CSE 5542 - Real Time Rendering
Week 11, 12, 13,14

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Texture Mapping

Courtesy: Ed Angel

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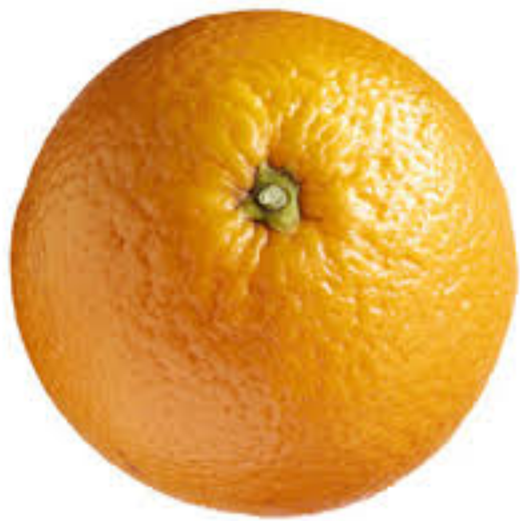
Limits of Geometric Modeling

Millions of Polygons/Second

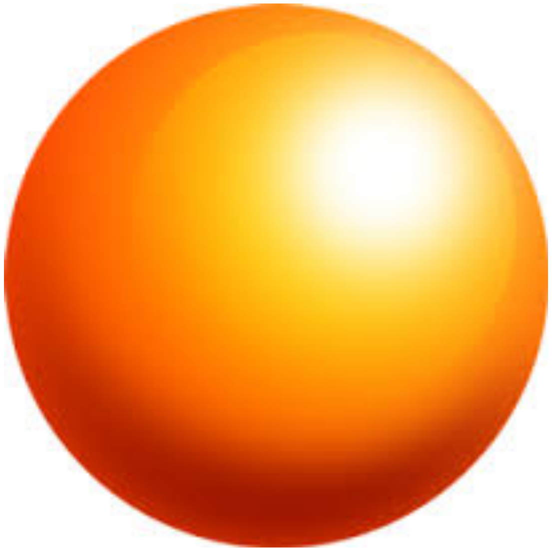
Cannot Do

Use Textures

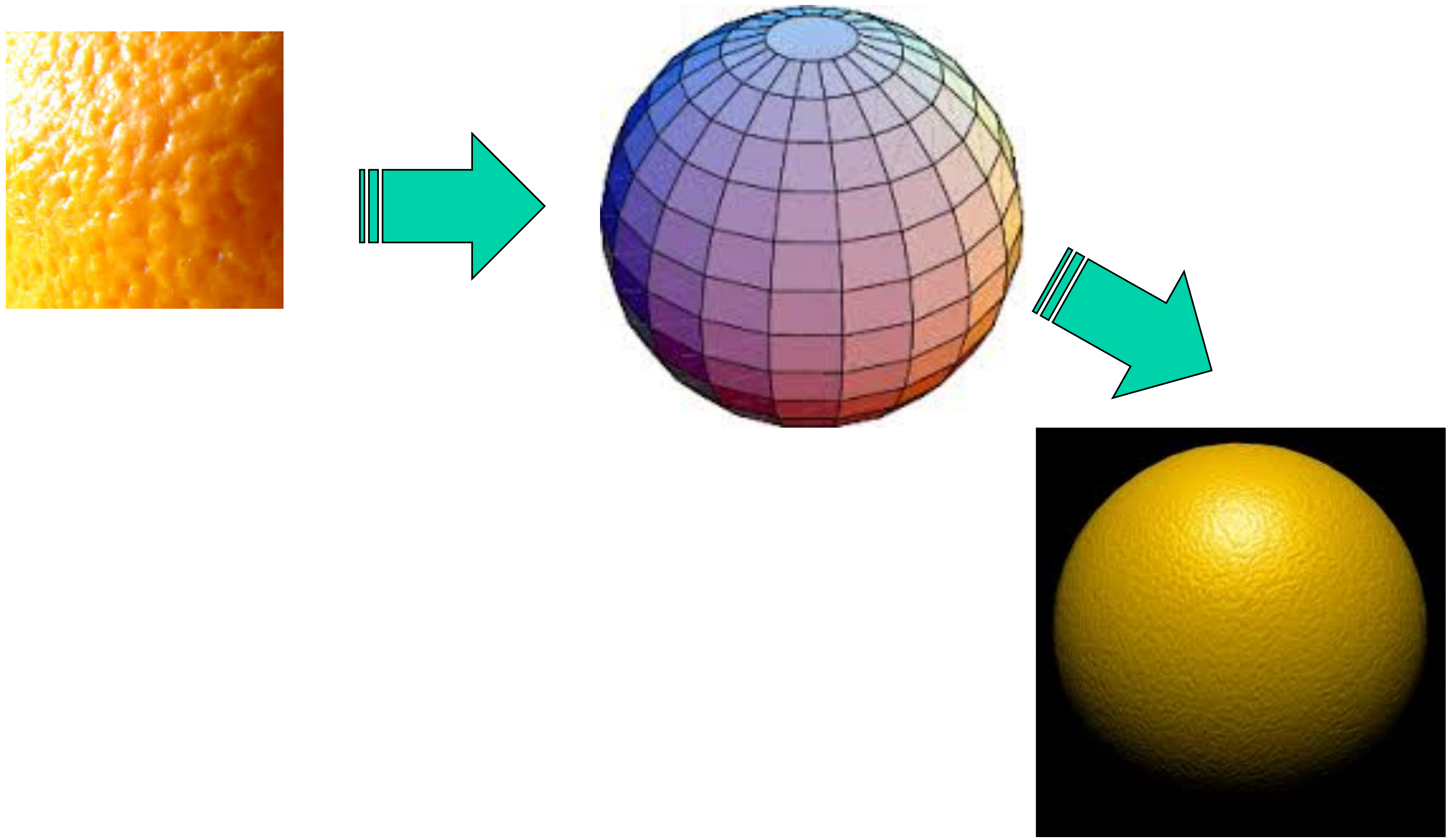
Orange



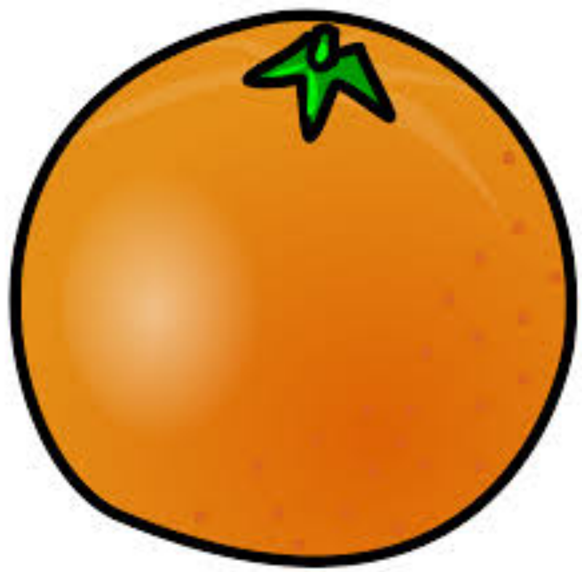
Orange Spheres



Texture Mapping

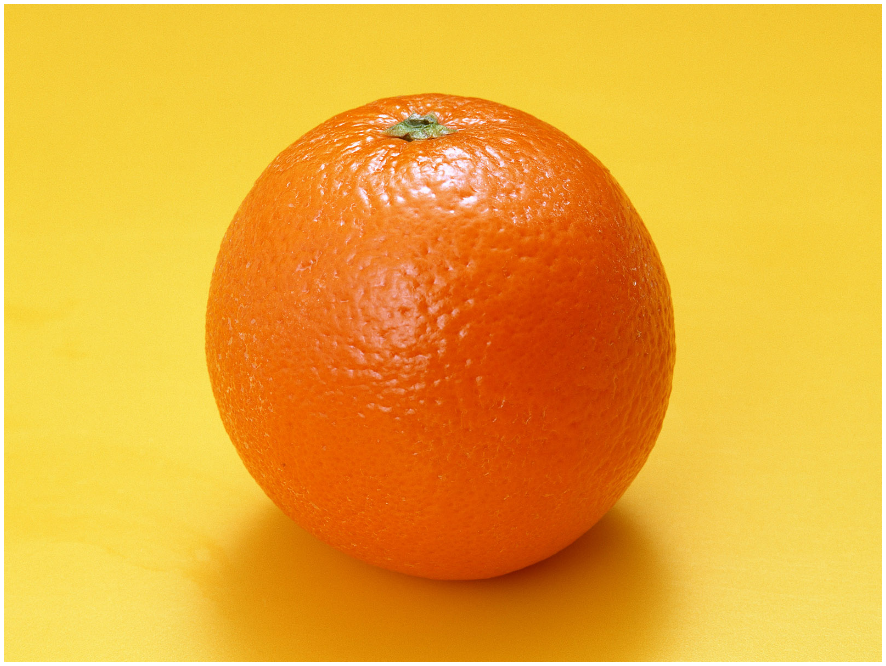


Looking Better

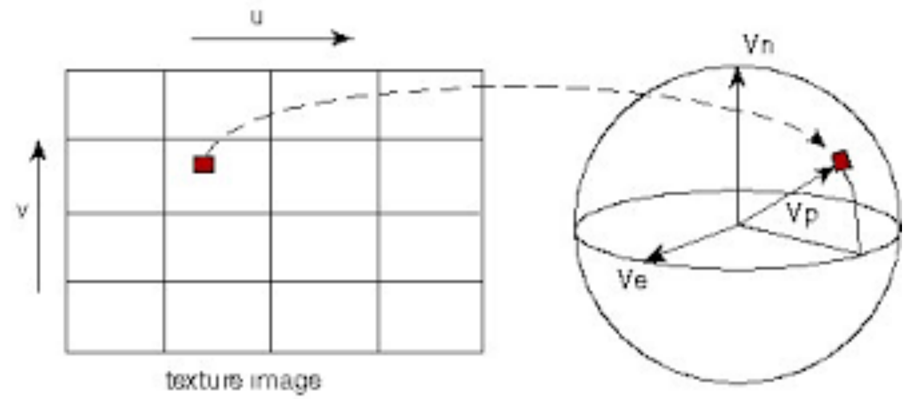


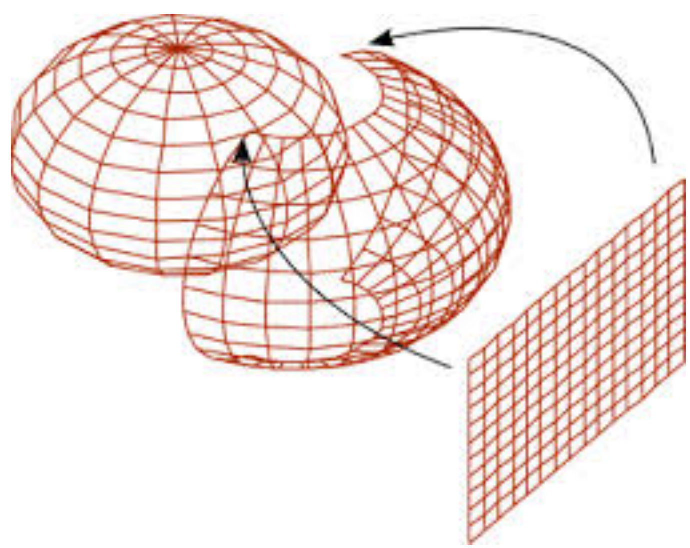
Still Not Enough

Local Variation

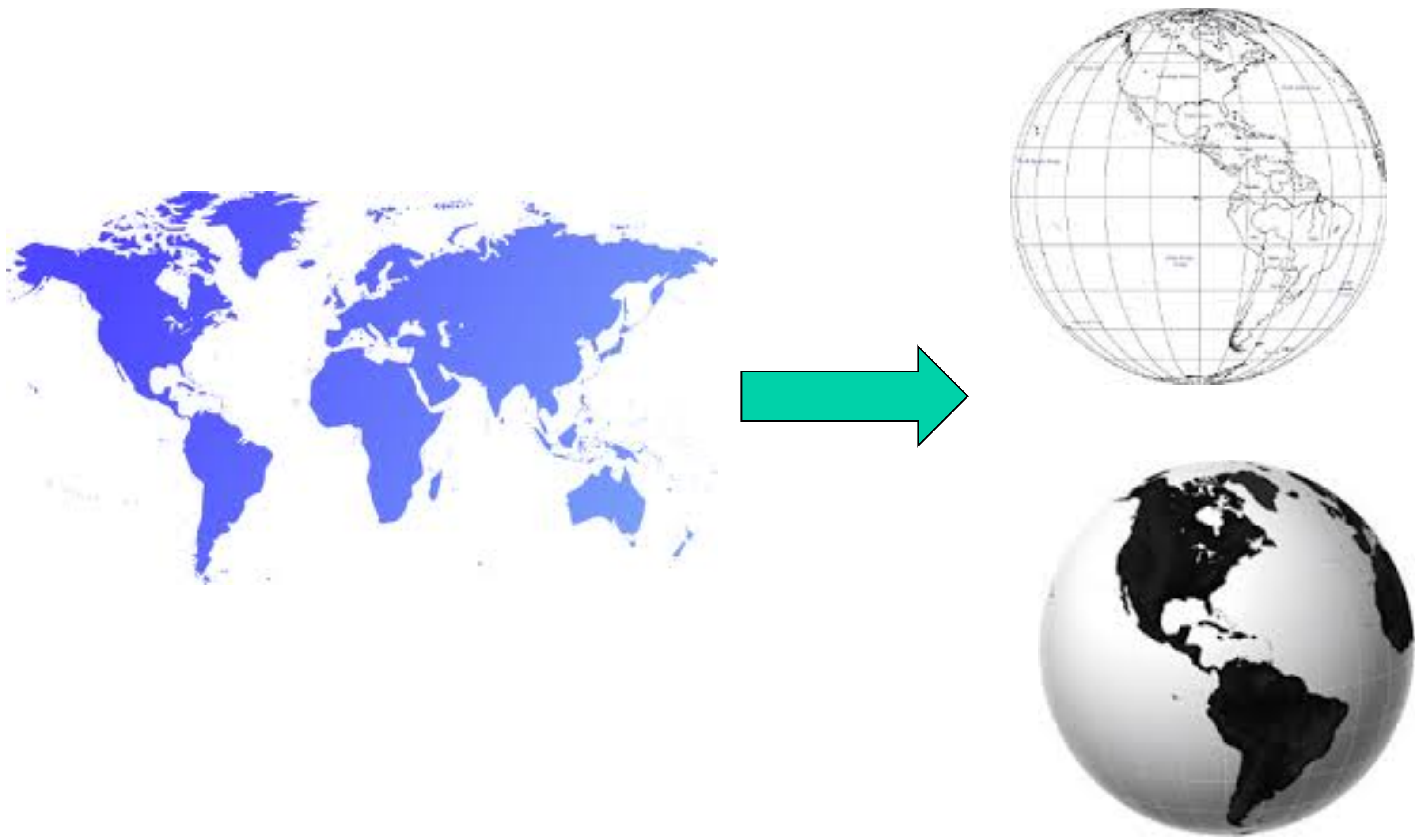


Texture Mapping

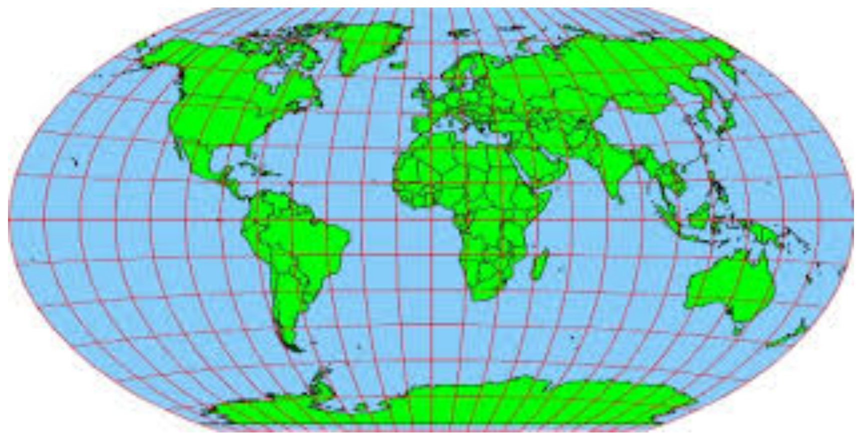




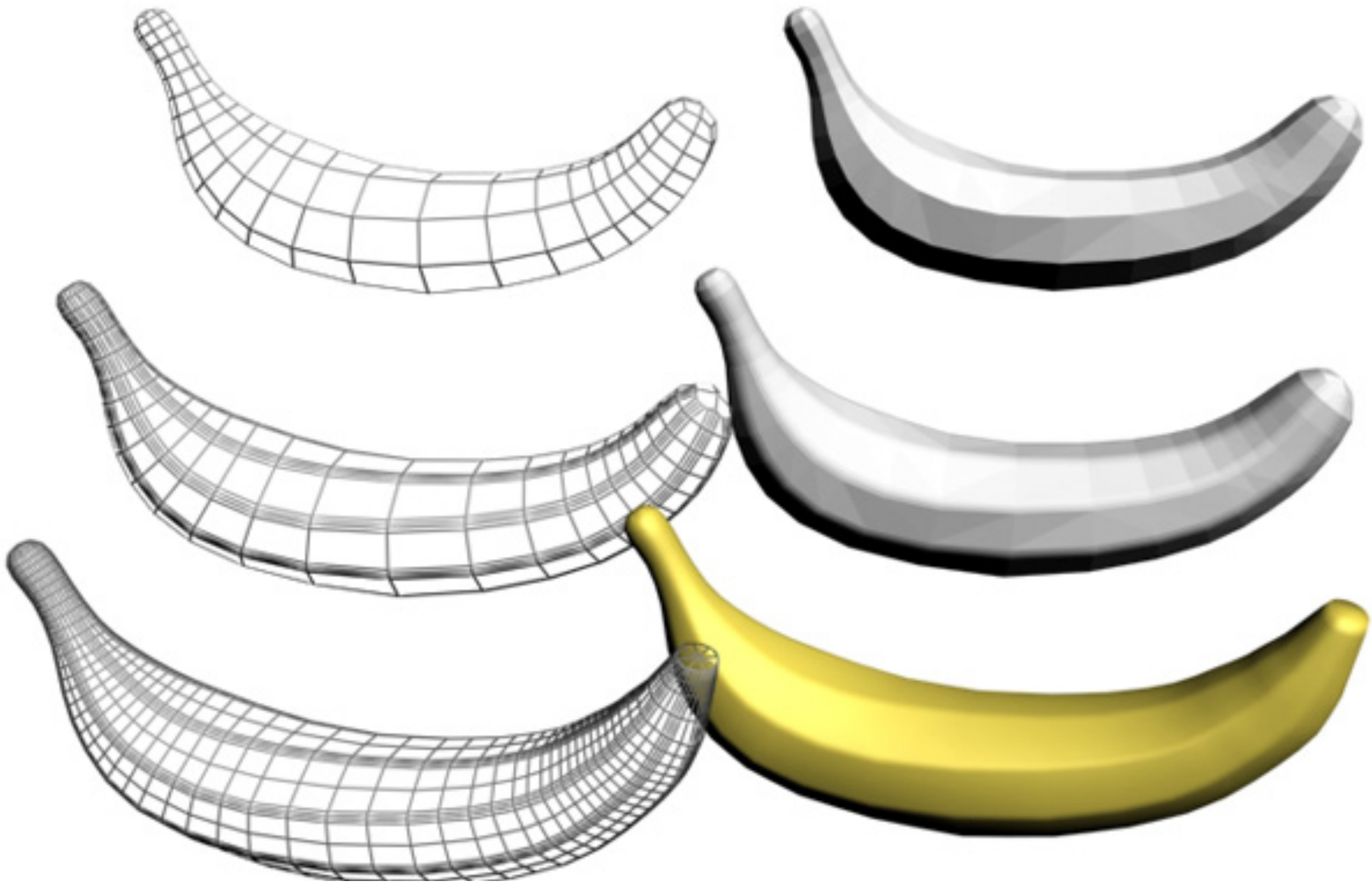
Globe



Not Mercator



Yet Another Fruit

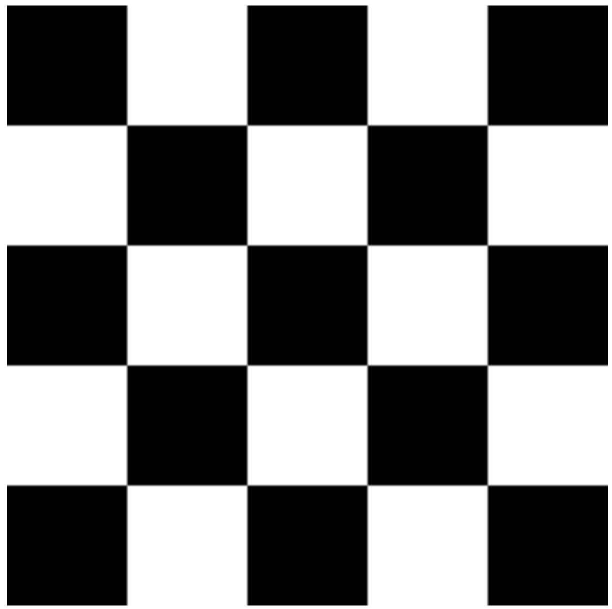


Three Types of Mapping

Generating Textures

Pictures

Algorithms

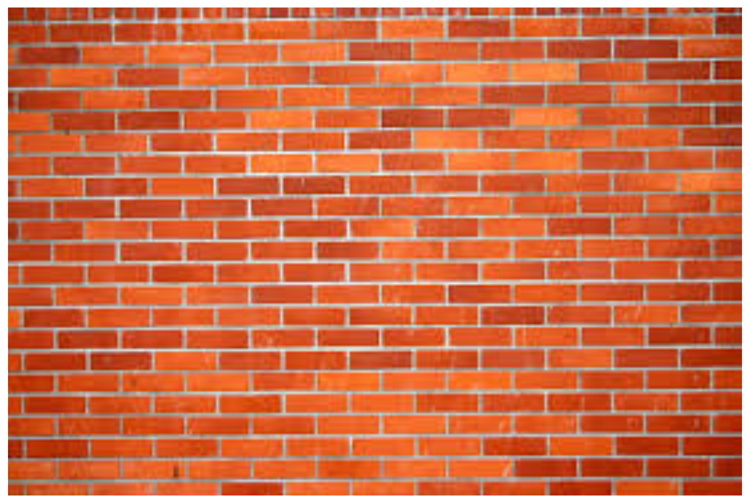


Checkerboard Texture

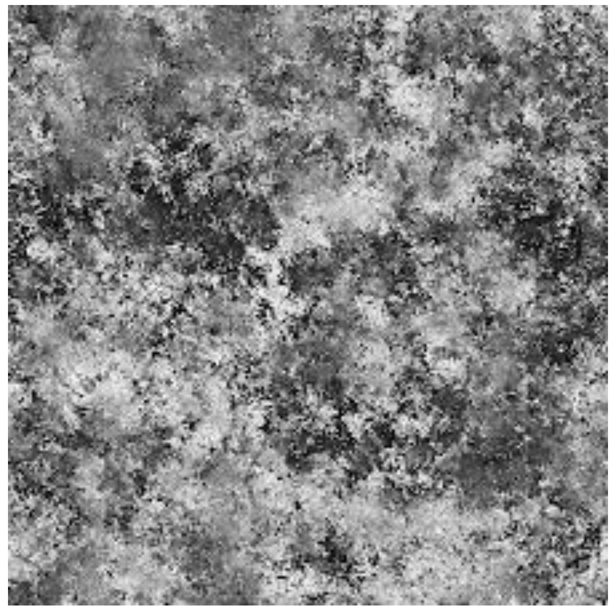
```
GLubyte image[64][64][3];

// Create a  64 x 64 checkerboard pattern
    for ( int i = 0; i < 64; i++ ) {
        for ( int j = 0; j < 64; j++ ) {
            GLubyte c = (((i & 0x8) == 0) ^ ((j & 0x8)  == 0)) * 255;
            image[i][j][0]  = c;
            image[i][j][1]  = c;
            image[i][j][2]  = c;
```

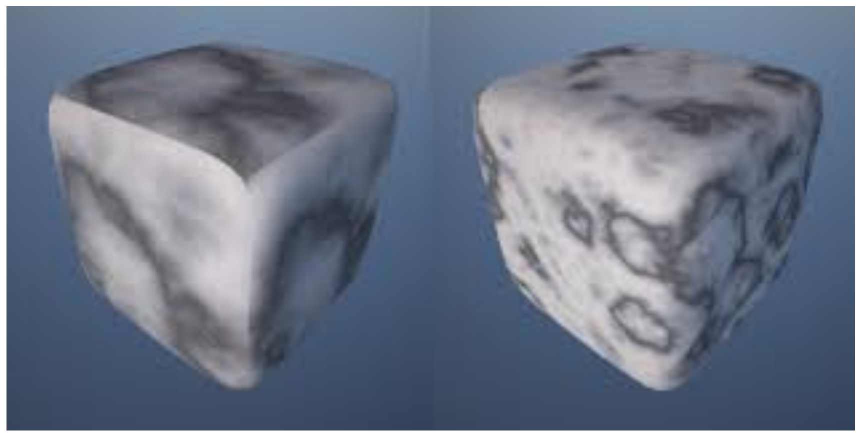
Brick Wall



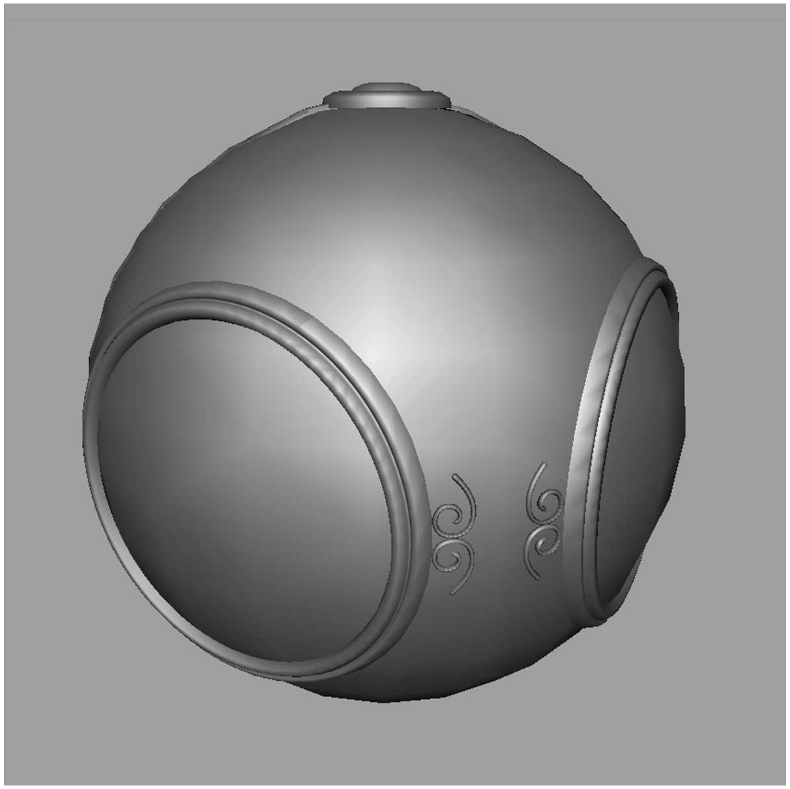
Noise



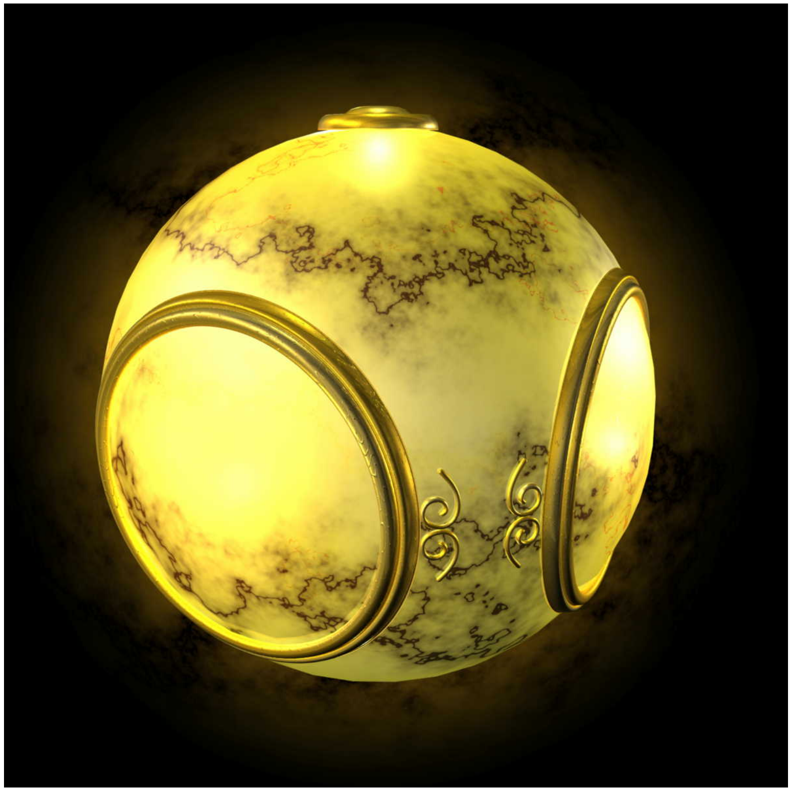
Marble



Texture Mapping



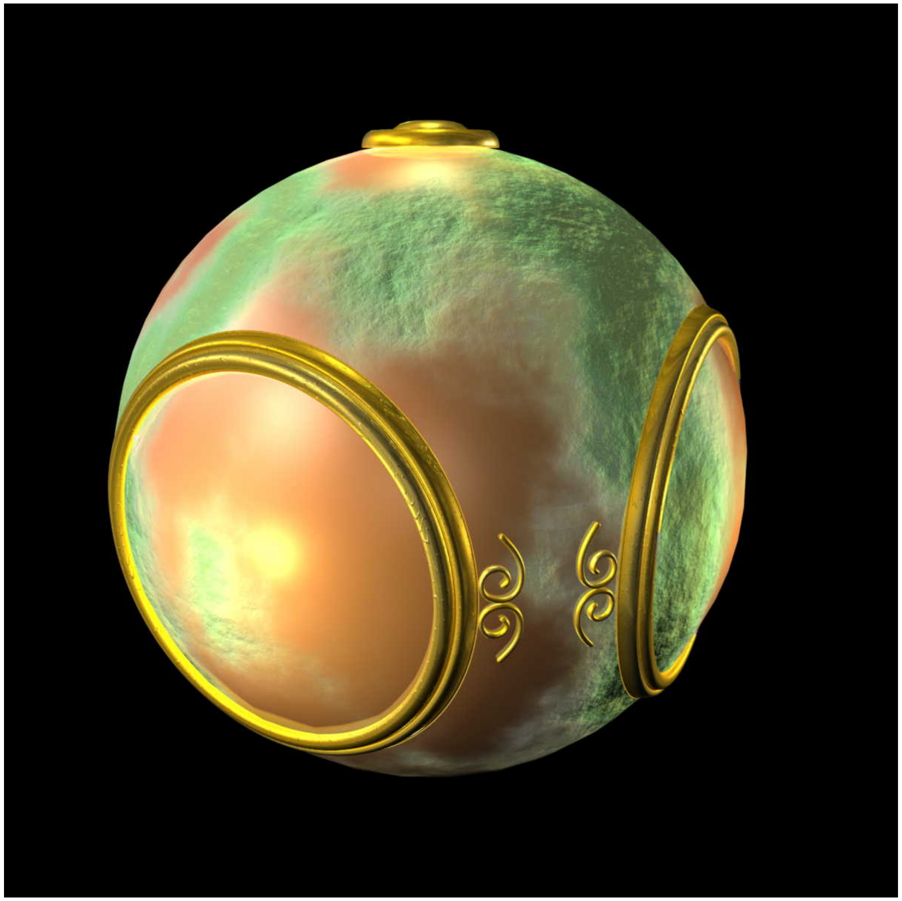
geometric model



texture mapped

Environment Mapping

Bump Mapping



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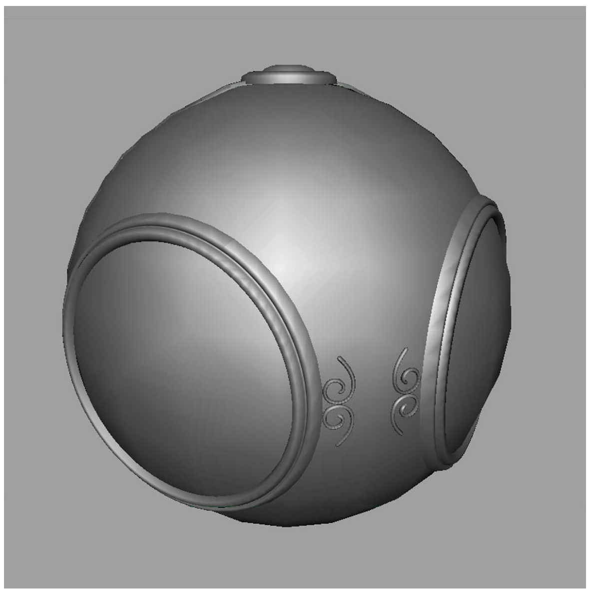
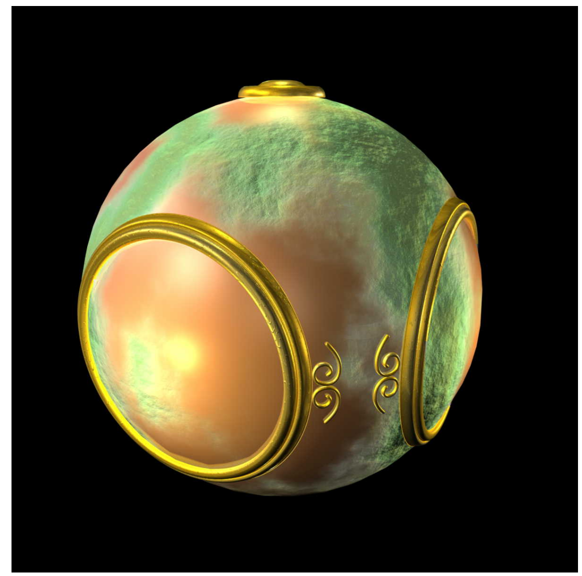
Three Types

Texture mapping



smooth shading

environment mapping

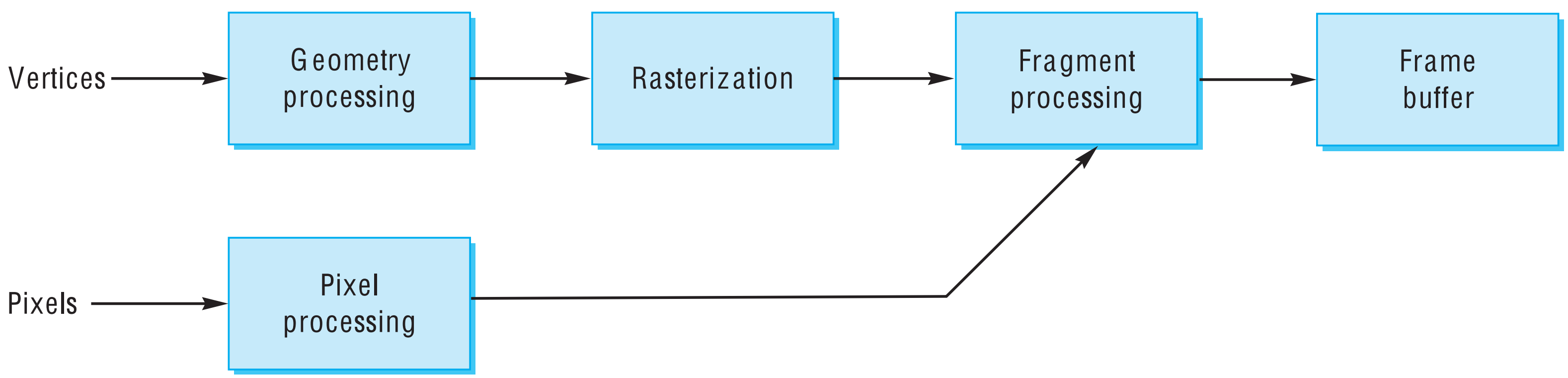


bump mapping

Texture Mapping - Pipeline

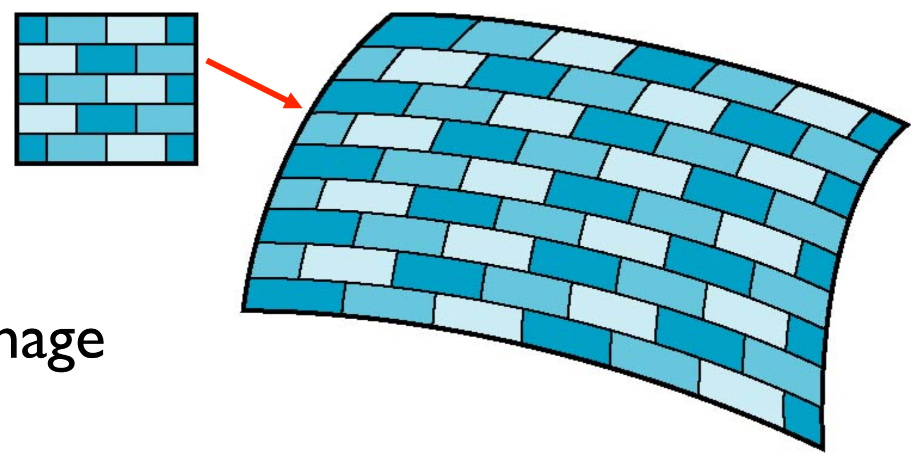
Mapping techniques are implemented at the end of the rendering pipeline

