CS559: Computer Graphics

Lecture 22: Texture mapping

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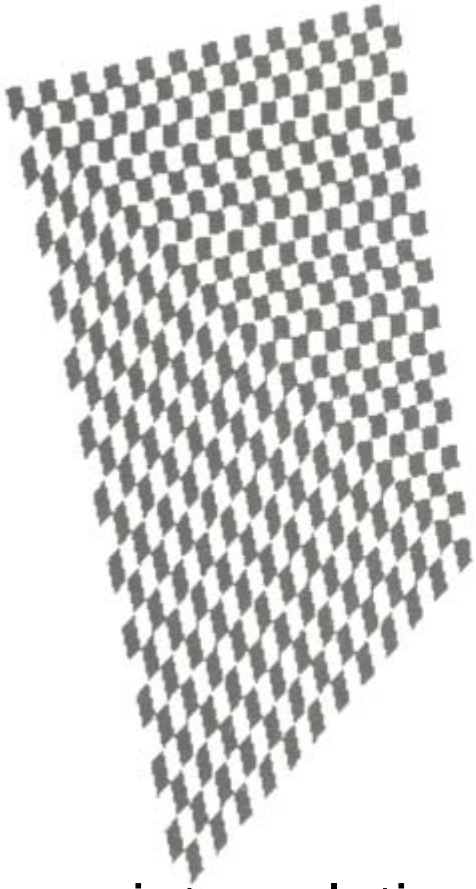
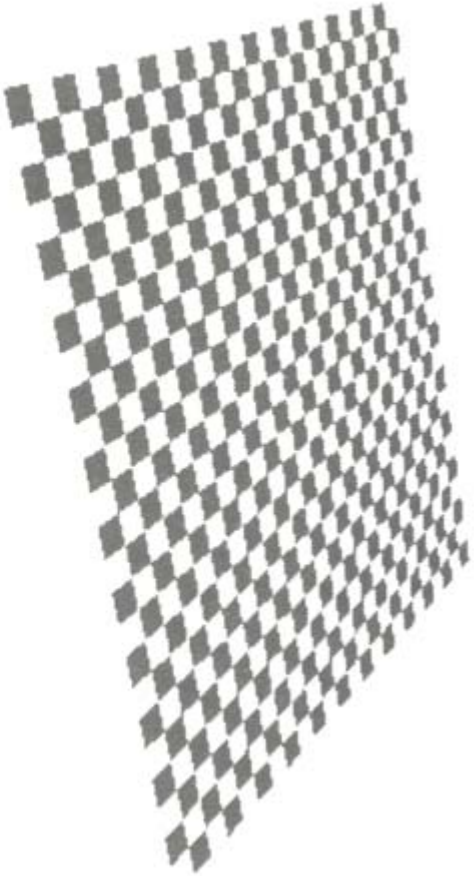
Spring 2010

Many slides from Ravi Ramamoorthi, Columbia Univ, Greg Humphreys, UVA and Rosalee Wolfe, DePaul tutorial teaching texture mapping visually

Texture Mapping



Linear interpolation
of texture coordinates



Correct interpolation
with perspective divide

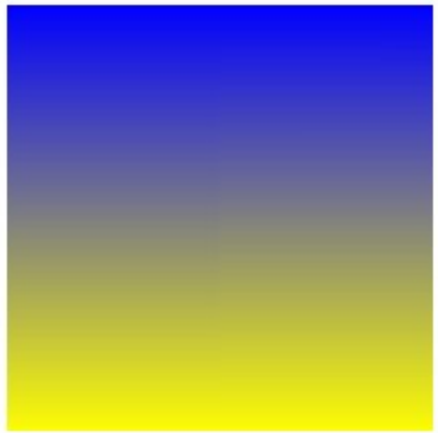
http://graphics.lcs.mit.edu/classes/6.837/F98/Lecture21/Slide14.html

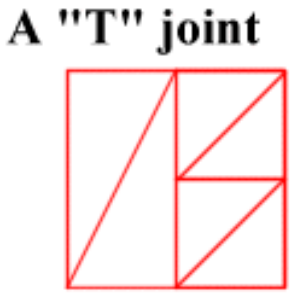
Hill Figure 8.42

Why don’t we notice?

Traditional screen-space Gourand shading is wrong. However, you usually will not notice because the transition in colors is very smooth (And we don't know what the right color should be anyway, all we care about is a pretty picture). There are some cases where the errors in Gourand shading become obvious.

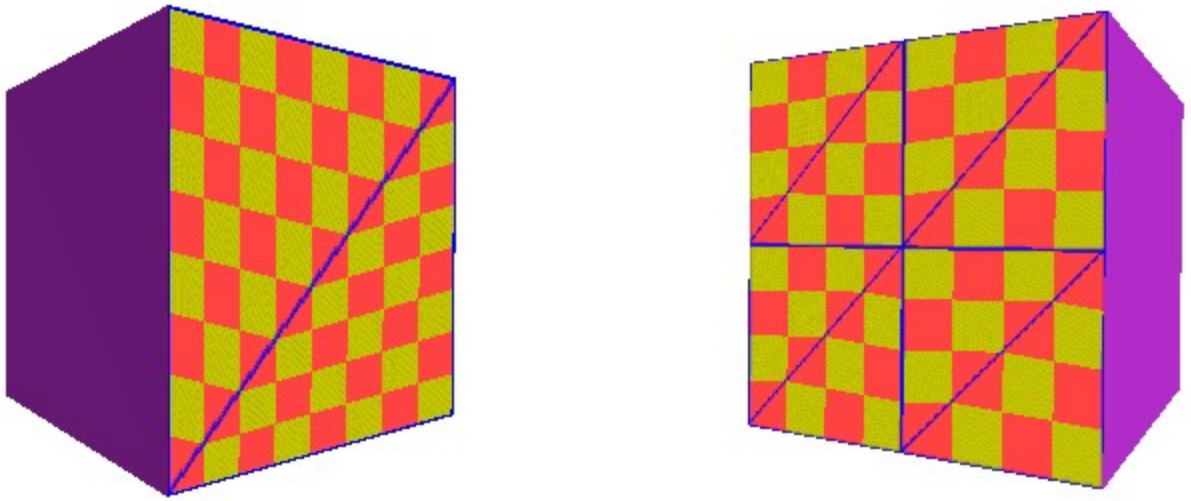
- When do we notice?
  - When switching between different levels-of-detail representations
  - At "T" joints.





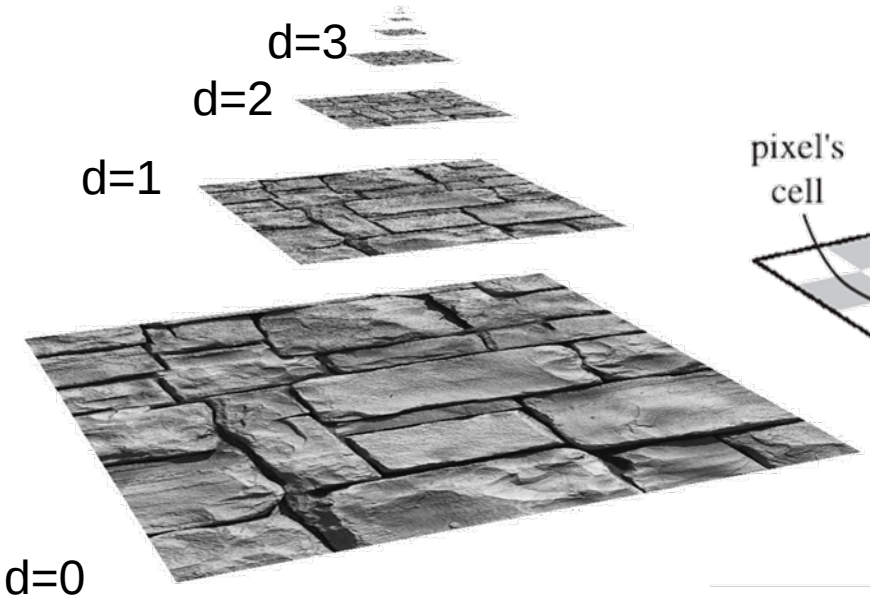
Dealing with Incorrect Interpolation

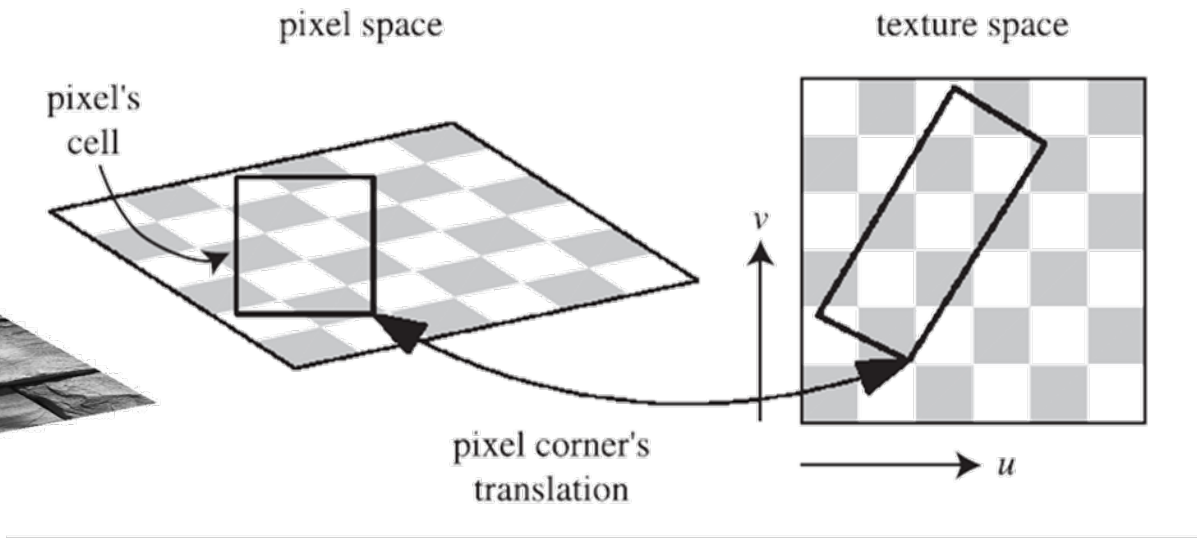
You can reduce the perceived artifacts of non-perspective correct interpolation by subdividing the texture-mapped triangles into smaller triangles (why does this work?). But, fundamentally the screen-space interpolation of projected parameters is `inherently flawed`.



http://groups.csail.mit.edu/graphics/classes/6.837/F98/Lecture21/Slide15.html

Mipmap





Let d = |PIX| be a measure of pixel size

Sample (u,v,d)

Using tri-linear interpolation

What's the memory overhead?

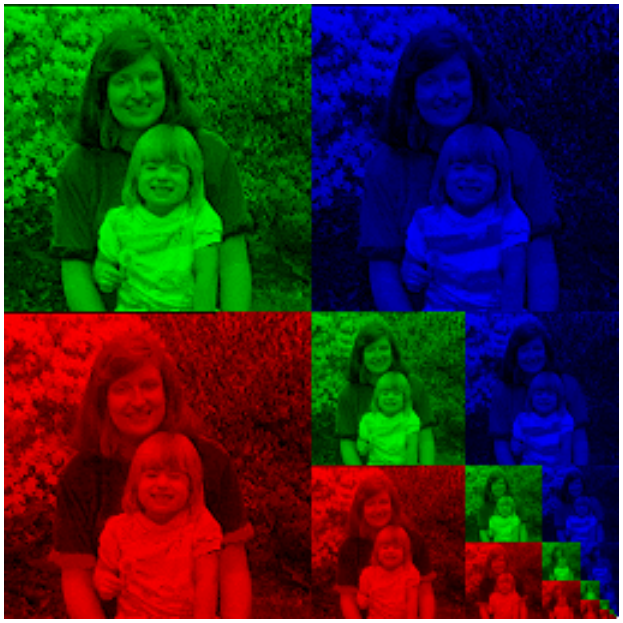
Option 1: use the longer edge of the quadrilateral formed by the pixel's cell to approximate the pixel's coverage

Option 2: use the max of |du/dx|, |du/dy|, |dv/x|, |dv/dy|

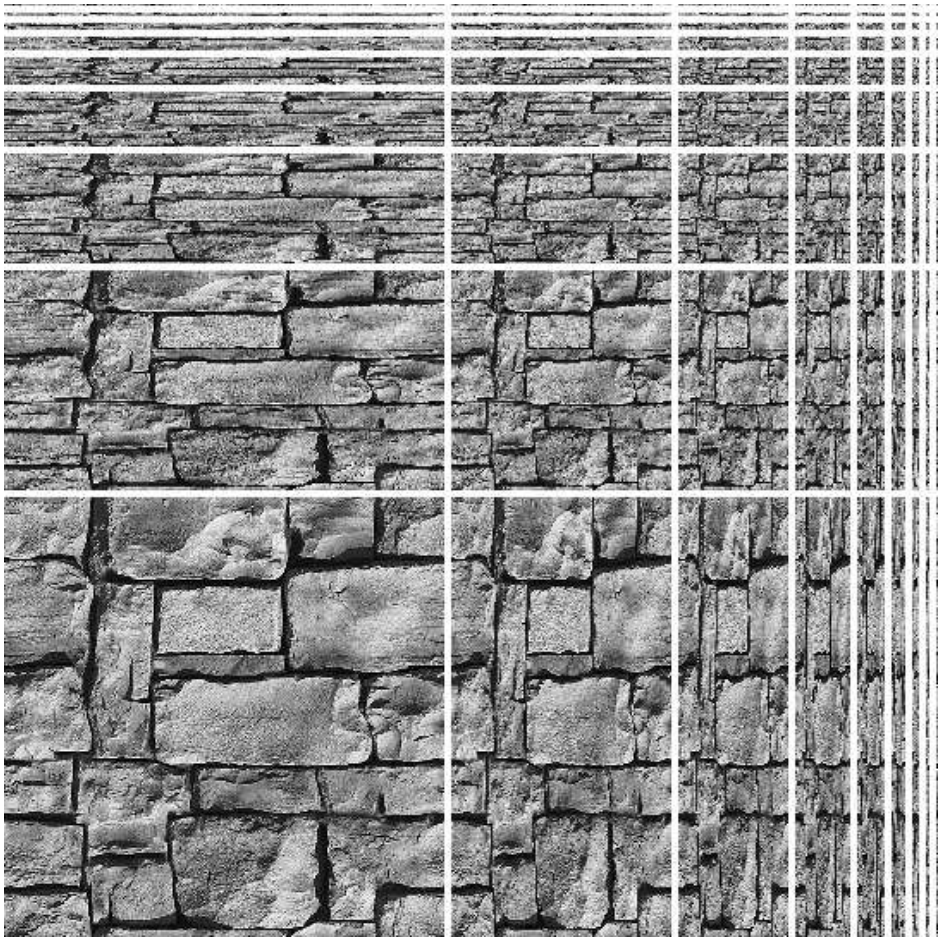
Then take logarithm

Storing MIP Maps

- One convienent method of storing a MIP map is shown below (It also nicely illustrates the 1/3 overhead of maintaining the MIP map).



