Shadow Mapping with Today's OpenGL Hardware

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GAMEDevelopers CONFERENCE 2001

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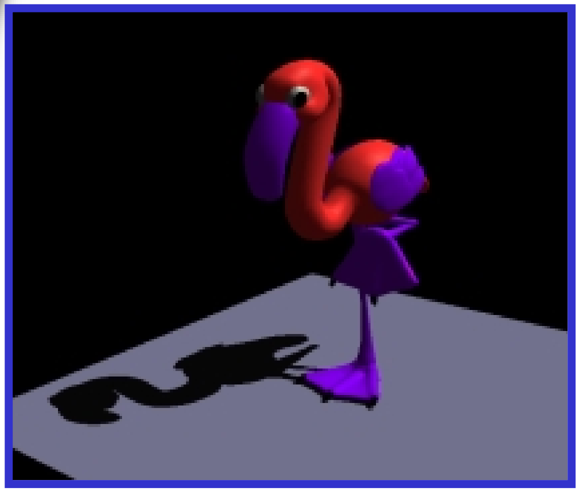
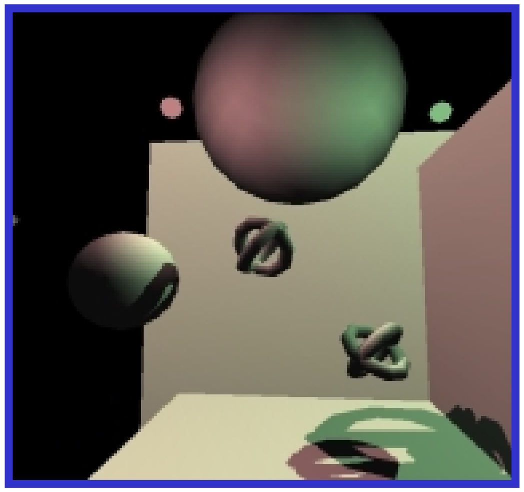
Motivation for Better Shadows

- Shadows increase scene realism
  - Real world has shadows
  - More control of the game's feel
    - dramatic effects
    - spooky effects
  - Other art forms recognize the value of shadows
  - But yet most games lack realistic shadows

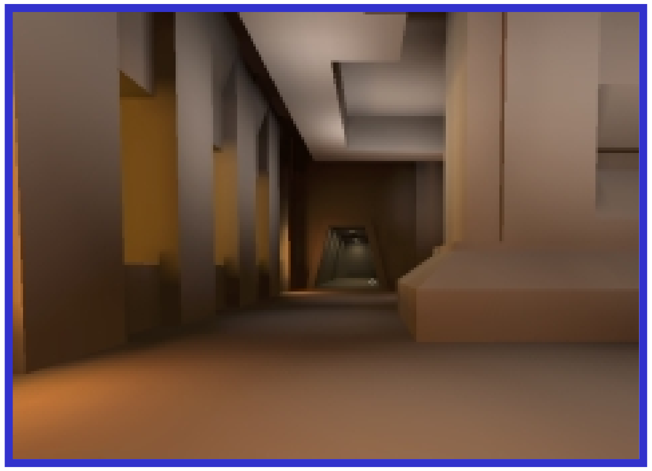
Common Real-time Shadow Techniques



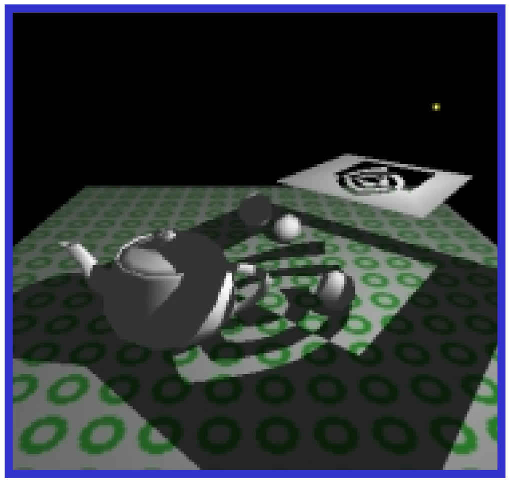
Projected planar shadows



Shadow volumes



Light maps



Hybrid approaches

Problems with Common Shadow Techniques

- Mostly tricks with lots of limitations
  - Projected planar shadows
    - well works only on flat surfaces
  - Stenciled shadow volumes
    - determining the shadow volume is hard work
  - Light maps
    - totally unsuited for dynamic shadows
  - In general, hard to get everything shadowing everything

Stenciled Shadow Volumes

- Powerful technique, excellent results possible

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)

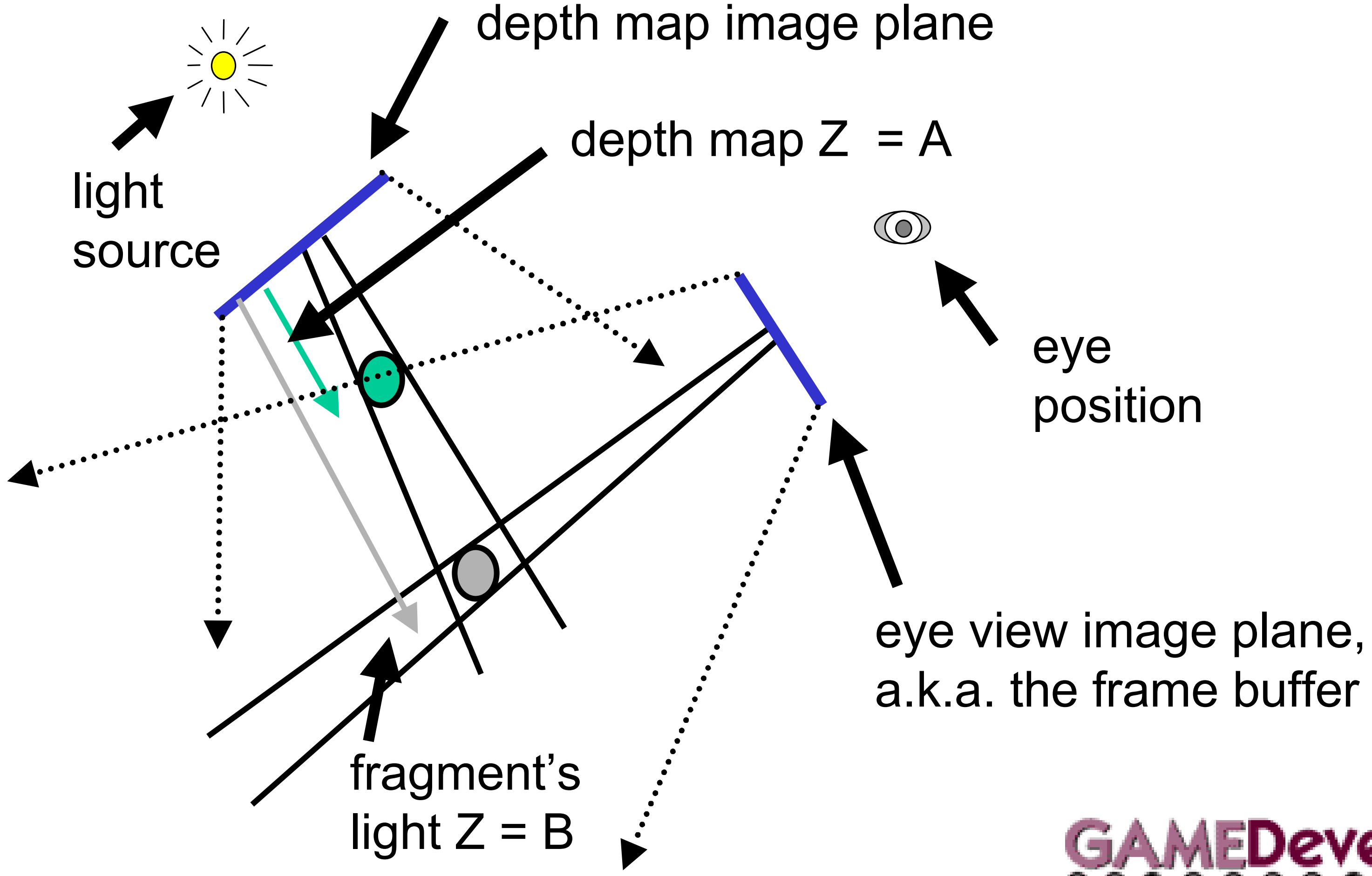
- Shadow determination with the depth map
  - Second, render scene from the eye’s point-of-view
  - For each rasterized fragment
    - determine fragment’s XYZ position relative to the light
    - this light position should be setup to match the frustum used to create the depth map
    - compare the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

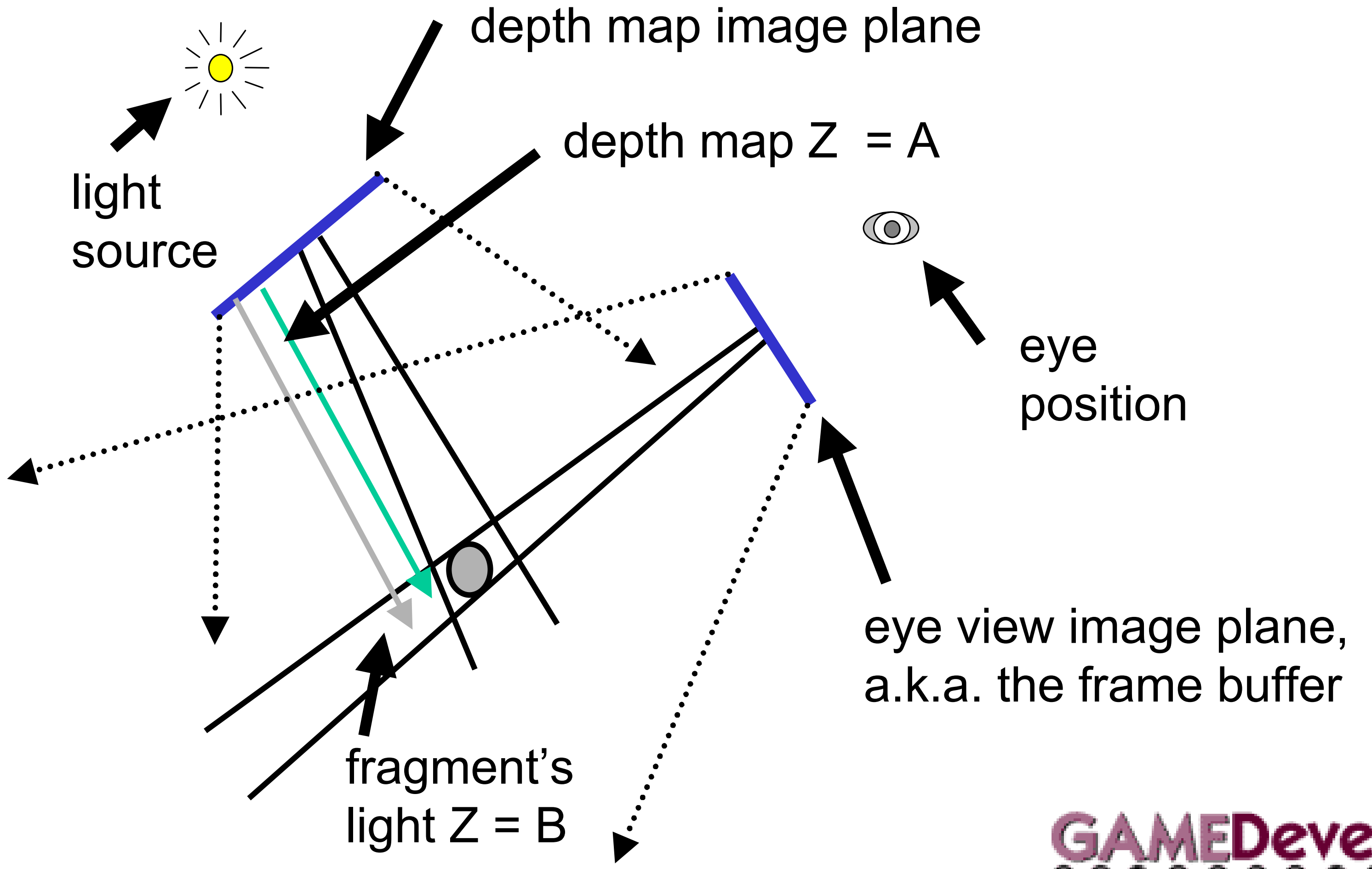
Shadow Mapping with a Picture in 2D (1)

The A < B shadowed fragment case



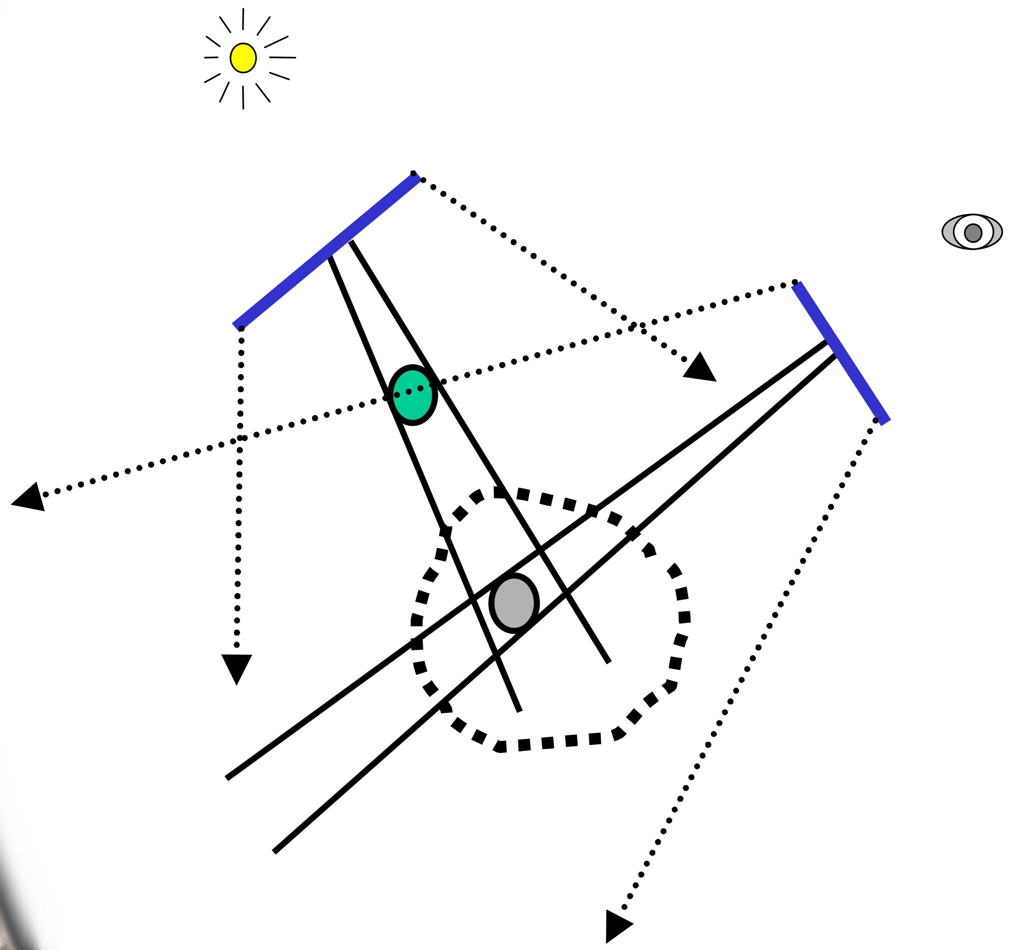
Shadow Mapping with a Picture in 2D (2)

The A ≅ B unshadowed fragment case



Shadow Mapping with a Picture in 2D (3)

Note image precision mismatch!