– Very efficient because few polygons make it past the clipper

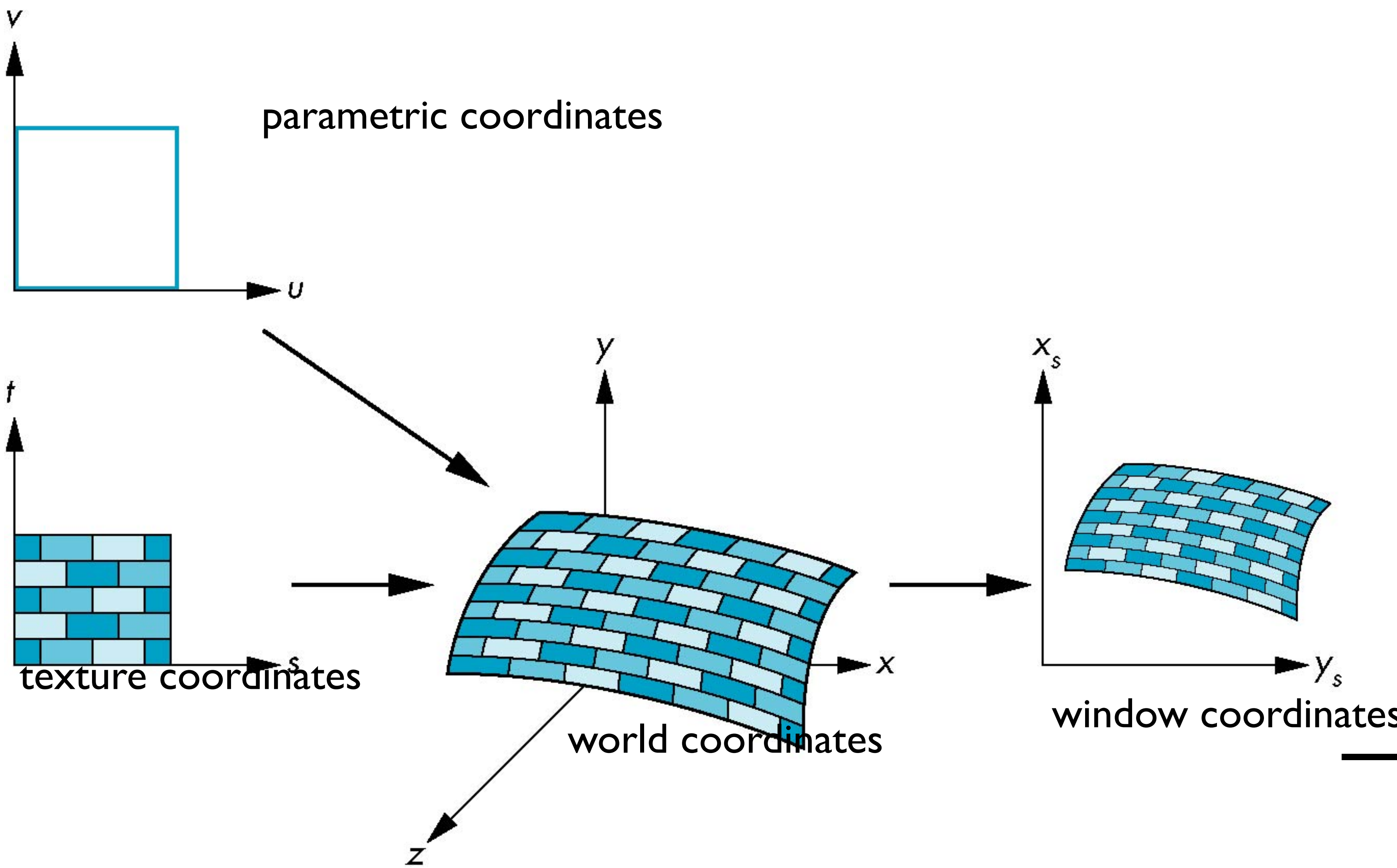


Mapping Mechanics

3 or 4 coordinate systems involved



Texture Mapping



Coordinate Systems

- Parametric coordinates
  - Model curves and surfaces
- Texture coordinates
  - Identify points in image to be mapped
- Object or World Coordinates
  - Conceptually, where the mapping takes place
- Screen Coordinates
  - Where the final image is really produced

Mapping Functions

Mapping from texture coords to point on surface

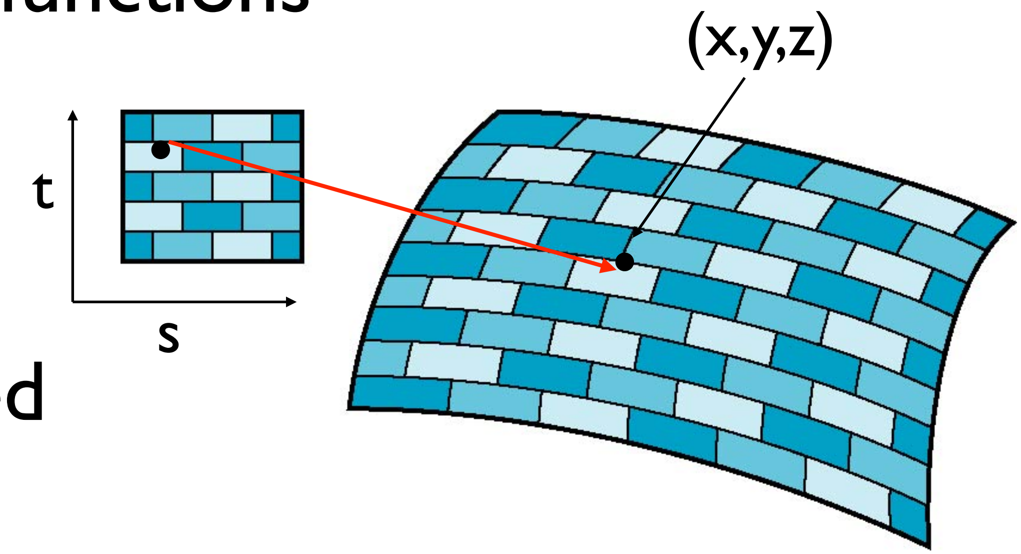
- Appear to need three functions

  x = x(s,t)

  y = y(s,t)

  z = z(s,t)

- Other direction needed



Backward Mapping

Mechanics

– Given a pixel want point on object it corresponds
– Given point on object want point in the texture it corresponds

Need a map of the form

$s = s(x,y,z)$

$t = t(x,y,z)$

Such functions are difficult to find in general

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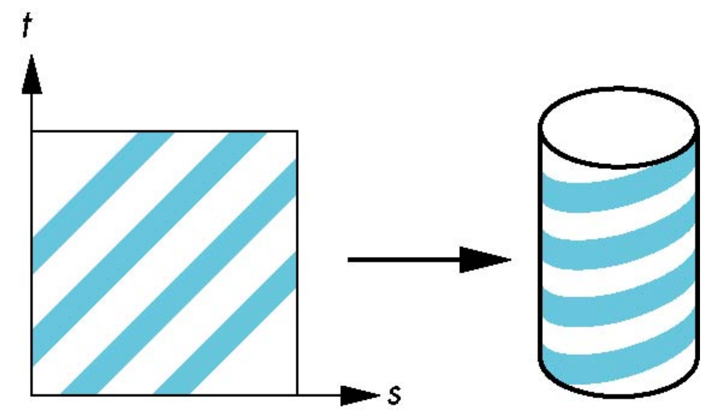
Two-part mapping

- First map texture to a simple intermediate surface

- Map to cylinder



Cylindrical Mapping

parametric cylinder

$$x = r \cos 2\pi\, u$$
$$y = r \sin 2\pi u$$
$$z = v/h$$

maps rectangle in u,v space to cylinder
of radius r and height h in world coordinates

$$s = u$$
$$t = v$$

maps from texture space

Spherical Map

We can use a parametric sphere

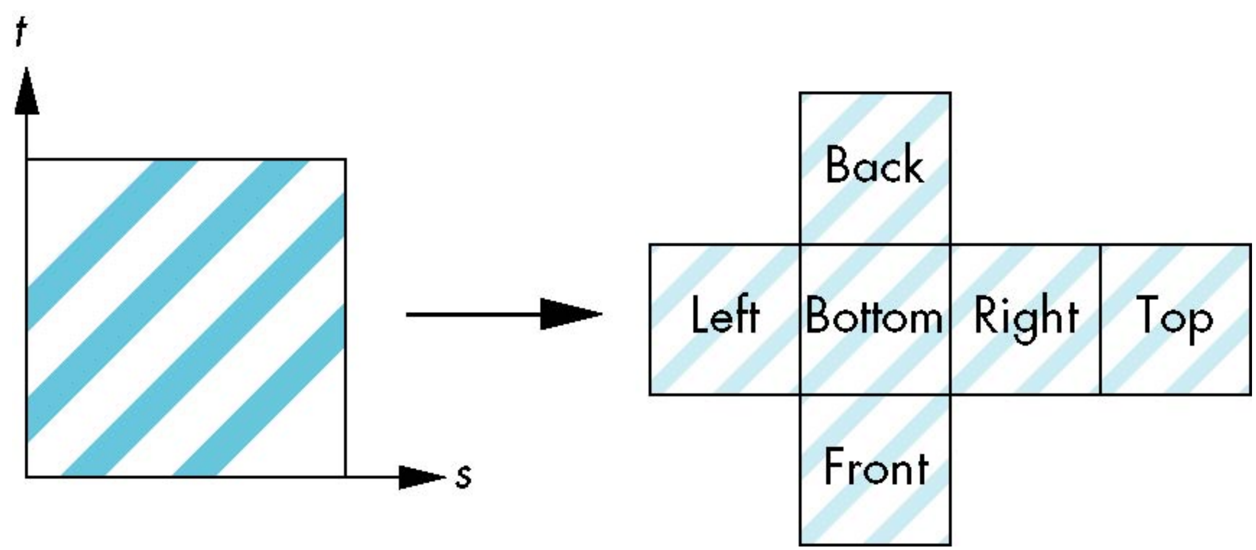
$$x = r \cos 2\pi u$$
$$y = r \sin 2\pi u \cos 2\pi v$$
$$z = r \sin 2\pi u \sin 2\pi v$$

in a similar manner to the cylinder
but have to decide where to put
the distortion

Spheres are used in environmental maps

Box Mapping

- Easy to use with simple orthographic projection
- Also used in environment maps



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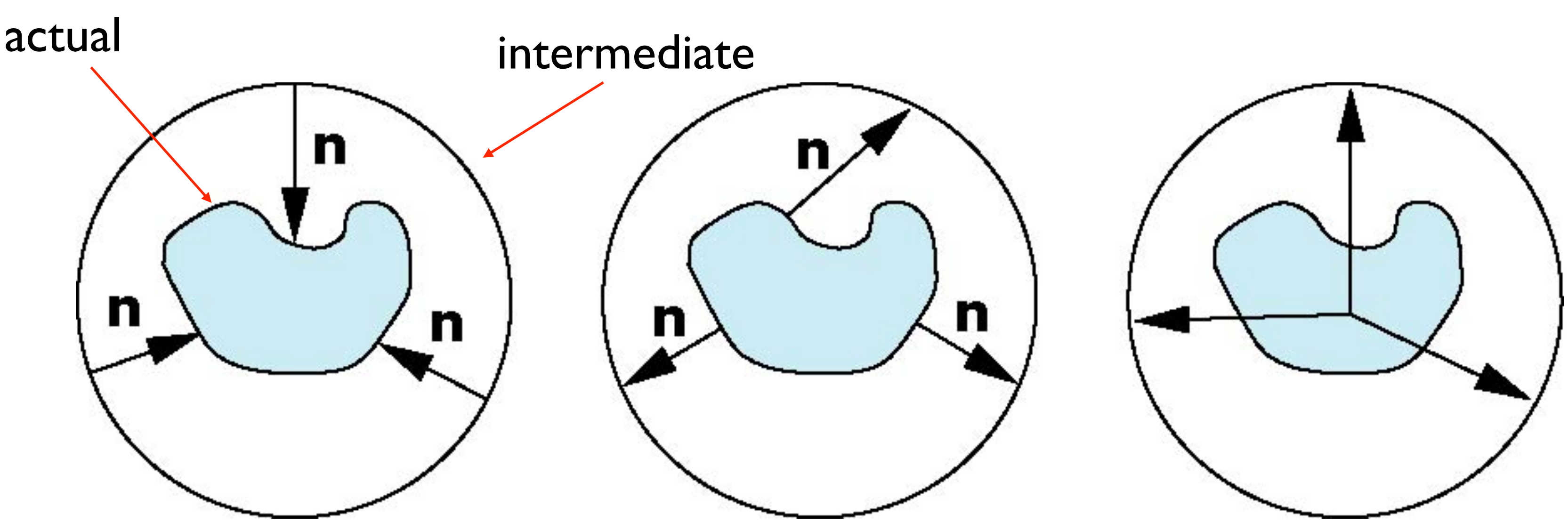
Second Mapping

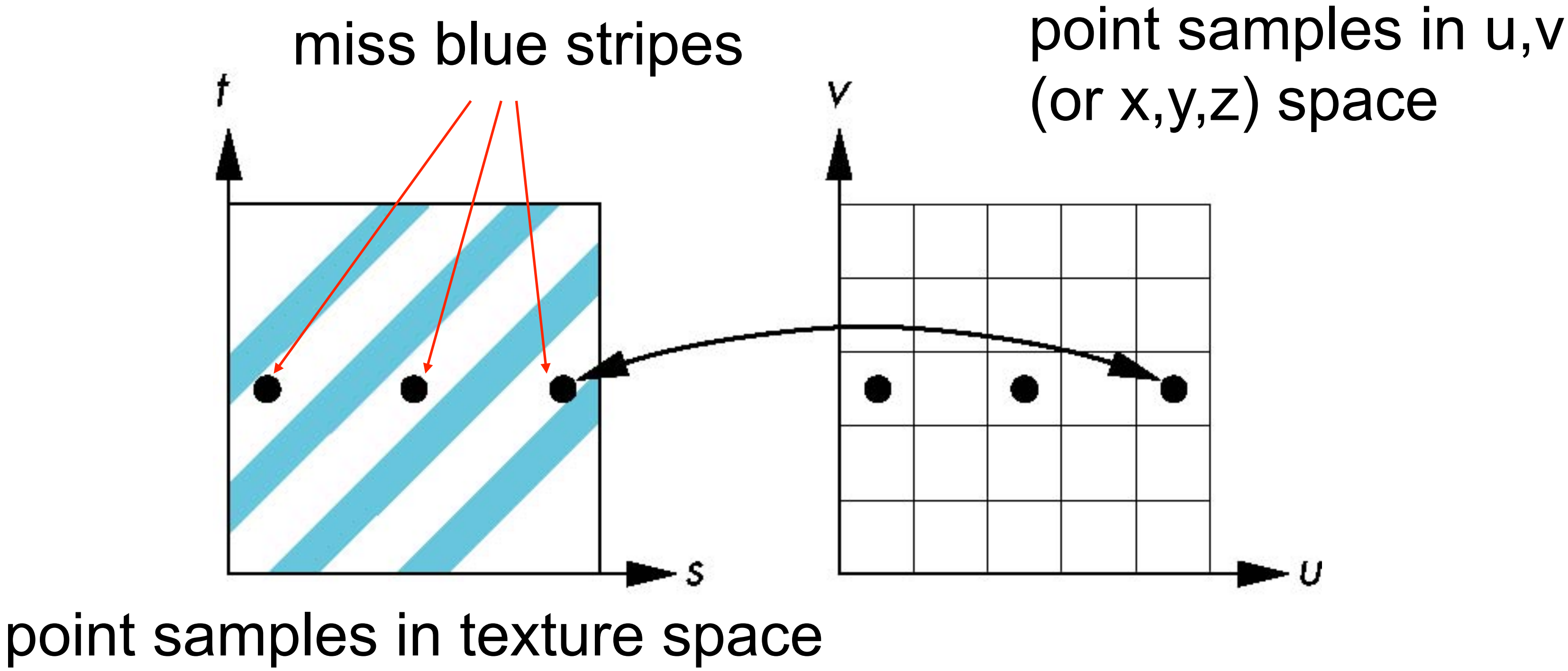
Map from intermediate object to actual object

- Normals from intermediate to actual
- Normals from actual to intermediate
- Vectors from center of intermediate



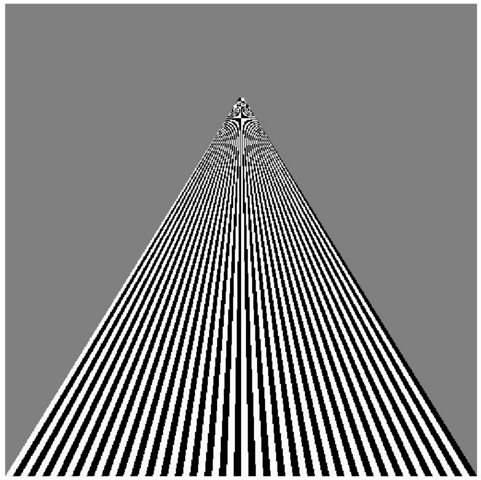
Aliasing

Point sampling of texture leads to aliasing errors

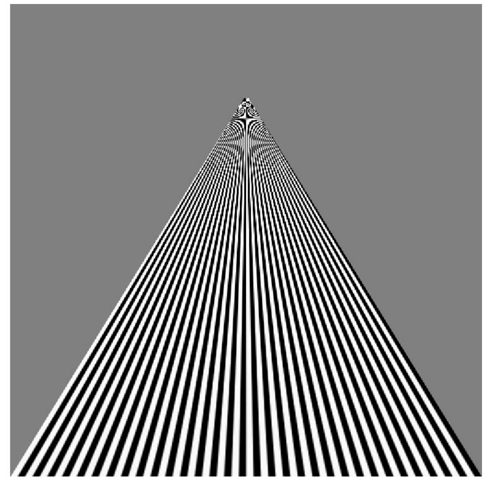


Anti-Aliasing in Textures

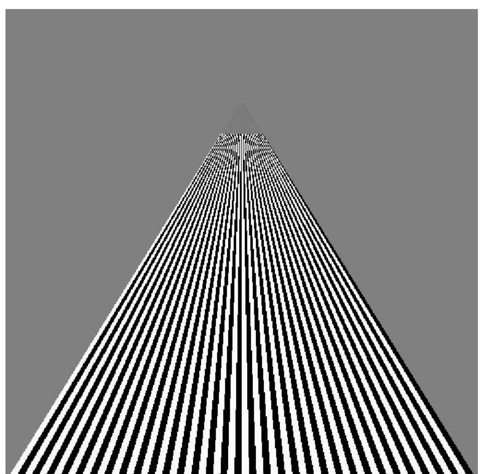
point sampling



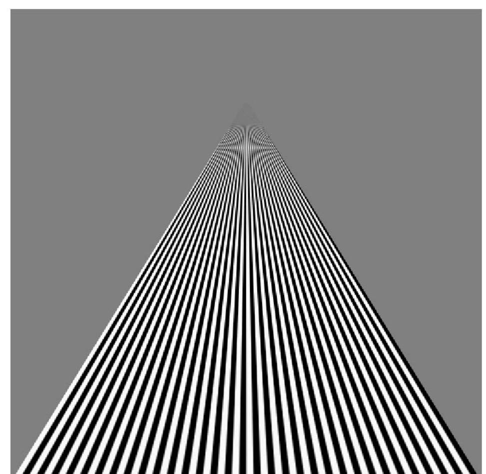
linear filtering



mipmapped point sampling



mipmapped linear filtering



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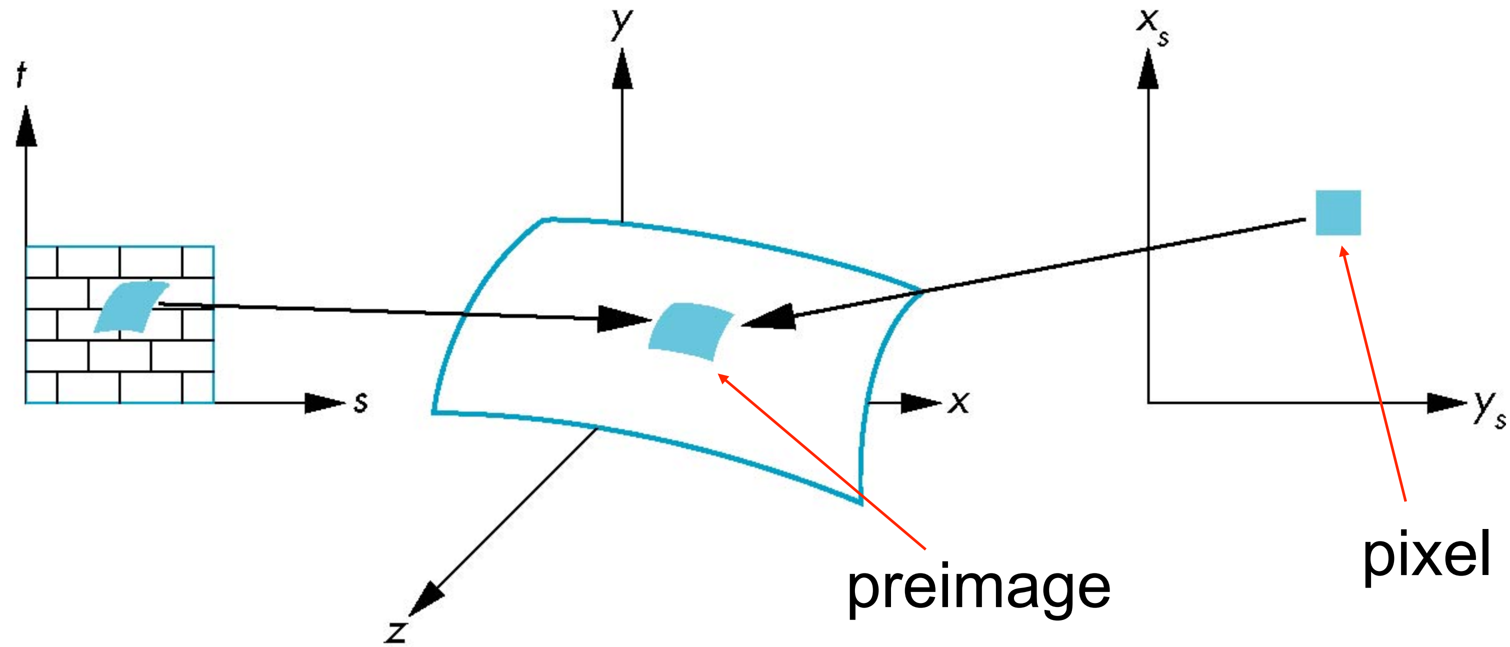
Area Averaging

A better but slower option is to use *area averaging*



Note that *preimage* of pixel is curved

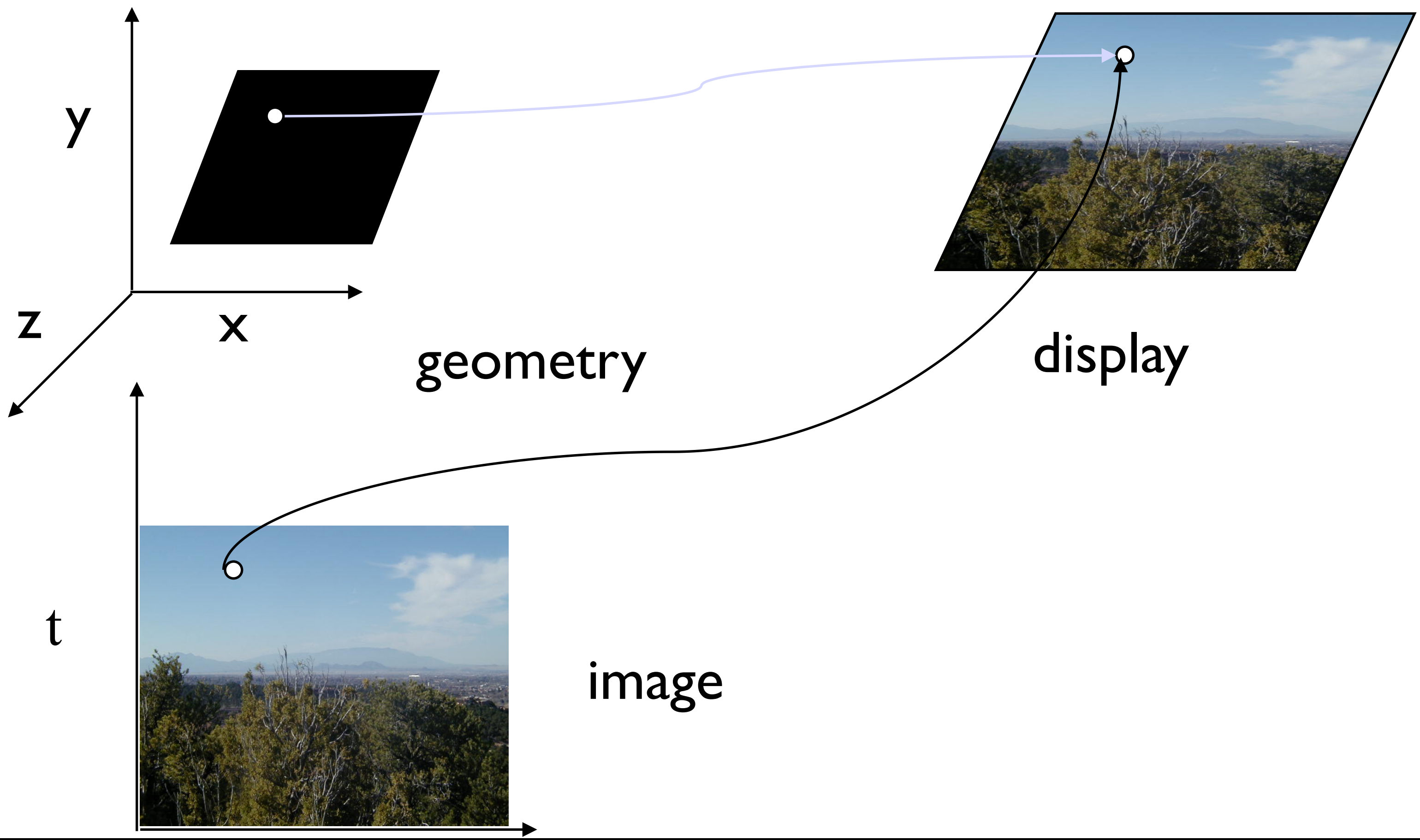
OpenGL Texture

Basic Stragegy

Three steps

1. Specify texture
   - read or generate image
   - assign to texture
   - enable texturing
2. Assign texture coordinates to vertices
   - Proper mapping function is left to application
3. Specify texture parameters
   - wrapping, filtering

Texture Mapping



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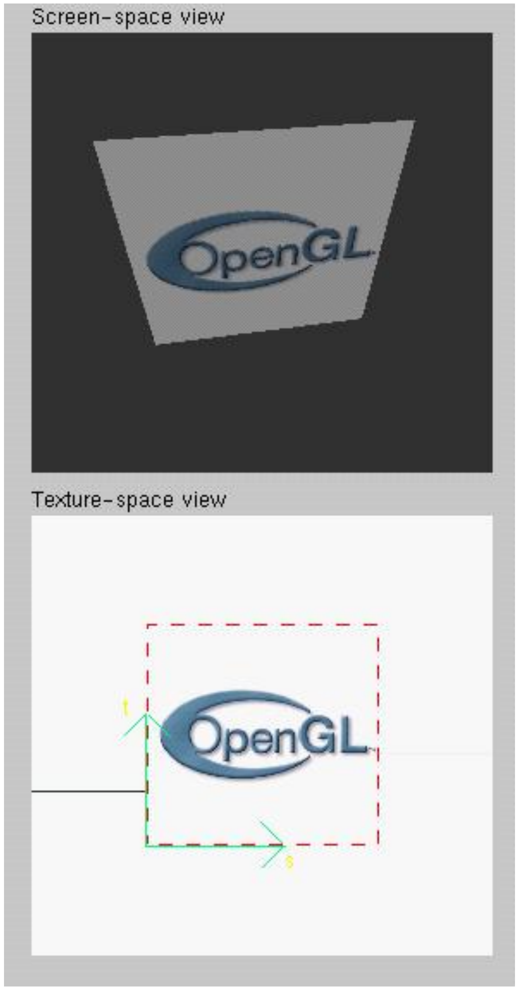
Texture Example



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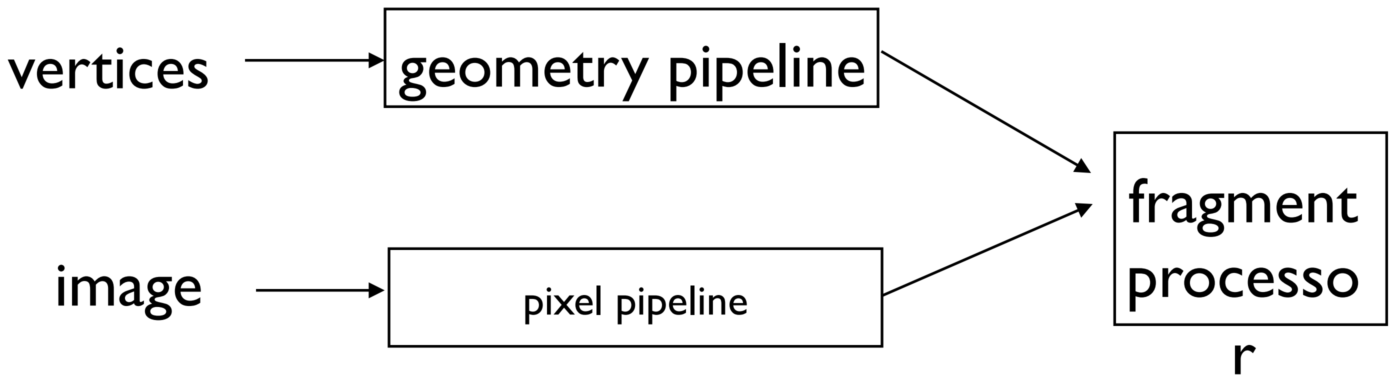
Texture Mapping in OpenGL



Specifying a Texture Image

- Define a texture image from an array of *texels* (texture elements) in CPU memory
  Glubyte my_texels[512][512];
- Define as any other pixel map
  - Scanned image
  - Generate by application code
- Enable texture mapping
  - **glEnable(GL_TEXTURE_2D)**
  - OpenGL supports 1-4 dimensional texture maps

Defining a Texture Image

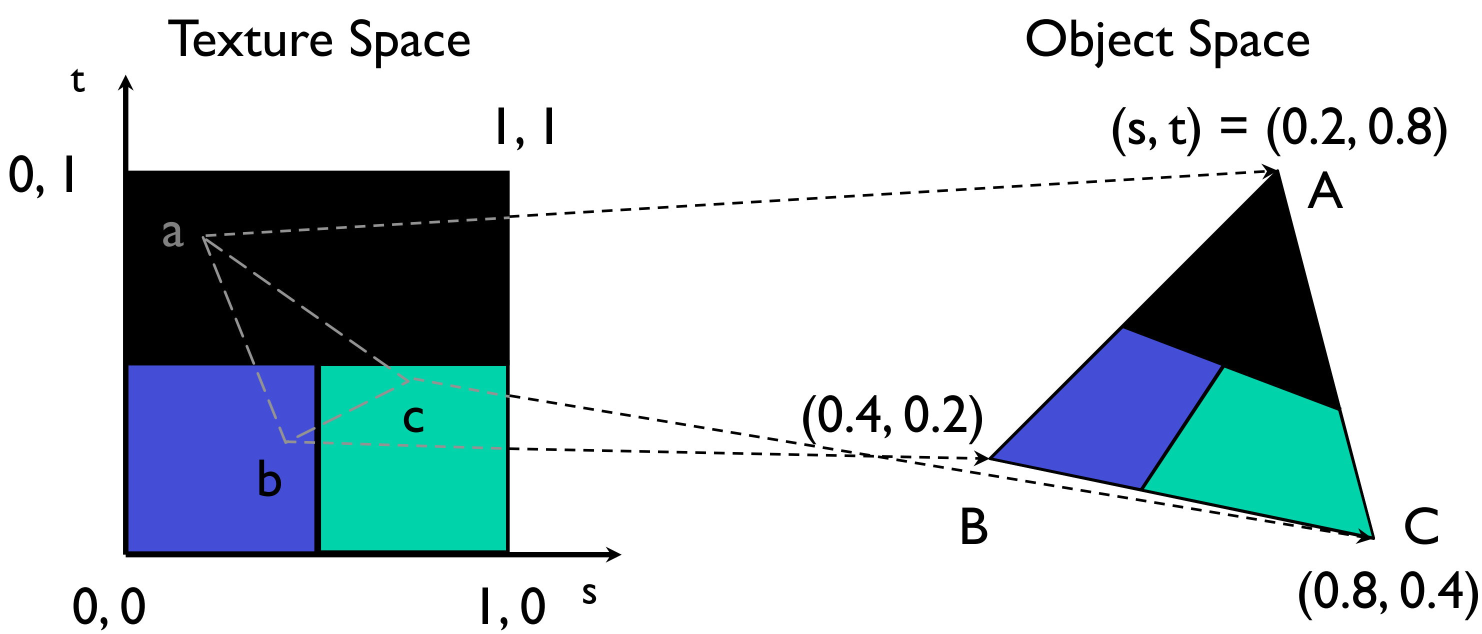
glTexImage2D(target, level, components, w, h, border, format, type, texels);

- target: type of texture, e.g. GL_TEXTURE_2D
- level: used for mipmapping
- components: elements per texel
- w, h: width and height of texels in pixels
- border: used for smoothing
- format and type: describe texels
- texels: pointer to texel array

```
glTexImage2D(GL_TEXTURE_2D, 0, 3, 512, 512, 0, GL_RGB,
    GL_UNSIGNED_BYTE, my_texels);
```

Mapping a Texture

- Based on parametric texture coordinates
- **glTexCoord*()** specified at each vertex



GLSL - Typical Code

```
offset = 0;
GLuint vPosition = glGetAttribLocation( program, "vPosition" );
glEnableVertexAttribArray( vPosition );
glVertexAttribPointer( vPosition, 4, GL_FLOAT, GL_FALSE,
    0,BUFFER_OFFSET(offset) );

offset += sizeof(points);
GLuint vTexCoord = glGetAttribLocation( program, "vTexCoord" );
glEnableVertexAttribArray( vTexCoord );
glVertexAttribPointer( vTexCoord, 2,GL_FLOAT,
   GL_FALSE, 0, BUFFER_OFFSET(offset) );
```

Adding Texture Coordinates

```
void quad( int a, int b, int c, int d )
{
    quad_colors[Index] = colors[a];
    points[Index] = vertices[a];
    tex_coords[Index] = vec2( 0.0, 0.0 );
    index++;
   quad_colors[Index] = colors[a];
    points[Index] = vertices[b];
    tex_coords[Index] = vec2( 0.0, 1.0 );
    Index++;

// other vertices
}
```

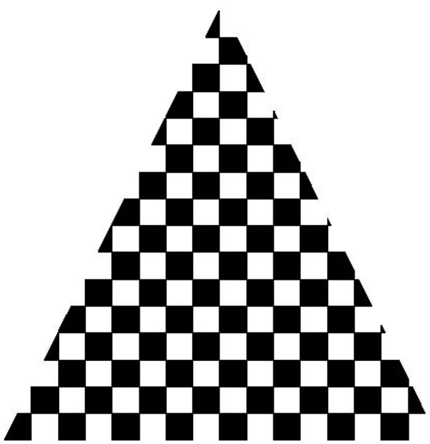
Role of Interpolation

Interpolation

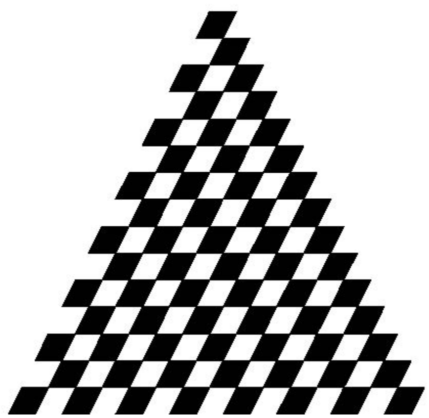
OpenGL uses interpolation to find proper texels from specified texture coordinates

Can be distorted

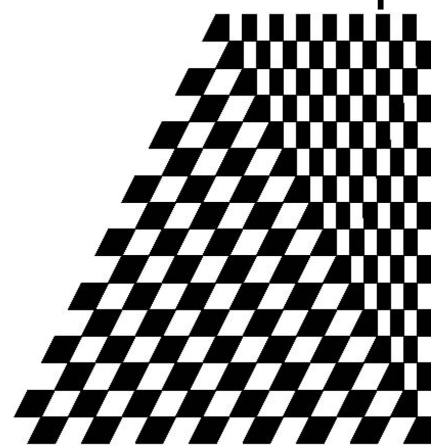
good selection of tex coordinates



poor selection of tex coordinates



texture stretched over trapezoid showing effects of bilinear interpolation



Interpolation

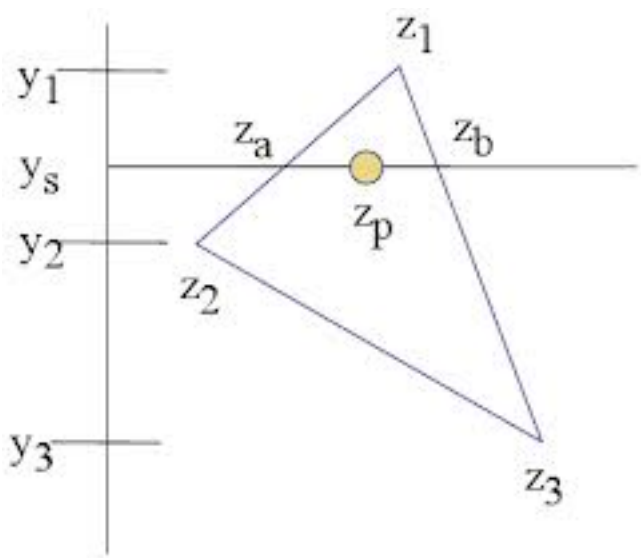
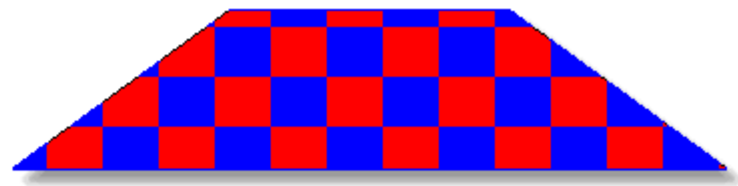
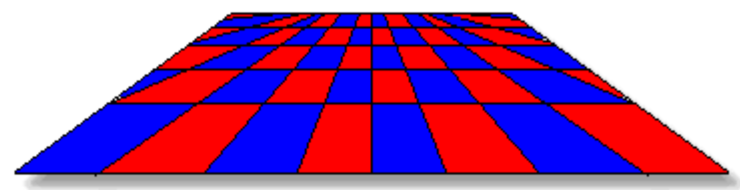


Figure 1.0 - Affine and perspective texture mapped polygons.



a. Affine texture mapping - notice no perspective cues.



b. Perspective texture mapping - notice 3D perspective both near and far.