Ripmap



Sample (u,v,du,dv) Using Trilinaer => quadrilinear

What's the memory overhead?

Summed Area Table

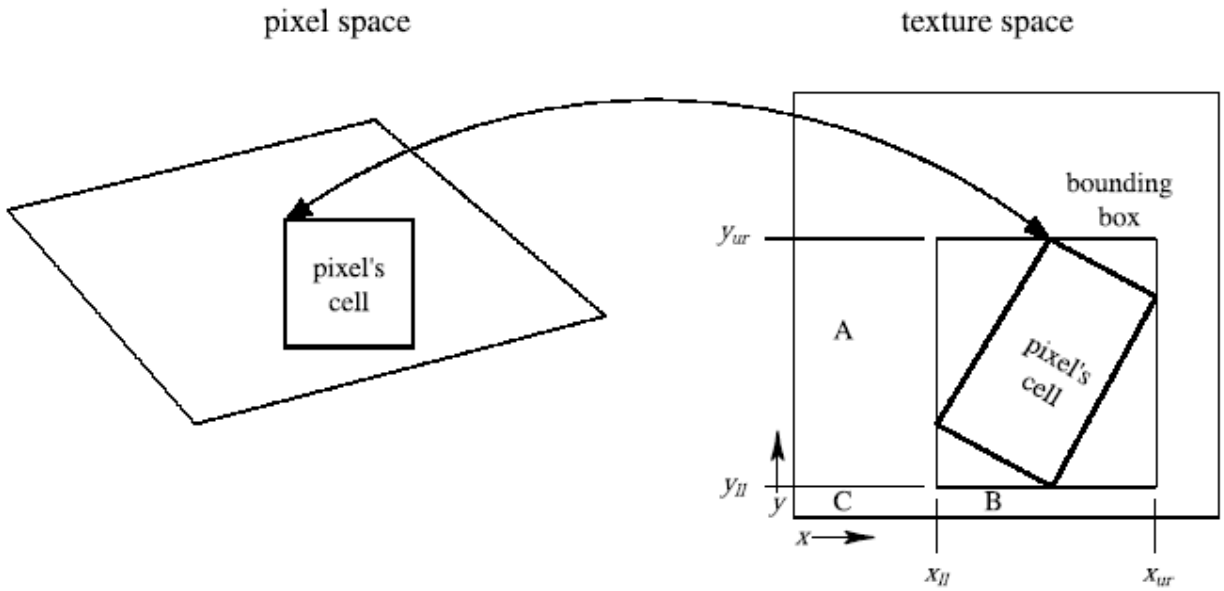


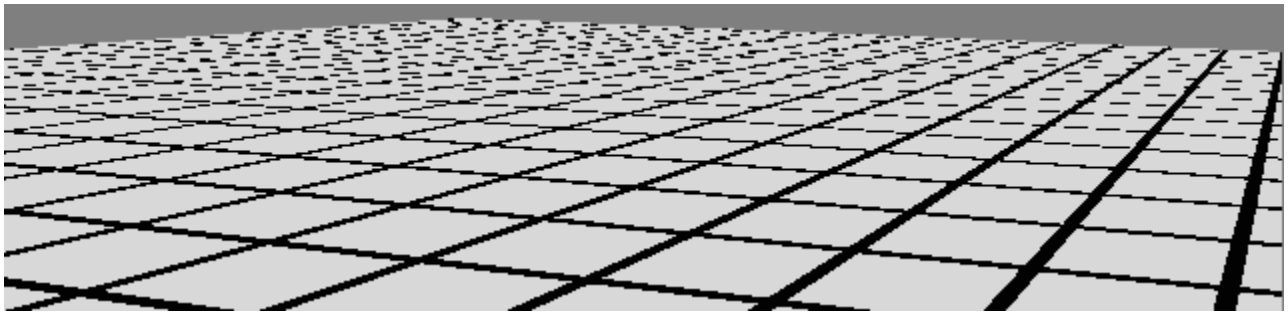
Figure 6.15: The pixel cell is back-projected onto the texture, bound by a rectangle, and the four corners of the rectangle are used to access the summed-area table.

$$\mathbf{c} = \frac{\mathbf{s}[x_{ur}, y_{ur}] - \mathbf{s}[x_{ur}, y_{ll}] - \mathbf{s}[x_{ll}, y_{ur}] + \mathbf{s}[x_{ll}, y_{ll}]}{(x_{ur} - x_{ll})(y_{ur} - y_{ll})}$$

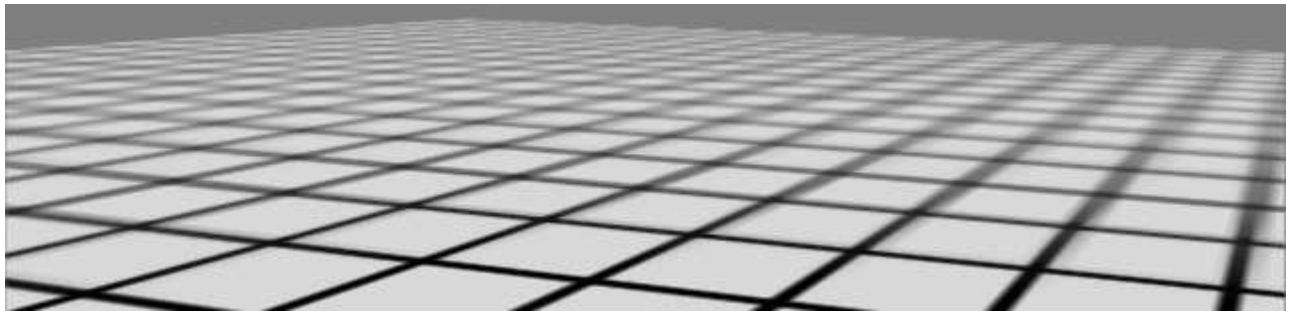
1	6	8	3
0	0	3	7
4	7	8	8
5	0	9	9

1	7	15	18
1	7	18	28
5	18	37	55
10	23	51	78

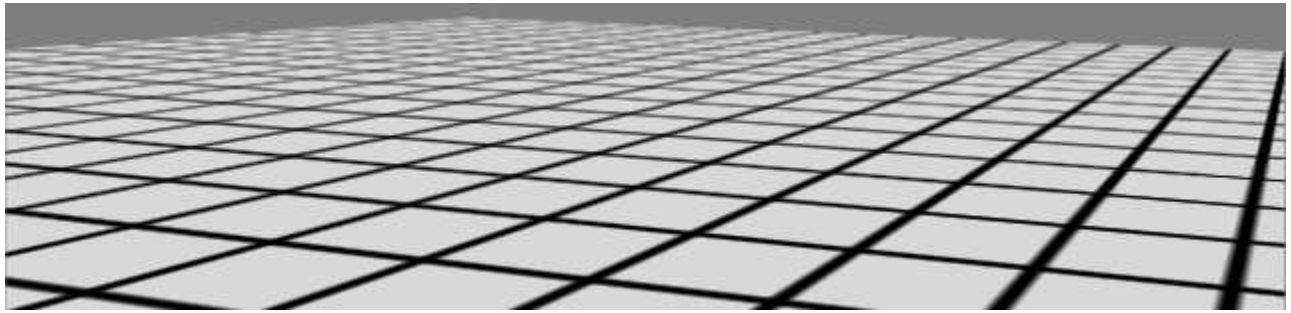
What's the memory overhead?



Nearest Neighbor Sampling



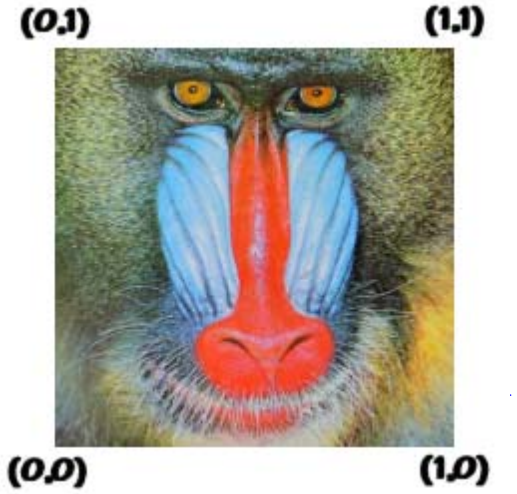
Mipmap Sampling



Summed Area Table

Simple OpenGL Example

- Specify a texture coordinate at each vertex *(s, t)*
- Canonical coordinates where *s* and *t* are between 0 and 1




```
public void Draw() {
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
    glLoadIdentity();
    glTranslated(centerx, centery, depth);
    glMultMatrixf(Rotation);
            :
    // Draw Front of the Cube
    glEnable(GL_TEXTURE_2D);
    glBegin(GL_QUADS);
        glTexCoord2d(0, 1);
        glVertex3d( 1.0, 1.0, 1.0);
        glTexCoord2d(1, 1);
        glVertex3d(-1.0, 1.0, 1.0);
        glTexCoord2d(1, 0);
        glVertex3d(-1.0,-1.0, 1.0);
        glTexCoord2d(0, 0);
        glVertex3d( 1.0,-1.0, 1.0);
    glEnd();
    glDisable(GL_TEXTURE_2D);
:
    glFlush();
```

glTexCoord works like glColor

Slides from Jingyi Yu

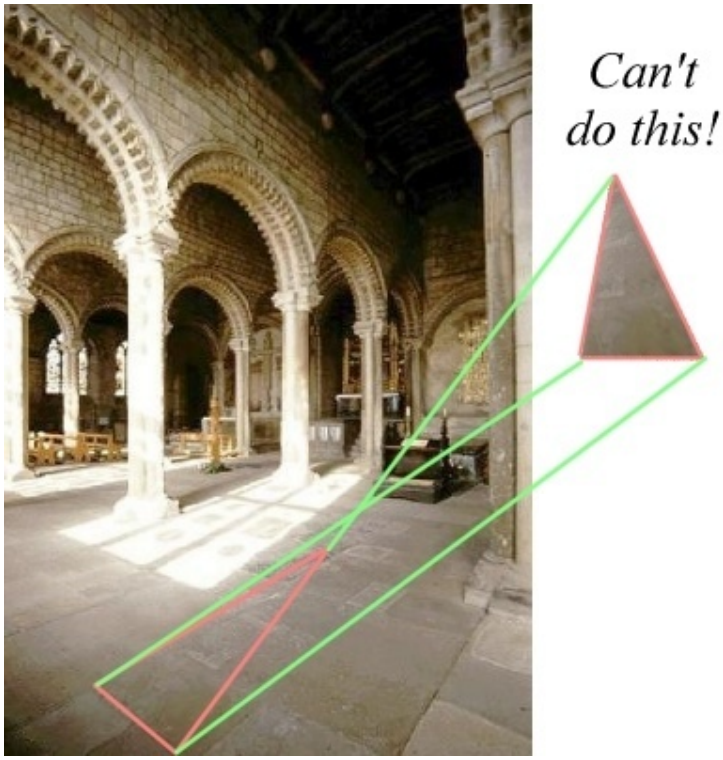
Initializing Texture Mapping

```
static GLubyte image[64][64][4];
static GLuint  texname;

void init(void) {
        glClearColor (0.0, 0.0, 0.0, 0.0);
        glShadeModel(GL_FLAT);
        glEnable(GL_DEPTH_TEST);
        //load in or generate image;
        …
        glPixelStorei(GL_UNPACK_ALIGNMENT, 1);

        glGenTextures(1, &texName);
        glBindTexture(GL_TEXTURE_2D, texName);

        glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT);
        glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT);
        glTexPrameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_NEAREST);
        glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_NEAREST);
        glTexImage2D(GL_TEXTURE_2D, 0, GL_RGBA, checkImageWidth, checkImageHeight, 0,
                GL_RGBA, GL_UNSIGNED_BYTE, image);
}
```

Level index in the Pyramid

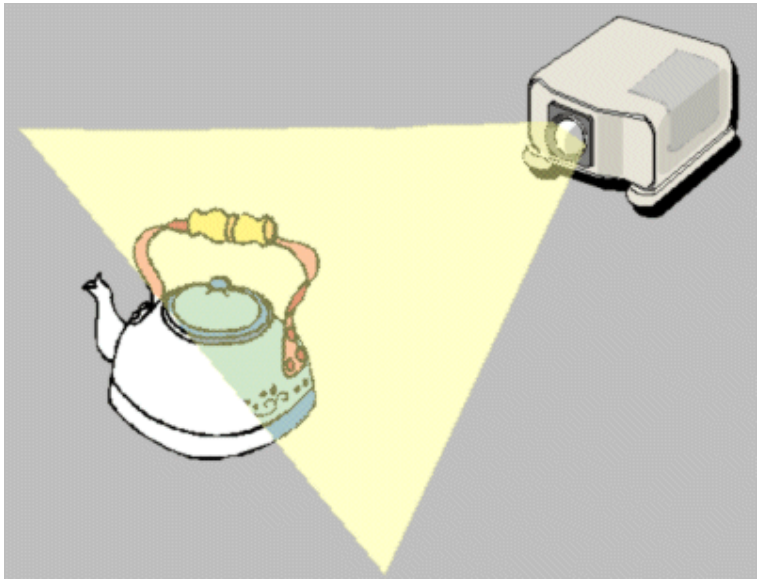
Other Issues with Textures

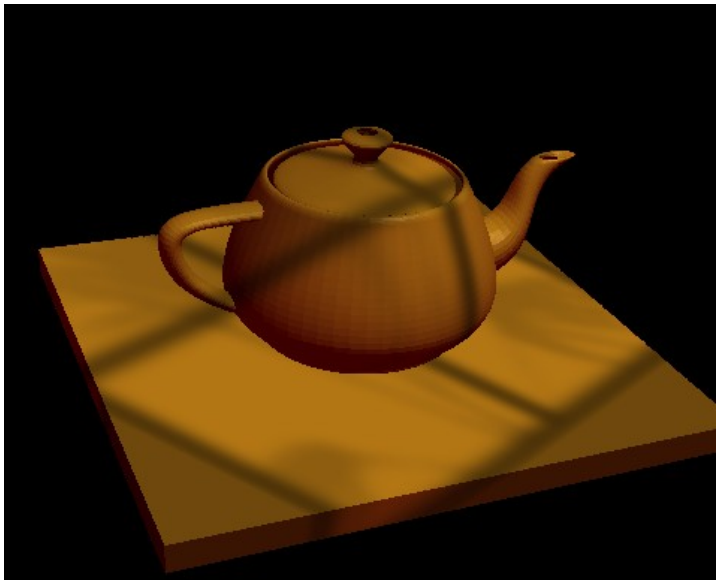
- Tedious to specify texture coordinates for every triangle
- Textures are attached to the geometry
- Can't use just any image as a texture
- **The "texture" can't have projective distortions**
  Reminder: linear interpolation in image space is not equivalent to linear interpolation in 3-space (This is why we need "perspective-correct" texturing).
  The converse is also true.
- Makes it hard to use pictures as textures



