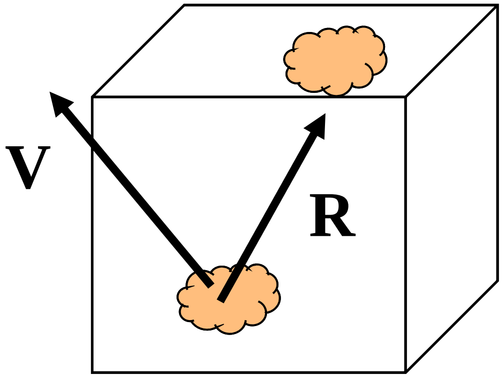
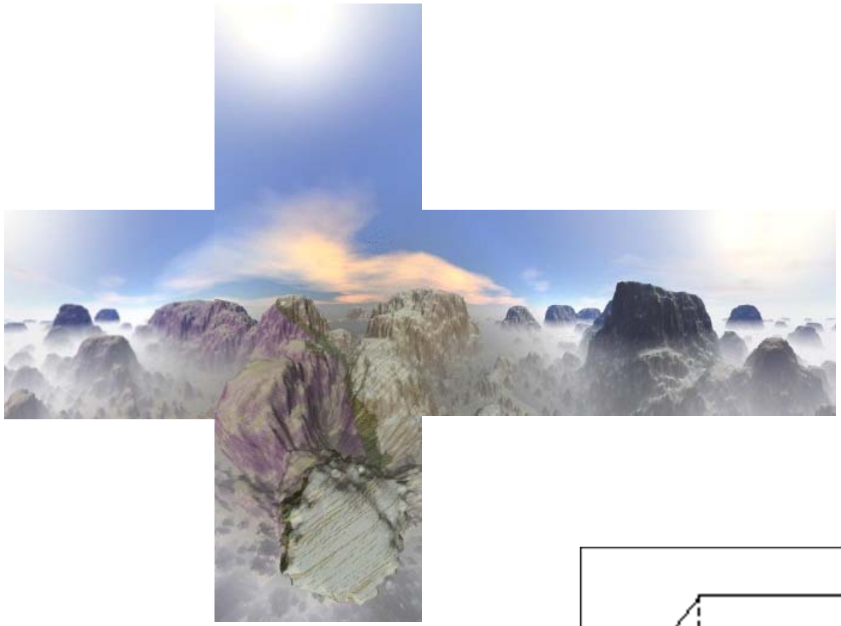
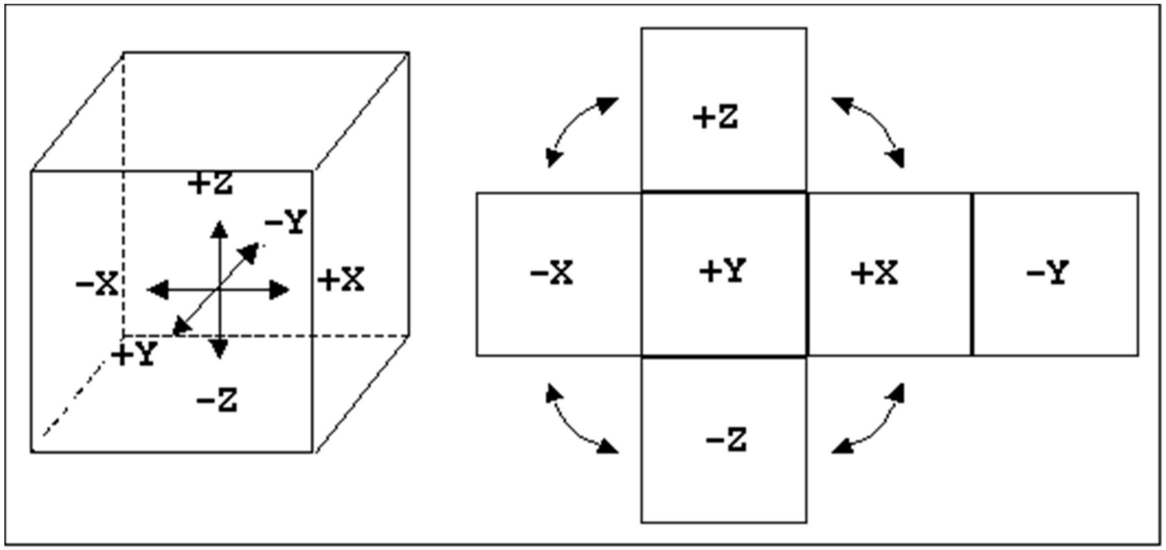
Recall: Indexing into Cube Map

- Compute **R** = 2(**N·V**)**N-V**
- Object at origin
- Use **largest magnitude component** of R to determine face of cube
- Other 2 components give texture coordinates

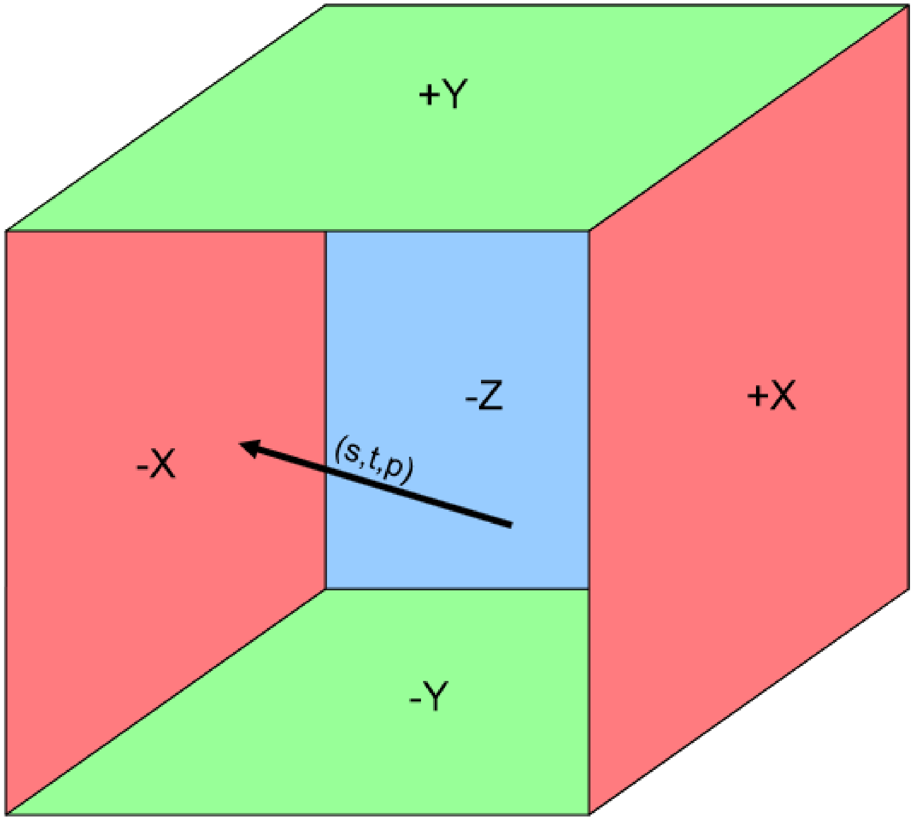


Cube Map Layout





Cube Map Texture Lookup:
Given an (s,t,p) direction vector , what (r,g,b) does that correspond to?