Control of Texture Mapping

Texture Parameters

OpenGL has a variety of parameters that determine how texture is applied

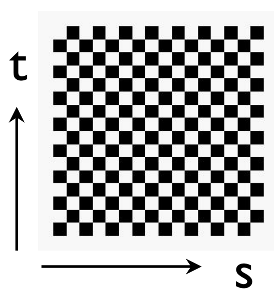
- Wrapping parameters determine what happens if s and t are outside the (0,1) range
- Filter modes allow us to use area averaging instead of point samples
- Mipmapping allows us to use textures at multiple resolutions
- Environment parameters determine how texture mapping interacts with shading

Wrapping Mode

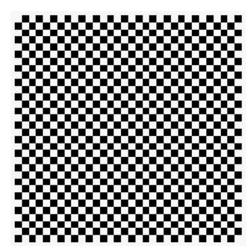
Clamping: if s,t > 1 use 1, if s,t <0 use 0

Wrapping: use s,t modulo 1

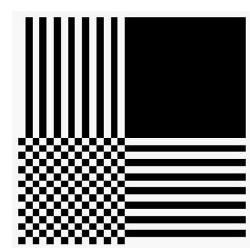
```
glTexParameteri( GL_TEXTURE_2D,
    GL_TEXTURE_WRAP_S, GL_CLAMP )
glTexParameteri( GL_TEXTURE_2D,
    GL_TEXTURE_WRAP_T, GL_REPEAT )
```



texture



GL_REPEAT wrapping

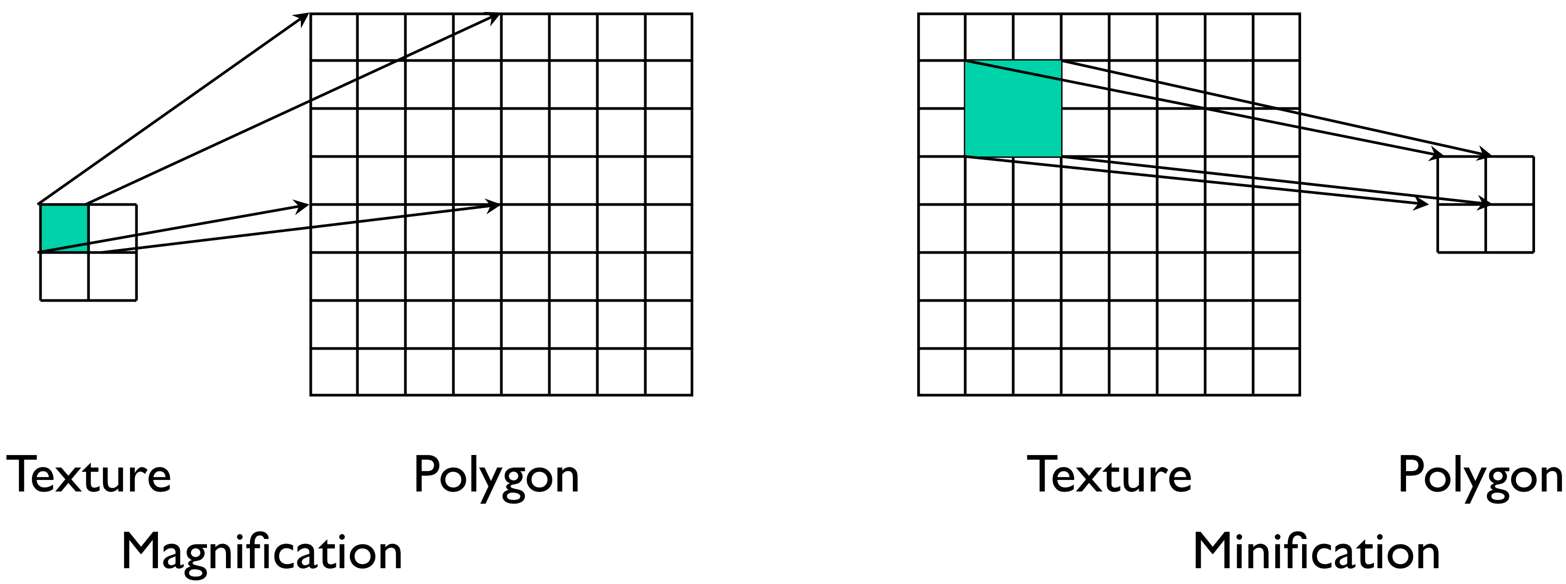


GL_CLAMP wrapping

Magnification/Minification

More than one texel can cover a pixel (*minification*) or more than one pixel can cover a texel (*magnification*)

Can use point sampling (nearest texel) or linear filtering (2 x 2 filter) to obtain texture values



Filter Modes

Modes determined by

- **glTexParameteri(target, type, mode)**

```
glTexParameteri(GL_TEXTURE_2D, GL_TEXURE_MAG_FILTER,
        GL_NEAREST);

glTexParameteri(GL_TEXTURE_2D, GL_TEXURE_MIN_FILTER,
        GL_LINEAR);
```

Note that linear filtering requires a border of an extra texel for filtering at edges (border = 1)

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Mipmapped Textures

- *Mipmapping* allows for prefiltered texture maps of decreasing resolutions
- Lessens interpolation errors for smaller textured objects
- Declare mipmap level during texture definition

  glTexImage2D(GL_TEXTURE_*D, level, …)

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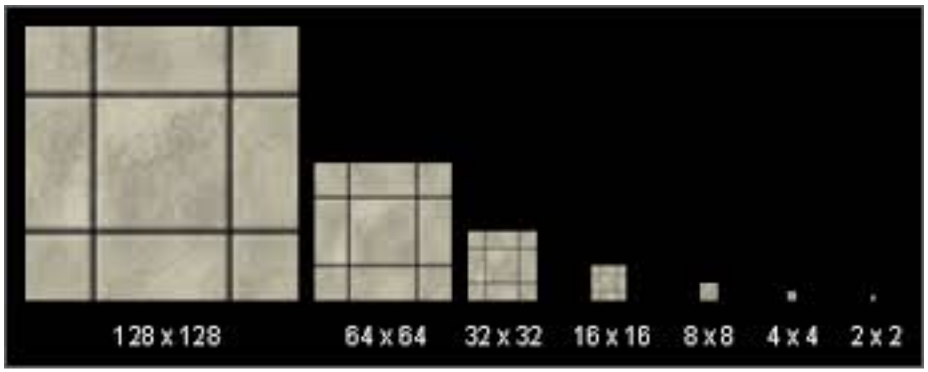
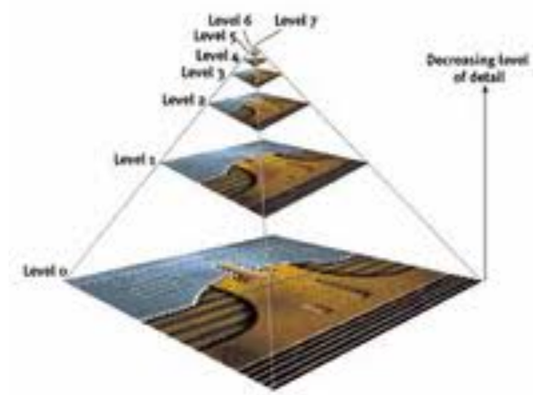
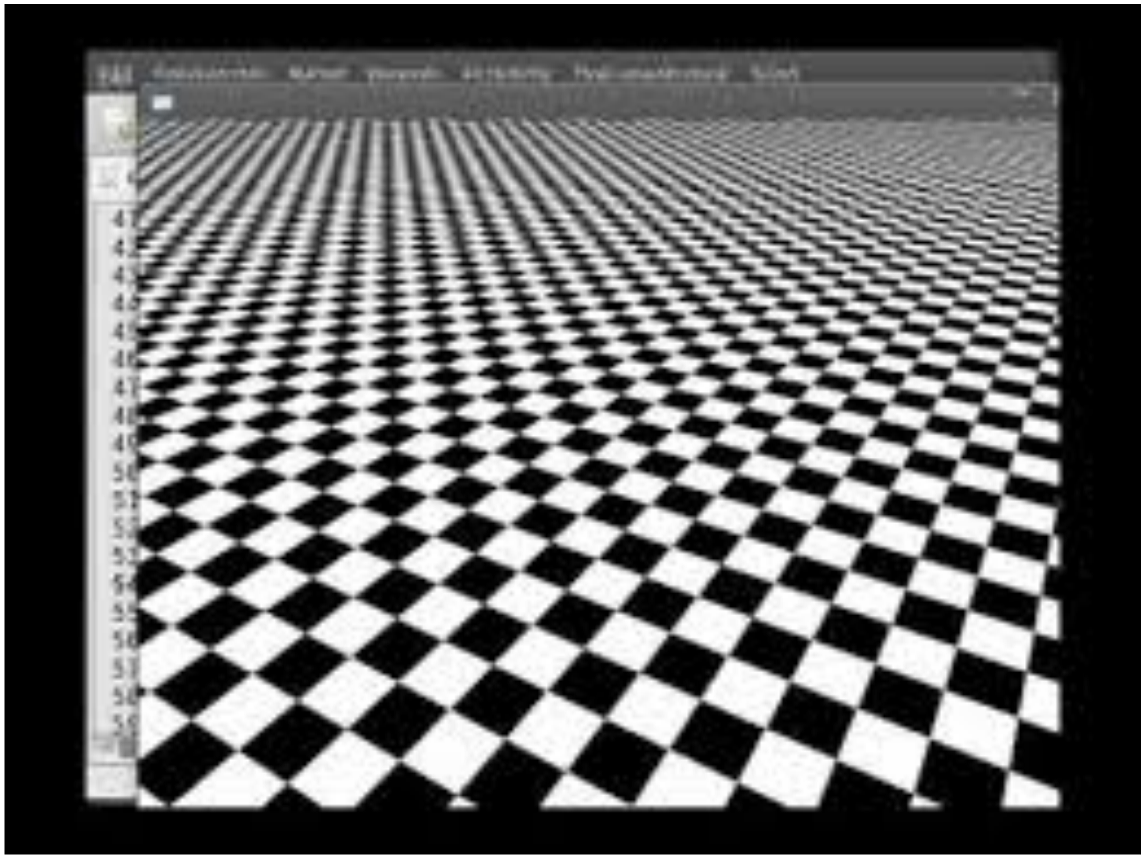
MipMaps


128 x 128
64 x 64
32 x 32
16 x 16
8 x 8
4 x 4
2 x 2


Level 7
Level 6
Level 5
Level 4
Level 3
Level 2
Level 1
Level 0
Decreasing level of detail

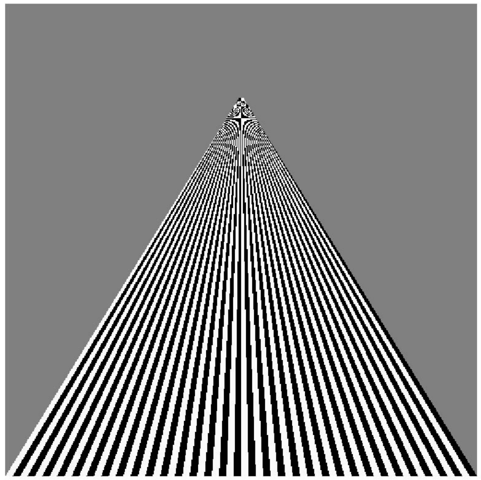
Mip-Mapping

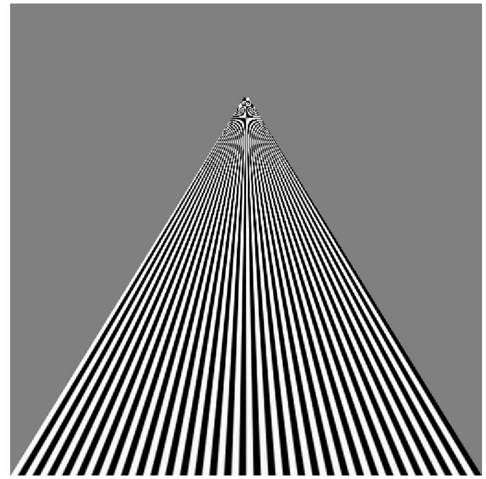
Mip-Mapping



Example

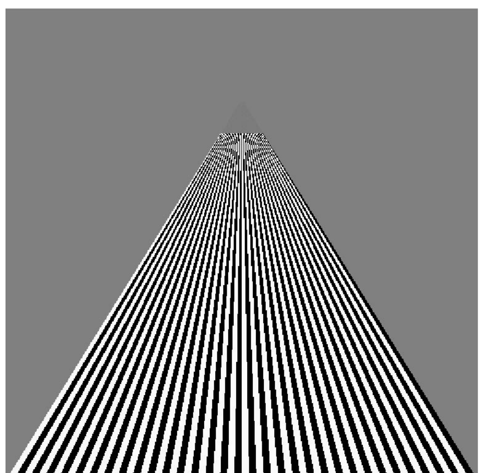
point sampling

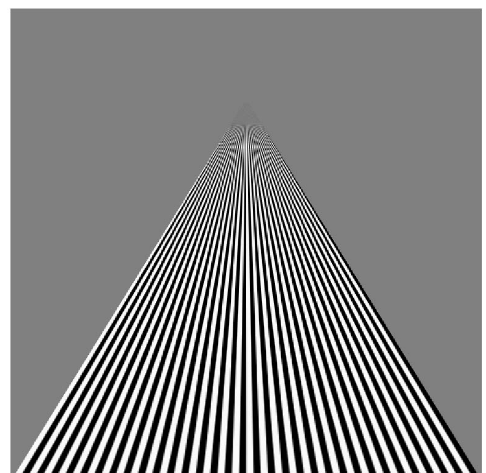




linear filtering

mipmapped point sampling





mipmapped linear filtering

Texture Functions

- Controls how texture is applied
  - **glTexEnv{fi}[v](GL_TEXTURE_ENV, prop, param)**
- **GL_TEXTURE_ENV_MODE** modes
  - **GL_MODULATE:** modulates with computed shade
  - **GL_BLEND:** blends with an environmental color
  - **GL_REPLACE:** use only texture color
  - **GL(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE);**
- Set blend color with **GL_TEXTURE_ENV_COLOR**

Using Texture Objects

1. specify textures in texture objects
2. set texture filter
3. set texture function
4. set texture wrap mode
5. set optional perspective correction hint
6. bind texture object
7. enable texturing
8. supply texture coordinates for vertex
   - coordinates can also be generated

Other Texture Features

- Environment Maps
  - Start with image of environment through a wide angle lens
    - Can be either a real scanned image or an image created in OpenGL
  - Use this texture to generate a spherical map
  - Alternative is to use a cube map
- Multitexturing
  - Apply a sequence of textures through cascaded texture units

GLSL

Samplers

https://www.opengl.org/wiki/Sampler_(GLSL)

Applying Textures

- Textures are applied during fragment shading by a **sampler**
- Samplers return a texture color from a texture object

```
in vec4 color;  //color from rasterizer
in vec2 texCoord; //texure coordinate from rasterizer
uniform sampler2D texture; //texture object from application

void main()  {
    gl_FragColor = color * texture2D( texture, texCoord );
}
```

Vertex Shader

- Usually vertex shader will output texture coordinates to be rasterized
- Must do all other standard tasks too
  - Compute vertex position
  - Compute vertex color if needed

```
in vec4 vPosition; //vertex position in object coordinates
in vec4 vColor;  //vertex color from application
in vec2 vTexCoord; //texture coordinate from application

out vec4 color; //output color to be interpolated
out vec2 texCoord; //output tex coordinate to be
interpolated
```

Adding Texture Coordinates

```
void quad( int a, int b, int c, int d )
{
    quad_colors[Index] = colors[a];
    points[Index] = vertices[a];
    tex_coords[Index] = vec2( 0.0, 0.0 );
    index++;
   quad_colors[Index] = colors[a];
    points[Index] = vertices[b];
    tex_coords[Index] = vec2( 0.0, 1.0 );
    Index++;

// other vertices
}
```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Texture Object

```
GLuint textures[1];
glGenTextures( 1, textures );

glBindTexture( GL_TEXTURE_2D, textures[0] );
glTexImage2D( GL_TEXTURE_2D, 0, GL_RGB, TextureSize,
  TextureSize, 0, GL_RGB, GL_UNSIGNED_BYTE, image );
glTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S,
   GL_REPEAT );
glTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T,
    GL_REPEAT );
glTexParameterf( GL_TEXTURE_2D,
     GL_TEXTURE_MAG_FILTER, GL_NEAREST );
glTexParameterf( GL_TEXTURE_2D,
     GL_TEXTURE_MIN_FILTER, GL_NEAREST );
glActiveTexture( GL_TEXTURE0 );
```

Linking with Shaders

```
GLuint vTexCoord = glGetAttribLocation( program, "vTexCoord" );
glEnableVertexAttribArray( vTexCoord );
glVertexAttribPointer( vTexCoord, 2, GL_FLOAT, GL_FALSE, 0,
                       BUFFER_OFFSET(offset) );

// Set the value of the fragment shader texture sampler variable
//   ("texture") to the the appropriate texture unit. In this case,
//   zero, for GL_TEXTURE0 which was previously set by calling
//   glActiveTexture().
glUniform1i( glGetUniformLocation(program, "texture"), 0 );
```

Vertex Shader Applications

- Moving vertices
  - Morphing
  - Wave motion
  - Fractals
- Lighting
  - More realistic models
  - Cartoon shaders

Wave Motion Vertex Shader

```
uniform float time;
uniform float xs, zs, // frequencies
uniform float h; // height scale
uniform mat4 ModelView, Projection;
in vec4 vPosition;

void main() {
  vec4 t =vPosition;
  t.y = vPosition.y
     + h*sin(time + xs*vPosition.x)
     + h*sin(time + zs*vPosition.z);
  gl_Position = Projection*ModelView*t;
}
```

Particle System

```
uniform vec3 init_vel;
uniform float g, m, t;
uniform mat4 Projection, ModelView;
in vPosition;
void main(){
vec3 object_pos;
object_pos.x = vPosition.x + vel.x*t;
object_pos.y = vPosition.y + vel.y*t
      + g/(2.0*m)*t*t;
object_pos.z = vPosition.z + vel.z*t;
gl_Position = Projection*
  ModelView*vec4(object_pos,1);
}
```

Example

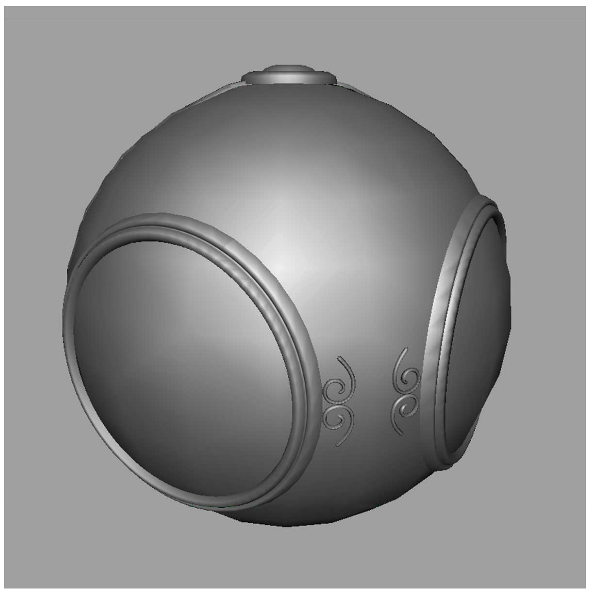
http://www.lighthouse3d.com/tutorials/glsl-core-tutorial/glsl-core-tutorial-texturing-with-images/

Example

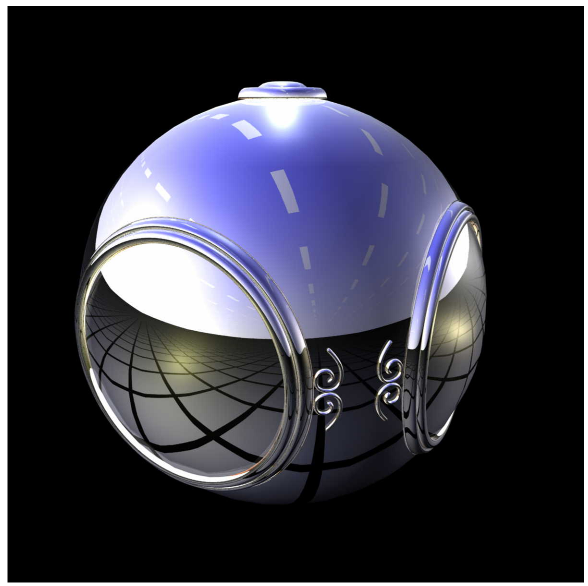
http://www.lighthouse3d.com/tutorials/glsl-tutorial/simple-texture/

Fragment Shader

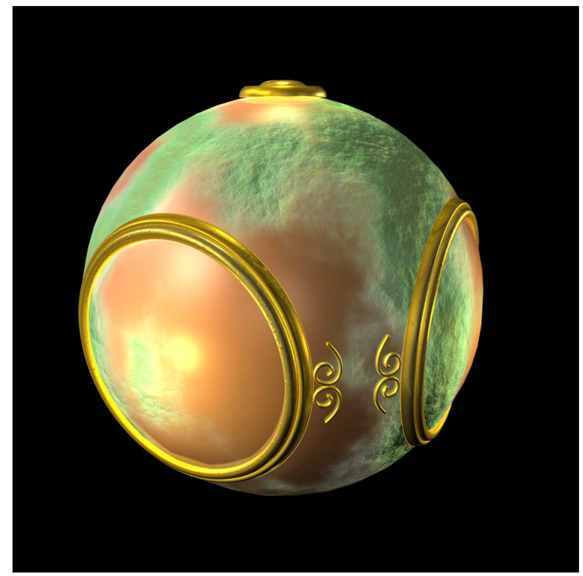
Texture mapping



smooth shading



environment mapping



bump mapping

Cube Maps

- We can form a cube map texture by defining six 2D texture maps that correspond to the sides of a box
- Supported by OpenGL
- Also supported in GLSL through cubemap sampler

```
vec4 texColor = textureCube(mycube, texcoord);
```

- Texture coordinates must be 3D

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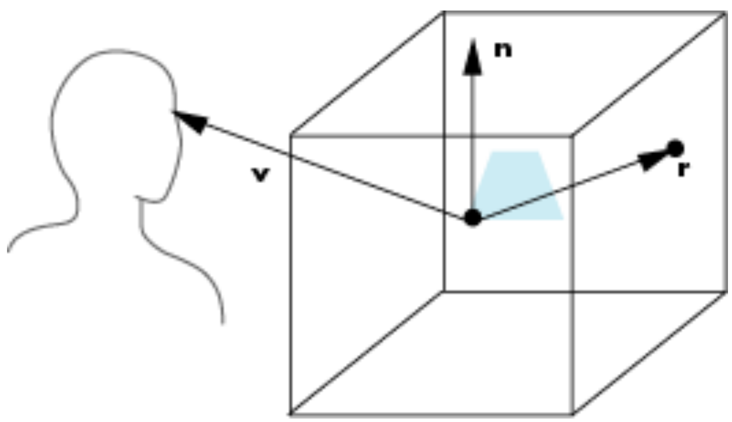
Environment Map

Use reflection vector to locate texture in cube map



Environment Maps with Shaders

- Computed in world coordinates
  - keep track of modeling matrix & pass as a uniform variable
- Use reflection map or refraction map
- Simulate water

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Reflection Map Vertex Shader

```
uniform mat4 Projection, ModelView, NormalMatrix;
in vec4 vPosition;
in vec4 normal;
out vec3 R;

void main(void)
{
   gl_Position = Projection*ModelView*vPosition;
   vec3 N = normalize(NormalMatrix*normal);
   vec4 eyePos = ModelView*gvPosition;
   R = reflect(-eyePos.xyz, N);
}
```

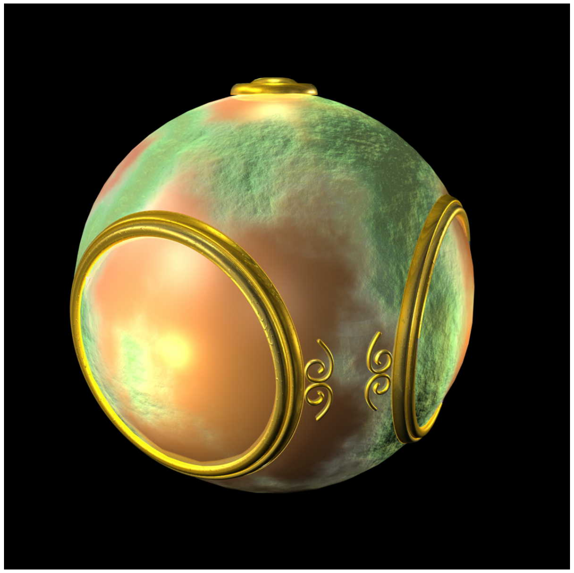
Reflection Map Fragment Shader

```
in vec3 R;
uniform samplerCube texMap;

void main(void)
{
    gl_FragColor = textureCube(texMap, R);
}
```

Bump Mapping

- Perturb normal for each fragment
- Store perturbation as textures



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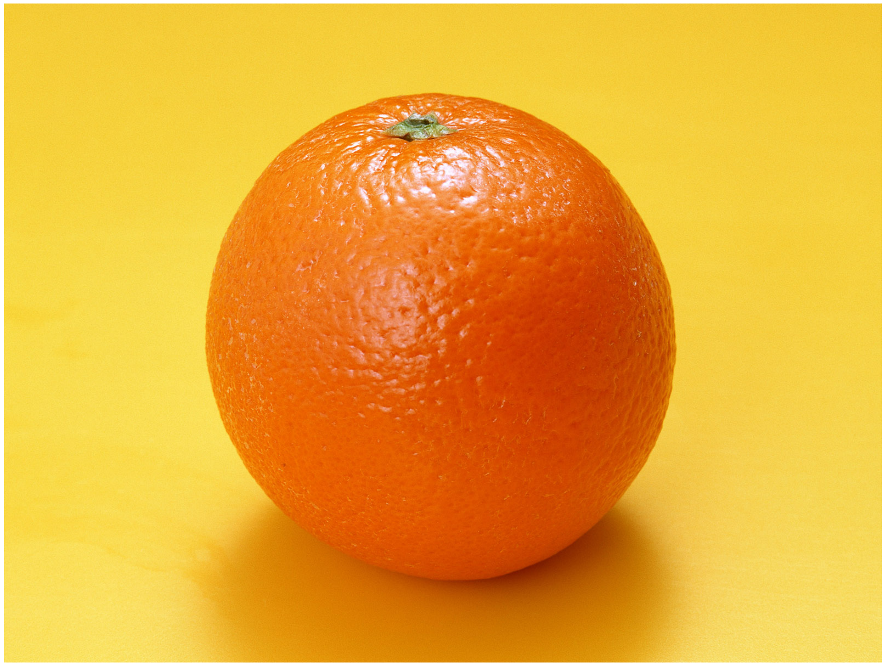
Back 2 Orange



The Orange

- Texture map a photo of an orange onto a surface
  - Captures dimples
  - Will not be correct if we move viewer or light
  - We have shades of dimples rather than their correct orientation
- Ideally perturb normal across surface of object and compute a new color at each interior point

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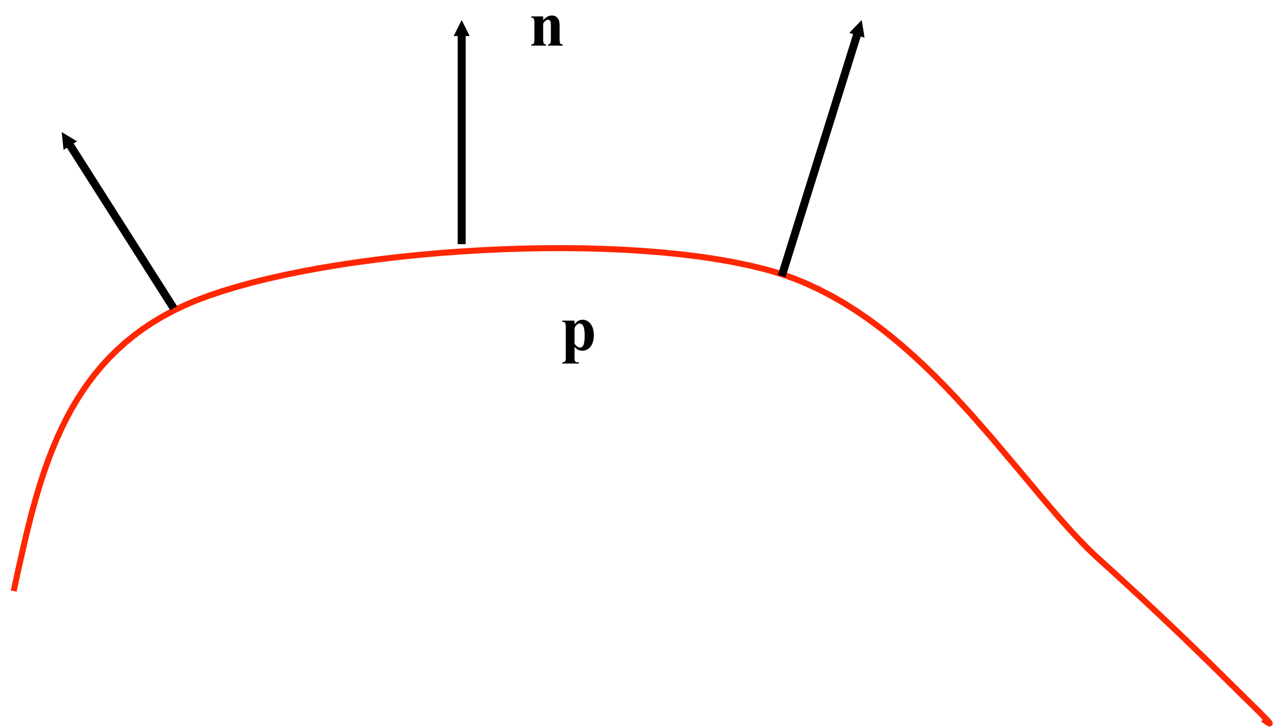
Bump Mapping (Blinn)

Consider a smooth surface



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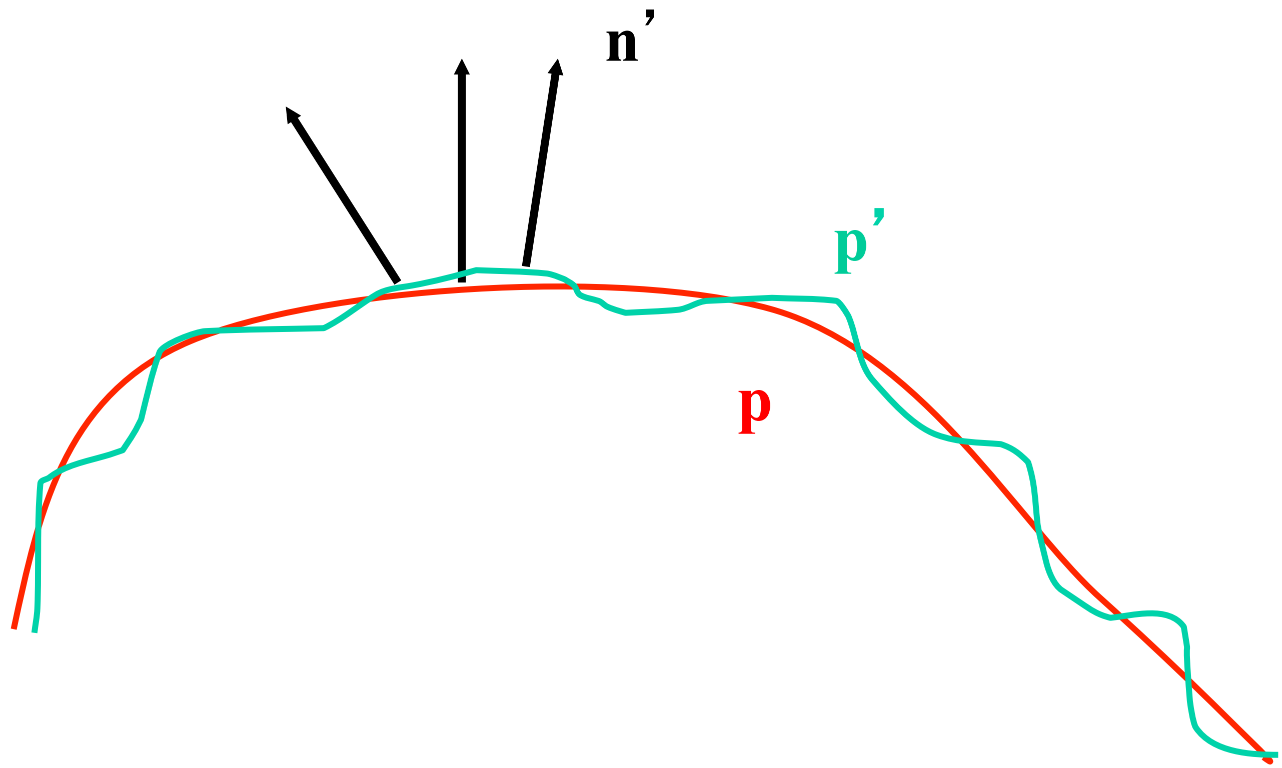
Rougher Version



