Color (wrap up)
Shadows

Wolfgang Heidrich

Course News

Assignment 3 (project)

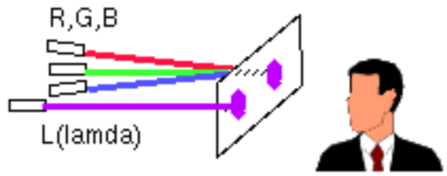
- Due April 1

Reading

- Chapter 11.8, 10

Color Matching Experiments

Performed in the 1930s



Idea: perceptually based measurement

- Shine given wavelength (λ) on a screen
- User must control three pure lights producing three other wavelengths (say R=700 nm, G=546 nm, and B=438 nm)
- Adjust intensity of RGB until colors are identical

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Color Matching Experiment

Results

- It was found that any color S(λ) could be matched with three suitable primaries A(λ), B(λ), and C(λ)
  - *Used monochromatic light at 438, 546, and 700 nanometers*
- Also found the space is linear, I.e. if

$$R(\lambda) \equiv S(\lambda)$$

then

$$R(\lambda) + M(\lambda) \equiv S(\lambda) + M(\lambda)$$

and

$$k \cdot R(\lambda) \equiv k \cdot S(\lambda)$$

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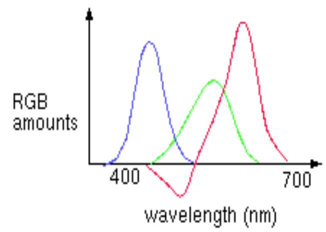
Negative Lobes

Actually:

- Exact target match possible sometimes requires “negative light”



- Some red has to be added to target color to permit exact match using “knobs” on RGB intensity output
- Equivalent mathematically to removing red from RGB output

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Notation

Don’t confuse:

- Primaries: the spectra of the three different light sources: **R**, **G**, **B**
  - *For the matching experiments, these were* ***monochromatic*** *(I.e. single wavelength) light!*
  - *Primaries for displays usually have a wider spectrum*
- Coefficients *R, G, B*
  - *Specify how much of* **R**, **G**, **B** *is in a given color*
- Color matching functions: r(λ), g (λ), b (λ)
  - *Specify how much of* **R**, **G**, **B** *is needed to produce a color that is a metamer for pure monochromatic light of wavelength λ*

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Negative Lobes

So:

- Can't generate all other wavelengths with any set of three positive monochromatic lights!

Solution:

- Convert to new synthetic "primaries" to make the color matching easy

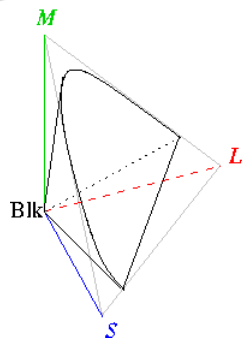
$$\begin{pmatrix} \mathbf{X} \\ \mathbf{Y} \\ \mathbf{Z} \end{pmatrix} = \begin{pmatrix} 2.36460 & -0.51515 & 0.00520 \\ -0.89653 & 1.42640 & -0.01441 \\ -0.46807 & 0.08875 & 1.00921 \end{pmatrix} \begin{pmatrix} \mathbf{R} \\ \mathbf{G} \\ \mathbf{B} \end{pmatrix}$$

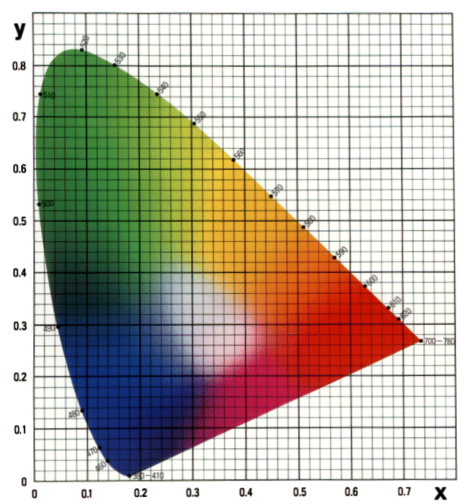
Note:

- **R, G, B** are the same monochromatic primaries as before
- The corresponding matching functions x(λ), y(λ), z(λ) are now positive everywhere
- But the primaries contain "negative" light contributions, and are therefore not physically realizable

CIE Gamut and λ Chromaticity Diagram

3D gamut

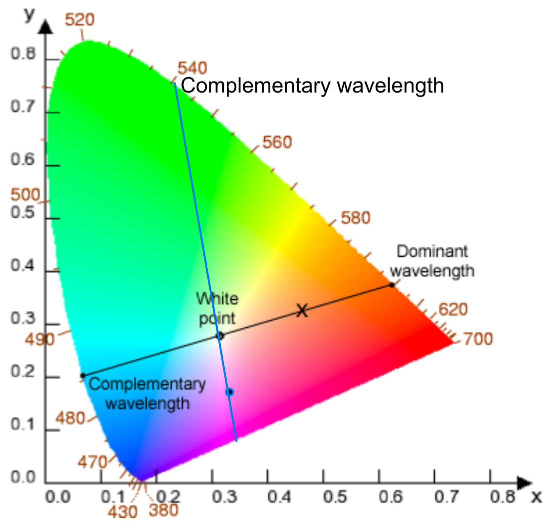




Chromaticity diagram

- Hue only, no intensity

Color Interpolation, Dominant & Opponent Wavelength



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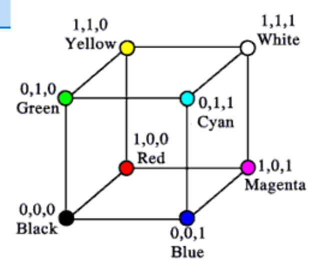
RGB Color Space (Color Cube)

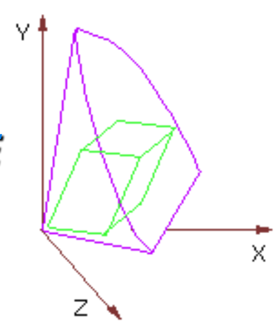
Define colors with (r, g, b) amounts of red, green, and blue

- Used by OpenGL
- Hardware-centric
- Describes the colors that can be generated with specific RGB light sources

RGB color cube sits within CIE

- Subset of perceivable colors
- Scaled, rotated, sheared cube

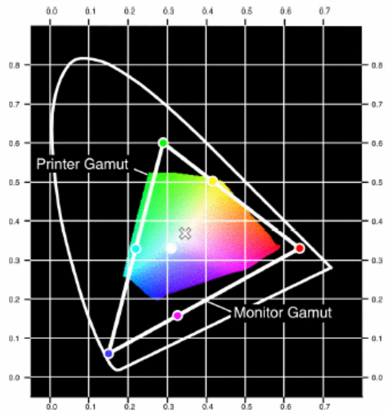


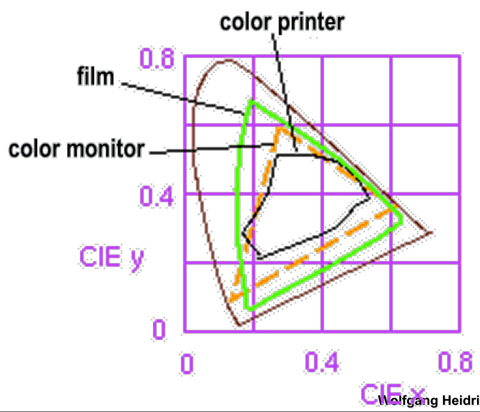


Device Color Gamuts

Use CIE chromaticity diagram to compare the gamuts of various devices

- X, Y, and Z are hypothetical light sources, not used in practice as device primaries