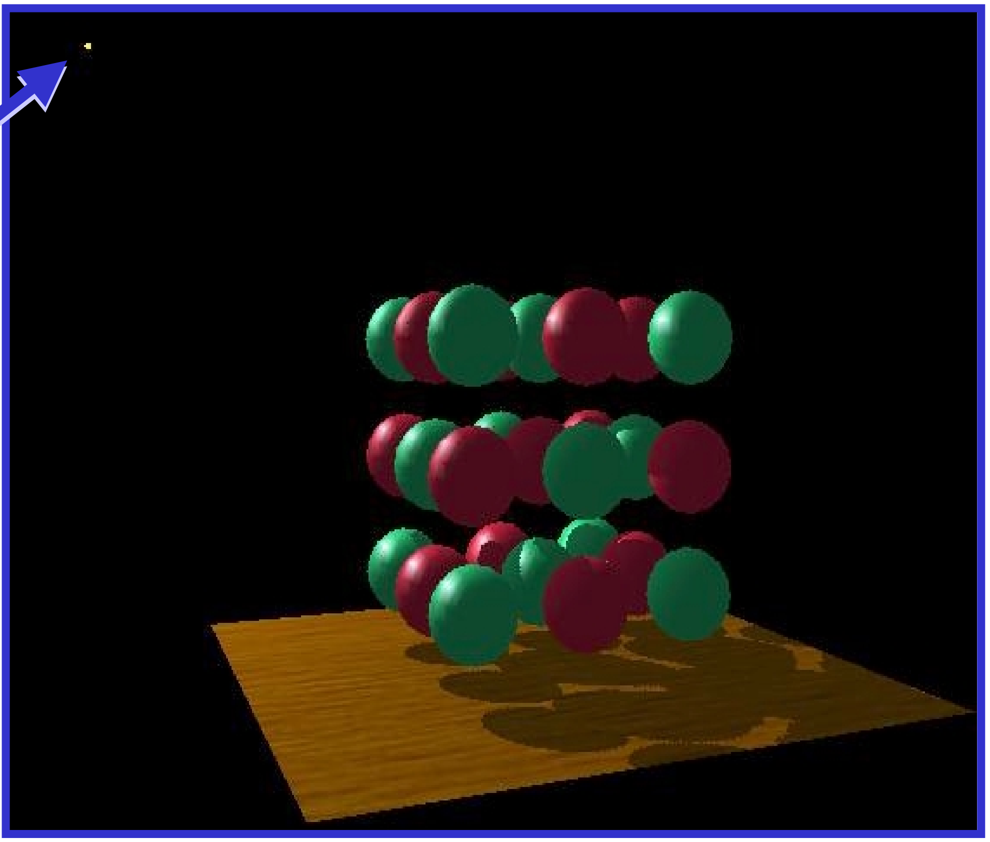
The depth map could be at a different resolution from the framebuffer

This mismatch can lead to artifacts

Visualizing the Shadow Mapping Technique (1)

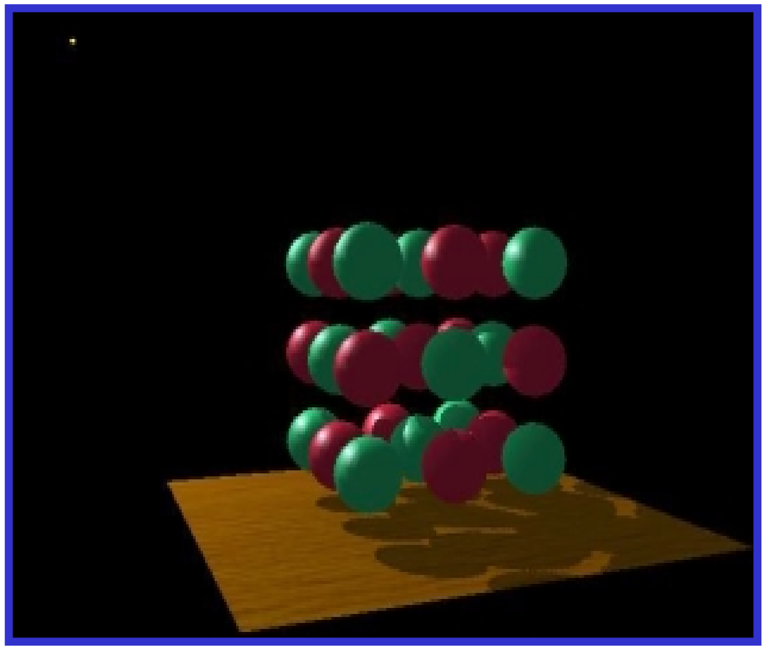
- **A fairly complex scene with shadows**

the point light source

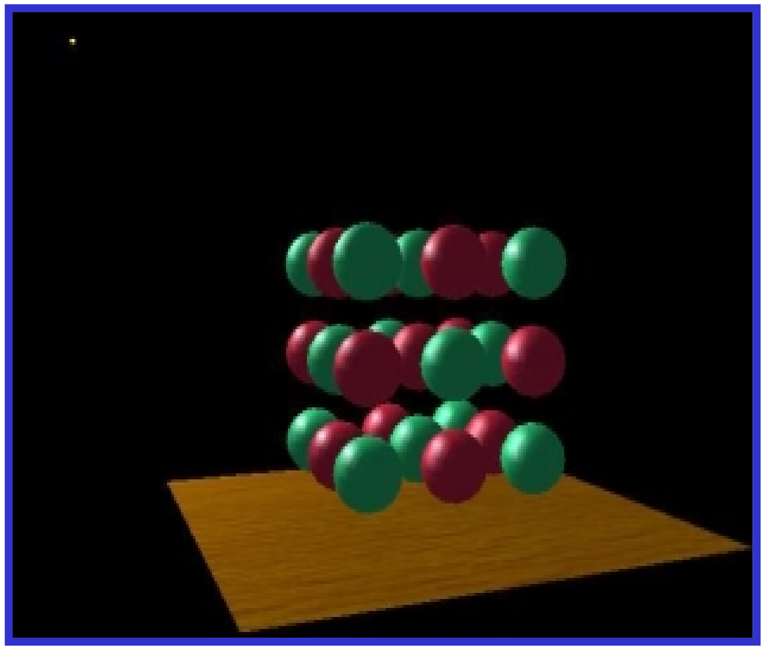


Visualizing the Shadow Mapping Technique (2)

- **Compare with and without shadows**



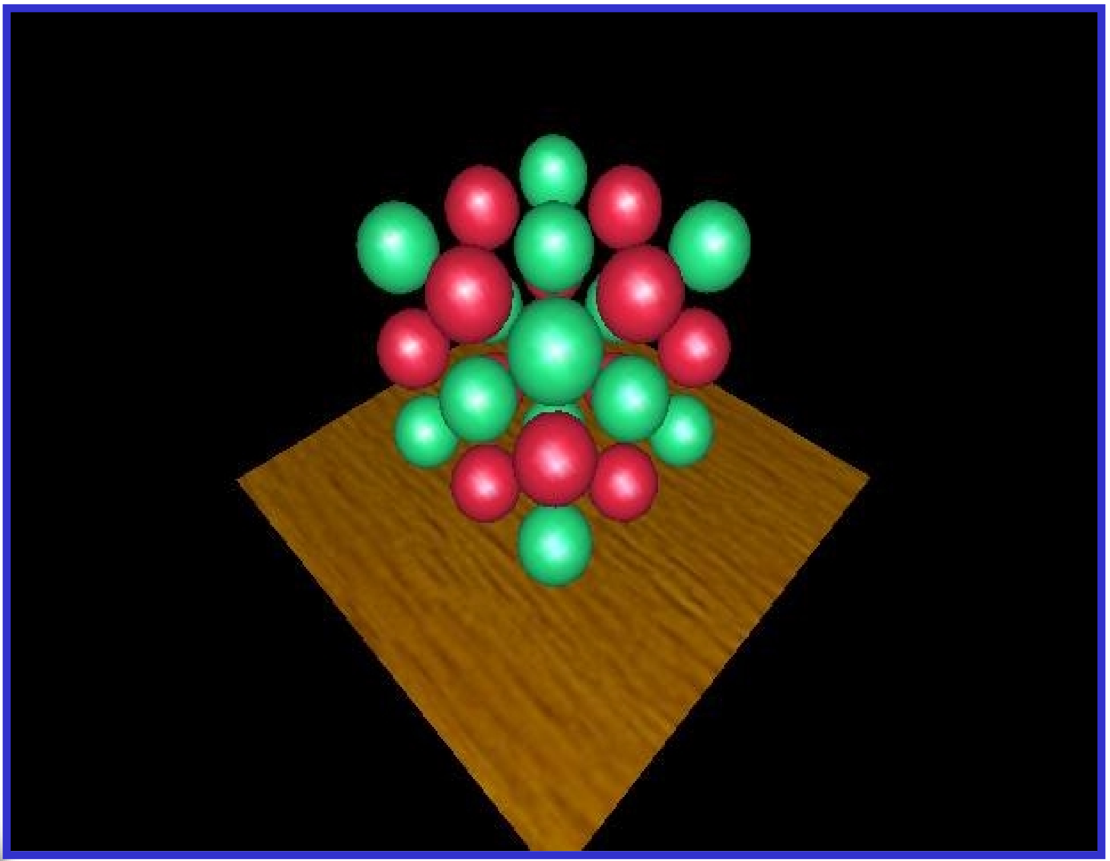
with shadows

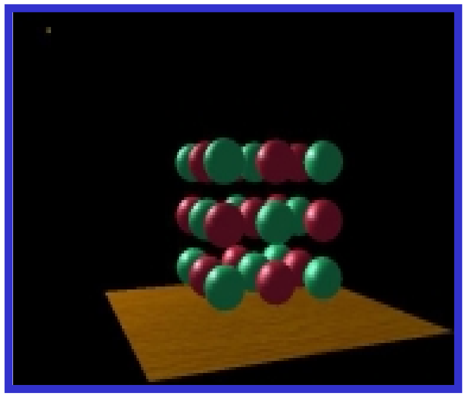


without shadows

Visualizing the Shadow Mapping Technique (3)

- The scene from the light's point-of-view

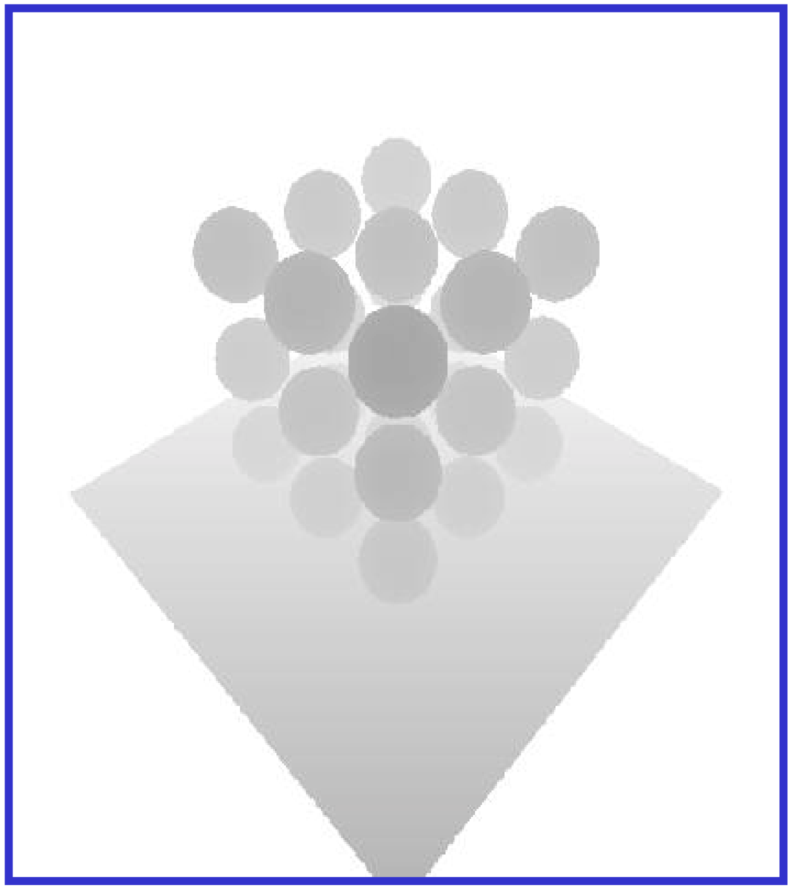


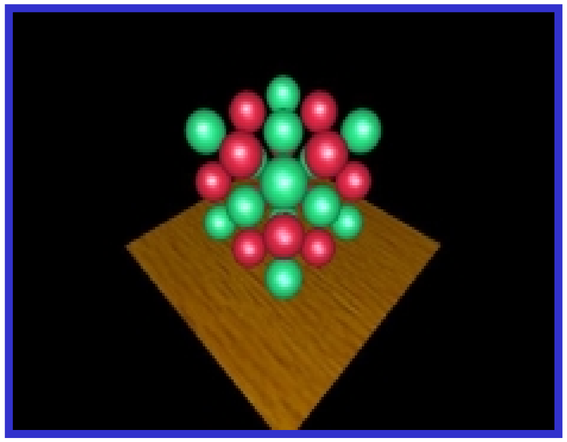


FYI: from the eye's point-of-view again

Visualizing the Shadow Mapping Technique (4)

- The depth buffer from the light's point-of-view

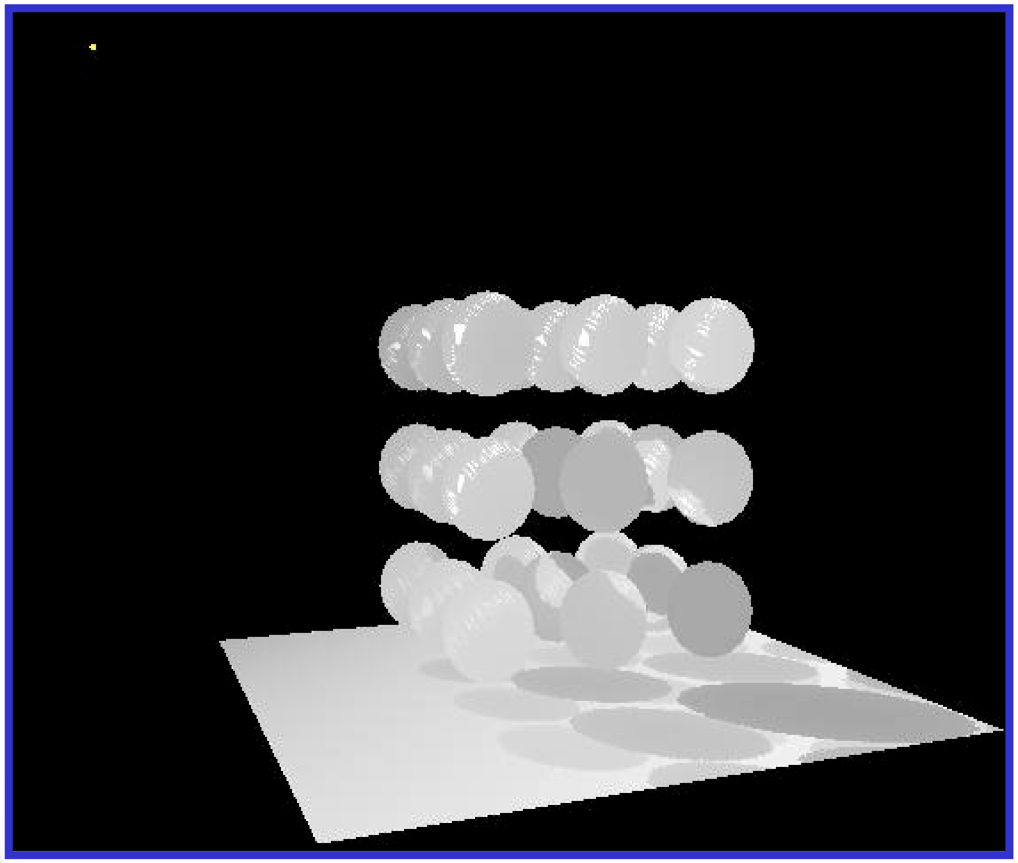


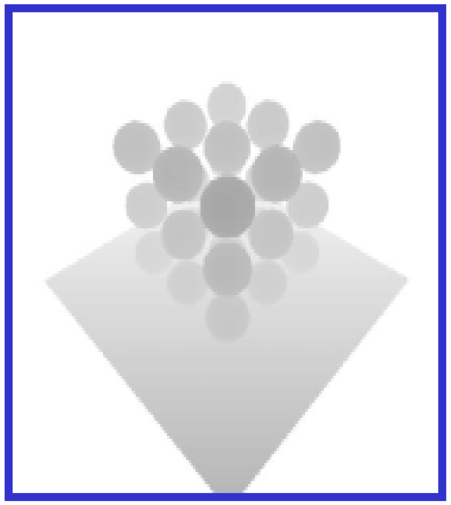


FYI: from the light's point-of-view again

Visualizing the Shadow Mapping Technique (5)

- Projecting the depth map onto the eye's view

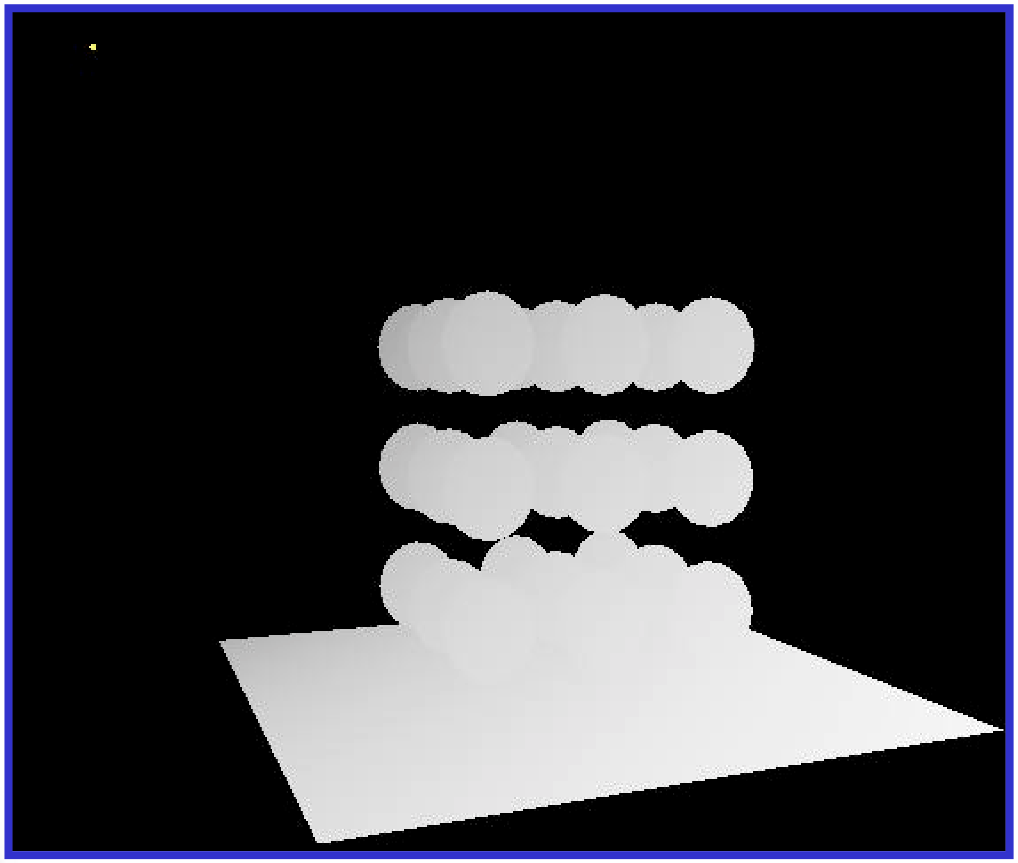




FYI: depth map for light's point-of-view again

Visualizing the Shadow Mapping Technique (6)