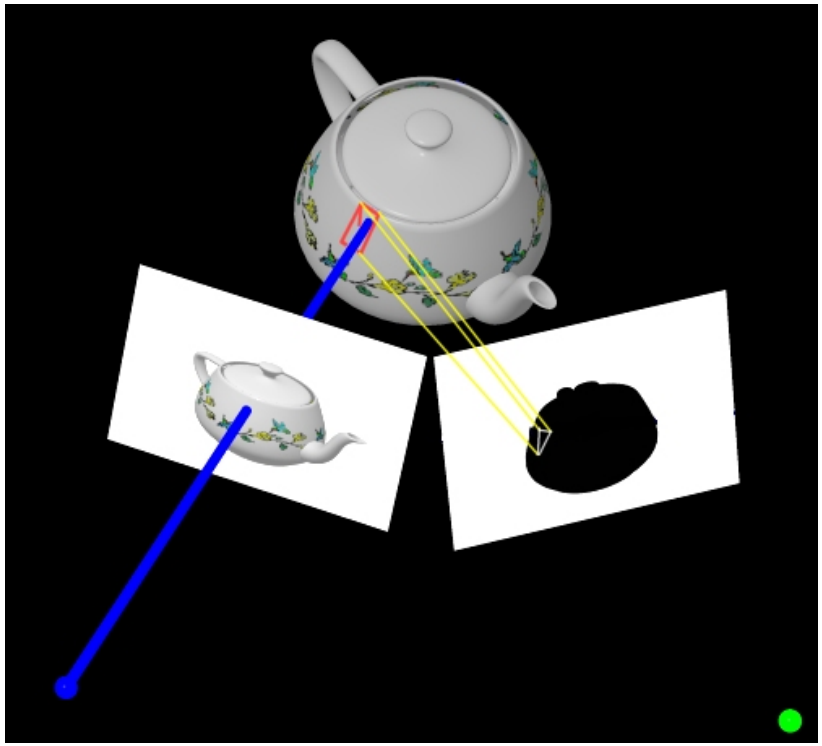
Projective Textures

- Treat the texture as a light source (like a slide projector)
- No need to specify texture coordinates explicitly
- A good model for shading variations due to illumination (cool spotlights)
- A fair model for view-dependent reflectance (can use pictures)





The Mapping Process

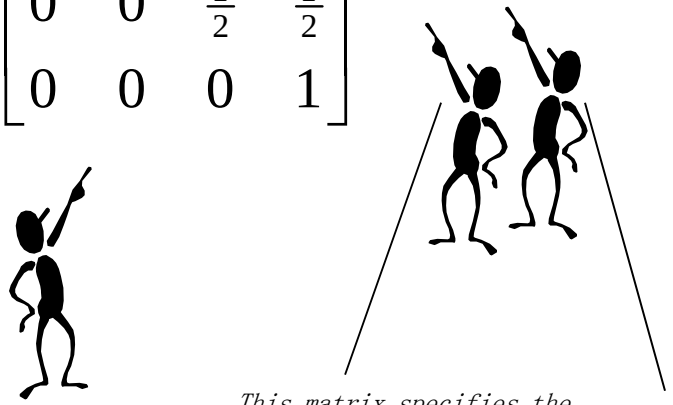


This is the same process, albeit with an additional transform, as perspective correct texture mapping. Thus, we can do it for free! Almost.

What transformation do we need?

- OpenGL is able to insert this extra projection transformation for textures by including another matrix stack, called GL_TEXTURE.
- Also we can use 3d vertex coordinate as texture coordinates
- The transform we want is:

$$T_{eye} = \begin{bmatrix} \frac{1}{2} & 0 & 0 & \frac{1}{2} \\ 0 & \frac{1}{2} & 0 & \frac{1}{2} \\ 0 & 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & 0 & 0 & 1 \end{bmatrix} \mathbf{P}_{proj} \mathbf{V}_{proj}$$



This extra matrix maps from normalized device coordinates ranging from [-1,1] to valid texture coordinates ranging from [0,1].

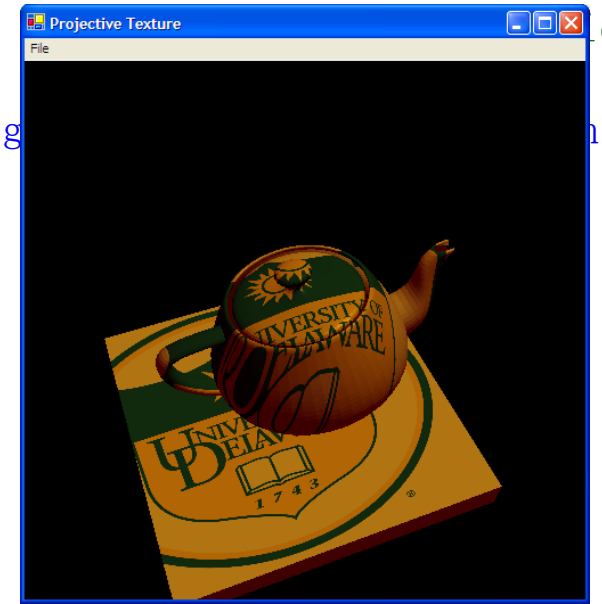
This matrix specifies the frustum of the projector . It is a non-affine, projection matrix. You can use any of the projection transformations to establish it, such as glFrustum(), glOrtho() or gluPerspective() .

This matrix positions the projector in the world, much like the viewing matrix positions the eye within the world. (HINT, you can use gluLookAt() to set this up if you want.

OpenGL Example

Here is where the extra "Texture" transformation on the vertices is inserted.

```
        private void projectTexture() {

            glMatrixMode(GL_TEXTURE);
            glLoadIdentity();
            glTranslated(0.5, 0.5, 0.5);     // Scale and bias the [-1,1]
 NDC values
            glScaled(0.5, 0.5, 0.5);           // to the [0,1] range of the
 texture map
            gluPerspective(15, 1, 5, 7);                                  on"
 and view matrices
            gluLookAt(lightPosition[0],lig                                n[2],
 0,0,0, 0,1,0);
            glMatrixMode(GL_MODELVIEW);

        }
```



How to know where the light is to project an captured image?

CS766 Computer Vision

OpenGL Example (Shortcut)

Here is a code fragment implementing projective textures in OpenGL

```
glTexGeni(GL_S, GL_TEXTURE_GEN_MODE, (int) GL_OBJECT_LINEAR);
glTexGeni(GL_T, GL_TEXTURE_GEN_MODE, (int) GL_OBJECT_LINEAR);
glTexGeni(GL_R, GL_TEXTURE_GEN_MODE, (int) GL_OBJECT_LINEAR);
glTexGeni(GL_Q, GL_TEXTURE_GEN_MODE, (int) GL_OBJECT_LINEAR);

// These calls initialize the TEXTURE_MAPPING function to identity. We will be using
// the Texture matrix stack to establish this mapping indirectly.

float [] eyePlaneS = { 1.0f, 0.0f, 0.0f, 0.0f };
float [] eyePlaneT = { 0.0f, 1.0f, 0.0f, 0.0f };
float [] eyePlaneR = { 0.0f, 0.0f, 1.0f, 0.0f };
float [] eyePlaneQ = { 0.0f, 0.0f, 0.0f, 1.0f };

glTexGenfv(GL_S, GL_EYE_PLANE, eyePlaneS);
glTexGenfv(GL_T, GL_EYE_PLANE, eyePlaneT);
glTexGenfv(GL_R, GL_EYE_PLANE, eyePlaneR);
glTexGenfv(GL_Q, GL_EYE_PLANE, eyePlaneQ);
```

OpenGL Example (Shortcut)

Here is a code fragment implementing projective textures in OpenGL

```
// The following information is associated with the current active texture
// Basically, the first group of setting says that we will not be supplying texture
coordinates.
// Instead, they will be automatically established based on the vertex coordinates in
 “EYE-SPACE”
// (after application of the MODEL_VIEW matrix).

glTexGeni(GL_S, GL_TEXTURE_GEN_MODE, (int) GL_EYE_LINEAR);
glTexGeni(GL_T, GL_TEXTURE_GEN_MODE, (int) GL_EYE_LINEAR);
glTexGeni(GL_R, GL_TEXTURE_GEN_MODE, (int) GL_EYE_LINEAR);
glTexGeni(GL_Q, GL_TEXTURE_GEN_MODE, (int) GL_EYE_LINEAR);

// These calls initialize the TEXTURE_MAPPING function to identity. We will be using
// the Texture matrix stack to establish this mapping indirectly.

float [] eyePlaneS = { 1.0f, 0.0f, 0.0f, 0.0f };
float [] eyePlaneT = { 0.0f, 1.0f, 0.0f, 0.0f };
float [] eyePlaneR = { 0.0f, 0.0f, 1.0f, 0.0f };
float [] eyePlaneQ = { 0.0f, 0.0f, 0.0f, 1.0f };

glTexGenfv(GL_S, GL_EYE_PLANE, eyePlaneS);
glTexGenfv(GL_T, GL_EYE_PLANE, eyePlaneT);
glTexGenfv(GL_R, GL_EYE_PLANE, eyePlaneR);
glTexGenfv(GL_Q, GL_EYE_PLANE, eyePlaneQ);
```

GL_OBJECT_LINEAR vs GL_EYE_LINEAR

When the mode is GL_OBJECT_LINEAR, the texture coordinate is calculated using the the plane-equation coefficients that are passed via `glTexGenfv(GL_S, GL_OBJECT_PLANE, planeCoefficients)`.

The coordinate (S in this case) is computed as:

```
S = Ax + By + Cz + D
```

using the [x y z] coordinates of the vertex (the values passed to glVertex).

If [A B C] is a unit vector, this means that the texture coordinate S is equal to the distance of the vertex from the texgen plane.

GL_EYE_LINEAR works similarly, with the coefficients passed via `glTexGenfv(GL_S, GL_EYE_PLANE, planeCoefficients)`.

The difference is that GL_OBJECT_LINEAR operates in "object coordinates", while GL_EYE_LINEAR works in "eye coordinates".

This means that the texture coordinates computed with GL_OBJECT_LINEAR depend solely on the values passed to glVertex, and do not change as the object (or camera) moves via transformations.

The texture coordinates computed with GL_EYE_LINEAR use the positions of vertices after all modeling & viewing transformations - i.e. they use the positions of the vertices on the screen.

http://resumbrae.com/ub/dms424_s05/10/print.html

OpenGL Example (cont)

The following code fragment is inserted into Draw( ) or Display( )

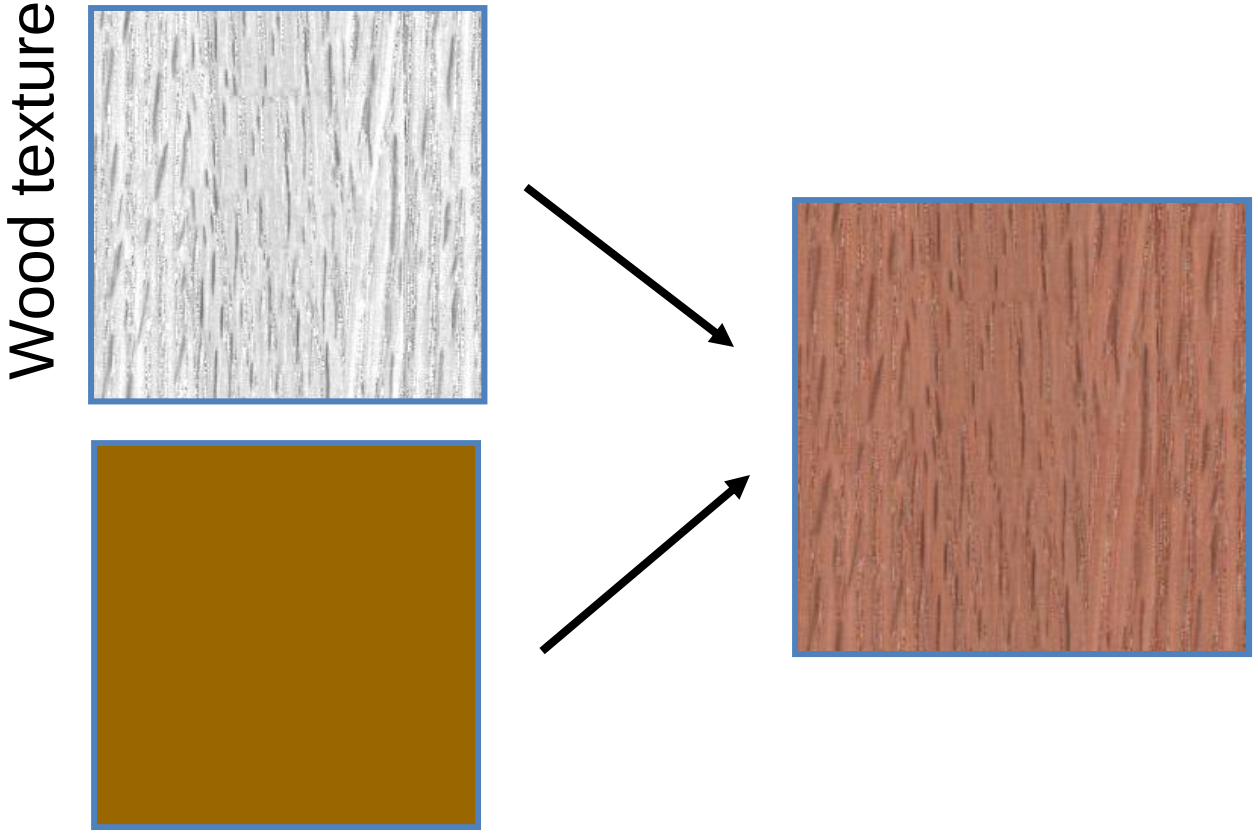
```
if (projTexture) {
    glEnable(GL_TEXTURE_2D);
    glEnable(GL_TEXTURE_GEN_S);
    glEnable(GL_TEXTURE_GEN_T);
    glEnable(GL_TEXTURE_GEN_R);
    glEnable(GL_TEXTURE_GEN_Q);
    projectTexture();
}

// … draw everything that the texture is projected onto

if (projTexture) {
    glDisable(GL_TEXTURE_2D);
    glDisable(GL_TEXTURE_GEN_S);
    glDisable(GL_TEXTURE_GEN_T);
    glDisable(GL_TEXTURE_GEN_R);
    glDisable(GL_TEXTURE_GEN_Q);
 }
```