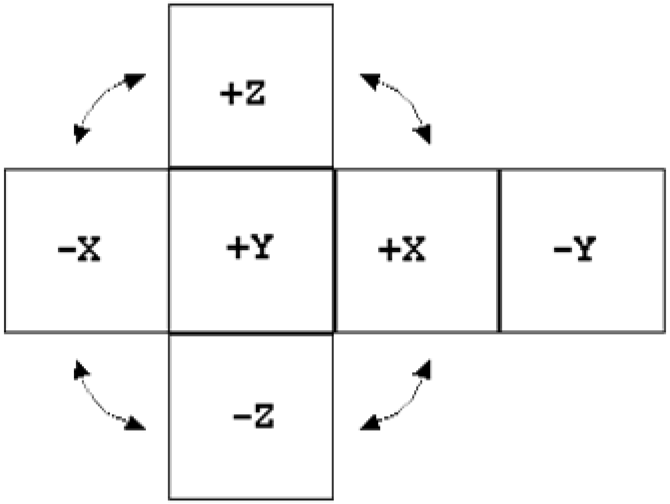
- Let L be the texture coordinate of (s, t, and p) with the largest magnitude
- L determines which of the 6 2D texture “walls” is being hit by the vector (-X in this case)
- The texture coordinates in that texture are the remaining two texture coordinates divided by L: (a/L,b/L)

Built-in GLSL functions

```
vec3 ReflectVector = reflect( vec3 eyeDir, vec3 normal );

vec3 RefractVector = refract( vec3 eyeDir, vec3 normal, float Eta );
```

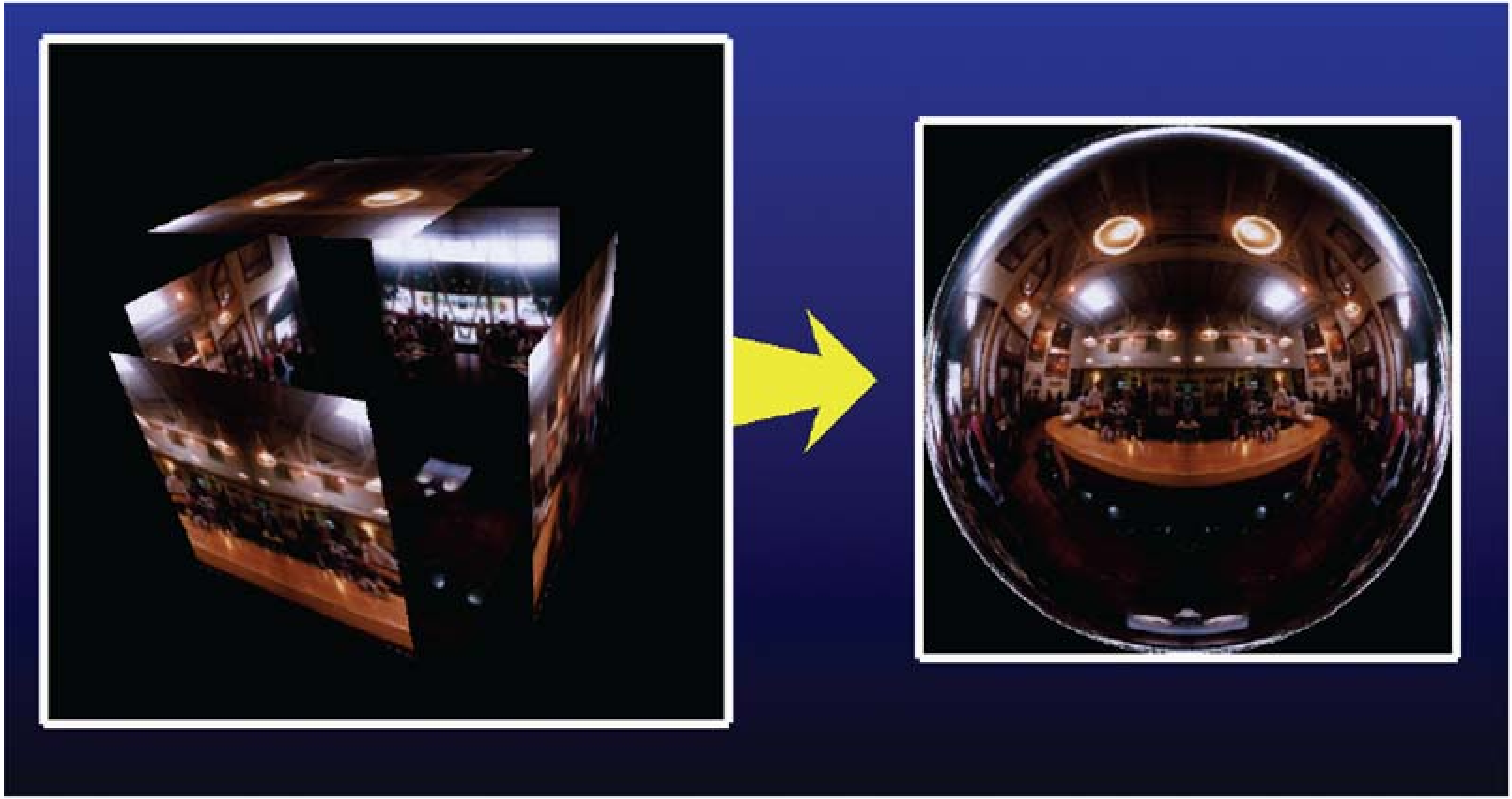
Example



- **R** = (-4, 3, -1)
- Same as **R** = (-1, 0.75, -0.25)
- Use face x = -1 and y = 0.75, z = -0.25
- Not quite right since cube defined by x, y, z = ± 1 rather than [0, 1] range needed for texture coordinates
- Remap by from [-1,1] to [0,1] range
  - s = ½ + ½ y, t = ½ + ½ z
- Hence, s =0.875, t = 0.375

Sphere Environment Map

- Cube can be replaced by a sphere (sphere map)



Sphere Mapping

- Original environmental mapping technique
- Proposed by Blinn and Newell
- Uses lines of longitude and latitude to map parametric variables to texture coordinates
- OpenGL supports sphere mapping
- Requires a circular texture map equivalent to an image taken with a fisheye lens

Sphere Map

- A sphere maps is basically a photograph of a reflective sphere in an environment