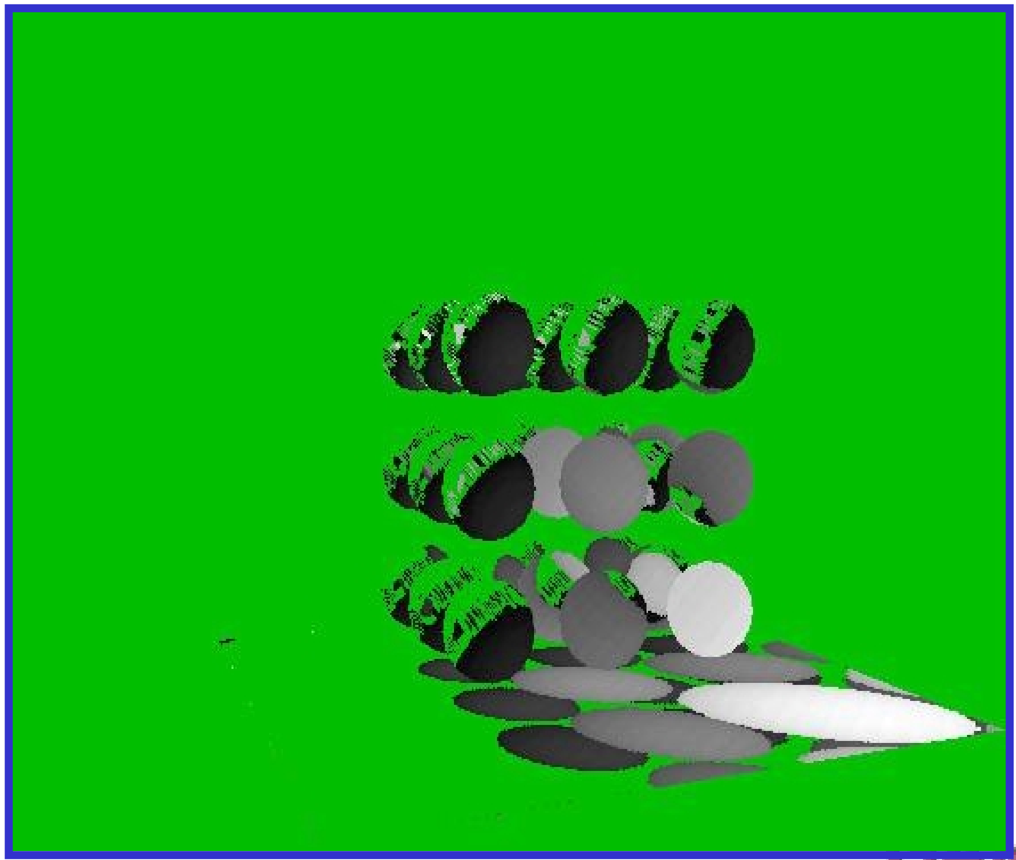
- Projecting light's planar distance onto eye's view



Visualizing the Shadow Mapping Technique (6)

- **Comparing light distance to light depth map**

Green is where the light planar distance and the light depth map are approximatel y equal

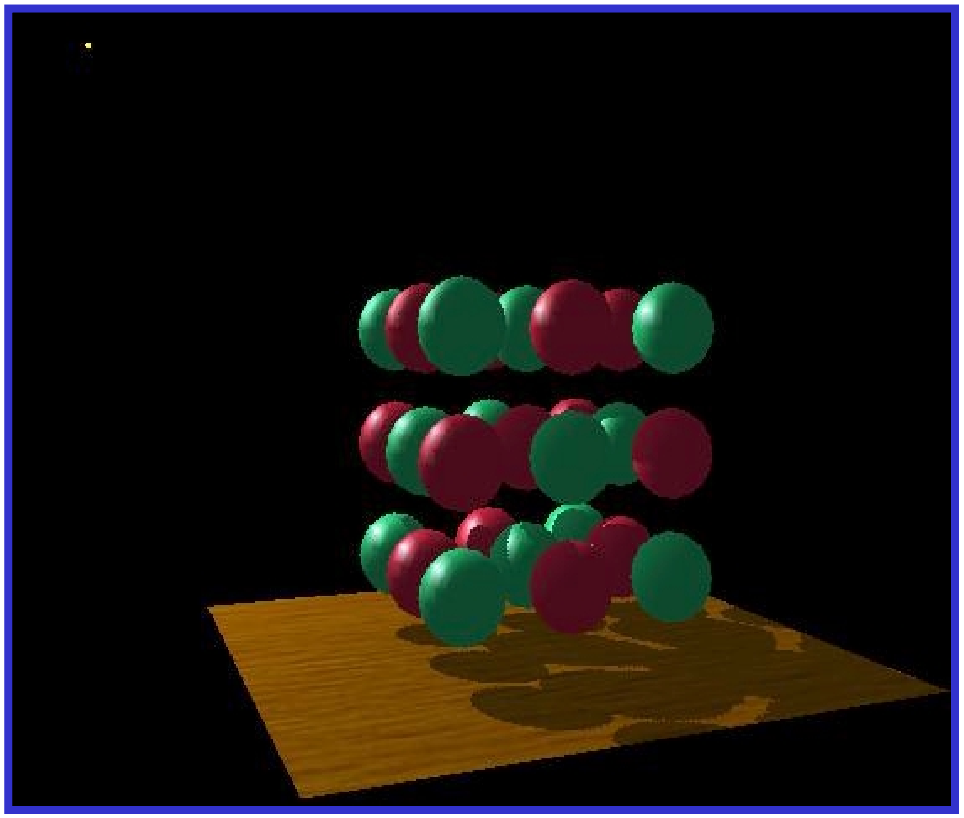


Non-green is where shadows should be

Visualizing the Shadow Mapping Technique (7)

- **Scene with shadows**

Notice how specular highlights never appear in shadows



Notice how curved surfaces cast shadows on each other

Construct
Light View Depth Map

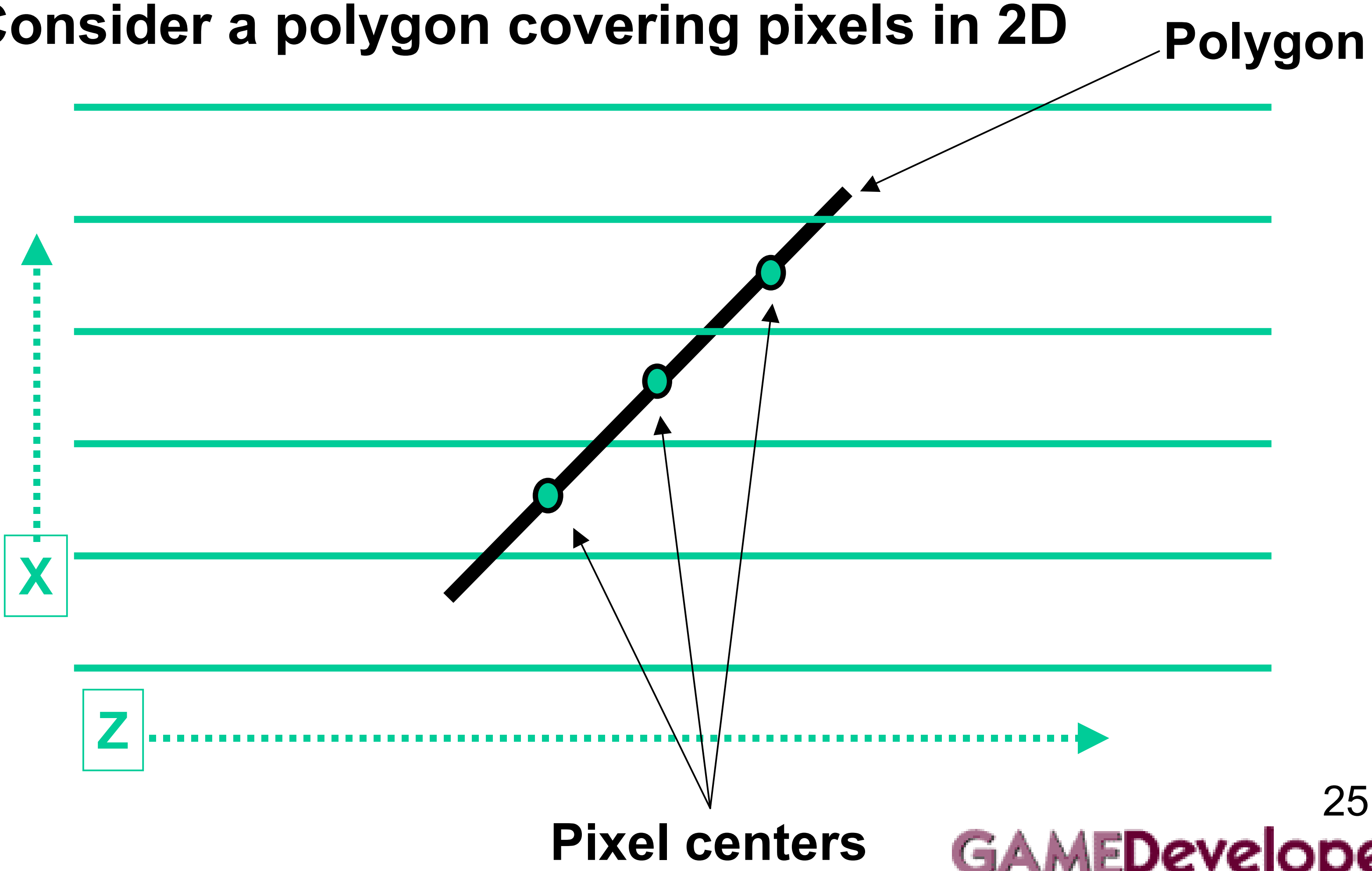
- Realizing the theory in practice
  - Constructing the depth map
    - use existing hardware depth buffer
    - use glPolygonOffset to offset depth value back
    - read back the depth buffer contents
  - Depth map can be copied to a 2D texture
    - unfortunately, depth values tend to require more precision than 8-bit typical for textures
    - depth precision typically 16-bit or 24-bit

Justification for glPolygonOffset When Constructing Shadow Maps

- Depth buffer contains “window space” depth values
  - Post-perspective divide means non-linear distribution
  - glPolygonOffset is guaranteed to be a window space offset
- Doing a “clip space” glTranslatef is not sufficient
  - Common shadow mapping implementation mistake
  - Actual bias in depth buffer units will vary over the frustum
  - No way to account for slope of polygon

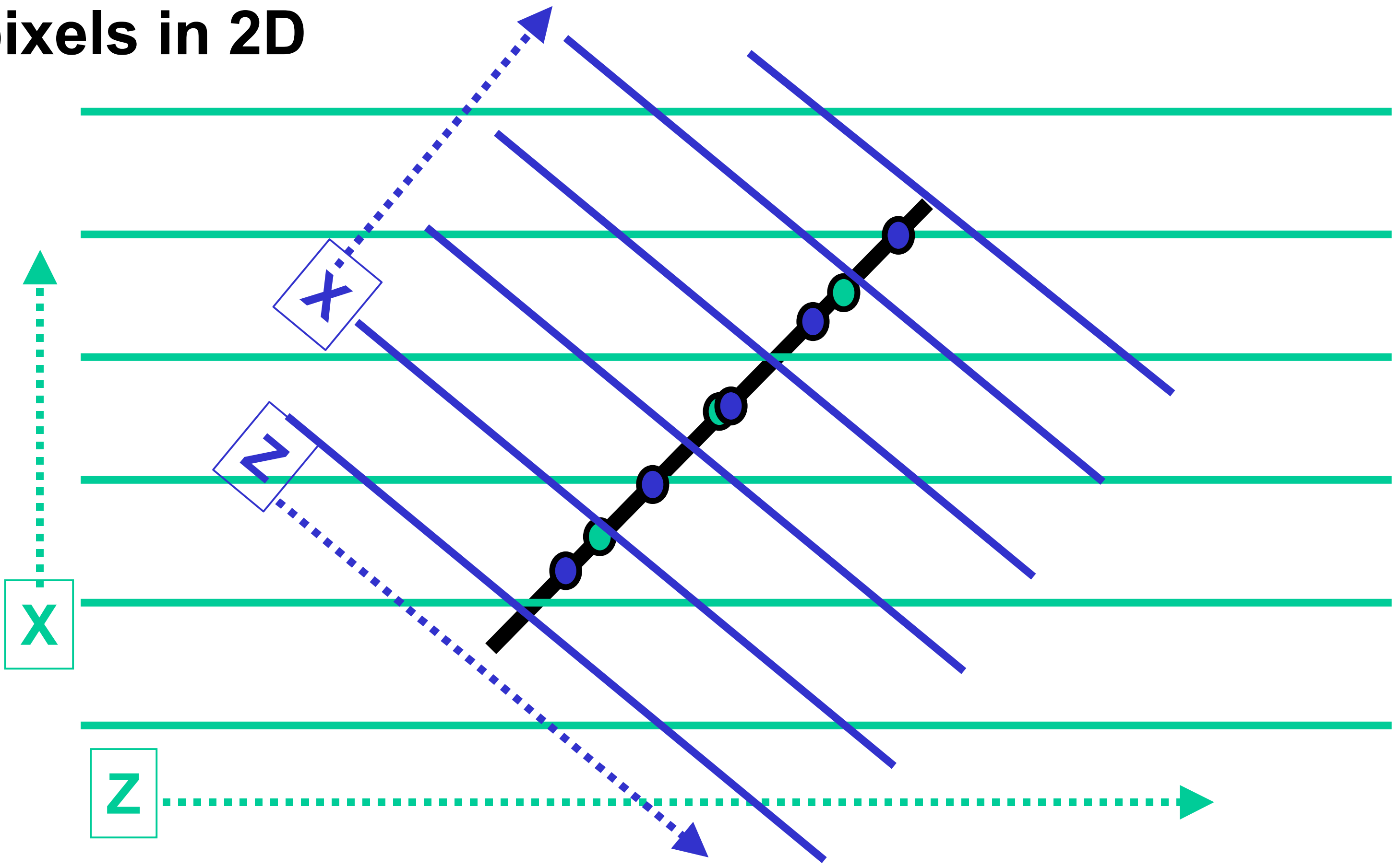
Sampling a Polygon's Depth at Pixel Centers (1)

- Consider a polygon covering pixels in 2D



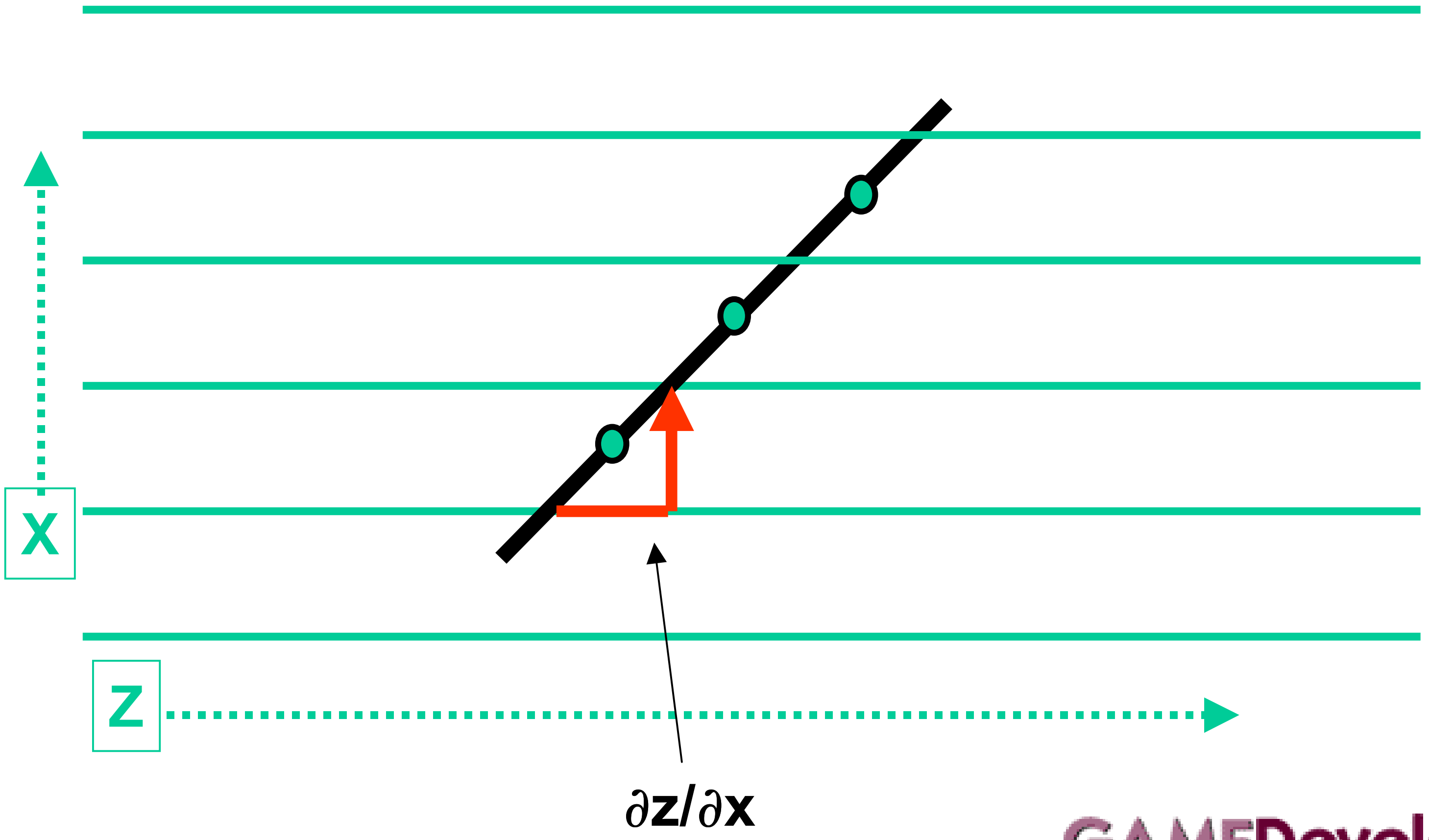
Sampling a Polygon's Depth at Pixel Centers (2)

- Consider a 2nd grid for the polygon covering pixels in 2D



Sampling a Polygon's Depth at Pixel Centers (3)