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Equations

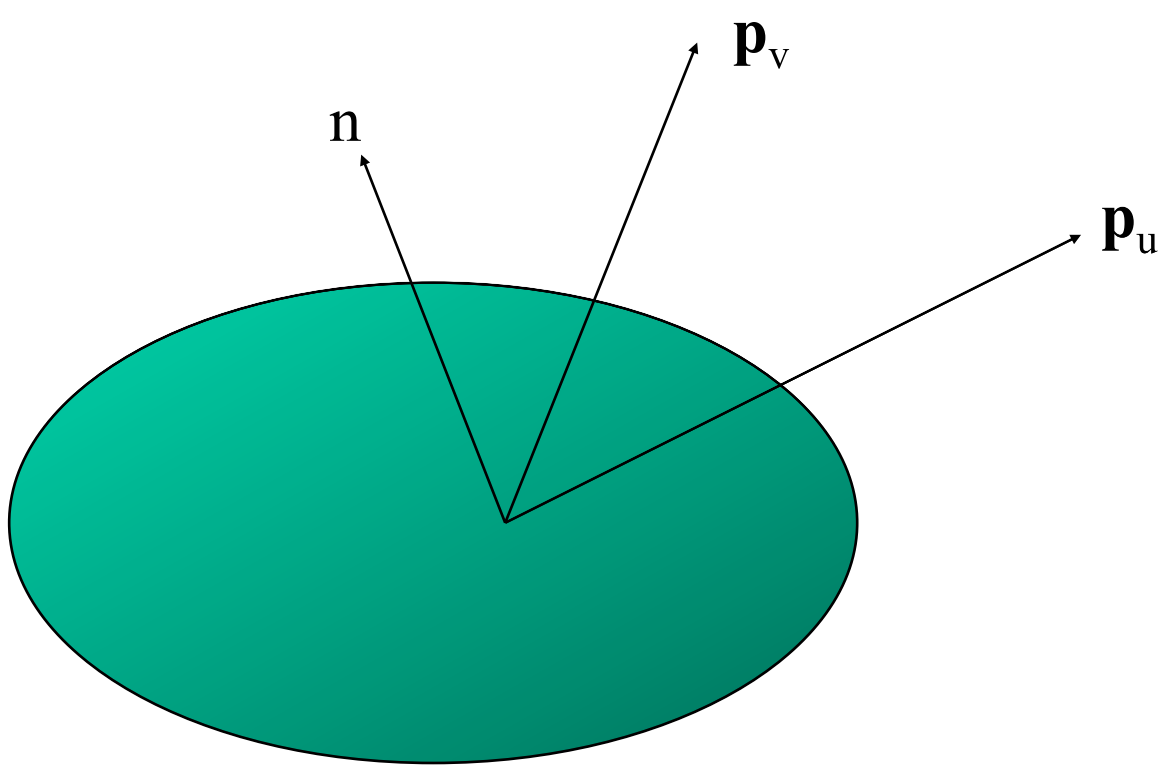
$$\mathbf{p}(u,v) = [x(u,v),\ y(u,v),\ z(u,v)]^T$$

$$\mathbf{p}_u = [\ \partial x/\ \partial u,\ \partial y/\ \partial u,\ \partial z/\ \partial u]^T$$

$$\mathbf{p}_v = [\ \partial x/\ \partial v,\ \partial y/\ \partial v,\ \partial z/\ \partial v]^T$$

$$\mathbf{n} = (\mathbf{p}_u \times \mathbf{p}_v\ ) \,/\, |\ \mathbf{p}_u \times \mathbf{p}_v\ |$$

Tangent Plane



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Displacement Function

$$\mathbf{p}' = \mathbf{p} + d(u,v)\,\mathbf{n}$$

d(u,v) is the bump or displacement function

$|d(u,v)| \ll 1$

Perturbed Normal

$$\mathbf{n}' = \mathbf{p}'_u \times \mathbf{p}'_v$$

$$\mathbf{p}'_u = \mathbf{p}_u + (\partial d / \partial u)\mathbf{n} + d(u,v)\mathbf{n}_u$$

$$\mathbf{p}'_v = \mathbf{p}_v + (\partial d / \partial v)\mathbf{n} + d(u,v)\mathbf{n}_v$$

If d is small, we can neglect last term

Approximating the Normal

$$\mathbf{n}' = \mathbf{p}'_u \times \mathbf{p}'_v$$

$$\approx \mathbf{n} + (\partial d / \partial u)\mathbf{n} \times \mathbf{p}_v + (\partial d / \partial v)\mathbf{n} \times \mathbf{p}_u$$

The vectors $n \times p_v$ and $n \times p_u$ lie in the tangent plane

Hence the normal is displaced in the tangent plane

Must precompute the arrays $\partial d / \partial u$ and $\partial d / \partial v$

Finally, we perturb the normal during shading

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Compositing & Blending

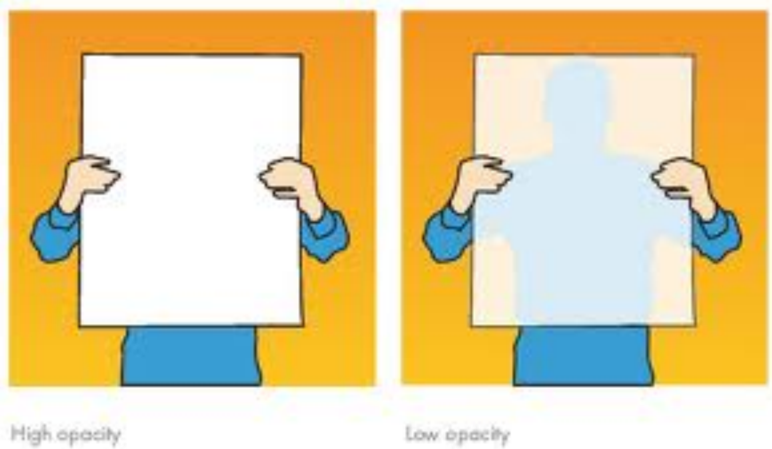
A

– Blending for translucent surfaces

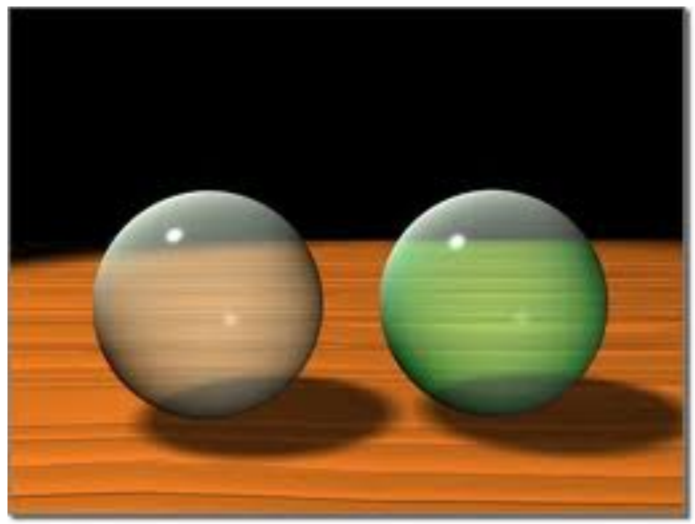
– Compositing images

– Antialiasing

A



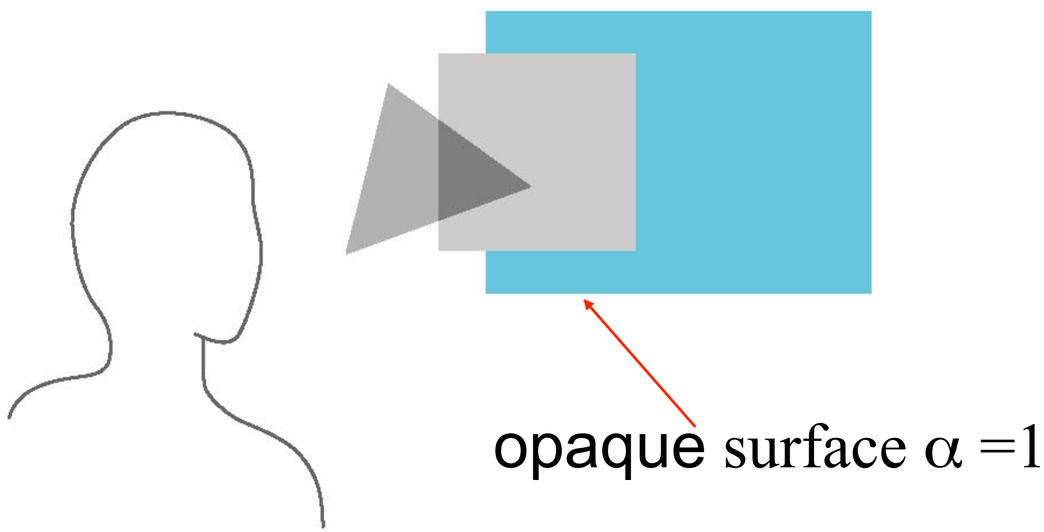
A



A

- Opaque surfaces permit no light to pass through
- Transparent surfaces permit all light to pass
- Translucent surfaces pass some light

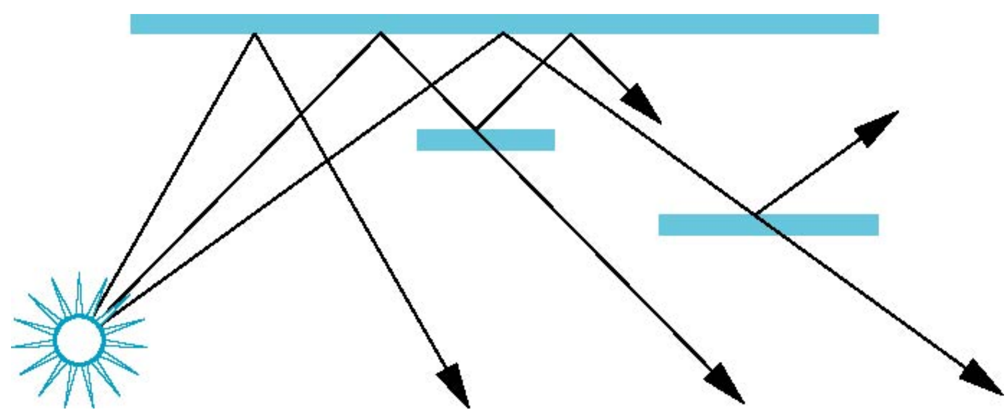
translucency = 1 – opacity (α)



Physical Models

Translucency in a physically correct manner is difficult

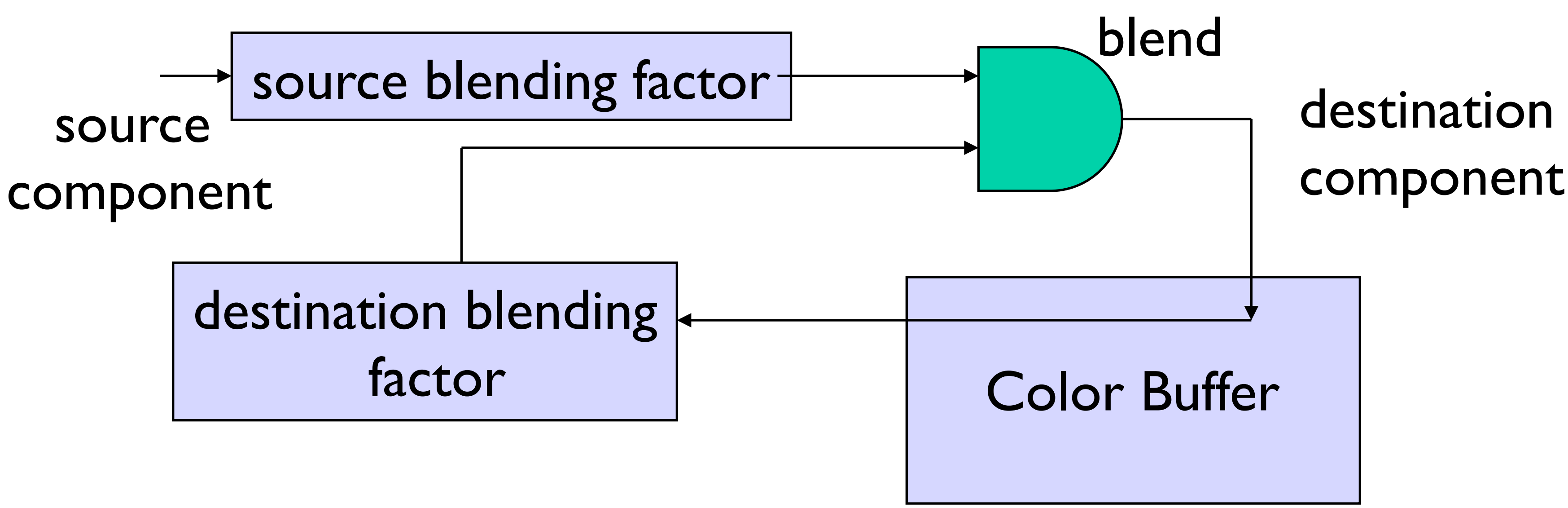
- the complexity of the internal interactions of light and matter
- Using a pipeline renderer



Compositing Operation

Rendering Model

- Use A component of RGBA (or RGBa) color for opacity
- During rendering expand to use RGBA values



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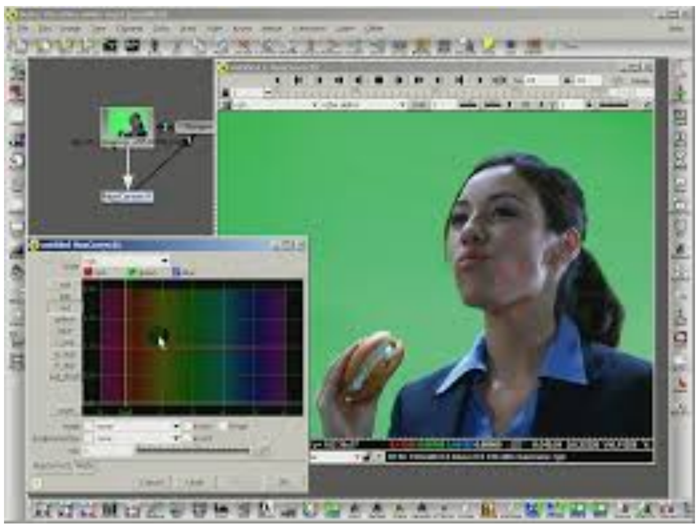
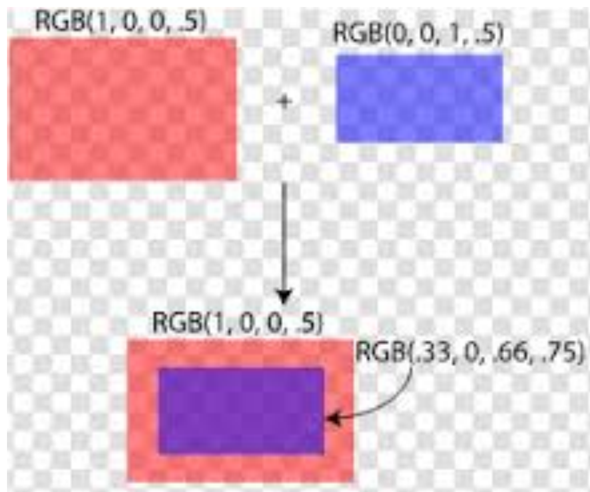
Examples



One Method



Blending Equation

We can define source and destination blending factors for each RGBA component

$\mathbf{s} = [s_r, s_g, s_b, s_a]$

$\mathbf{d} = [d_r, d_g, d_b, d_a]$

Suppose that the source and destination colors are

$\mathbf{b} = [b_r, b_g, b_b, b_a]$

$\mathbf{c} = [c_r, c_g, c_b, c_a]$

Blend as

$\mathbf{c}' = [b_r s_r + c_r d_r, b_g s_g + c_g d_g, b_b s_b + c_b d_b, b_a s_a + c_a d_a]$

OpenGL

Must enable blending and pick source and destination factors

glEnable(GL_BLEND)

glBlendFunc(source_factor,
  destination_factor)

Only certain factors supported

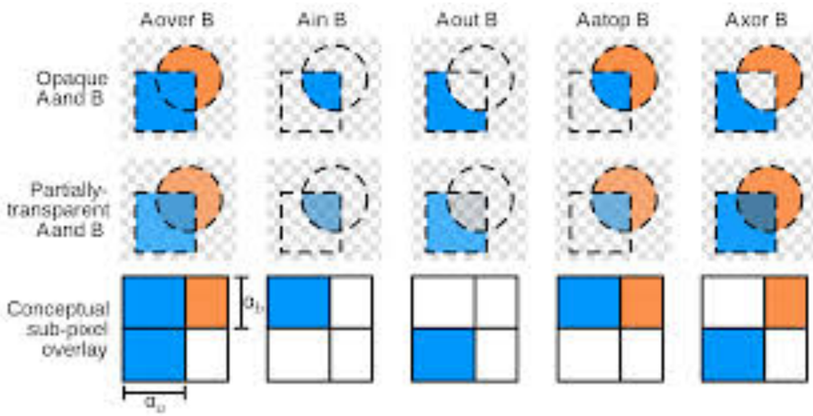
GL_ZERO, GL_ONE

GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA

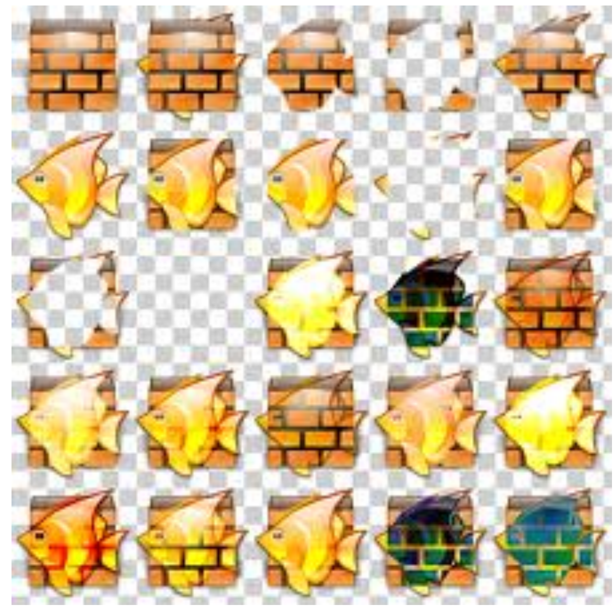
GL_DST_ALPHA, GL_ONE_MINUS_DST_ALPHA

See Redbook for complete list

Operator



Aover B
Ain B
Aout B
Aatop B
Axor B
Opaque A and B
Partially-transparent A and B
Conceptual sub-pixel overlay



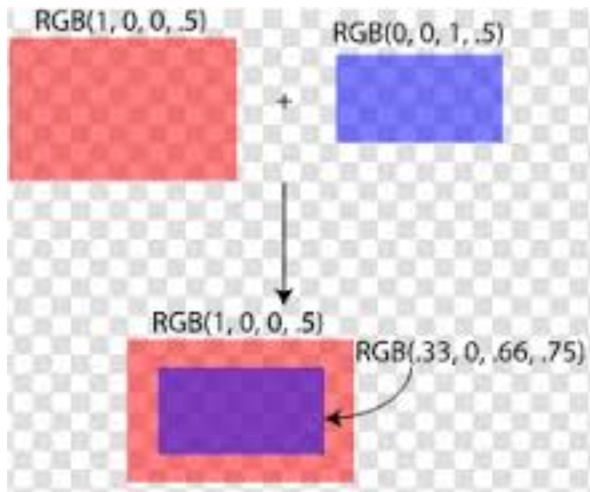
Example

- Start with the opaque background color $(R_0, G_0, B_0, 1)$
  - Initial destination color
- Blend in a translucent polygon with color (R_1, G_1, B_1, a_1)
- Select **GL_SRC_ALPHA** and **GL_ONE_MINUS_SRC_ALPHA** as the source and destination blending factors

$$R'_1 = a_1 R_1 + (1 - a_1) R_0, \ldots\ldots$$

- Note this formula is correct if polygon is either opaque or transparent

Works Here Too…



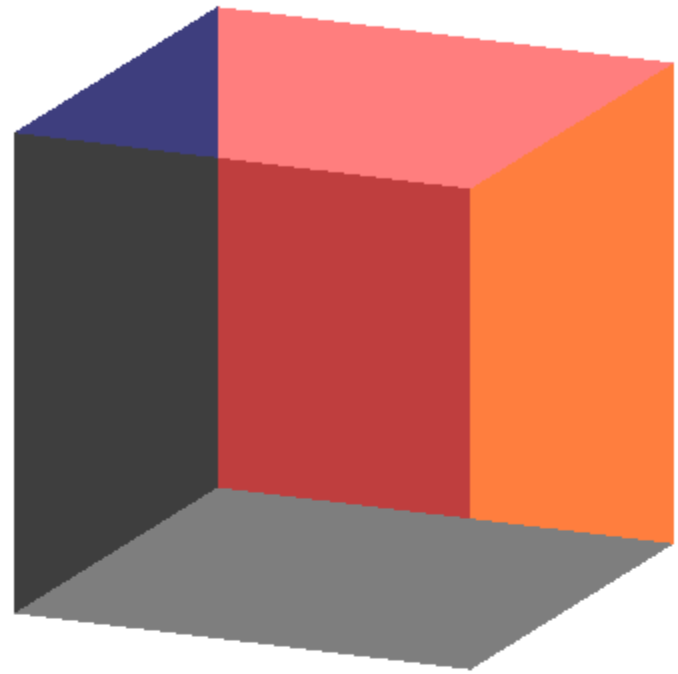
Clamping and Accuracy

- All RGBA are clamped to the range (0,1)
- RGBA values 8 bits !
  - Loose accuracy after much components together
  - Example: add together n images
    - Divide all color components by n to avoid clamping
    - Blend with source factor = 1, destination factor = 1
    - But division by n loses bits

Order Dependency

Order Dependency

- Is this image correct?
  – Probably not
  – Polygons are rendered in the order they pass down the pipeline
  – Blending functions are order dependent



HSR with A

- Polygons which are opaque & translucent
- Opaque polygons block all polygons behind & affect depth buffer
- Translucent polygons should not affect depth buffer
  - Render with **glDepthMask(GL_FALSE)** which makes depth buffer read-only
- Sort polygons first to remove order dependency

Fog

Simulate Fog

- Composite with fixed color and have blending factors depend on depth
  - Simulates a fog effect
- Blend source color C_s and fog color C_f by

$$C_s' = f\,C_s + (1-f)\,C_f$$

- f is the *fog factor*
  - Exponential
  - Gaussian
  - Linear (depth cueing)

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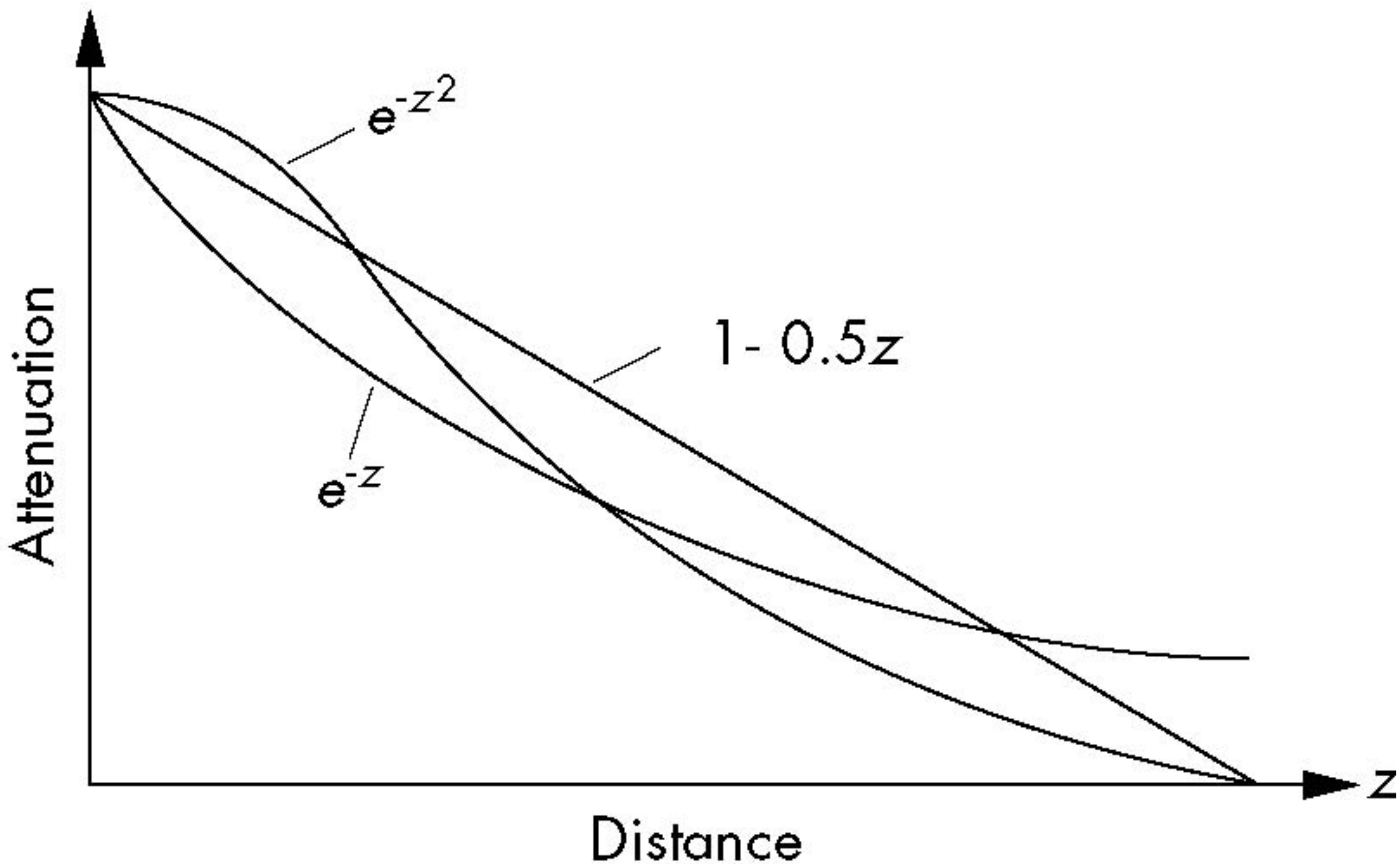
F - Fog Functions



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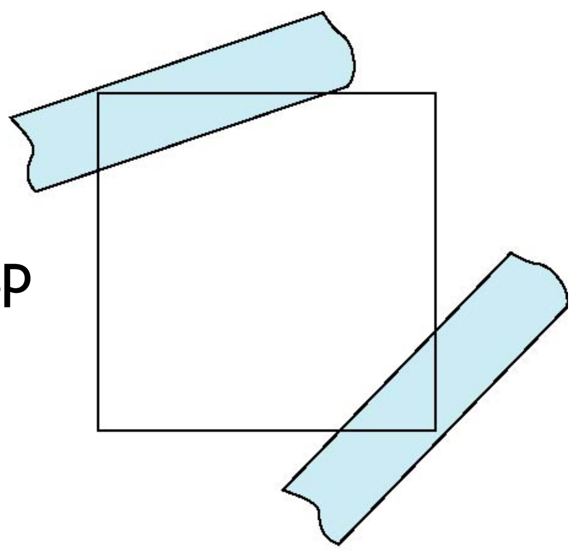
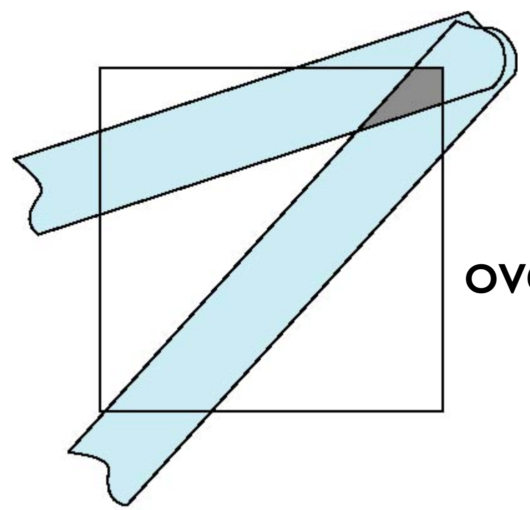
Antialiasing

Color a pixel by adding fraction of color to frame buffer

- Fraction depends on percentage of pixel covered by fragment
- Fraction depends on whether there is overlap

no overlap

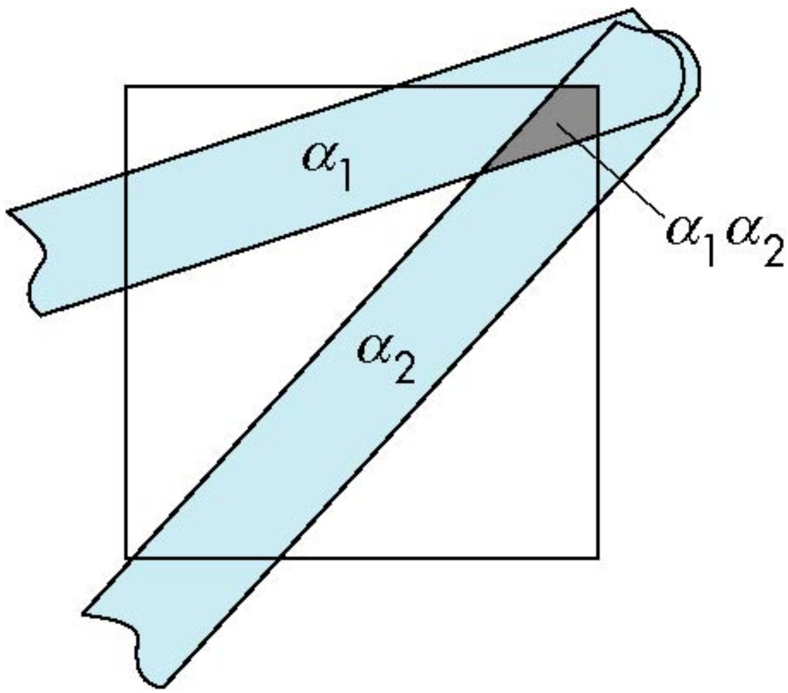




overlap

Area Averaging

Use average area $a_1+a_2-a_1a_2$ as blending factor



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OpenGL Antialiasing

Enable separately for points, lines, or polygons

```
glEnable(GL_POINT_SMOOTH);
glEnable(GL_LINE_SMOOTH);
glEnable(GL_POLYGON_SMOOTH);

glEnable(GL_BLEND);
glBlendFunc(GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);
```


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Accumulation

- Compositing/blending limited by resolution of frame buffer
  - Typically 8 bits per color component
- A*ccumulation buffer* was a high resolution buffer (16 or more bits per component) that avoided this problem
- Could write into it or read from it with a scale factor
- Slower than direct compositing into the frame buffer

Particle Systems

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Many Uses

- Used to model
  - Natural phenomena
    - Clouds
    - Terrain
    - Plants
  - Crowd Scenes
  - Real physical processes

Newtonian Particle

- Particle system is a set of particles
- Each particle is an ideal point mass
- Six degrees of freedom
  - Position
  - Velocity
- Each particle obeys Newtons' law

$$f = ma$$

Particle Equations

$\mathbf{p}_i = (x_i, y_i\ z_i)$

$\mathbf{v}_i = d\mathbf{p}_i /dt = \mathbf{p}_i{}' = (dx_i /dt, dy_i /dt , z_i /dt)$

$m\ \mathbf{v}_i{}' = \mathbf{f}_i$

Hard part is defining force vector

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Force Vector

- Independent Particles
  - Gravity
  - Wind forces
  - O(n) calulation
- Coupled Particles O(n)
  - Meshes
  - Spring-Mass Systems
- Coupled Particles $O(n^2)$
  - Attractive and repulsive forces

Solution of Particle Systems

```
float time, delta state[6n], force[3n];
state = initial_state();
for(time = t0; time<final_time, time+=delta) {
force =  force_function(state, time);
state = ode(force, state, time, delta);
render(state, time)
}
```

Simple Forces

- Consider force on particle i

$$\mathbf{f}_i = \mathbf{f}_i(\mathbf{p}_i, \mathbf{v}_i)$$

- Gravity $\mathbf{f}_i = \mathbf{g}$

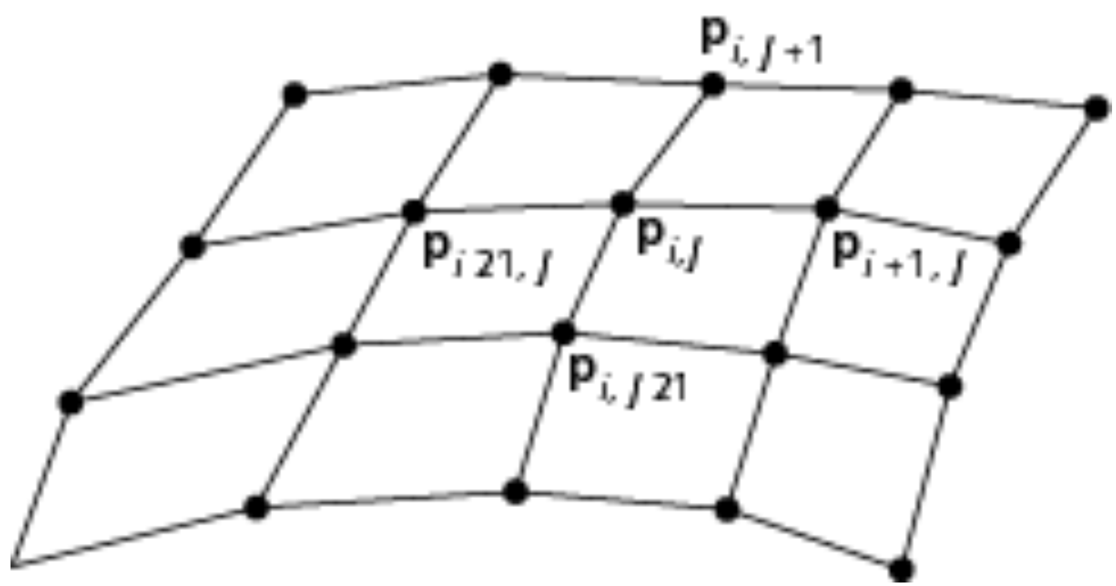
$$\mathbf{g} = (0, -g, 0)$$

- Wind forces
- Drag

$\mathbf{p}_i(t_0), \mathbf{v}_i(t_0)$

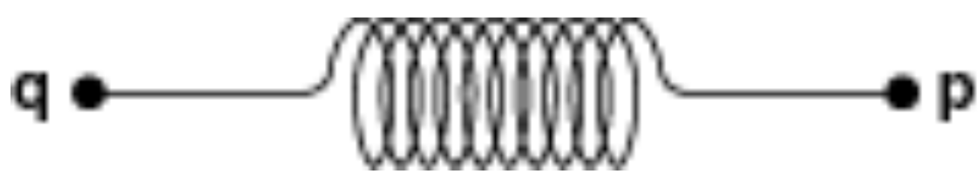
Meshes

- Connect each particle to its closest neighbors
  - O(n) force calculation
- Use spring-mass system



Spring Forces

- Assume each particle has unit mass and is connected to its neighbor(s) by a spring
- Hooke's law: force proportional to distance (d = ||**p** – **q**||) between the points



Hooke's Law

Let s be the distance when there is no force

$$\mathbf{f} = -k_s(|\mathbf{d}| - s)\ \mathbf{d}/|\mathbf{d}|$$

k_s is the spring constant

d/|**d**| is a unit vector pointed from **p** to **q**

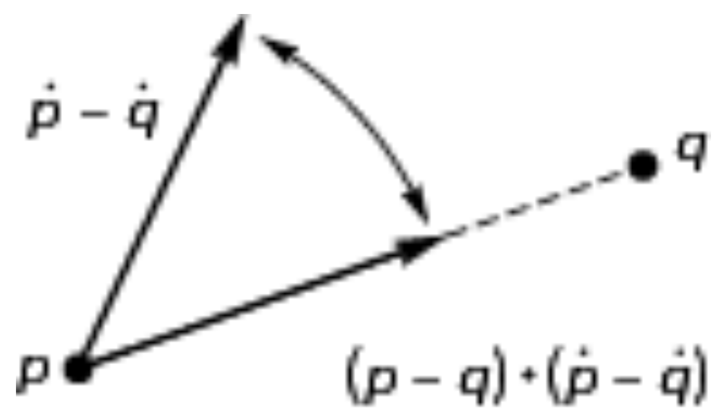
Each interior point in mesh has four forces applied to it

Spring Damping

- A pure spring-mass will oscillate forever
- Must add a damping term

$$\mathbf{f} = -(k_s(|\mathbf{d}| - s) + k_d\, \mathbf{d}\cdot\dot{\mathbf{d}}/|\mathbf{d}|)\mathbf{d}/|\mathbf{d}|$$

- Must project velocity



Attraction and Repulsion

- Inverse square law

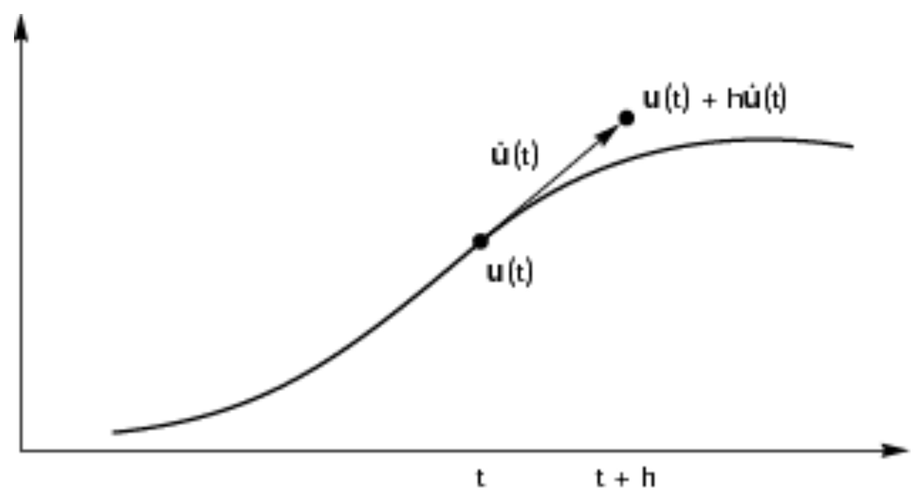
$$\mathbf{f} = -k_r \mathbf{d}/|\mathbf{d}|^3$$

- General case requires $O(n^2)$ calculation

- In most problems, the drop off is such that not many particles contribute to the forces on any given particle
- Sorting problem: is it O(n log n)?

