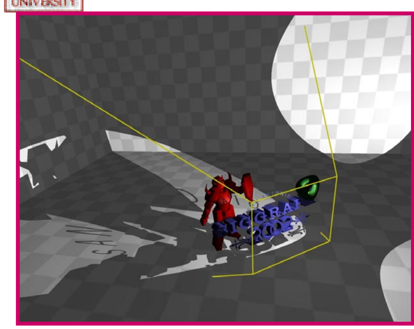
Examples

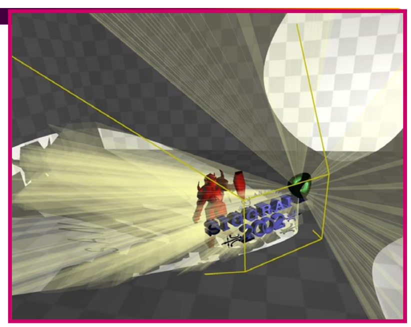
Details worth noting . . .

Fine details: Shadows of the A, N, and T letters on the knight's armor and shield.

Hard case: The shadow volume from the front-facing hole would definitely intersect the near clip plane.

Examples

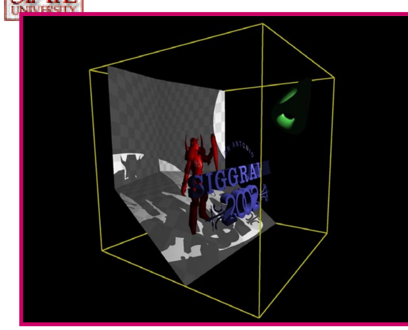


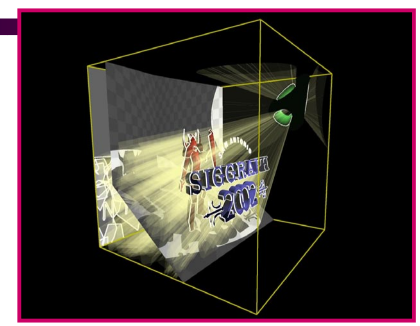


Alternate view of same scene with shadows. Yellow lines indicate previous view's view frustum boundary. Recall shadows are view-independent.

Shadow volumes from the alternate view.

Examples



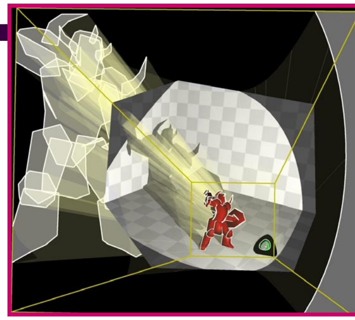


Clip-space view. Original view's scene seen from clip space. The back plane is "at infinity" with very little effective depth precision near infinity.

Clip-space view of shadow volumes. Back-facing triangles w.r.t. light are seen projected onto far plane at infinity.

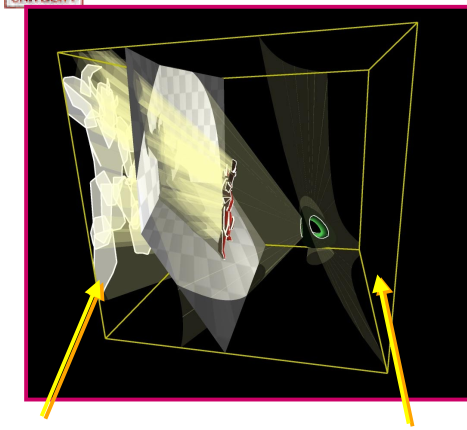
Examples

Original eye's view. Again, yellow light is embedded in the green three-holed object. P_{inf} is used for all the following scenes.



Eye-space view of previous eye's view. Clipped to the previous eye's P_{inf} view frustum. Shows knight's projection to infinity.

Examples



Clip-space view of previous eye's view. Shows shadow volume closed at infinity and other shadow volume's intersection with the near clip plane.

Original eye's **far** clip plane

Original eye's **near** clip plane

Stenciled Shadow Volumes with Multiple Lights

Three colored lights. Diffuse/specular bump mapped animated characters with shadows. 34 fps on GeForce4 Ti 4600; 80+ fps for one light.

Stenciled Shadow Volumes for Simulating Soft Shadows

Cluster of 12 dim lights approximating an area light source. Generates a soft shadow effect; careful about banding. 8 fps on GeForce4 Ti 4600.

The cluster of point lights.

Issues With Shadow Volumes

- The addition of shadow volume polygons can greatly increase your database size
- Using the stencil buffer approach, pixel fill becomes a key speed factor
- Create a shadow volume from the silhouette of an object instead of each polygon
- Take care when coding the algorithm

Hardware Enhancements: Wrapping Stencil Operations

- Conventional OpenGL 1.0 stencil operations
  - GL_INCR increments and clamps to 2^N-1
  - GL_DECR decrements and clamps to zero
- DirectX 6 introduced "wrapping" stencil operations
- Exposed by OpenGL's EXT_stencil_wrap extension
  - GL_INCR_WRAP_EXT increments modulo 2^N
  - GL_DECR_WRAP_EXT decrements modulo 2^N
- Avoids saturation throwing off the shadow volume depth count
  - Still possible, though very rare, that 2^N, 2×2^N, 3×2^N, etc. can alias to zero

Hardware Enhancements: Two-sided Stencil Testing (1)

- Current stenciled shadow volumes required rendering shadow volume geometry twice
  - First, rasterizing front-facing geometry
  - Second, rasterizing back-facing geometry
- Two-sided stencil testing requires only one pass
  - Two sets of stencil state: front- and back-facing
  - Boolean enable for two-sided stencil testing
  - When enabled, back-facing stencil state is used for stencil testing back-facing polygons
  - Otherwise, front-facing stencil state is used
  - Rasterizes just as many fragments, but more efficient for CPU & GPU

Hardware Enhancements: Two-sided Stencil Testing (2)

NV_stencil_two_side OpenGL extension

- Enable applies if GL_STENCIL_TEST also enabled
  ```
  glEnable(GL_STENCIL_TEST_TWO_SIDE_NV);
  glDisable(GL_STENCIL_TEST_TWO_SIDE_NV);
  ```
- Control of front- and back-facing stencil state update
  ```
  glActiveStencilFaceNV(GL_FRONT);
  glActiveStencilFaceNV(GL_BACK);
  ```
- Existing stencil routines (glStencilOp, glStencilMask, glStencilFunc) update the active stencil face state
- glClear and non-polygon primitives always use the front-facing stencil state

- Expect on future GPUs

Usage of NV_stencil_two_side & EXT_stencil_wrap

OLD SCHOOL

```
glDepthMask(0);
glColorMask(0,0,0,0);
glEnable(GL_CULL_FACE);
glEnable(GL_STENCIL_TEST);
glStencilMask(~0);
glStencilFunc(GL_ALWAYS, 0, ~0);
 // Increment for back faces
glCullFace(GL_BACK);
glStencilOp(GL_KEEP,   // stencil test fail
            GL_INCR,   // depth test fail
            GL_INCR);  // depth test pass
renderShadowVolumePolygons();
// Decrement for front faces
glCullFace(GL_FRONT);
glStencilOp(GL_KEEP,   // stencil test fail
            GL_DECR,   // depth test fail
            GL_KEEP);  // depth test pass
renderShadowVolumePolygons();
```

NEW SCHOOL

```
glDepthMask(0);
glColorMask(0,0,0,0);
glDisable(GL_CULL_FACE);
glEnable(GL_STENCIL_TEST);
glEnable(GL_STENCIL_TEST_TWO_SIDE_NV);
glActiveStencilFaceNV(GL_BACK);
glStencilOp(GL_KEEP,            // stencil test fail
            GL_INCR_WRAP_EXT,   // depth test fail
            GL_KEEP);           // depth test pass
glStencilMask(~0);
glStencilFunc(GL_ALWAYS, 0, ~0);
glActiveStencilFaceNV(GL_FRONT);
glStencilOp(GL_KEEP,    // stencil test fail
            GL_DECR_WRAP_EXT,  // depth test fail
            GL_KEEP);   // depth test pass
glStencilMask(~0);
glStencilFunc(GL_ALWAYS, 0, ~0);
renderShadowVolumePolygons();
```

New approach calls renderShadowVolumePolygons() just once.