Outline

- *Types of mappings*
- Interpolating texture coordinates
- Texture Resampling
- Texture mapping in OpenGL
- *Broader use of textures*

Modulation textures

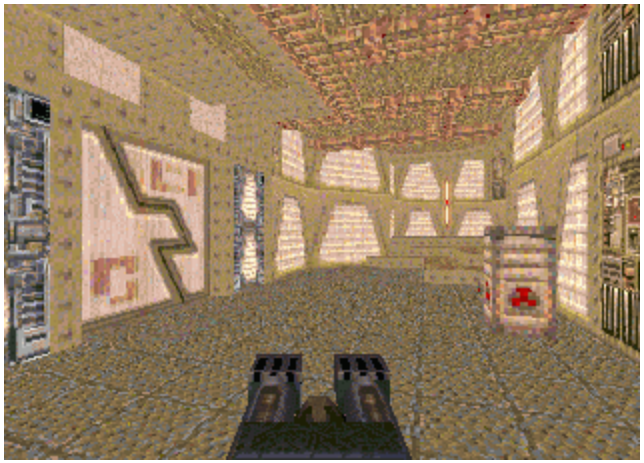
Map texture values to scale factor

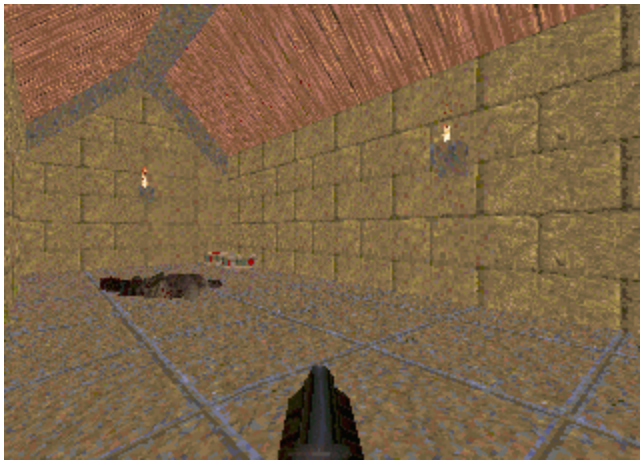


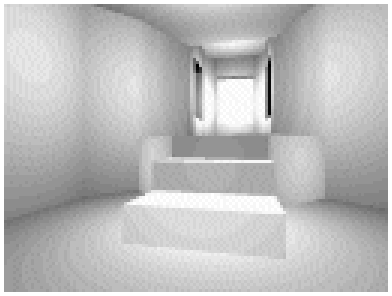
Illumination Maps

- Quake introduced *illumination maps* or *light maps* to capture lighting effects in video games

Texture map:

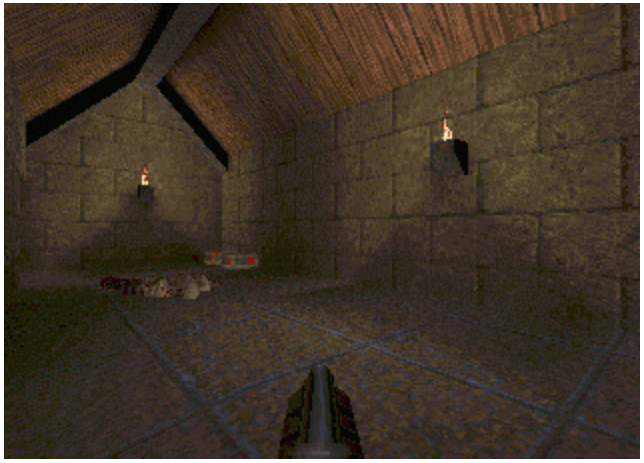






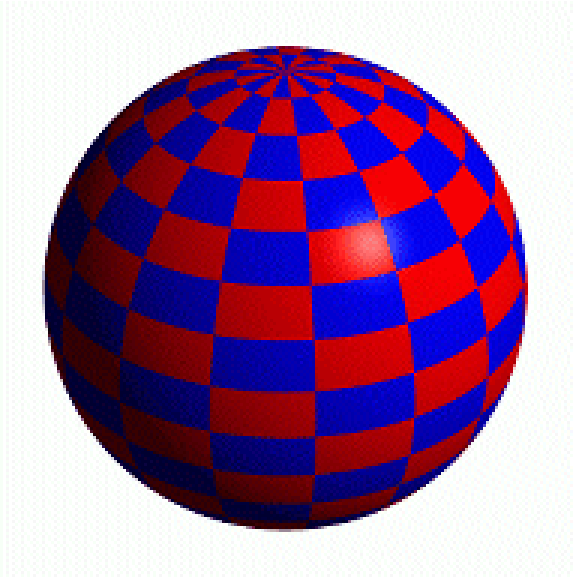
Light map

Texture map + light map:

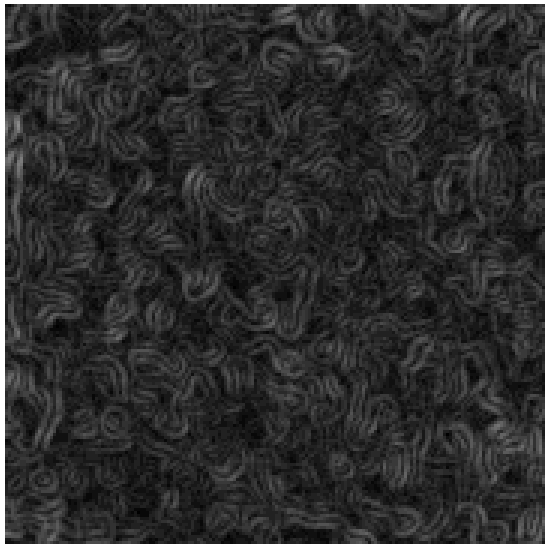


Bump Mapping

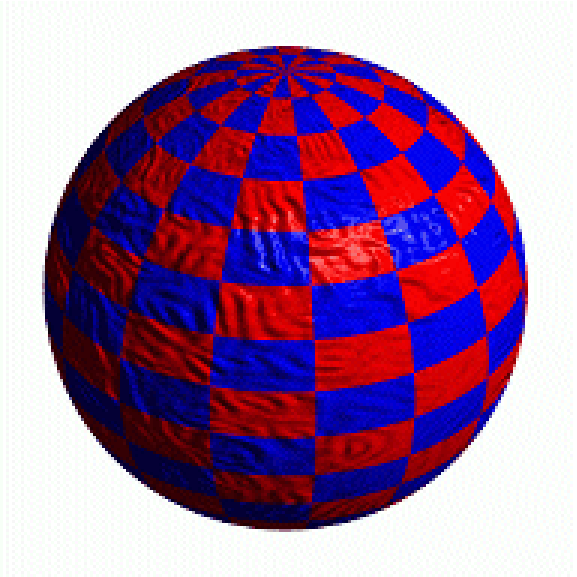
- Texture = change in surface normal!



Sphere w/ diffuse texture

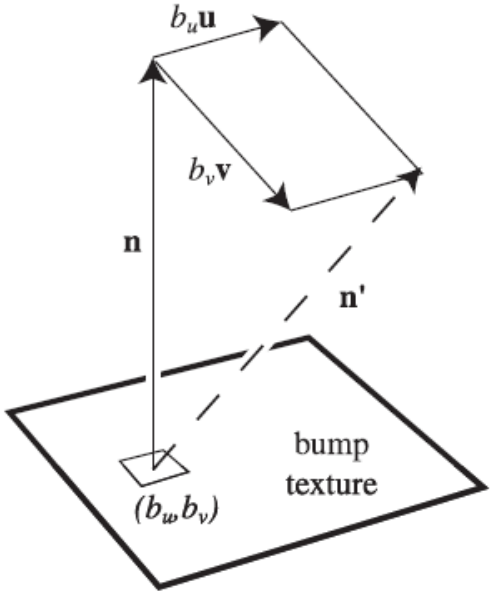


Swirly bump map

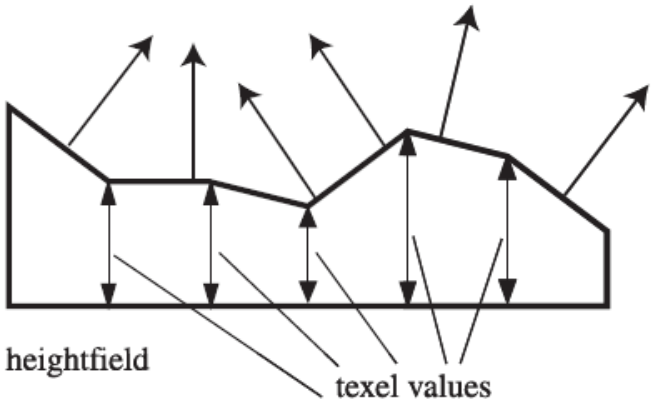


Sphere w/ diffuse texture and swirly bump map

Bump map respresentation



(bu, bv) as texel values



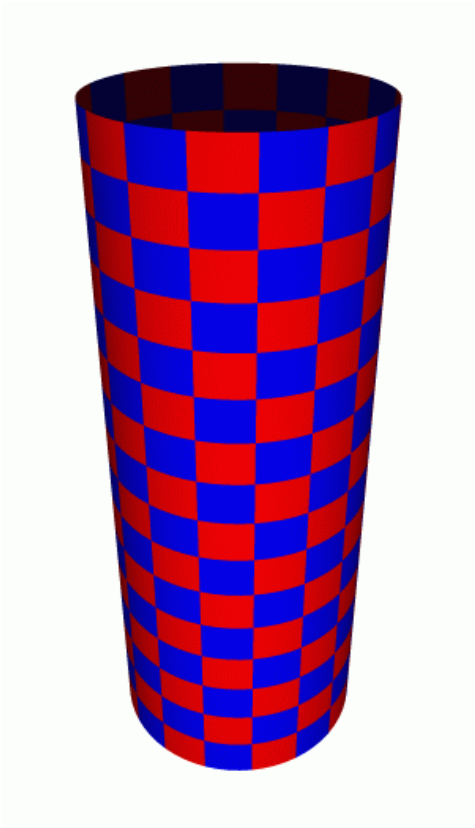
High values as texel values need to converted to normal

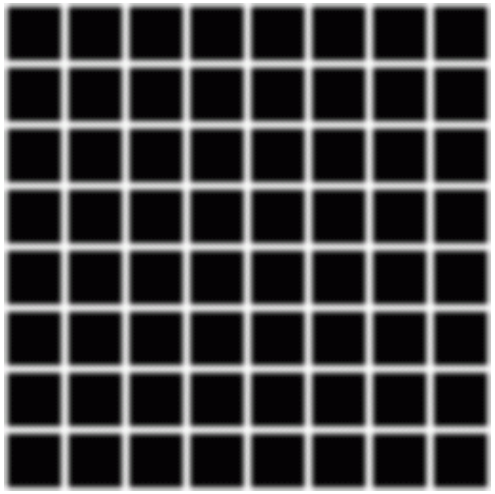
What happens if the light is head on?