Paul DeBevec, www.debevec.org

Sphere map

- example

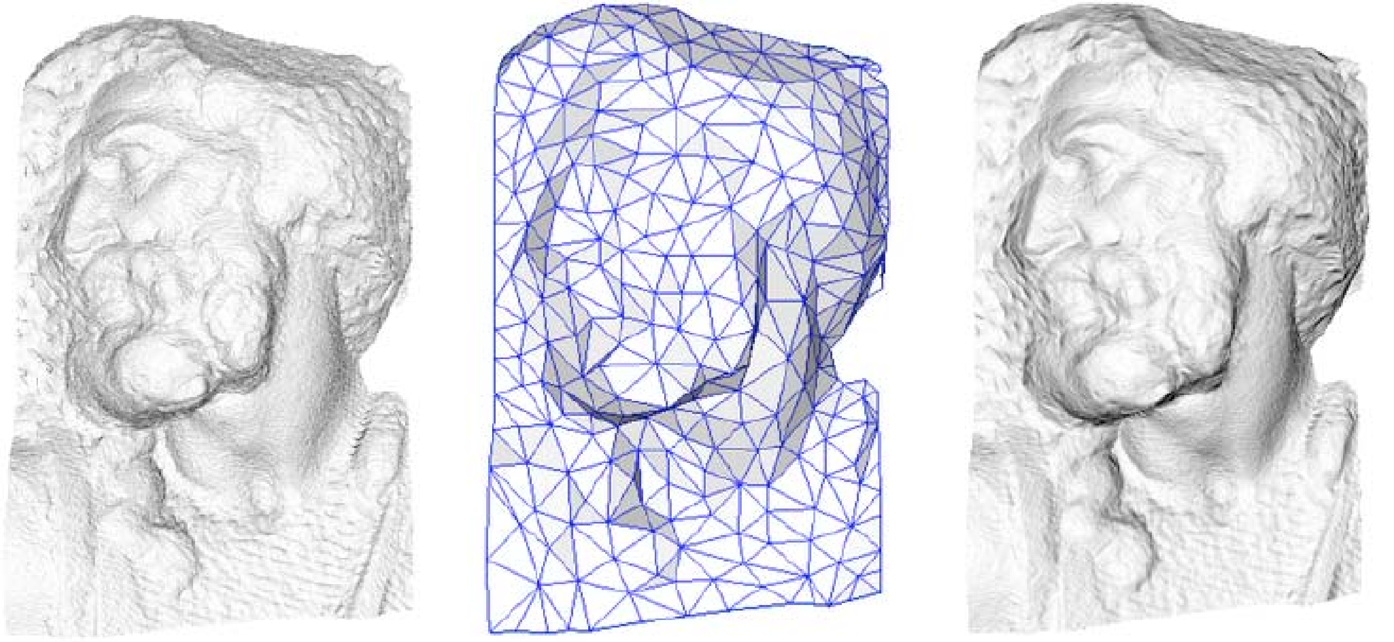
Sphere map
(texture)

Sphere map
applied on torus

Capturing a Sphere Map

Normal Mapping

- Store normals in texture
- Very useful for making low-resolution geometry look like it's much more detailed



original mesh
4M triangles

simplified mesh
500 triangles

simplified mesh
and normal mapping
500 triangles

Computer Graphics (CS 4731)
Lecture 21: Shadows and Fog

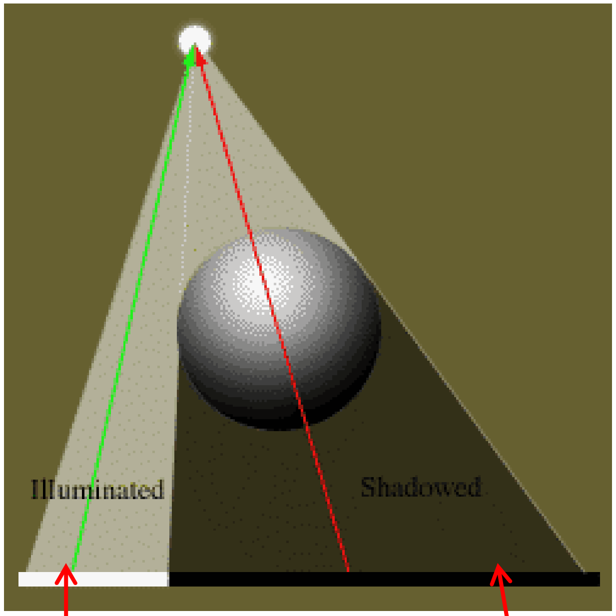
Prof Emmanuel Agu

Computer Science Dept.

Worcester Polytechnic Institute (WPI)

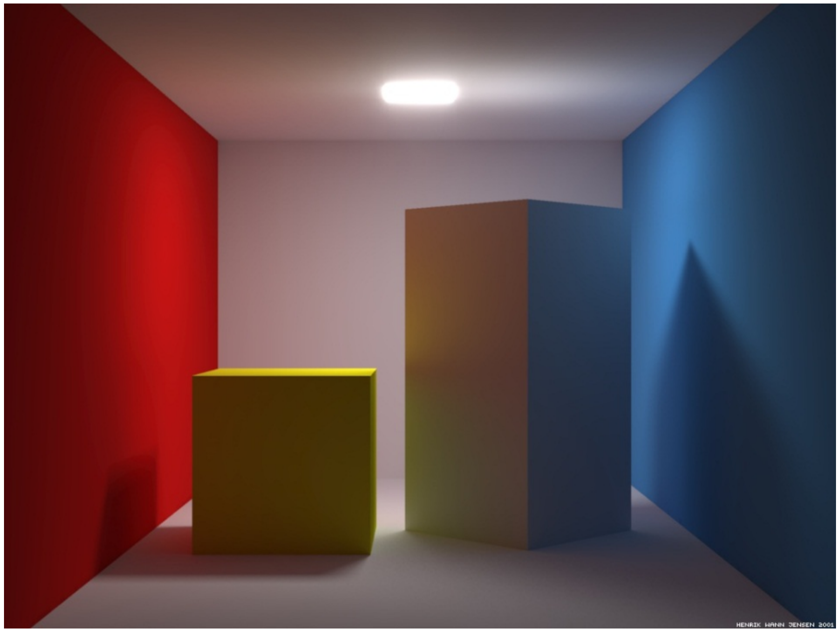
Introduction to Shadows

- Shadows give information on relative positions of objects



Use ambient + diffuse + specular components

Use just ambient component

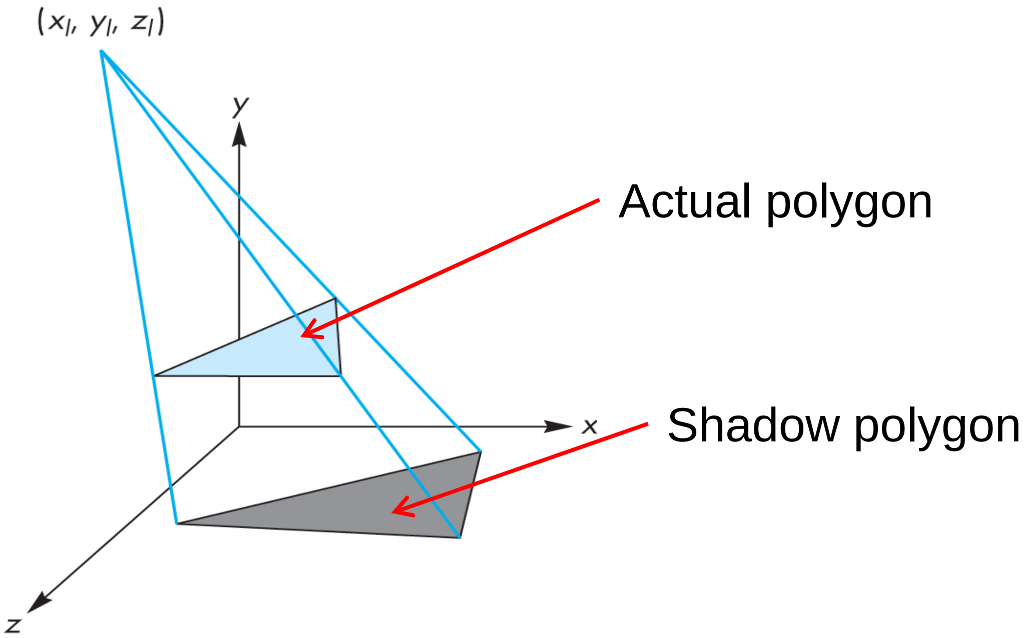


Introduction to Shadows

- Two popular shadow rendering methods:
    1. Shadows as texture (projection)
    2. Shadow buffer
- Third method used in ray-tracing (covered in grad class)

