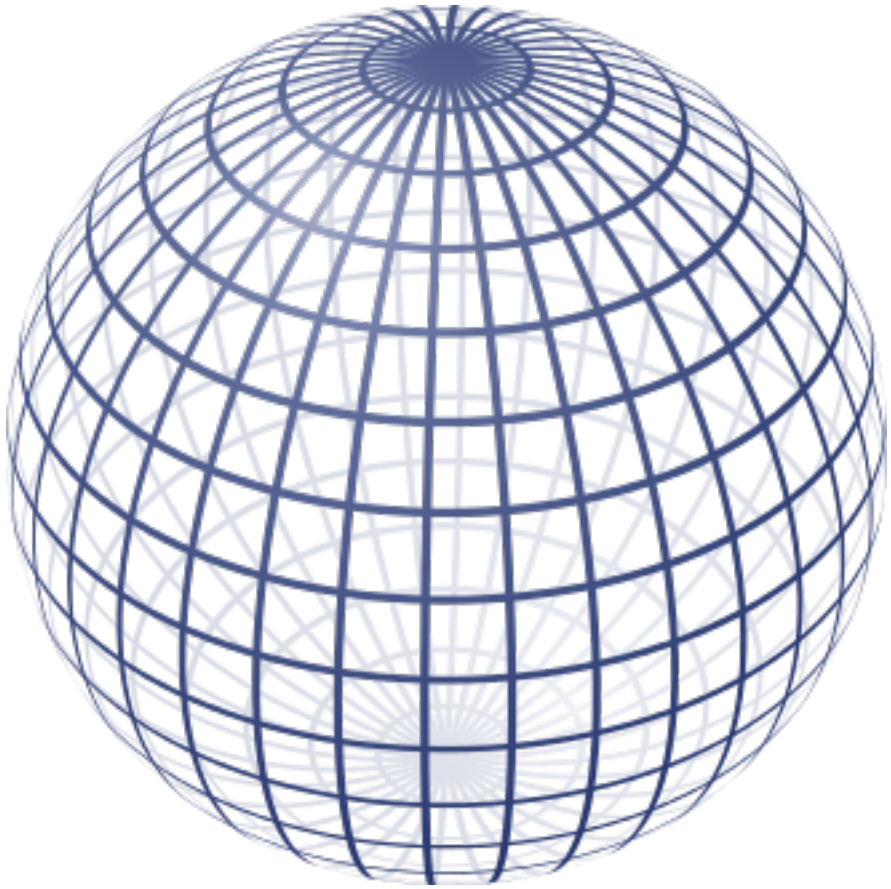
CSE 5542 - Real Time Rendering
Week 11, 12, 13

THE OHIO STATE UNIVERSITY
DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING

Lab 4 Stuff

Spheres



Direct Method

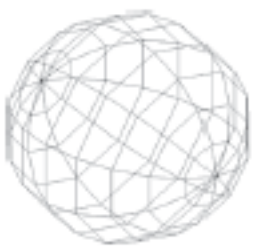
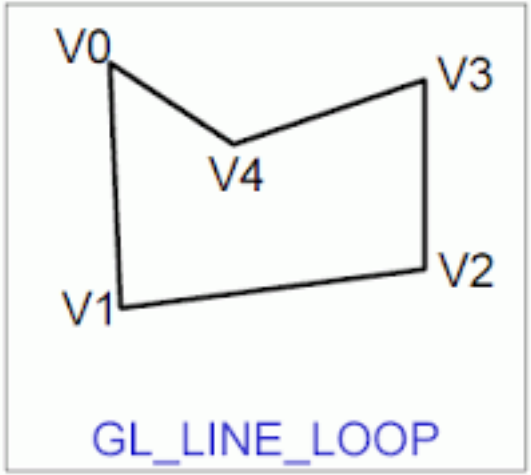


FIGURE 2.15 Sphere approximation with quadrilaterals.

$$x(\theta, \phi) = \sin\theta \cos\phi,$$
$$y(\theta, \phi) = \cos\theta \cos\phi,$$
$$z(\theta, \phi) = \sin\phi.$$

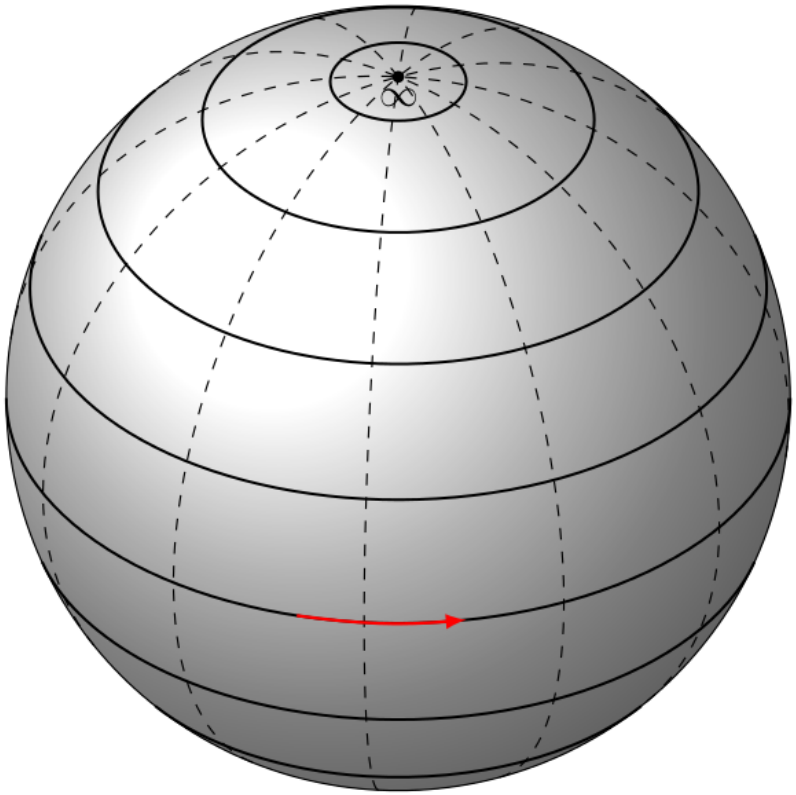
```
const float DegreesToRadians = M_PI / 180.0; // M_PI = 3.14159...

point3 quad_data[342];   // 8 rows of 18 quads

int k = 0;
for(float phi = -80.0; phi <= 80.0; phi += 20.0)
{
    float phir   = phi*DegreesToRadians;
    float phir20 = (phi + 20.0)*DegreesToRadians;

    for(float theta = -180.0; theta <= 180.0; theta += 20.0)
    {
        float thetar = theta*DegreesToRadians;
        quad_data[k] = point3(sin(thetar)*cos(phir),
                              cos(thetar)*cos(phir), sin(phir));
        k++;
        quad_data[k] = point3(sin(thetar)*cos(phir20),
                              cos(thetar)*cos(phir20), sin(phir20));
        k++;
    }
}
```

GL_LINE_LOOP

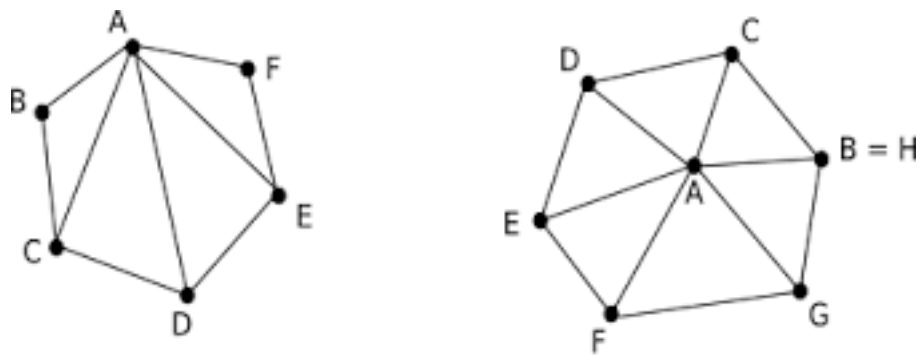



```
glDrawArrays(GL_LINE_LOOP,...)
```

Problems - @ poles



Use GL_TRIANGLE FAN



TRIANGLE_FANs

```
const float DegreesToRadians = M_PI / 180.0; // M_PI = 3.14159...

int k = 0;
point3 strip_data[40];

strip_data[k] = point3(0.0, 0.0, 1.0);
k++;

float sinB0 = sin(B0.0*DegreesToRadians);
float cosB0 = cos(B0.0*DegreesToRadians);


for(float theta = -180.0; theta <= 180.0; theta += 20.0)
{
    float thetar = theta*DegreesToRadians;
    strip_data[k] = point3(sin(thetar)*cosB0,
                           cos(thetar)*cosB0, sinB0);
    k++;
}

strip_data[k] = point3(0.0, 0.0, -1.0);
k++;

for(float theta = -180.0; theta <= 180.0; theta += 20.0)
{
    float thetar = theta;
    strip_data[k] = point3(sin(thetar)*cosB0,
                           cos(thetar)*cosB0, sinB0);
    k++;
}
```

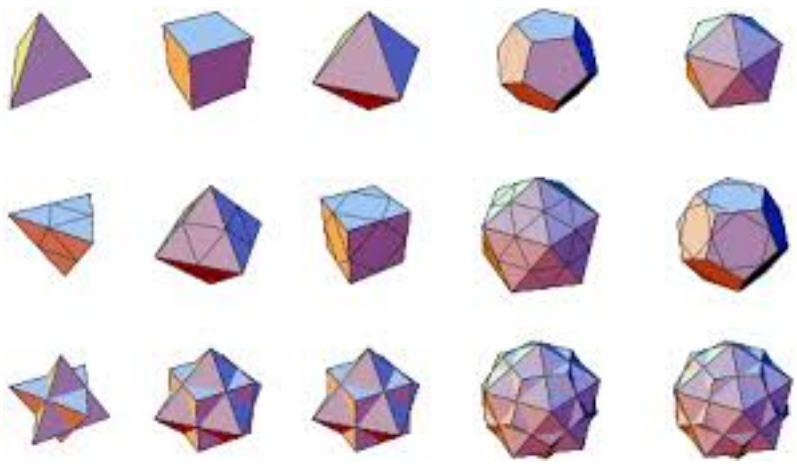
```
glDrawArrays(GL_TRIANGLE_FAN, ....)
```

Method II

YAS (Yet Another Solution)

http://www.andrewnoske.com/wiki/Generating_a_sphere_as_a_3D_mesh

Platonic Solids



Procedure

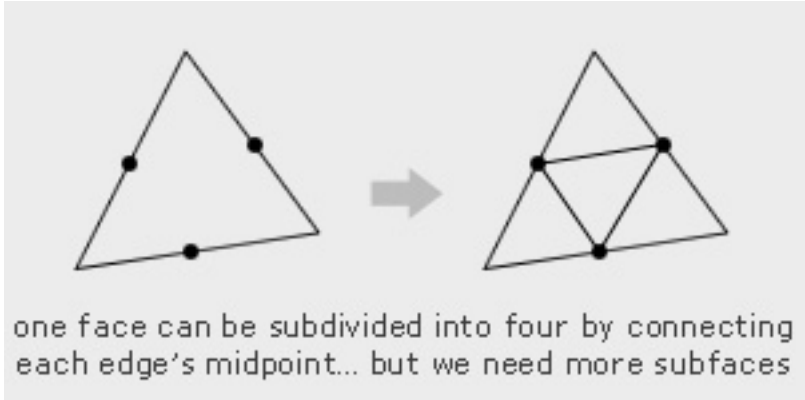
Create Platonic Solid –

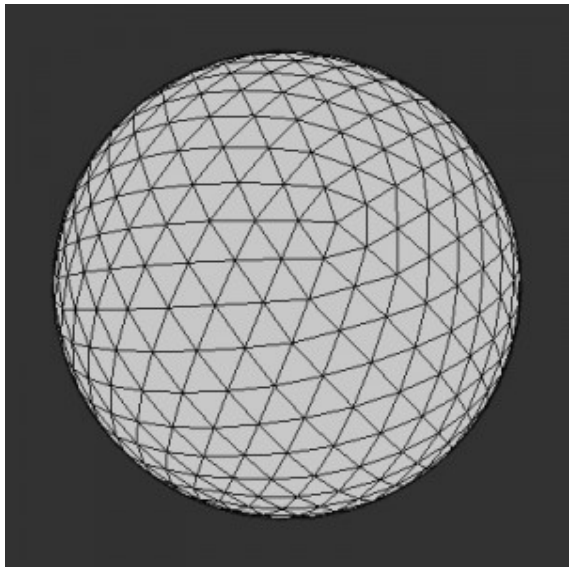
http://www.csee.umbc.edu/~squire/reference/polyhedra.shtml#icosahedron

Subdivide each face –

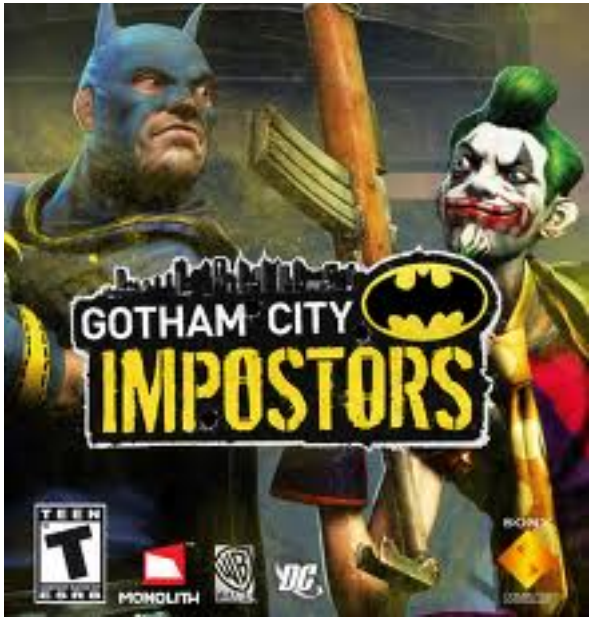
http://donhavey.com/blog/tutorials/tutorial-3-the-icosahedron-sphere/

Think Sierpinski-like





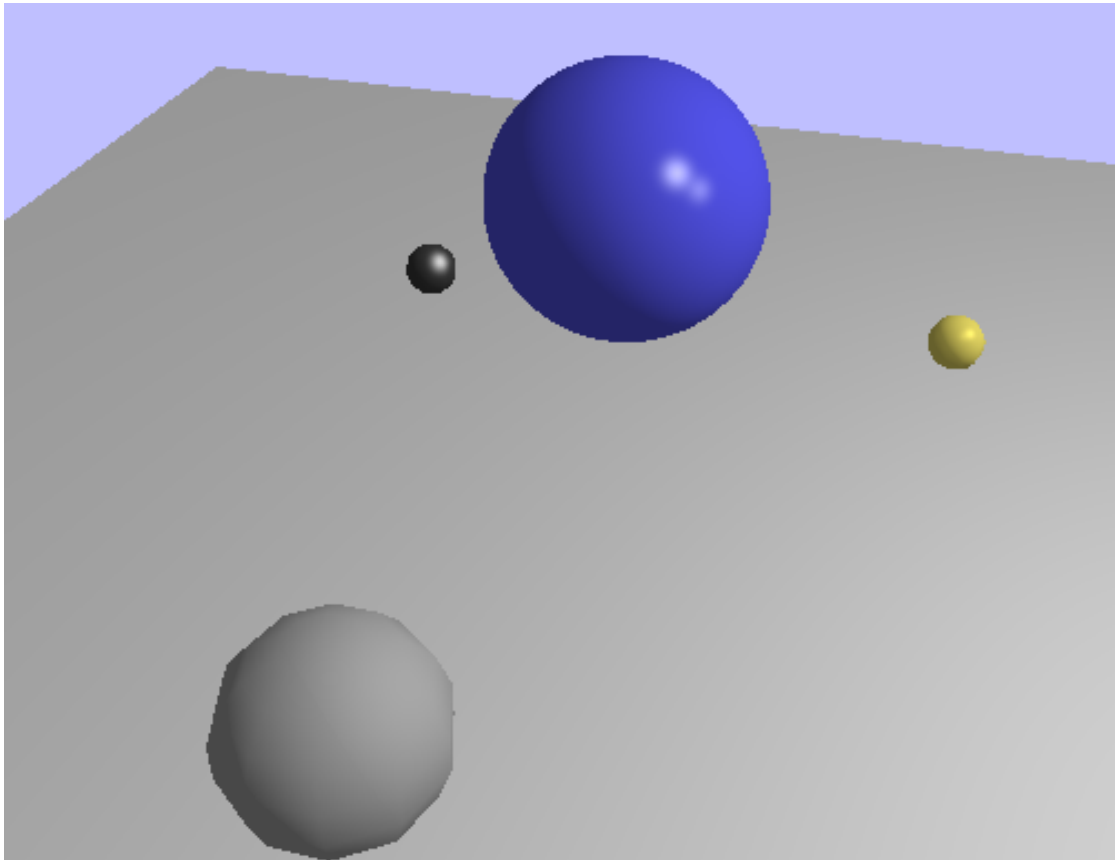
Method III


GOTHAM CITY
IMPOSTORS
TEEN
T
MONOLITH
DC

Impostor Spheres

http://www.arcsynthesis.org/gltut/Illumination/Tutorial%2013.html

Impostors



Rendering Spheres

Spheres - Application

A.7 PER-FRAGMENT LIGHTING OF SPHERE MODEL

A.7.1 Application Code

```
// fragment shading of sphere model

#include "Angel.h"

const int NumTimesToSubdivide = 5;
const int NumTriangles        = 4096;
// (4 faces)^(NumTimesToSubdivide + 1)
const int NumVertices         = 3 * NumTriangles;

typedef Angel::vec4 point4;
typedef Angel::vec4 color4;

point4 points[NumVertices];
vec3   normals[NumVertices];

// Model-view and projection matrices uniform location
```

FIGURE 5.32 Tetrahedron.