Shadow Volume History (1)

- Invented by Frank Crow ['77]
  - Software rendering scan-line approach
- Brotman and Badler ['84]
  - Software-based depth-buffered approach
  - Used lots of point lights to simulate soft shadows
- Pixel-Planes [Fuchs, et.al. '85] hardware
  - First hardware approach
  - Point within a volume, rather than ray intersection
- Bergeron ['96] generalizations
  - Explains how to handle open models
  - And non-planar polygons

Shadow Volume History (2)

- Fournier & Fussell ['88] theory
  - Provides theory for shadow volume counting approach within a frame buffer
- Akeley & Foran invent the stencil buffer
  - IRIS GL functionality, later made part of OpenGL 1.0
  - Patent filed in '92
- Heidmann [*IRIS Universe article, '91*]
  - IRIS GL stencil buffer-based approach
- Deifenbach's thesis ['96]
  - Used stenciled volumes in multi-pass framework

Shadow Volume History (3)

- Dietrich slides [March '99] at GDC
  - Proposes *zfail* based stenciled shadow volumes
- Kilgard whitepaper [March '99] at GDC
  - *Invert* approach for planar cut-outs
- Bilodeau slides [May '99] at Creative seminar
  - Proposes way around near plane clipping problems
  - Reverses depth test function to reverse stencil volume ray intersection sense
- Carmack [unpublished, early 2000]
  - First detailed discussion of the equivalence of *zpass* and *zfail* stenciled shadow volume methods

Shadow Volume History (4)

- Kilgard [2001] at GDC and CEDEC Japan
  - Proposes *zpass* capping scheme
    - Project back-facing (w.r.t. light) geometry to the near clip plane for capping
    - Establishes *near plane ledge* for crack-free near plane capping
  - Applies homogeneous coordinates (w=0) for rendering infinite shadow volume geometry
- Cass and Kilgard [2001] presented most of these slides at GDC. See their papers on the nVidia web site.
- Carmack's Doom engine uses this technique.

Shadow Maps

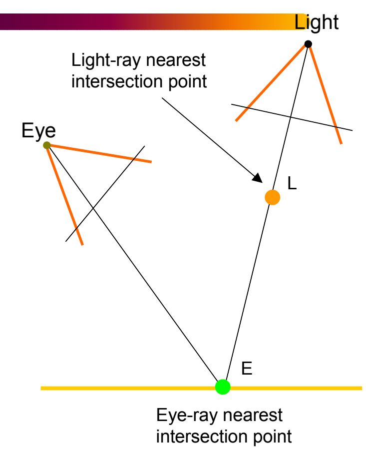
- Basic Theory
- Several Implementations
  - Hardware shadow maps
  - Multi-texturing and shadow maps
  - Object buffers

Z-Buffer Shadow Maps

- Define a coordinate system (*light space*) such that the light is the center of projection
- Render a depth buffer (*z-buffer*) of the visible scene, each pixel (x', y', z')
- For each visible surface point in eye space transform to *light space*
  - $(x_c, y_c, z_c) => (x_l, y_l, z_l)$
- If $z_l > z'$ then point is in shadow

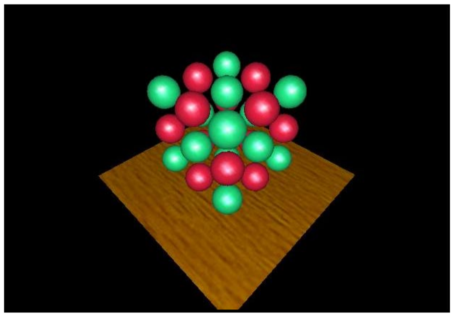
Shadow Map

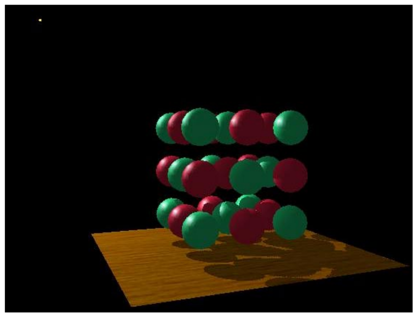
- Visible surface point E is in shadow and occluded by point L when transformed to *light space*



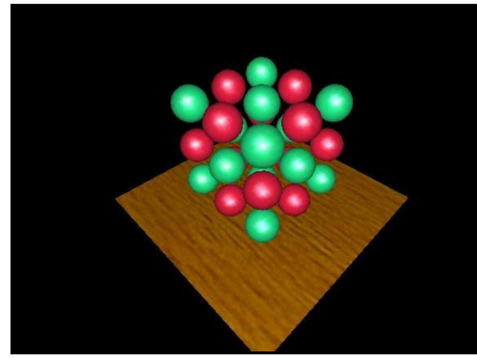
If L is closer to the light than E, then E is in shadow

Shadow Map : Two Pass Approach

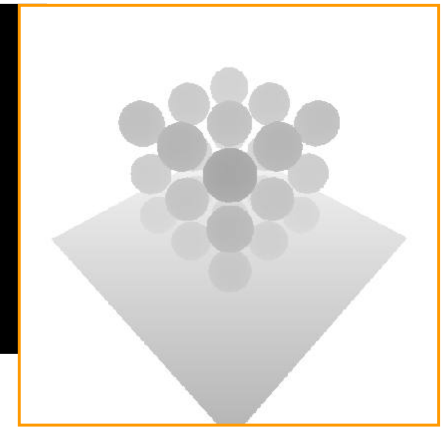




1st Pass

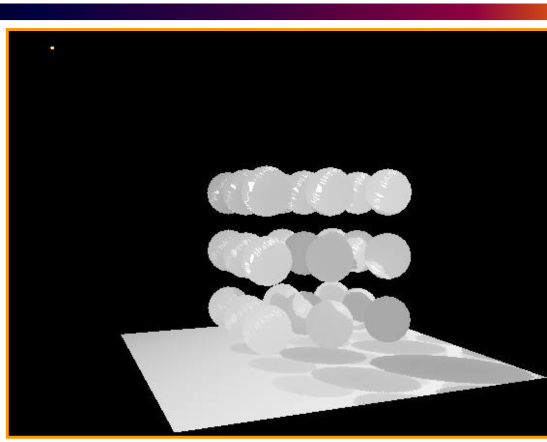


View from light



Depth Buffer

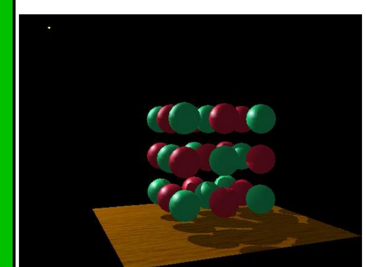
2nd Pass



Visible surface depth

2nd Pass

Non-green in shadow



Final Image

Shadow Maps With Graphics Hardware

- Render scene using the light as a camera
- Read depth buffer out and copy to a 2D texture.
  - Rather than Binary projected shadow, we now have a depth texture.
- Fragment's light position can be generated using eye-linear texture coordinate generation
    - specifically OpenGL's GL_EYE_LINEAR texgen
    - generate homogenous (s, t, r, q) texture coordinates as light-space (x, y, z, w)

Introducing Another Technique: Shadow Mapping

- Image-space shadow determination
  - Lance Williams published the basic idea in 1978
    - By coincidence, same year Jim Blinn invented bump mapping (a great vintage year for graphics)
  - Completely image-space algorithm
    - means no knowledge of scene's geometry is required
    - must deal with aliasing artifacts
  - Well known software rendering technique
    - Pixar's RenderMan uses the algorithm
    - Basic shadowing technique for Toy Story, etc.