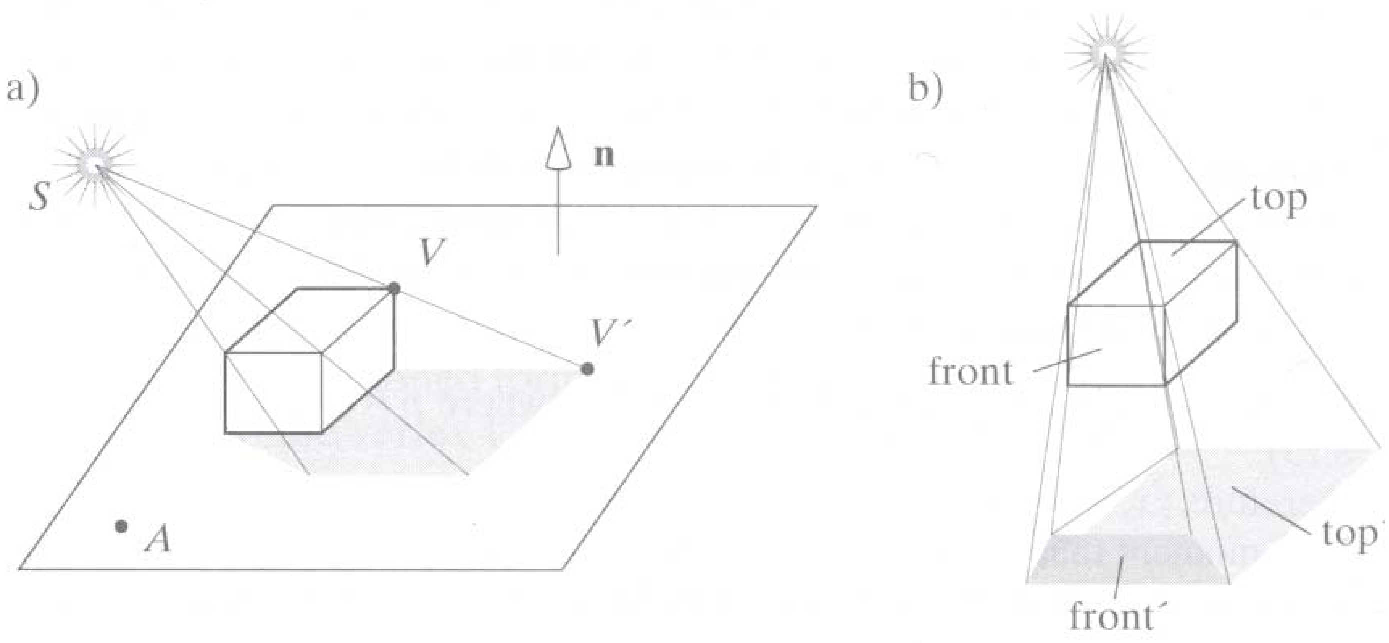
Projective Shadows

- Oldest method: Used in early flight simulators
- Projection of polygon is polygon called **shadow polygon**



Projective Shadows

- Works for flat surfaces illuminated by point light
- For each face, project vertices **V** to find **V’** of shadow polygon
- Object shadow = union of projections of faces

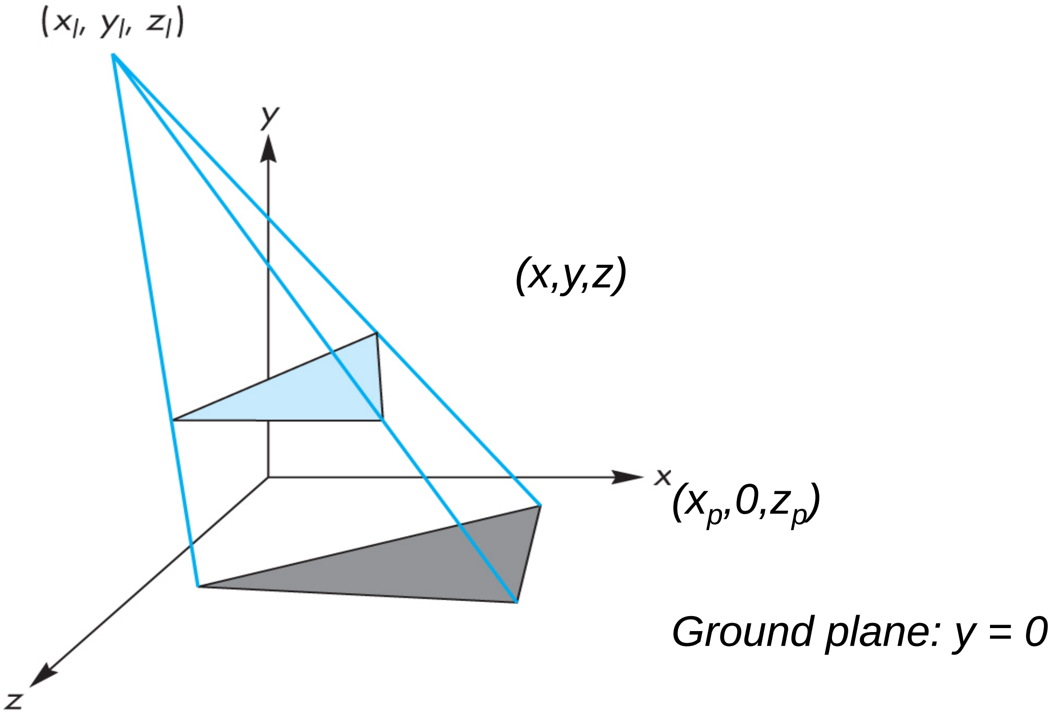


Projective Shadow Algorithm

- Project light-object edges onto plane
- Algorithm:
  - First, draw ground plane/scene using specular+diffuse+ambient components
  - Then, draw shadow projections (face by face) using only ambient component

Projective Shadows for Polygon

1. If light is at (x_l, y_l, z_l)
2. Vertex at (x, y, z)
3. Would like to calculate shadow polygon vertex V projected onto ground at $(x_p, 0, z_p)$