FIGURE 5.33 Subdivision of a triangle by (a) bisecting angles, (b) computing the centroid, and (c) bisecting sides.

```
GLuint  ModelView, Projection;

//----------------------------------------------------------------------

int Index = 0;

void
triangle( const point4& a, const point4& b, const point4& c )
{
    vec3  normal = normalize( cross(b - a, c - b) );

    normals[Index] = normal;  points[Index] = a;  Index++;
    normals[Index] = normal;  points[Index] = b;  Index++;
    normals[Index] = normal;  points[Index] = c;  Index++;
}

//----------------------------------------------------------------------

point4
unit( const point4& p )
{
    float len = p.x*p.x + p.y*p.y + p.z*p.z;

    point4 t;
    if ( len > DivideByZeroTolerance ) {
        t = p / sqrt(len);
        t.w = 1.0;
    }

    return t;
}
```

Sphere-Definition

```
void
divide_triangle( const point4& a, const point4& b,
      const point4& c, int count )
{
    if ( count > 0 ) {
        point4 v1 = unit( a + b );
        point4 v2 = unit( a + c );
        point4 v3 = unit( b + c );
        divide_triangle(  a, v1, v2, count - 1 );
        divide_triangle(  c, v2, v3, count - 1 );
        divide_triangle(  b, v3, v1, count - 1 );
        divide_triangle( v1, v3, v2, count - 1 );
    }
    else {
        triangle( a, b, c );
    }
}
```

```
void
tetrahedron( int count )
{
    point4 v[4] = {
        vec4( 0.0, 0.0, 1.0, 1.0 ),
        vec4( 0.0, 0.942809, -0.333333, 1.0 ),
        vec4( -0.816497, -0.471405, -0.333333, 1.0 ),
        vec4( 0.816497, -0.471405, -0.333333, 1.0 )
    };

    divide_triangle( v[0], v[1], v[2], count );
    divide_triangle( v[3], v[2], v[1], count );
    divide_triangle( v[0], v[3], v[1], count );
    divide_triangle( v[0], v[2], v[3], count );
}
```

FIGURE 5.34 Sphere approximations using subdivision.

Sphere-Lighting


```
// OpenGL initialization
void
init( void )
{
    // Subdivide a tetrahedron into a sphere
    tetrahedron( NumTimesToSubdivide );

    // Create a vertex array object
    GLuint vao;
    glGenVertexArrays( 1, &vao );
    glBindVertexArray( vao );

    // Create and initialize a buffer object
    GLuint buffer;
    glGenBuffers( 1, &buffer );
    glBindBuffer( GL_ARRAY_BUFFER, buffer );
    glBufferData( GL_ARRAY_BUFFER, sizeof(points) + sizeof(normals),
        NULL, GL_STATIC_DRAW );
    glBufferSubData( GL_ARRAY_BUFFER, 0, sizeof(points), points );
    glBufferSubData( GL_ARRAY_BUFFER, sizeof(points),
          sizeof(normals), normals );

    // Load shaders and use the resulting shader program
    GLuint program = InitShader( "vshader66.glsl", "fshader66.glsl" );
    glUseProgram( program );

    // set up vertex arrays
    GLuint vPosition = glGetAttribLocation( program, "vPosition" );
    glEnableVertexAttribArray( vPosition );
    glVertexAttribPointer( vPosition, 4, GL_FLOAT, GL_FALSE, 0,
           BUFFER_OFFSET(0) );
```

VBOs & VAOs

```
// set up vertex arrays
GLuint vPosition = glGetAttribLocation( program, "vPosition" );
glEnableVertexAttribArray( vPosition );
glVertexAttribPointer( vPosition, 4, GL_FLOAT, GL_FALSE, 0,
        BUFFER_OFFSET(0) );
```

```
GLuint vNormal = glGetAttribLocation( program, "vNormal" );
glEnableVertexAttribArray( vNormal );
glVertexAttribPointer( vNormal, 3, GL_FLOAT, GL_FALSE, 0,
        BUFFER_OFFSET(sizeof(points)) );
```

Material Properties

```
GLuint vNormal = glGetAttribLocation( program, "vNormal" );
glEnableVertexAttribArray( vNormal );
glVertexAttribPointer( vNormal, 3, GL_FLOAT, GL_FALSE, 0,
        BUFFER_OFFSET(sizeof(points)) );

// Initialize shader lighting parameters
point4 light_position( 0.0, 0.0, 2.0, 0.0 );
color4 light_ambient( 0.2, 0.2, 0.2, 1.0 );
color4 light_diffuse( 1.0, 1.0, 1.0, 1.0 );
color4 light_specular( 1.0, 1.0, 1.0, 1.0 );

color4 material_ambient( 1.0, 0.0, 1.0, 1.0 );
color4 material_diffuse( 1.0, 0.8, 0.0, 1.0 );
color4 material_specular( 1.0, 0.0, 1.0, 1.0 );
float  material_shininess = 5.0;

color4 ambient_product = light_ambient * material_ambient;
color4 diffuse_product = light_diffuse * material_diffuse;
color4 specular_product = light_specular * material_specular;

glUniform4fv( glGetUniformLocation(program, "AmbientProduct"),
    1, ambient_product );
glUniform4fv( glGetUniformLocation(program, "DiffuseProduct"),
    1, diffuse_product );
glUniform4fv( glGetUniformLocation(program, "SpecularProduct"),
    1, specular_product );

glUniform4fv( glGetUniformLocation(program, "LightPosition"),
    1, light_position );

glUniform1f( glGetUniformLocation(program, "Shininess"),
    material_shininess );

// Retrieve transformation uniform variable locations
ModelView = glGetUniformLocation( program, "ModelView" );
Projection = glGetUniformLocation( program, "Projection" );

glEnable( GL_DEPTH_TEST );

glClearColor( 1.0, 1.0, 1.0, 1.0 ); // white background
```

The Usual

```
void
display( void )
{
    glClear( GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT );

    point4 at( 0.0, 0.0, 0.0, 1.0 );


    point4 eye( 0.0, 0.0, 2.0, 1.0 );
    vec4   up( 0.0, 1.0, 0.0, 0.0 );

    mat4 model_view = LookAt( eye, at, up );
    glUniformMatrix4fv( ModelView, 16, GL_TRUE, model_view );

    glDrawArrays( GL_TRIANGLES, 0, NumVertices );
    glutSwapBuffers( void );
}
```

```
void
keyboard( unsigned char key, int x, int y )
{
    switch( key ) {
        case 033: // Escape Key
        case 'q': case 'Q':
            exit( EXIT_SUCCESS );
            break;
    }
}

//----------------------------------------------------------------------

void
reshape( int width, int height )
{
    glViewport( 0, 0, width, height );

    GLfloat left = -2.0, right = 2.0;
    GLfloat top = 2.0, bottom = -2.0;
    GLfloat zNear = -20.0, zFar = 20.0;

    GLfloat aspect = GLfloat(width)/height;

    if ( aspect > 1.0 ) {
        left *= aspect;
        right *= aspect;
    }
    else {
        top /= aspect;
        bottom /= aspect;
    }

    mat4 projection = Ortho( left, right, bottom, top, zNear, zFar );
    glUniformMatrix4fv( Projection, 1, GL_TRUE, projection );
}

//----------------------------------------------------------------------
```

Finally

```
int
main( int argc, char **argv )
{

    glutInit( &argc, argv );
    glutInitDisplayMode( GLUT_RGBA | GLUT_DEPTH );
    glutInitWindowSize( 512, 512 );
    glutCreateWindow( "Sphere" );

    glewInit( void );

    init( void );

    glutDisplayFunc( display );
    glutReshapeFunc( reshape );
    glutKeyboardFunc( keyboard );

    glutMainLoop( void );
    return 0;
}
```

But …

Vertex Shader – Object Space

A.7.2 Vertex Shader

```
#version 150

in   vec4 vPosition;
in   vec3 vNormal;

// output values that will be interpolated per-fragment
out  vec3 fN;
out  vec3 fE;
out  vec3 fL;

uniform mat4 ModelView;
uniform vec4 LightPosition;
uniform mat4 Projection;

void main()
{
    fN = vNormal;
    fE = vPosition.xyz;
    fL = LightPosition.xyz;

    if( LightPosition.w != 0.0 ) {
        fL = LightPosition.xyz - vPosition.xyz;
    }

    gl_Position = Projection*ModelView*vPosition;
}
```

Fragment Shader

A.7.3 Fragment Shader

```
#version 150

// per-fragment interpolated values from the vertex shader
in  vec3 fN;
in  vec3 fL;
in  vec3 fE;

out vec4 fColor;

uniform vec4 AmbientProduct, DiffuseProduct, SpecularProduct;
uniform mat4 ModelView;
uniform vec4 LightPosition;
uniform float Shininess;

void main()
{
    // Normalize the input lighting vectors
    vec3 N = normalize(fN);
    vec3 E = normalize(fE);
    vec3 L = normalize(fL);

    vec3 H = normalize( L + E );

    vec4 ambient = AmbientProduct;

    float Kd = max(dot(L, N), 0.0);
    vec4 diffuse = Kd*DiffuseProduct;

    float Ks = pow(max(dot(N, H), 0.0), Shininess);
    vec4 specular = Ks*SpecularProduct;

    // discard the specular highlight if the light's behind the vertex
    if( dot(L, N) < 0.0 ) {
        specular = vec4(0.0, 0.0, 0.0, 1.0);
    }

    fColor = ambient + diffuse + specular;
    fColor.a = 1.0;
}
```

Yet Another Way

Vertex Lighting Shaders I

```
// vertex shader
in vec4 vPosition;
in vec3 vNormal;
out vec4 color;  //vertex shade

// light and material properties
uniform vec4 AmbientProduct, DiffuseProduct, SpecularProduct;
uniform mat4 ModelView;
uniform mat4 Projection;
uniform vec4 LightPosition;
uniform float Shininess;
```

Vertex Lighting Shaders II

```
void main()
{
    // Transform vertex  position into eye coordinates
    vec3 pos = (ModelView * vPosition).xyz;

    vec3 L = normalize( LightPosition.xyz - pos );
    vec3 E = normalize( -pos );
    vec3 H = normalize( L + E );

    // Transform vertex normal into eye coordinates
    vec3 N = normalize( ModelView*vec4(vNormal, 0.0) ).xyz;
```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Vertex Lighting Shaders II

```
void main()
{
    // Transform vertex  position into eye coordinates
    vec3 pos = (ModelView * vPosition).xyz;

    vec3 L = normalize( LightPosition.xyz - pos );
    vec3 E = normalize( -pos );
    vec3 H = normalize( L + E );

    // Transform vertex normal into eye coordinates
    vec3 N = normalize( ModelView*vec4(vNormal, 0.0) ).xyz;
```


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Vertex Lighting Shaders III

```
// Compute terms in the illumination equation
    vec4 ambient = AmbientProduct;

    float Kd = max( dot(L, N), 0.0 );
    vec4  diffuse = Kd*DiffuseProduct;
    float Ks = pow( max(dot(N, H), 0.0), Shininess );
    vec4  specular = Ks * SpecularProduct;
    if( dot(L, N) < 0.0 )  specular = vec4(0.0, 0.0, 0.0, 1.0);
    gl_Position = Projection * ModelView * vPosition;

    color = ambient + diffuse + specular;
    color.a = 1.0;
}
```

Vertex Lighting Shaders IV

```
// fragment shader

in vec4 color;

void main()
{
    gl_FragColor = color;
}
```


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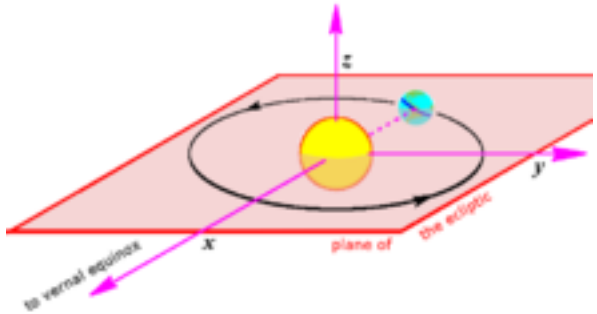
Hierarchical Modeling

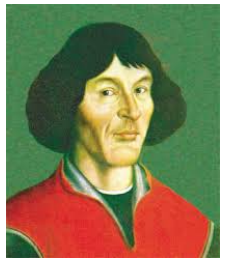
Cars, Robots, Solar System

Our Goal ☺


Pluto
Neptune
Uranus
Saturn
Jupiter
Mars
Moon
Earth
Venus
Mercury

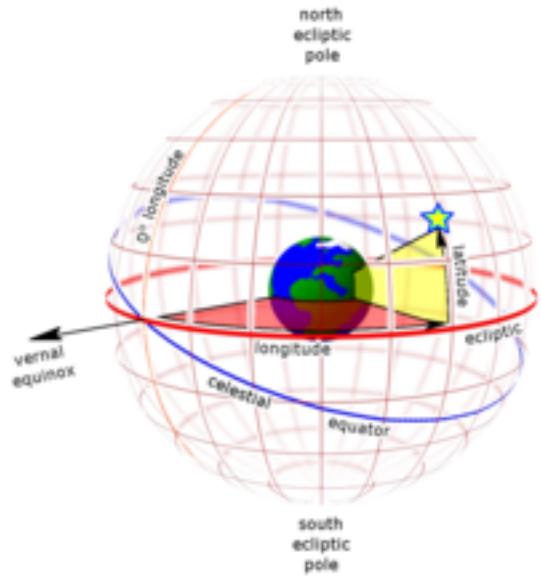
Heliocentric Coordinates



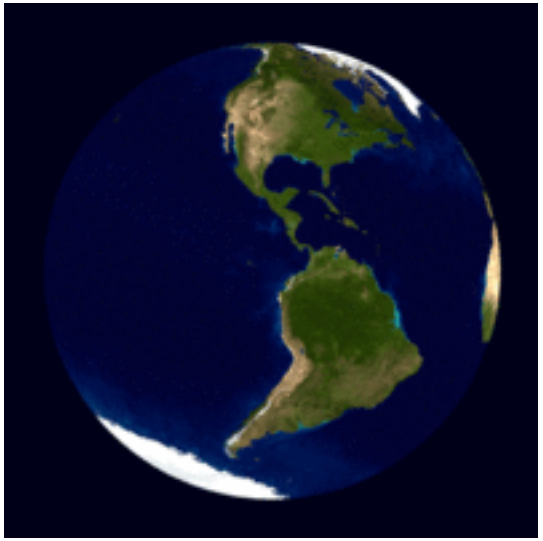


Heliocentric ecliptic coordinates. The origin is the center of the Sun. The fundamental plane is the plane of the ecliptic. The primary direction (the x axis) is the vernal equinox. A right-handed convention specifies a y axis 90° to the east in the fundamental plane; the z axis points toward the north ecliptic pole. The reference frame is relatively stationary, aligned with the vernal equinox.

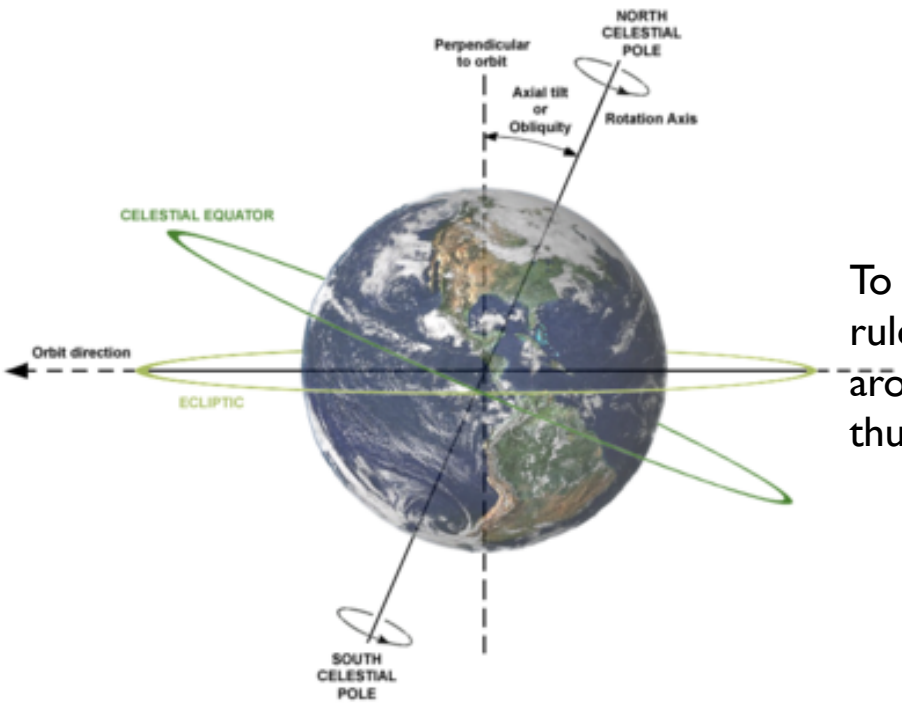
Inclinations



Axial Tilt

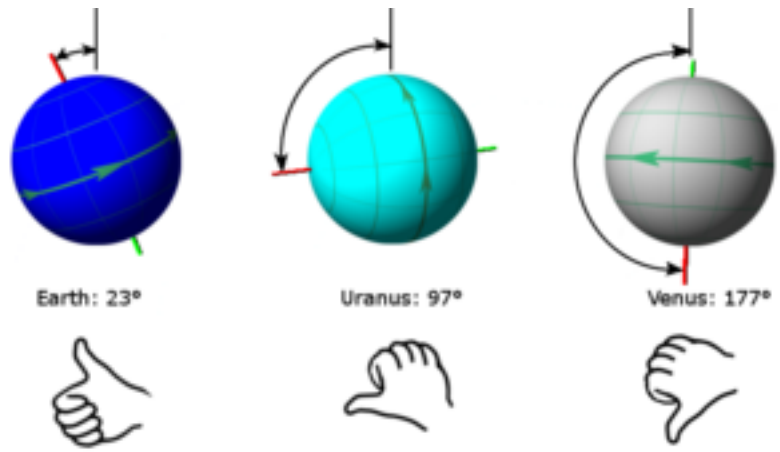


W. Pedia says



To understand axial tilt, we employ the right-hand rule. When the fingers of the right hand are curled around in the direction of the planet's rotation, the thumb points in the direction of the north pole.

Axial Tilts of Planets



The axial tilt of three planets: Earth, Uranus, and Venus. Here, a vertical line (black) is drawn perpendicular to the plane of each planet's orbit. The angle between this line and the planet's north pole (red) is the tilt. The surrounding arrows (green) show the direction of the planet's rotation.