Shadow Mapping References

- Important SIGGRAPH papers
  - Lance Williams, "Casting Curved Shadows on Curved Surfaces," SIGGRAPH 78
  - William Reeves, David Salesin, and Robert Cook (Pixar), "Rendering antialiased shadows with depth maps," SIGGRAPH 87
  - Mark Segal, et. al. (SGI), "Fast Shadows and Lighting Effects Using Texture Mapping," SIGGRAPH 92

The Shadow Mapping Concept (1)

- Depth testing from the light's point-of-view
  - Two pass algorithm
  - First, render depth buffer from the light's point-of-view
    - the result is a "depth map" or "shadow map"
    - essentially a 2D function indicating the depth of the closest pixels to the light
  - This depth map is used in the second pass

The Shadow Mapping Concept (2)

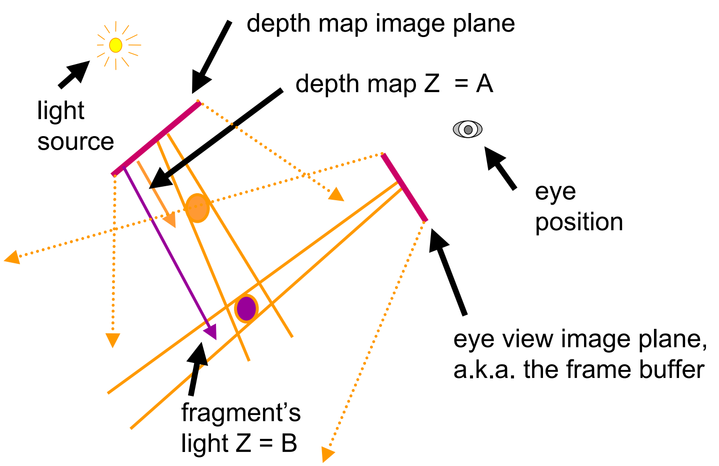
- Shadow determination with the depth map
  - Second, render scene from the eye's point-of-view
  - For each rasterized fragment
    - determine fragment's XYZ position relative to the light
    - this light position should be setup to match the frustum used to create the depth map
    - compare the depth value at light position XY in the depth map to fragment's light position Z

The Shadow Mapping Concept (3)

- The Shadow Map Comparison
  - Two values
    - A = Z value from depth map at fragment's light XY position
    - B = Z value of fragment's XYZ light position
  - If B is greater than A, then there must be something closer to the light than the fragment
    - then the fragment is shadowed
  - If A and B are approximately equal, the fragment is lit

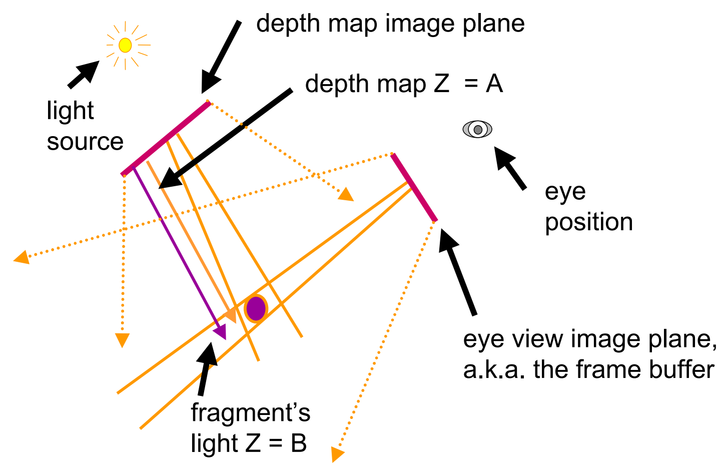
Shadow Mapping with a Picture in 2D (1)

The A < B shadowed fragment case



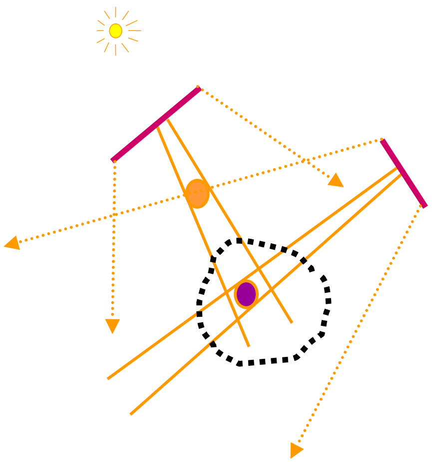
Shadow Mapping with a Picture in 2D (2)

The A ≅ B unshadowed fragment case



Shadow Mapping with a Picture in 2D (3)

Note image precision mismatch!



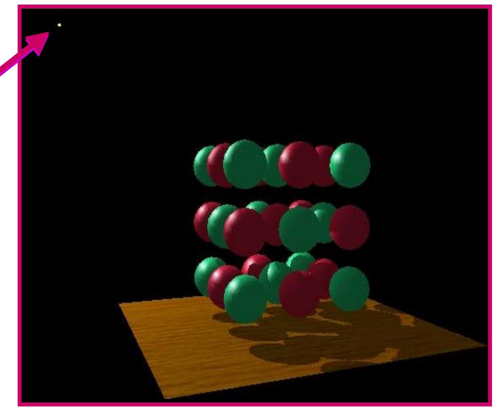
The depth map could be at a different resolution from the framebuffer

This mismatch can lead to artifacts

Visualizing the Shadow Mapping Technique (1)

- A fairly complex scene with shadows

the point light source

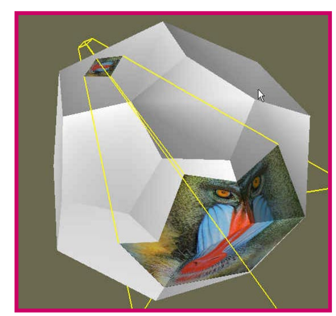


Render Scene and Access the Depth Texture

- Realizing the theory in practice
  - Fragment's light position can be generated using eye-linear texture coordinate generation
    - specifically OpenGL's GL_EYE_LINEAR texgen
    - generate homogenous (s, t, r, q) texture coordinates as light-space (x, y, z, w)
    - T&L engines such as GeForce accelerate texgen!
    - relies on <u>projective texturing</u>

Recall Projective Texturing

- A slide projector analogy



Source: Wolfgang Heidrich [99]

Projective Texture Shadows

Light's point-of-view

Shadow projective texture (modulation image or light-map)

Eye's point-of-view, projective texture applied to ground-plane (self-shadowing is from another algorithm)

Projective Texture Shadows

Two-pass approach

- For each light source:
  - Create a light camera that encloses shadowed area
  - Render shadow casting objects into light's view

    only need to create a light map (1 in light, 0 in shadow)
  - Create projective texture from light's view
  - Render fully-lit shadow receiving objects with applied modulation projective-textures (need additive blending for all light sources except first one)
- Render fully-lit shadow casting objects

Perspective-Correct Texturing

- First, what is perspective-correct texturing?
  - Normal 2D texture mapping uses (s, t) coordinates
  - 2D perspective-correct texture mapping
    - means (s, t) should be interpolated linearly in eye-space
    - so compute per-vertex s/w, t/w, and 1/w
    - linearly interpolate these three parameters over polygon
    - per-fragment compute s' = (s/w) / (1/w) and t' = (t/w) / (1/w)
    - results in per-fragment perspective correct (s', t')

Projective Texturing

- So what is projective texturing?
  - Now consider homogeneous texture coordinates
    - (s, t, r, q) --> (s/q, t/q, r/q)
    - Similar to homogeneous clip coordinates where (x, y, z, w) = (x/w, y/w, z/w)
  - Idea is to have (s/q, t/q, r/q) be projected per-fragment
  - This requires a per-fragment divider
    - yikes, dividers in hardware are fairly expensive

Projective Texturing

- Hardware designer's view of texturing
  - Perspective-correct texturing is a practical requirement
    - otherwise, textures "swim"
    - perspective-correct texturing already requires the hardware expense of a per-fragment divider
  - Clever idea [Segal, et.al. '92]
    - interpolate q/w instead of simply 1/w
    - so projective texturing is practically free if you already do perspective-correct texturing!