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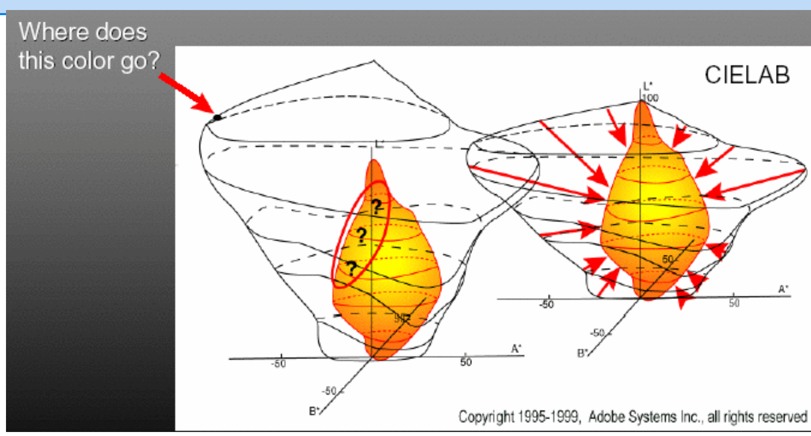
Gamut Mapping



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Additive vs. Subtractive Colors

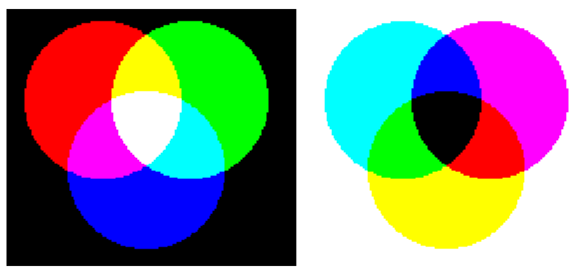
Additive: light

- Monitors, LCDs
- RGB model

Subtractive: pigment

- Printers
- CMY(K) model

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



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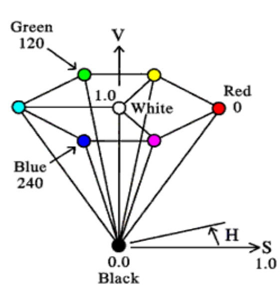
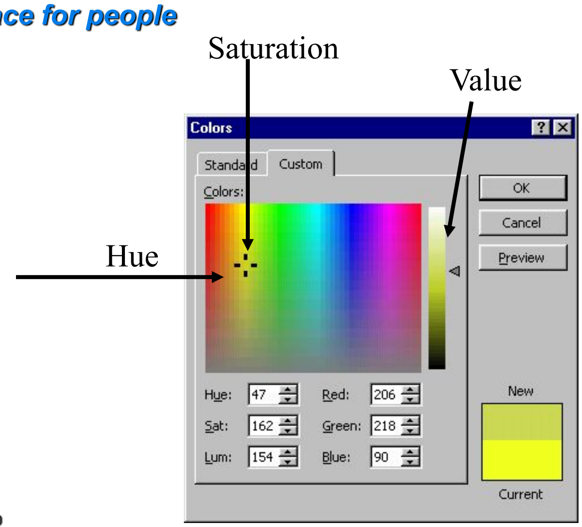
HSV Color Space

More intuitive color space for people

- H = Hue
- S = Saturation
- V = Value
  - *Or brightness B*
  - *Or intensity I*





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Monitors

Monitors have nonlinear response to input

- Characterize by gamma

$$\text{displayedIntensity} = a^{\gamma} \cdot \text{maxIntensity}$$

Gamma correction

$$\text{displayedIntensity} = \left(a^{1/\gamma}\right)^{\gamma} \cdot \text{maxIntensity}$$

Gamma for CRTs:

- Around 2.4

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Shadows

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Shadows

What are shadows?

- What distinguishes a point in shadow from a lit point?

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Shadows

Types of light sources

- Point, directional
- Area lights and generally shaped lights
  - *Not considered here*
  - *Later: ray-tracing for such light sources*

Problem statement

- A shadow algorithm for point and directional lights determines which scene points are
  - *Visible from the light source (I.e. illuminated)*
  - *Invisible from the light source (I.e. in shadow)*
- Thus: shadow casting is a visibility problem!