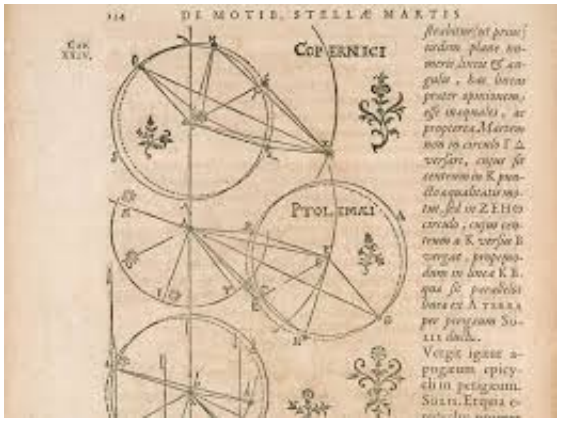
Ecliptic Coordinate System

$$\begin{bmatrix} x_{equatorial} \\ y_{equatorial} \\ z_{equatorial} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\epsilon & -\sin\epsilon \\ 0 & \sin\epsilon & \cos\epsilon \end{bmatrix} \cdot \begin{bmatrix} x_{ecliptic} \\ y_{ecliptic} \\ z_{ecliptic} \end{bmatrix}$$

$$\begin{bmatrix} x_{ecliptic} \\ y_{ecliptic} \\ z_{ecliptic} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\epsilon & \sin\epsilon \\ 0 & -\sin\epsilon & \cos\epsilon \end{bmatrix} \cdot \begin{bmatrix} x_{equatorial} \\ y_{equatorial} \\ z_{equatorial} \end{bmatrix}$$

where \epsilon is the obliquity of the ecliptic.

Roots


DE MOTIB. STELLÆ MARTIS
COPERNICI
PTOLEMAI


MARS
EARTH
VENUS
MERCURY
JUPITER
SATURN

Back 2 Earth ☺

Texture Mapping

Courtesy: Ed Angel

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Limits of Geometric Modeling

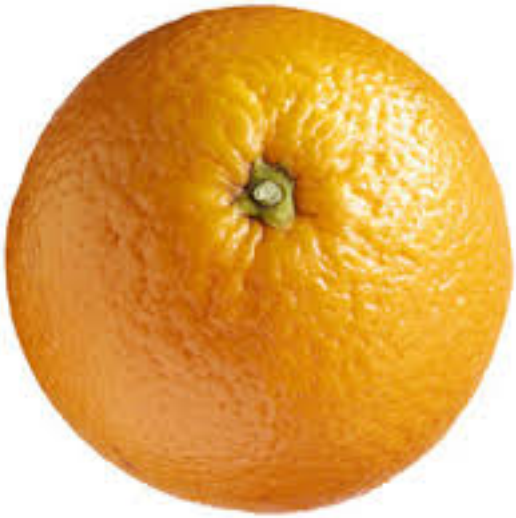
Millions of Polygons/Second

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

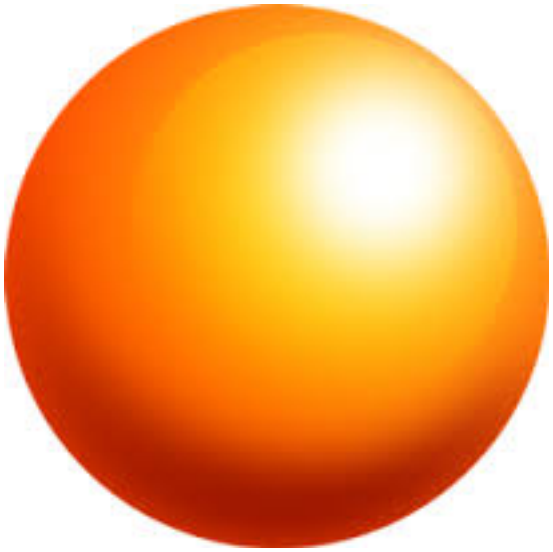
Cannot Do

Use Textures

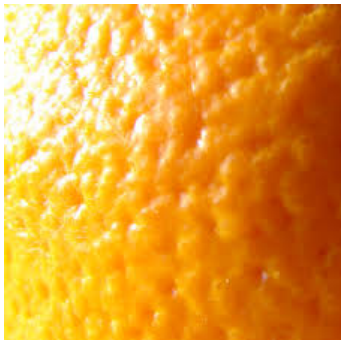
Orange

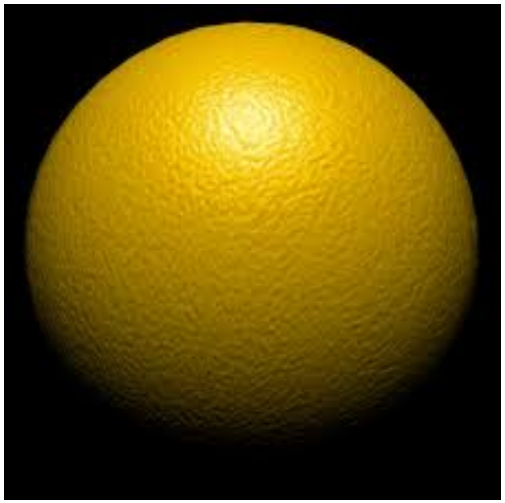


Orange Spheres

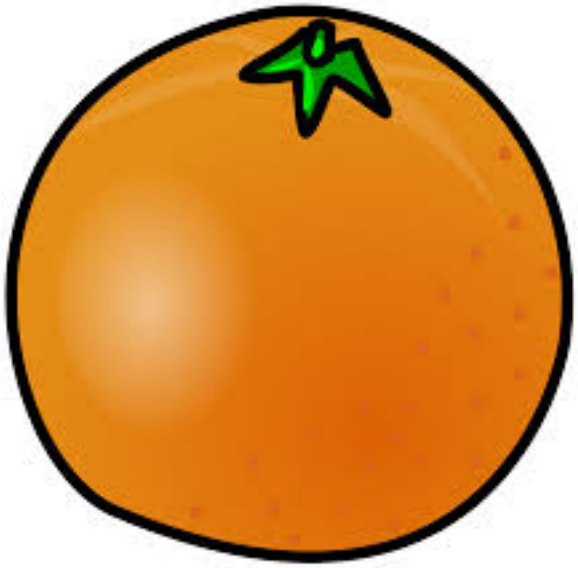


Texture Mapping



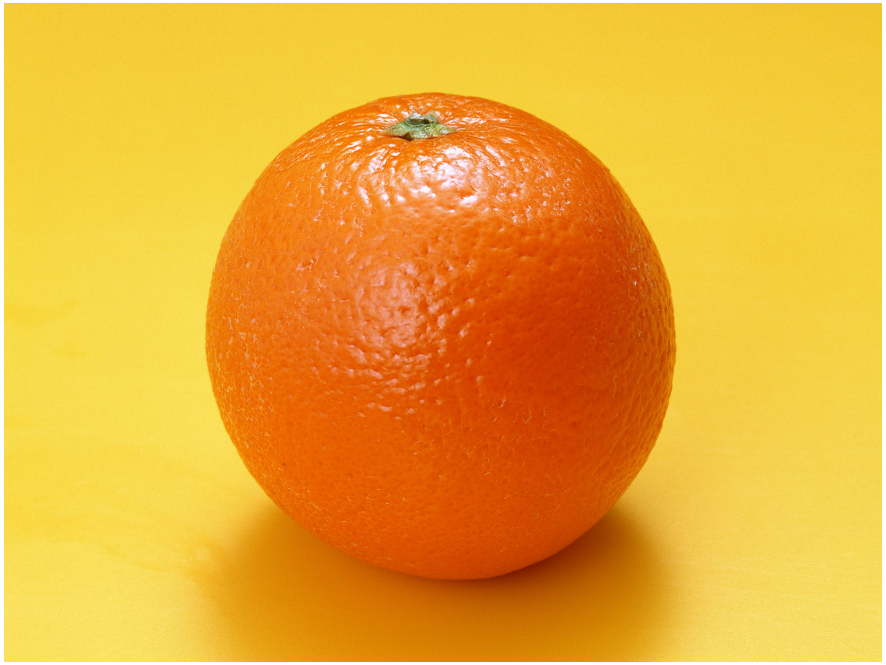


Looking Better

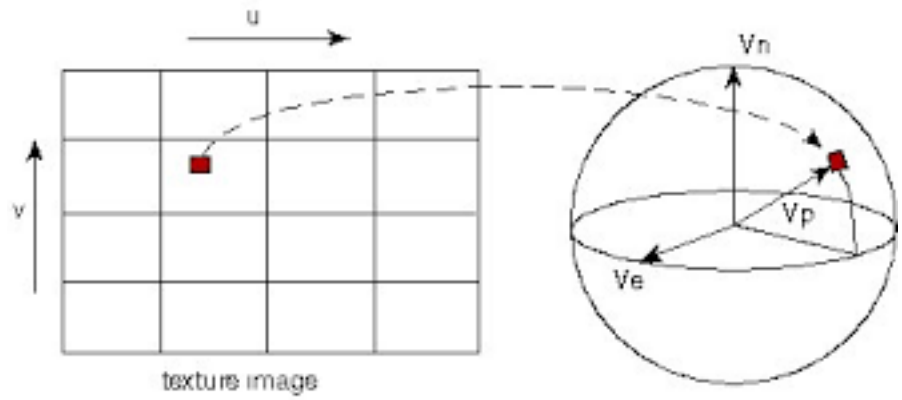


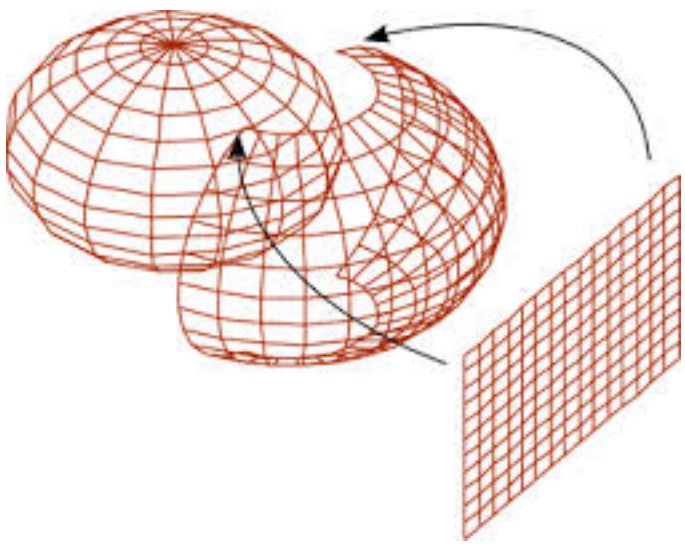
Still Not Enough

Local Variation



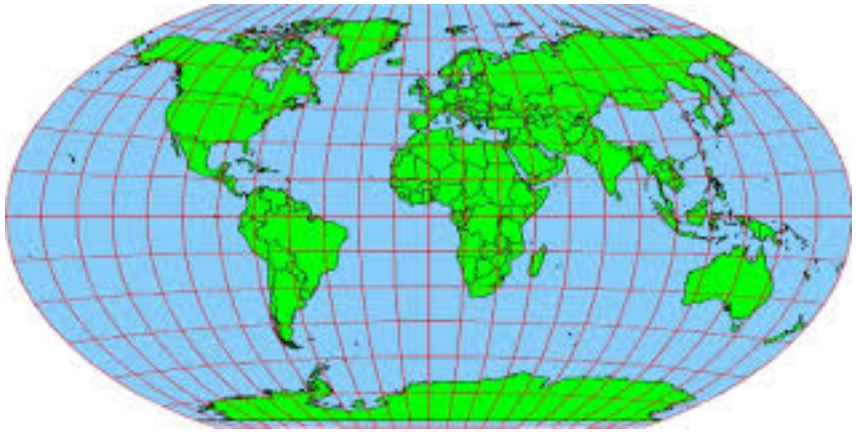
Texture Mapping



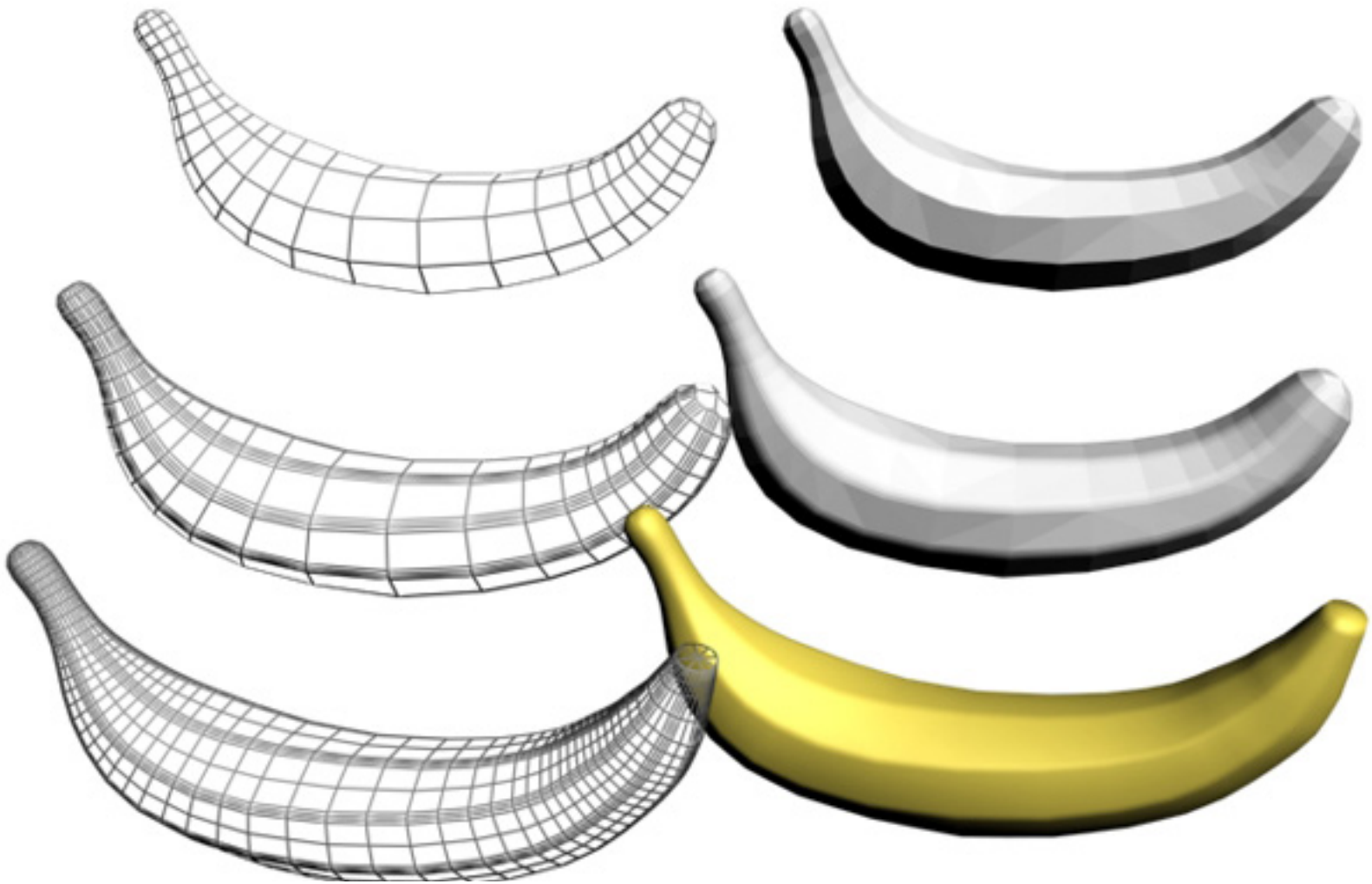


Globe

Not Mercator



Yet Another Fruit



Three Types of Mapping

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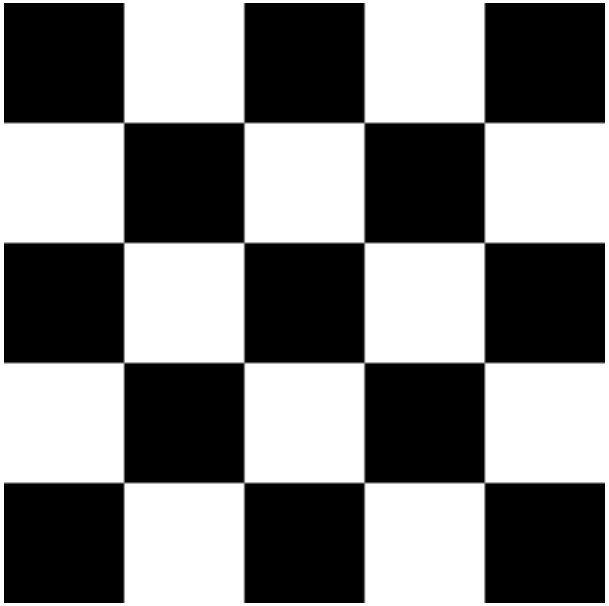
Generating Textures

Pictures

Algorithms

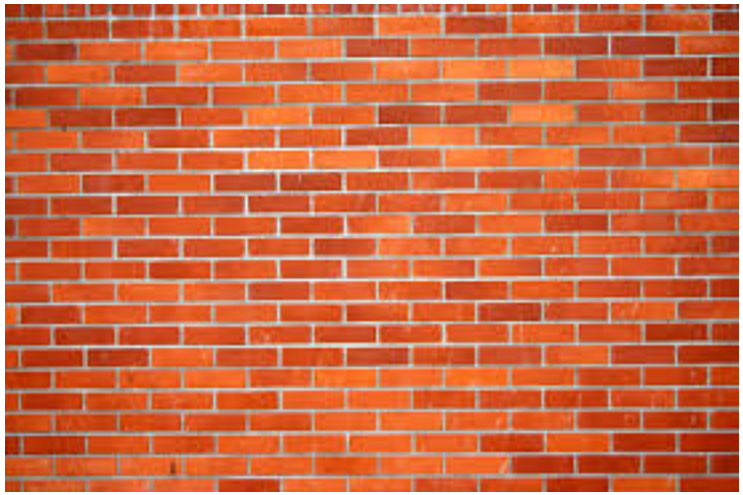


Checkerboard Texture

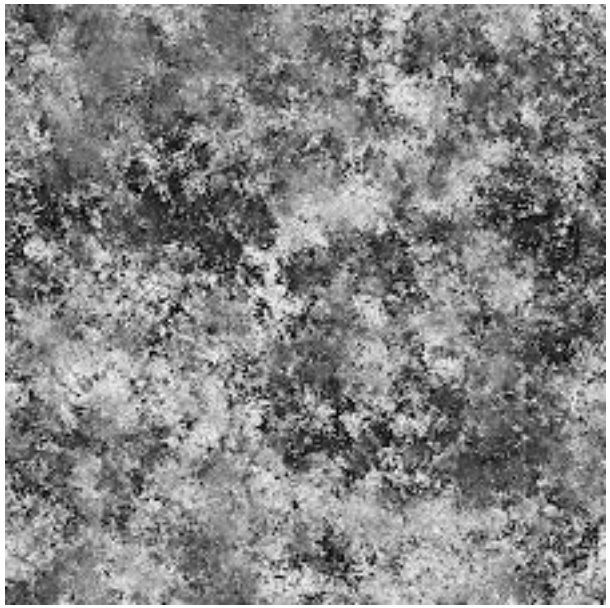
```
GLubyte image[64][64][3];

// 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;
```