Projective Texturing

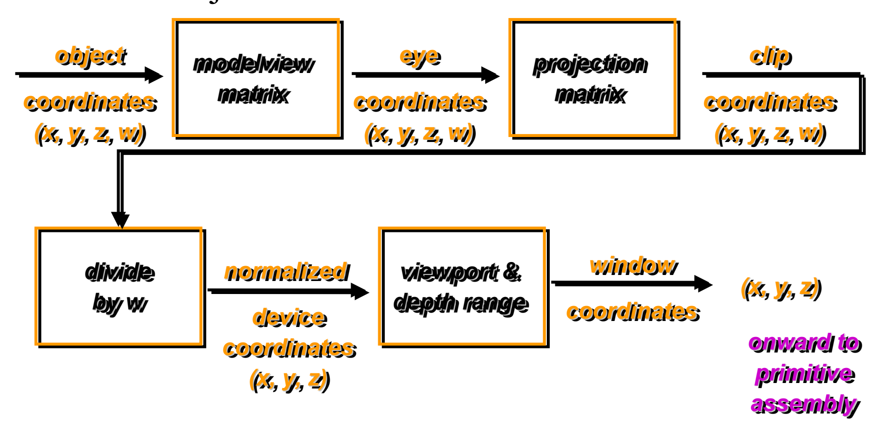
- Tricking hardware into doing projective textures
  - By interpolating q/w, hardware computes per-fragment
    - (s/w) / (q/w) = s/q
    - (t/w) / (q/w) = t/q
  - Net result: projective texturing
    - OpenGL specifies projective texturing
    - only overhead is multiplying 1/w by q
    - but this is per-vertex

Projected Shadow Maps

- Assign light-space texture coordinates via texgen
  - Transform eye-space (x, y, z, w) coordinates to the light's view frustum (match how the light's depth map is generated)
  - Further transform these coordinates to map directly into the light view's depth map
  - Expressible as a projective transform
    - load this transform into the 4 eye linear plane equations for S, T, and Q coordinates
  - (s/q, t/q) will map to light's depth map texture

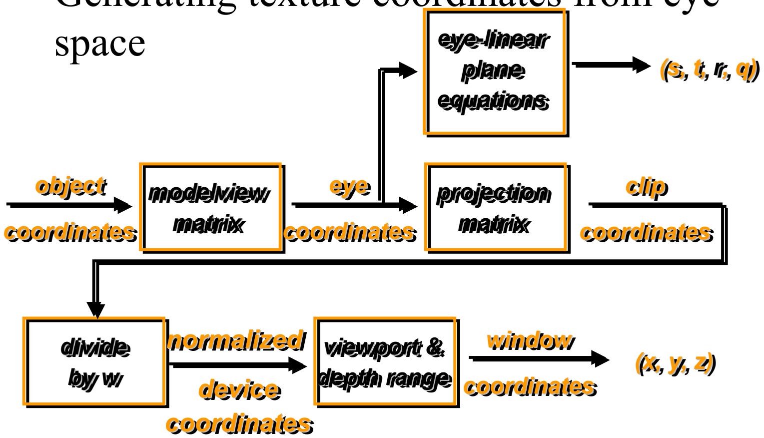
OpenGL's Standard Vertex Coordinate Transform

- From object coordinates to window coordinates



Eye Linear Texture Coordinate Generation

- Generating texture coordinates from eye-space



Setting Up Eye Linear Texgen

- With OpenGL
  - GLfloat Splane[4], Tplane[4], Rplane[4], Qplane[4];
  - glTexGenfv(GL_S, GL_EYE_PLANE, Splane);
  - glTexGenfv(GL_T, GL_EYE_PLANE, Tplane);
  - glTexGenfv(GL_R, GL_EYE_PLANE, Rplane);
  - glTexGenfv(GL_Q, GL_EYE_PLANE, Qplane);
  - glEnable(GL_TEXTURE_GEN_S);
  - glEnable(GL_TEXTURE_GEN_T);
  - glEnable(GL_TEXTURE_GEN_R);
  - glEnable(GL_TEXTURE_GEN_Q);
- Each plane equation is transformed by current inverse modelview matrix (a very handy thing for us)

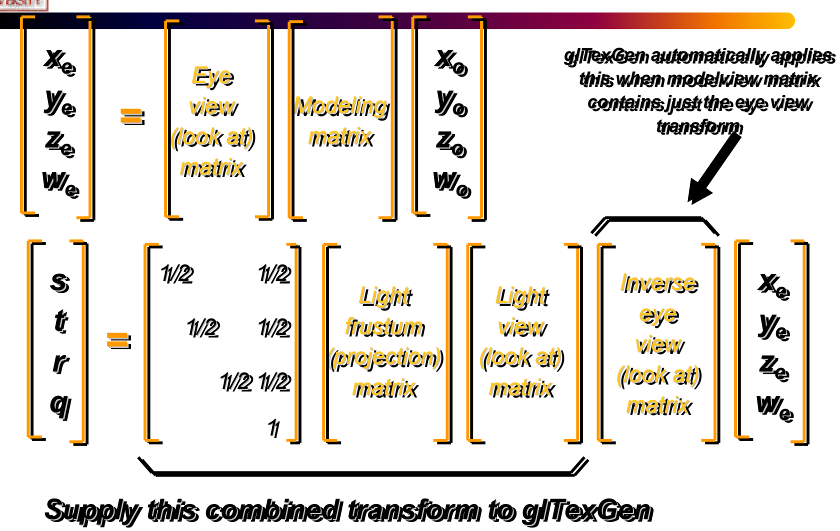
Eye Linear Texgen Transform

- Plane equations form a projective transform

$$\begin{bmatrix} s \\ t \\ r \\ q \end{bmatrix} = \begin{bmatrix} Splane[0] & Splane[1] & Splane[2] & Splane[3] \\ Tplane[0] & Tplane[1] & Tplane[2] & Tplane[3] \\ Rplane[0] & Rplane[1] & Rplane[2] & Rplane[3] \\ Qplane[0] & Qplane[1] & Qplane[2] & Qplane[3] \end{bmatrix} \begin{bmatrix} x_e \\ y_e \\ z_e \\ w_e \end{bmatrix}$$

- The 4 eye linear plane equations form a 4x4 matrix (No need for the texture matrix!)

Shadow Map Eye Linear Texgen Transform



Shadow Map Operation

- Automatic depth map lookups
  - After the eye linear texgen with the proper transform loaded
    - (s/q, t/q) is the fragment's corresponding location within the light's depth texture
    - r/q is the Z planar distance of the fragment relative to the light's frustum, scaled and biased to [0,1] range
  - Next compare texture value at (s/q, t/q) to value r/q
    - if texture[s/q, t/q] ≅ r/q then *not shadowed*
    - if texture[s/q, t/q] < r/q then *shadowed*

Shadow Map Construction

- Set up your view matrix to be the light's "LookAt" matrix
- Set up the projection matrix based on the light type
  - For spotlights, use the penumbra angle for the FOV
  - For directional lights, use an orthographic projection
  - For point lights, use a cubemap
    - And render once for each face with a 90 degree FOV

Shadow Map Construction

- Render your depth value into the texture
  - As an Alpha or Color Value
    - 0 means at the light plane
    - FF means at the edge of the light's range
  - Or into the depth buffer
    - Extract it with glReadPixels
    - Extract with new extensions (more later)
    - Map it into a hi-precision texture.

Dedicated Hardware Shadow Mapping Support

- SGI RealityEngine, InfiniteReality, and GeForce3 Hardware
  - Performs the shadow test as a texture filtering operation
    - looks up texel at (s/q, t/q) in a 2D texture
    - compares lookup value to r/q
    - if texel is greater than or equal to r/q, then generate 1.0
    - if texel is less than r/q, then generate 0.0
  - Modulate color with result
    - zero if fragment is shadowed or unchanged color if not

OpenGL Extensions for Shadow Map Hardware

- Two extensions work together
  - SGIX_depth_texture
    - supports high-precision depth texture formats
    - copy from depth buffer to texture memory supported
  - SGIX_shadow
    - adds "shadow comparison" texture filtering mode
    - compares r/q to texel value at (s/q, t/q)
  - Multi-vendor support: SGI, NVIDIA, others?
    - Brian Paul has implemented these extensions in Mesa!