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Types of Shadow Algorithms

Object Space

- Like object space visibility algorithms, the method computes in object space which polygon parts that are illuminated and which are in shadow
  - *Individual parts are then drawn with different intensity*
- Typically slow, O(n^2), not for dynamic scenes

Image Space

- Determine visibility per pixel in the final image
  - *Sort of like depth buffer*
  - *Shadow maps*
  - *Shadow volumes*

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Credits

- The following shadow mapping slides are taken from Mark Kilgard's OpenGL course at Siggraph 2002.

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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

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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

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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

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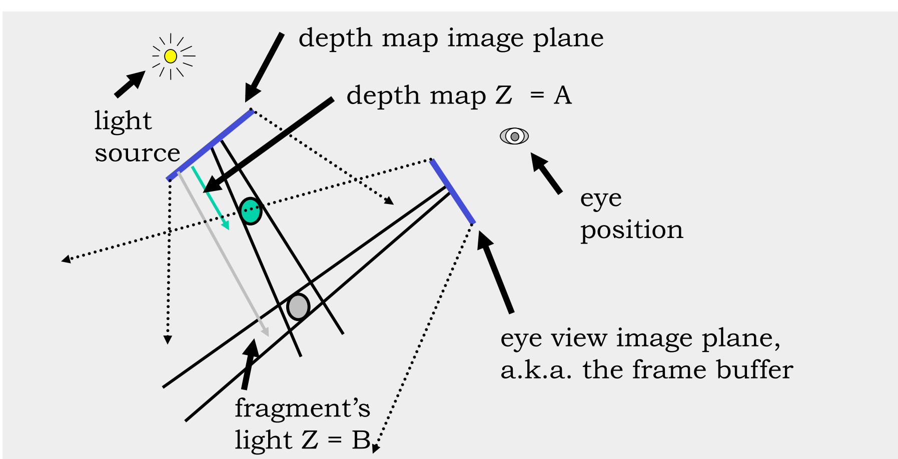
Shadow Mapping with a Picture in 2D (1)

The A < B shadowed fragment case



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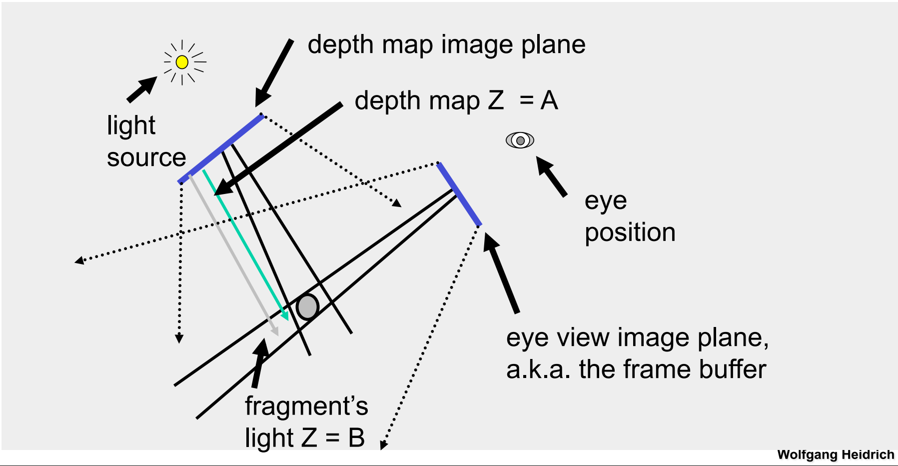
Shadow Mapping with a Picture in 2D (2)

The A = B lit fragment case



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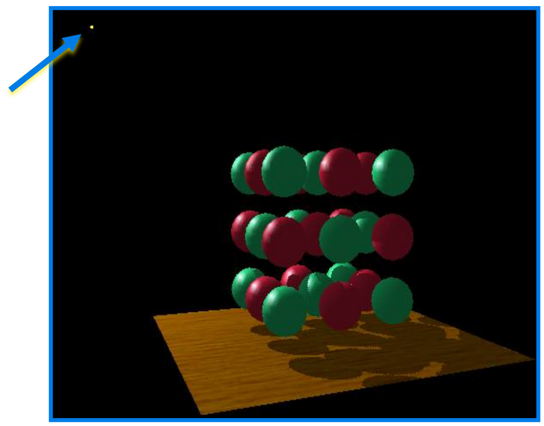
Visualizing the Shadow Mapping Technique (1)