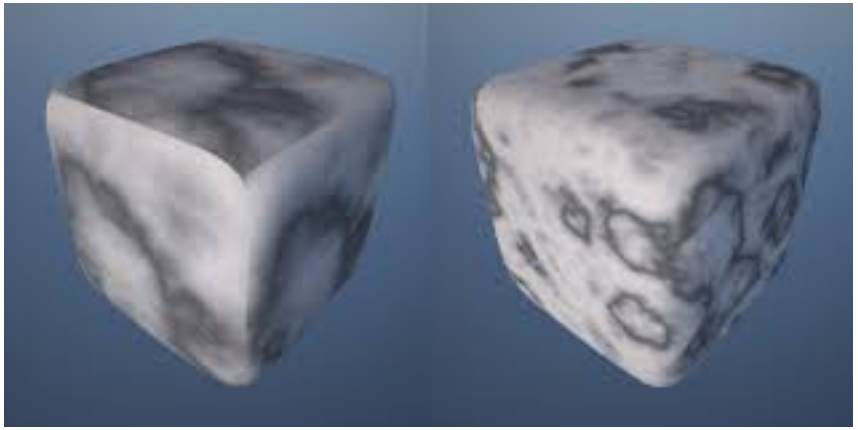
Brick Wall



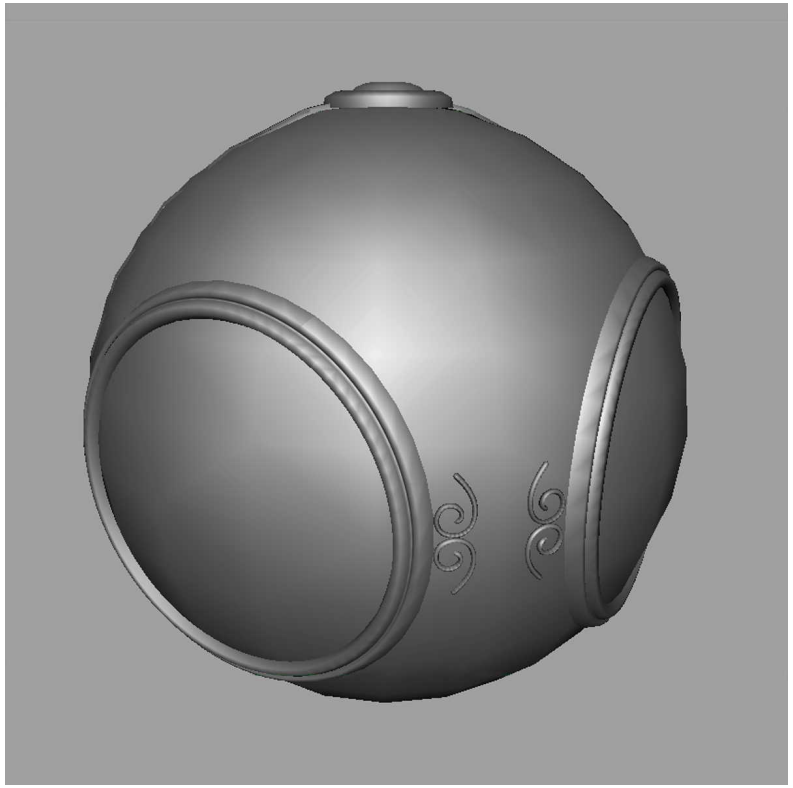
Noise



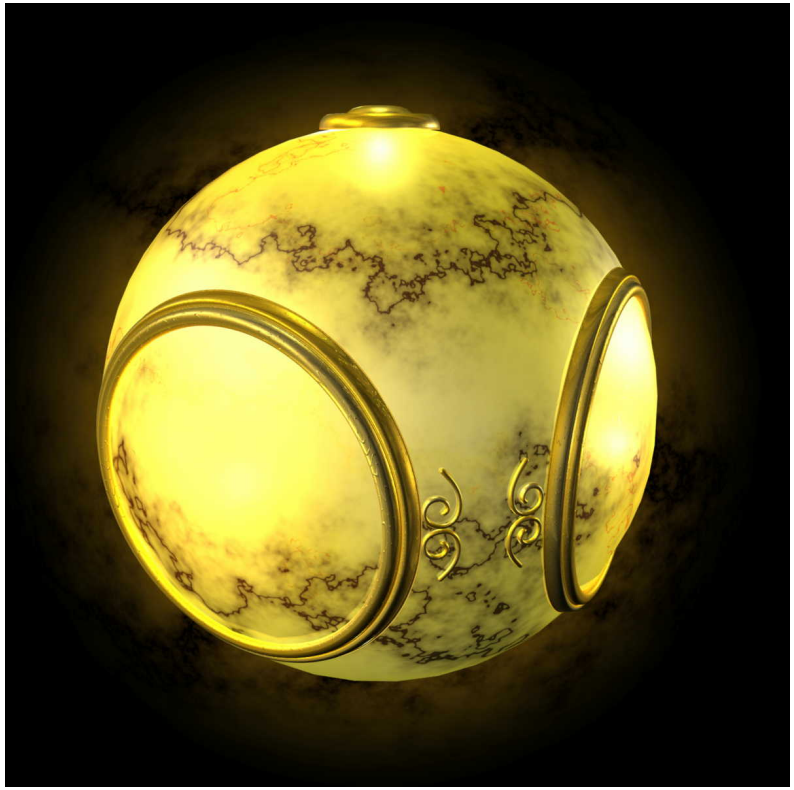
Marble



Texture Mapping



geometric model



texture mapped

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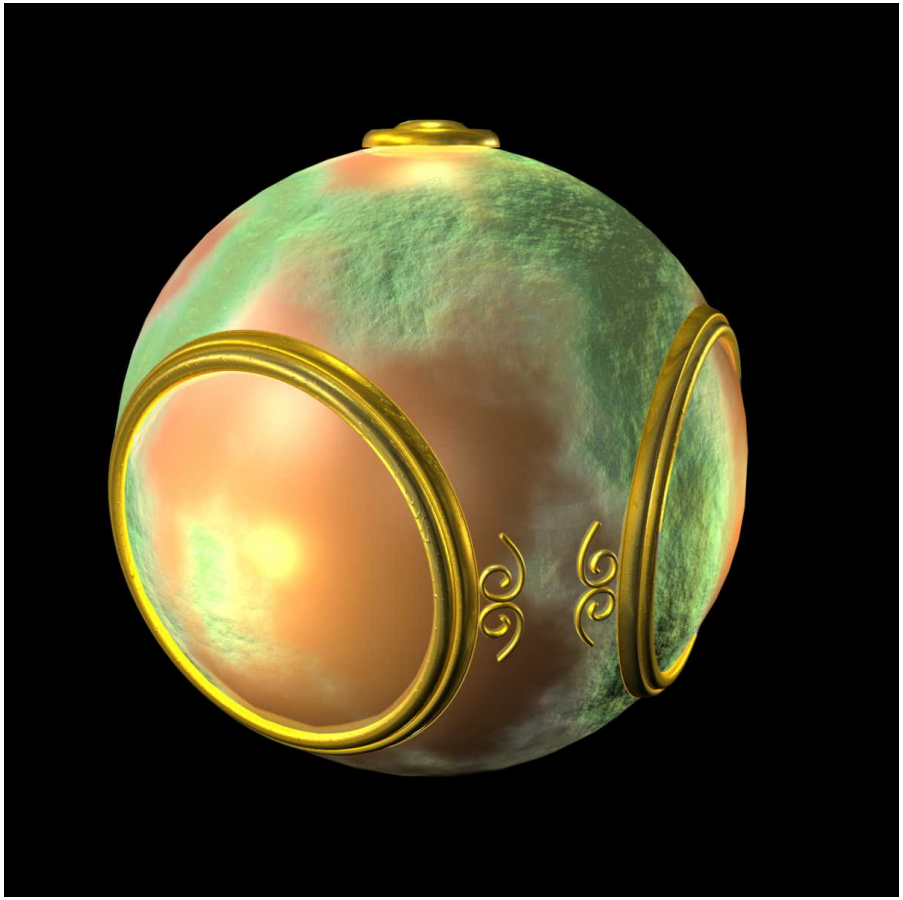
Environment Mapping

Bump Mapping



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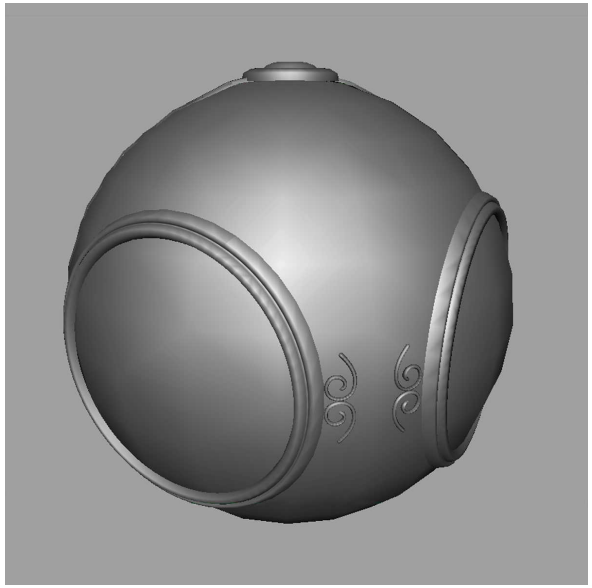
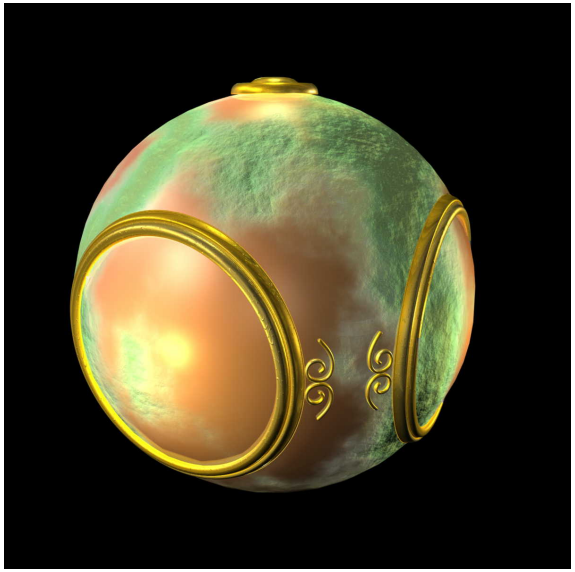
Three Types

Texture mapping



smooth shading

environment mapping



bump mapping

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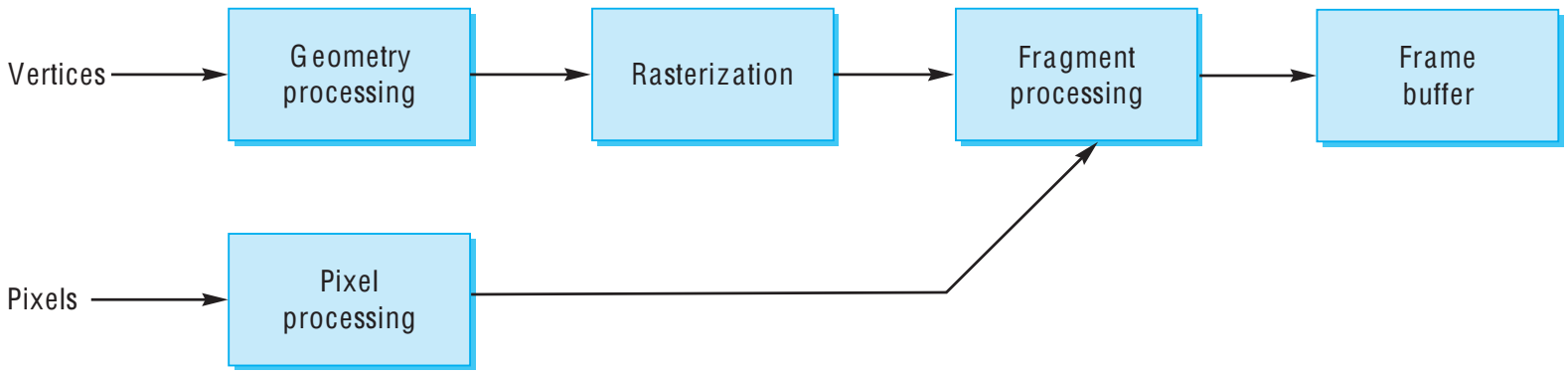
Texture Mapping - Pipeline

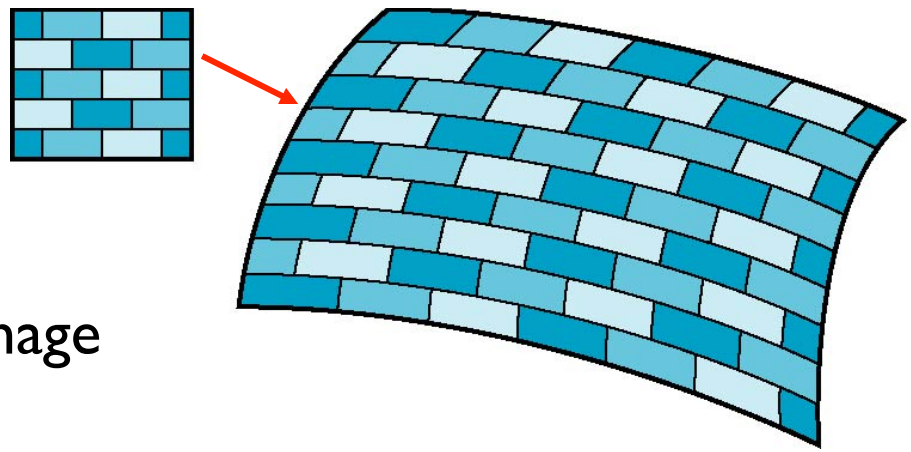
Mapping techniques are implemented at the end of the rendering pipeline

- Very efficient because few polygons make it past the clipper



Mapping Mechanics

3 or 4 coordinate systems involved



2D image

3D surface

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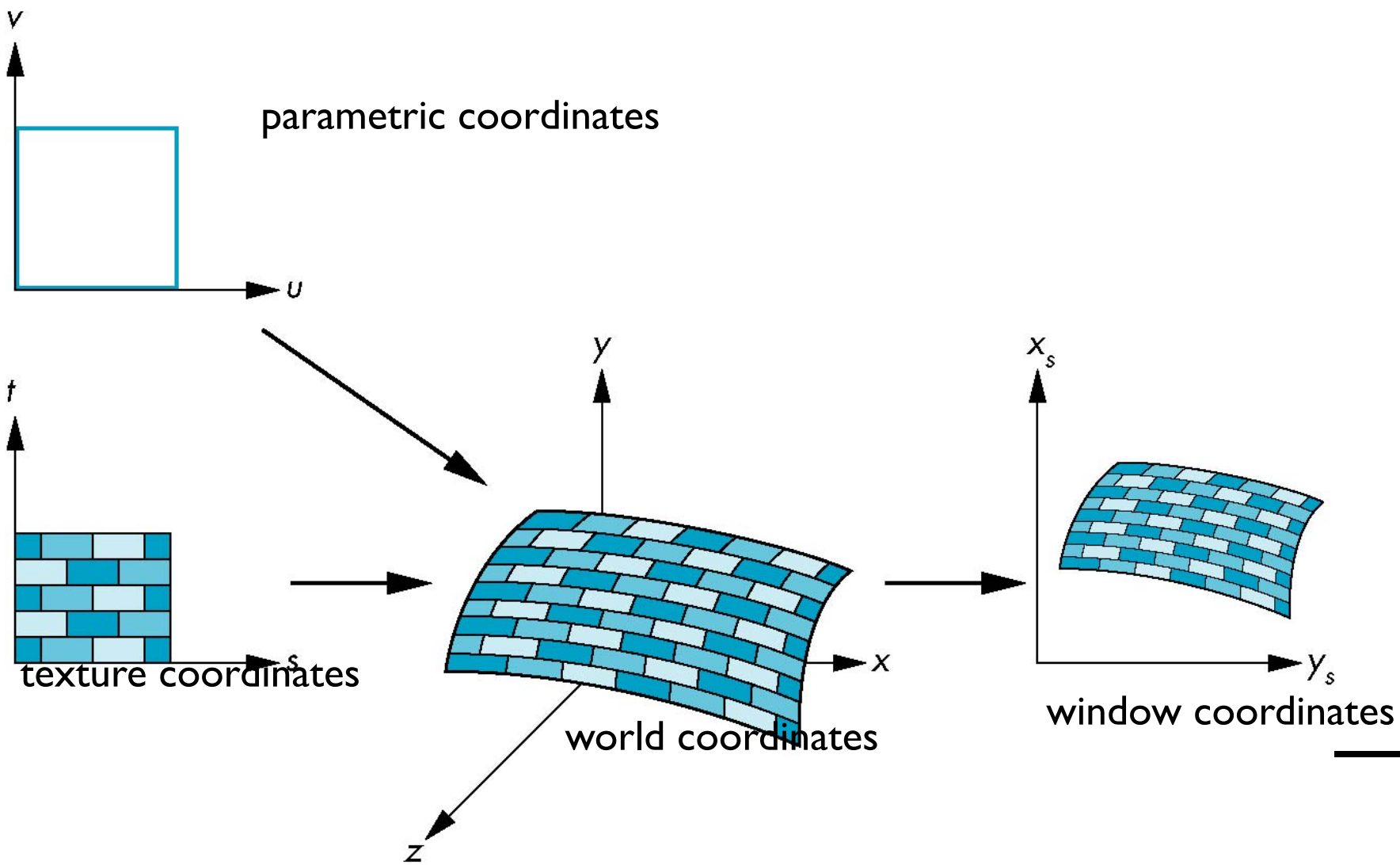
Texture Mapping