New Depth Texture Internal Texture Formats

- SGIX_depth_texture supports textures containing depth values for shadow mapping
- Three new internal formats
  - GL_DEPTH_COMPONENT16_SGIX
  - GL_DEPTH_COMPONENT24_SGIX
  - GL_DEPTH_COMPONENT32_SGIX (same as 24-bit on GeForce3)
- Use GL_DEPTH_COMPONENT for your external format
- Work with glCopySubTexImage2D for fast copies from depth buffer to texture
  - NVIDIA optimizes these copy texture paths

Depth Texture Details

- Usage example:

```
glCopyTexImage2D(GL_TEXTURE_2D,level=0,
    internalfmt=GL_DEPTH_COMPONENT24_SGIX,
    x=0, y=0, w=256, h=256, border=0);
```

- Then use glCopyTexSubImage2D for faster updates once texture internal format initially defined

Depth Texture Details

- Hint: use GL_DEPTH_COMPONENT for your texture internal format
  - Leaving off the "n_SGIX" precision specifier tells the driver to match your depth buffer's precision
  - Copy texture performance is optimum when depth buffer precision matches the depth texture precision

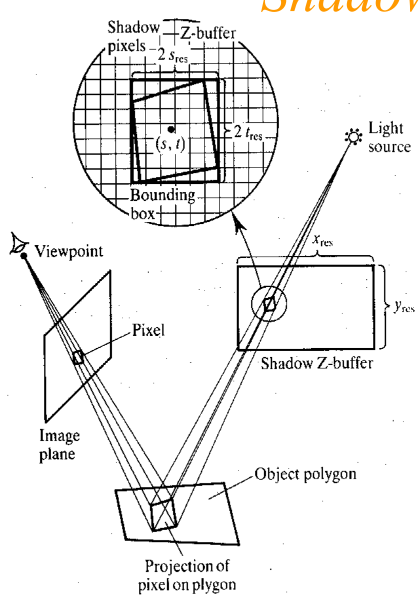
Texture Copy Performance

- The more depth values you copy, the slower the performance
  - 512x512 takes 4 times longer to copy than 256x256
  - Tradeoff: better defined shadows require higher resolution shadow maps, but slows copying
- 16-bit depth values copy twice as fast as 24-bit depth values (which are contained in 32-bit words)
  - Requesting a 16-bit depth buffer (even with 32-bit color buffer) and copying to a 16-bit depth texture is faster than using a 24-bit depth buffer
  - Note that using 16-bit depth buffer usually requires giving up stencil

Issues With Shadow Maps

- Compute shadow maps for all light sources
- Need space to store shadow maps
- How do you filter the shadow map when indexing into it?
- Does a mismatch in shadow map resolution and screen resolution matter?

Shadow-Maps

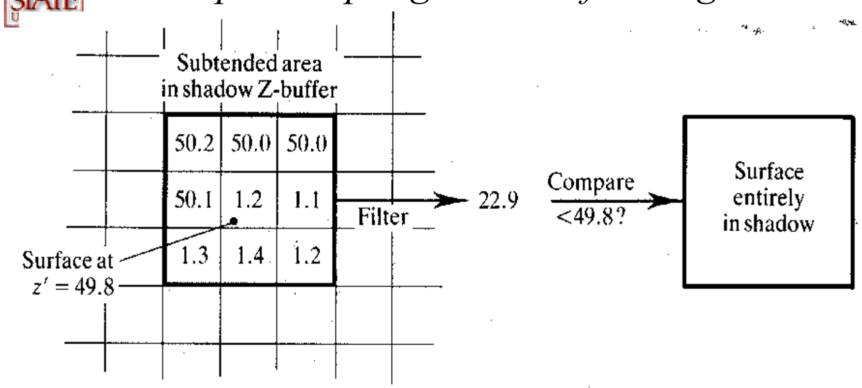


Depth Sampling Problems

- Can we just use the nearest sample?
- How would you anti-alias depth?
- What is we move closer to the reciever?
  - Opposite problem

Shadow-Maps

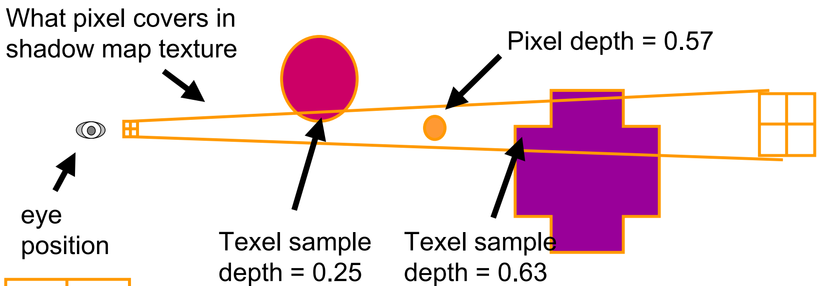
Depth sampling: normal filtering



- Averaging depth doesn't really make sense (unrelated to surface, especially at shadow boundaries!)
- Still a binary result, (no anti-aliased *softer* shadows)

Depth Values are not Blend-able

- **Traditional filtering is inappropriate**

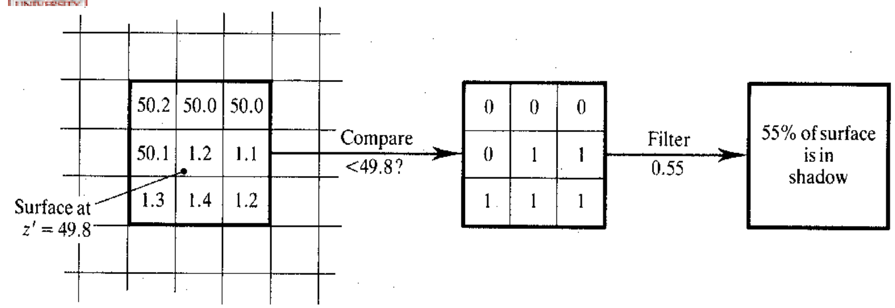


0.25	0.25
0.63	0.63

Average(0.25, 0.25, 0.63, 0.63) = 0.44
0.57 > 0.44 so pixel is **wrongly** "in shadow"
Truth: nothing is at 0.44, just 0.25 and 0.63

Shadow-Maps

Depth sampling: percentage closer filtering (Reeves87)



- Could average binary results of all depth map pixels covered
- Soft anti-aliased shadows
- Very similar to point-sampling across an area light source in ray-traced shadow computation

Shadow-Maps

How do you choose the samples?

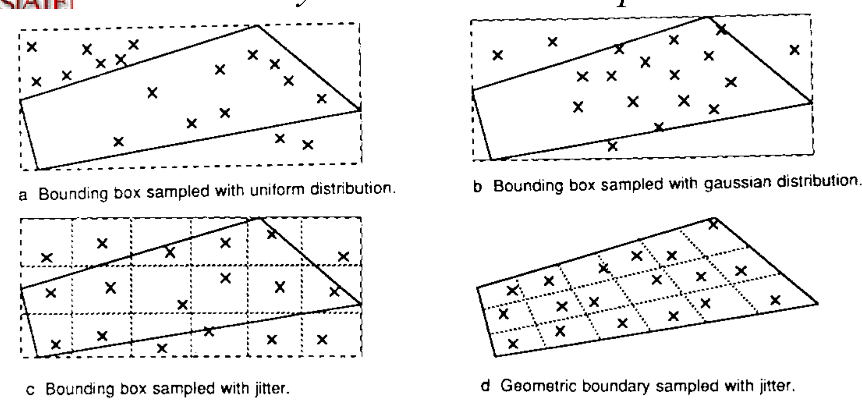


Figure 3. Different methods for choosing samples.