Solution of ODEs

- Particle system has 6n ordinary differential equations
- Write set as d**u/**dt = g(**u**,t)
- Solve by approximations using Taylor's Thm



Euler's Method

$\mathbf{u}(t + h) \approx \mathbf{u}(t) + h\, d\mathbf{u}/dt = \mathbf{u}(t) + h\mathbf{g}(\mathbf{u}, t)$

Per step error is $O(h^2)$

Require one force evaluation per time step

Problem is numerical instability

depends on step size

Improved Euler

$\mathbf{u}(t + h) \approx \mathbf{u}(t) + h/2(\mathbf{g}(\mathbf{u}, t) + \mathbf{g}(\mathbf{u}, t+h))$

Per step error is $O(h^3)$

Also allows for larger step sizes

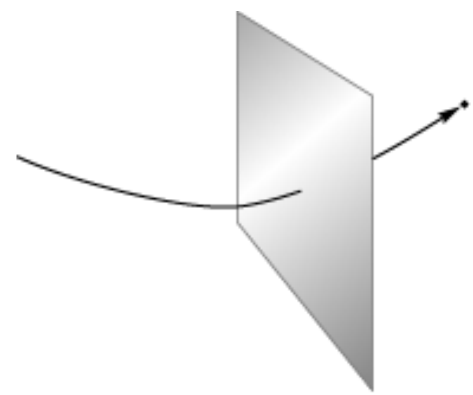
But requires two function evaluations per step

Also known as Runge-Kutta method of order 2

Contraints

- Easy in computer graphics to ignore physical reality
- Surfaces are virtual
- Must detect collisions separately if we want exact solution
- Can approximate with

repulsive forces



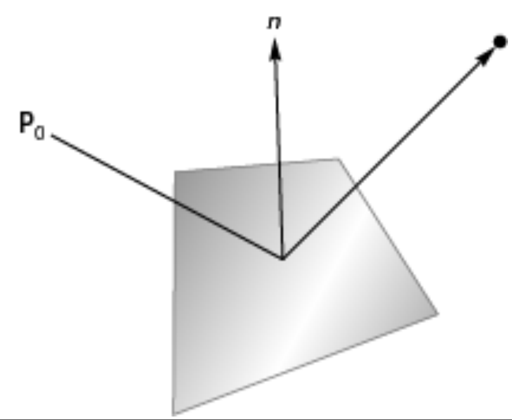
Collisions

Once we detect a collision, we can calculate new path

Use coefficient of resititution

Reflect vertical component

May have to use partial time step

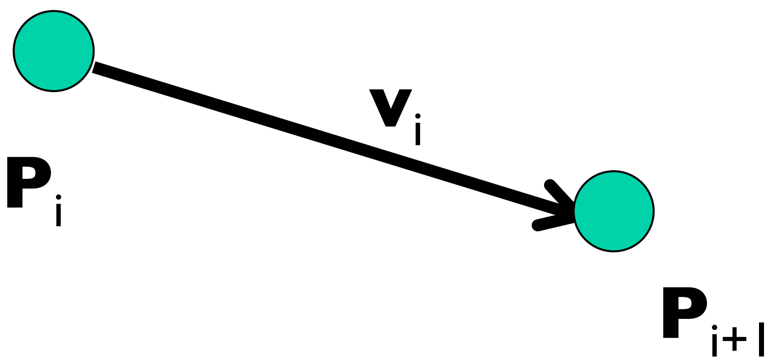


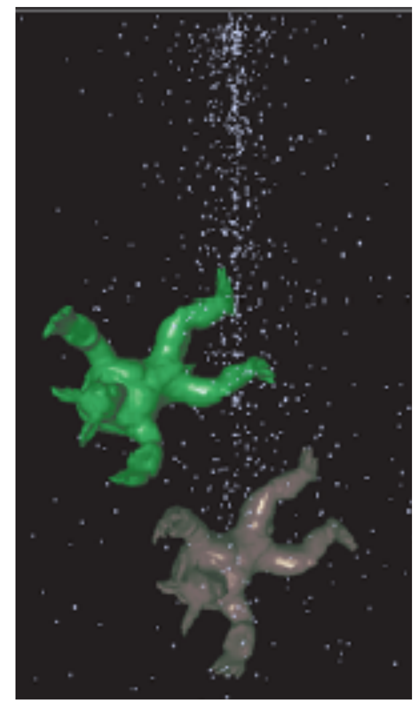
Example

$\mathbf{p}_i = (x_i, y_i\ z_i)$

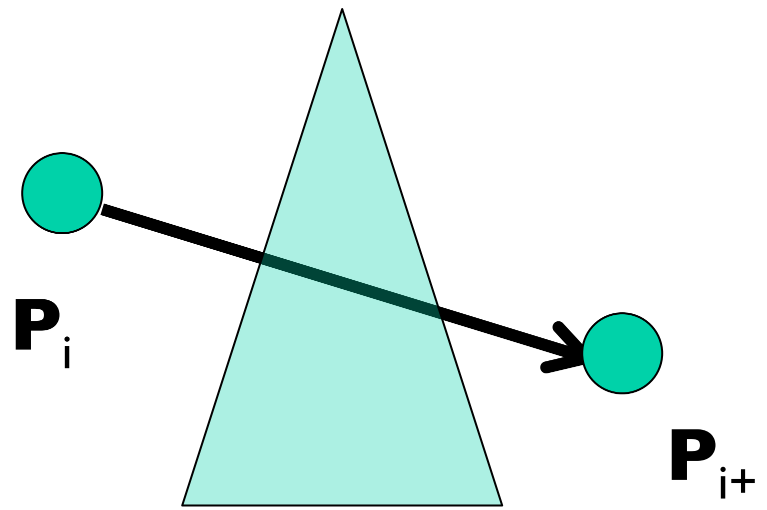
$\mathbf{v}_i = d\mathbf{p}_i\ /dt = \mathbf{p}_i{}' = (dx_i\ /dt, dy_i\ /dt\ , z_i\ /dt)$

$m\ \mathbf{v}_i{}' = \mathbf{f}_i$





Collision ?



Problem:
Triangle & Ray Distinct Objects

Ray/Triangle Intersection

Fast, Minimum Storage Ray/Triangle Intersection

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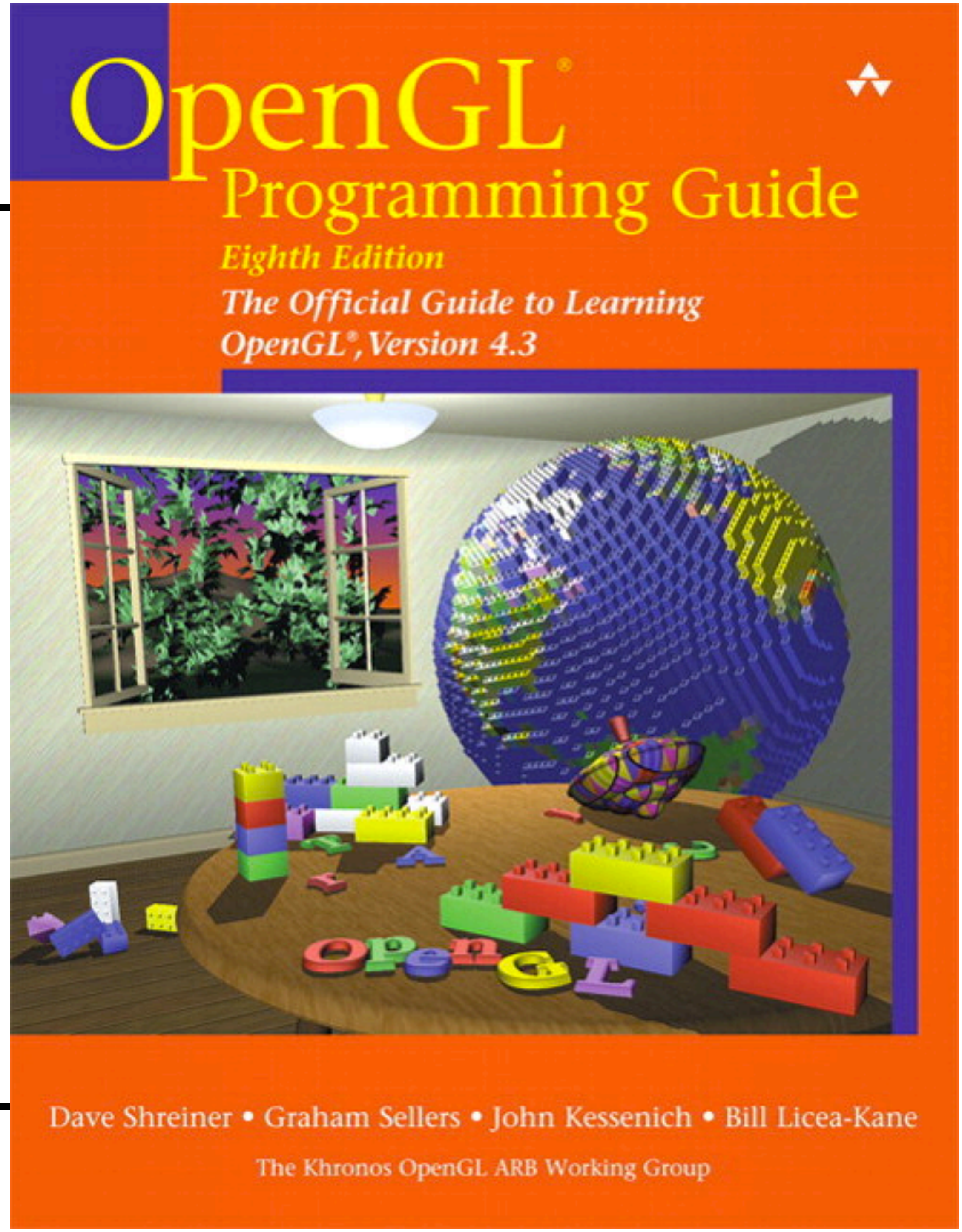
Advanced Features of GLSL
TF - Transform Feedback
TBO – Texture Buffer Obejct

Chapter 5



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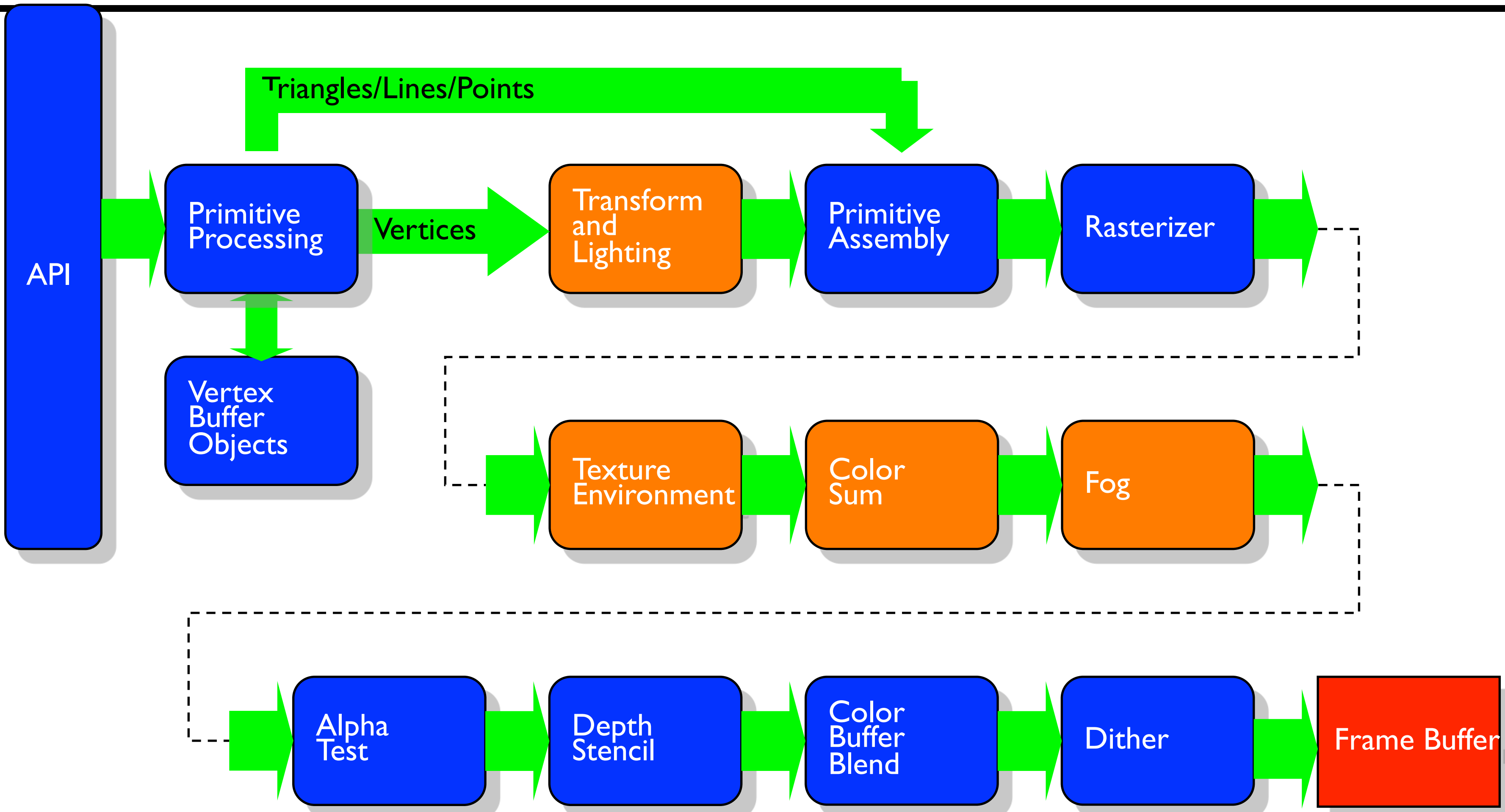
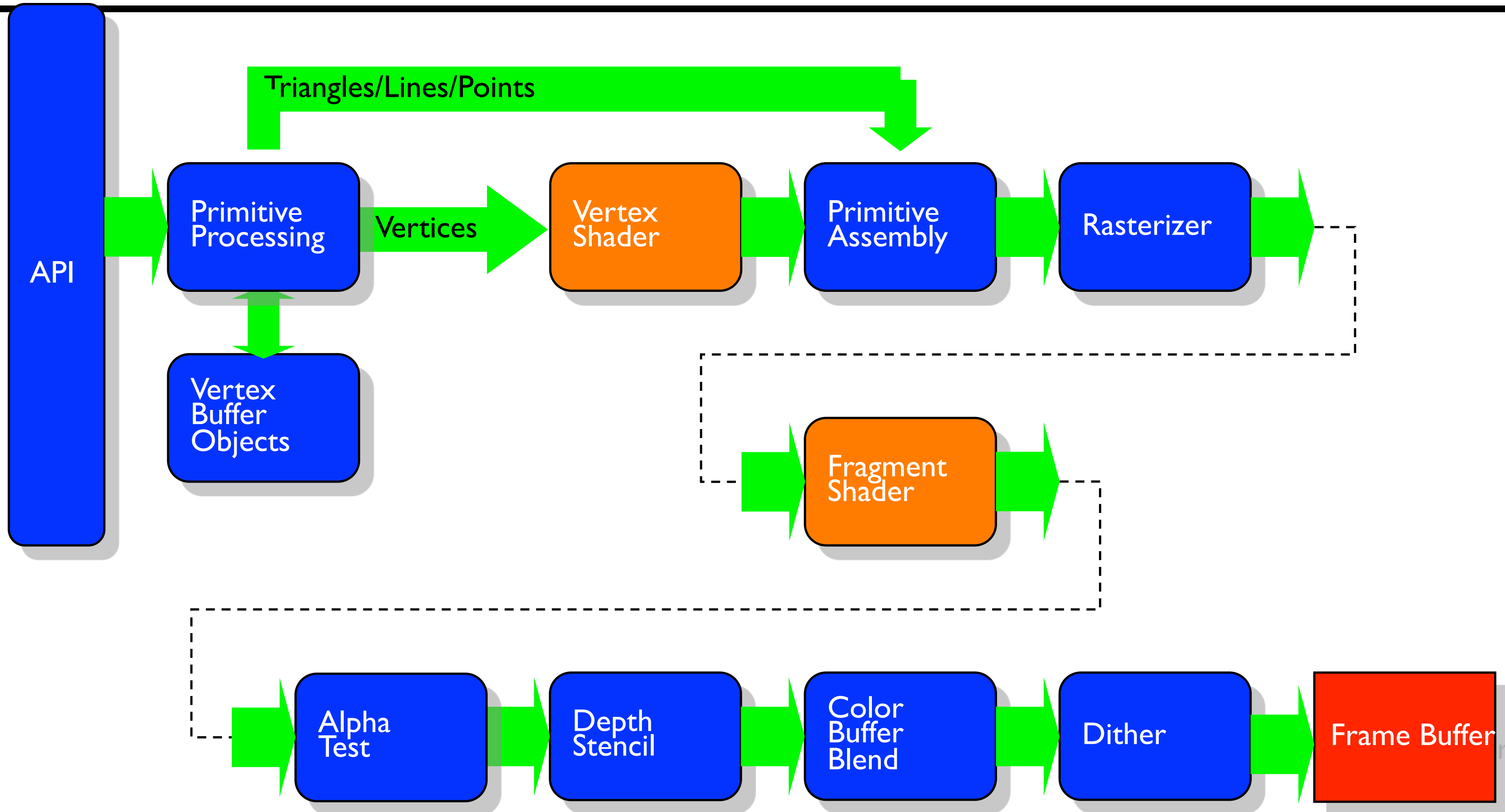
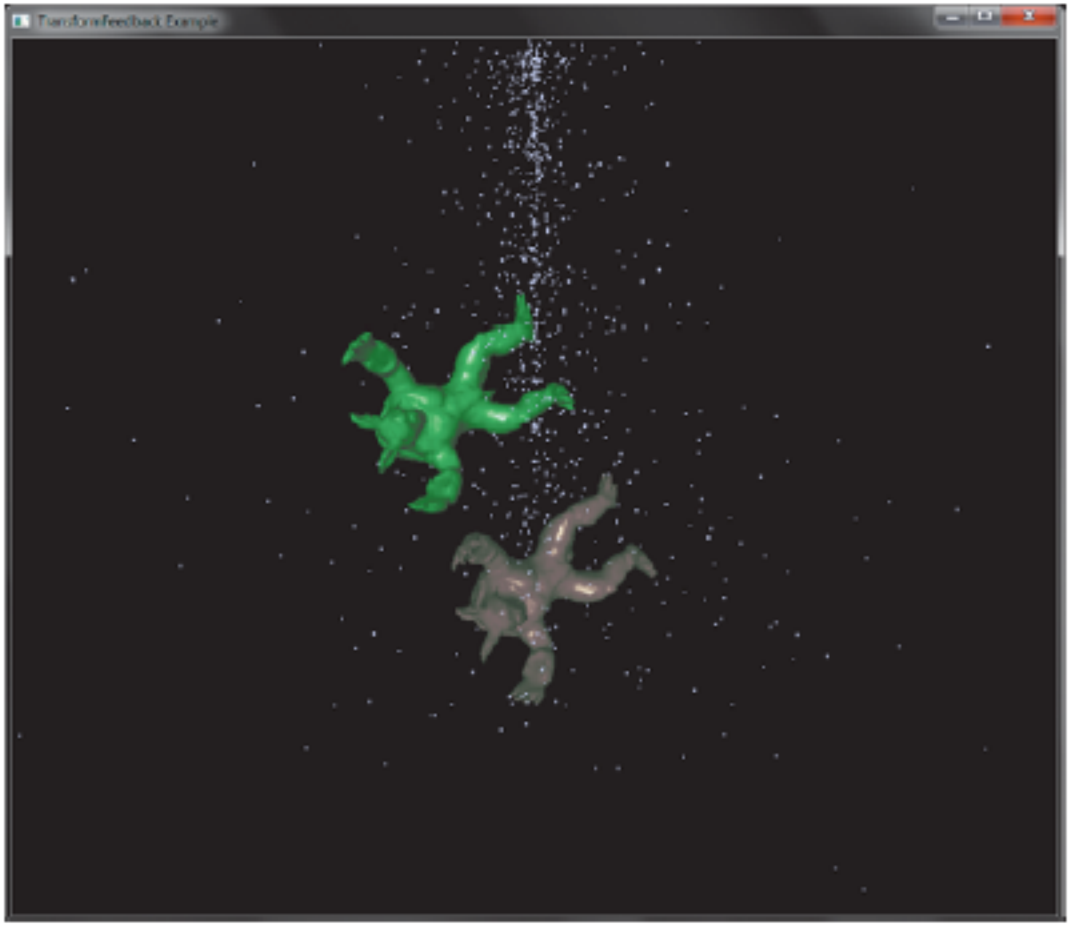
Fixed Functionality Pipeline



Programmable Shader Pipeline



Back2Particles



Schema

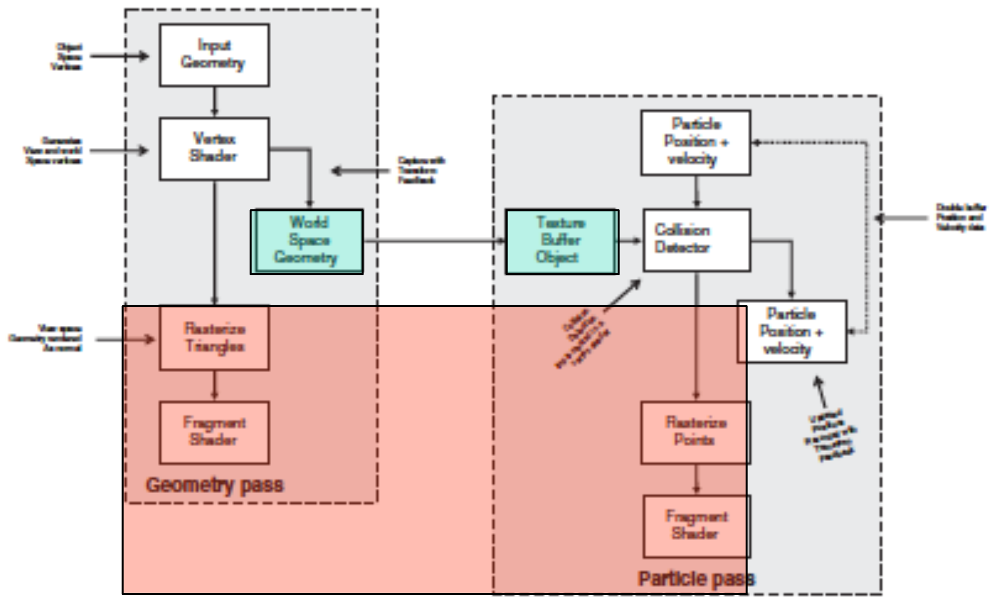


Figure 5.19 Schematic of the particle system simulator

Geometry Pass

Example 5.8 Vertex Shader Used in Geometry Pass of Particle System Simulator

```
#version 420 core

uniform mat4 model_matrix;
uniform mat4 projection_matrix;

layout (location = 0) in vec4 position;
layout (location = 1) in vec3 normal;

out vec4 world_space_position;

out vec3 vs_fs_normal;

void main(void)
{
    vec4 pos = (model_matrix * (position * vec4(1.0, 1.0, 1.0, 1.0)));
    world_space_position = pos;
    vs_fs_normal = normalize((model_matrix * vec4(normal, 0.0)).xyz);
    gl_Position = projection_matrix * pos;
};
```

Storing Geometry

Example 5.9 Configuring the Geometry Pass of the Particle System Simulator

```
static const char * varyings2[] =
{
    "world_space_position"
};

glTransformFeedbackVaryings(render_prog, 1, varyings2,
                            GL_INTERLEAVED_ATTRIBS);
glLinkProgram(render_prog);
```

TBO writing

Transform Feedback

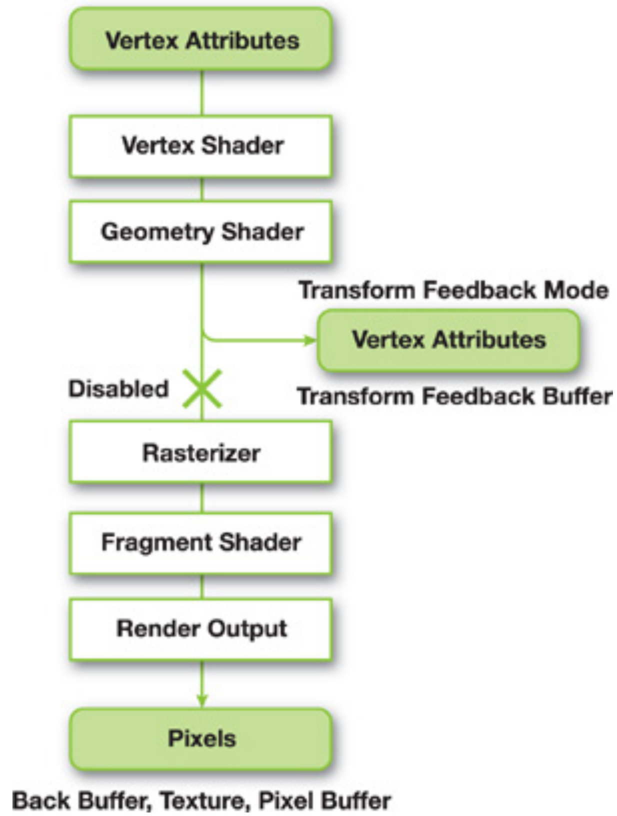
```
void glTransformFeedbackVaryings(GLuint program,
                                 GLsizei count,
                                 const GLchar ** varyings,
                                 GLenum bufferMode);
```

Sets the varyings to be recorded by transform feedback for the program specified by *program*. *count* specifies the number of strings contained in the array *varyings*, which contains the names of the varyings to be captured. *buferMode* is the mode in which the varyings will be captured—either separate mode (specified by GL_SEPARATE_ATTRIBS) or interleaved mode (specified by GL_INTERLEAVED_ATTRIBS).

Transform feedback?

RedBook says: "Transform Feedback is the process of altering the rendering pipeline so that primitives processed by a Vertex Shader and optionally a Geometry Shader will be written to buffer objects. This allows one to preserve the post-transform rendering state of an object and resubmit this data multiple times."

Transform Feedback diagram



Absence of Transform Feedback

To update Vertex Buffer Object's attributes:

1. OpenGL copies VBO from GPU memory to CPU memory

2. Update in CPU and send back

3. Consumes time and bandwidth

Role of TF

1. All computations are now conducted in GPU

2. A special buffer after shaders and send transformations

CPU not needed and little application involvement

Transform Feedback Examples

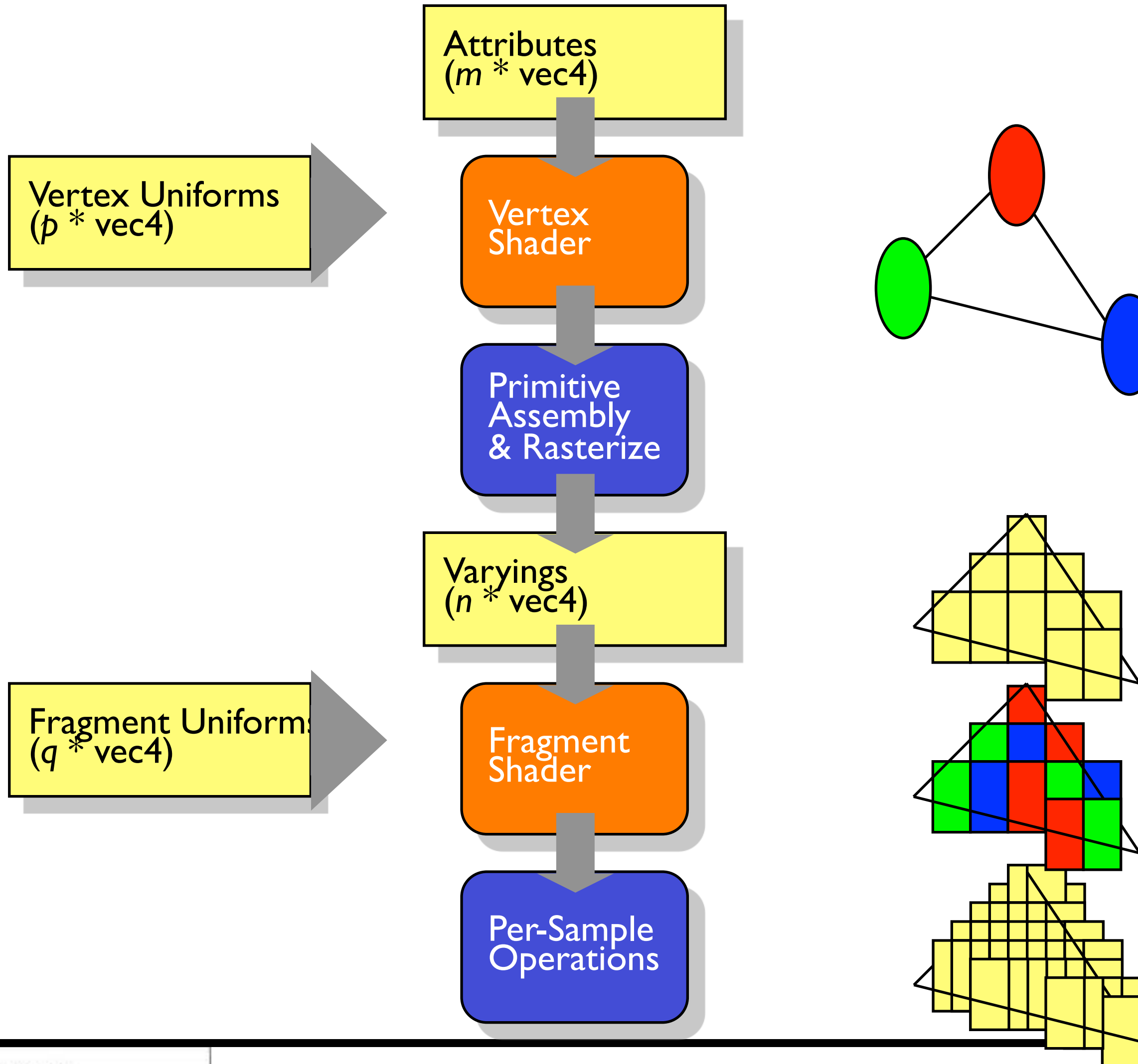
http://www.youtube.com/watch?v=SiCq8ETTqRk

- Uses TF to render a particle smoke system with fire spreading

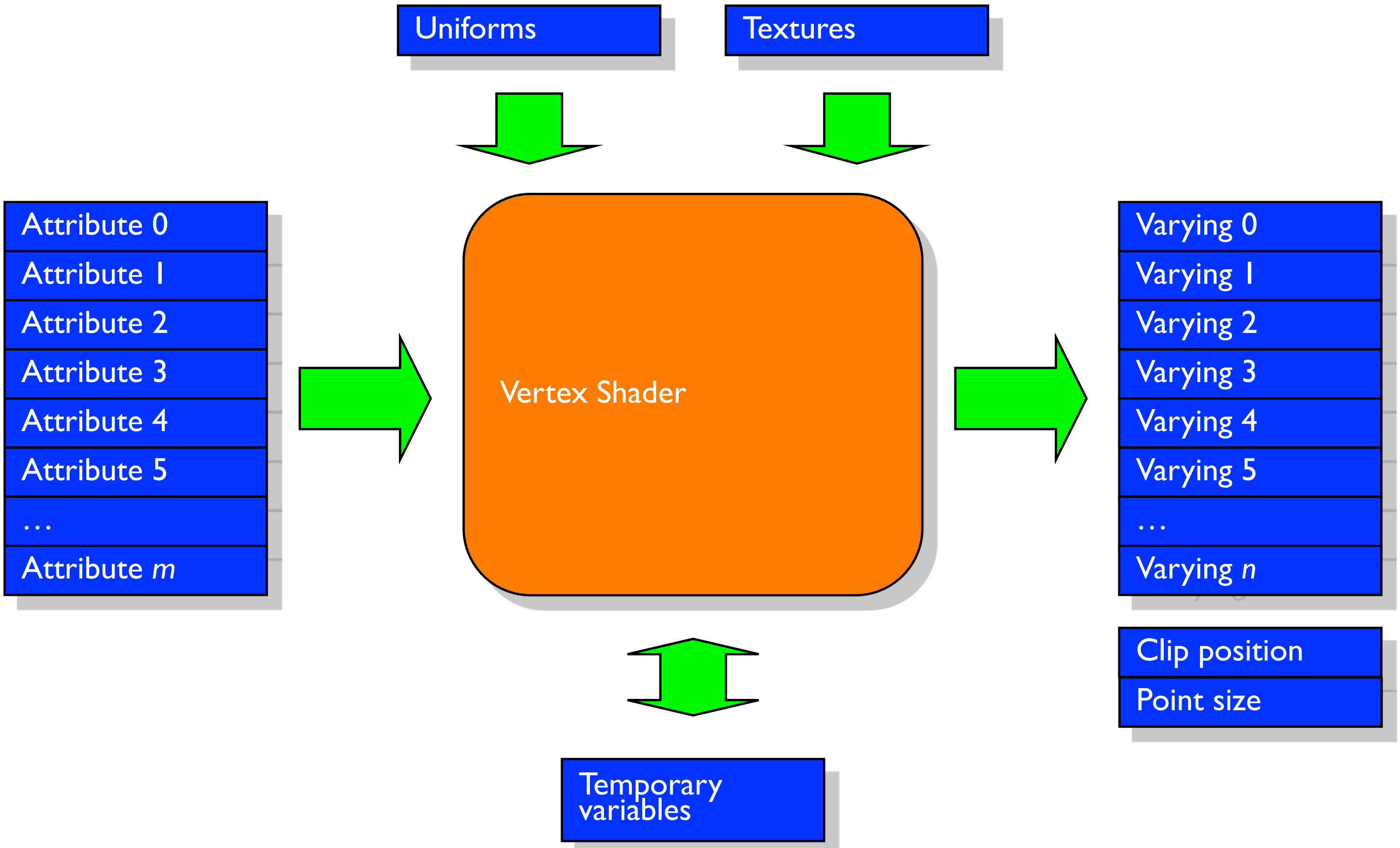
http://www.youtube.com/watch?v=E636tYOxoVI

Attain good performance can be by using TF. It controls all of the particles in this on the GPU.