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

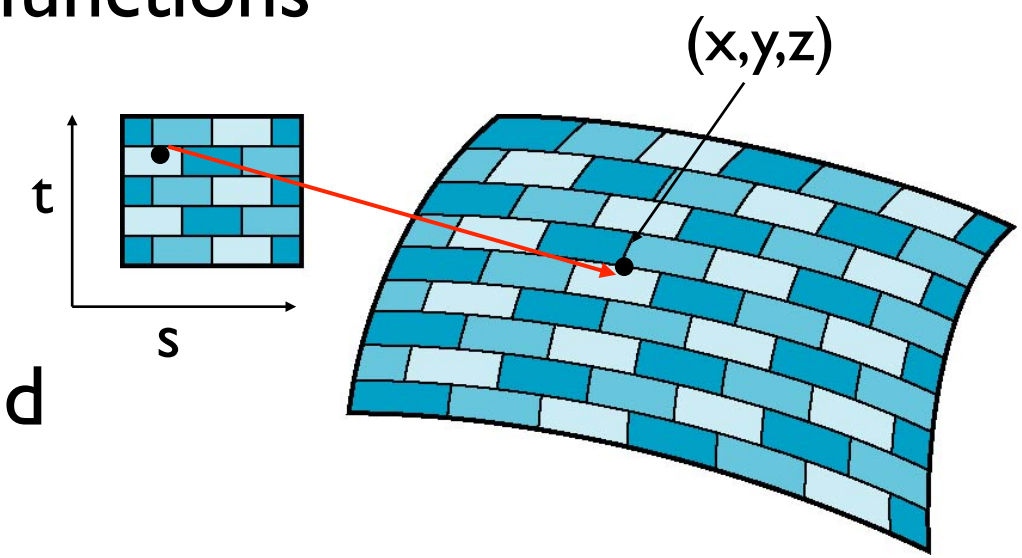
- Appear to need three functions

  $x = x(s,t)$

  $y = y(s,t)$

  $z = z(s,t)$

- 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

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

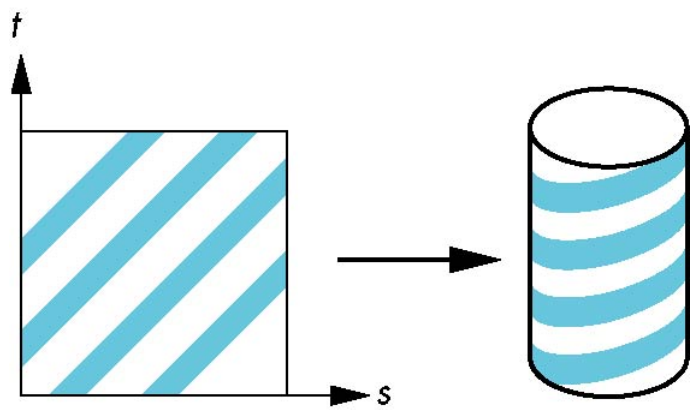
$$t = t(x,y,z)$$

<u>Such functions are difficult to find in general</u>

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

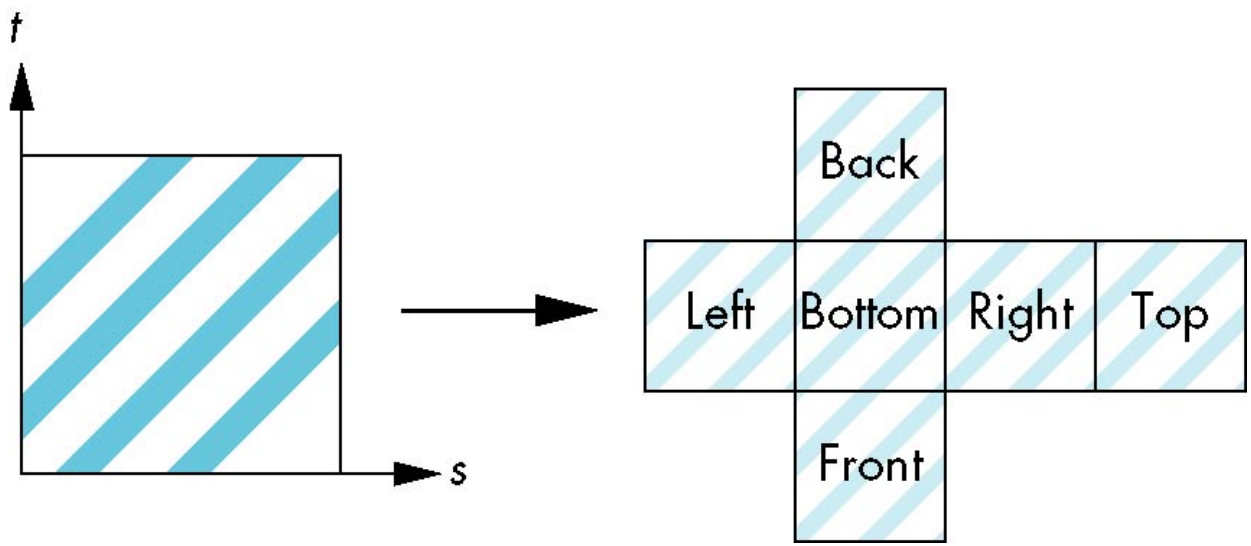
$$x = r \cos 2\pi u$$
$$y = r \sin 2\pi u \cos 2\pi v$$
$$z = r \sin 2\pi u \sin 2\pi v$$

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

Spheres are used in environmental maps

Box Mapping

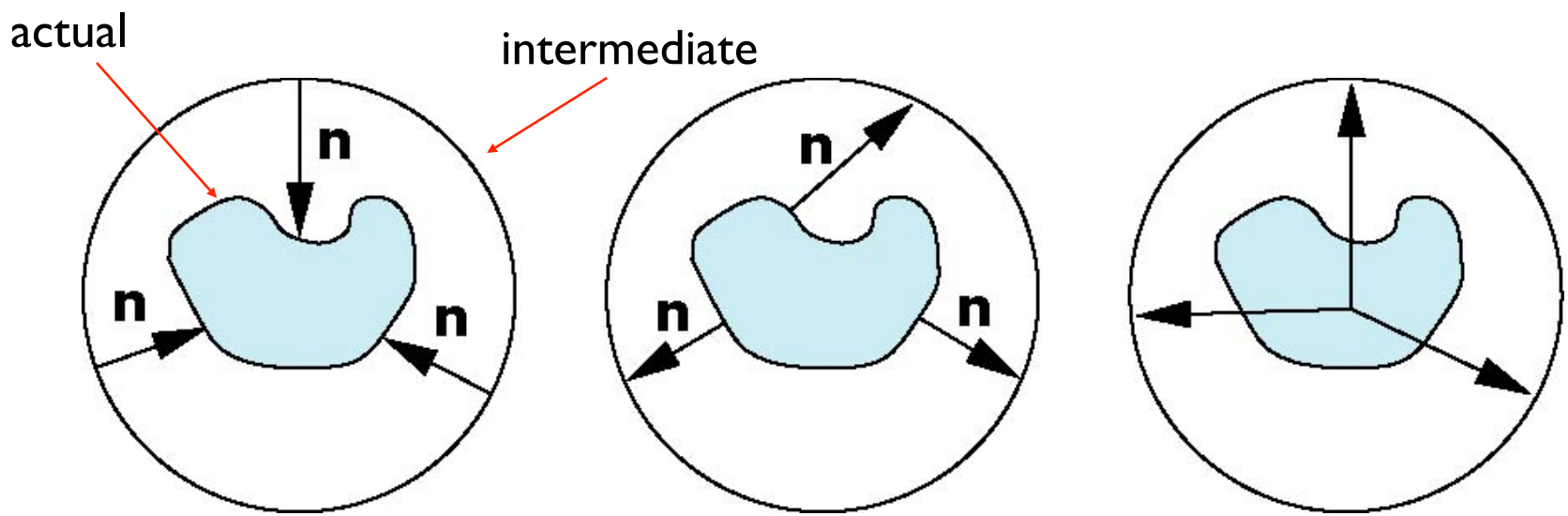
- Easy to use with simple orthographic projection
- Also used in environment maps



Second Mapping

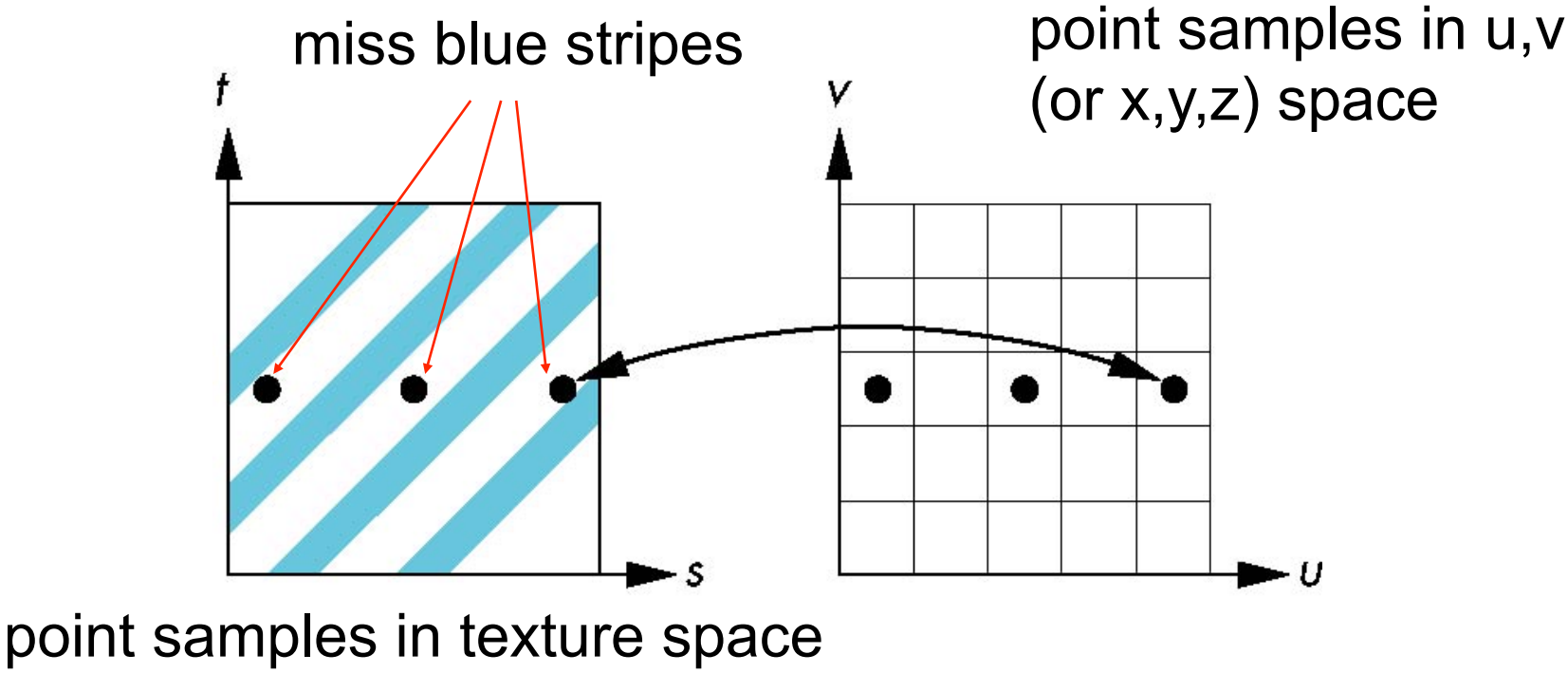
Map from intermediate object to actual object

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



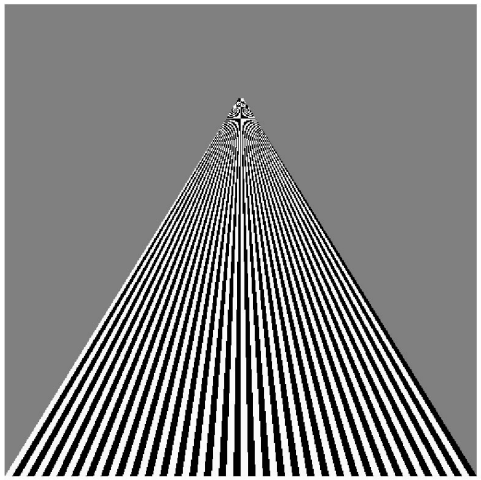
Aliasing

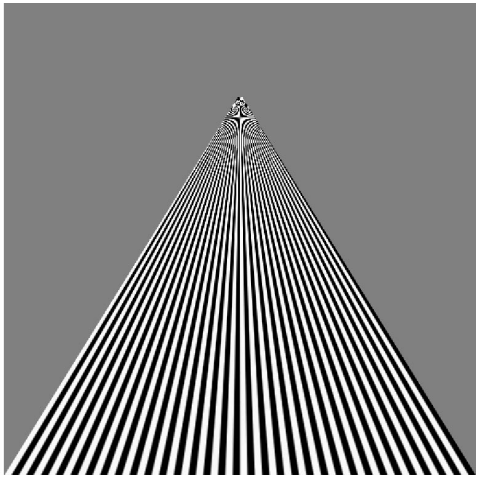
Point sampling of texture leads to aliasing errors