Quadrilateral represents the area covered by a pixel's projection onto a polygon after being projected into the shadow-map

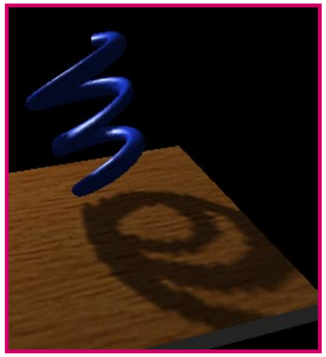
Hardware Shadow Map Filtering

- "Percentage Closer" filtering
  - Provides anti-aliasing at shadow map edges
    - Not soft shadows in the umbra/penumbra sense
- Does not do full filtering
  - Will lead to aliasing for picket-fence shadows.

Hardware Shadow Map Filtering Example

GL_NEAREST: blocky

GL_LINEAR: antialiased edges



Low shadow map resolution used to heighten filtering artifacts

Issues with Shadow Mapping

- Not without its problems
  - Prone to aliasing artifacts
    - "percentage closer" filtering helps this
    - normal color filtering does **not** work well
  - Depth bias is not completely foolproof
  - Requires extra shadow map rendering pass and texture loading
  - Higher resolution shadow map reduces blockiness
    - but also increases texture copying expense

Issues with Shadow Mapping

- Not without its problems
  - Shadows are limited to view frustums
    - could use six view frustums for omni-directional light
  - Objects outside or crossing the near and far clip planes are not properly accounted for by shadowing
    - move near plane in as close as possible
    - but too close throws away valuable depth map precision when using a projective frustum

Shadow Map Resolutions

- **Requires knowing how pixels (samples) in the light's view compare to the size of pixels (samples) in the eye's view**
  - **A re-sampling problem**
- **When light source frustum is reasonably well aligned with the eye's view frustum, the ratio of sample sizes is close to 1.0**
  - **Great match if eye and light frustum's are nearly identical**
  - **But that implies very few viewable shadows**
  - **Consider a miner's lamp (i.e., a light attached to your helmet)**
  - **The chief reason for such a lamp is you don't see shadows from the lamp while wearing it**

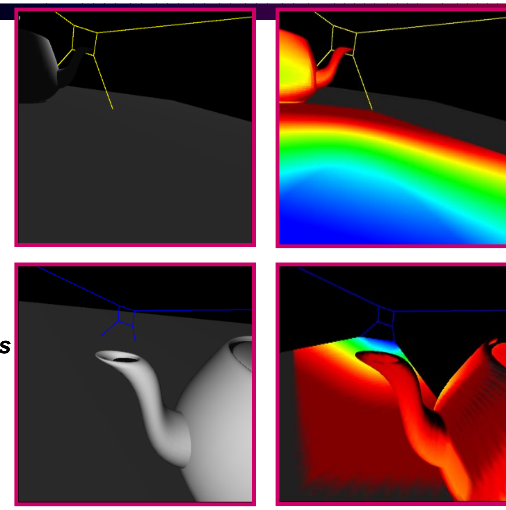
Shadow Map Resolution

- So best case is miner's lamp
- Worst case is shadows from light shining at the viewer
  - "that deer in the headlights" problem – definitely worst case for the deer
  - Also known as the "dueling frusta" problem (frusta, plural of frustum)
- Let's attempt to visualize what happens…

Dueling Frusta Case

Eye's View

Light's View



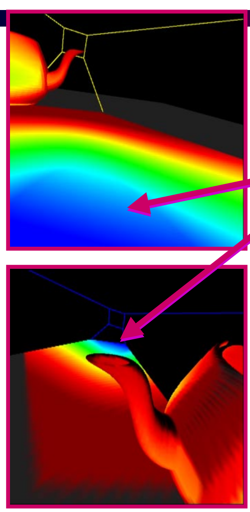
Eye's View with projection of color-coded mipmap levels from light: Blue = magnification Red = minification

Light's View with re-projection of above image from the eye

Dueling Frusta Case

Eye's View

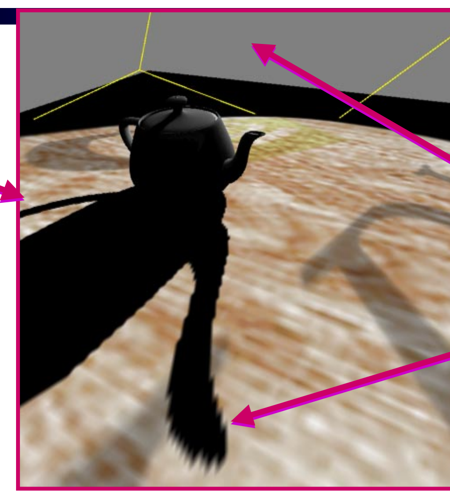
Light's View



Region that is smallest in the light's view is a region that is very large in the eye's view. This implies that it would require a very high-resolution shadow map to avoid obvious blocky shadow edge artifacts.

Dueling Frusta

Notice that shadow edge is well defined in the distance.



Light position out here pointing towards the viewer.

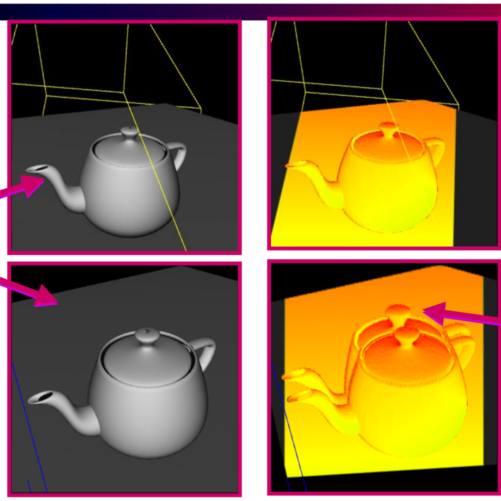
Blocky shadow edge artifacts.

Good Situation, Close to the Miner's Lamp

Eye's View

Very similar views

Light's View

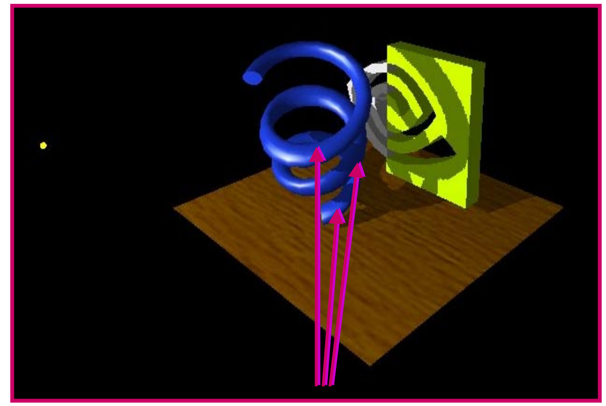


Note how the color-coded images share similar pattern and the coloration is uniform. Implies single depth map resolution would work well for most of the scene.

Ghosting is where projection would be in shadow.

More Examples

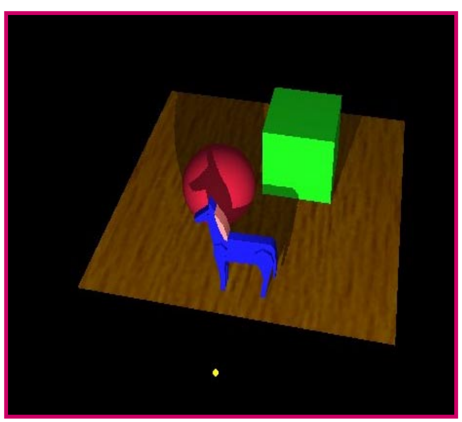
- Smooth surfaces with object self-shadowing



Note object self-shadowing

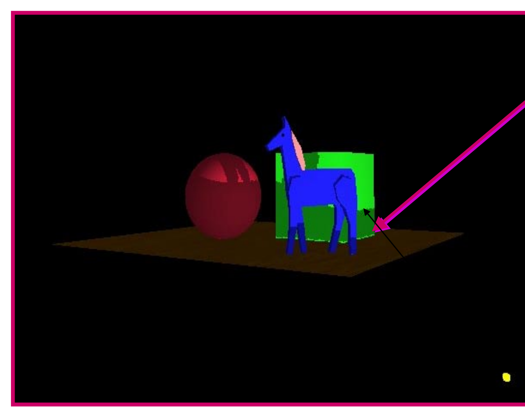
More Examples

- Complex objects all shadow



More Examples

- Even the floor casts shadow

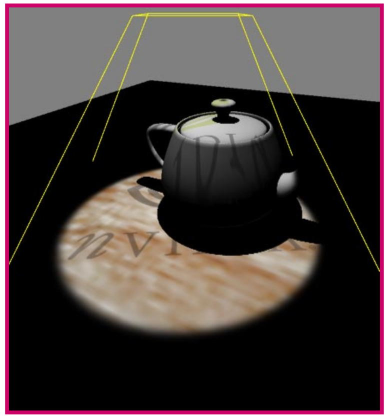


Note shadow leakage due to infinitely thin floor

Could be fixed by giving floor thickness

Projective Texturing for Spotlight Shadows

- Use a spotlight-style projected texture to give shadow maps a spotlight falloff.