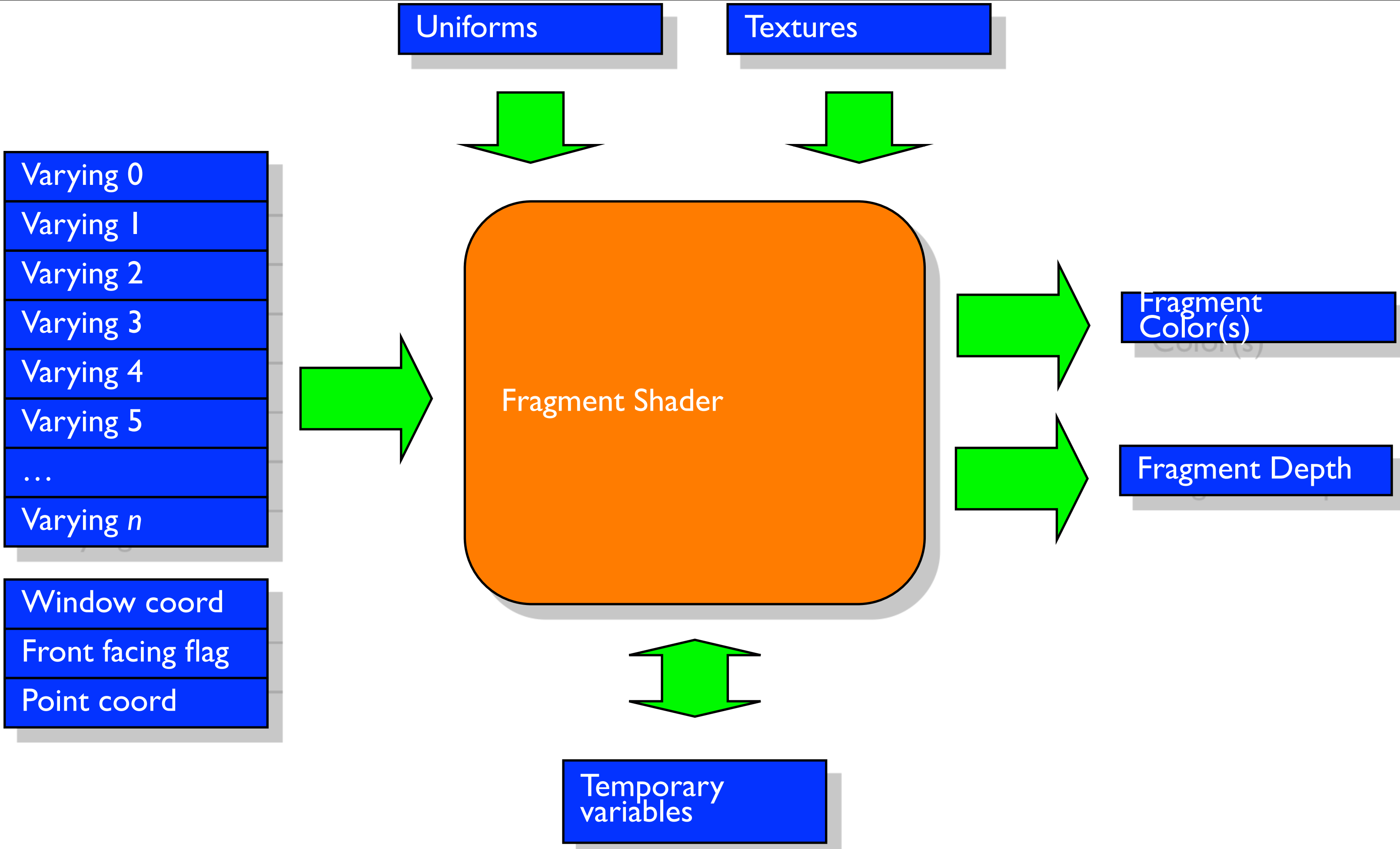
Programmer’s Model



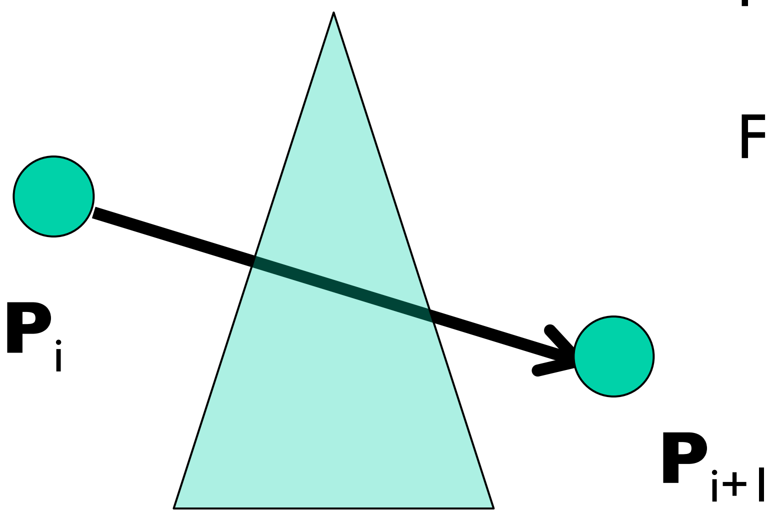
Vertex Shader Environment



Fragment Shader Environment



Collision Detection



Find intersection of ray with plane

Find actual intersection

Ray/Triangle Intersection

Fast, Minimum Storage Ray/Triangle Intersection

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Ben Trumbore
Program of Computer Graphics
Cornell University
E-mail: wbt@graphics.cornell.edu

Some Math

A ray $R(t)$ with origin O and normalized direction D is defined as

$$R(t) = O + tD \tag{1}$$

A point, $T(u, v)$, on a triangle is given by

$$T(u, v) = (1 - u - v)V_0 + uV_1 + vV_2, \tag{2}$$

Some Math

interpolation, color interpolation etc. Computing the intersection between the ray, $R(t)$, and the triangle, $T(u,v)$, is equivalent to $R(t) = T(u,v)$, which yields:

$$O + tD = (1 - u - v)V_0 + uV_1 + vV_2 \tag{3}$$

Rearranging the terms gives:

$$\begin{bmatrix} -D, & V_1 - V_0, & V_2 - V_0 \end{bmatrix} \begin{bmatrix} t \\ u \\ v \end{bmatrix} = O - V_0 \tag{4}$$

This means the barycentric coordinates (u,v) and the distance, t, from the ray origin to the intersection point can be found by solving the linear system of equations above.

Fast Ray-Triangle Intersection

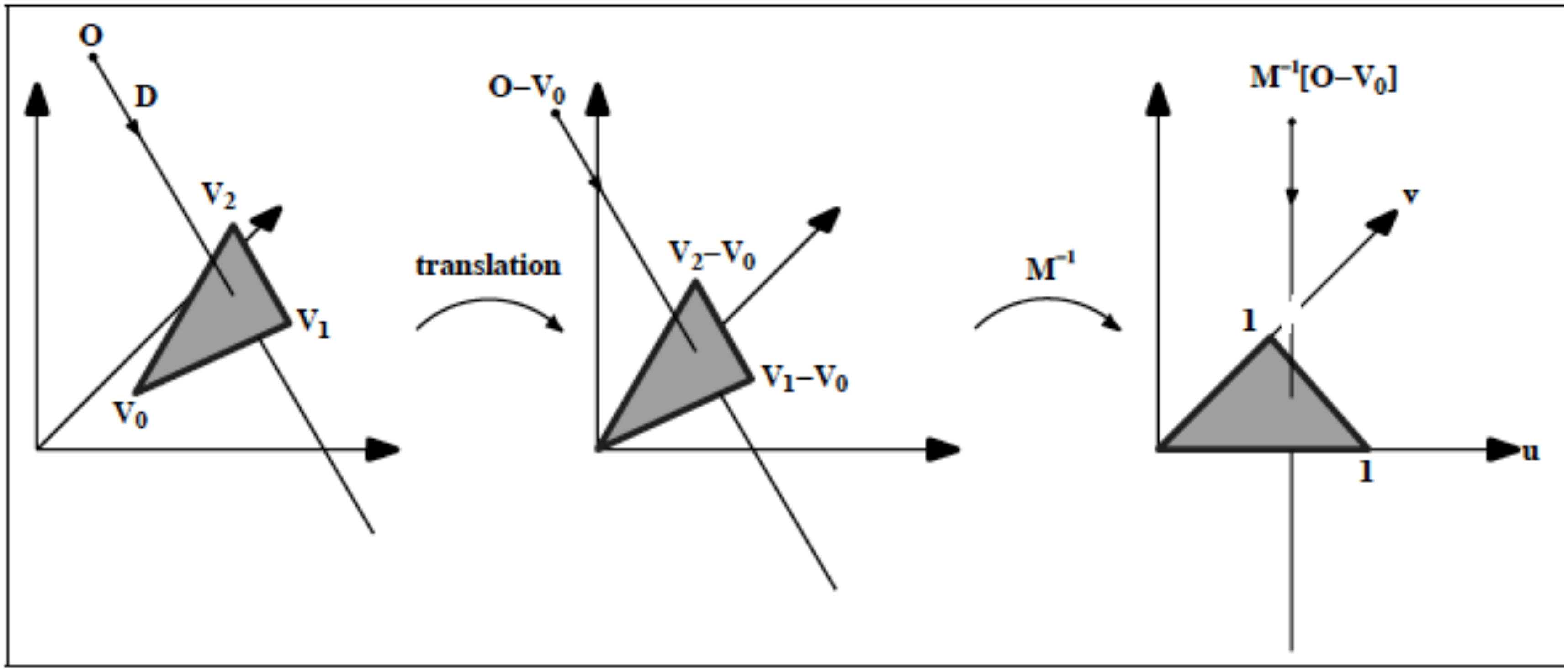

Figure 1: Translation and change of base of the ray origin.

Final Computations

$$\begin{bmatrix} t \\ u \\ v \end{bmatrix} = \frac{1}{(D \times E_2) \cdot E_1} \begin{bmatrix} (T \times E_1) \cdot E_2 \\ (D \times E_2) \cdot T \\ (T \times E_1) \cdot D \end{bmatrix} = \frac{1}{P \cdot E_1} \begin{bmatrix} Q \cdot E_2 \\ P \cdot T \\ Q \cdot D \end{bmatrix}, \qquad (6)$$

where $P = (D \times E_2)$ and $Q = T \times E_1$. In our implementation we reuse these

Geometry Pass

Vertex Shader

Example 5.8 Vertex Shader Used in Geometry Pass of Particle System Simulator

```
#version 420 core

uniform mat4 model_matrix;
uniform mat4 projection_matrix;

layout (location = 0) in vec4 position;
layout (location = 1) in vec3 normal;

out vec4 world_space_position;

out vec3 vs_fs_normal;

void main(void)
{
    vec4 pos = (model_matrix * (position * vec4(1.0, 1.0, 1.0, 1.0)));
    world_space_position = pos;
    vs_fs_normal = normalize((model_matrix * vec4(normal, 0.0)).xyz);
    gl_Position = projection_matrix * pos;
};
```

Configuring Geometry Pass

Example 5.9 Configuring the Geometry Pass of the Particle System Simulator

```
static const char * varyings2[] =
{
    "world_space_position"
};

glTransformFeedbackVaryings(render_prog, 1, varyings2,
                            GL_INTERLEAVED_ATTRIBS);
glLinkProgram(render_prog);
```

TBO writing

Particle Pass

Example 5.10 Vertex Shader Used in Simulation Pass of Particle System Simulator

```
#version 420 core

uniform mat4 model_matrix;
uniform mat4 projection_matrix;
uniform int triangle_count;

layout (location = 0) in vec4 position;
layout (location = 1) in vec3 velocity;

out vec4 position_out;
out vec3 velocity_out;

uniform samplerBuffer geometry_tbo;
uniform float time_step = 0.02;

bool intersect(vec3 origin, vec3 direction, vec3 v0, vec3 v1, vec3 v2,
                out vec3 point)
{
    vec3 u, v, n;
    vec3 w0, w;
    float r, a, b;

    u = (v1 - v0);
    v = (v2 - v0);
    n = cross(u, v);

    w0 = origin - v0;
    a = -dot(n, w0);
    b = dot(n, direction);

    r = a / b;
    if (r < 0.0 || r > 1.0)
        return false;

    point = origin + r * direction;

    float uu, uv, vv, wu, wv, D;

    uu = dot(u, u);
    uv = dot(u, v);
    vv = dot(v, v);
    w = point - v0;
```

Find intersection of ray and plane with triangle

http://en.wikipedia.org/wiki/Line%E2%80%93plane_intersection

Find actual intersection

```
    wu = dot(w, u);
    wv = dot(w, v);
    D = uv * uv - uu * vv;

    float s, t;

    s = (uv * wv - vv * wu) / D;
    if (s < 0.0 || s > 1.0)
        return false;
    t = (uv * wu - uu * wv) / D;
    if (t < 0.0 || (s + t) > 1.0)
        return false;

    return true;
}

vec3 reflect_vector(vec3 v, vec3 n)
{
    return v - 2.0 * dot(v, n) * n;
}

void main(void)
{
    vec3 acceleration = vec3(0.0, -0.3, 0.0);
    vec3 new_velocity = velocity + acceleration * time_step;
    vec4 new_position = position + vec4(new_velocity * time_step, 0.0);
    vec3 v0, v1, v2;
    vec3 point;
    int i;
    for (i = 0; i < triangle_count; i++)
    {
        v0 = texelFetch(geometry_tbo, i * 3).xyz;
        v1 = texelFetch(geometry_tbo, i * 3 + 1).xyz;
        v2 = texelFetch(geometry_tbo, i * 3 + 2).xyz;
        if (intersect(position.xyz, position.xyz - new_position.xyz,
                      v0, v1, v2, point))
        {
            vec3 n = normalize(cross(v1 - v0, v2 - v0));
            new_position = vec4(point
                               + reflect_vector(new_position.xyz -
                                 point, n), 1.0);
            new_velocity = 0.8 * reflect_vector(new_velocity, n);
        }
    }
    if (new_position.y < -40.0)
    {
        new_position = vec4(-new_position.x * 0.3, position.y + 80.0,
                            0.0, 1.0);
        new_velocity *= vec3(0.2, 0.1, -0.3);
    }
    velocity_out = new_velocity * 0.9999;
    position_out = new_position;
    gl_Position = projection_matrix * (model_matrix * position);
};
```

$$\begin{bmatrix} t \\ u \\ v \end{bmatrix} = \frac{1}{(D \times E_2) \cdot E_1} \begin{bmatrix} (T \times E_1) \cdot E_2 \\ (D \times E_2) \cdot T \\ (T \times E_1) \cdot D \end{bmatrix} = \frac{1}{P \cdot E_1} \begin{bmatrix} Q \cdot E_2 \\ P \cdot T \\ Q \cdot D \end{bmatrix}, \qquad (6)$$

where $P = (D \times E_2)$ and $Q = T \times E_1$. In our implementation we reuse these

https://www.opengl.org/sdk/docs/man/html/texelFetch.xhtml

Configuring Particle Pass

Example 5.11 Configuring the Simulation Pass of the Particle System Simulator

```
static const char * varyings[] =
{
    "position_out", "velocity_out"
};

glTransformFeedbackVaryings(update_prog, 2, varyings,
                            GL_INTERLEAVED_ATTRIBS);

glLinkProgram(update_prog);
```

Example 5.12 Main Rendering Loop of the Particle System Simulator

```
glUseProgram(render_prog);
glUniformMatrix4fv(render_model_matrix_loc, 1, GL_FALSE, model_matrix);
glUniformMatrix4fv(render_projection_matrix_loc, 1, GL_FALSE,
                   projection_matrix);

glBindVertexArray(render_vao);

glBindBufferBase(GL_TRANSFORM_FEEDBACK_BUFFER, 0, geometry_vbo);
glBeginTransformFeedback(GL_TRIANGLES);
object.Render();
glEndTransformFeedback();

glUseProgram(update_prog);
glUniformMatrix4fv(model_matrix_loc, 1, GL_FALSE, model_matrix);
glUniformMatrix4fv(projection_matrix_loc, 1, GL_FALSE,
                   projection_matrix);
glUniform1i(triangle_count_loc, object.GetVertexCount() / 3);

if ((frame_count & 1) != 0)
{
    glBindVertexArray(vao[1]);
    glBindBufferBase(GL_TRANSFORM_FEEDBACK_BUFFER, 0, vbo[0]);
 else
 {
     glBindVertexArray(vao[0]);
     glBindBufferBase(GL_TRANSFORM_FEEDBACK_BUFFER, 0, vbo[1]);
 }

 glBeginTransformFeedback(GL_POINTS);
 glDrawArrays(GL_POINTS, 0, min(point_count, (frame_count >> 3)));
 glEndTransformFeedback();

 glBindVertexArray(0);

 frame_count++;
```

Shadows

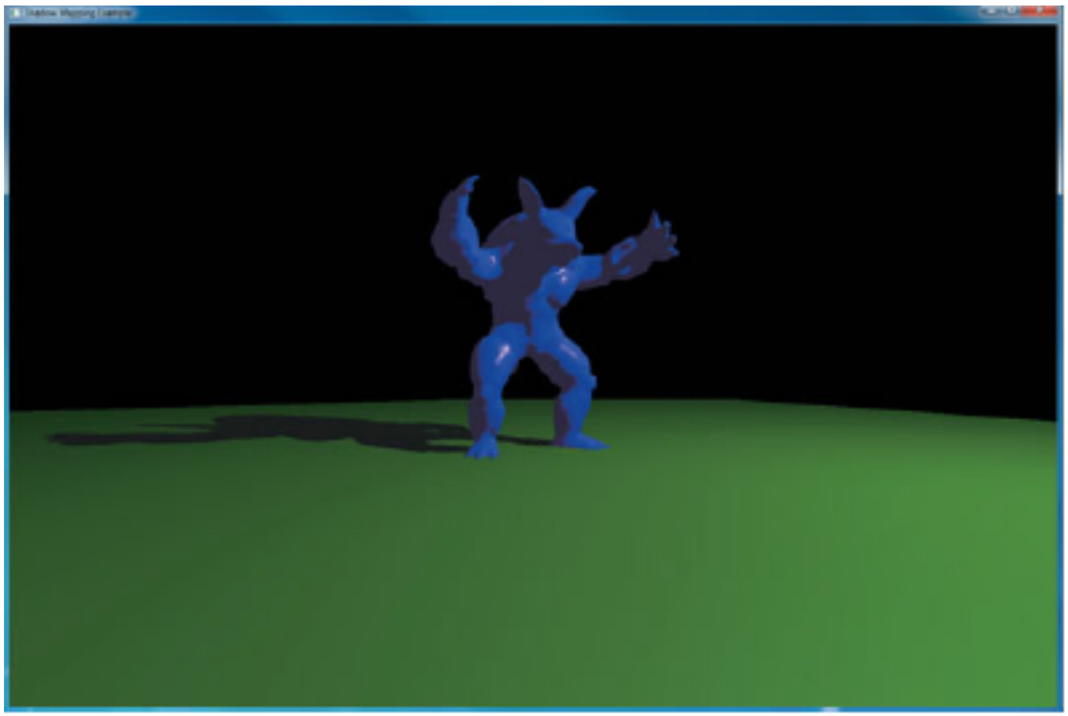

Figure 7.11 Final rendering of shadow map

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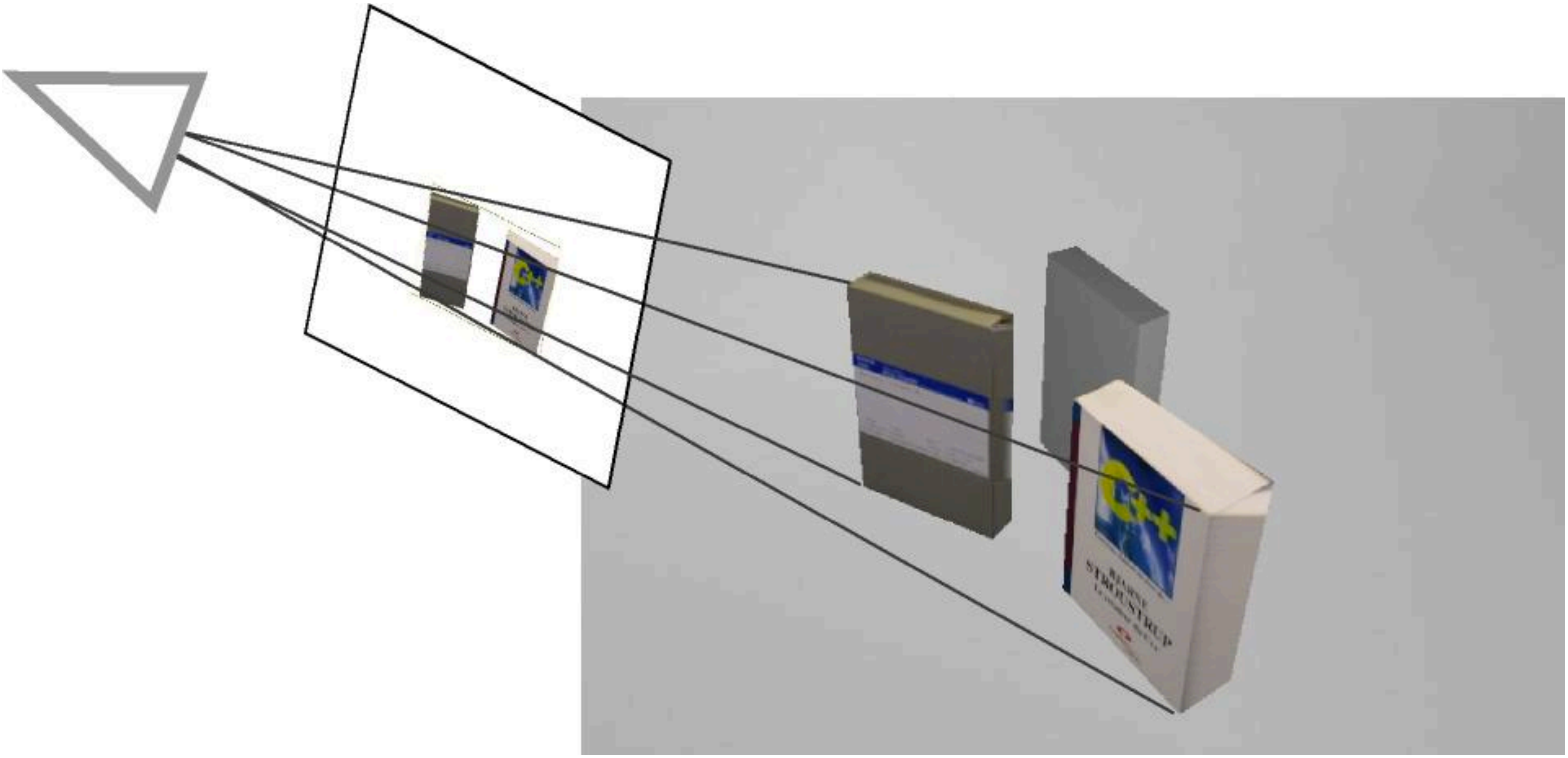
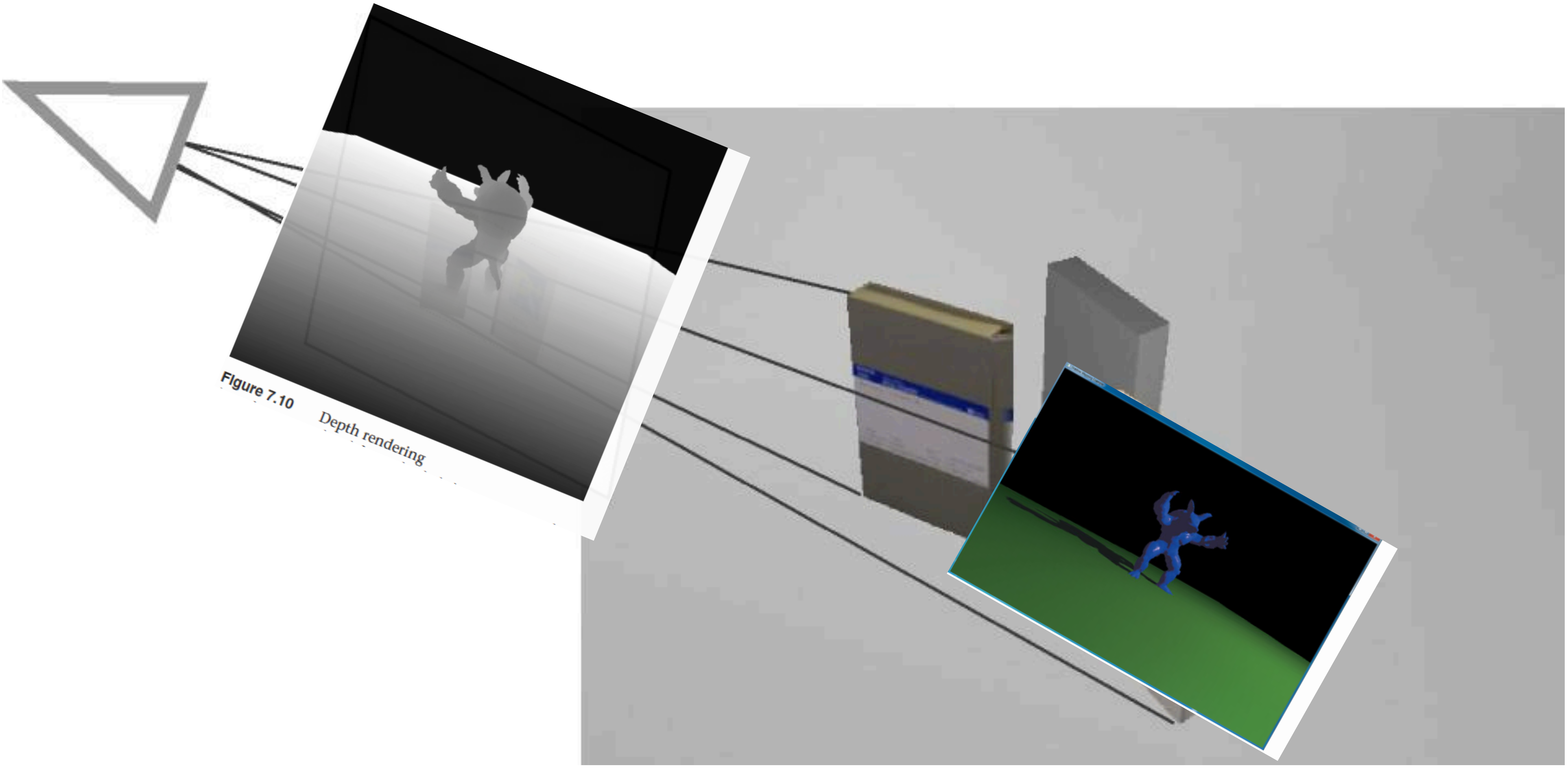
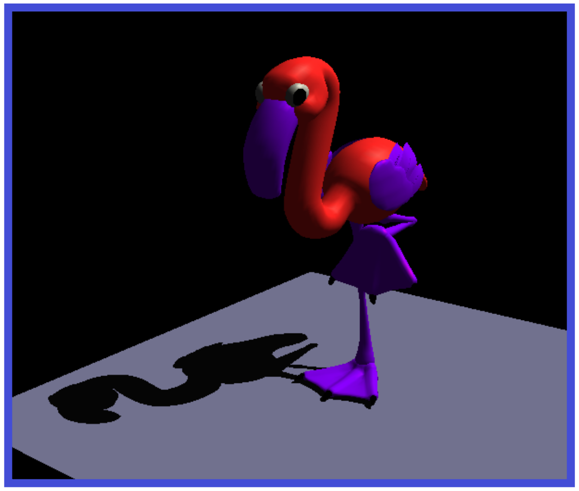
Shadows & Textures ?



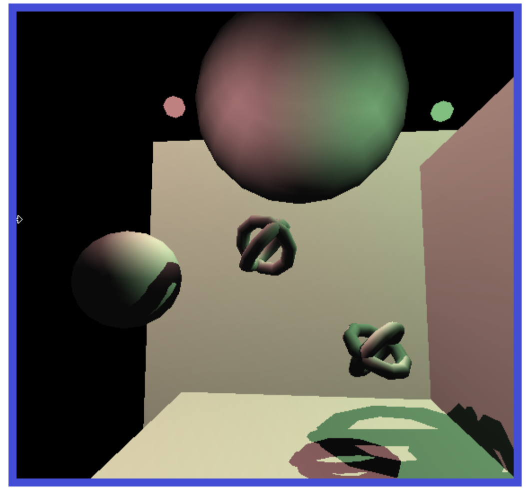
Shadows & Textures ?



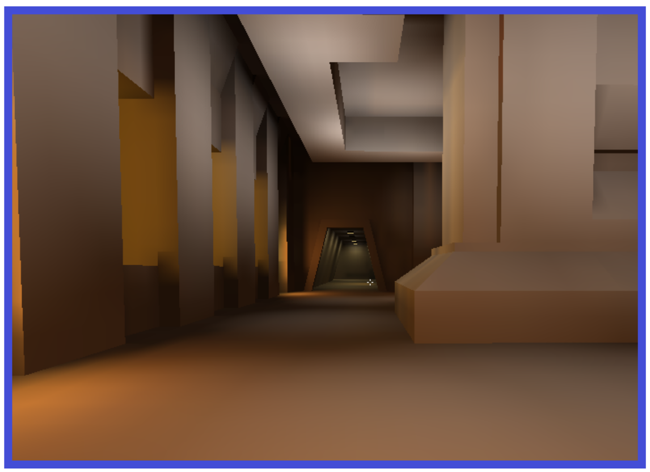
Real-time Shadow Techniques



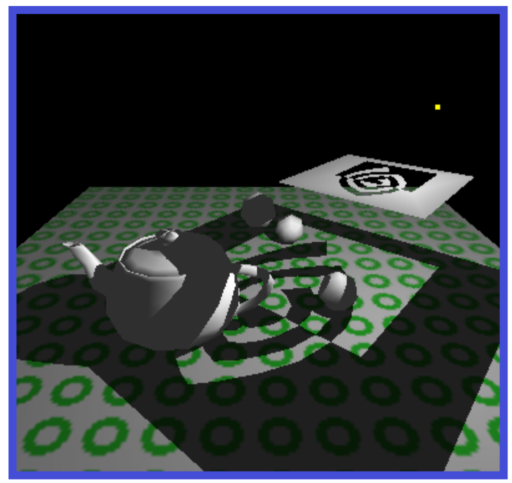
Projected planar shadows



Shadow volumes



Light maps



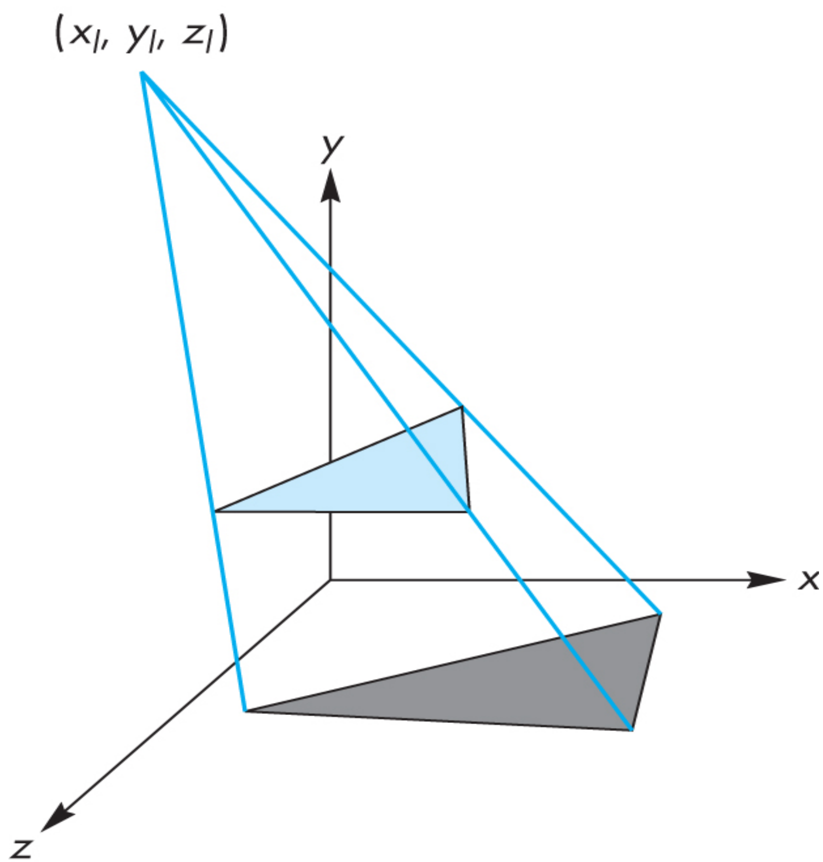
Hybrid approaches

Luxo Jr. – The Famous One

- Luxo Jr. has two animated lights and one overhead light
  - Three shadow maps *dynamically* generated per frame
- Complex geometry (cords and lamp arms) all correctly shadowed
- User controls the view, shadowing just works

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

Shadow Mapping



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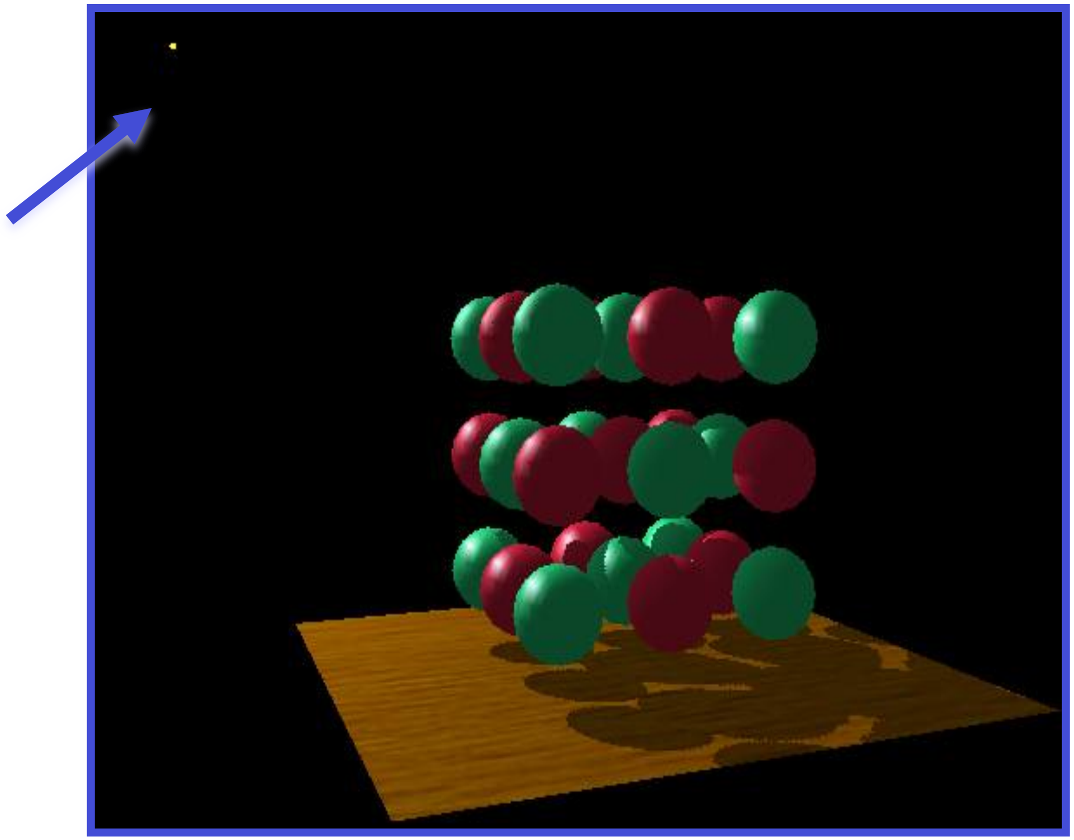
Projective Shadows

- Projection of a polygon is a polygon called a shadow polygon
- Given a point light source and a polygon, the vertices of the shadow polygon are the projections of the original polygon's vertices from a point source onto a surface