A scene with fairly complex shadows

the point light source



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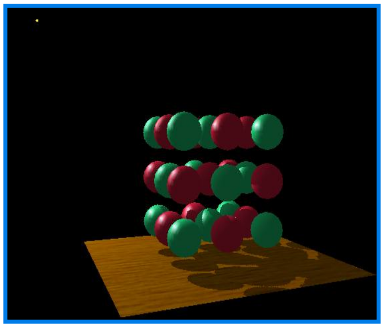
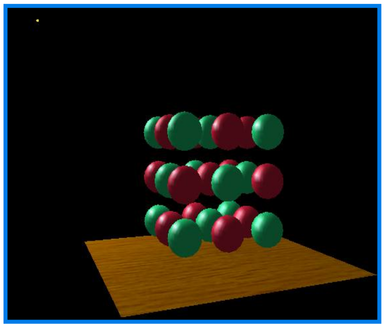
Visualizing the Shadow Mapping Technique (2)

Compare with and without shadows



with shadows



without shadows

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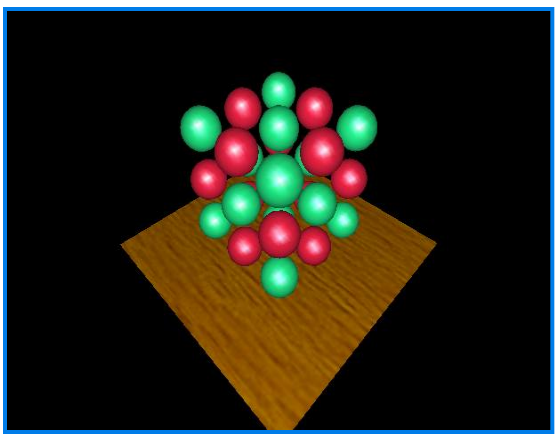
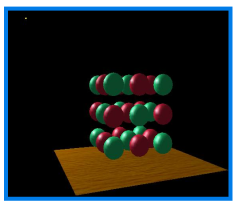
Visualizing the Shadow Mapping Technique (3)

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





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

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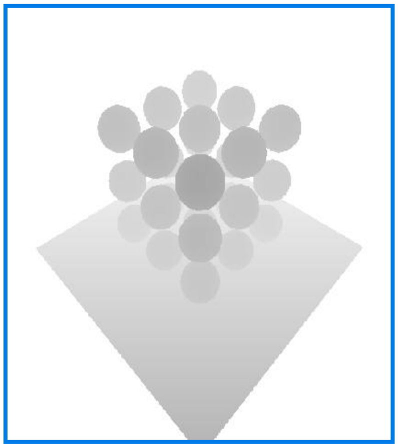
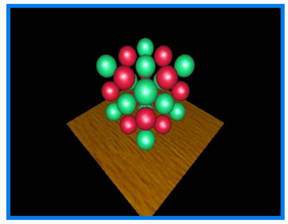
Visualizing the Shadow Mapping Technique (4)

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





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

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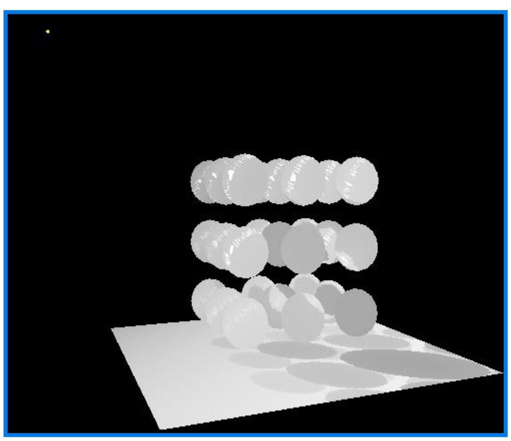
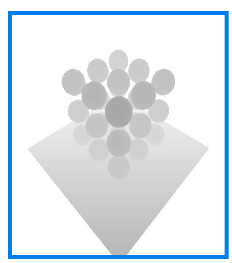
Visualizing the Shadow Mapping Technique (5)