Multi-texturing Shadow Maps

- Consumer 3D hardware solution
  - Proposed by Wolfgang Heidrich in his 1999 Ph.D. thesis
  - Leverages today's consumer multi-texture hardware
    - 1st texture unit accesses 2D depth map texture
    - 2nd texture unit accesses 1D Z range texture
  - Extended texture environment subtracts 2nd texture from 1st
    - shadowed if greater than zero, unshadowed otherwise
    - use alpha test to discard shadowed fragments

Dual-texture Shadow Mapping Approach

- Constructing the depth map texture
  - Render scene from the light view (can disable color writes)
  - Use projective textures and a shadow map as before.

Dual-texture Shadow Mapping Approach

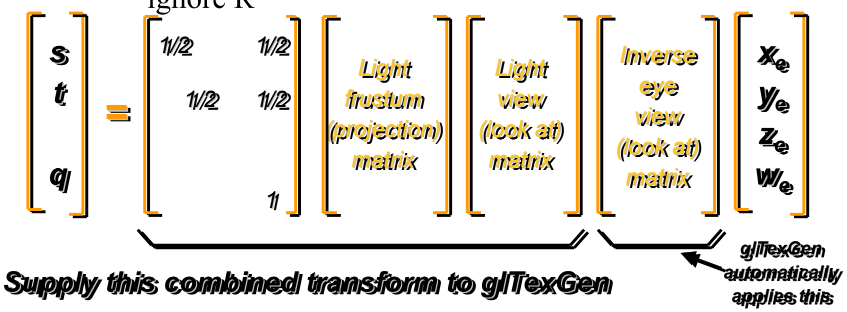
- Two-pass shadow determination
  - 1st pass: draw everything shadowed
    - render scene with light disabled -or- dimmed substantially and specular light color of zero
    - with depth testing enabled
  - 2nd pass: draw unshadowed, rejecting shadowed fragments
    - use *glDepthFunc*(*GL_EQUAL*) to match 1st pass pixels
    - enable the light source, un-rejected pixels = *un*shadowed
    - use dual-texture as described in subsequent slides

Dual-texture Shadow Mapping Approach

- Dual-texture configuration
  - 1st texture unit
    - bind to 2D texture containing light's depth map texture
    - intensity texture format (same value in RGB and alpha)
  - 2nd texture unit
    - bind to 1D texture containing a linear ramp from 0 to 1
    - maps S texture coordinate in [0, 1] range to intensity value in [0, 1] range

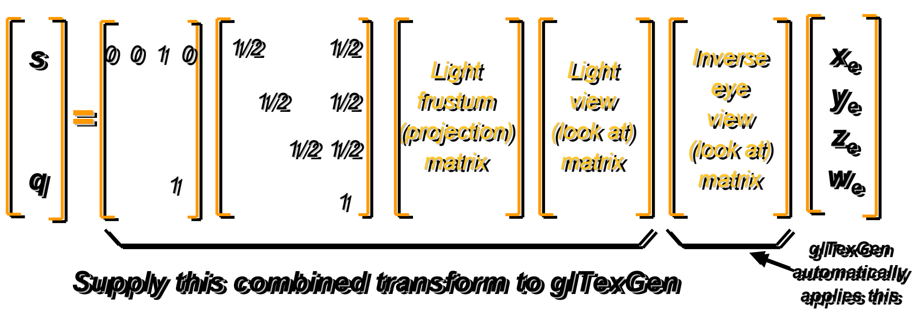
Dual-texture Shadow Mapping Approach

- Texgen Configuration
  - 1st texture unit using 2D texture
    - generate (s/q, t/q) to access depth map texture, ignore R



Dual-texture Shadow Mapping Approach

- Texgen Configuration
  - 2nd texture unit using 1D texture
    - generate Z planar distance in S, flips what R is into S



Dual-texture Shadow Mapping Approach

- Texture environment (texenv) configuration
  - Compute the difference between **Tex0** from **Tex1**
    - un-extended OpenGL texenv cannot subtract
  - But can use standard *EXT_texture_env_combine* extension
    - add signed operation
    - compute fragment alpha as
      alpha(**Tex0**) + (1 - alpha(**Tex1**)) - 0.5
    - result is greater or equal to 0.5 when **Tex0** >= **Tex1**
      result is less than 0.5 when **Tex0** < **Tex1**

Dual-texture Shadow Mapping Approach

- Texture environment (texenv) specifics

```
glActiveTextureARB(GL_TEXTURE0_ARB);
glTexEnvi(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_COMBINE_EXT);

glTexEnvi(GL_TEXTURE_ENV, GL_COMBINE_RGB_EXT, GL_REPLACE);
glTexEnvi(GL_TEXTURE_ENV, GL_SOURCE0_RGB_EXT, GL_PRIMARY_COLOR_EXT);
glTexEnvi(GL_TEXTURE_ENV, GL_OPERAND0_RGB_EXT, GL_SRC_COLOR);

glTexEnvi(GL_TEXTURE_ENV, GL_COMBINE_ALPHA_EXT, GL_REPLACE);
glTexEnvi(GL_TEXTURE_ENV, GL_SOURCE0_ALPHA_EXT, GL_TEXTURE);
glTexEnvi(GL_TEXTURE_ENV, GL_OPERAND0_ALPHA_EXT, GL_SRC_ALPHA);

glActiveTextureARB(GL_TEXTURE1_ARB);
glTexEnvi(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_COMBINE_EXT);

glTexEnvi(GL_TEXTURE_ENV, GL_COMBINE_RGB_EXT, GL_REPLACE);
glTexEnvi(GL_TEXTURE_ENV, GL_SOURCE0_RGB_EXT, GL_PREVIOUS_EXT);
glTexEnvi(GL_TEXTURE_ENV, GL_OPERAND0_RGB_EXT, GL_SRC_COLOR);

glTexEnvi(GL_TEXTURE_ENV, GL_COMBINE_ALPHA_EXT, GL_ADD_SIGNED_EXT);
glTexEnvi(GL_TEXTURE_ENV, GL_SOURCE0_ALPHA_EXT, GL_PREVIOUS_EXT);
glTexEnvi(GL_TEXTURE_ENV, GL_OPERAND0_ALPHA_EXT, GL_SRC_ALPHA);
glTexEnvi(GL_TEXTURE_ENV, GL_SOURCE1_ALPHA_EXT, GL_TEXTURE);
glTexEnvi(GL_TEXTURE_ENV, GL_OPERAND1_ALPHA_EXT, GL_ONE_MINUS_SRC_ALPHA);
```