- How Z changes with respect to X

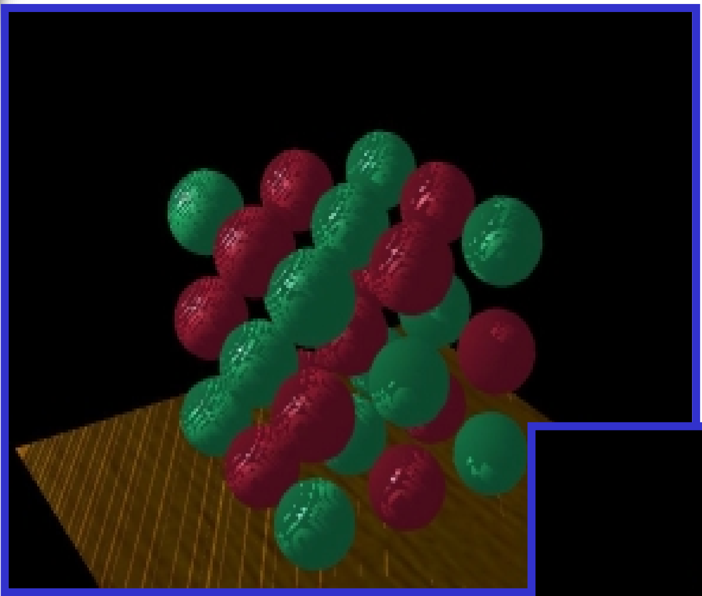


Why You Need glPolygonOffset's Slope

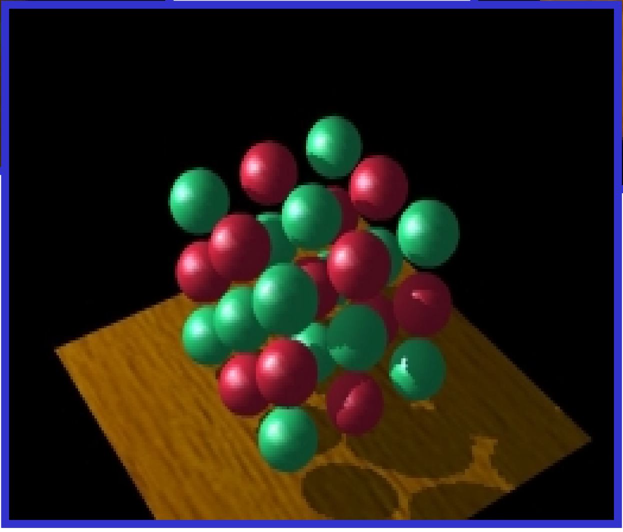
- Say pixel center is re-sampled to another grid
  - For example, the shadow map texture's grid!
- The re-sampled depth could be off by
  $+/-0.5\ \partial z/\partial x$ and $+/-0.5\ \partial z/\partial y$
- The maximum absolute error would be
  $|\ 0.5\ \partial z/\partial x\ | + |\ 0.5\ \partial z/\partial y\ | \approx \max(\ |\ \partial z/\partial x\ |\ ,\ |\ \partial z/\partial y\ |\ )$
  - This assumes the two grids have pixel footprint area ratios of 1.0
  - Otherwise, we might need to scale by the ratio
- Exactly what polygon offset's "slope" depth bias does

Depth Map Bias Issues

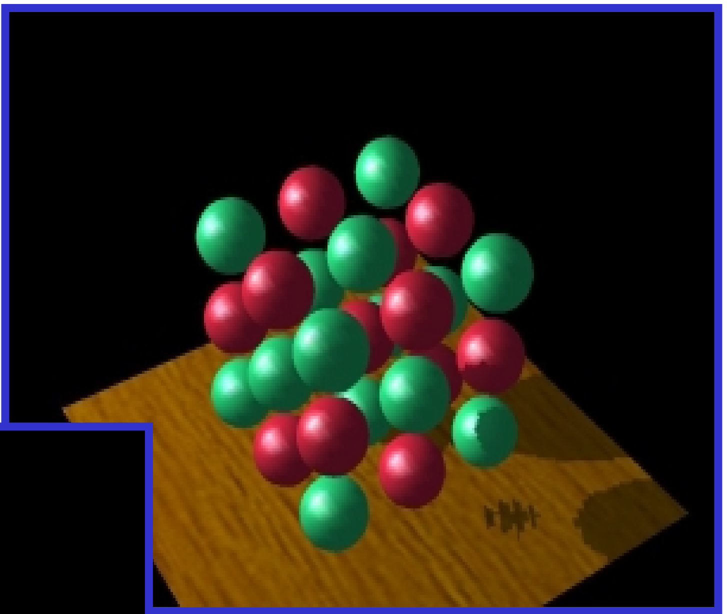
- How much polygon offset bias depends



Too little bias, everything begins to shadow



Just right



Too much bias, shadow starts too far back

Selecting the Depth Map Bias

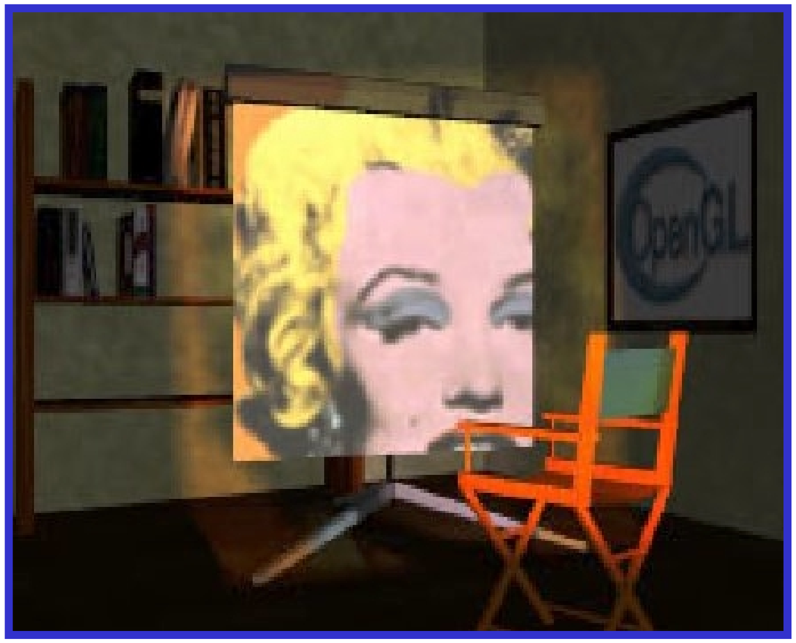
- Not that hard
  - Usually the following works well
    - glPolygonOffset(scale = 1.1, bias = 4.0)
  - Usually better to error on the side of too much bias
    - adjust to suit the shadow issues in your scene
  - Depends somewhat on shadow map precision
    - more precision requires less of a bias
  - When the shadow map is being magnified, a larger scale is often required

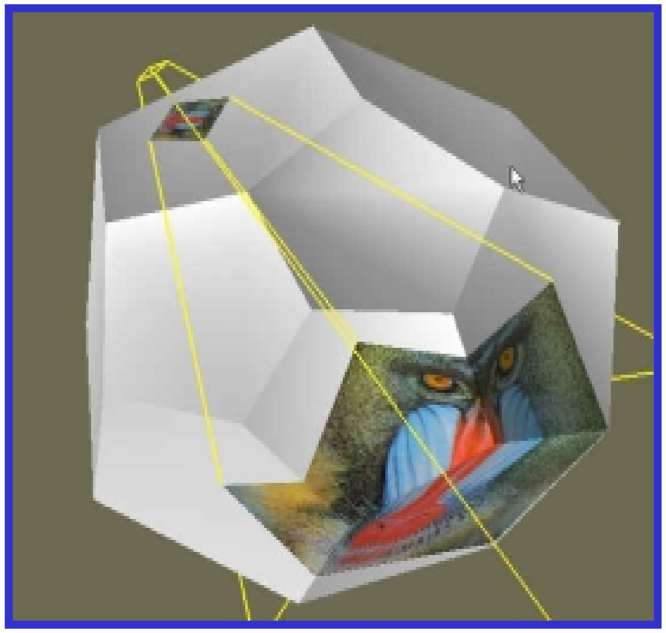
Render Scene and Access the Depth Texture

- 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 projective texturing

What is Projective Texturing?

- An intuition for projective texturing
  - The slide projector analogy





Source: Wolfgang Heidrich [99]

About Projective Texturing (1)

- 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 interpolated 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’)

About
Projective Texturing (2)

- 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

About Projective Texturing (3)

- 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!

About
Projective Texturing (4)

- 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

Projective Texturing Multitexturing

- An aside about projective multi-texturing
  - Multi-texturing is easier if all texture units are required only to be perspective-correct
    - just requires a single hyperbolic interpolator (effectively shares a single divider among multiple texture units)
    - because 1/w is the same for all texture units
  - But multi-textured projective textures is harder
    - each texture unit could have a different q
    - therefore a different q/w per texture unit

NVIDIA’s Projective Texturing Story

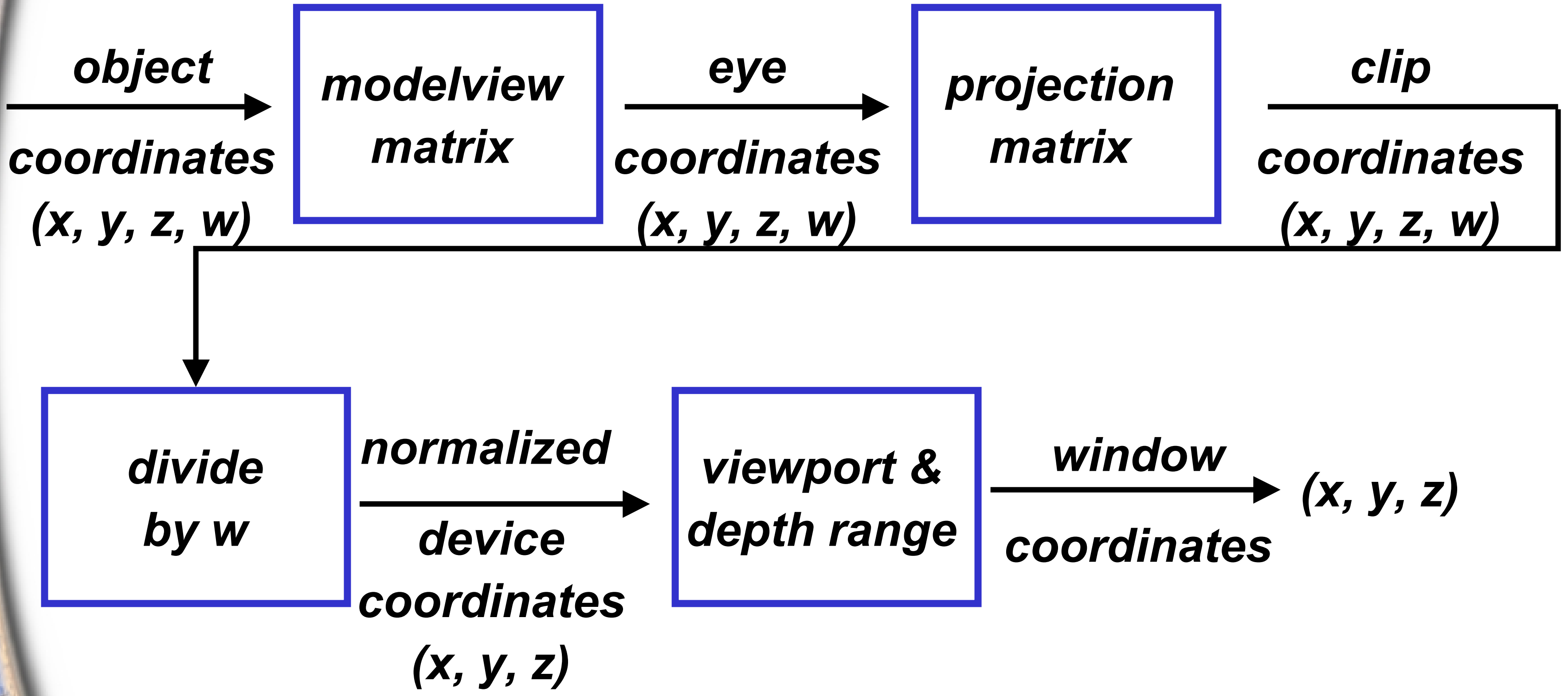
- Different generations differ
  - TNT generation has a single shared hyperbolic interpolator
    - independently projected dual textures do not work
    - not enough gates for dual-projective in TNT timeframe
  - GeForce generation has distinct q/w hyperbolic interpolators for both texture units (bigger gate budget buys correctness)
    - dual projective textures works
  - Not sure what other vendors do

Back to the Shadow Mapping Discussion . . .

- 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

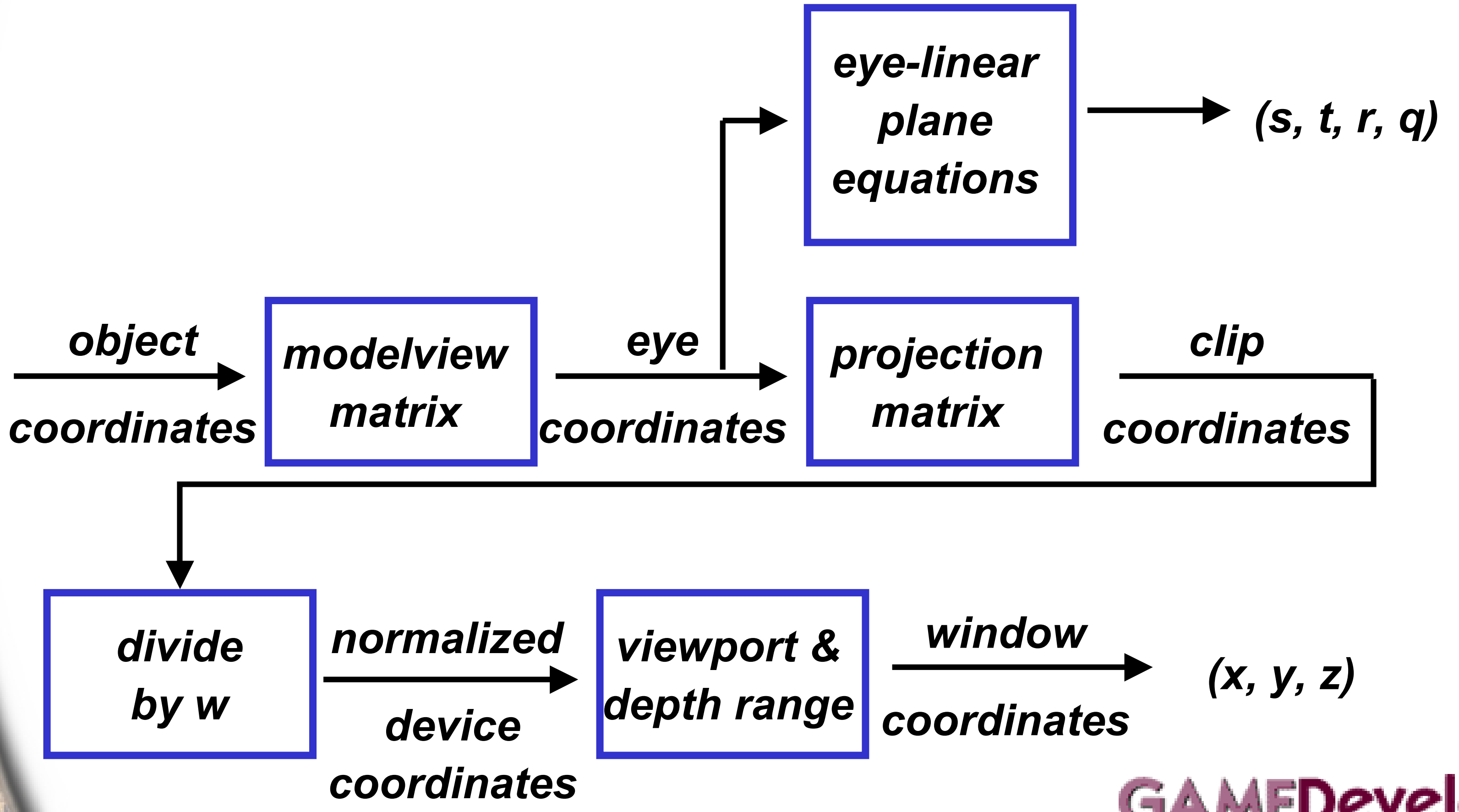
OpenGL's Standard Vertex Coordinate Transform

- **From object coordinates to window coordinates**


object coordinates (x, y, z, w)
modelview matrix
eye coordinates (x, y, z, w)
projection matrix
clip coordinates (x, y, z, w)
divide by w
normalized device coordinates (x, y, z)
viewport & depth range
window coordinates
(x, y, z)

Eye Linear Texture Coordinate Generation

- Generating texture coordinates from eye-space



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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 eye plane equation is transformed by current inverse modelview matrix (a very handy thing for us)
  - Note: texgen object planes are ***not*** transformed
    by the inverse modelview

Eye Linear Texgen Transform

- Plane equations form a projective transform

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

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

Shadow Map Eye Linear Texgen Transform

$$\begin{bmatrix} x_e \\ y_e \\ z_e \\ w_e \end{bmatrix} = \begin{bmatrix} \text{Eye} \\ \text{view} \\ \text{(look at)} \\ \text{matrix} \end{bmatrix} \begin{bmatrix} \text{Modeling} \\ \text{matrix} \end{bmatrix} \begin{bmatrix} x_o \\ y_o \\ z_o \\ w_o \end{bmatrix}$$

$$\begin{bmatrix} s \\ t \\ r \\ q \end{bmatrix} = \underbrace{\begin{bmatrix} 1/2 & & & 1/2 \\ & 1/2 & & 1/2 \\ & & 1/2 & 1/2 \\ & & & 1 \end{bmatrix} \begin{bmatrix} \text{Light} \\ \text{frustum} \\ \text{(projection)} \\ \text{matrix} \end{bmatrix} \begin{bmatrix} \text{Light} \\ \text{view} \\ \text{(look at)} \\ \text{matrix} \end{bmatrix}}_{\text{Supply this combined transform to glTexGen}} \overbrace{\begin{bmatrix} \text{Inverse} \\ \text{eye} \\ \text{view} \\ \text{(look at)} \\ \text{matrix} \end{bmatrix}}^{\text{glTexGen automatically applies this when modelview matrix contains just the eye view transform}} \begin{bmatrix} x_e \\ y_e \\ z_e \\ w_e \end{bmatrix}$$

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] $\cong$ r/q then *not shadowed***
    - **if texture[s/q, t/q] < r/q then *shadowed***