Projecting the depth map onto the eye's view





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

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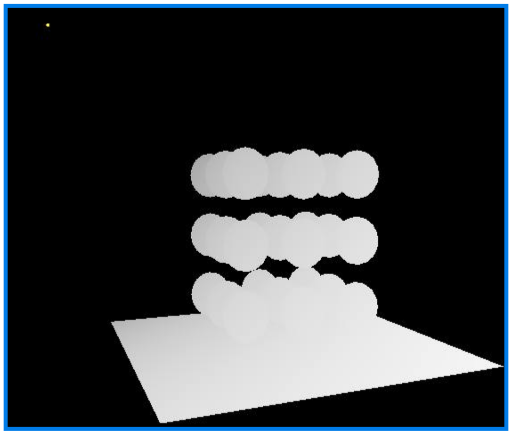
Visualizing the Shadow Mapping Technique (6)

Projecting light's planar distance onto eye's view



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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 approximately equal

Non-green is where shadows should be

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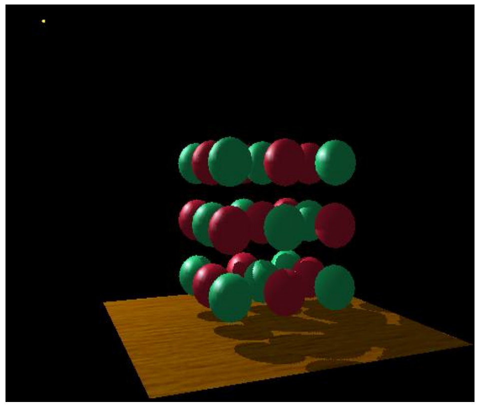
Visualizing the Shadow Mapping Technique (7)

Complete scene with shadows

Notice how specular highlights never appear in shadows



Notice how curved surfaces cast shadows on each other

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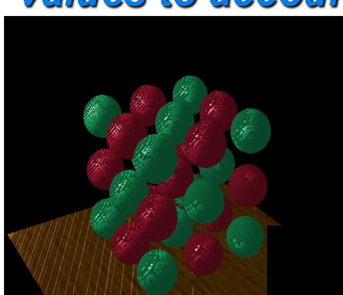
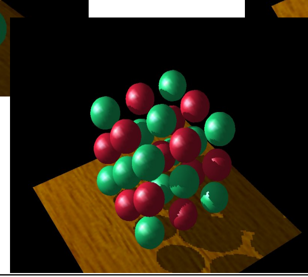
In Practice: Depth Map Precision Issues

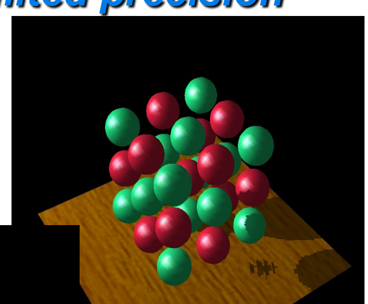
Have to add a little offset to depth map values to account for limited precision



Too little bias, everything begins to shadow



Just right



Too much bias, shadow starts too far back

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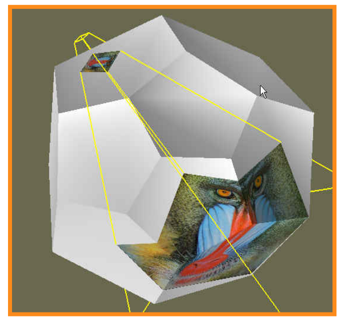
What is Projective Texturing?

An intuition for projective texturing

- The slide projector analogy



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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')*

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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

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Back to the Shadow Mapping Discussion . . .