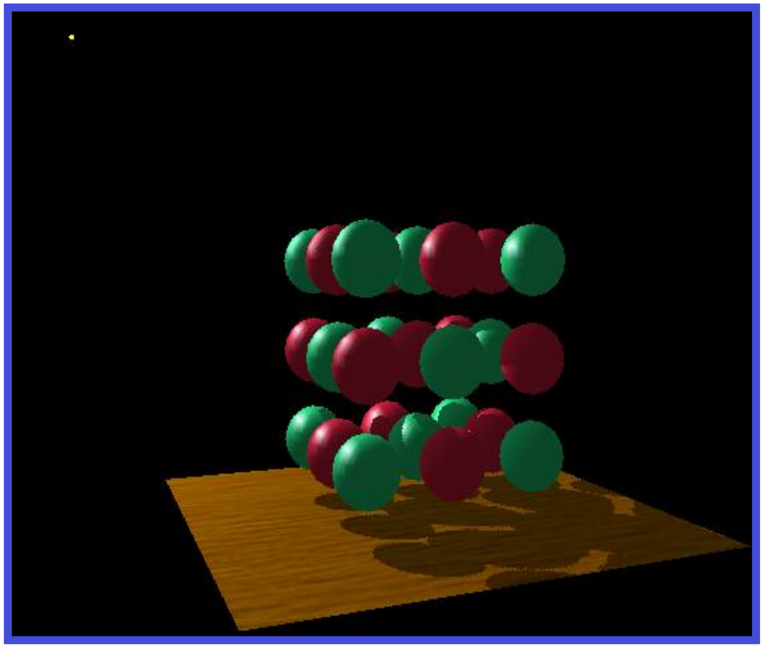
Visualizing Shadow Mapping

the point light source

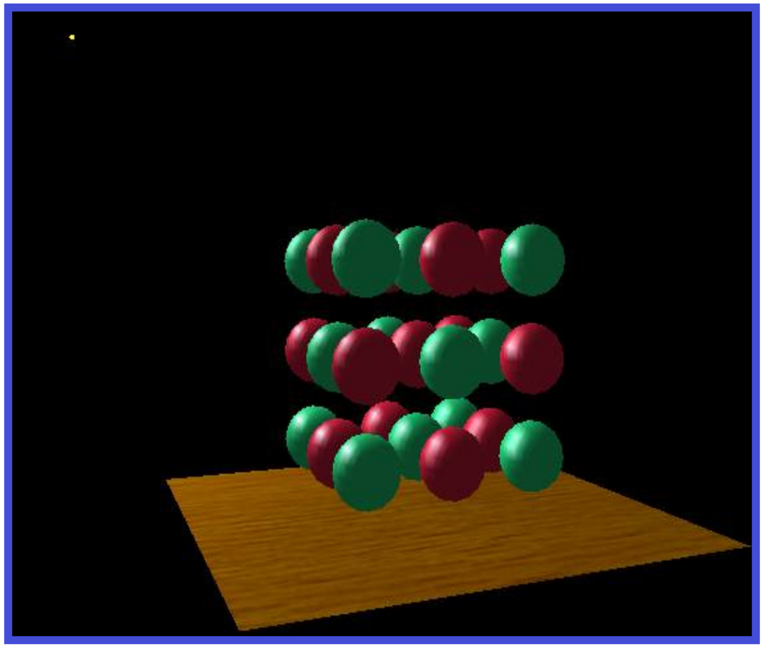


Visualizing Shadow Mapping

Compare with and without shadows



with shadows



without shadows

Shadow Process

1. Put two identical triangles and their colors on GPU (black for shadow triangle)
2. Compute two model view matrices as uniforms
3. Send model view matrix for original triangle
4. Render original triangle
5. Send second model view matrix
6. Render shadow triangle

– Note shadow triangle undergoes two transformations
– Note hidden surface removal takes care of depth issues

Shadow Map Matrices

1. Source at (x_l, y_l, z_l)
2. Vertex at (x, y, z)
3. Consider simple case of shadow projected onto ground at $(x_p, 0, z_p)$
4. Translate source to origin with $T(-x_l, -y_l, -z_l)$
5. Perspective projection

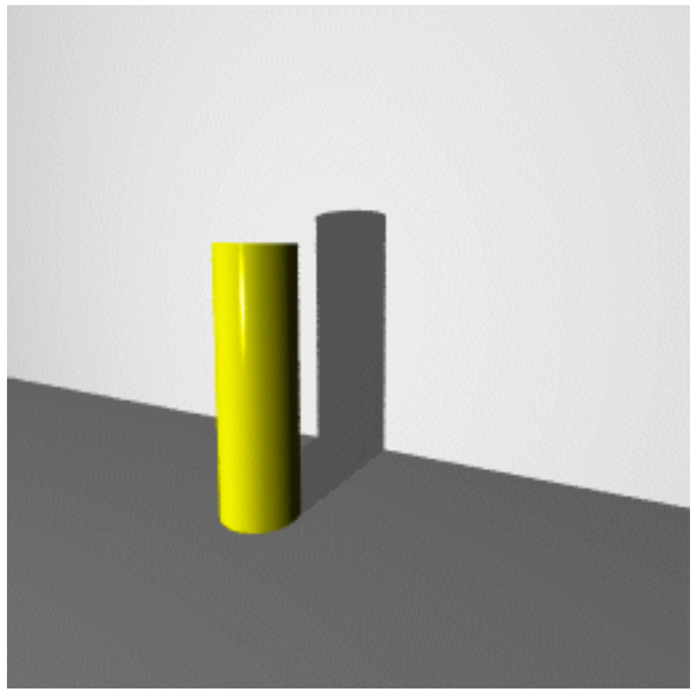
$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & \frac{1}{-y_l} & 0 & 0 \end{bmatrix}$$

6. Translate back

Shadow Maps

- Render a scene from a light source; depth buffer will contain the distances from the source to each fragment.
- Store depths in texture called **depth/shadow map**
- Render image in shadow map with light - anything lit is not in shadow.
- Form a shadow map for each source

Example



Shadows

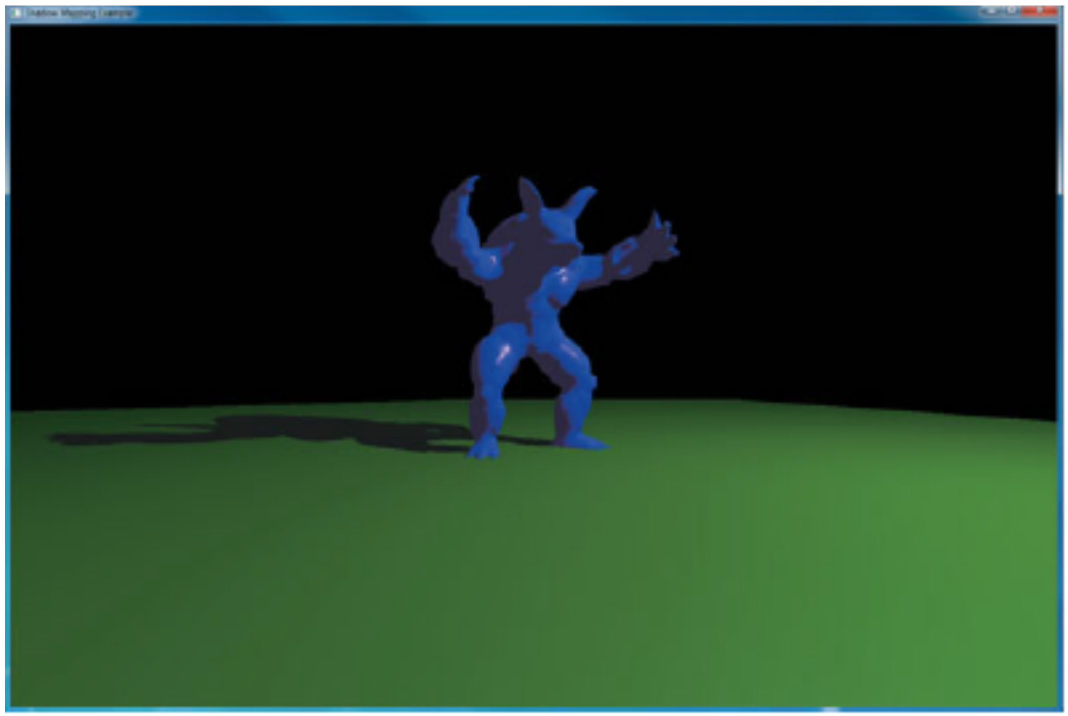


Figure 7.11 Final rendering of shadow map

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Shadow Map

Figure 7.10 Depth rendering

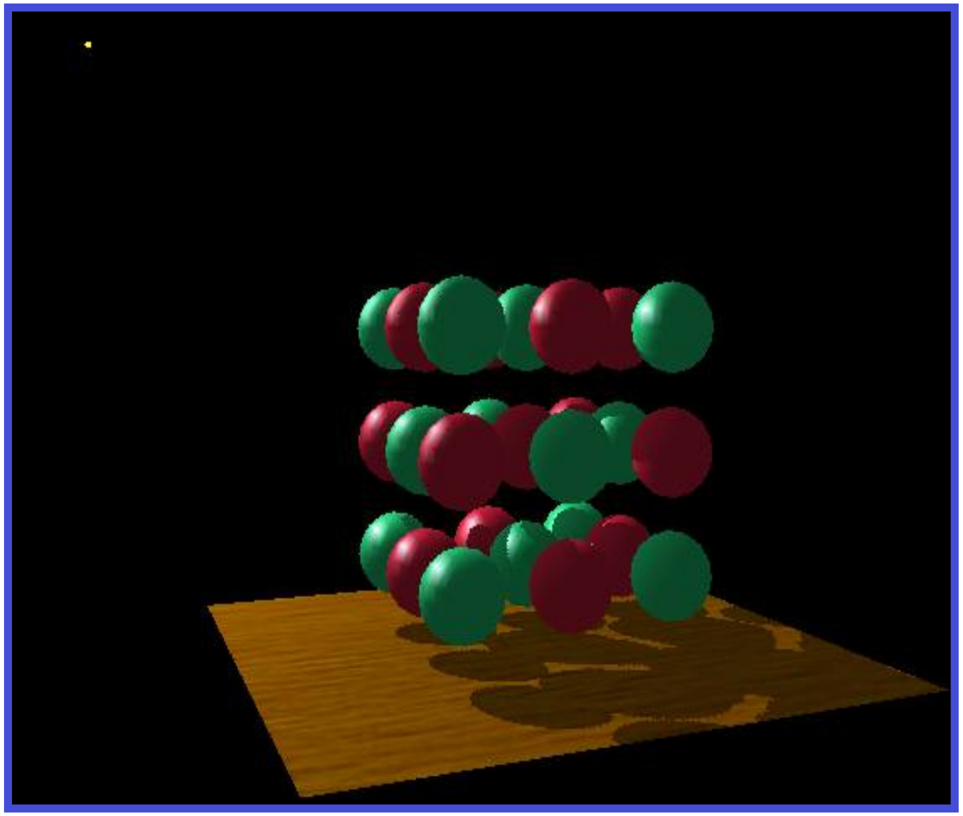
Final Rendering

- Compare distance from fragment to light source with distance in the shadow map
- If depth in shadow map is less than distance from fragment to source, fragment is in shadow (from this source)
- Otherwise we use rendered color

Visualizing Shadow Mapping

Scene with shadows

Notice how specular highlights never appear in shadows



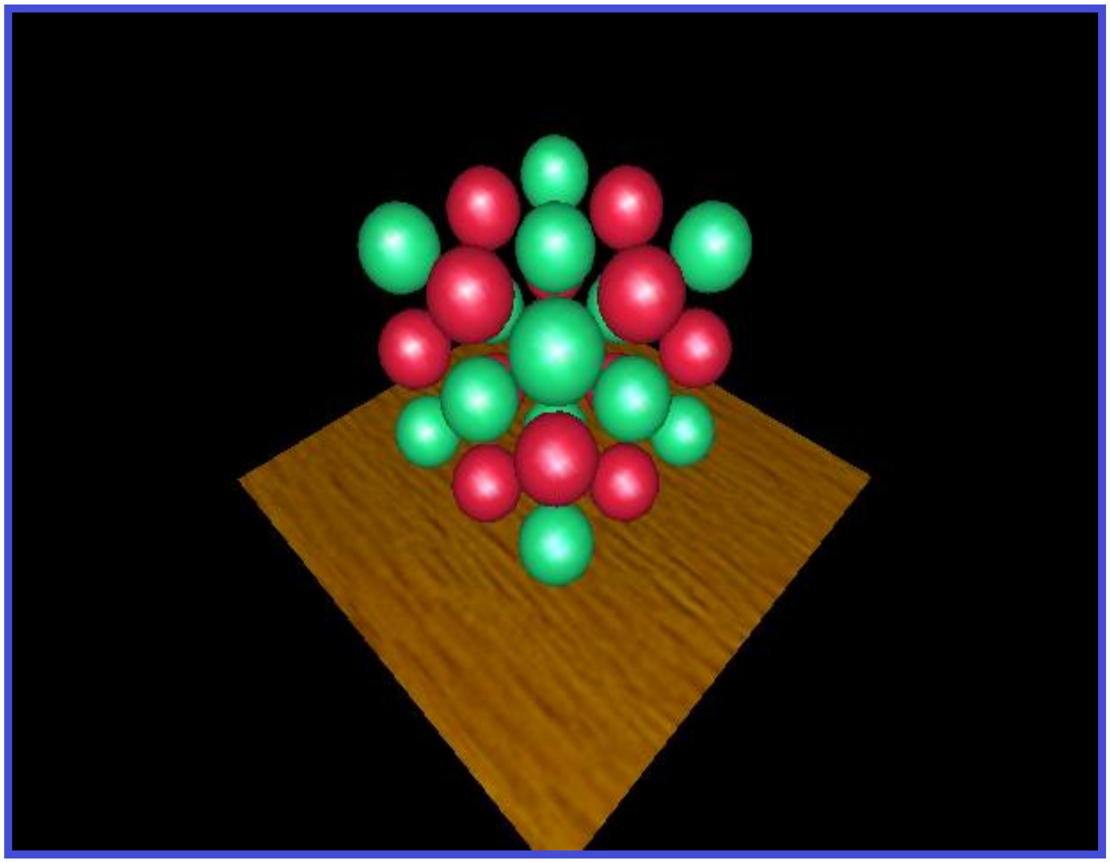
Notice how curved surfaces cast shadows on each other

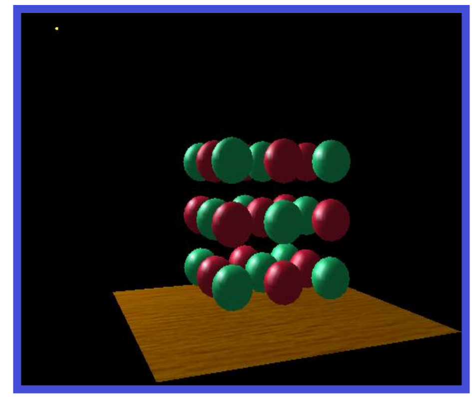
Applications Side

- Start with vertex in object coordinates
- Want to convert representation to texture coordinates
- Form LookAt matrix from light source to origin in object coordinates (MVL)
- From projection matrix for light source (PL)
- From a matrix to convert from [-1, 1] clip coordinates to [0, 1] texture coordinates
- Concatenate to form object to texture coordinate matrix (OTC)

Visualizing Shadow Mapping

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

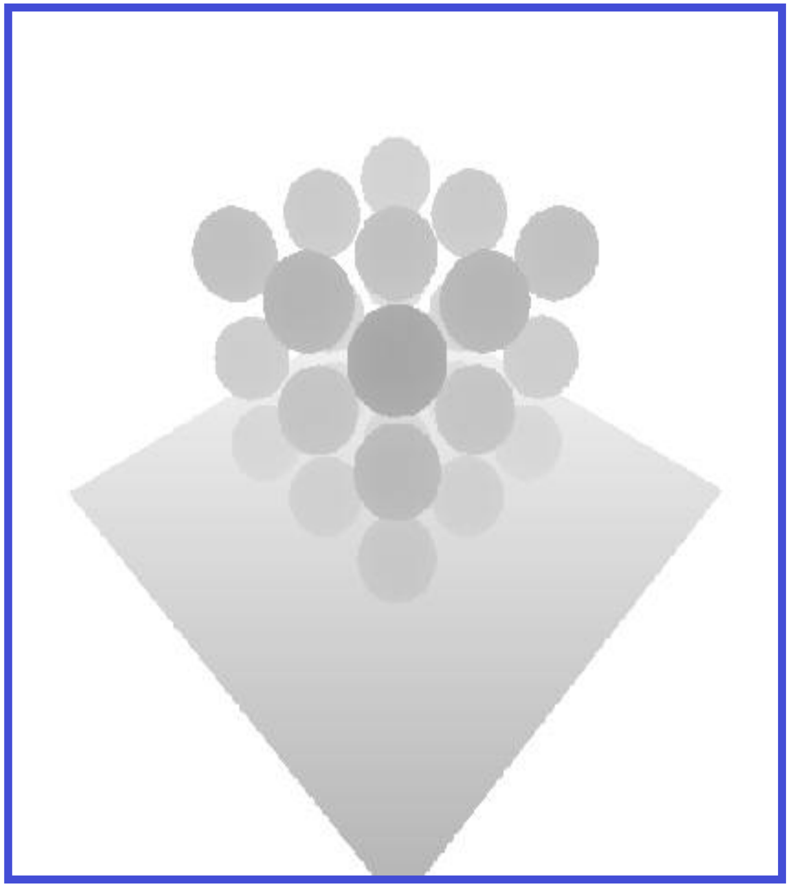


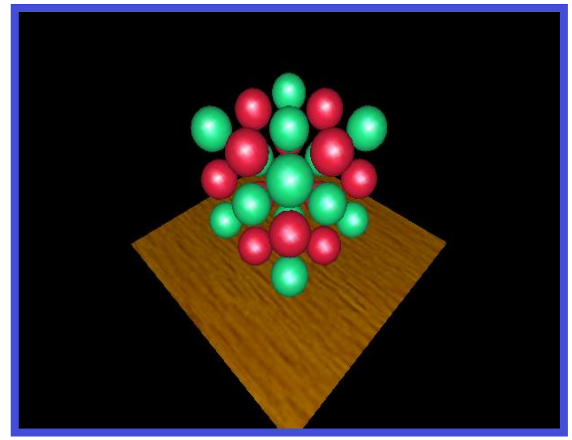


FYI: from the eye's point-of-view again

Visualizing Shadow Mapping

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

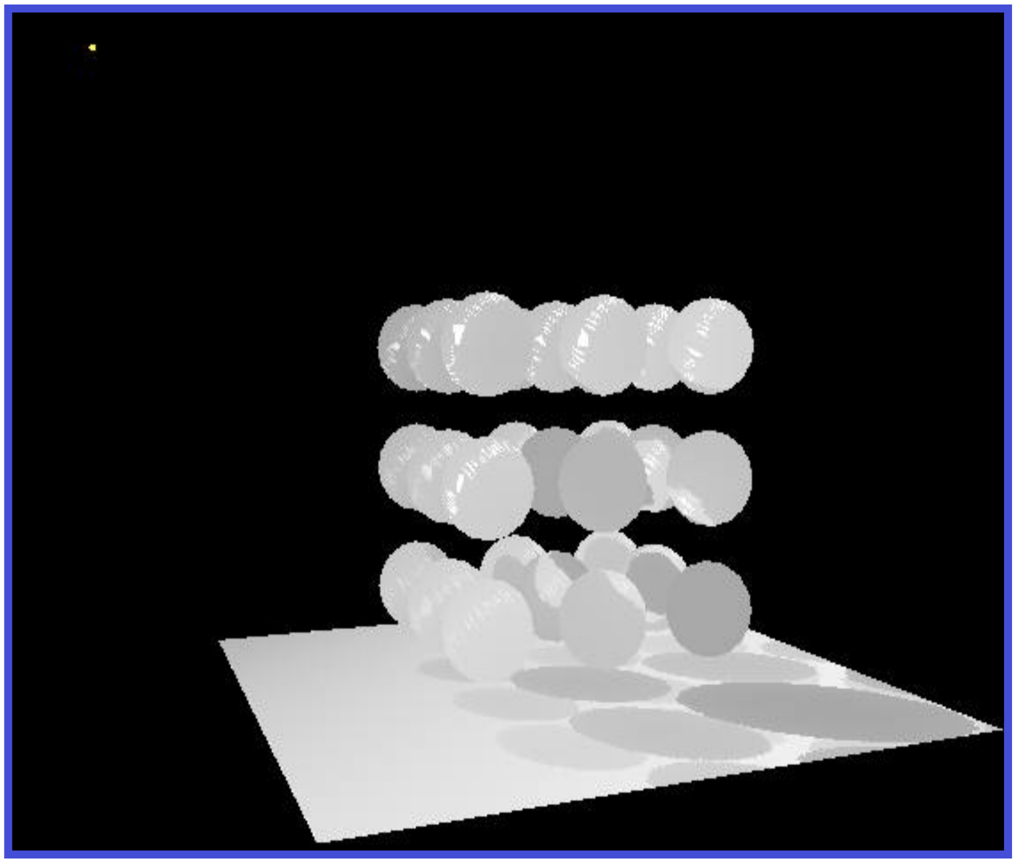


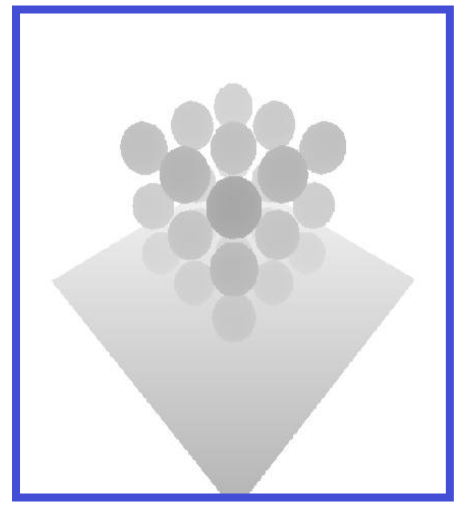


FYI: from the light's point-of-view again

Visualizing Shadow Mapping

Projecting the depth map onto the eye's view

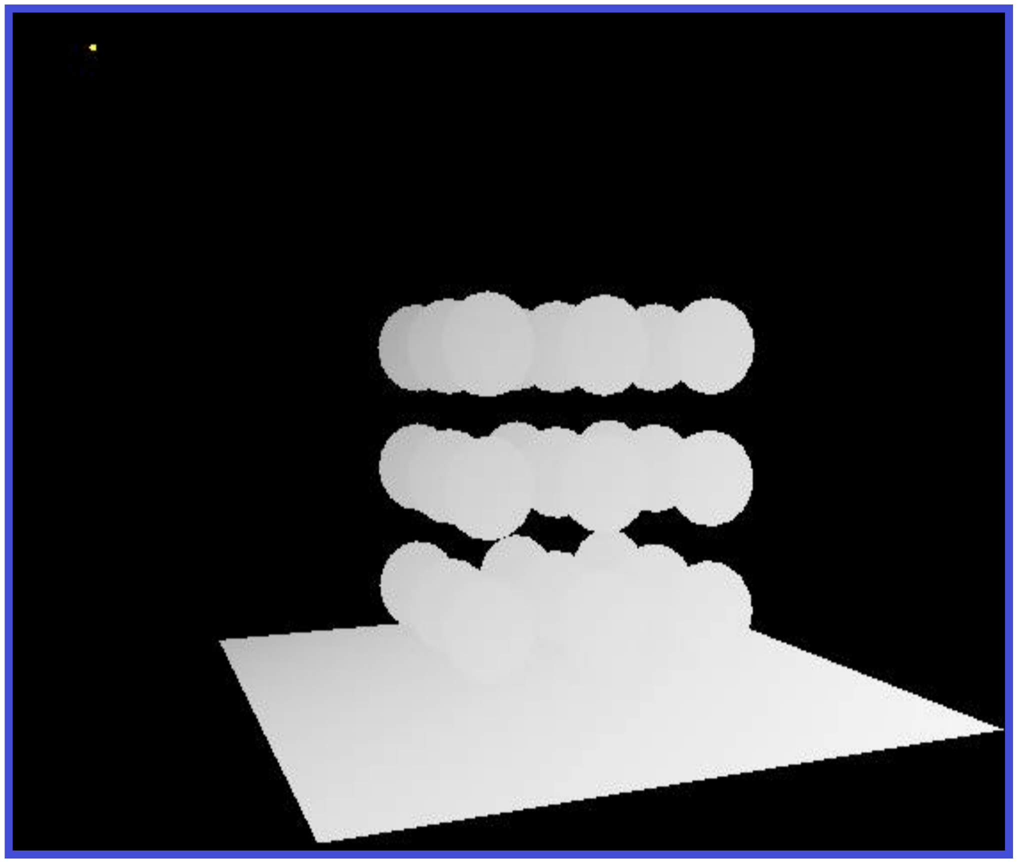




FYI: depth map for light's point-of-view again

Visualizing Shadow Mapping

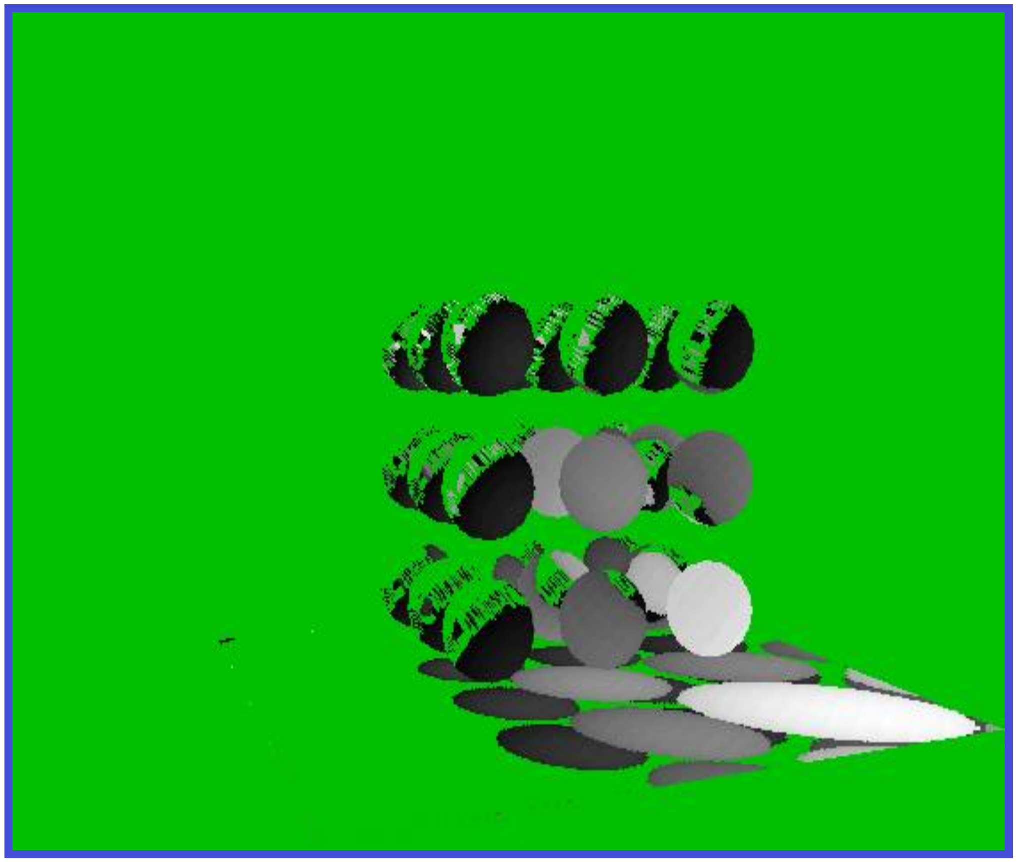
Projecting light's planar distance onto eye's view



Visualizing Shadow Mapping

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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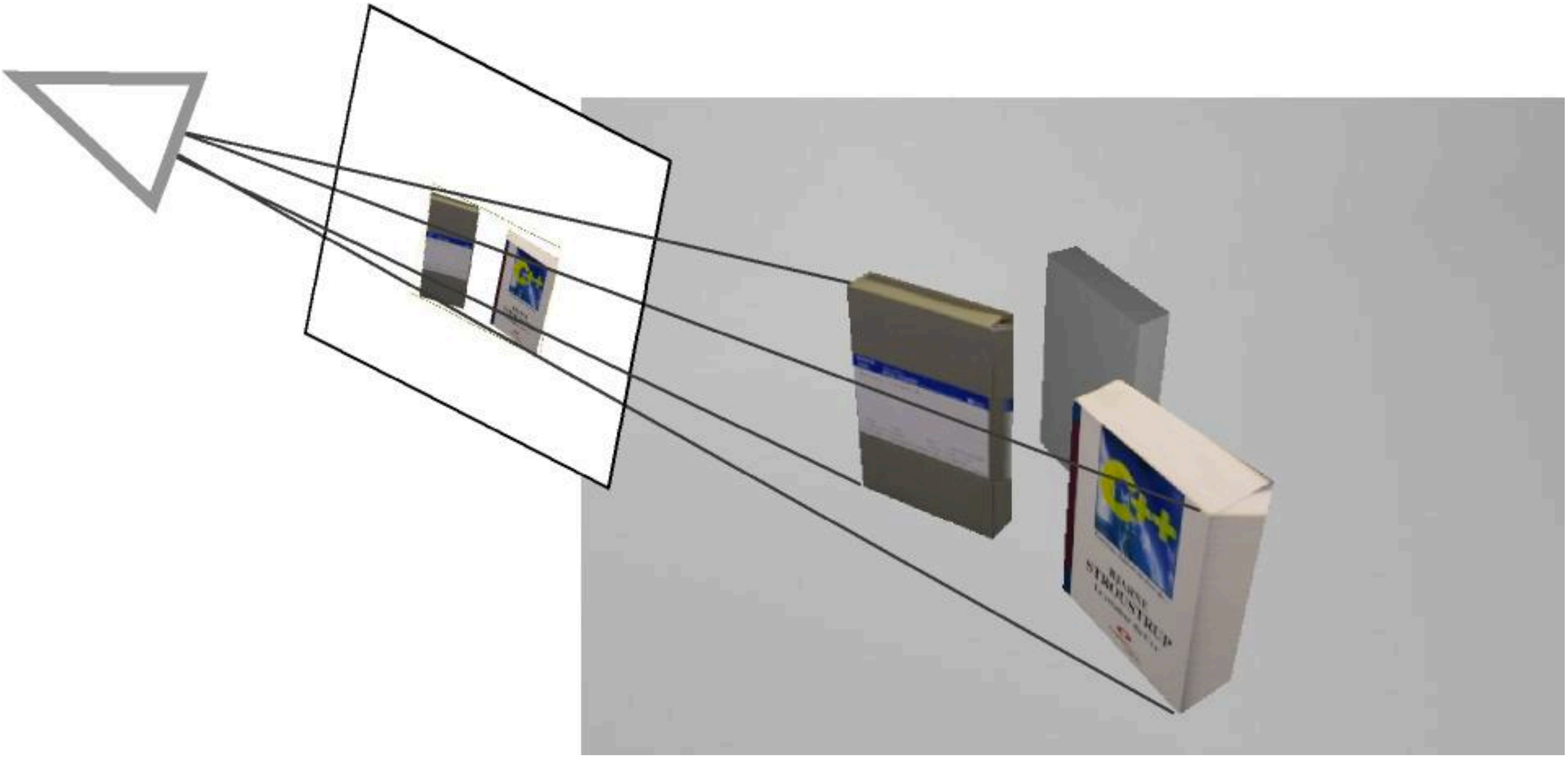
Generalized Shadows

- Approach was OK for shadows on a single flat surface
- Cannot handle shadows on general objects

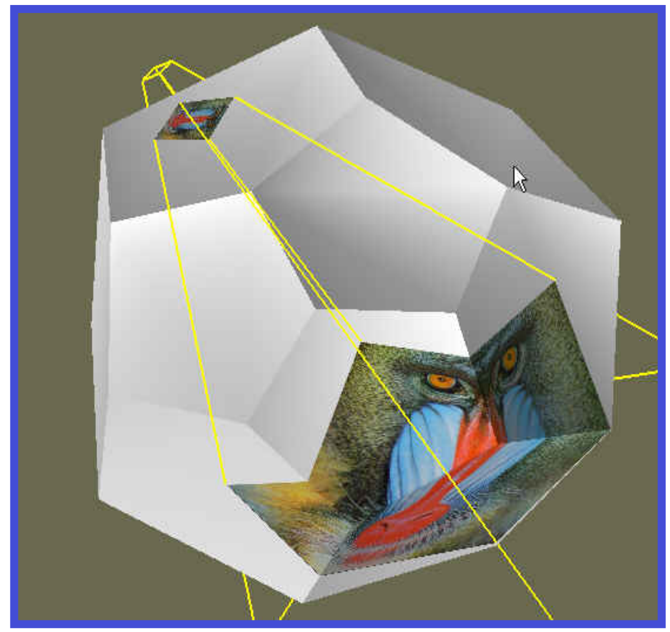
Projective Textures



Projective Texturing?

An intuition for projective texturing

- The slide projector analogy



Source: Wolfgang Heidrich [99]

Image Based Lighting

- Project texture onto surface; treat texture as "slide projector"
- Projective textures and image based lighting
- OpenGL/GLSL – 4D texture coordinates

Projective Texturing

Key - perspective-correct texturing?