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 glCopySubTexImage2D for faster updates once texture internal format initially defined
- 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

Depth Texture Copy Performance

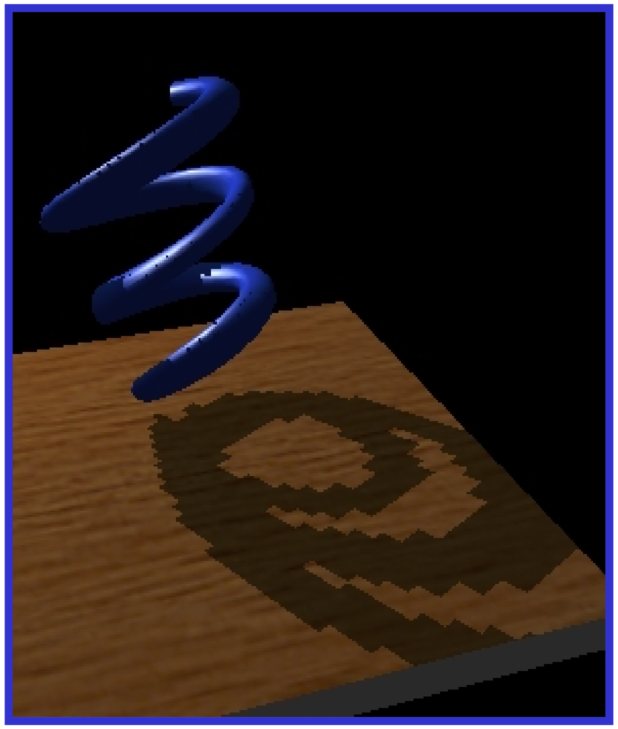
- The more depth values you copy, the slower the performance
  - 512x512 takes 4 times longer to copy than 256x256
  - Tradeoff: better defined shadows require higher resolution shadow maps, but slows copying
- 16-bit depth values copy twice as fast as 24-bit depth values (which are contained in 32-bit 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

Hardware Shadow Map Filtering

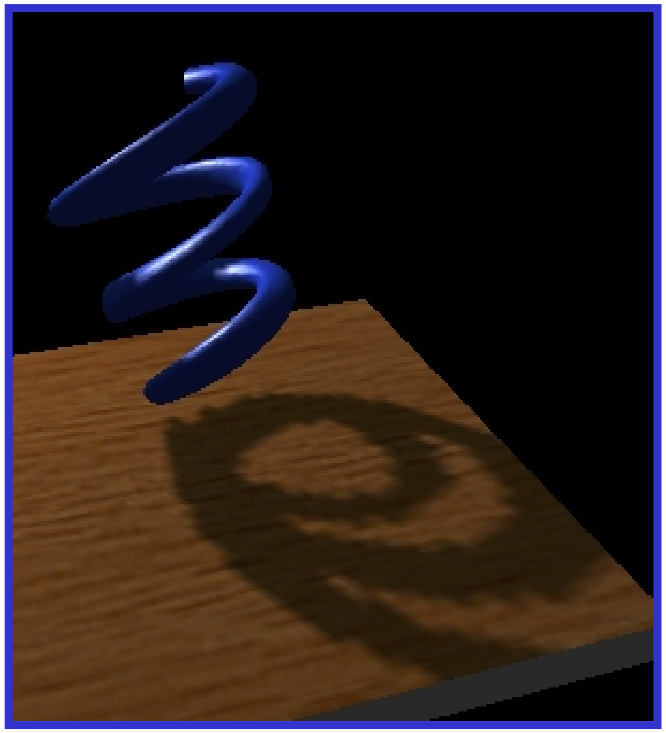
- "Percentage Closer" filtering
  - Normal texture filtering just averages color components
  - Averaging depth values does NOT work
  - Solution [Reeves, SIGGARPH 87]
    - Hardware performs comparison for each sample
    - Then, averages results of comparisons
  - Provides anti-aliasing at shadow map edges
    - Not soft shadows in the umbra/penumbra sense

Hardware Shadow Map Filtering Example

GL_NEAREST: blocky



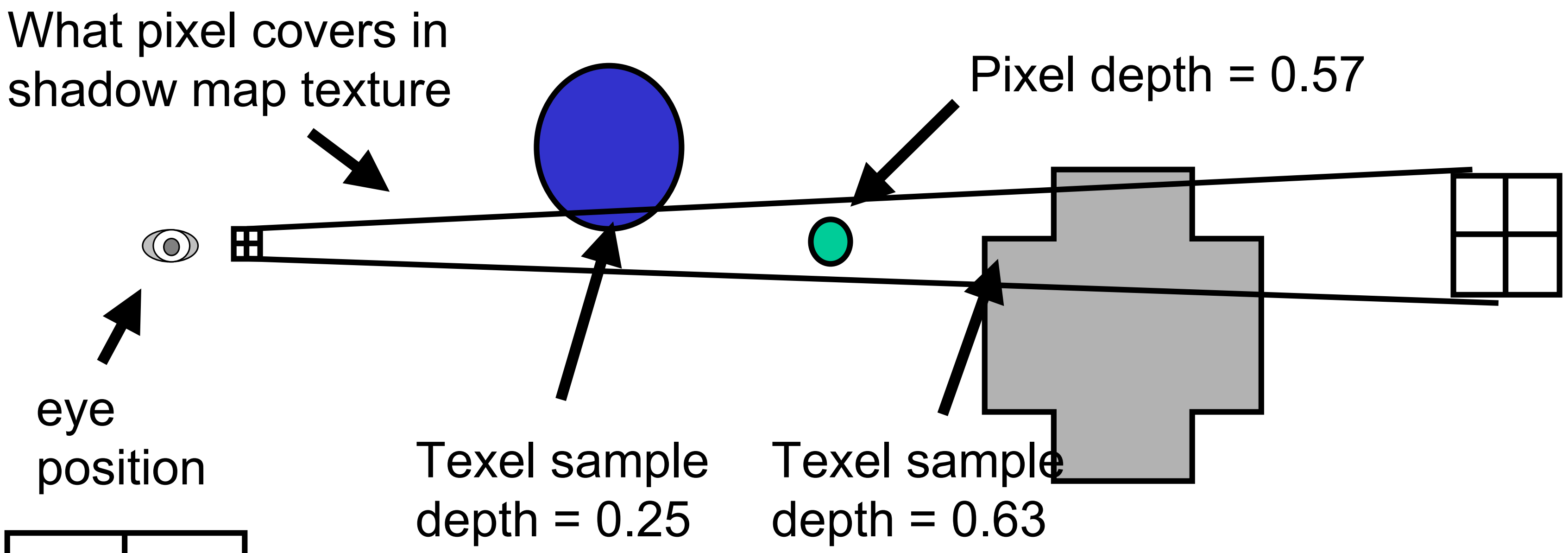
GL_LINEAR: antialiased edges



Low shadow map resolution used to heightens filtering artifacts

Depth Values are not Blend-able

- **Traditional filtering is inappropriate**

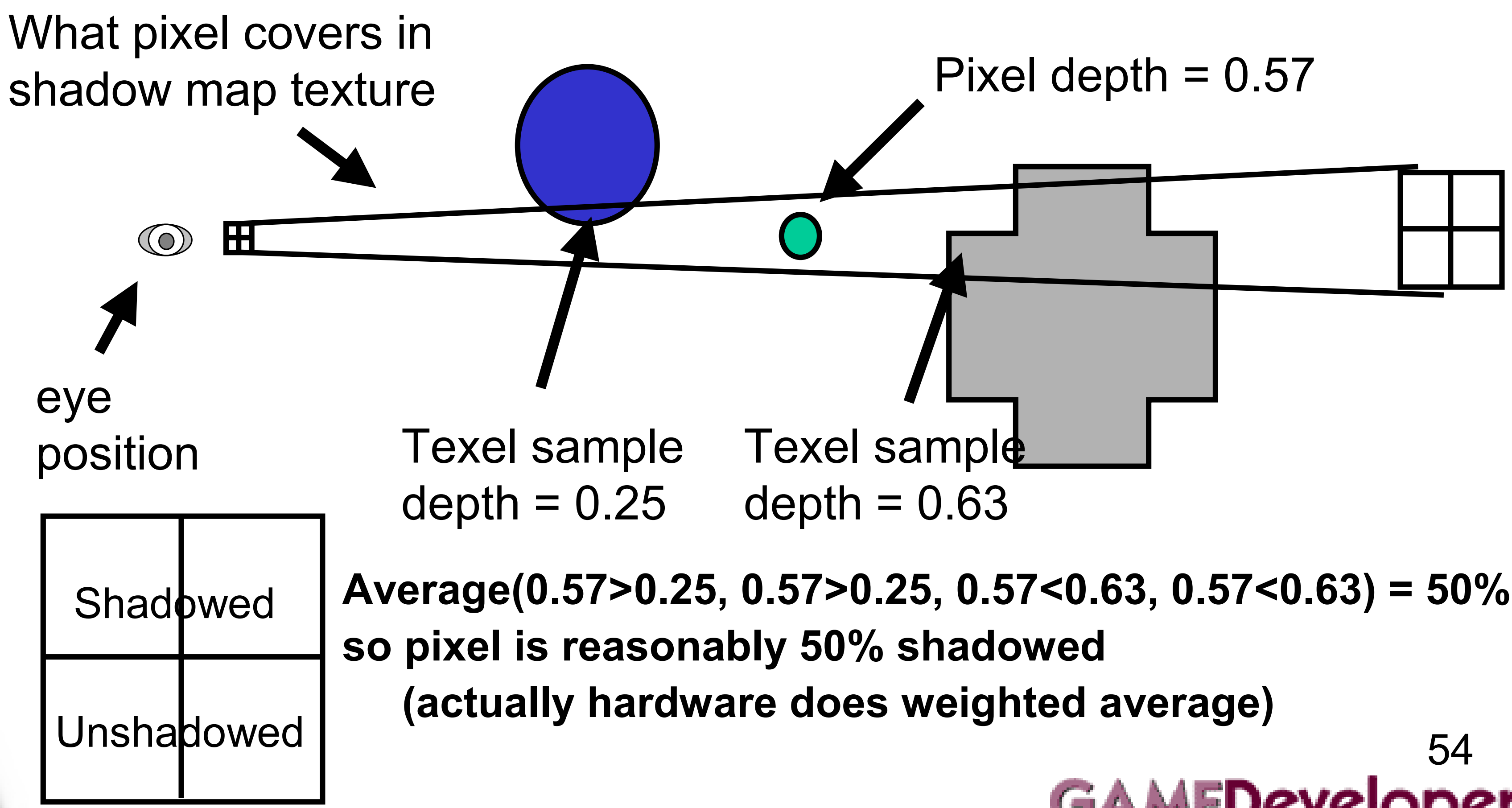

What pixel covers in shadow map texture
Pixel depth = 0.57
eye position
Texel sample depth = 0.25
Texel sample depth = 0.63

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 0.57

Percentage Closer Filtering

- **Average comparison *results*, not depth values**


What pixel covers in shadow map texture
Pixel depth = 0.57
eye position
Texel sample depth = 0.25
Texel sample depth = 0.63
Shadowed
Unshadowed

Average(0.57>0.25, 0.57>0.25, 0.57<0.63, 0.57<0.63) = 50%
so pixel is reasonably 50% shadowed
(actually hardware does weighted average)

Mipmap Filtering for Depth Textures with Percentage Closer Filtering (1)

- **Mipmap filtering works**
  - **Averages the results of comparisons form the one or two mipmap levels sampled**
- **You *cannot* use gluBuild2DMipmaps to construct depth texture mipmaps**
  - **Again, because you cannot blend depth values!**
- **If you do want mipmaps, the best approach is re-rendering the scene at each required resolution**
  - **Usually too expensive to be practical for all mipmap levels**
  - **OpenGL 1.2 LOD clamping can help avoid rendering all the way down to the 1x1 level**

Mipmap Filtering for Depth Textures with Percentage Closer Filtering (2)

- Mipmaps can make it harder to find an appropriate polygon offset scale & bias that guarantee avoidance of self-shadowing
- You can get “8-tap” filtering by using (for example) two mipmap levels, 512x512 and 256x256, and setting your min and max LOD clamp to 0.5
  - Uses OpenGL 1.2 LOD clamping

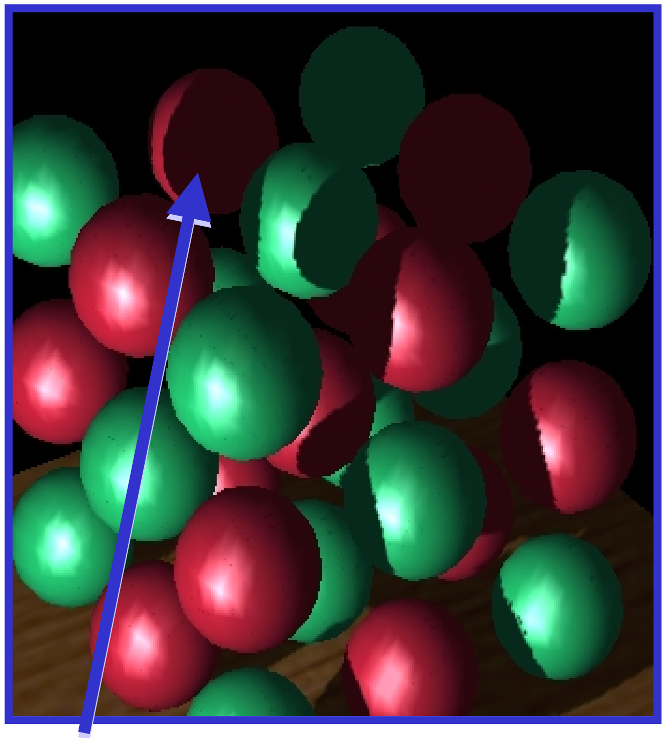
Advice for Shadowed Illumination Model (1)

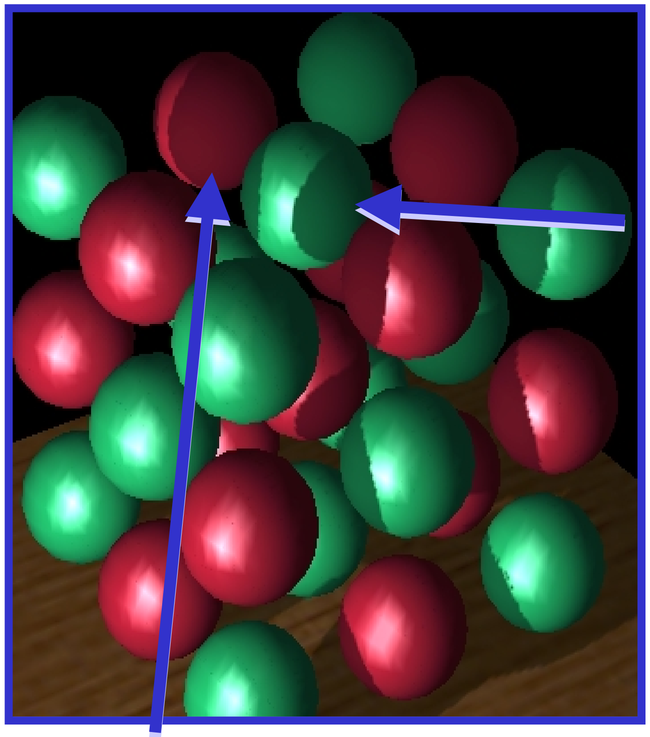
- Typical illumination model with decal texture:
  *(ambient + diffuse) * decal + specular*
- The shadow map supplies a shadowing term
- Assume shadow map supplies a shadowing term, ***shade***
  - Percentage shadowed
  - 100% = fully visible, 0% = fully shadowed
- Obvious updated illumination model for shadowing:
  *(ambient + shade * diffuse) * decal + shade * specular*
- Problem is real-world lights don’t 100% block diffuse shading on shadowed surfaces
  - Light scatters; real-world lights are not ideal points

The Need for Dimming Diffuse

No dimming; shadowed regions have 0% diffuse and 0% specular

With dimming; shadowed regions have 40% diffuse and 0% specular





No specular in shadowed regions in both versions.

Front facing shadowed regions appear unnaturally flat.

Still evidence of curvature in shadowed regions.