Assign light-space texture coordinates to polygon vertices

- 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*
- (s/q, t/q) will map to light's depth map texture

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Shadow Map Operation

Next Step:

- Compare depth map value to distance of fragment from light source
- Different GPU generations support different means of implementing this
  - *Today's GPUs: pixel shader!*
  - *Earlier: special hardware for implmenting this feature (e.g. SGI), or just using alpha blending [Heidrich'99]*

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Issues with Shadow Mapping (1)

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 increase texture copying expense*

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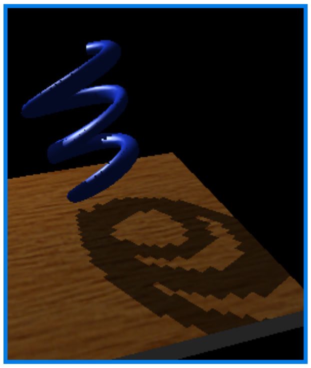
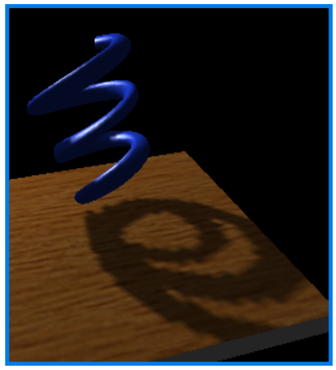
Hardware Shadow Map Filtering Example

GL_NEAREST: blocky ***GL_LINEAR: antialiased edges***





Low shadow map resolution used to heightens filtering artifacts

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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*

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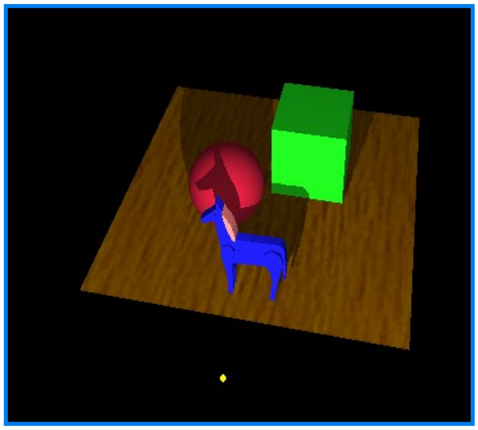
More Examples

Complex objects all shadow



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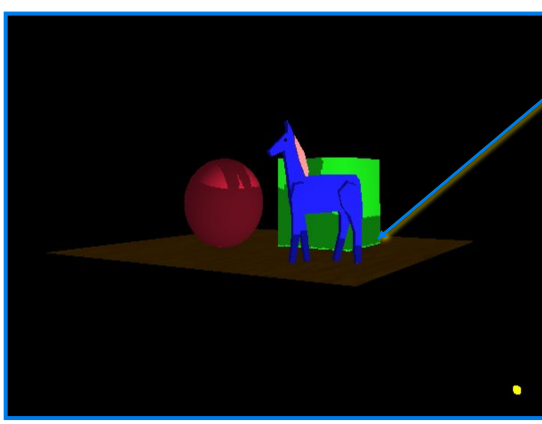
More Examples

Even the floor casts shadow



Note shadow leakage due to infinitely thin floor

Could be fixed by giving floor thickness

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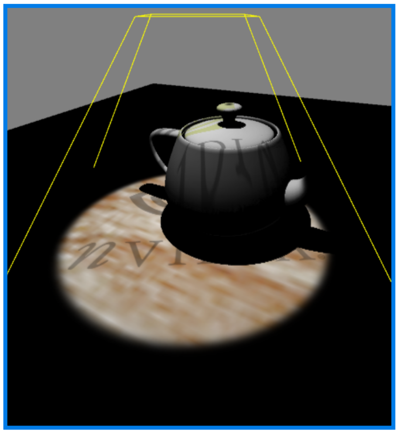
Combining Projective Texturing for Spotlights