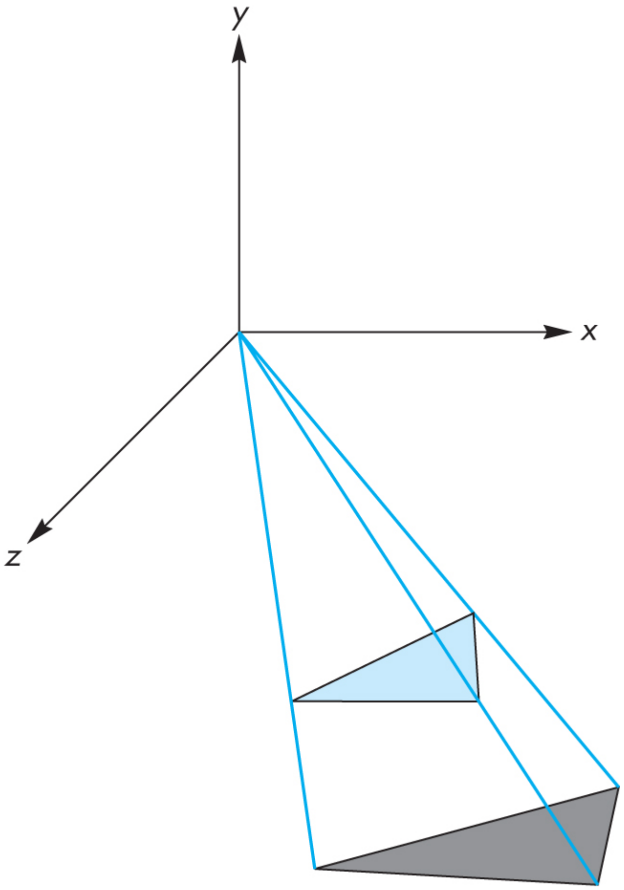


Projective Shadows for Polygon

- If we move original polygon so that light source is at origin
- Matrix *M* projects a vertex V to give

  its projection V’ in shadow polygon

$$m = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & \frac{1}{-y_l} & 0 & 0 \end{bmatrix}$$



Building Shadow Projection Matrix

1. Translate source to origin with T(-x_l, -y_l, -z_l)
2. Perspective projection
3. Translate back by T(x_l, y_l, z_l)

$$M = \begin{bmatrix} 1 & 0 & 0 & x_l \\ 0 & 1 & 0 & y_l \\ 0 & 0 & 1 & z_l \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & \frac{1}{-y_l} & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -x_l \\ 0 & 1 & 0 & -y_l \\ 0 & 0 & 1 & -z_l \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Final matrix that projects
Vertex V onto V’ in shadow polygon

Code snippets?

- Set up projection matrix in OpenGL application

```
float light[3];  // location of light
mat4 m;    // shadow projection matrix initially identity

M[3][1] = -1.0/light[1];
```

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & \dfrac{1}{-y_l} & 0 & 0 \end{bmatrix}$$

Projective Shadow Code

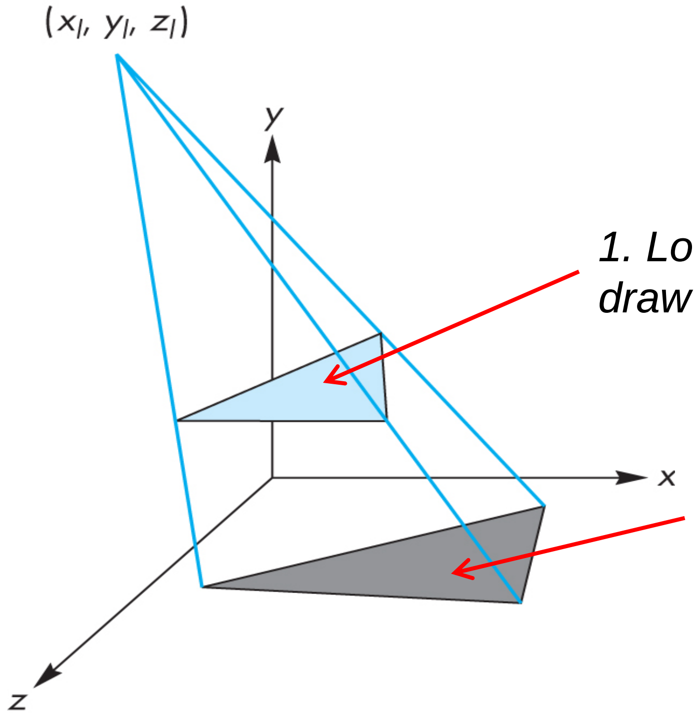
- Set up object (e.g a square) to be drawn

```
point4 square[4] = {vec4(-0.5, 0.5, -0.5, 1.0}
                  {vec4(-0.5, 0.5, -0.5, 1.0}
                  {vec4(-0.5, 0.5, -0.5, 1.0}
                  {vec4(-0.5, 0.5, -0.5, 1.0}
```

- Copy square to VBO
- Pass modelview, projection matrices to vertex shader

What next?

- Next, we load model_view as usual then draw original polygon
- Then load shadow projection matrix, change color to black, re-render polygon



1. Load modelview draw polygon as usual

2. Modify modelview with Shadow projection matrix Re-render as black (or ambient)

Shadow projection Display( ) Function

```
void display( )
{
     mat4 mm;
     // clear the window
     glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);

     // render red square (original square) using modelview
     // matrix as usual (previously set up)
     glUniform4fv(color_loc, 1, red);
     glDrawArrays(GL_TRIANGLE_STRIP, 0, 4);
```

Shadow projection Display( ) Function

```
    // modify modelview matrix to project square
    // and send modified model_view matrix to shader
    mm = model_view
         * Translate(light[0], light[1], light[2]
         *m
         * Translate(-light[0], -light[1], -light[2]);
    glUniformMatrix4fv(matrix_loc, 1, GL_TRUE, mm);

    //and re-render square as
    // black square (or using only ambient component)
     glUniform4fv(color_loc, 1, black);
     glDrawArrays(GL_TRIANGLE_STRIP, 0, 4);
     glutSwapBuffers( );
}
```

$$M = \begin{bmatrix} 1 & 0 & 0 & x_l \\ 0 & 1 & 0 & y_l \\ 0 & 0 & 1 & z_l \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & \frac{1}{-y_l} & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -x_l \\ 0 & 1 & 0 & -y_l \\ 0 & 0 & 1 & -z_l \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

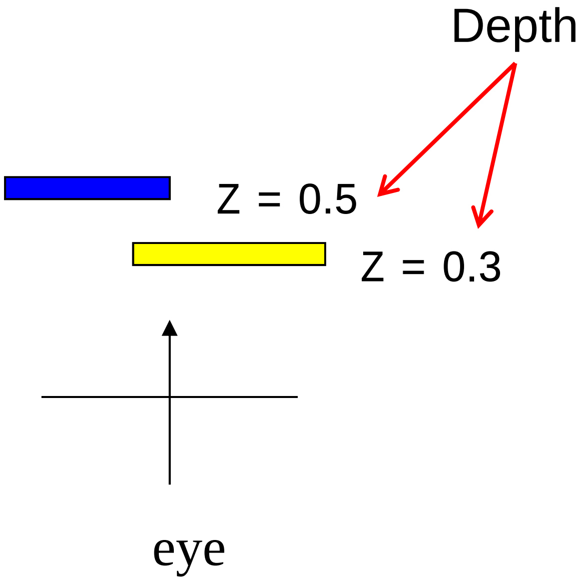
Shadow Buffer Approach

- Uses second depth buffer called **shadow buffer**
- Pros: not limited to plane surfaces
- Cons: needs lots of memory
- Depth buffer?