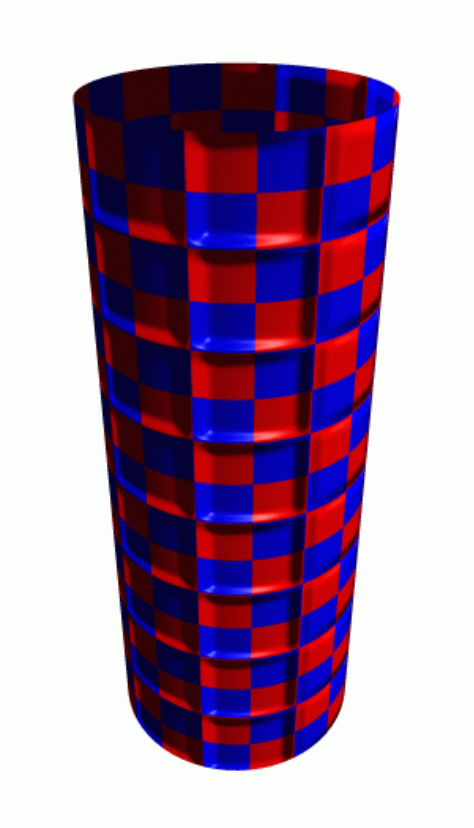
Figure 6.22 from RTR book

More Bump Map Examples

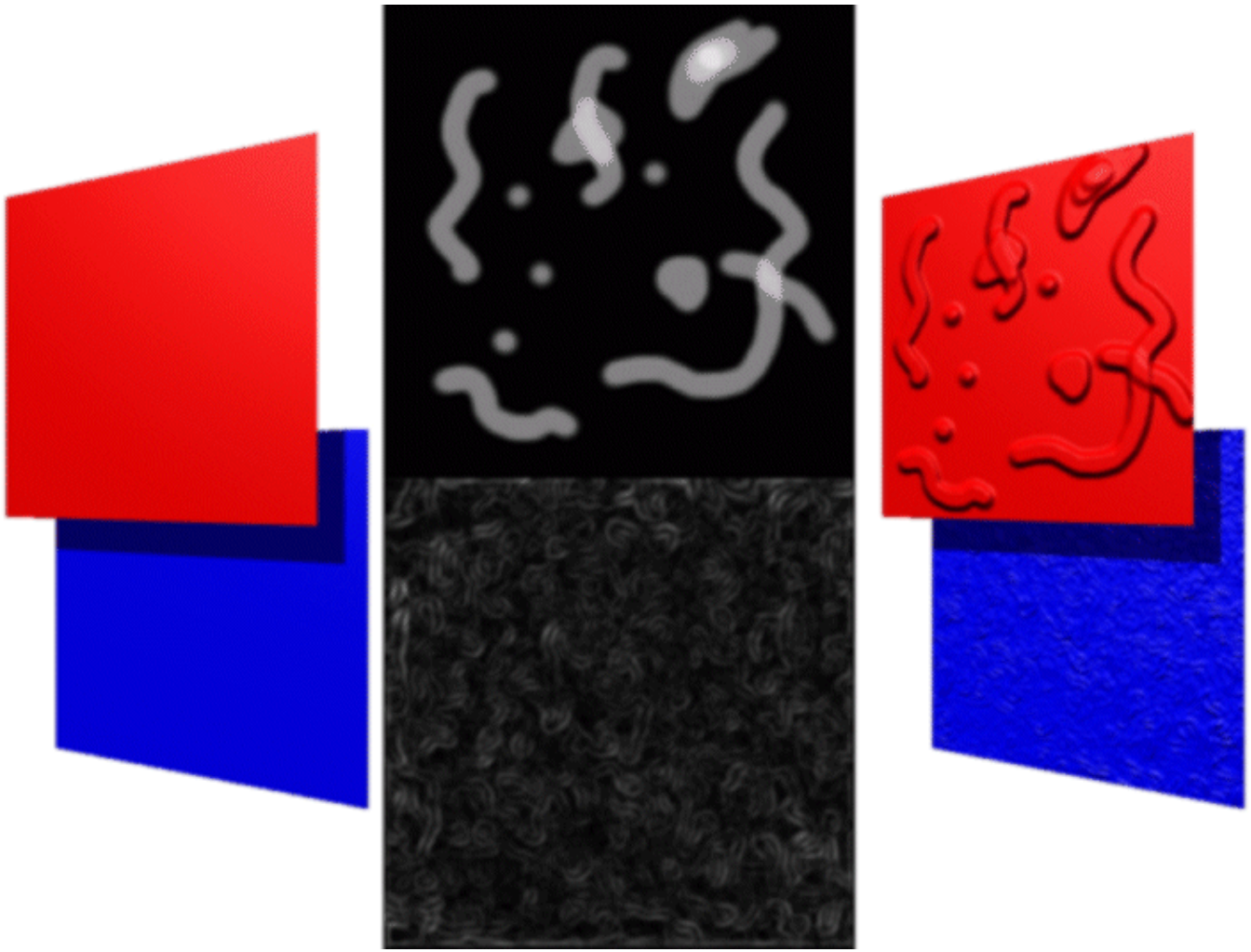
Since the actual shape of the object does not change, the silhouette edge of the object will not change. Bump Mapping also assumes that the Illumination model is applied at every pixel (as in Phong Shading or ray tracing).



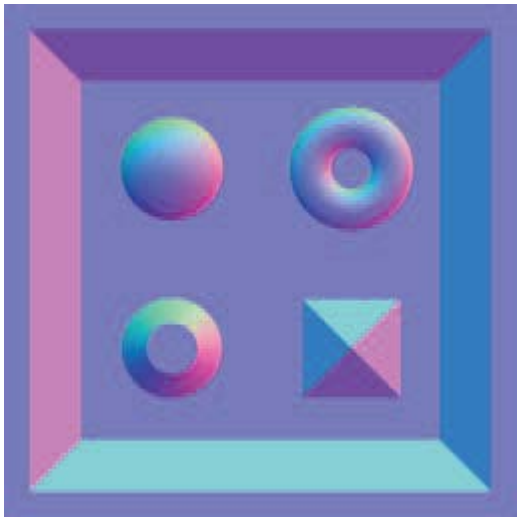




One More Bump Map Example



Dot product normal map



(r,g,b) encodes (nx,ny,nz)

Figure 6.24 from RTR book

Bump map in shading

$$I = k_e + k_a L_a + k_d L_d \cdot \max(0, \mathbf{L} \cdot \mathbf{N}) + k_s L_s \cdot \max(0, \mathbf{V} \cdot \mathbf{R})^{n_s}$$

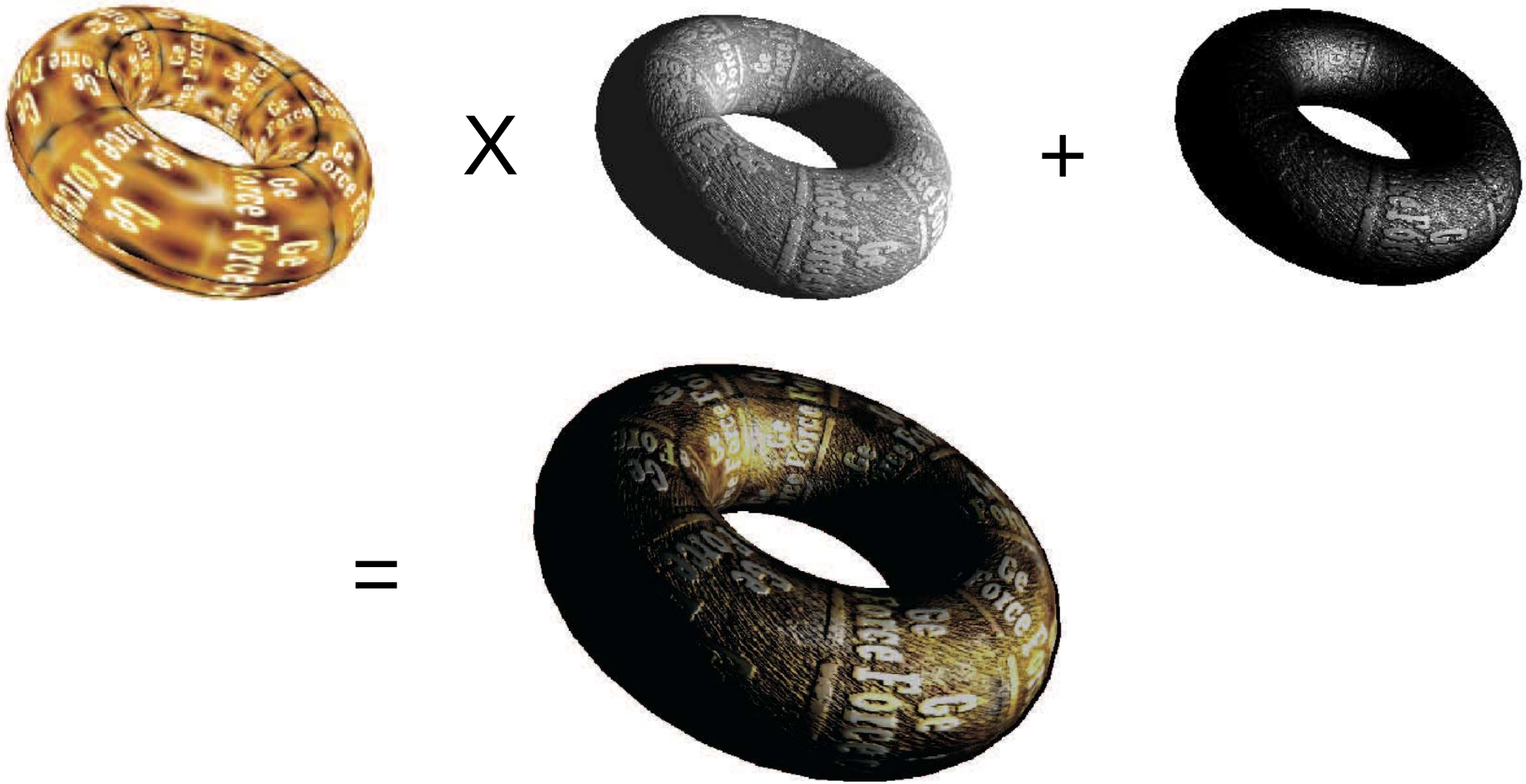
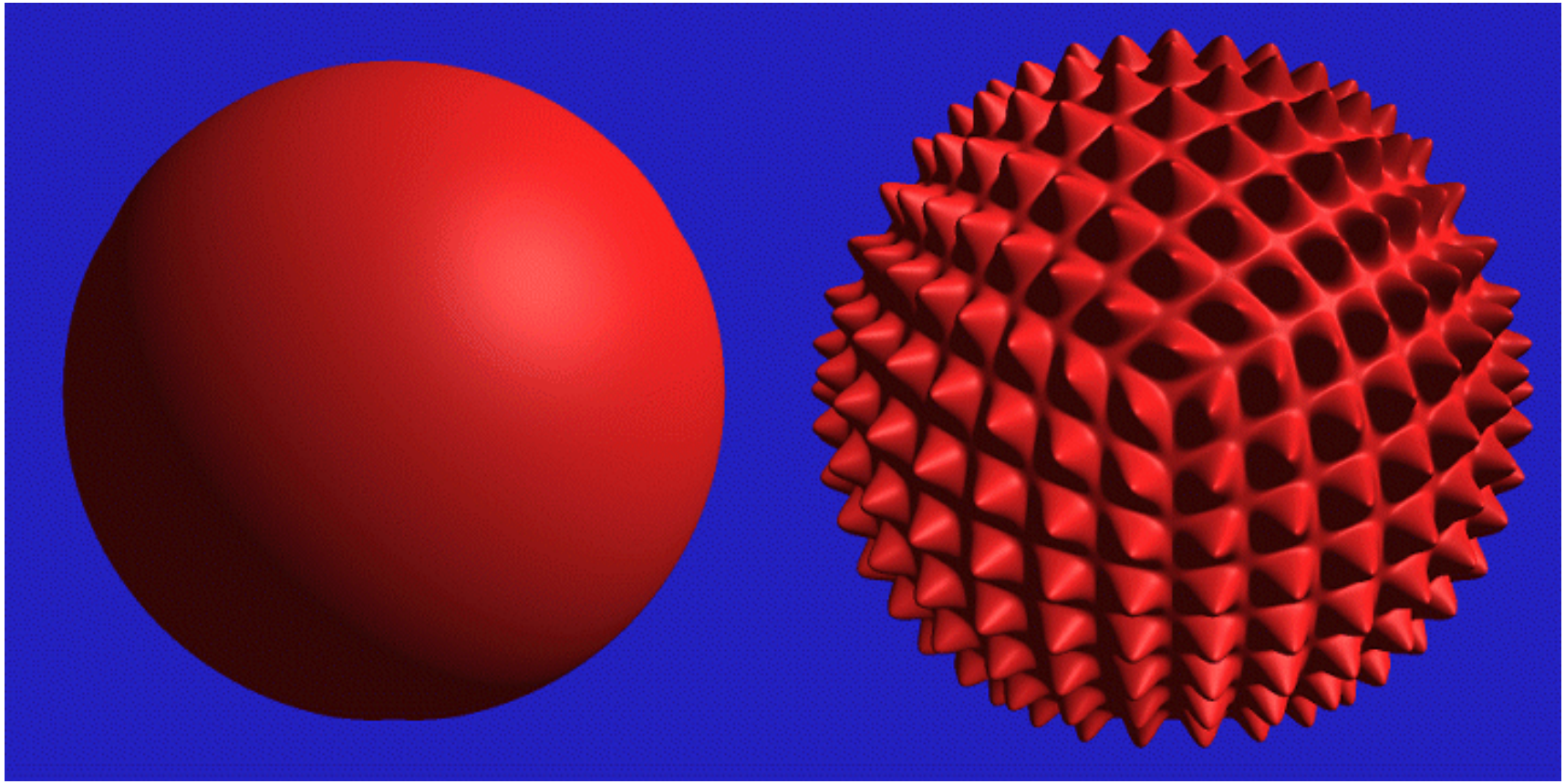


Figure 6.26 from RTR book

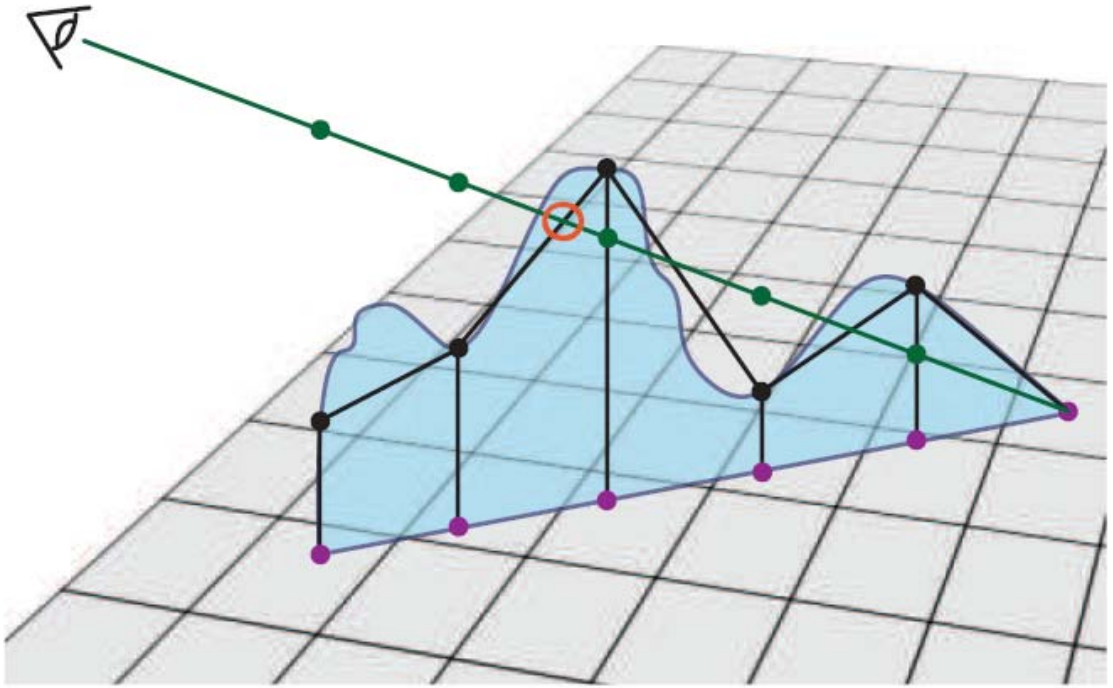
Displacement Mapping

Texture maps can be used to actually move surface points. This is called *displacement mapping*. How is this fundamentally different than bump mapping?