Advice for Shadowed Illumination Model (2)

- **Illumination model with dimming:**

  *(ambient + diffuseShade * diffuse) * decal + specular * shade*

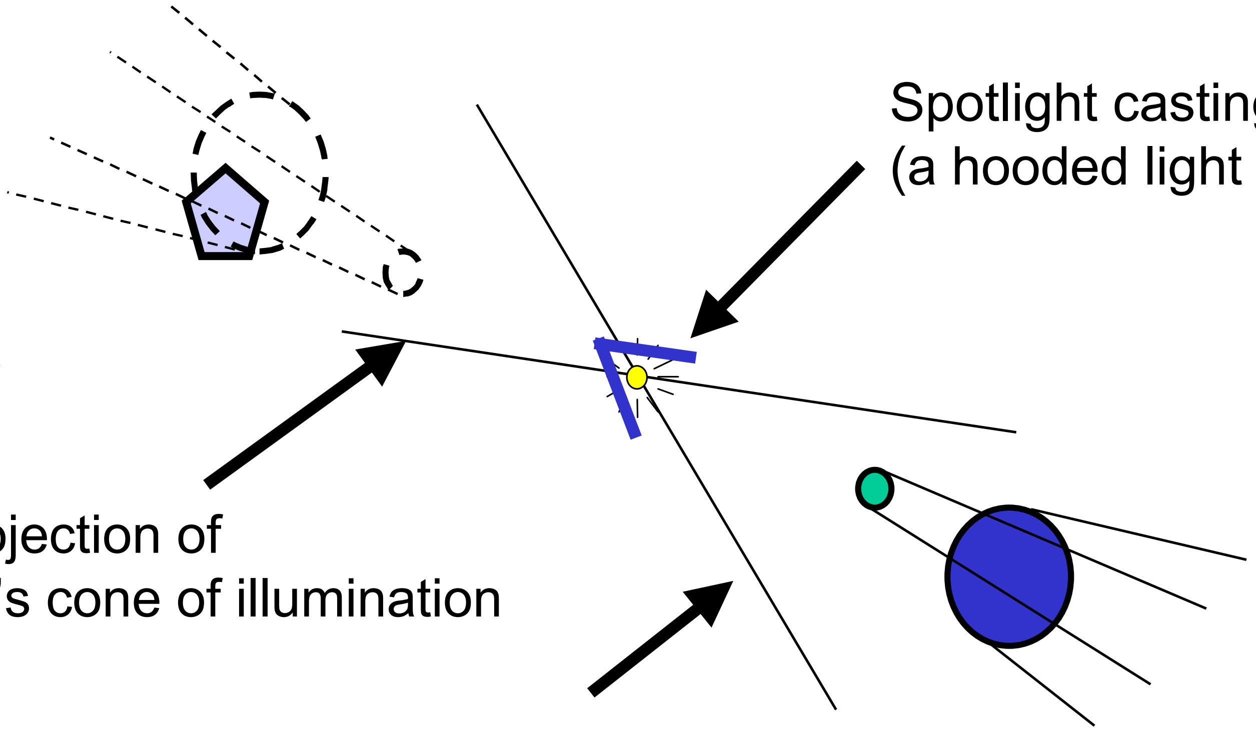
  where *diffuseShade* **is**

  *diffuseShade = dimming + (1.0 – dimming) * shade*

- **Easy to implement with NV_register_combiners & OpenGL 1.2 "separate specular color" support**
  - Separate specular keeps the diffuse & specular per-vertex lighting results distinct
  - NV_register_combiners can combine the primary (diffuse) and secondary (specular) colors per-pixel with the above math

Careful about Back Projecting Shadow Maps (1)

- **Just like standard projective textures, shadow maps can back-project**


Pentagon would be incorrectly lit by back-projection if not specially handled
Spotlight casting shadow (a hooded light source)
Back-projection of spotlight's cone of illumination
Spotlight's of cone of illumination where "true" shadows can form

Careful about Back Projecting Shadow Maps (2)

- **Techniques to eliminate back-projection:**
  - Modulate shadow map result with lighting result from a single per-vertex spotlight with the proper cut off (ensures is light “off” behind the spotlight)
  - Use a small 1D texture where “s” is planar distance from the light (generated “s” with a planar texgen mode), then 1D texture is 0.0 for negative distances and 1.0 for positive distances.
  - Use a clip plane positioned at the plane defined by the light position and spotlight direction
  - Simply avoid drawing geometry “behind” the light when applying the shadow map (better than a clip plane)
  - NV_texture_shader’s GL_PASS_THROUGH_NV mode

Other Useful OpenGL Extensions for Improving Shadow Mapping

- **ARB_pbuffer** – create off-screen rendering surfaces for rendering shadow map depth buffers
  - Normally, you can construct shadow maps in your back buffer and copy them to texture
  - But if the shadow map resolution is larger than your window resolution, use pbuffers.
- **NV_texture_rectangle** – new 2D texture target that does not require texture width and height to be powers of two
  - Limitations
    - No mipmaps or mipmap filtering supported
    - No wrap clamp mode
    - Texture coords in [0..w]x[0..h] rather than [0..1]x[0..1] range.
  - Quite acceptable for for shadow mapping

Combining Shadow Mapping with other Techniques

- Good in combination with techniques
  - Use stencil to tag pixels as inside or outside of shadow
  - Use other rendering techniques in extra passes
    - bump mapping
    - texture decals, etc.
  - Shadow mapping can be integrated into more complex multi-pass rendering algorithms
- Shadow mapping algorithm does not require access to vertex-level data
  - Easy to mix with vertex programs and such

An Alternative to Dedicated Shadow Mapping Hardware

- 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 *glPolygonOffset* to bias depth values to avoid surfaces shadowing themselves in subsequent shadow test pass**
    - **perform bias during depth map construct instead of during shadow testing pass so bias will be in depth buffer space**
  - **Read back depth buffer with *glReadPixels* as unsigned bytes**
  - **Load same bytes into *GL_INTENSITY8* texture via *glTexImage2D***

Dual-texture Shadow Mapping Approach

- Depth map texture issues
  - limited to 8-bit precision
    - not a lot of precision of depth
    - more about this issue later
  - un-extended OpenGL provides no direct depth copy
    - cannot copy depth buffer to a texture directly
    - must *glReadPixels*, then *glTexImage2D*

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**

$$\begin{bmatrix} s \\ t \\ \\ q \end{bmatrix} = \underbrace{\begin{bmatrix} 1/2 & & & 1/2 \\ & 1/2 & & 1/2 \\ & & & \\ & & & 1 \end{bmatrix} \begin{bmatrix} \textit{Light} \\ \textit{frustum} \\ \textit{(projection)} \\ \textit{matrix} \end{bmatrix} \begin{bmatrix} \textit{Light} \\ \textit{view} \\ \textit{(look at)} \\ \textit{matrix} \end{bmatrix}}_{\textit{Supply this combined transform to glTexGen}} \underbrace{\begin{bmatrix} \textit{Inverse} \\ \textit{eye} \\ \textit{view} \\ \textit{(look at)} \\ \textit{matrix} \end{bmatrix}}_{\textit{glTexGen automatically applies this}} \begin{bmatrix} x_e \\ y_e \\ z_e \\ w_e \end{bmatrix}$$

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**

$$\begin{bmatrix} s \\ \\ \\ q \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 0 & 1 & 0 \\ & & & \\ & & & \\ & & & 1 \end{bmatrix} \begin{bmatrix} 1/2 & & & 1/2 \\ & 1/2 & & 1/2 \\ & & 1/2 & 1/2 \\ & & & 1 \end{bmatrix} \begin{bmatrix} \text{Light} \\ \text{frustum} \\ \text{(projection)} \\ \text{matrix} \end{bmatrix} \begin{bmatrix} \text{Light} \\ \text{view} \\ \text{(look at)} \\ \text{matrix} \end{bmatrix}}_{\textit{Supply this combined transform to glTexGen}} \underbrace{\begin{bmatrix} \text{Inverse} \\ \text{eye} \\ \text{view} \\ \text{(look at)} \\ \text{matrix} \end{bmatrix}}_{\textit{glTexGen automatically applies this}} \begin{bmatrix} x_e \\ y_e \\ z_e \\ w_e \end{bmatrix}$$

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

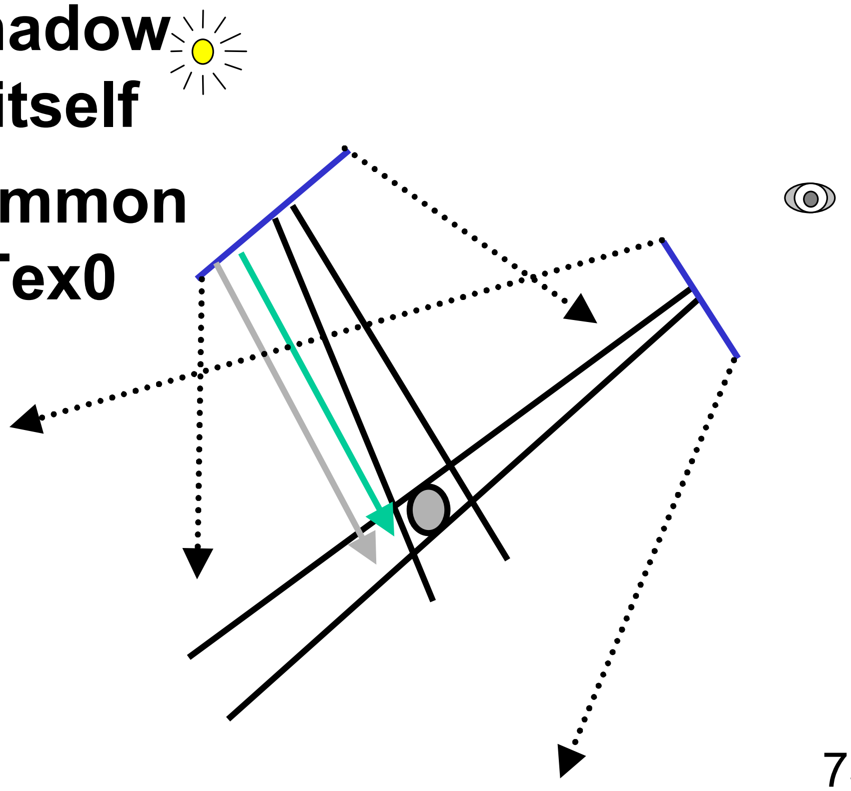
- Post-texture environment result
  - RGB is lit color (lighting is enabled during second pass)
  - Alpha is the biased difference of T0 and T1
    - unshadowed fragments have alpha >= 0.5
    - shadowed fragments have an alpha of < 0.5

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

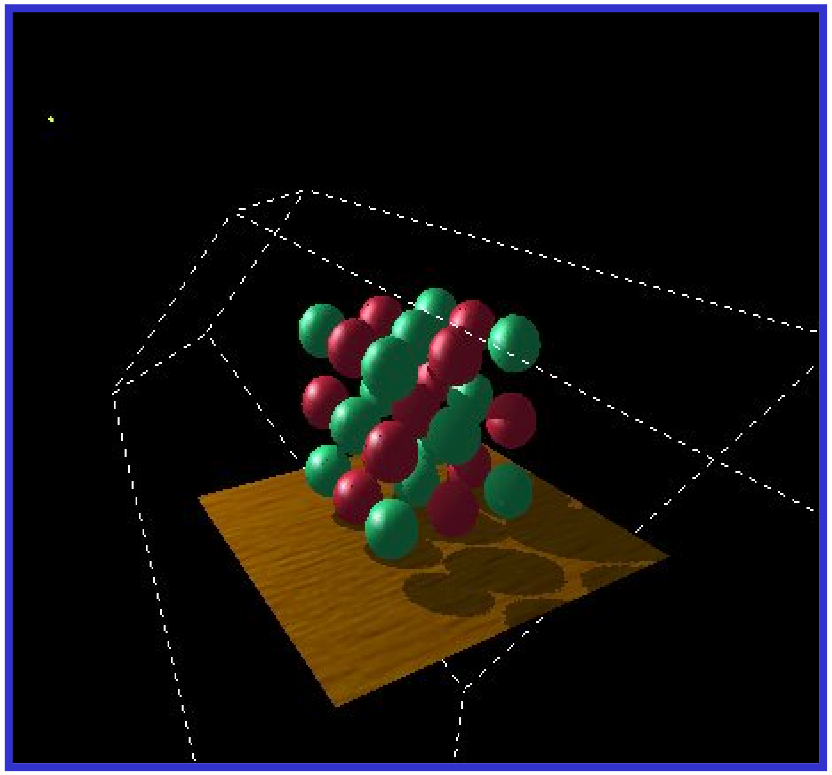
- **Biasing values in depth map helps**
  - **recall *glPolygonOffset* suggestion during the depth map construction pass**
  - **this bias should be done during depth map construction**
    - **biases in the texgen transform do <u>not</u> work**
    - **problem is depth map has non-linear distribution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

Dual-texture Shadow Mapping Precision

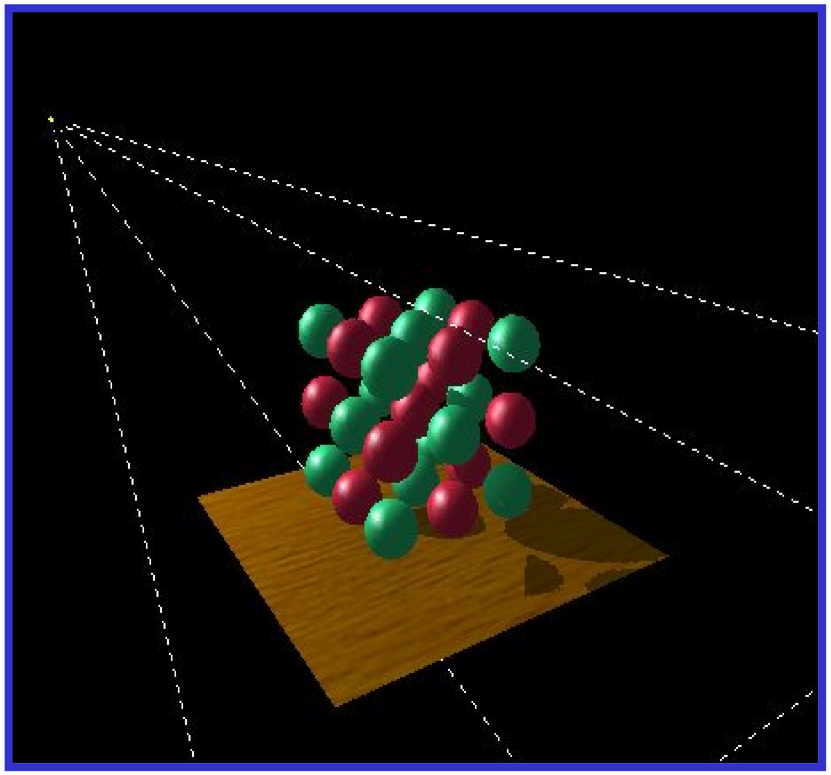
- Is 8-bit precision enough?
  - yes, for some simple scenes
    - when the objects are relatively distant from the light, but still relatively close together
  - no, in general
    - an 8-bit depth buffer is not enough depth discrimination
    - and the precision is badly distributed because of perspective

Dual-texture Shadow Mapping Precision

- **Conserving your 8-bit depth map precision**



Frustum confined to objects of interest



Frustum expanded out considerably breaks down the shadows

Improving Depth Map Precision

- Use linear depth precision [Wolfgang 99]
  - During depth map construction
    - generate S texture coordinate as eye planar Z distance scaled to [0, 1] range
    - lookup S in identity 1D intensity texture
    - write texture result into color frame buffer
    - still using standard depth testing
    - read alpha (instead of depth) and load it in depth map texture
    - alpha will have linear depth distribution (better!)

Improving Depth Map Precision

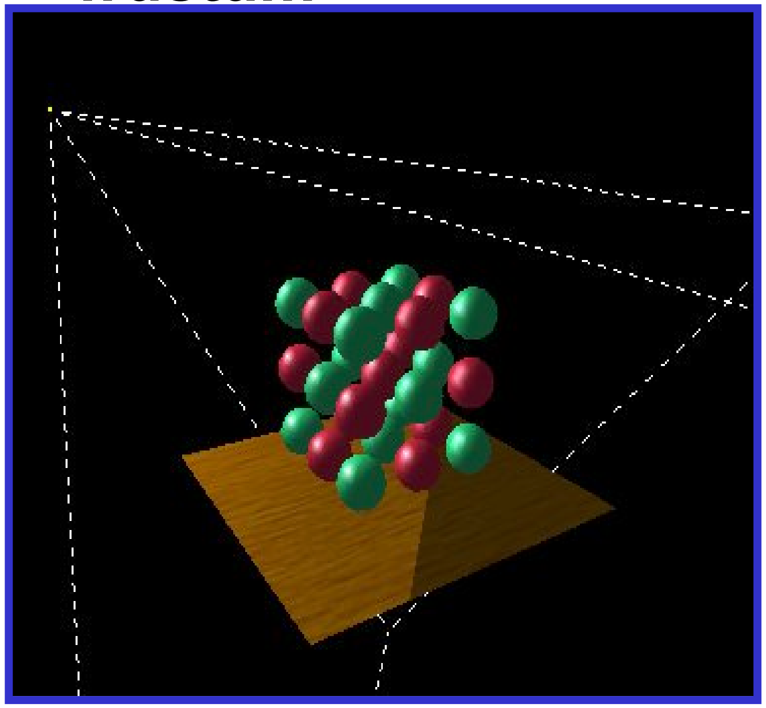
- More hardware color component precision
  - high-end workstations support more color precision
    - SGI's InfiniteReality, RealityEngine, and Octane workstations support 12-bit color component precision
  - but no high precision color buffers in consumer 3D space
    - consumer 3D designs too tied to 32-bit memory word size of commodity RAM
    - and overkill for most consumer applications anyway

Improving Depth Map Precision

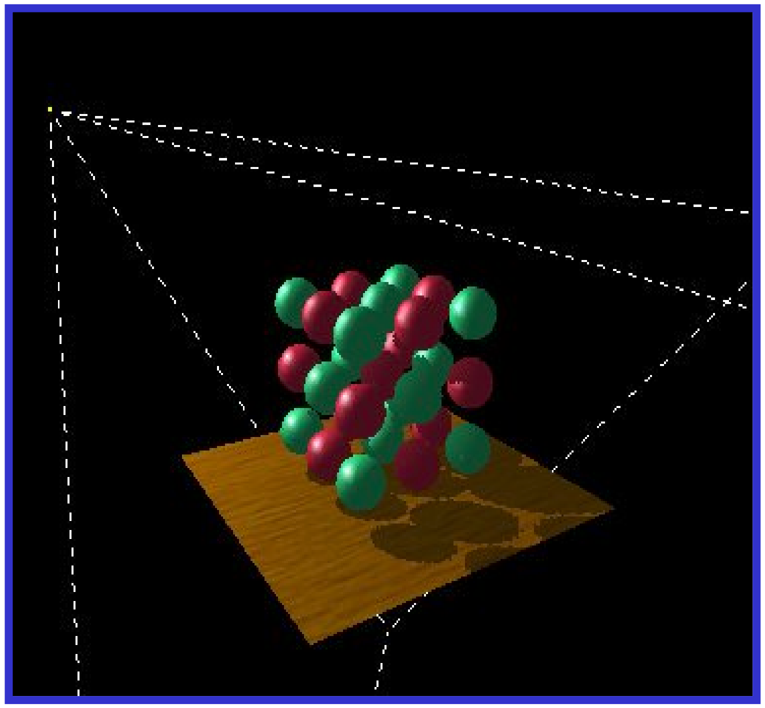
- Use multi-digit comparison
  - fundamental shadow determination operation is a comparison
    - comparisons (unlike multiplies or other operations) are easy to extend to higher precision
  - think about comparing two 2-digit numbers: 54 and 82
    - 54 is less than 82 simply based on the first digit (5 < 8)
    - only when most-significant digits are equal do you need to look at subsequent digits