OpenGL Depth Buffer (Z Buffer)

- **Depth:** While drawing objects, depth buffer stores distance of each polygon from viewer
- **Why?** If multiple polygons overlap a pixel, only closest one polygon is drawn

1.0	1.0	1.0	1.0
1.0	0.3	0.3	1.0
0.5	0.3	0.3	1.0
0.5	0.5	1.0	1.0



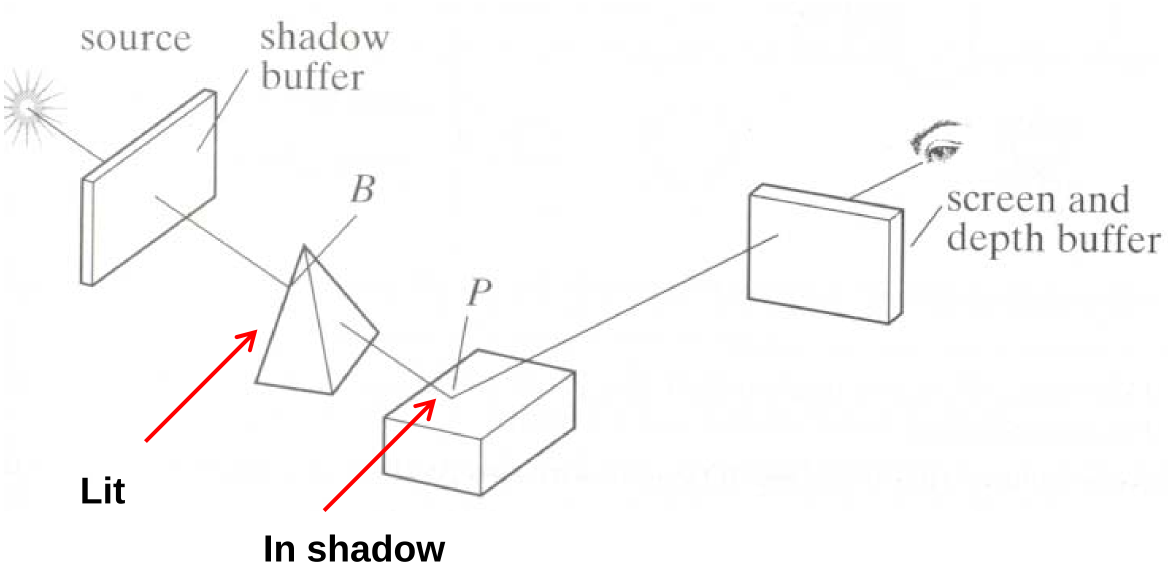
Setting up OpenGL Depth Buffer

- **Note:** You did this in order to draw solid cube, meshes

1. `glutInitDisplayMode(GLUT_DEPTH | GLUT_RGB)` instructs openGL to create depth buffer
2. `glEnable(GL_DEPTH_TEST)` enables depth testing
3. `glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT)` Initializes depth buffer every time we draw a new picture

Shadow Buffer Theory

- Along each path from light
  - Only closest object is lit
  - Other objects on that path in shadow
- Shadow buffer stores closest object on each path

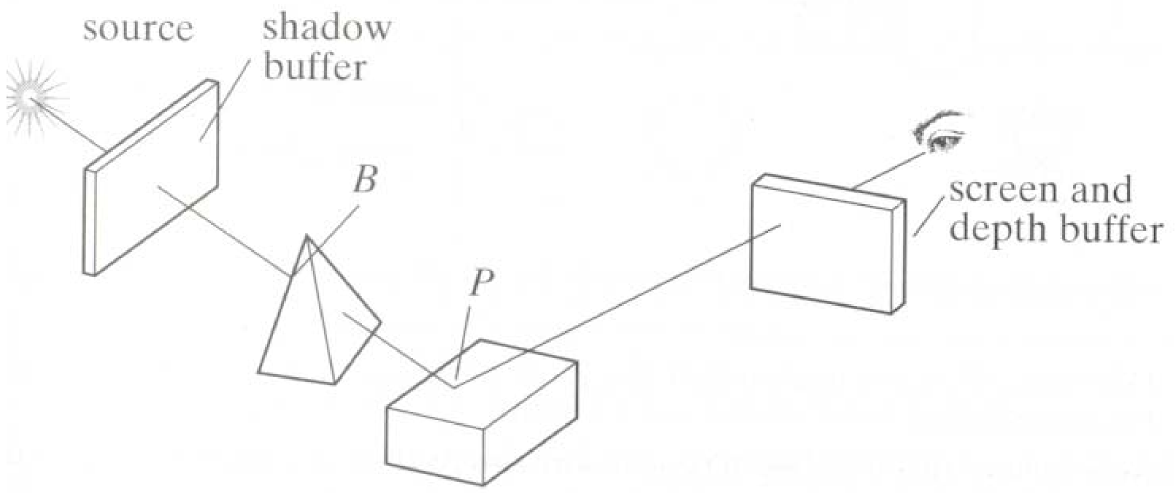


Shadow Buffer Approach

- Rendering in two stages:
    - Loading shadow buffer
    - Render the scene

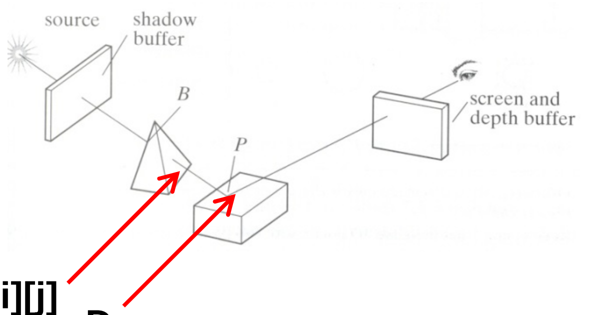
Loading Shadow Buffer

- Initialize each element to 1.0
- Position a camera at light source
- Rasterize each face in scene updating closest object
- Shadow buffer tracks smallest depth on each path



Shadow Buffer (Rendering Scene)

- Render scene using camera as usual
- While rendering a pixel find:
  - pseudo-depth D from light source to P
  - Index location [i][j] in shadow buffer, to be tested
  - Value d[i][j] stored in shadow buffer
- If d[i][j] < D (other object on this path closer to light)
  - point P is in shadow
  - lighting = ambient
- Otherwise, not in shadow
  - Lighting = amb + diffuse + specular