Bump map does not have occlusion effects.

Rendering Displacement map is tricky



How to find the intersection?
See RTR book

Figure 6.29 from RTR book

Bump map vs Displacement map

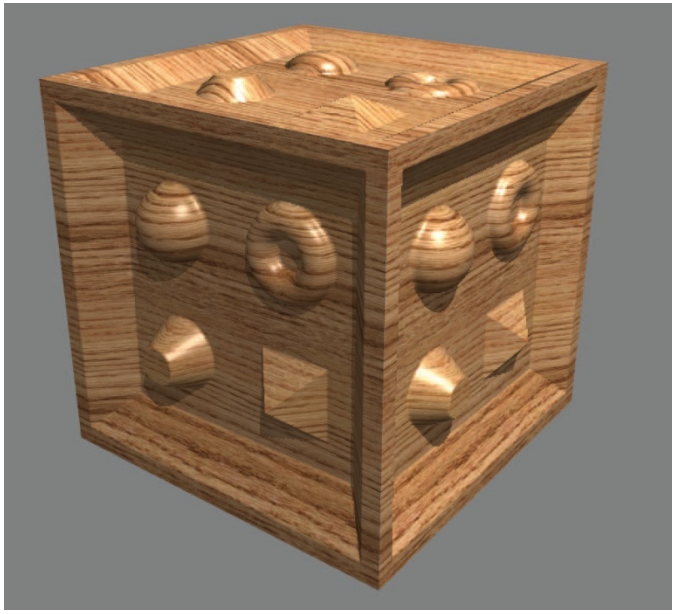
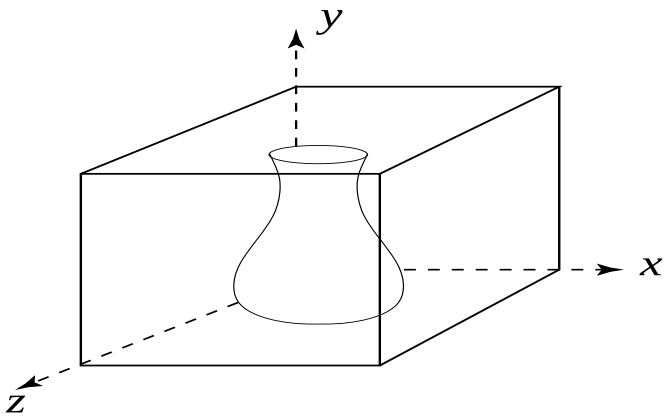


Figure 6.24 and 30 from RTR book

Displacement map in a scene

Solid textures



- Use model-space coordinates to index into a 3D texture
- Like “carving” the object from the material

- One difficulty of solid texturing is coming up with the textures.

Solid textures (cont'd)

- Here's an example for a vase cut from a solid marble texture:

- *Solid marble texture by Ken Perlin*

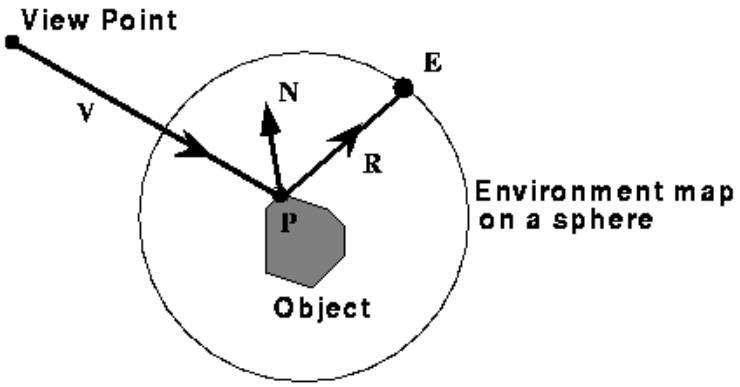
http://legakis.net/justin/MarbleApplet/

Environment Maps

Images from *Illumination and Reflection Maps:*
Simulated Objects in Simulated and Real Environments
Gene Miller and C. Robert Hoffman
SIGGRAPH 1984 "Advanced Computer Graphics Animation" Course Notes

Environment Maps

Instead of using transformed vertices to index the projected texture', we can use transformed *surface normal* s to compute indices into the texture map. These sorts of mapping can be used to simulate reflections, and other shading effects. This approach is not completely accurate. It assumes that all reflected rays begin from the same point, and that all objects in the scene are the same distance from that point.



Applications of Environment Map

"Interface", courtesy of
Lance Williams, 1985

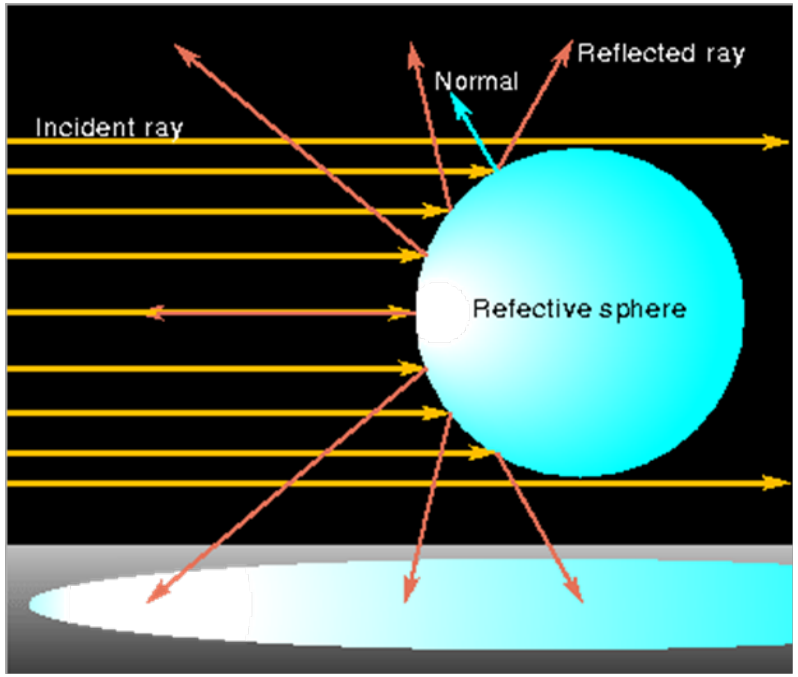
williams_robot4.mov

Terminator 2, 1991

More history info on Reflectance map
http://www.debevec.org/ReflectionMapping/

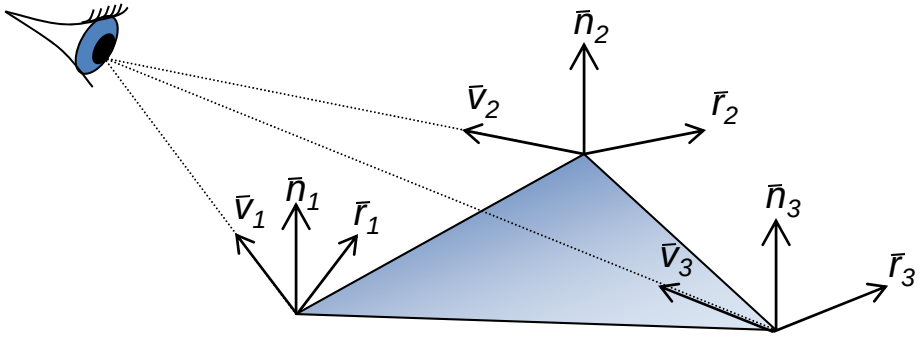
Sphere Mapping Basics

- OpenGL provides special support for a particular form of Normal mapping called sphere mapping. It maps the normals of the object to the corresponding normal of a sphere. It uses a texture map of a sphere viewed from infinity to establish the color for the normal.



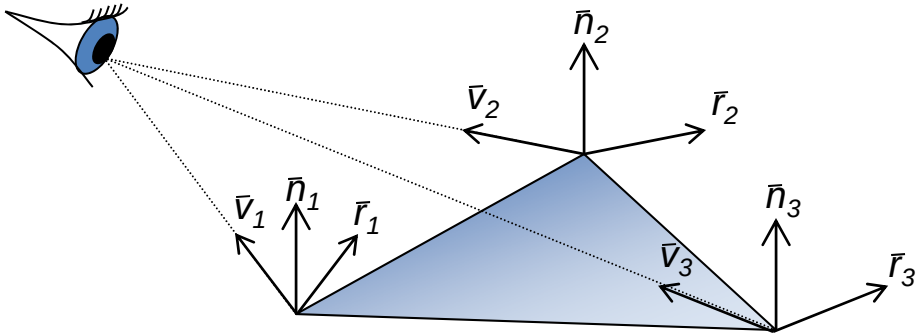
Sphere Mapping

- Mapping the normal to a point on the sphere



Sphere Mapping

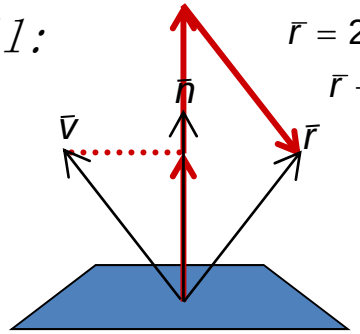
- Mapping the normal to a point on the sphere



Recall:

$$\bar{r} = 2(\bar{n}\cdot\bar{v})\bar{n} - \bar{v}$$

$$\bar{r} + \bar{v} = \alpha\bar{n}$$

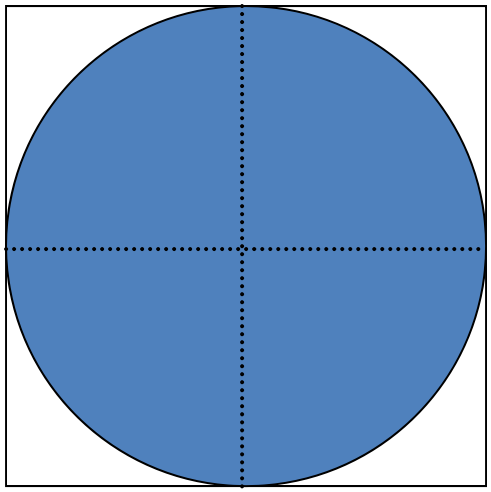


$$\alpha\bar{n} = \bar{r} + \bar{v} = \begin{bmatrix} r_x \\ r_y \\ r_z \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

$$\frac{\alpha\bar{n}}{\|\alpha\bar{n}\|} = \begin{bmatrix} \frac{r_x}{p} \\ \frac{r_y}{p} \\ \frac{r_z+1}{p} \\ 0 \end{bmatrix}$$

$$p = \sqrt{r_x^2 + r_y^2 + (r_z+1)^2}$$

(1, 1)



(−1, −1)

$$\bar{n} = \begin{bmatrix} s \\ t \\ \sqrt{1 - s^2 - t^2} \\ 0 \end{bmatrix}$$

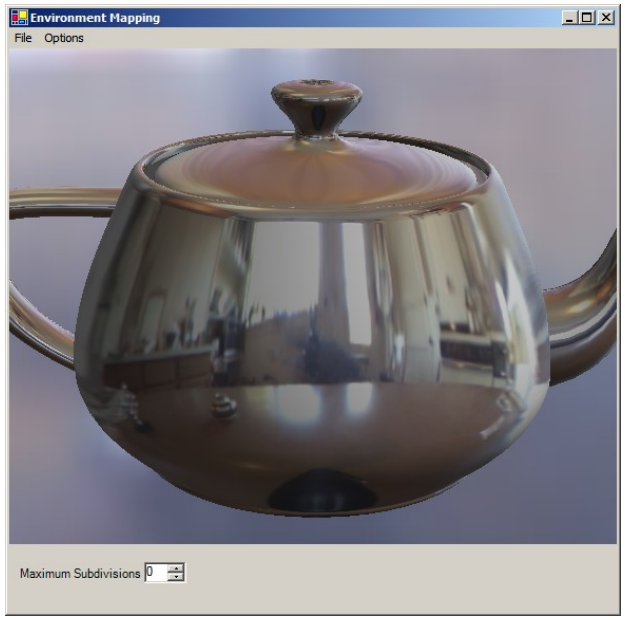
$$s = \frac{r_x}{p} \quad t = \frac{r_y}{p}$$

$$s' = \frac{s}{2} + \frac{1}{2} \quad t' = \frac{t}{2} + \frac{1}{2}$$

$$s' = \frac{r_x}{2p} + \frac{1}{2} \quad t' = \frac{r_y}{2p} + \frac{1}{2}$$

OpenGL code Example

```
// this gets inserted where the texture is created

glTexGeni(GL_S, GL_TEXTURE_GEN_MODE, (int) GL_SPHERE_MAP);
glTexGeni(GL_T, GL_TEXTURE_GEN_MODE, (int) GL_SPHERE_MAP);

glEnable(GL_TEXTURE_2D);
glEnable(GL_TEXTURE_GEN_S);
glEnable(GL_TEXTURE_GEN_T);
```



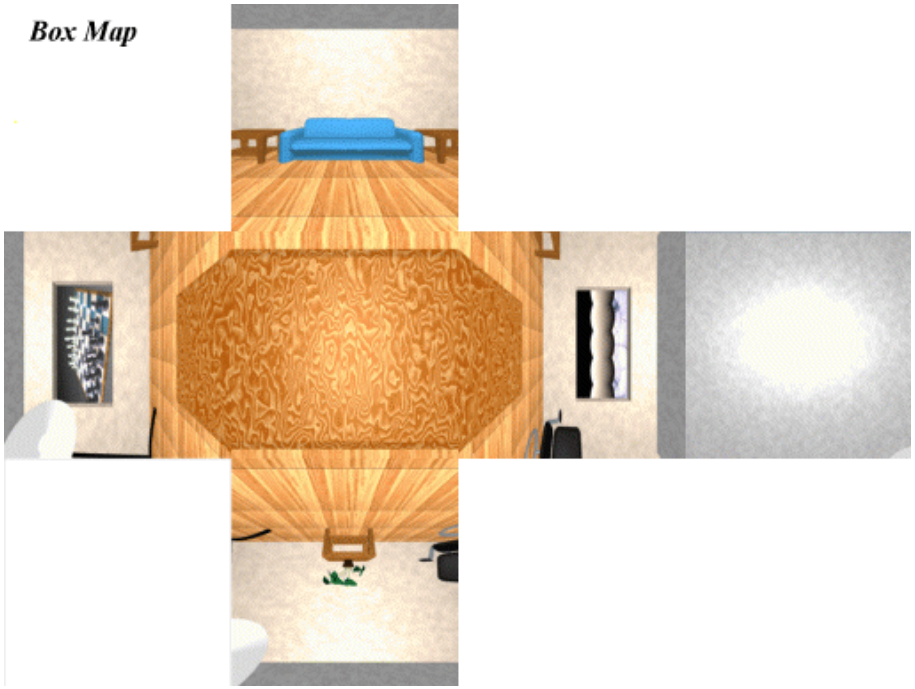
Without a mirror ball, where to get environment map images?
http://www.debevec.org/probes/

When doesn't EM work well?