Anti-Aliasing in Textures

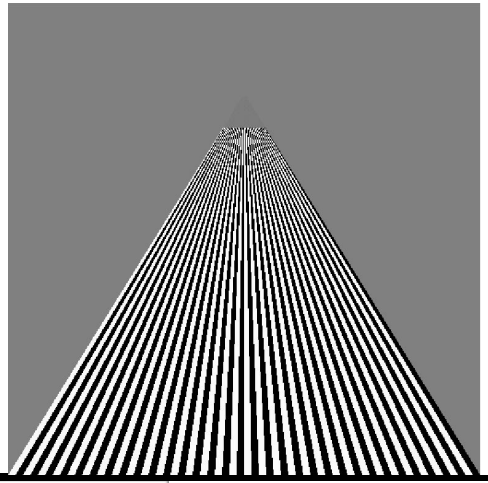
point sampling

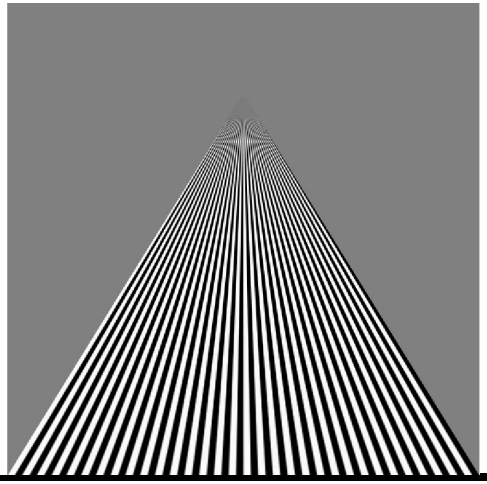




linear filtering

mipmapped point sampling

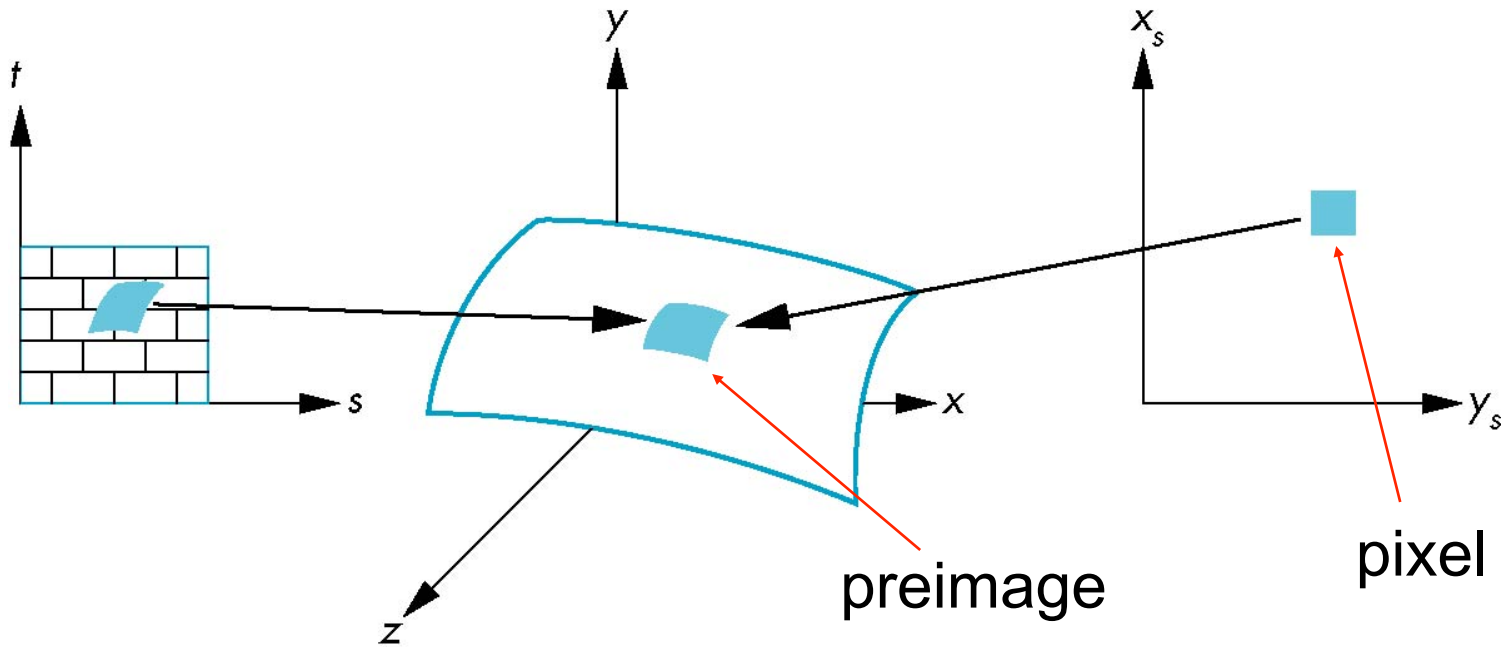




mipmapped linear filtering

Area Averaging

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



Note that *preimage* of pixel is curved

OpenGL Texture

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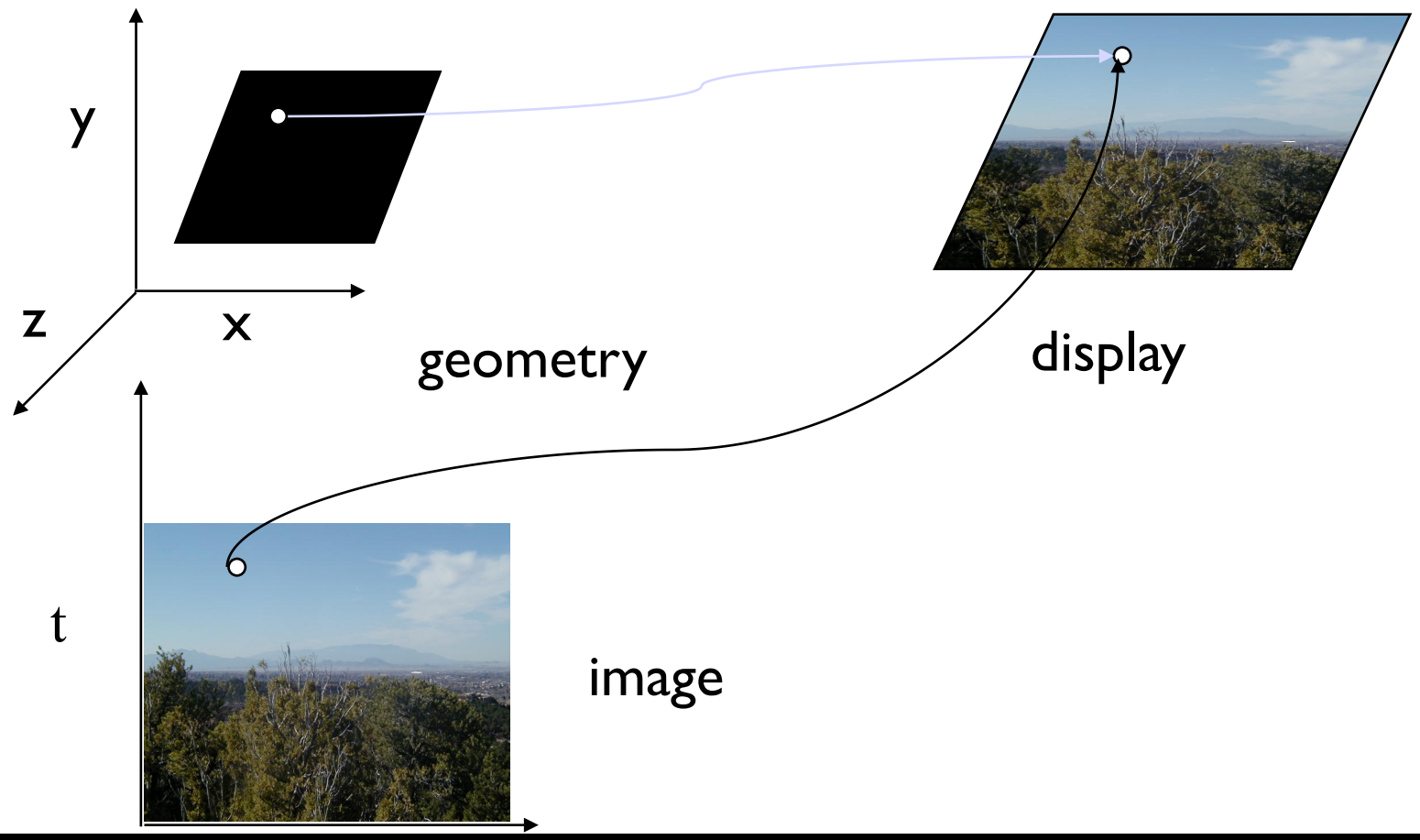
Basic Stragegy

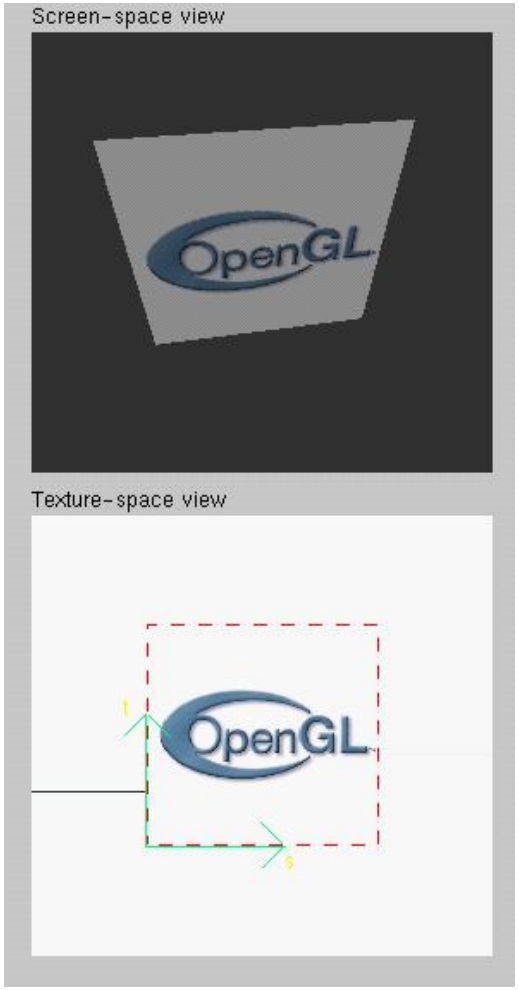
Three steps

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

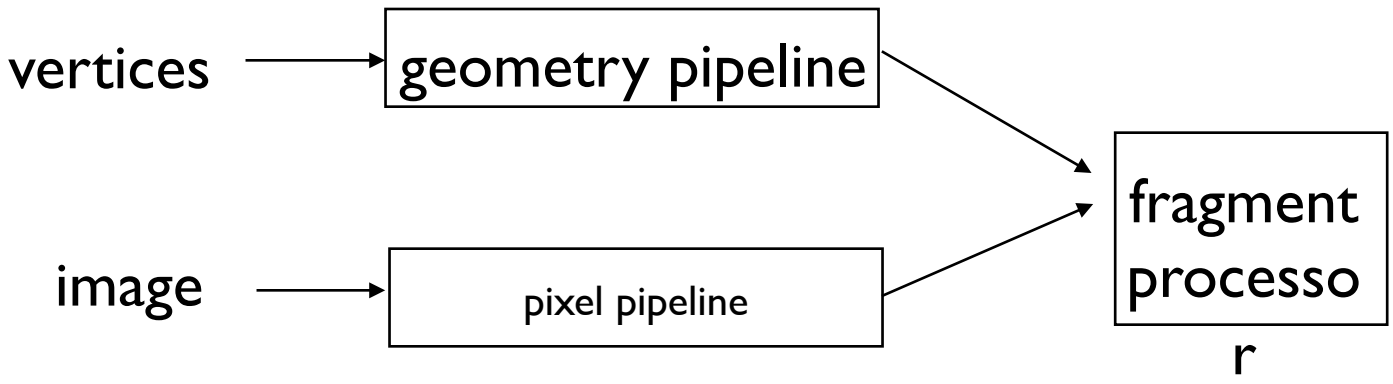
Texture Mapping



Texture Example



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

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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