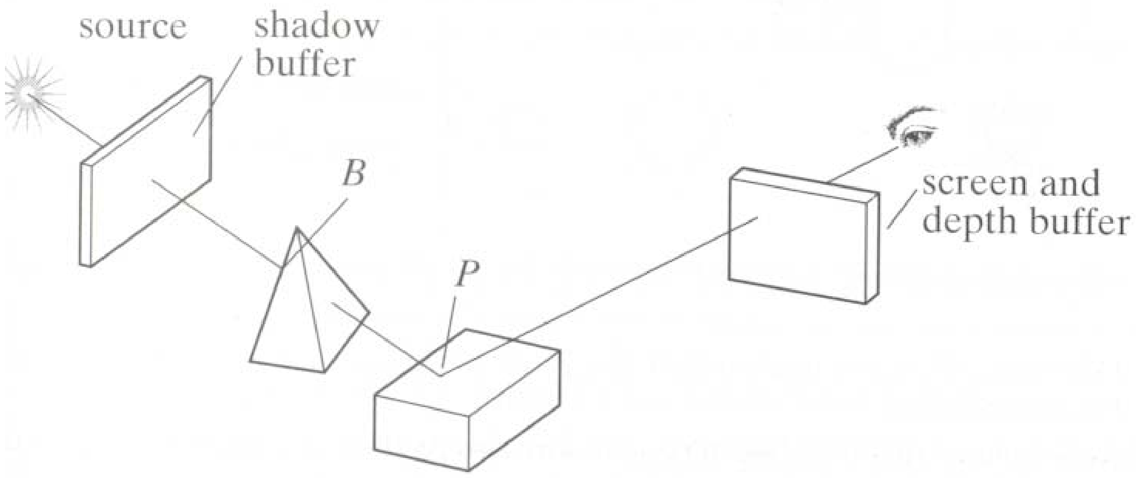
D[i][j]

D

In shadow

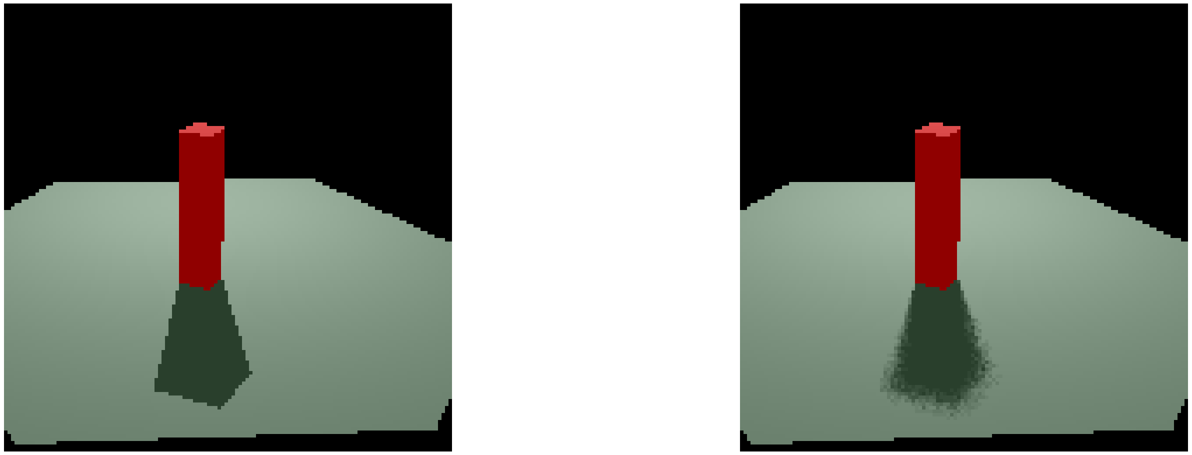
Loading Shadow Buffer

- Shadow buffer calculation is independent of eye position
- In animations, shadow buffer loaded once
- If eye moves, no need for recalculation
- If objects move, recalculation required

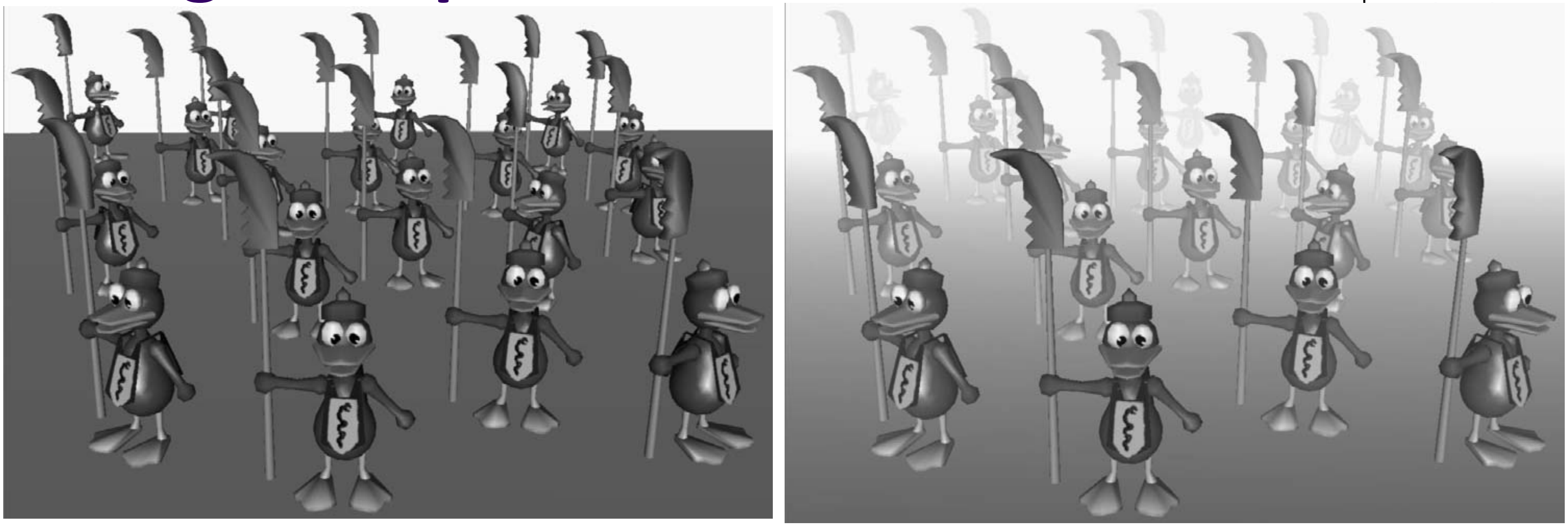


Soft Shadows

- Point light sources => simple hard shadows, unrealistic
- Extended light sources => more realistic
- Shadow has two parts:
  - Umbra (Inner part) => no light
  - Penumbra (outer part) => some light



Fog example



- Fog is atmospheric effect
  - Better realism, helps determine distances

Fog

- Fog was part of OpenGL fixed function pipeline
- Programming fixed function fog
  - **Parameters:** Choose fog color, fog model
  - **Enable:** Turn it on
- Fixed function fog **deprecated!!**
- Shaders can implement even better fog
- **Shaders implementation:** fog applied in fragment shader just before display