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

Projective Texturing

- 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)
- Project (s/q, t/q, r/q) per-fragment

Projective Texturing

Tricking hardware into doing projective textures

- By interpolating q/w, hardware computes per-fragment
  - (s/w) / (q/w) = s/q
  - (t/w) / (q/w) = t/q
- Net result: projective texturing

4D Textures Coordinates

- Texture coordinates (s, t, r, q) affected by perspective division; actual coordinates (s/q, t/q, r/q) or (s/q, t/q) for 2D textures

- GLSL – *textureProj* uses the 2D/3D texture coordinate obtained by a perspective division of a 4D texture coordinate a texture value from a sampler

color = textureProj(my_sampler, tex_coord)

Shadow Map Generation

Matrices

Texture Parameters - OpenGL

Example 7.15 Creating a Framebuffer Object with a Depth Attachment

```
// Create a depth texture
glGenTextures(1, &depth_texture);
glBindTexture(GL_TEXTURE_2D, depth_texture);
// Allocate storage for the texture data
glTexImage2D(GL_TEXTURE_2D, 0, GL_DEPTH_COMPONENT32,
             DEPTH_TEXTURE_SIZE, DEPTH_TEXTURE_SIZE,
             0, GL_DEPTH_COMPONENT, GL_FLOAT, NULL);
// Set the default filtering modes
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR);
// Set up depth comparison mode
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_COMPARE_MODE,
                GL_COMPARE_REF_TO_TEXTURE);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_COMPARE_FUNC, GL_LEQUAL);
// Set up wrapping modes
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_CLAMP_TO_EDGE);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_CLAMP_TO_EDGE);
glBindTexture(GL_TEXTURE_2D, 0);

// Create FBO to render depth into
glGenFramebuffers(1, &depth_fbo);
glBindFramebuffer(GL_FRAMEBUFFER, depth_fbo);

// Attach the depth texture to it
glFramebufferTexture(GL_FRAMEBUFFER, GL_DEPTH_STENCIL_ATTACHMENT,
                     depth_texture, 0);
// Disable color rendering as there are no color attachments
glDrawBuffer(GL_NONE);
```

glFramebufferTexture(GL_FRAMEBUFFER, GL_DEPTH_STENCIL_ATTACHMENT, depth_texture, 0);

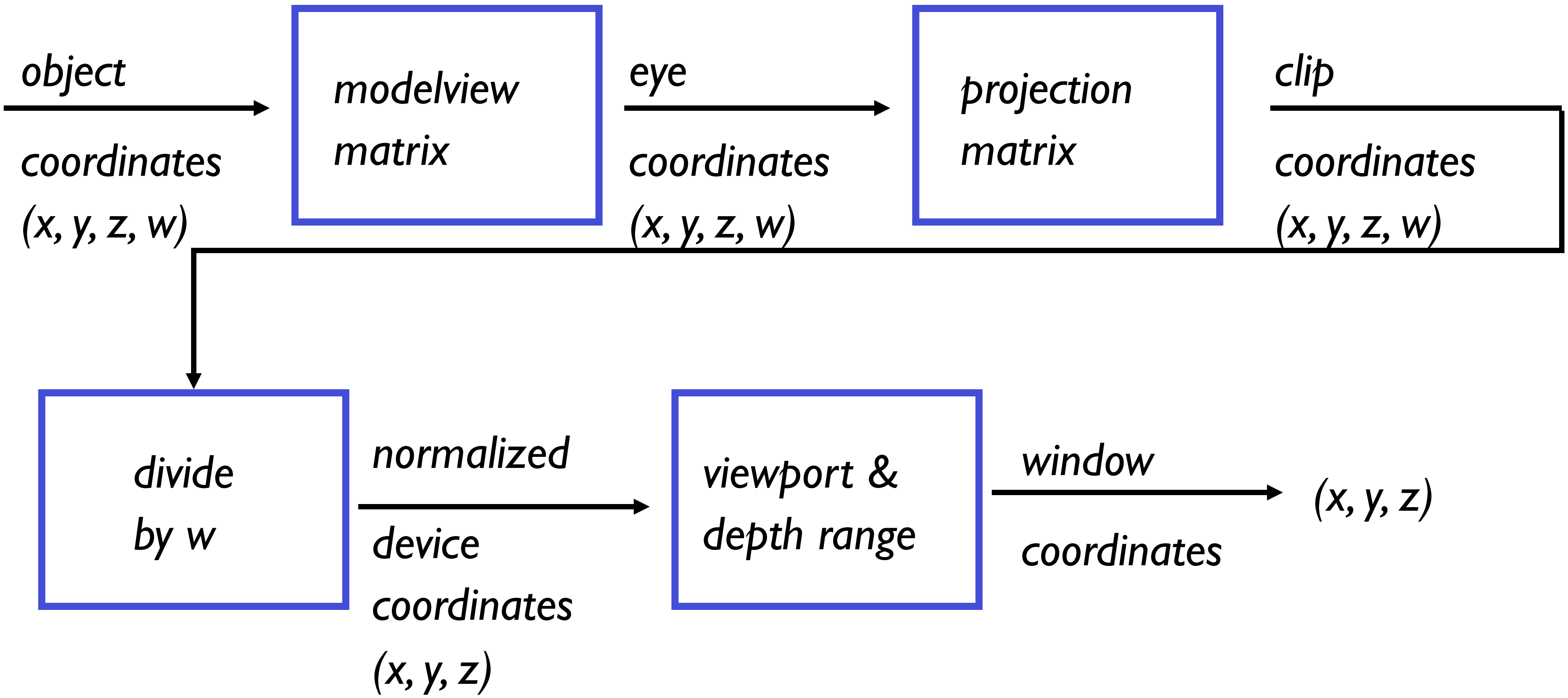
Check

http://openme.gl/opengl-4-tutorial-code/

glFramebufferTexture(GL_FRAMEBUFFER, GL_DEPTH_STENCIL_ATTACHMENT, depth_texture, 0);

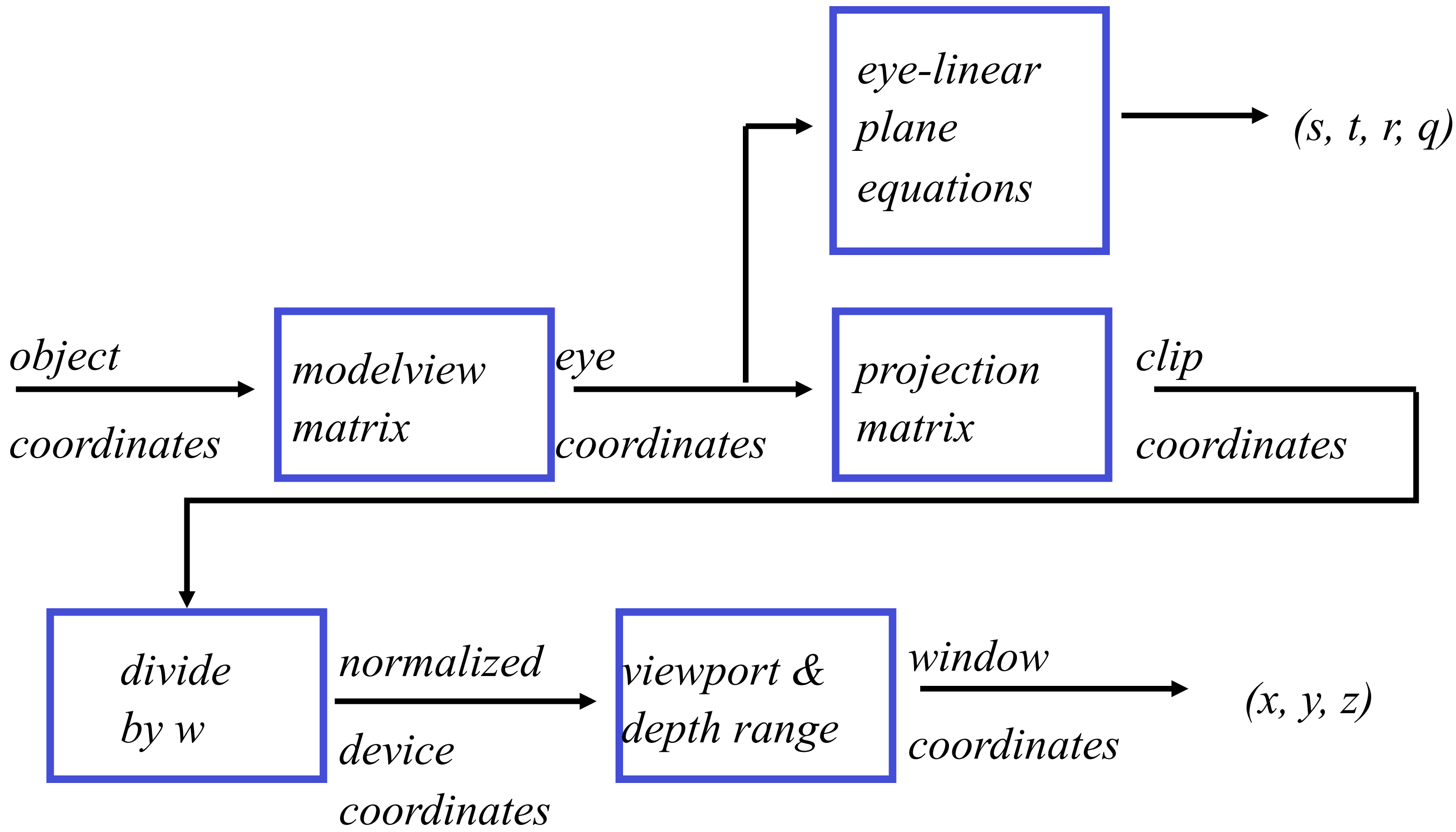
Vertex Coordinate Transform

From object to window coordinates



Eye Linear Texture Coordinate

Generating texture coordinates from eye-space



Transforms

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

Map Use

$$\begin{bmatrix} s \\ t \\ r \\ q \end{bmatrix} = \underbrace{\begin{bmatrix} 1/2 & & & 1/2 \\ & 1/2 & & 1/2 \\ & & 1/2 & 1/2 \\ & & & 1 \end{bmatrix} \begin{bmatrix} \text{Light frustum (projection) matrix} \end{bmatrix} \begin{bmatrix} \text{Light view (look at) matrix} \end{bmatrix}}_{\text{Map Generation}} \overbrace{\begin{bmatrix} \text{Inverse eye view (look at) matrix} \end{bmatrix}}^{\text{Map Use}} \begin{bmatrix} x_e \\ y_e \\ z_e \\ w_e \end{bmatrix}$$

Map Generation

Setting Up Matrices

Example 7.16 Setting up the Matrices for Shadow Map Generation

```
// Time varying light position
vec3 light_position = vec3(
   sinf(t * 6.0f * 3.141592f) * 300.0f,
   200.0f,
   cosf(t * 4.0f * 3.141592f) * 100.0f + 250.0f);

// Matrices for rendering the scene
mat4 scene_model_matrix = rotate(t * 720.0f, Y);

// Matrices used when rendering from the light's position
mat4 light_view_matrix = lookat(light_position, vec3(0.0f), Y);
mat4 light_projection_matrix(frustum(-1.0f, 1.0f, -1.0f, 1.0f,
                                     1.0f, FRUSTUM_DEPTH));

// Now we render from the light's position into the depth buffer.
// Select the appropriate program
glUseProgram(render_light_prog);

glUniformMatrix4fv(render_light_uniforms.MVPMatrix,
                   1, GL_FALSE,
                   light_projection_matrix *
                   light_view_matrix *
                   scene_model_matrix);
```

Simple Shaders

Example 7.17 Simple Shader for Shadow Map Generation

```
--------------------- Vertex Shader ---------------------
// Vertex shader for shadow map generation
#version 330 core
uniform mat4 MVPMatrix;
layout (location = 0) in vec4 position;
void main(void)
{
    gl_Position = MVPMatrix * position;
}
------------------- Fragment Shader ---------------------
// Fragment shader for shadow map generation
#version 330 core
layout (location = 0) out vec4 color;
void main(void)
{
    color = vec4(1.0);
}
```

Depth Rendering

Example 7.18 Rendering the Scene From the Light's Point of View

```
// Bind the "depth only" FBO and set the viewport to the size
// of the depth texture
glBindFramebuffer(GL_FRAMEBUFFER, depth_fbo);
glViewport(0, 0, DEPTH_TEXTURE_SIZE, DEPTH_TEXTURE_SIZE);

// Clear
glClearDepth(1.0f);
glClear(GL_DEPTH_BUFFER_BIT);

// Enable polygon offset to resolve depth-fighting isuses
glEnable(GL_POLYGON_OFFSET_FILL);
glPolygonOffset(2.0f, 4.0f);
// Draw from the light's point of view
DrawScene(true);
glDisable(GL_POLYGON_OFFSET_FILL);
```

In Practice

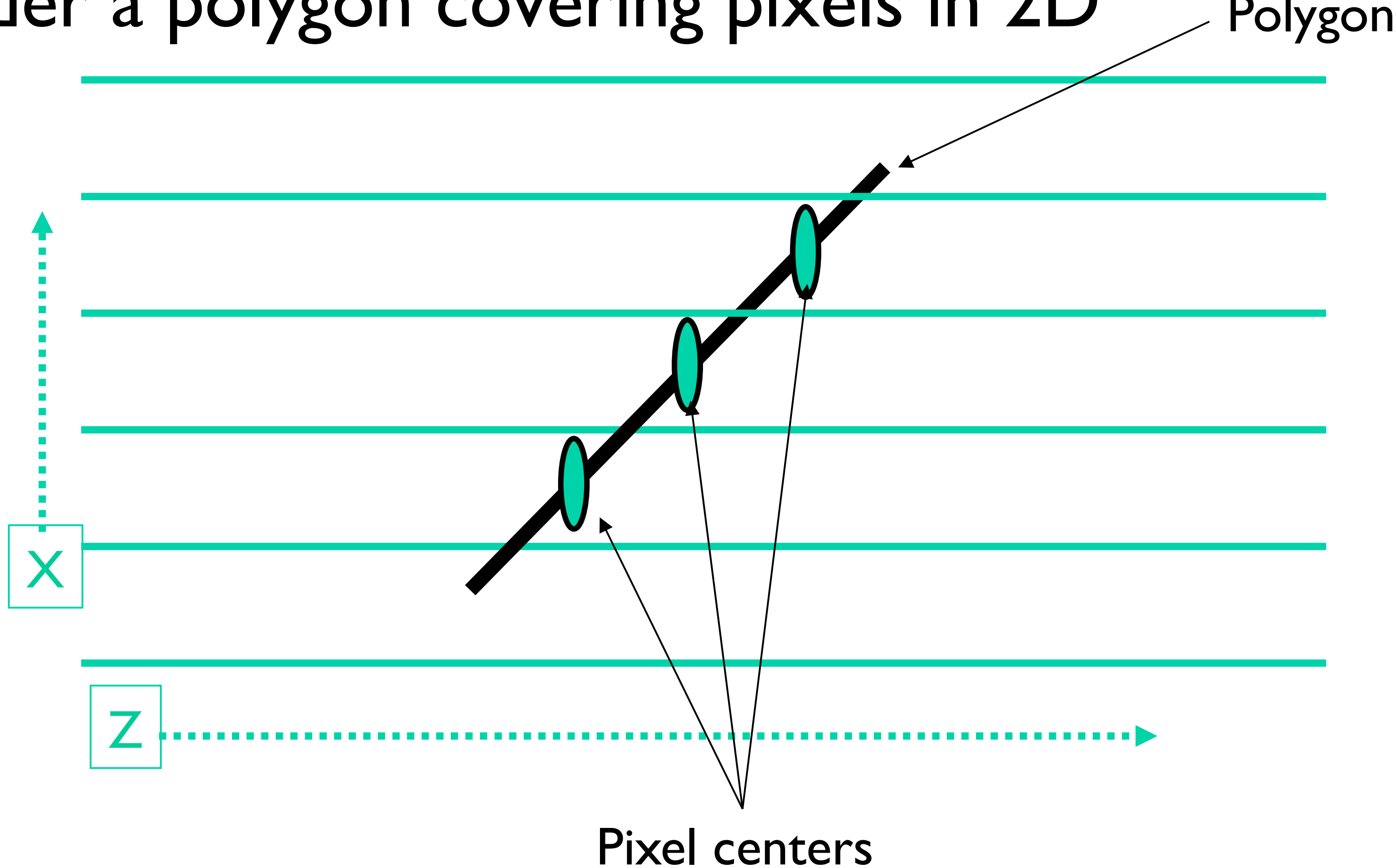
- Two Issues
  - Constructing the depth map
    - use existing hardware depth buffer
    - use glPolygonOffset to offset depth value back
    - read back the depth buffer contents
  - Depth map can be copied to a 2D texture
    - unfortunately, depth values tend to require more precision than 8-bit typical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

glPolygonOffset

- 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

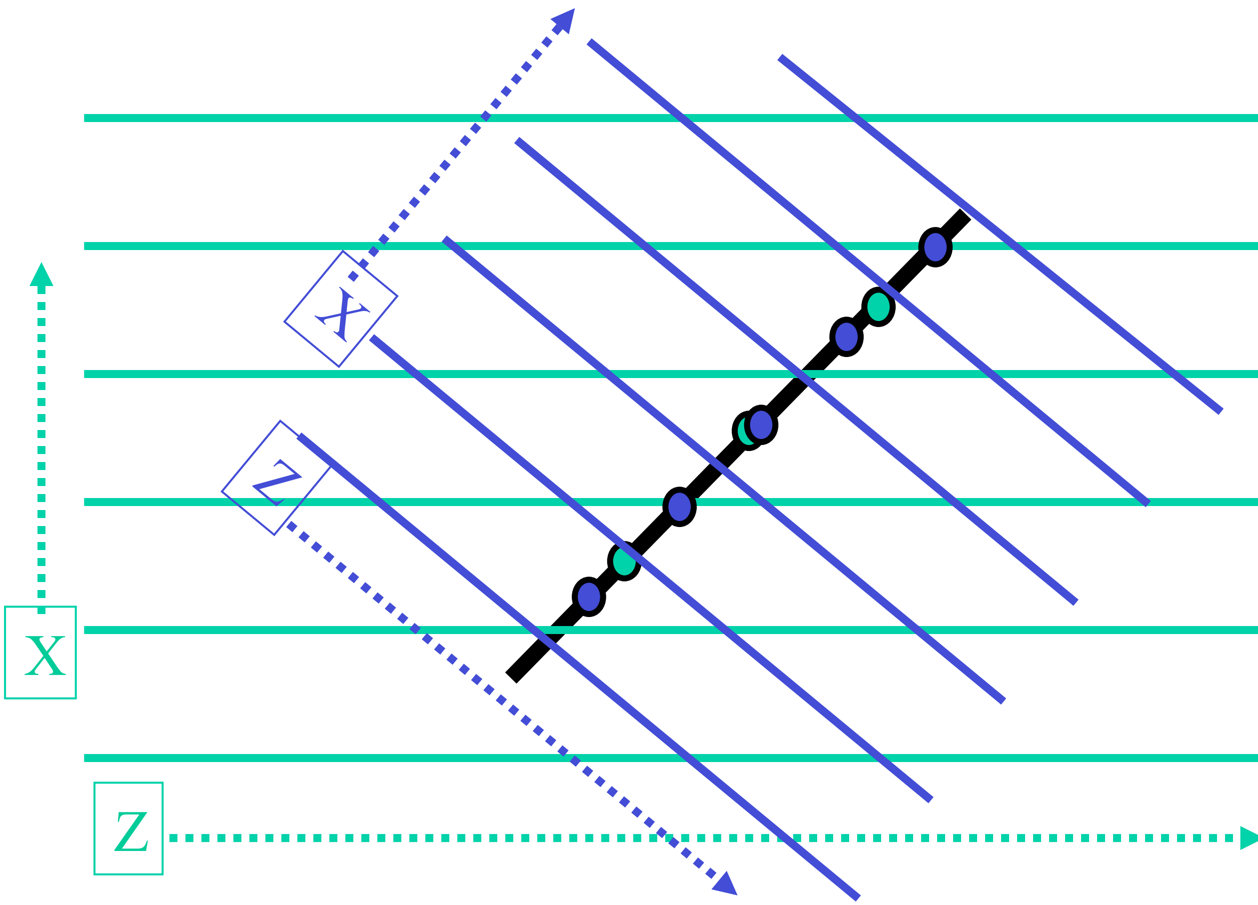
In Pictures - Pixel Centers

Consider a polygon covering pixels in 2D



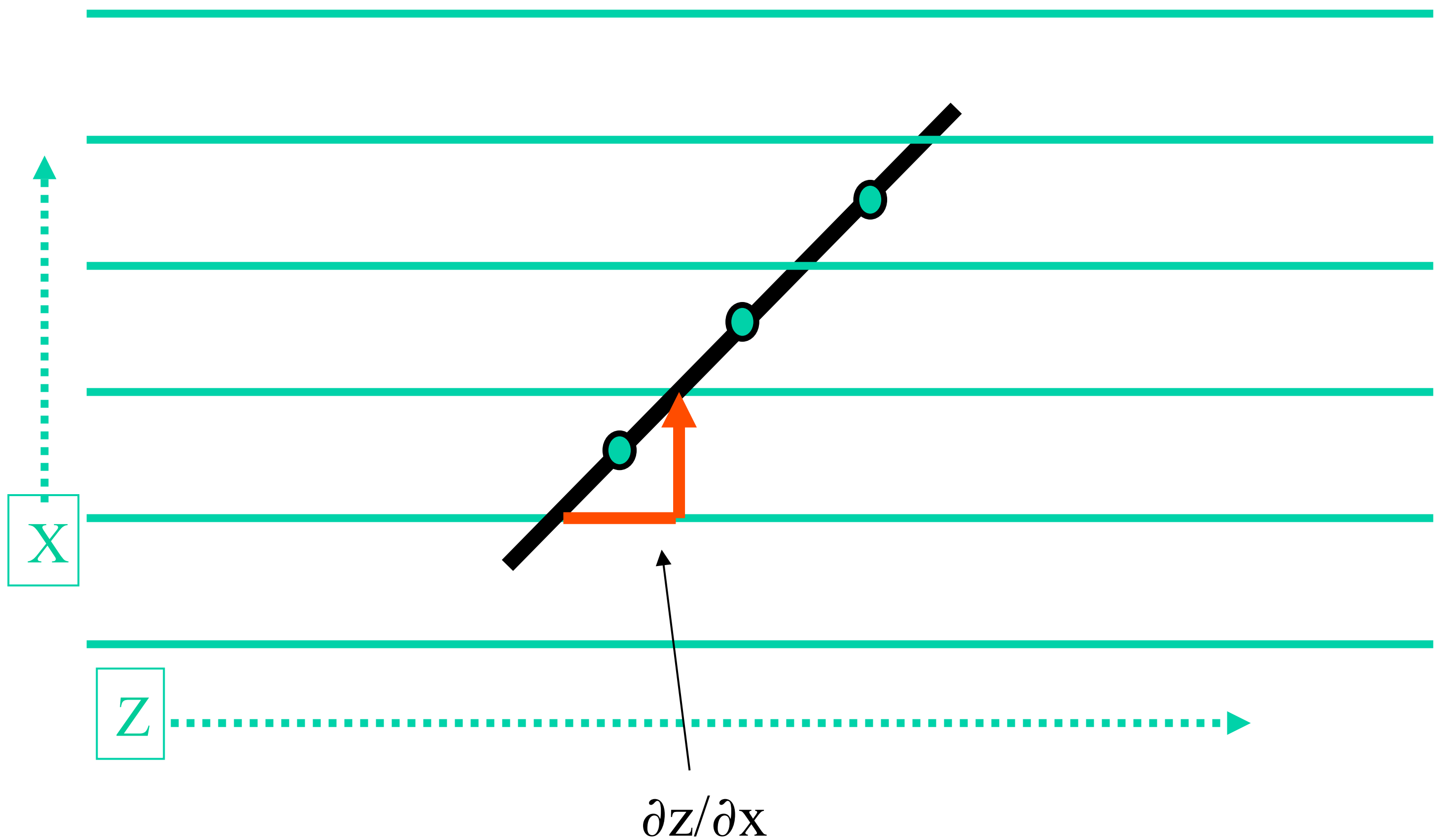
In Pictures - Pixel Centers

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



In Pictures - Pixel Centers

Change of Z with respect to X

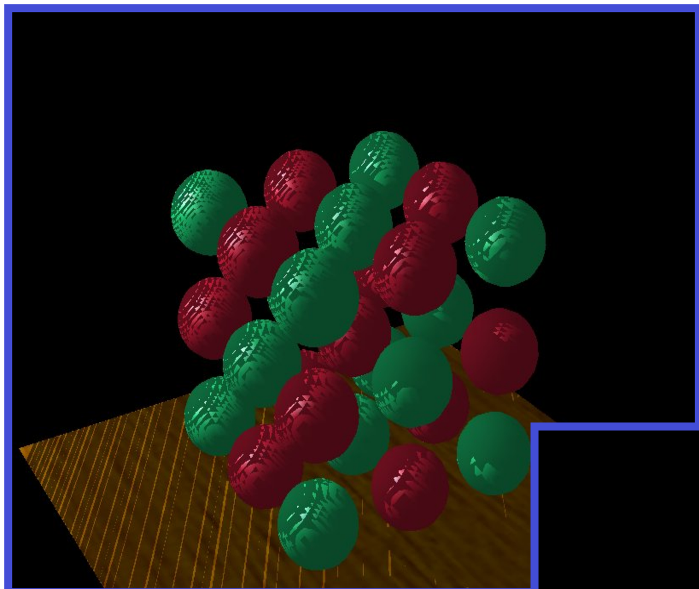


glPolygonOffset's Slope

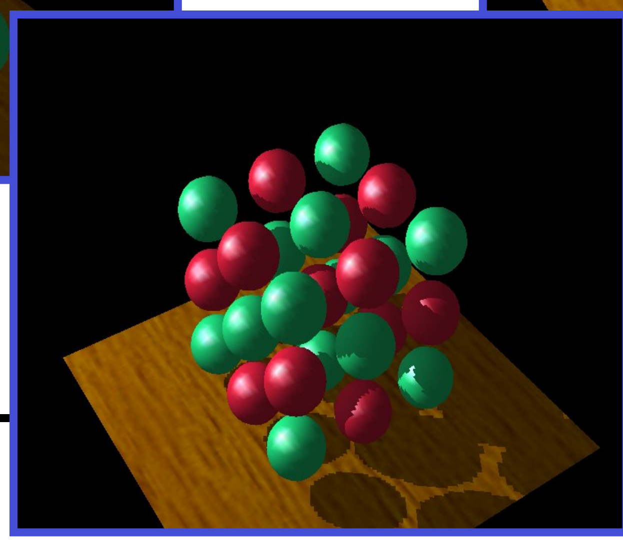
- Pixel center is re-sampled to another grid
  - For example, the shadow map texture's grid!
- The re-sampled depth could be off by
  $+/-0.5\ \partial z/\partial x$ and $+/-0.5\ \partial z/\partial y$
- The maximum absolute error would be
  $|\ 0.5\ \partial z/\partial x\ | + |\ 0.5\ \partial z/\partial y\ | \approx \max(\ |\ \partial z/\partial x\ |\ ,\ |\ \partial z/\partial y\ |\ )$
  - 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

Results

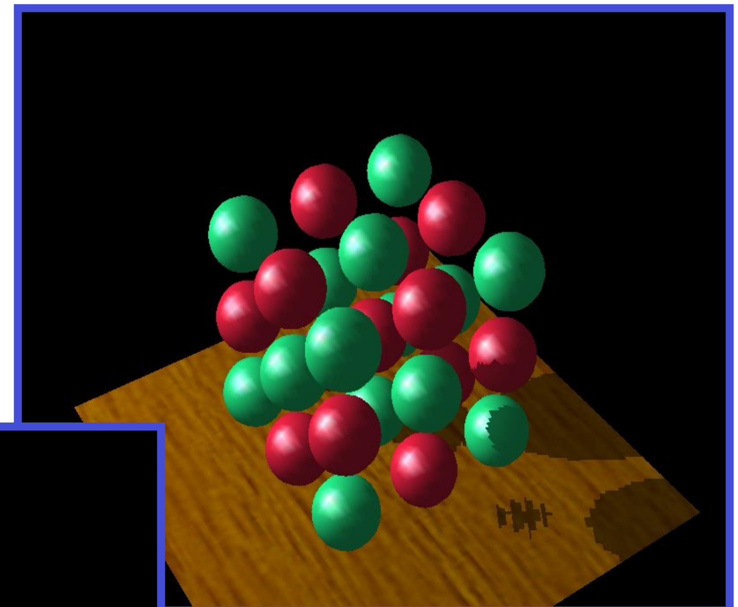
How much polygon offset bias depends



Too little bias, everything begins to shadow



Just right



Too much bias, shadow starts too far back

Selecting 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

Result

Figure 7.10 Depth rendering

Using Shadow Map

Matrices

Example 7.19 Matrix Calculations for Shadow Map Rendering

```
mat4 scene_model_matrix = rotate(t * 720.0f, Y);
mat4 scene_view_matrix = translate(0.0f, 0.0f, -300.0f);
mat4 scene_projection_matrix = frustum(-1.0f, 1.0f, -aspect, aspect,
                                        1.0f, FRUSTUM_DEPTH);
mat4 scale_bias_matrix = mat4(vec4(0.5f, 0.0f, 0.0f, 0.0f),
                              vec4(0.0f, 0.5f, 0.0f, 0.0f),
                              vec4(0.0f, 0.0f, 0.5f, 0.0f),
                              vec4(0.5f, 0.5f, 0.5f, 1.0f));
mat4 shadow_matrix = scale_bias_matrix *
                     light_projection_matrix *
                     light_view_matrix;
```

Vertex Shader

Example 7.20 Vertex Shader for Rendering from Shadow Maps

```
#version 330 core

uniform mat4 model_matrix;
uniform mat4 view_matrix;
uniform mat4 projection_matrix;

uniform mat4 shadow_matrix;

layout (location = 0) in vec4 position;
layout (location = 1) in vec3 normal;

out VS_FS_INTERFACE
{
    vec4 shadow_coord;
    vec3 world_coord;
    vec3 eye_coord;
    vec3 normal;
} vertex;

void main(void)
{
    vec4 world_pos = model_matrix * position;
    vec4 eye_pos = view_matrix * world_pos;
    vec4 clip_pos = projection_matrix * eye_pos;

    vertex.world_coord = world_pos.xyz;
    vertex.eye_coord = eye_pos.xyz;
    vertex.shadow_coord = shadow_matrix * world_pos;


 vertex.normal = mat3(view_matrix * model_matrix) * normal;

     gl_Position = clip_pos;
 }
```

Transforms

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

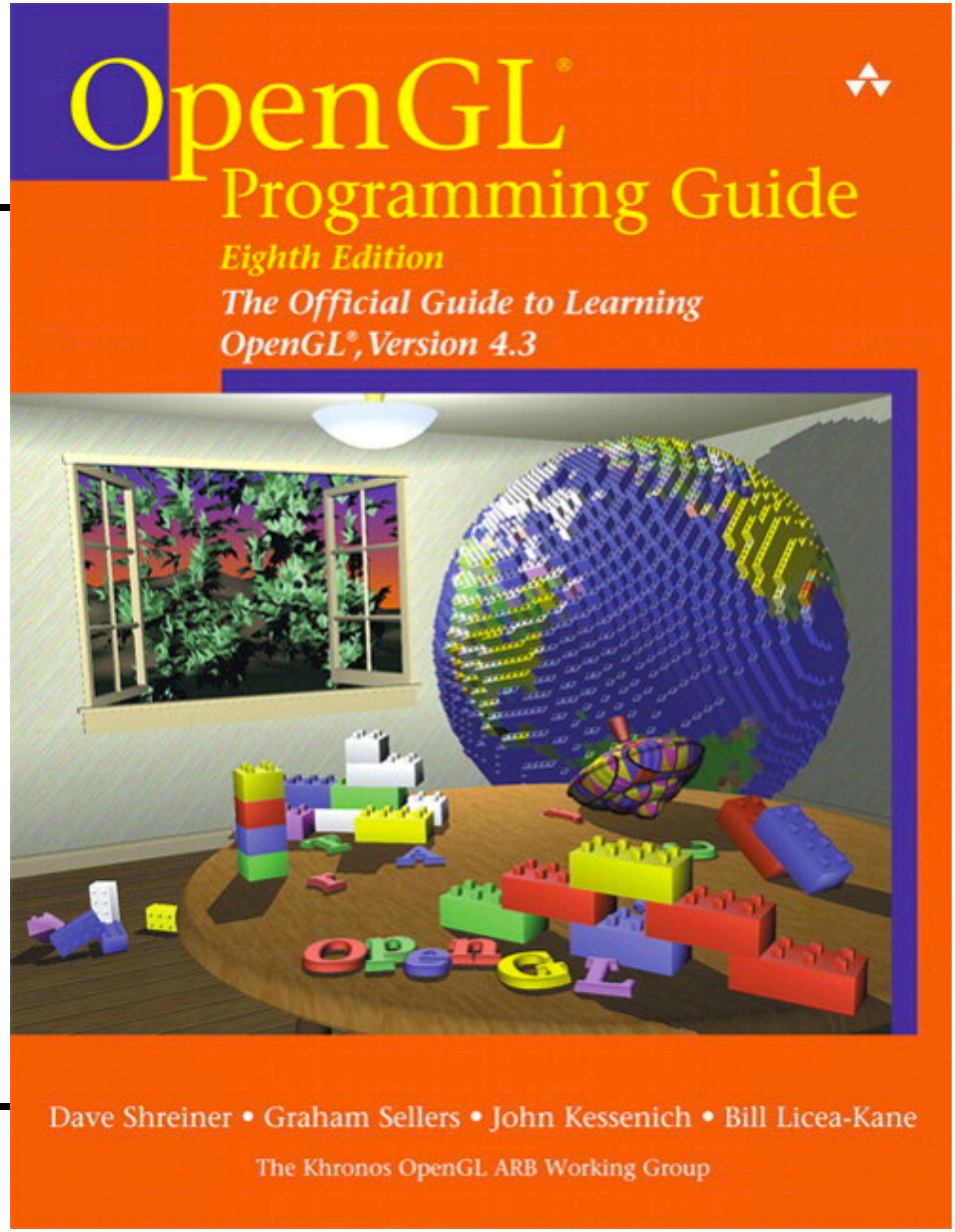
$$\begin{bmatrix} s \\ t \\ r \\ q \end{bmatrix} = \underbrace{\begin{bmatrix} 1/2 & & & 1/2 \\ & 1/2 & & 1/2 \\ & & 1/2 & 1/2 \\ & & & 1 \end{bmatrix} \begin{bmatrix} \text{Light} \\ \text{frustum} \\ \text{(projection)} \\ \text{matrix} \end{bmatrix} \begin{bmatrix} \text{Light} \\ \text{view} \\ \text{(look at)} \\ \text{matrix} \end{bmatrix}}_{\text{Map Generation}} \overbrace{\begin{bmatrix} \text{Inverse} \\ \text{eye} \\ \text{view} \\ \text{(look at)} \\ \text{matrix} \end{bmatrix}}^{\text{Map Use}} \begin{bmatrix} x_e \\ y_e \\ z_e \\ w_e \end{bmatrix}$$

Fragment Shader

Example 7.21 Fragment Shader for Rendering from Shadow Maps

```
#version 330 core

uniform sampler2DShadow depth_texture;
uniform vec3 light_position;

uniform vec3 material_ambient;
uniform vec3 material_diffuse;
uniform vec3 material_specular;
uniform float material_specular_power;

layout (location = 0) out vec4 color;

in VS_FS_INTERFACE
{
    vec4 shadow_coord;
    vec3 world_coord;
    vec3 eye_coord;
    vec3 normal;
} fragment;

void main(void)
{
    vec3 N = fragment.normal;
    vec3 L = normalize(light_position - fragment.world_coord);
    vec3 R = reflect(-L, N);
    vec3 E = normalize(fragment.eye_coord);
    float NdotL = dot(N, L);
    float EdotR = dot(-E, R);

    float diffuse = max(NdotL, 0.0);
    float specular = max(pow(EdotR, material_specular_power), 0.0);

    float f = textureProj(depth_texture, fragment.shadow_coord);

    color = vec4(material_ambient +
                 f * (material_diffuse * diffuse +
                      material_specular * specular), 1.0);
}
```

Chapter 8



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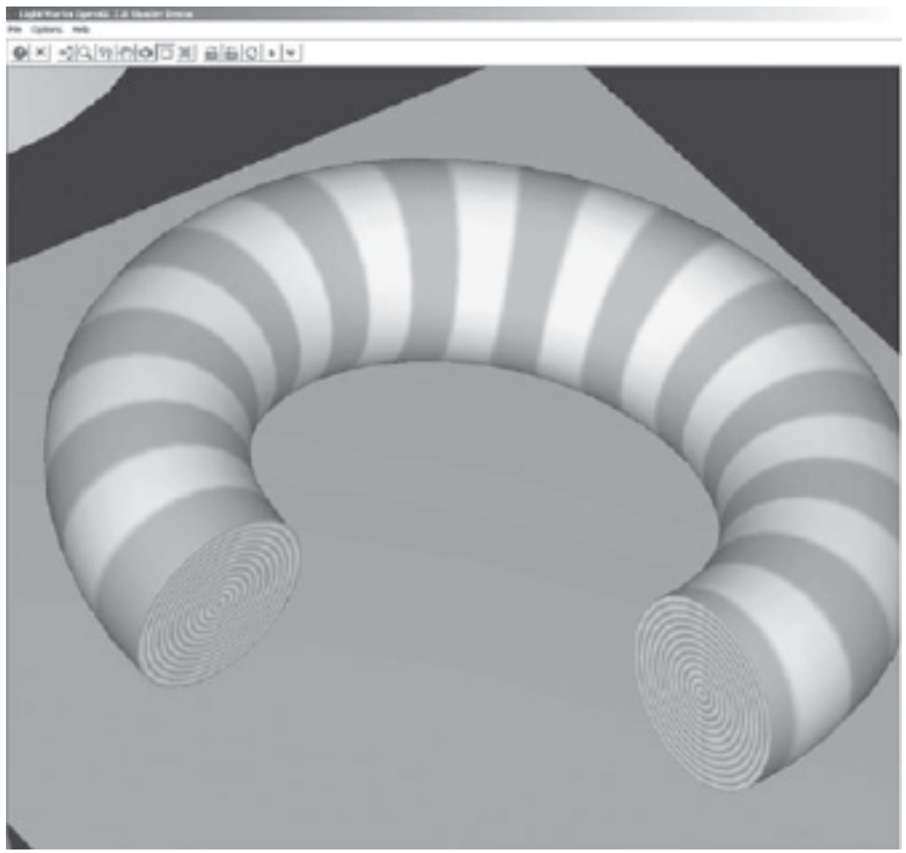
Procedural Texturing

Regular Patterns



Vertex Shader

Example 8.1 Vertex Shader for Drawing Stripes

```
#version 330 core

uniform vec3 LightPosition;
uniform vec3 LightColor;
uniform vec3 EyePosition;
uniform vec3 Specular;
uniform vec3 Ambient;

uniform float Kd;
uniform mat4 MVMatrix;
uniform mat4 MVPMatrix;
uniform mat3 NormalMatrix;

in vec4    MCVertex;
in vec3    MCNormal;
in vec2    TexCoord0;

out vec3   DiffuseColor;
out vec3   SpecularColor;
out float  TexCoord;

void main()
{
    vec3 ecPosition = vec3(MVMatrix * MCVertex);
    vec3 tnorm      = normalize(NormalMatrix * MCNormal);
    vec3 lightVec   = normalize(LightPosition - ecPosition);
    vec3 viewVec    = normalize(EyePosition - ecPosition);
    vec3 hvec       = normalize(viewVec + lightVec);

    float spec = clamp(dot(hvec, tnorm), 0.0, 1.0);
    spec = pow(spec, 16.0);

    DiffuseColor     = LightColor * vec3(Kd * dot(lightVec, tnorm));
    DiffuseColor     = clamp(Ambient + DiffuseColor, 0.0, 1.0);
    SpecularColor    = clamp((LightColor * Specular * spec), 0.0, 1.0);
    TexCoord         = TexCoord0.t;
    gl_Position      = MVPMatrix * MCVertex;
}
```

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Anti-aliasing

Figure 8.2 Stripes close-up
(Extreme close-up view of one of the stripes that shows the effect of the "fuzz" calculation from the stripe shader (courtesy of LightWork Design).)

Fragment Shader

Example 8.2 Fragment Shader for Drawing Stripes

```
#version 330 core

uniform vec3  StripeColor;
uniform vec3  BackColor;

uniform float Width;
uniform float Fuzz;
uniform float Scale;

in vec3  DiffuseColor;
in vec3  SpecularColor;
in float TexCoord;

out vec4 FragColor;

void main()
{
      float scaledT = fract(TexCoord * Scale);
      float frac1 = clamp(scaledT / Fuzz, 0.0, 1.0);
      float frac2 = clamp((scaledT - Width) / Fuzz, 0.0, 1.0);

      frac1 = frac1 * (1.0 - frac2);
      frac1 = frac1 * frac1 * (3.0 - (2.0 * frac1));

      vec3 finalColor = mix(BackColor, StripeColor, frac1);

      finalColor = finalColor * DiffuseColor + SpecularColor;
      FragColor = vec4(finalColor, 1.0);
}
```

Hermite Interpolation