More Precision Allows Larger Lights Frustums

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



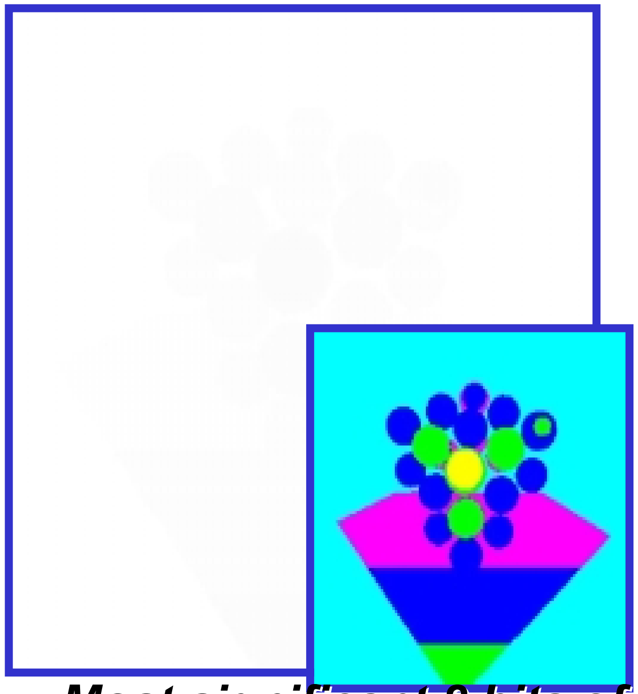
8-bit: Large frustum breaks down the shadows, not enough precision

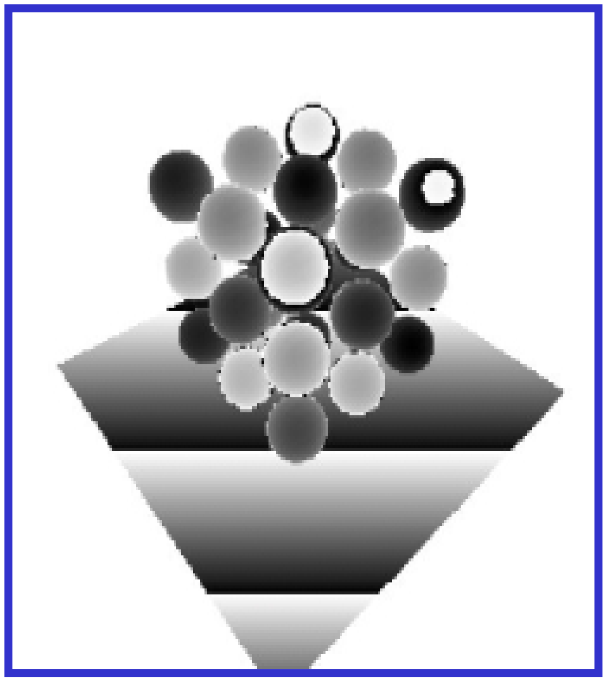


16-bit: Shadow looks just fine

Why Extra Precision Helps

- **Where the precision is for previous images**


Most significant 8 bits of the depth map, pseudo-color inset magnifies variations


Least significant 8 bits of the depth map, here is where the information is!

GeForce/Quadro Precision Extension

- Application of multi-digit comparison idea
  - Read back depth buffer as 16-bit unsigned short values
  - Load these values into GL_LUMINANCE8_ALPHA8 texture
    - think of depth map as two 8-bit digits
  - Two comparison passes
  - Uses NV_register_combiners extension
    - signed math and mux’ing helps
    - enough operations to test equality and greater/less than

GeForce/Quadro Precision Extension

- Multi-digit comparison passes
  - during clear, clear stencil buffer to 0
  - 1st pass draws unshadowed scene as before
  - 2nd pass draws unshadowed
    - alpha = bigDigit(Tex0) < bigDigit(Tex1)
    - alpha test with glAlphaFunc(GL_GREATER, 0.0)
    - and write 1 into stencil buffer when alpha test passes
  - needs 3rd pass for when bigDigit(Tex0) = bigDigit(Tex1)

GeForce/Quadro Precision Extension

- Third pass picks up the extra 8 bits of precision
  - Use NV_register_combiners to assign alpha as follows

    -
      ```
      if bigDigit(Tex1) > bigDigit(Tex0) then
         alpha = 0
      else
         alpha = littleDigit(Tex0) - littleDigit(Tex1)
      ```
  - Use alpha test with glAlphaFunc(GL_GREATER, 0.0)
  - Also reject fragment if the stencil value is 1
    - meaning the 2nd pass already updated the pixel

GeForce/Quadro Precision Extension

- Third pass needs 2 digits of light Z range
  - 2nd pass just requires a linear 1D texture
    - only needs 8 bits for bigDigit(Tex1)
  - 3rd pass
    - needs full 16-bit precision
    - needs both bigDigit(Tex1) and littleDigit(Tex1)
    - use a 2D texture, linear along both axis
    - setup texgen for S as before but texgen T = S*256

Issues with Shadow Mapping (1)

- Not without its problems
  - Prone to aliasing artifacts
    - “percentage closer” filtering helps this
    - normal color filtering does <u>not</u> 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 increase texture copying expense

Issues with Shadow Mapping (2)

- 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

Some Theory for Determining Your Shadow Map Resolution (1)

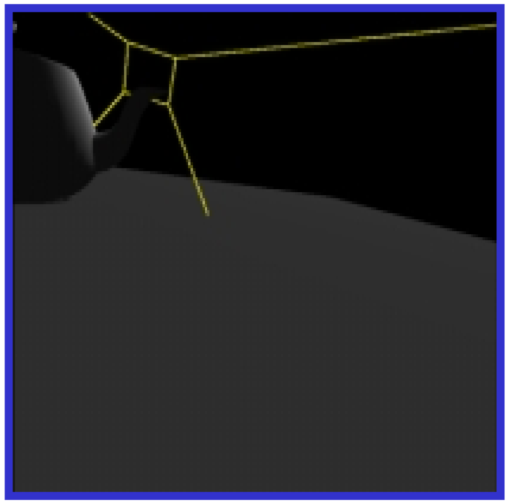
- Requires knowing how pixels (samples) in the light's view compare to the size of pixels (samples) in the eye's view
  - A re-sampling problem
- When light source frustum is reasonably well aligned with the eye's view frustum, the ratio of sample sizes is close to 1.0
  - Great match if eye and light 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

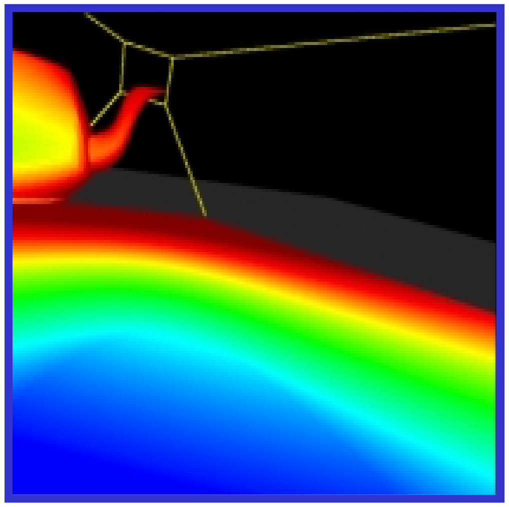
Some Theory for Determining Your Shadow Map Resolution (2)

- 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's happens

Four Images of Dueling Frusta Case

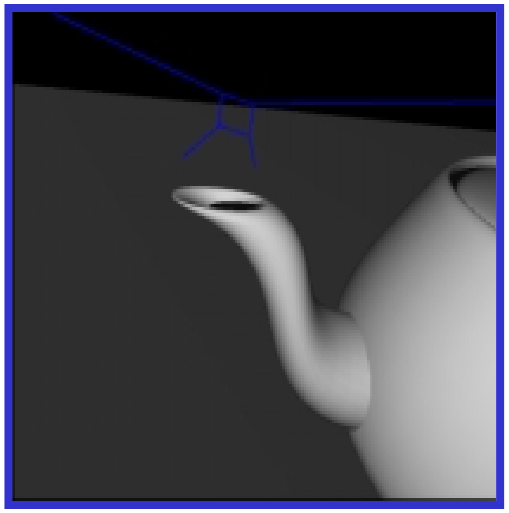
Eye's View

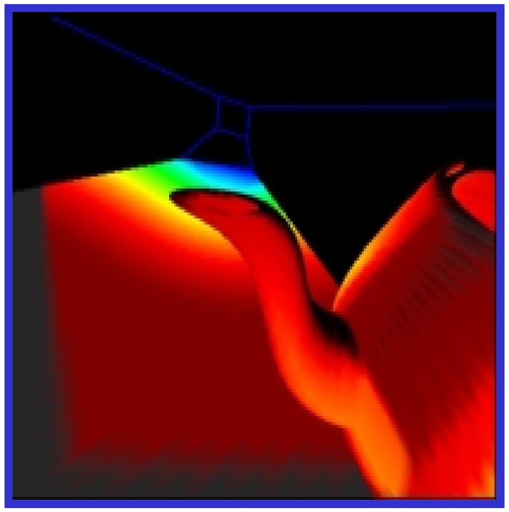




Eye's View with projection of color-coded mipmap levels from light: Blue = magnification Red = minification

Light's View

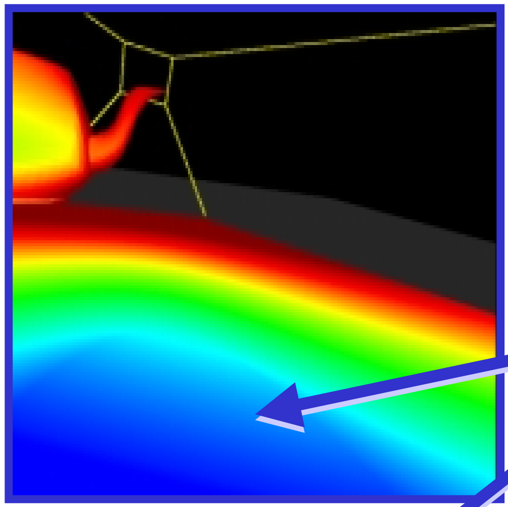




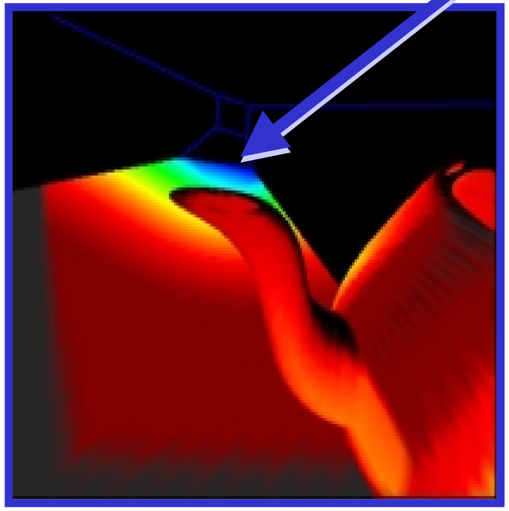
Light's View with re-projection of above image from the eye

Interpretation of the Four Images of the Dueling Frusta Case

Eye's View



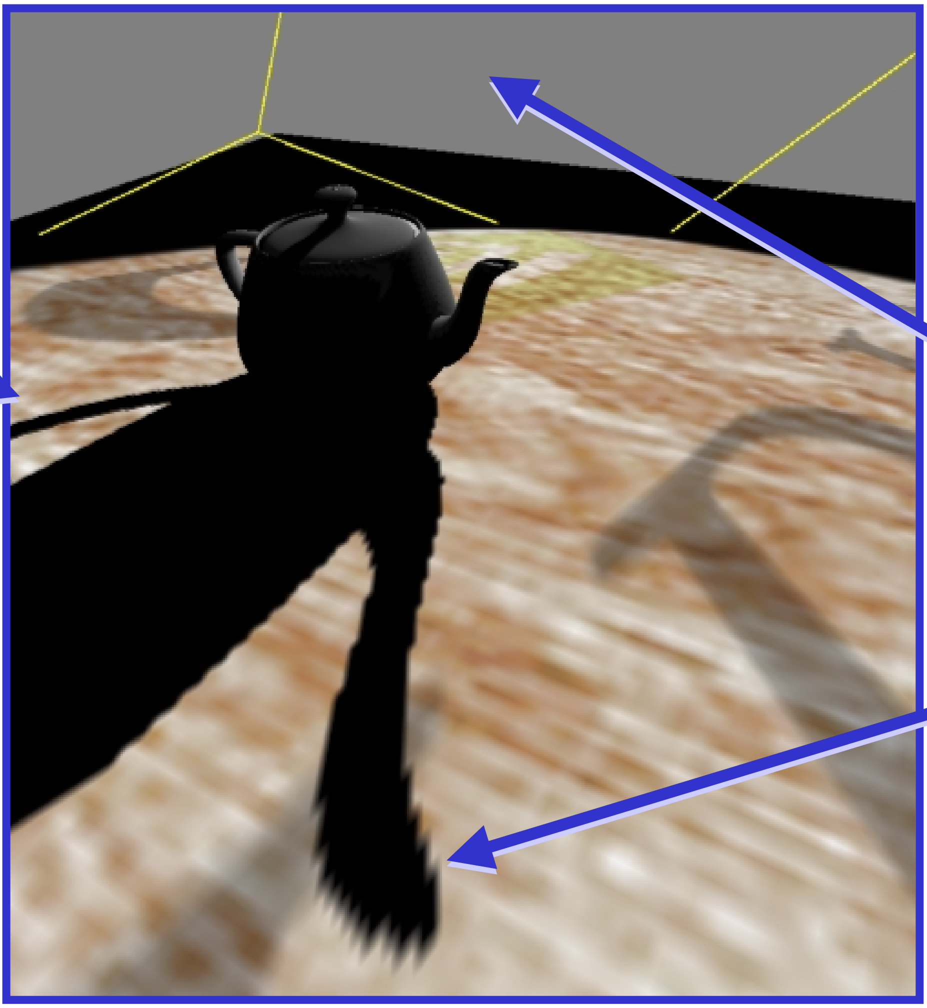
Light's View



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.

Example of Blocky Shadow Edge Artifacts in Dueling Frusta Situations

Notice that shadow edge is well defined in the distance.



Light position out here pointing towards the viewer.

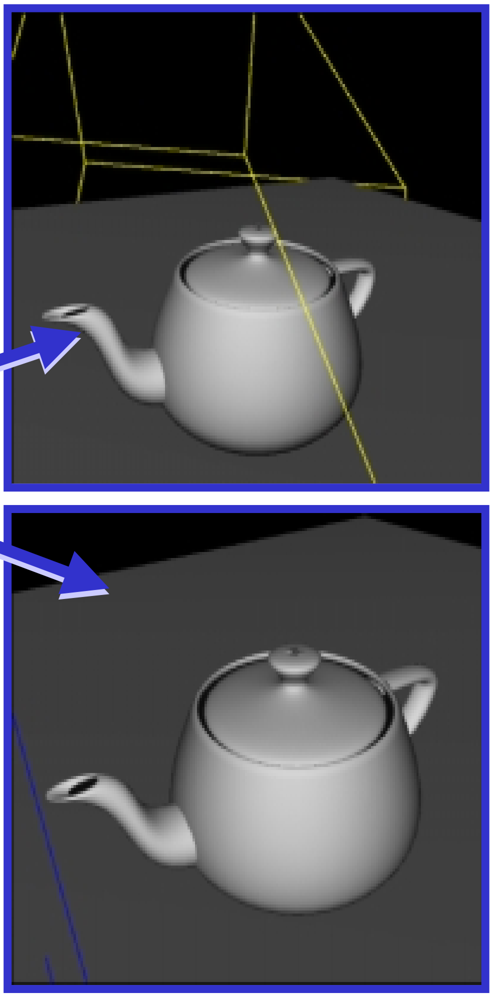
Blocky shadow edge artifacts.