- Flat/planar surface
  - In particular under orthographic projection

What's the Best Map?

A sphere map is not the only representation choice for environment maps. There are alternatives, with more uniform sampling properties, but they require different normal-to-texture mapping functions.



Multi-Texturing

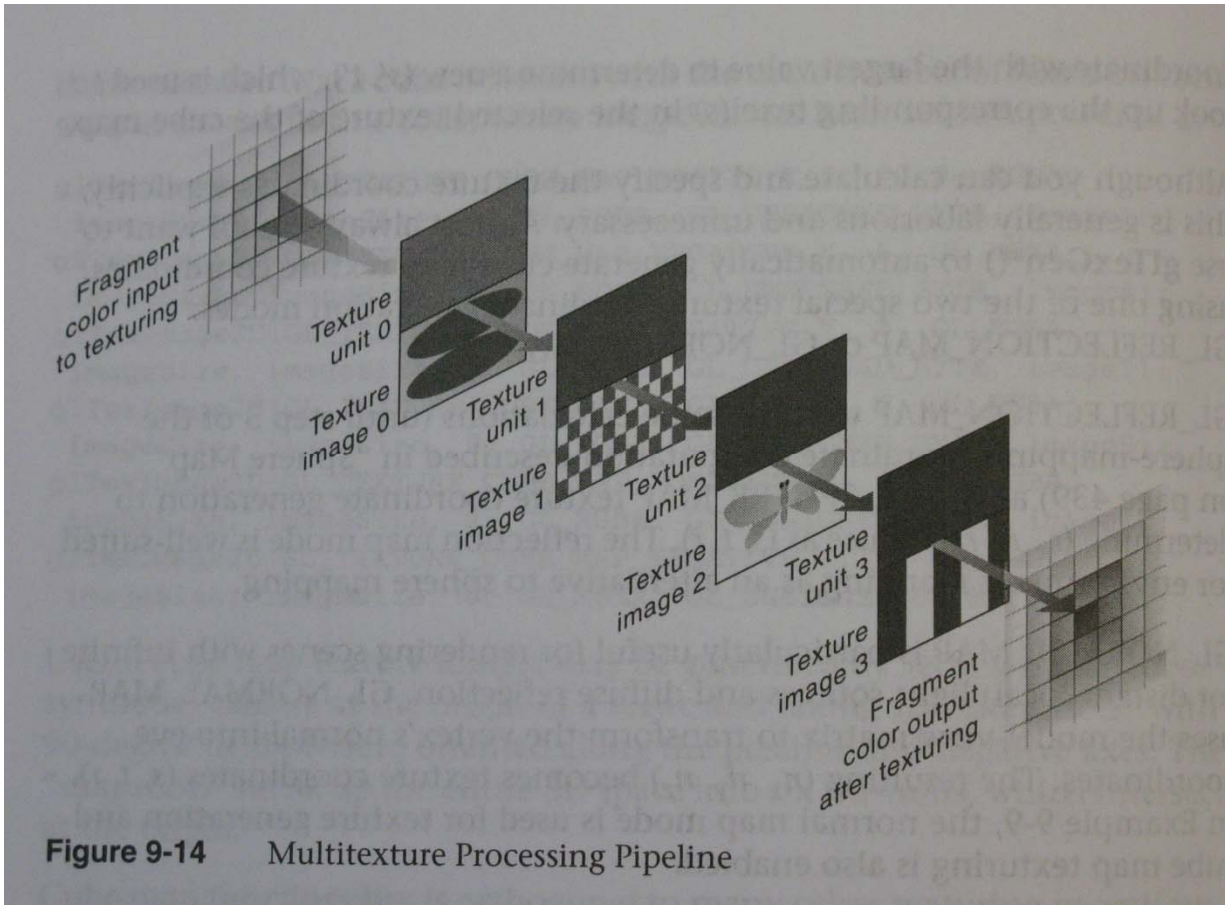


Figure 9-14 Multitexture Processing Pipeline

Why Multi-texturing

- Interpolating Textures
  - From day to night

- Implementing Bump maps
  - Create texture for diffuse coefficient, light vector, and normal maps: kd * max(L·n, 0)

Multi-Texture: OpenGL

Gluint texture0, texture1;
//in Initi() Load in images, Initialize textures as before
//in Display() do the following

```
// bind and enable texture unit 0
glActiveTexture (GL_TEXTURE0);
glBindTexture (GL_TEXTURE_2D, texture0);
glEnable (GL_TEXTURE_2D);

// bind and enable texture unit 1
glActiveTexture (GL_TEXTURE1);
glBindTexture (GL_TEXTURE_2D, texture1);
glEnable (GL_TEXTURE_2D);

// specify two sets of texture coordinates for each vertex
glBegin (GL_TRIANGLES);
    glMultiTexCoord2f (GL_TEXTURE0, 0.0, 1.0);
    glMultiTexCoord2f (GL_TEXTURE1, 1.0, 0.0);
    glVertex3f (...)
    ...
glEnd ();
```

Combining Textures

```
glActiveTexture( GL_TEXTURE0 );
glEnable( GL_TEXTURE_2D );
glBindTexture(GL_TEXTURE_2D, texName0);
glTexEnvi( GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_REPLACE );

glActiveTexture( GL_TEXTURE1 );
glEnable( GL_TEXTURE_2D );
glBindTexture(GL_TEXTURE_2D, texName1);
int choice = 0;
if (choice == 0) //modulate the two textures
{
   glTexEnvi( GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE );
}
else if (choice == 1) //interpolate the two textures using the alpha of current primary color
{
   glTexEnvi( GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_COMBINE );
   glTexEnvi( GL_TEXTURE_ENV, GL_COMBINE_RGB, GL_INTERPOLATE );
   glTexEnvi( GL_TEXTURE_ENV, GL_SRC0_RGB, GL_TEXTURE1);
   glTexEnvi( GL_TEXTURE_ENV, GL_SRC1_RGB, GL_PREVIOUS);
   glTexEnvi( GL_TEXTURE_ENV, GL_SRC2_RGB, GL_PRIMARY_COLOR);
   glTexEnvi( GL_TEXTURE_ENV, GL_OPERAND0_RGB, GL_SRC_COLOR);
   glTexEnvi( GL_TEXTURE_ENV, GL_OPERAND1_RGB, GL_SRC_COLOR);
   glTexEnvi( GL_TEXTURE_ENV, GL_OPERAND2_RGB, GL_SRC_ALPHA);
}
else                    //disable the second texture
 {
   glActiveTexture(GL_TEXTURE1);
   glDisable(GL_TEXTURE_2D);
}
// continue on the right
```

```
glColor4f(0,0,0,0.2);

glBegin(GL_QUADS);
glMultiTexCoord2f(GL_TEXTURE0, 0.0, 0.0);
glMultiTexCoord2f(GL_TEXTURE1, 0.0, 0.0);
glVertex3f(-2.0, -1.0, 0.0);

glMultiTexCoord2f(GL_TEXTURE0, 0.0, 1.0);
glMultiTexCoord2f(GL_TEXTURE1, 0.0, 1.0);
glVertex3f(-2.0, 1.0, 0.0);

glMultiTexCoord2f(GL_TEXTURE0, 1.0, 1.0);
glMultiTexCoord2f(GL_TEXTURE1, 1.0, 1.0);
glVertex3f(0.0, 1.0, 0.0);

glMultiTexCoord2f(GL_TEXTURE0, 1.0, 0.0);
glMultiTexCoord2f(GL_TEXTURE1, 1.0, 0.0);
glVertex3f(0.0, -1.0, 0.0);

glEnd();
```

Different Combinations for different apps

- Interpolate for fade-in-fade-out between textures
  - Night and day

- Dot product followed by modulation for bump map
  - http://www.paulsprojects.net/tutorials/simplebump/simplebump.html

Multi-Texture: OpenGL

- Each texture unit (GL_TEXTURE*) has its own state:
  - Texture image
  - Environment mode
  - Filtering parameters
  - Texture matrix stack
  - Automatic texture coordinate generation
  - …
- Create visual effect using your imagination.

GL Extensions

- Multi-texturing is not supported in visual studio.
- Need to download GL extension managers:
  - **GLEE** - http://elf-stone.com/glee.php - The "Easy" Gl Extension manager.
  - **GLEW** - http://glew.sourceforge.net/ - The Open GL Extension Wrangler.
  - More info: http://pages.cs.wisc.edu/~cs559-1/GlExtensions.htm

Texture animation

- Moving water texture to simulate flow
- zoom, rotation, and shearing image on a surface
- Fading in and fading out (Blending marble to skin) with multi-texturing

Shadow map

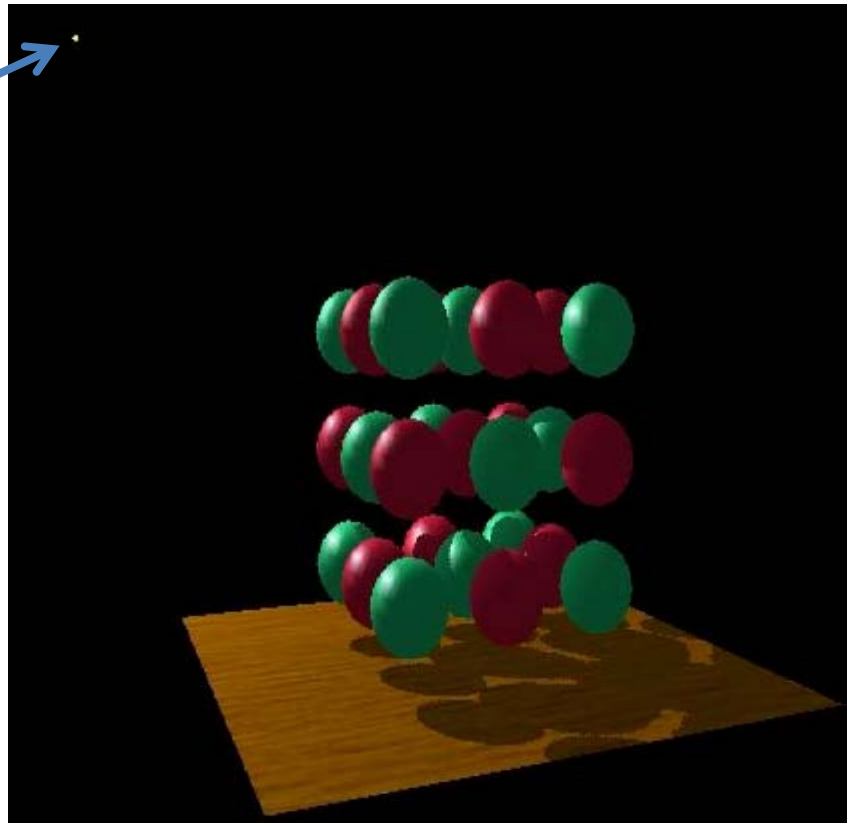
- Cast shadow on curved/non planar surfaces

Lance Williams, “Casting Curved Shadows on Curved Surfaces,” SIGGRAPH 78

Shadow map

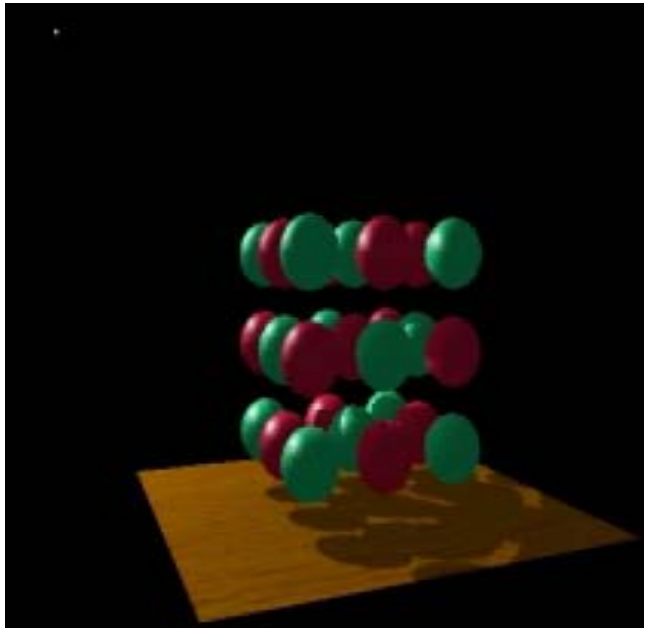
Let’s consider this scene:

Point light source

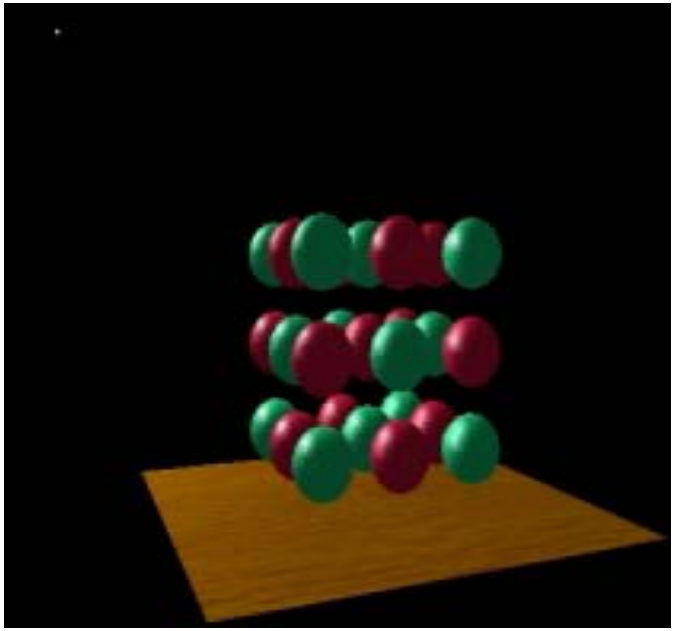


Q: Is hack shadow enough?