Dual-texture Shadow Mapping Approach

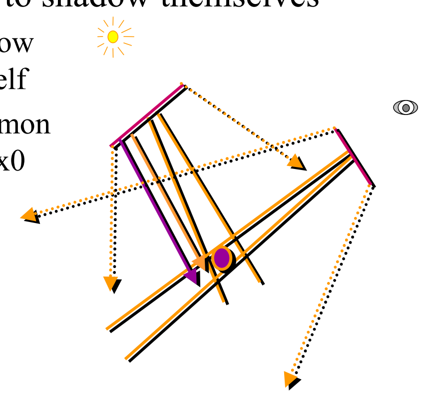
- Post-texture environment result
  - RGB is lit color (lighting is enabled during second pass)
  - Alpha is the biased difference of T0 and T1
    - unshadowed fragments have alpha >= 0.5
    - shadowed fragments have an alpha of < 0.5

Dual-texture Shadow Mapping Approach

- Next, reject shadowed fragments
  - shadowed or unshadowed depends on alpha value
    - less than 0.5 means shadowed
  - use the alpha test to rejected shadowed fragments
    - glEnable(GL_ALPHA_TEST)
    - glAlphaFunc(GL_GREATER, 0.5)

Dual-texture Shadow Mapping Approach

- Careful about self-shadowing
  - fragments are likely to shadow themselves
    - surface casting shadow must not shadow itself
    - "near equality" common when comparing Tex0 and Tex1

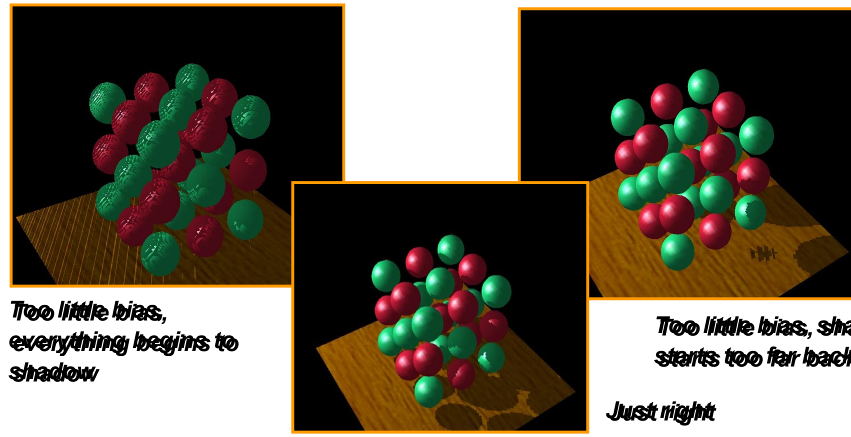


Dual-texture Shadow Mapping Approach

- Biasing values in depth map helps
  - recall *glPolygonOffset* suggestion during the depth map construction pass
  - this bias should be done during depth map construction
    - biases in the texgen transform do **not** work
    - problem is depth map has non-linear distribution due to projective frustum
  - polygon offset scale keeps edge-on polygons from self-shadowing

Depth Map Bias

- How much polygon offset bias depends



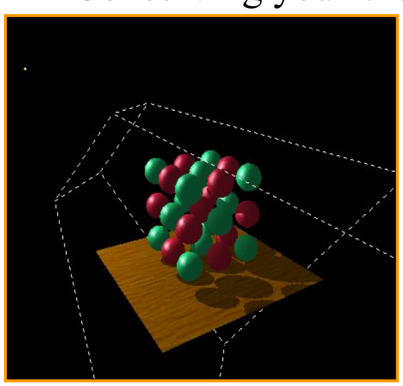
Too little bias, everything begins to shadow

Too little bias, shadow starts too far back

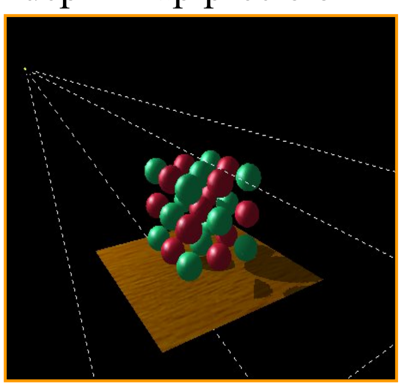
Just right

Shadow Mapping Precision

- Conserving your 8-bit depth map precision



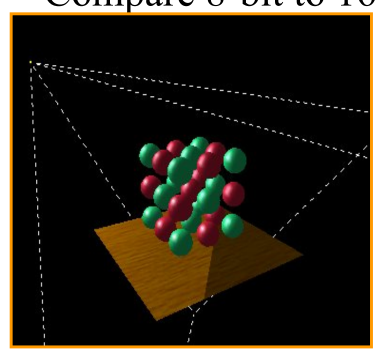
Frustum confined to objects of interest



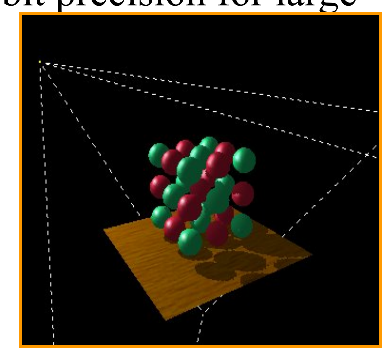
Frustum expanded out considerably breaks down the shadows

More Precision Allows Larger Lights Frustums

- Compare 8-bit to 16-bit precision for large



8-bit: Large frustum breaks down the shadows, not enough precision



16-bit: Shadow looks just fine

Object ID Buffers

- ObjectID buffers are similar to Shadow Depth buffers in that both are per-pixel approaches
- ObjectID Buffers work by identifying each "Object" in the light's range and giving it a unique numerical ID
  - An Object is defined as something that can't shadow itself
  - So, any convex object or piece of a convex object will do

Object ID Shadows

- Each object in the light's range has it's ID rendered to a texture (with depth testing).
  - After this step, the buffer contains the ID of the closest object for each pixel
- Map this texture as a projective texture.
- Render the scene from the eye-point.
  - Compare the ID of the object you are drawing to the texture value.
    - If they are the same, the pixel is lit
    - If they are different, that means there must be some other object closer, so the pixel is in shadow.

Object ID Shadows

- Some HW supports generating a unique ID for each polygon submitted
- This is more convenient, but doesn't solve the real issue
  - Two adjacent coplanar polygons with different IDs can alias with each other
- The only solutions are :
  - Use per-object ID's instead of per-triangle
  - Perform multiple jittered tests and only shadow if all tests agree the pixel is in shadow

Object ID Shadows

- Advantages of this Technique :
  - Can support any light range with equal precision
  - For convex objects, it works great
  - Doesn't suffer from 8 bit precision issues like the depth buffer approach
  - Works better for point lights

Object ID Shadows

- Disadvantages of this Technique :
  - Objects must be convex or they won't self-shadow
    - To handle this, you can break objects into smaller convex pieces, each with their own ID
  - Suffers from aliasing problems
    - When shadow testing, you won't always project exactly onto the same shadow buffer pixel, causing a different ID value to be found instead
  - Hard, jaggy edges

Combining Shadow and Object Maps

- ObjectIDs are great because they work at any light range at all – good for inter-object shadowing
- Shadow Depth Buffers are great because they support self shadowing – good for intra-object shadowing

Combining Shadow and Object Maps

- Combine the two:
  - Projective texture contains both an ObjectID and a "*depth*" value for each texel.
    - Each object has its own ID as before
    - The Shadow Depth buffer is actually computed per-object.
      - Depth range is limited to the object's bounding box.
      - Self-shadowing precision is thus, maximized

ObjectID & Depth Buffer Texture

Red Vertical Axis – ObjectID from 0 to ff

Green Horizontal Axis – Ramp from 0 to ff

Blue Horizontal Axis – Ramp from 0 to ff repeated 8 times – limited by max size of texture

Blue represents the 8 bits of depth.

Green distinguishes the proper shadow map (or shadow map range) to use.

Shadow Map Conclusions

- Shadow mapping offers real-time shadowing effects
  - Independent of scene complexity
  - Very compatible with multi-texturing
    - Does not mandate multi-pass as stenciled shadow volumes do
  - Ideal for shadows from spotlights
- Consumer hardware shadow map support here today
  - GeForce3
  - Dual-texturing technique supports legacy hardware
- Same basic technique used by Pixar to generate shadows in their computer-generated movies