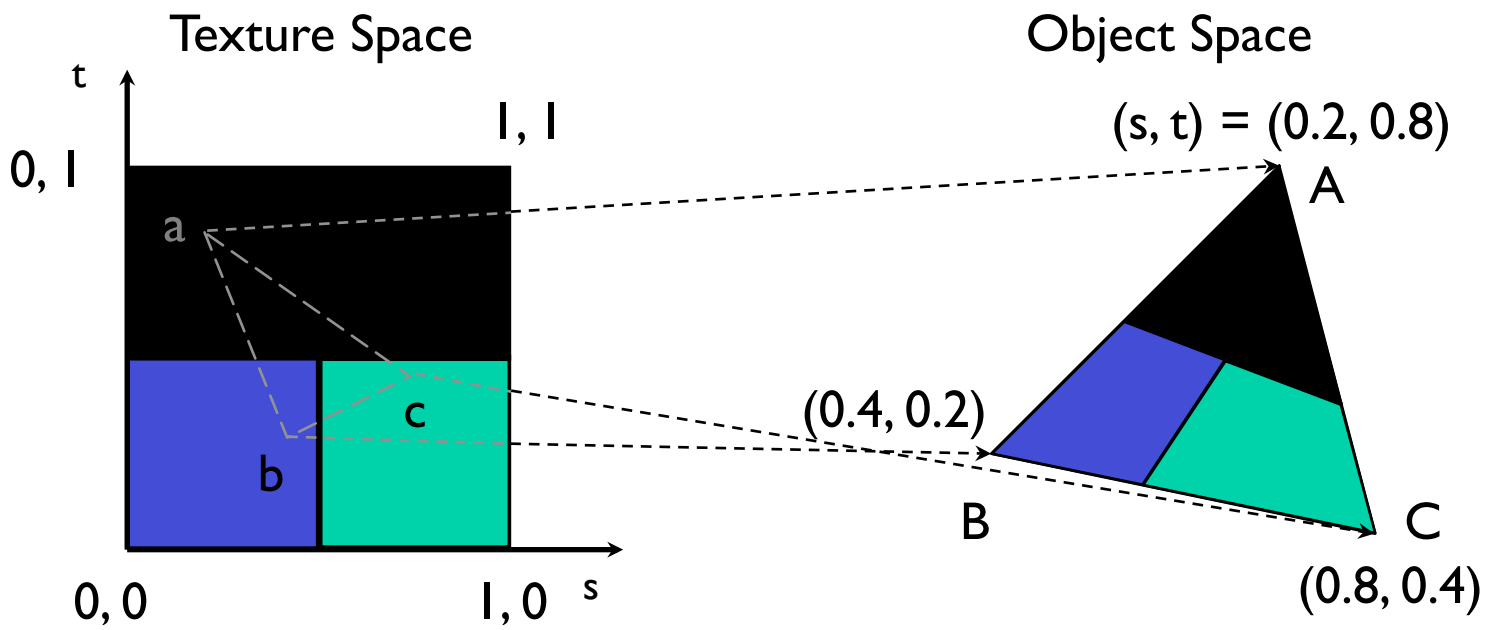
format and type: describe texels

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
}
```

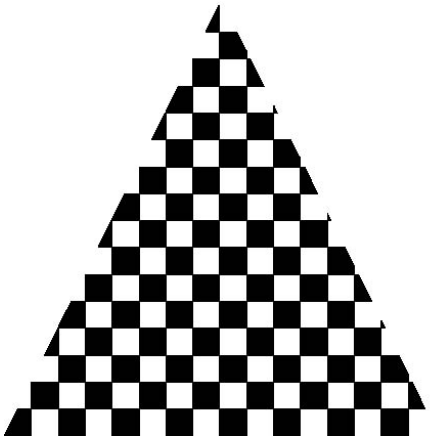
Role of Interpolation

Interpolation

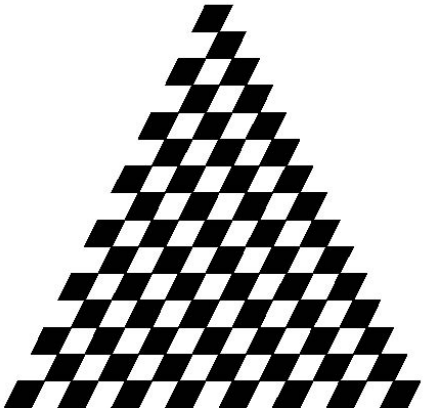
OpenGL uses interpolation to find proper texels from specified texture coordinates

Can be distorted

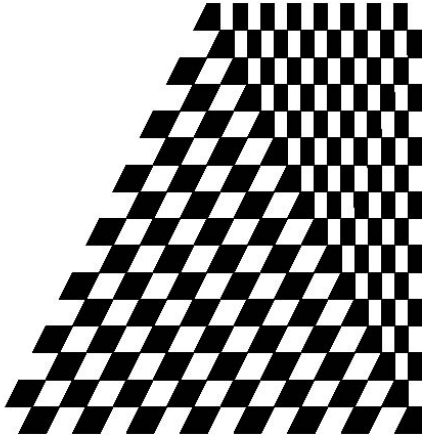
good selection of tex coordinates



poor selection of tex coordinates



texture stretched over trapezoid showing effects of bilinear interpolation



Interpolation

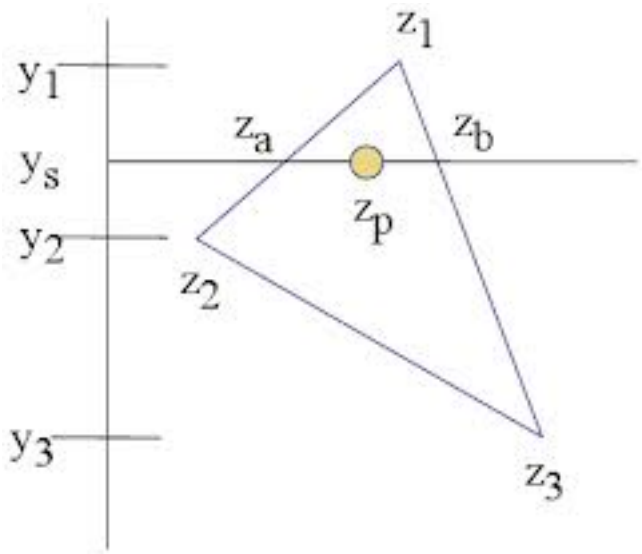
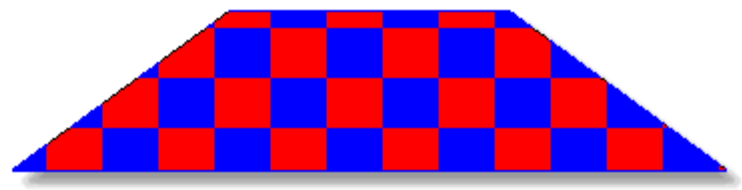
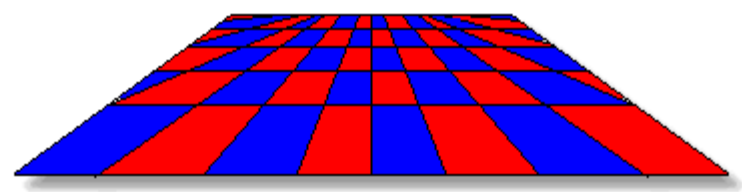


Figure 1.0 - Affine and perspective texture mapped polygons.



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

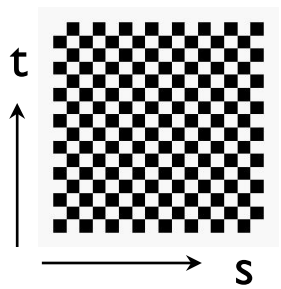
- Wrapping parameters determine what happens if s and t are outside the (0,1) range
- Filter modes allow us to use area averaging instead of point samples
- Mipmapping allows us to use textures at multiple resolutions
- Environment parameters determine how texture mapping interacts with shading

Wrapping Mode

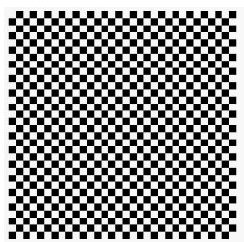
Clamping: if s,t > 1 use 1, if s,t <0 use 0

Wrapping: use s,t modulo 1

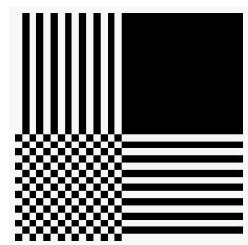
```
glTexParameteri( GL_TEXTURE_2D,
      GL_TEXTURE_WRAP_S, GL_CLAMP )
glTexParameteri( GL_TEXTURE_2D,
      GL_TEXTURE_WRAP_T, GL_REPEAT )
```



texture



GL_REPEAT wrapping

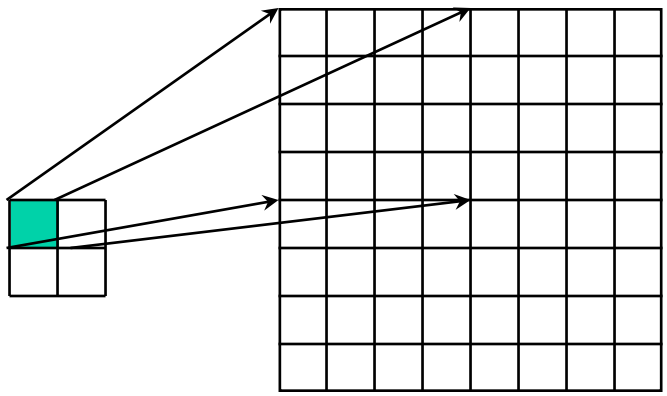


GL_CLAMP wrapping

Magnification/Minification

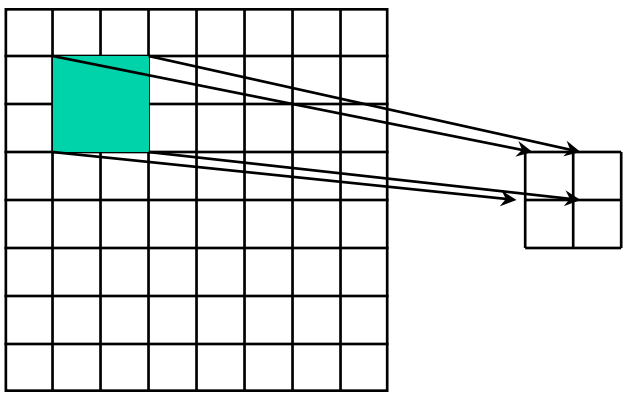
More than one texel can cover a pixel (*minification*) or more than one pixel can cover a texel (*magnification*)

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



Texture Polygon

Magnification



Texture Polygon

Minification

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)

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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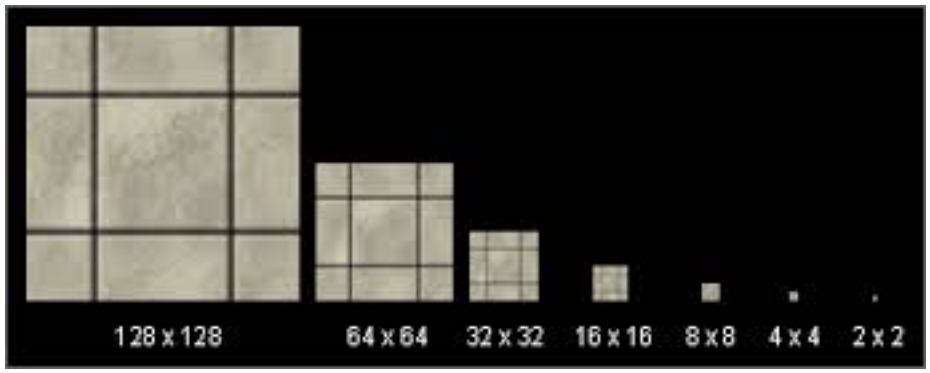
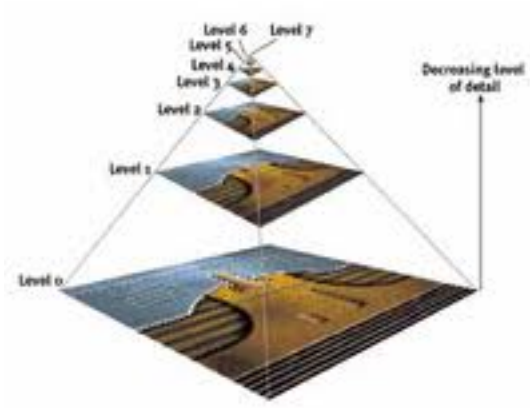
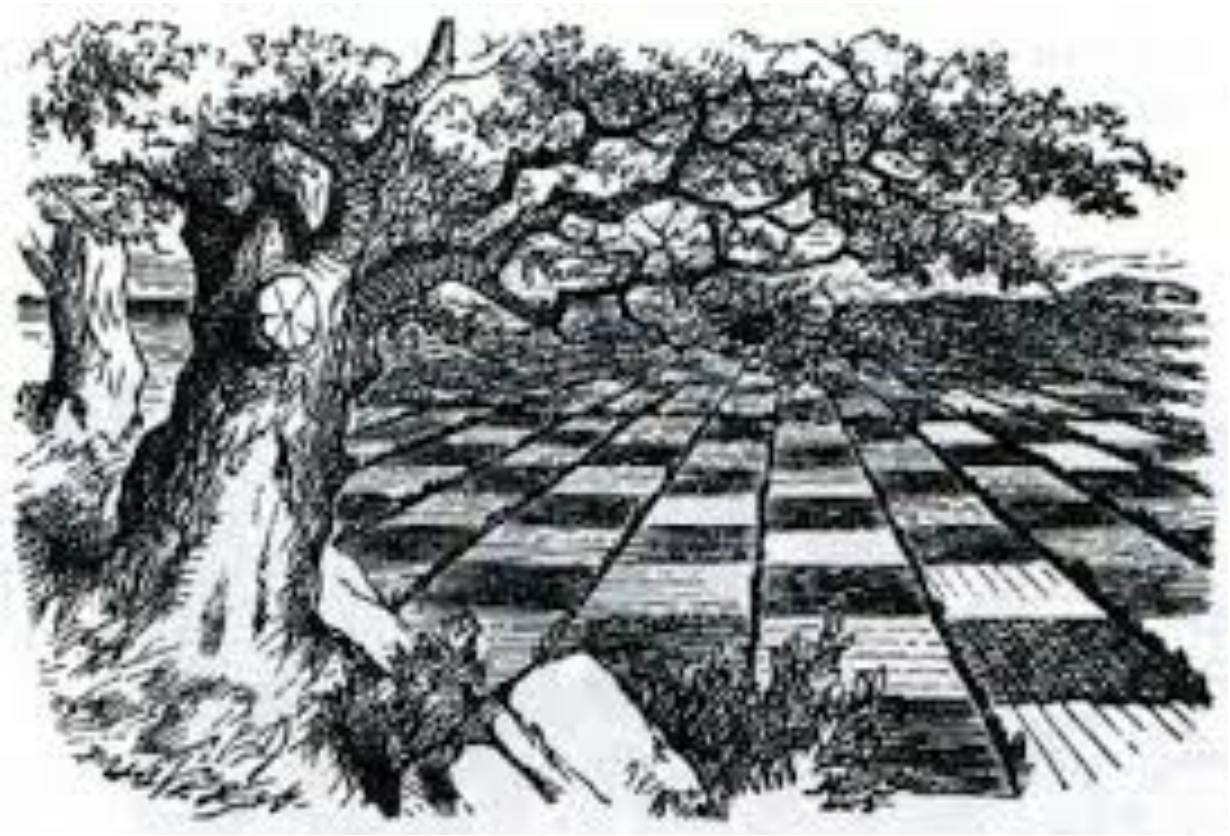
MipMaps

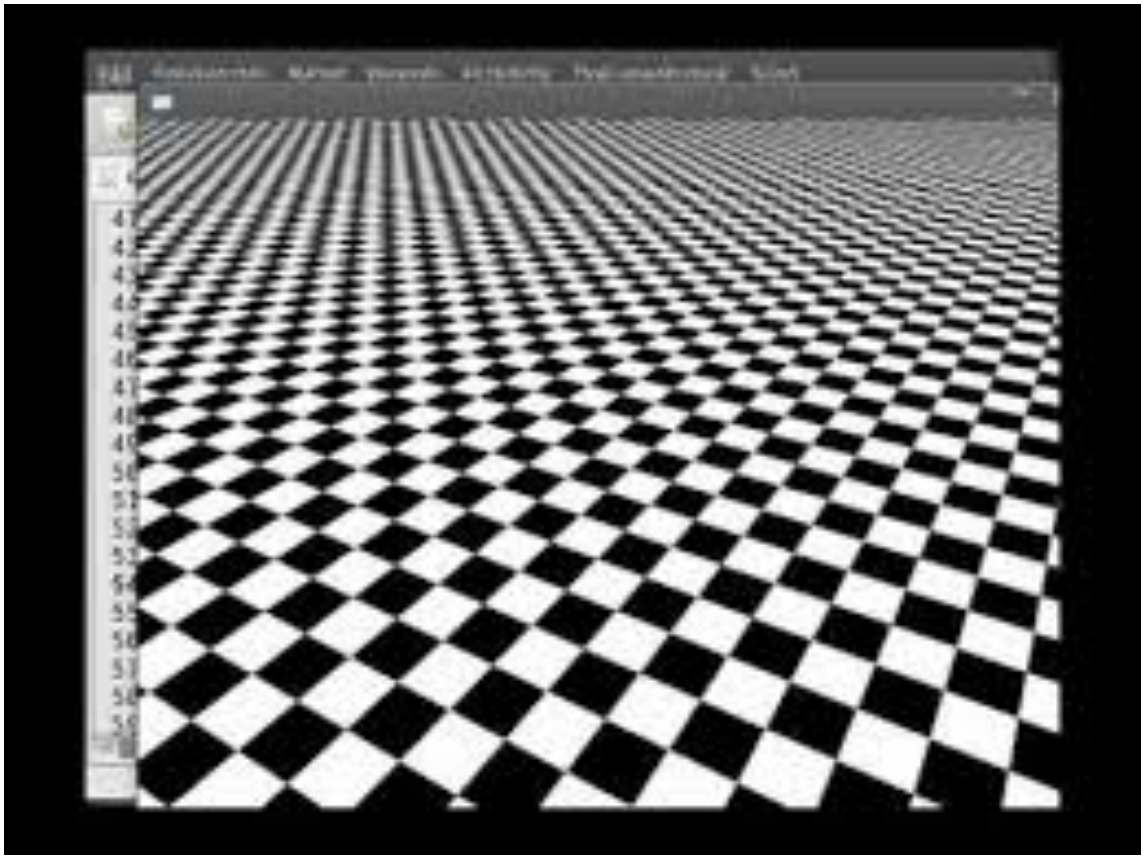

128 x 128
64 x 64
32 x 32
16 x 16
8 x 8
4 x 4
2 x 2


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

Mip-Mapping

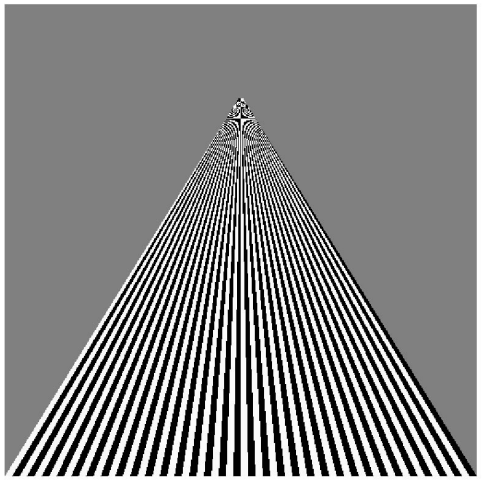


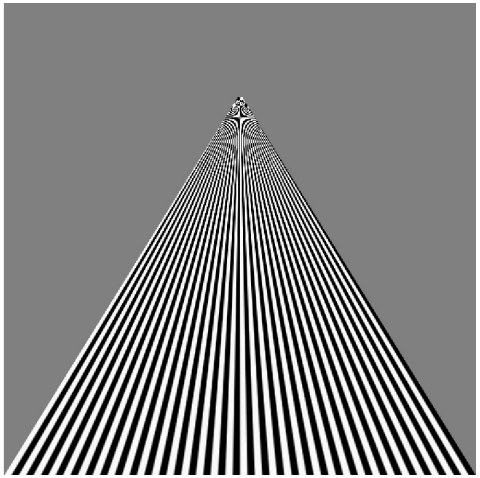
Mip-Mapping



Example

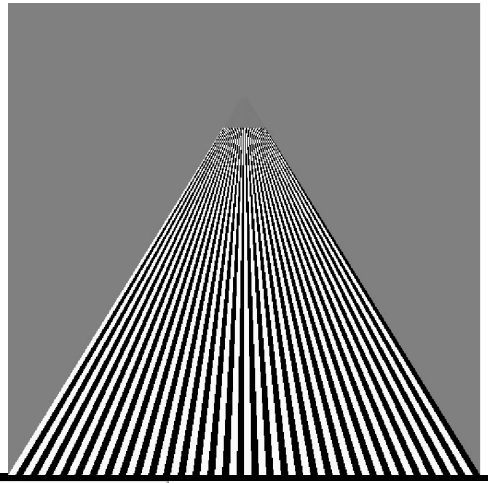
point sampling

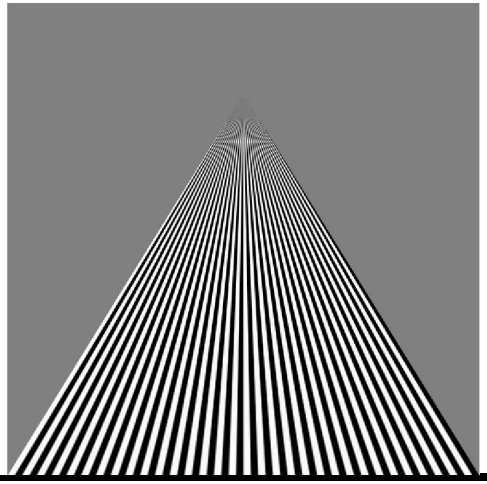




linear filtering

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

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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
}
```

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 );
```


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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

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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

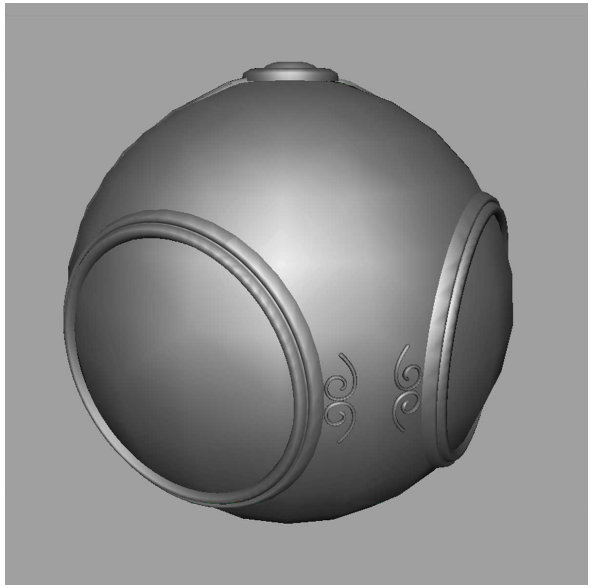
http://www.lighthouse3d.com/tutorials/glsl-core-tutorial/glsl-core-tutorial-texturing-with-images/

Example

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

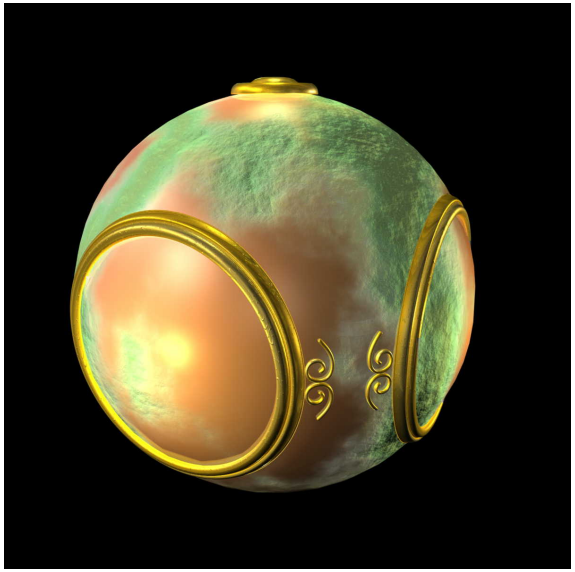
Fragment Shader

Texture mapping



smooth shading

environment mapping



bump mapping

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Cube Maps

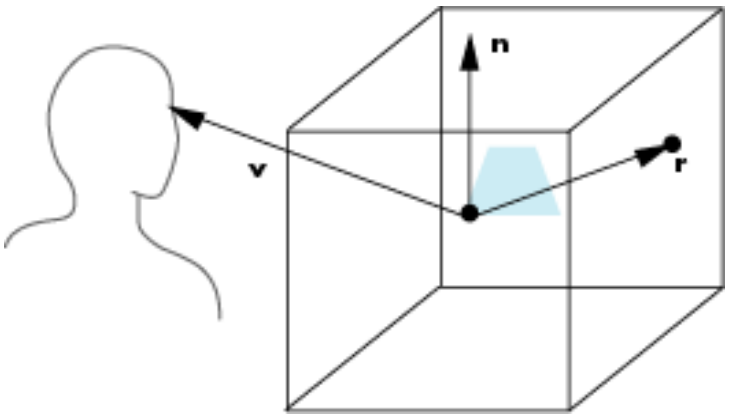
- We can form a cube map texture by defining six 2D texture maps that correspond to the sides of a box
- Supported by OpenGL
- Also supported in GLSL through cubemap sampler

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

- Texture coordinates must be 3D

Environment Map

Use reflection vector to locate texture in cube map



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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

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);
}
```


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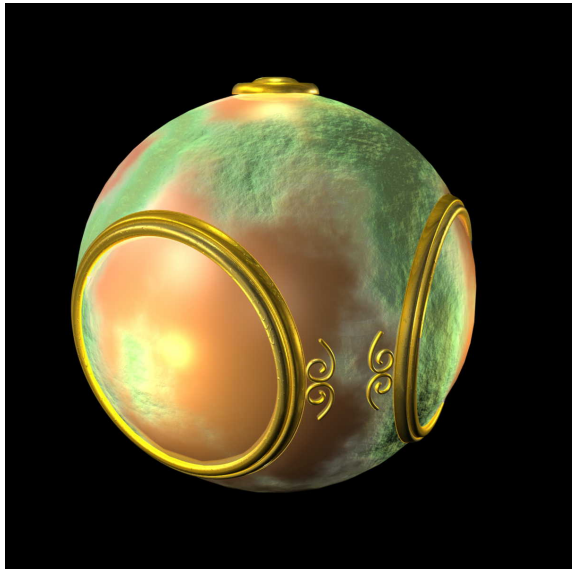
Bump Mapping

- Perturb normal for each fragment
- Store perturbation as textures



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Normalization Maps

- Cube maps can be viewed as lookup tables 1-4 dimensional variables
- Vector from origin is pointer into table
- Example: store normalized value of vector in the map
  - Same for all points on that vector
  - Use “normalization map” instead of normalization function
  - Lookup replaces sqrt, mults and adds

Fragment Program Examples

- Mapping methods
  - Texture mapping
  - Environmental (reflection) mapping
    - Variant of texture mapping
  - Bump mapping
    - Solves flatness problem of texture mapping

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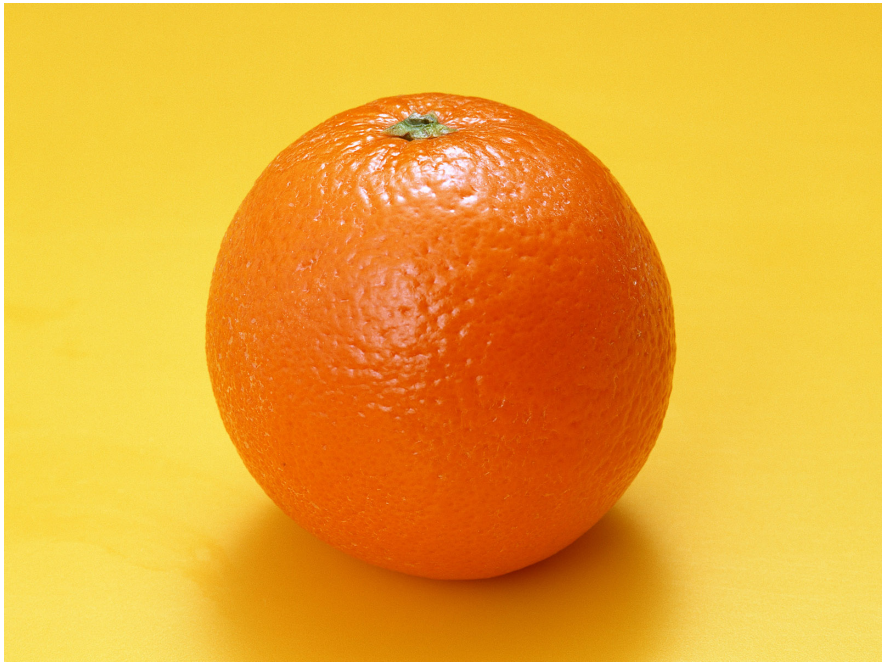
Back 2 Orange