Shadow map

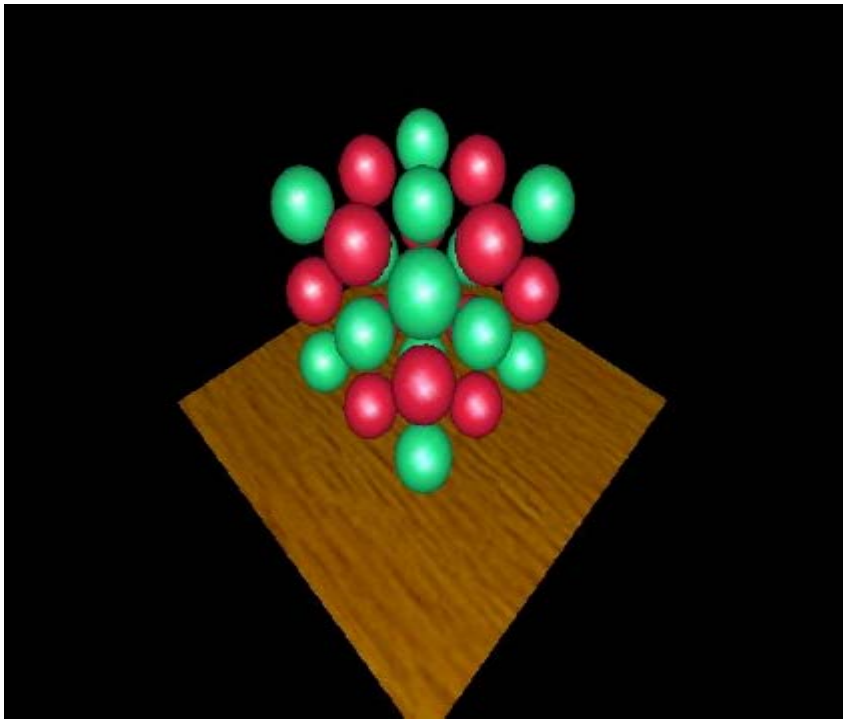


With shadow



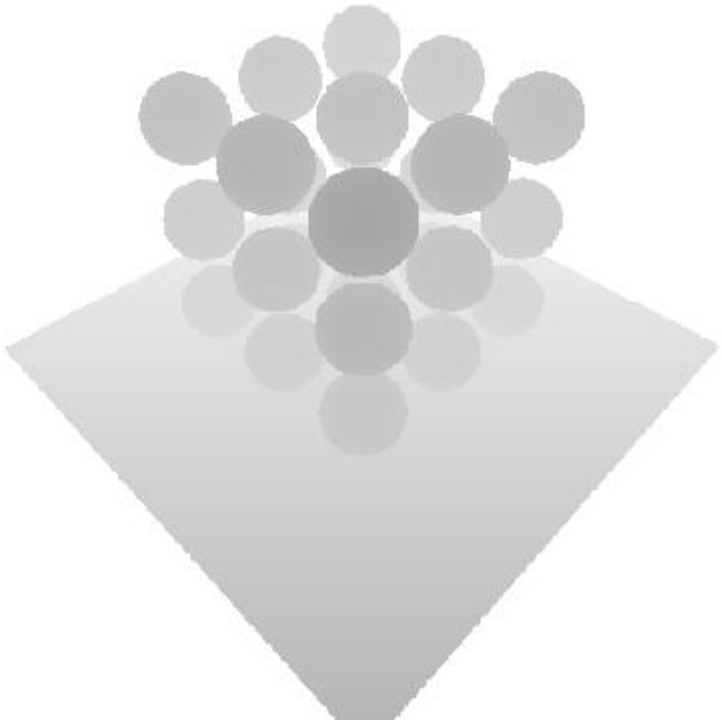
Without shadow

Shadow map



Scene from the light’s viewpoint

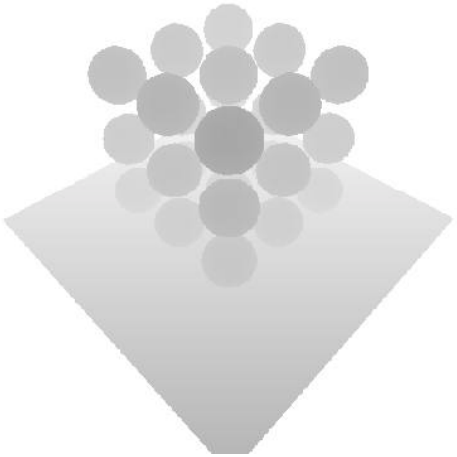
Shadow map



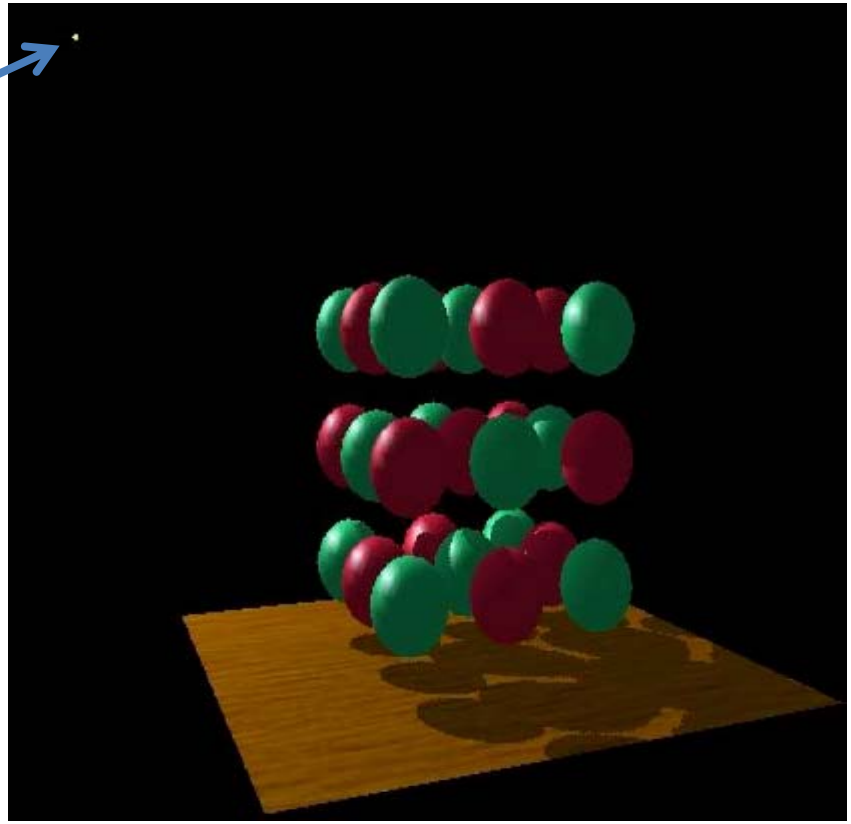
Depth map from the light’s viewpoint

Shadow map

Point light source

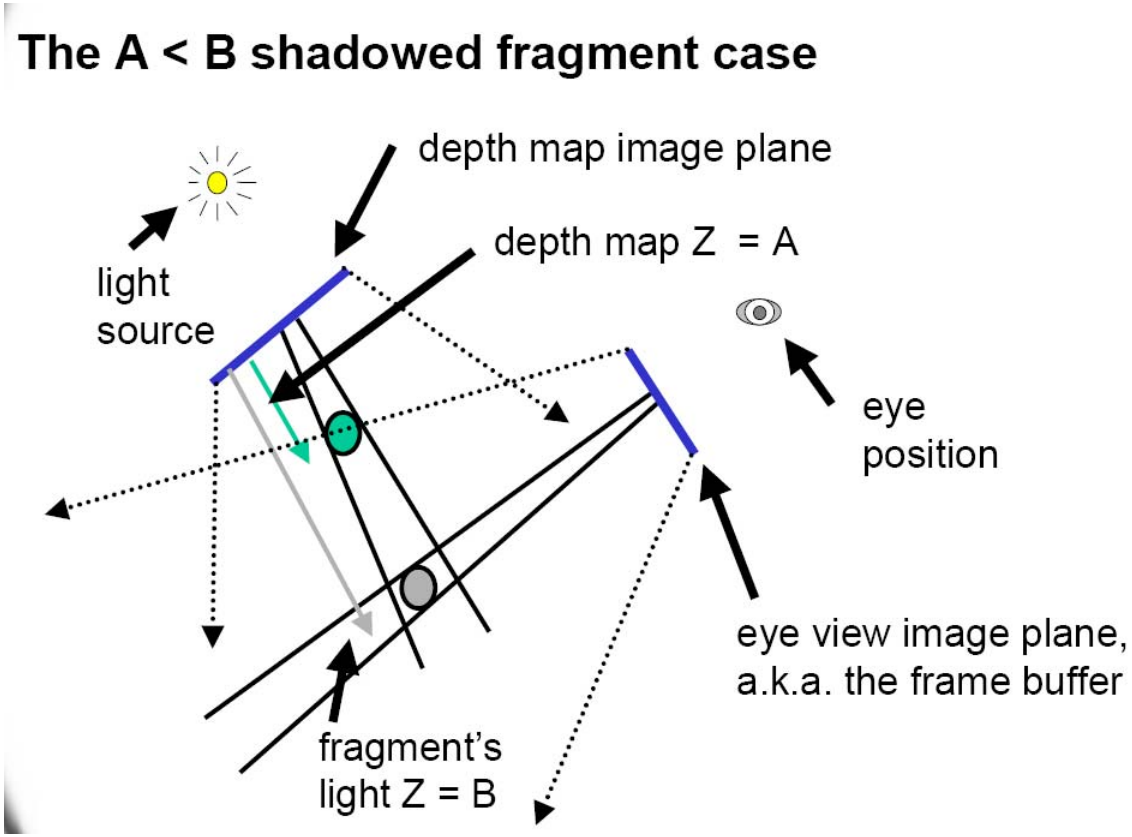


Depth Texture



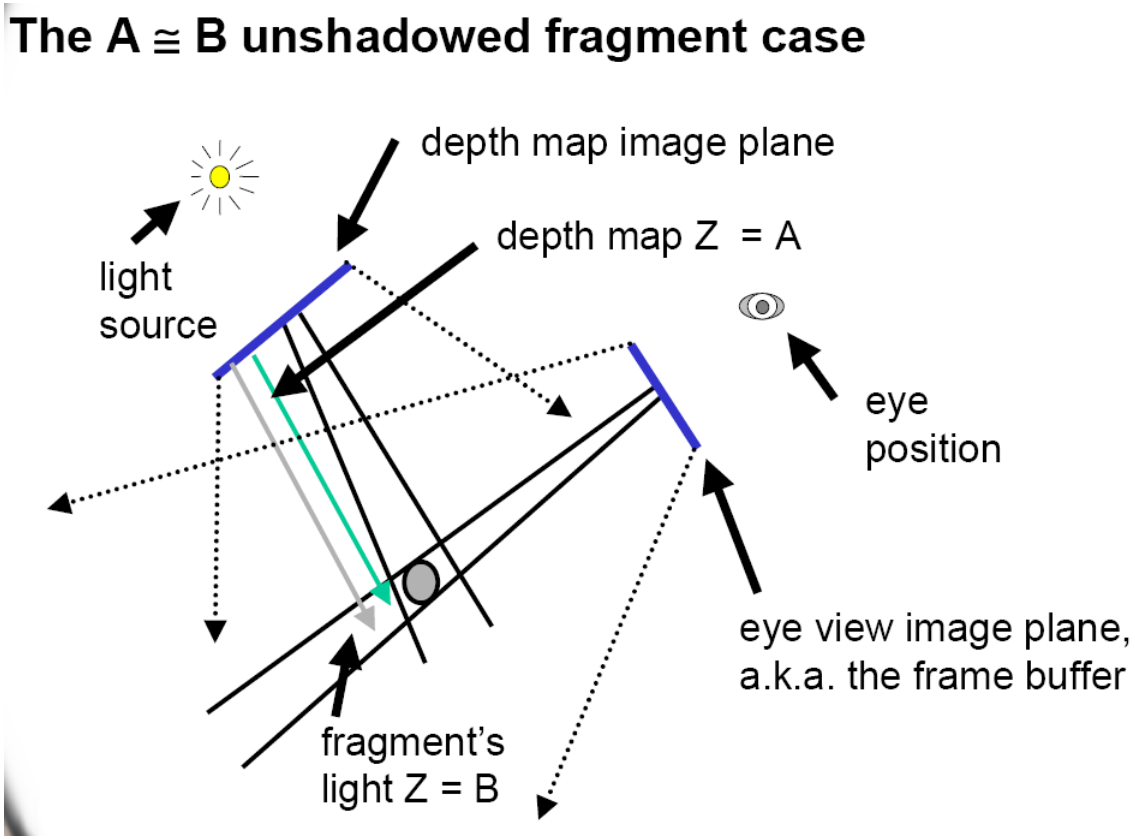
In rasterization, check light visibility using the depth map with respect to the light.

Shadow map




```
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_COMPARE_FUNC, GL_LEQUAL);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_COMPARE_MODE,
GL_COMPARE_R_TO_TEXTURE);
```

Shadow map




```
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_COMPARE_FUNC, GL_LEQUAL);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_COMPARE_MODE,
GL_COMPARE_R_TO_TEXTURE);
```

Shadow Map

- Depth testing from the light's point-of-view

A 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

Shadow Map

- 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
    - compare the depth value for XYZ and the depth value in the buffer computed in the first pass, relative to the light.

More details, see Red book v2.1. pp459-463
Free Version 1.1 does not have this feature.
Also see a tutorial
http://www.paulsprojects.net/tutorials/smt/smt.html