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



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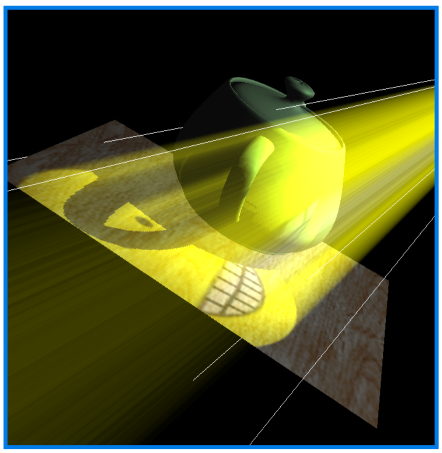
Combining Shadows with Atmospherics

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

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Shadow Maps

Approach for shadows from point light sources

- Surface point is in shadow if it is not visible from the light source
- Use depth buffer to test visibility:
  - *Render scene from the point light source*
  - *Store resulting depth buffer as texture map*
  - *For every fragment generated while rendering from the camera position, project the fragment into the depth texture taken from the camera, and check if it passes the depth test.*

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Shadow Volumes

Use new buffer: stencil buffer

- Just another channel of the framebuffer
- Can count how often a pixel is drawn

Algorithm (1):

- Generate silhouette polygons for all objects
  - *Polygons starting at silhouette edges of object*
  - *Extending away from light source towards infinity*
  - *These can be computed in vertex programs*

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Shadow Volumes

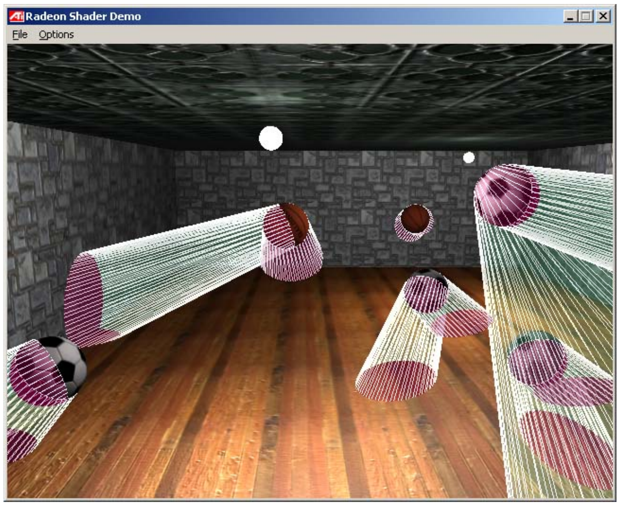

Image by ATI

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Shadow Volumes

Algorithm (2):

- Render all original geometry into the depth buffer
  - *I.e. do not draw any colors (or only draw ambient illumination term)*
- Render front-facing silhouette polygons while incrementing the stencil buffer for every rendered fragment
- Render back-facing silhouette polygons while decrementing the stencil buffer for every rendered fragment
- Draw illuminated geometry where the stencil buffer is 0, shadow elsewhere

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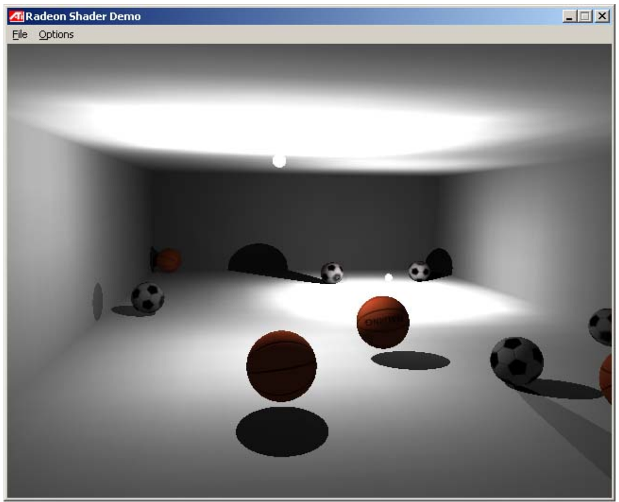
Shadow Volumes



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Shadow Volumes

Discussion:

- Object space method therefore no precision issues
- Lots of large polygons: can be slow
  - *High geometry count*
  - *Large number of pixels rendered*

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Coming Up:

Friday

- Ray-tracing

Next Week:

- Global illumination