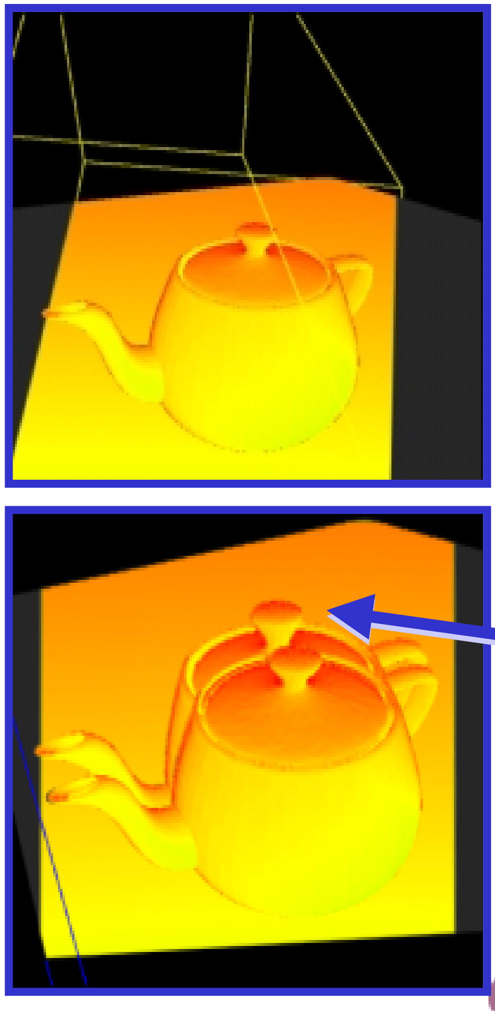
Good Situation, Close to the Miner's Lamp

Eye's View

Very similar views

Light's View



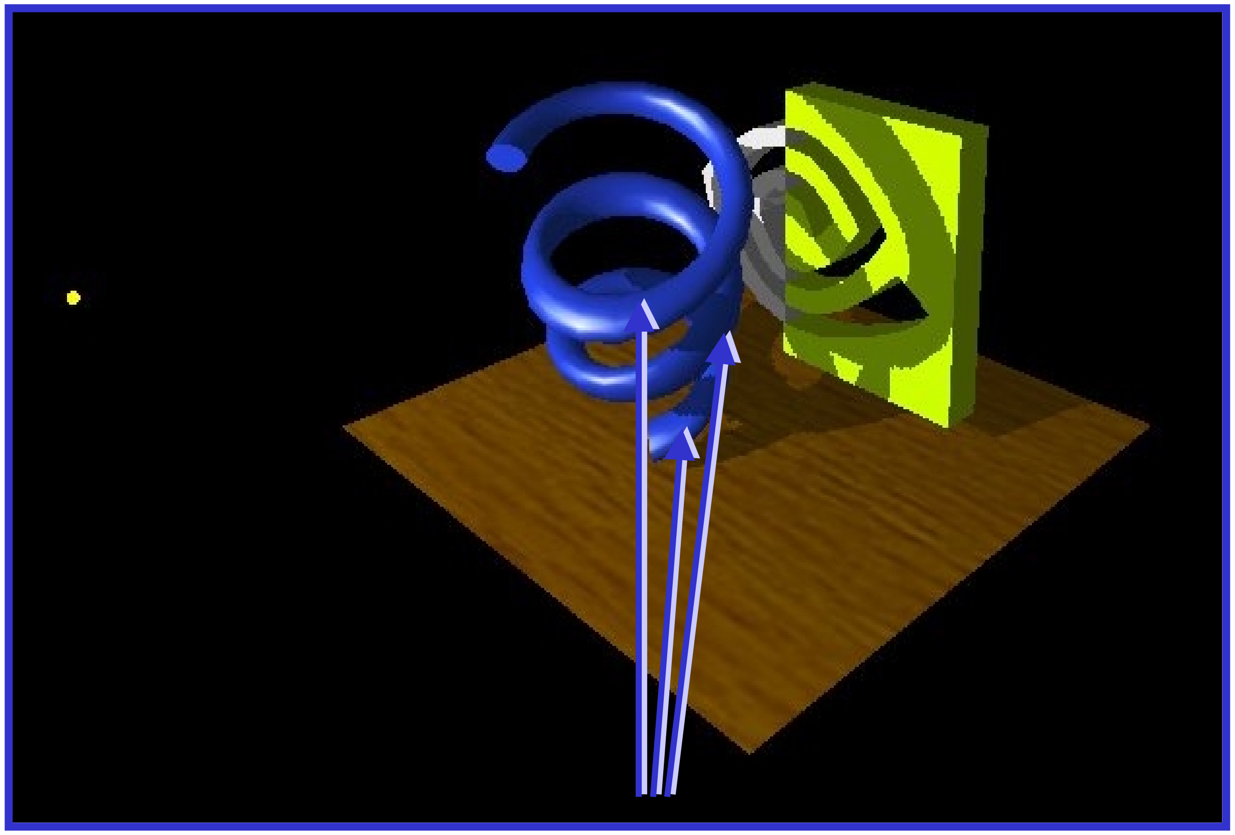


Note how the color-coded images share similar pattern and the coloration is uniform. Implies single depth map resolution would work well for most of the scene.

Ghosting is where projection would be in shadow.

More Examples

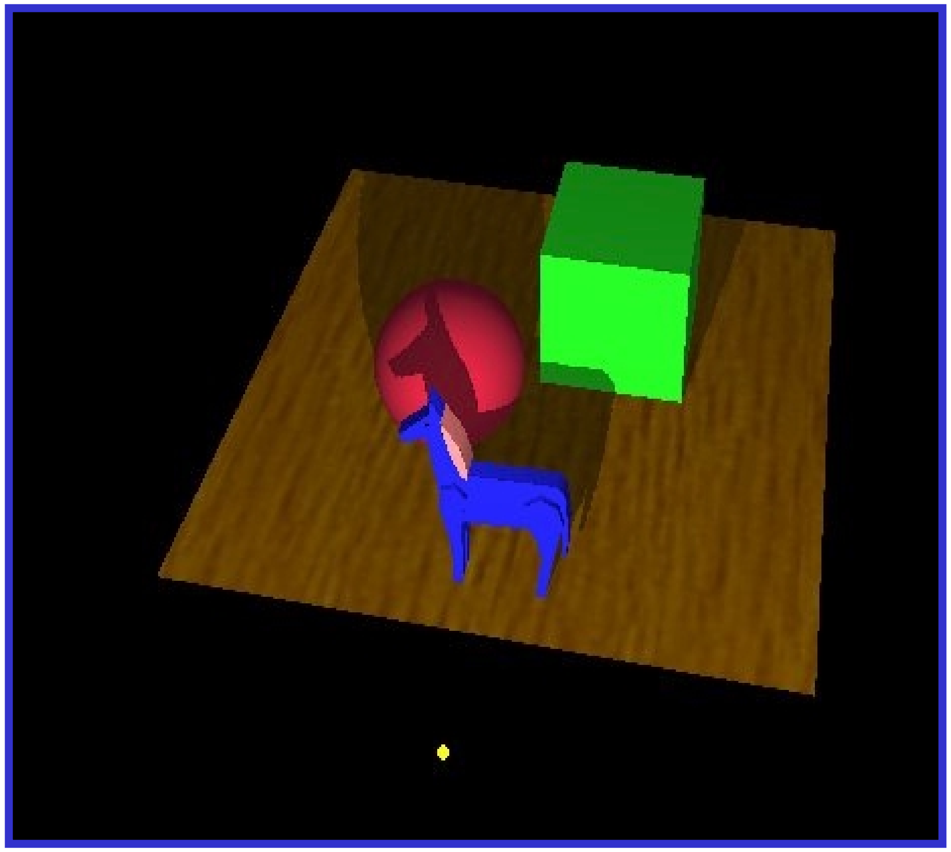
- Smooth surfaces with object self-shadowing



Note object self-shadowing

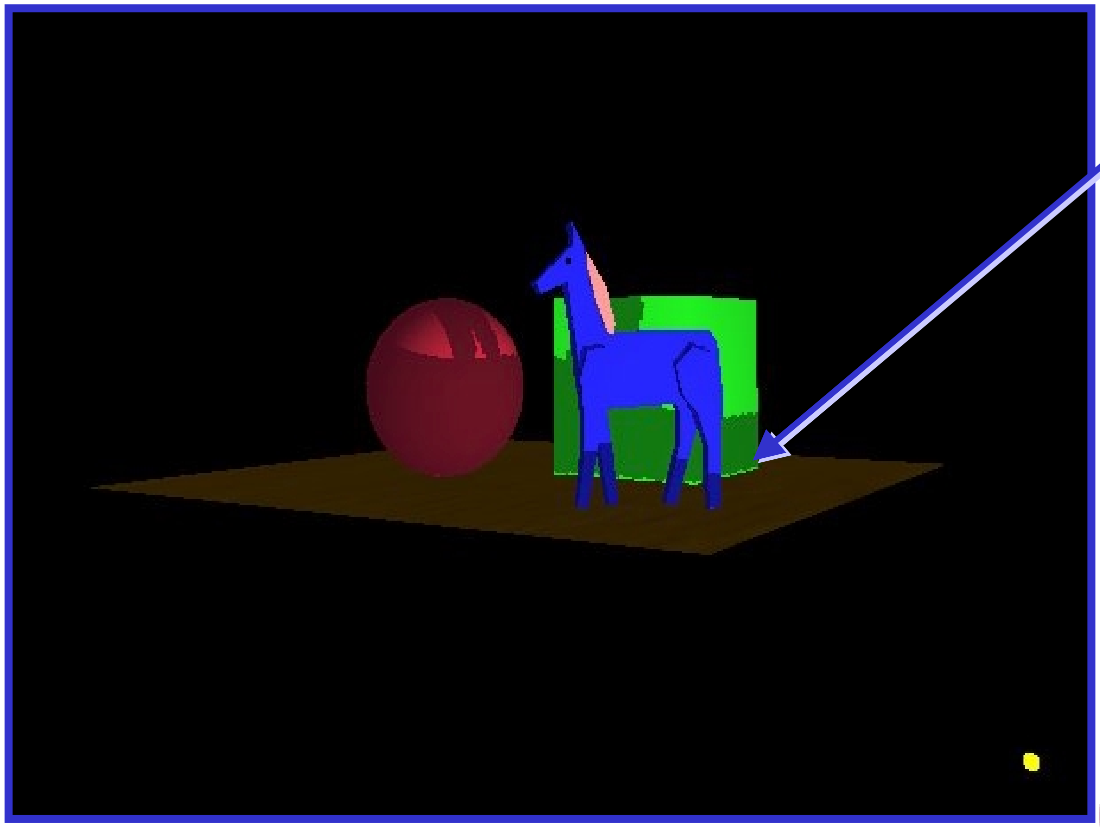
More Examples

- **Complex objects all shadow**



More Examples

- Even the floor casts shadow

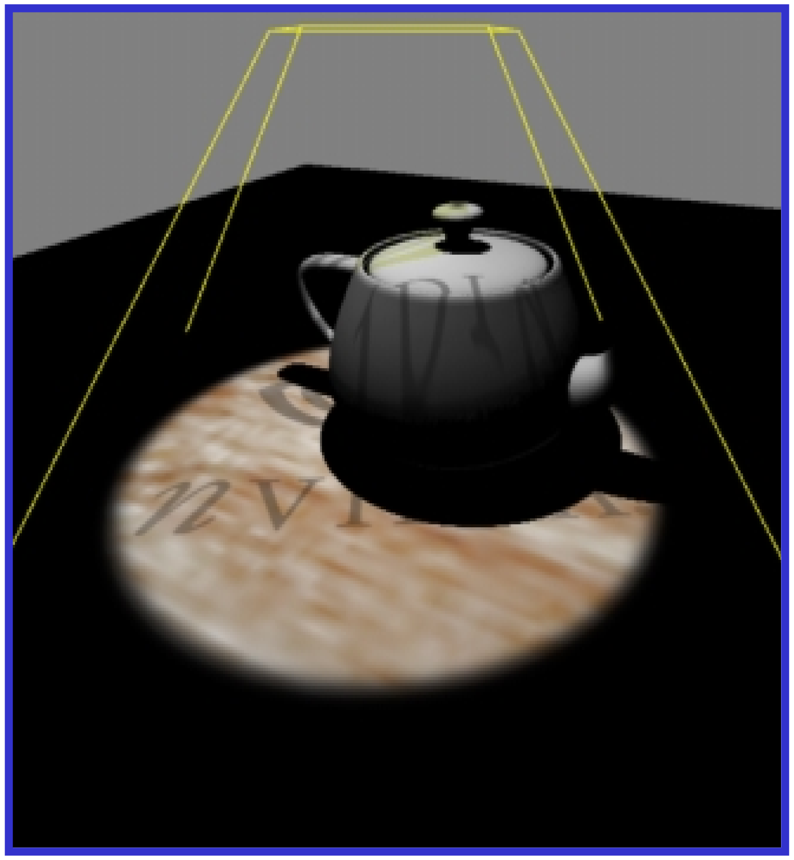


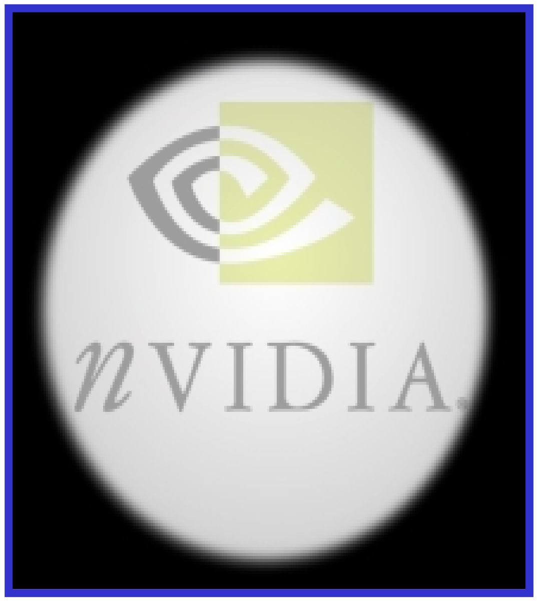
Note shadow leakage due to infinitely thin floor

Could be fixed by giving floor thickness

Combine with Projective Texturing for Spotlight Shadows

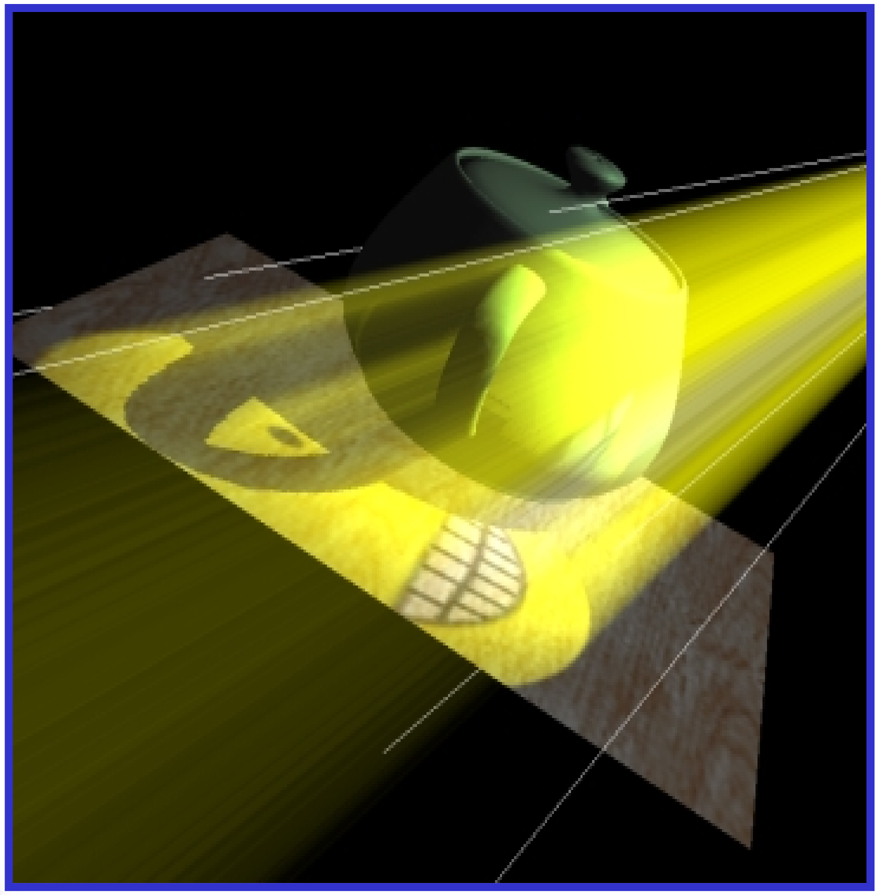
- Use a spotlight-style projected texture to give shadow maps a spotlight falloff





Combining Shadows with Atmospherics

- Shadows in a dusty room



Simulate atmospheric effects such as suspended dust

1) *Construct shadow map*
2) *Draw scene with shadow map*
3) *Modulate projected texture image with projected shadow map*
4) *Blend back-to-front shadowed slicing planes also modulated by projected texture image*

Credit: Cass Everitt

Hybrid of Shadow Volumes and Shadow Mapping

- Very clever idea [McCool 98]
  - Render scene from light source with depth testing
  - Read back the depth buffer
  - Use computer vision techniques to reconstruct the shadow volume *geometry* from the depth buffer *image*
  - Very reasonable results for complex scenes
  - Only requires stencil
    - no multitexture and texture environment differencing required
  - “Shadow volume reconstruction from depth maps,” *ACM Transactions on Graphics* (Jan. 2000)
    - Also on Michael McCool’s web site

Luxo Jr. in Real-time using Shadow Mapping

- Steve Jobs at MacWorld Japan shows this on a Mac with OpenGL using hardware shadow mapping

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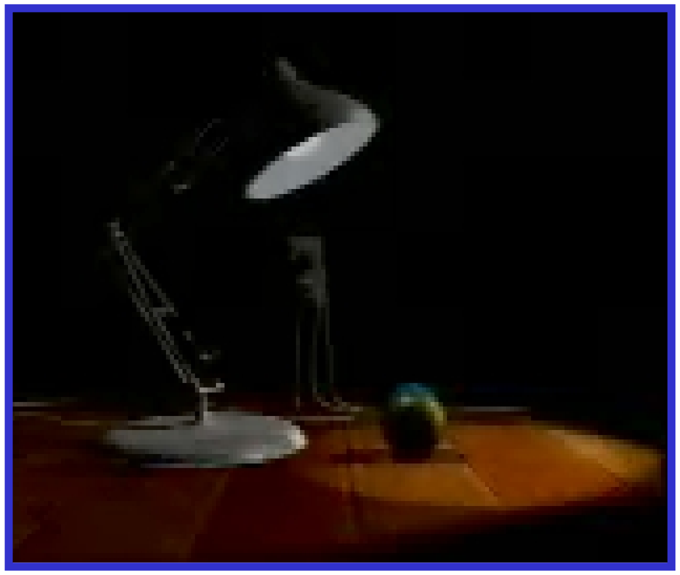

Luxo Jr. Demo Details

- Luxo Jr. has two animated lights and one overhead light
  - Three shadow maps *dynamically* generated per frame
- Complex geometry (cords correctly shadowed
- User controls the view, shadowing just works
- Real-time Luxo Jr. is technical triumph for OpenGL
- Only available in OpenGL.

(Sorry, no demo. Images are from web cast video of Apple's MacWorld Japan announcement.)

Shadow Mapping Source Code

- **Find it on the NVIDIA web site**
  - **The source code**
    - **“shadowcast” in OpenGL example code**
    - **Works on TNT, GeForce, Quadro, & GeForce3 using best available shadow mapping support**
    - **And vendors that support EXT_texture_env_combine**
  - ***NVIDIA OpenGL Extension Specifications***
    - **documents EXT_texture_env_combine, NV_register_combiners, SGIX_depth_texture, & SGIX_shadow**
  - **http://www.nvidia.com**

Credits

- The inspiration for these ideas
  - Wolfgang Heidrich, Max-Planck Institute for Computer Science
    - original dual-texture shadow mapping idea
    - read his thesis *High-quality Shading and Lighting for Hardware-accelerated Rendering*
  - Michael McCool, University of Waterloo
    - suggested idea for multi-digit shadow comparisons

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