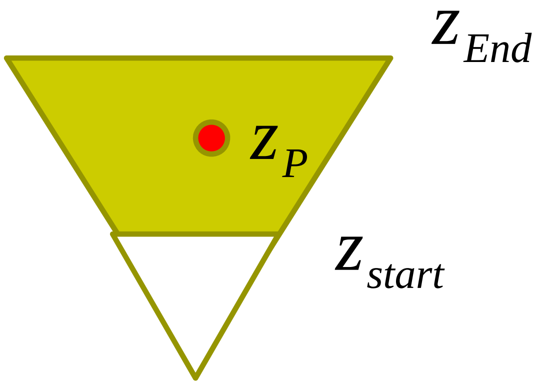
Rendering Fog

- Mix some color of fog: $\mathbf{c}_f$ + color of surface: $\mathbf{c}_s$

$$\mathbf{c}_p = f\mathbf{c}_f + (1-f)\mathbf{c}_s \qquad f \in [0,1]$$

- If *f = 0.25*, output color = 25% fog + 75% surface color
  - *f* computed as function of distance *z*
  - 3 ways: linear, exponential, exponential-squared
  - Linear:

$$f = \frac{z_{end} - z_p}{z_{end} - z_{start}}$$



Fog Shader Fragment Shader Example

$$f = \frac{z_{end} - z_p}{z_{end} - z_{start}}$$

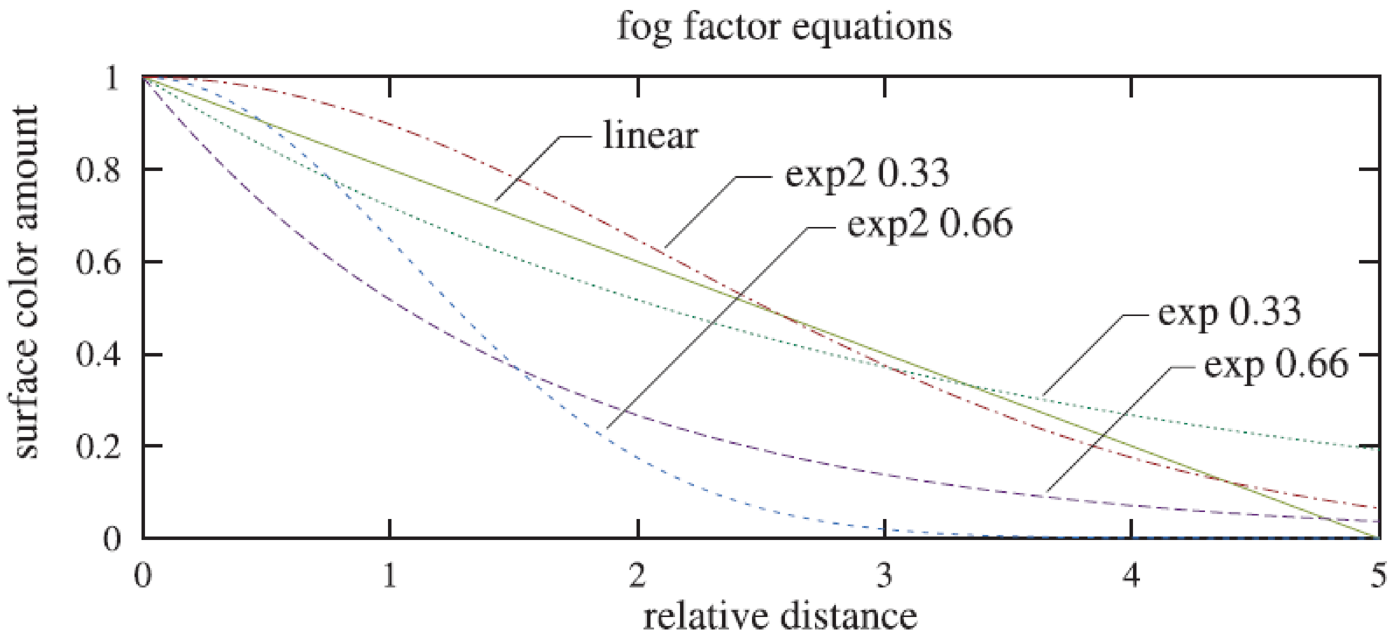
```
float dist = abs(Position.z);
Float fogFactor = (Fog.maxDist – dist)/
                            Fog.maxDist – Fog.minDist);
fogFactor = clamp(fogFactor, 0.0, 1.0);

vec3 shadeColor = ambient + diffuse + specular
vec3 color = mix(Fog.color, shadeColor,fogFactor);
FragColor = vec4(color, 1.0);
```

$$\mathbf{c}_p = f\mathbf{c}_f + (1 - f)\mathbf{c}_s$$

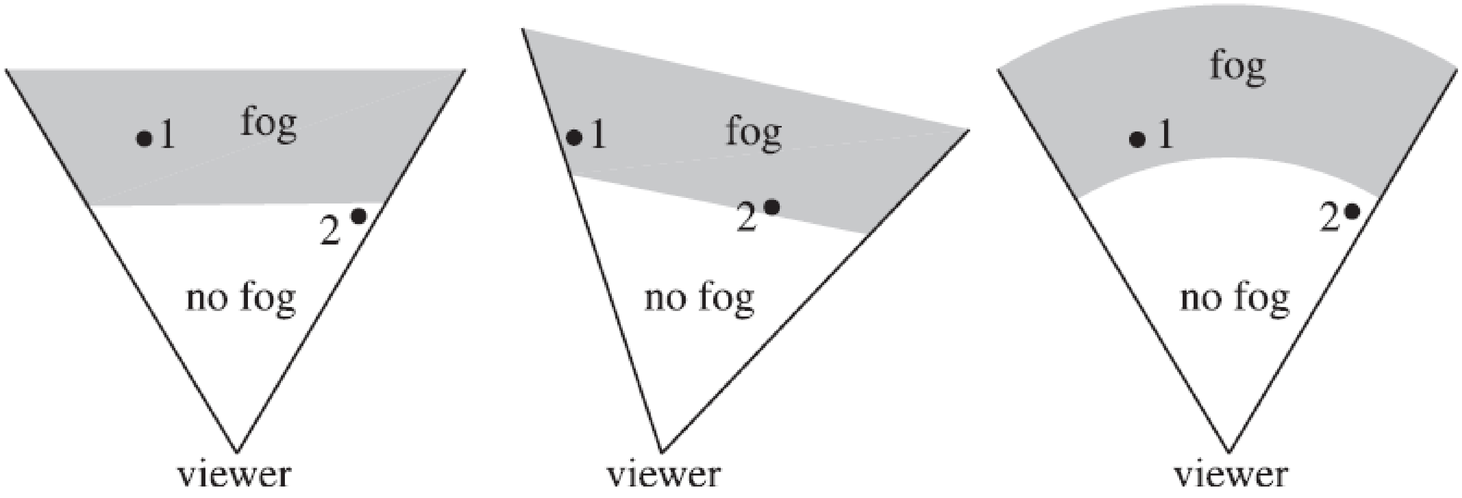
Fog

- Exponential $f = e^{-d_f z_p}$
- Squared exponential $f = e^{-(d_f z_p)^2}$
- Exponential derived from Beer's law
  - **Beer's law:** intensity of outgoing light diminishes exponentially with distance



Fog Optimizations

- *f* values for different depths (z_P)can be pre-computed and stored in a table on GPU
- Distances used in *f* calculations are planar
- Can also use Euclidean distance from viewer or radial distance to create ***radial fog***



References

- Interactive Computer Graphics (6th edition), Angel and Shreiner
- Computer Graphics using OpenGL (3rd edition), Hill and Kelley
- Real Time Rendering by Akenine-Moller, Haines and Hoffman