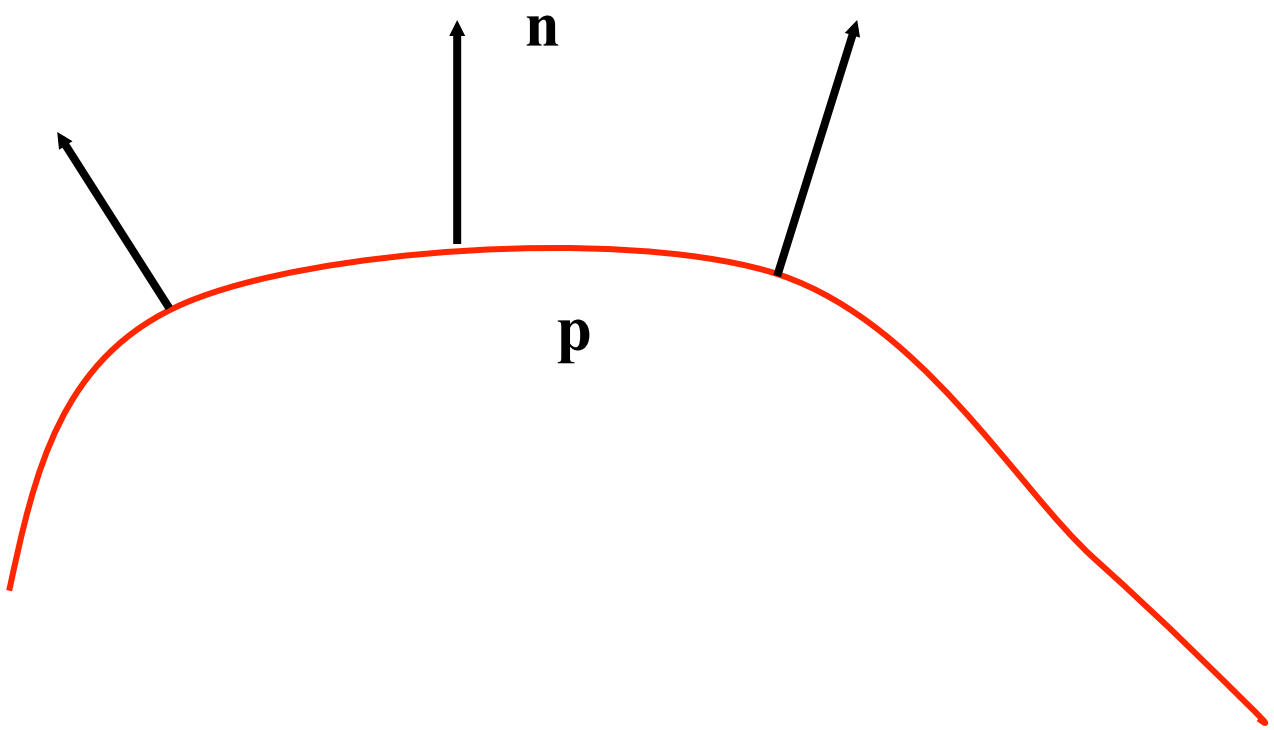


The Orange

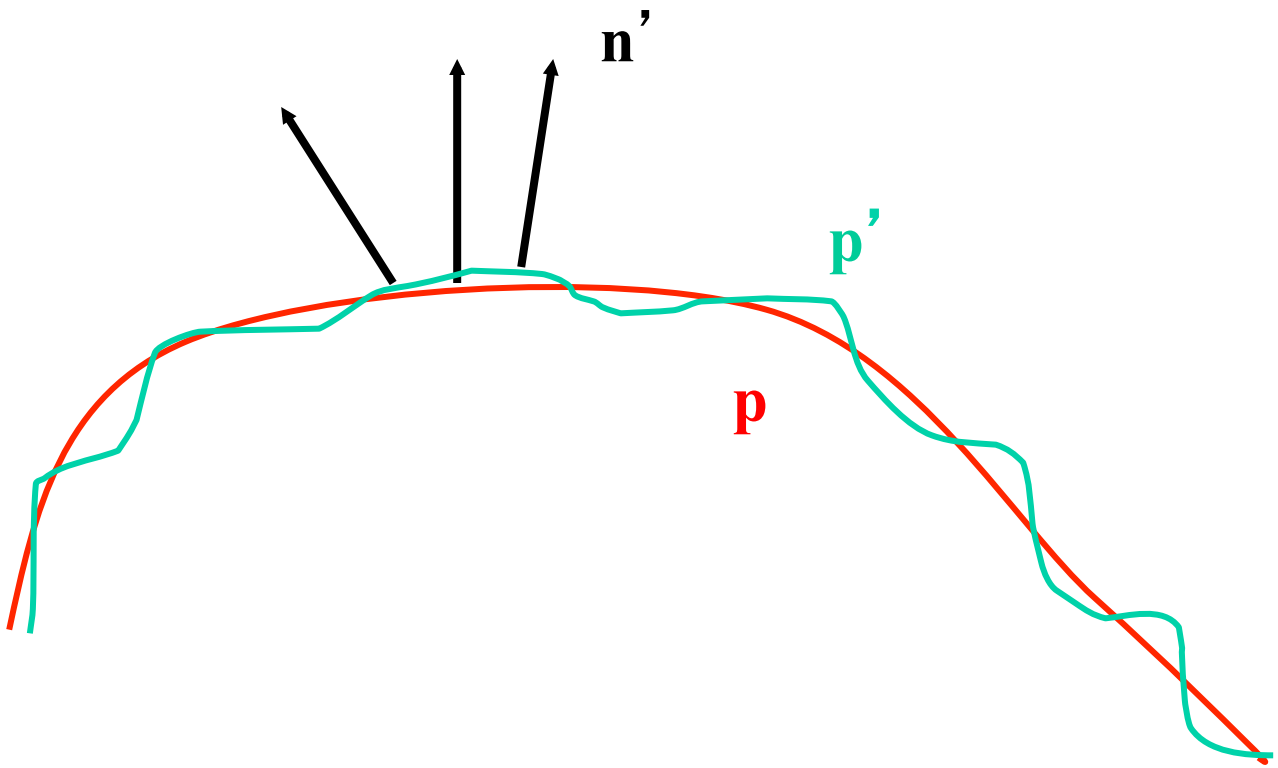
- Texture map a photo of an orange onto a surface
  - Captures dimples
  - Will not be correct if we move viewer or light
  - We have shades of dimples rather than their correct orientation
- Ideally perturb normal across surface of object and compute a new color at each interior point

Bump Mapping (Blinn)

Consider a smooth surface



Rougher Version



Equations

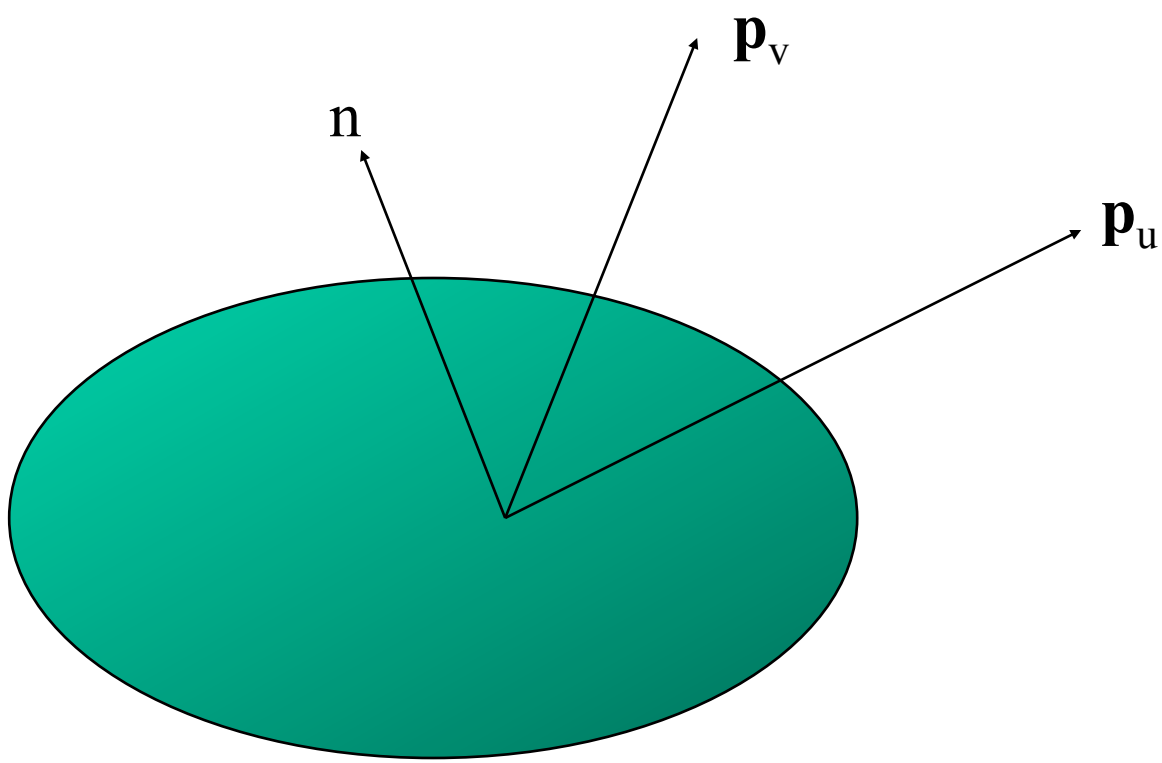
$$\mathbf{p}(u,v) = [x(u,v), y(u,v), z(u,v)]^T$$

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

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

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

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

$|d(u,v)| << 1$

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

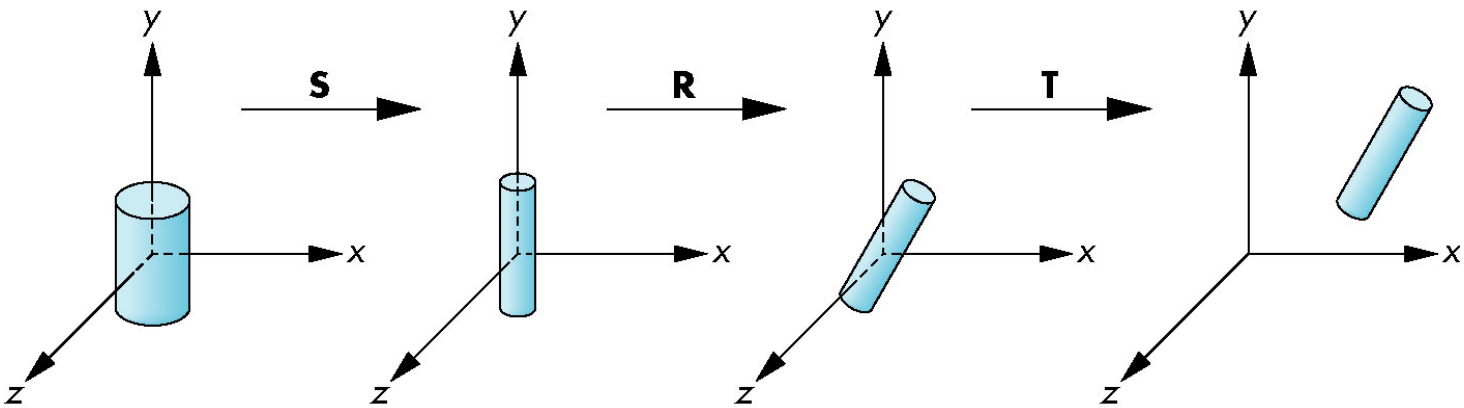
Hierarchical Modeling

Cars, Robots, Solar System

The Terminator

Instance Transformation

- Start with prototype object
- Each appearance of object in model is *instance*
  - Must scale, orient, position
  - Defines instance transformation



Symbol-Instance Table

Symbol	Scale	Rotate	Translate
1	s_x, s_y, s_z	$\theta_x, \theta_y, \theta_z$	d_x, d_y, d_z
2			
3			
1			
1			
.			
.			

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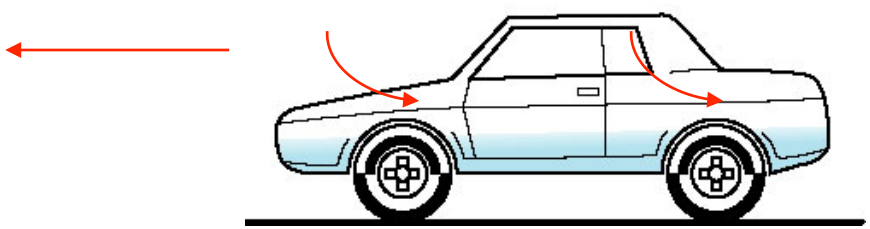
Relationships

- Car
  - Chassis + 4 identical wheels
  - Two symbols
- Rate of forward motion function of rotational speed of wheels

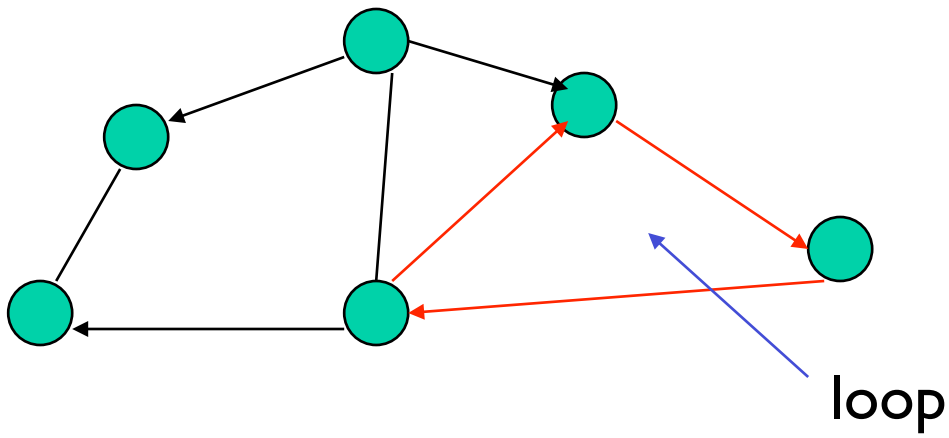


Move The Car

```
car(speed)
{
    chassis()
    wheel(right_front);
    wheel(left_front);
    wheel(right_rear);
    wheel(left_rear);
}
```

Graphs – Composition of Car

- Set of *nodes* and *edges (links)*
- Edge connects a pair of nodes
  - Directed or undirected
- *Cycle*: directed path that is a loop



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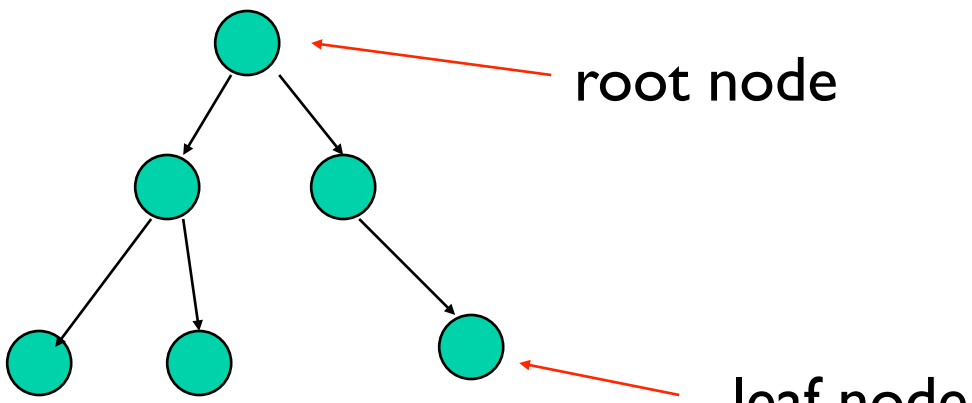
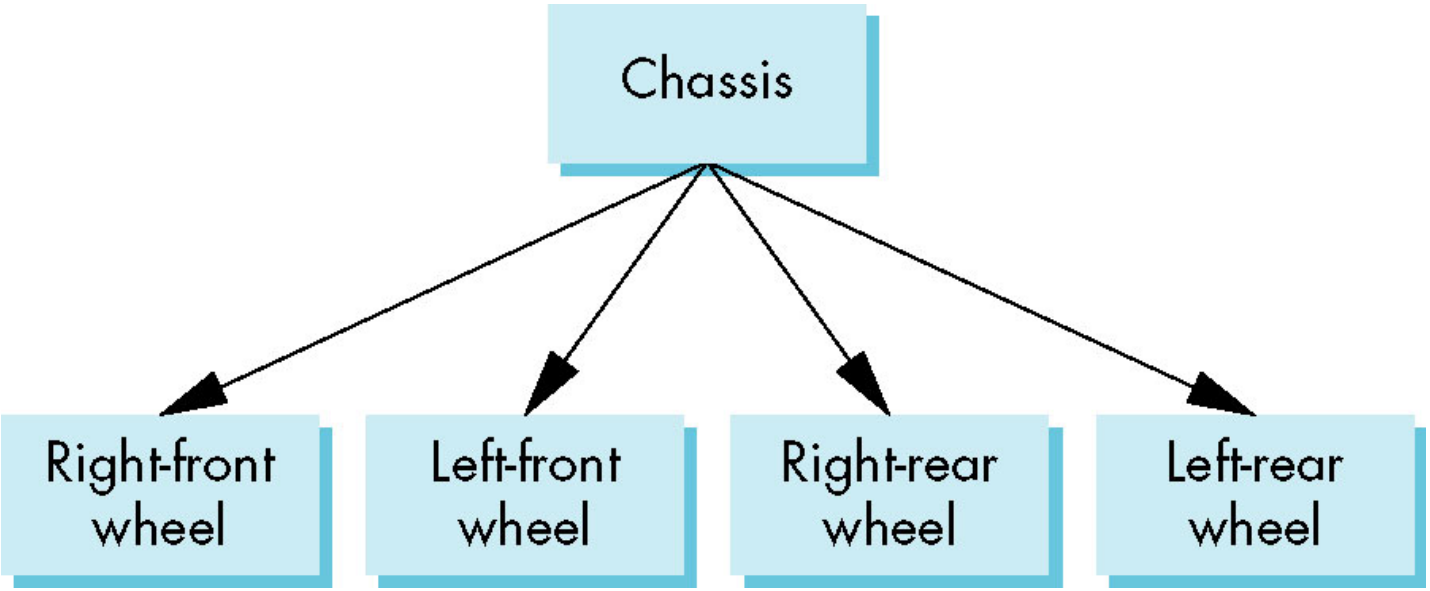
Tree – Composition of Car

Graph in which each node (except the root) has exactly one parent node

- May have multiple children
- Leaf or terminal node: no children



Tree Model of Car



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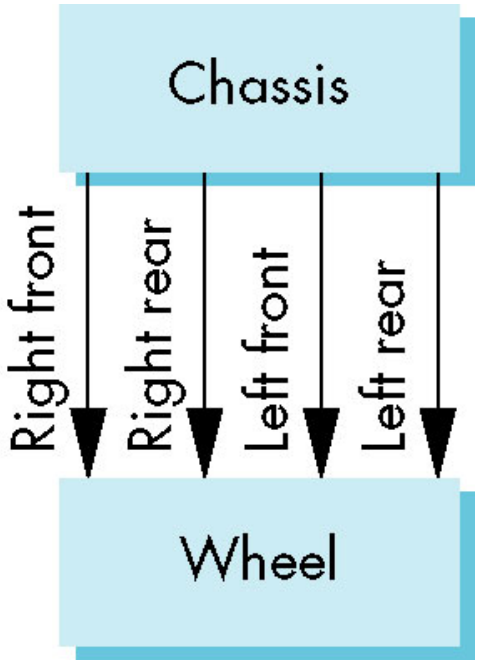
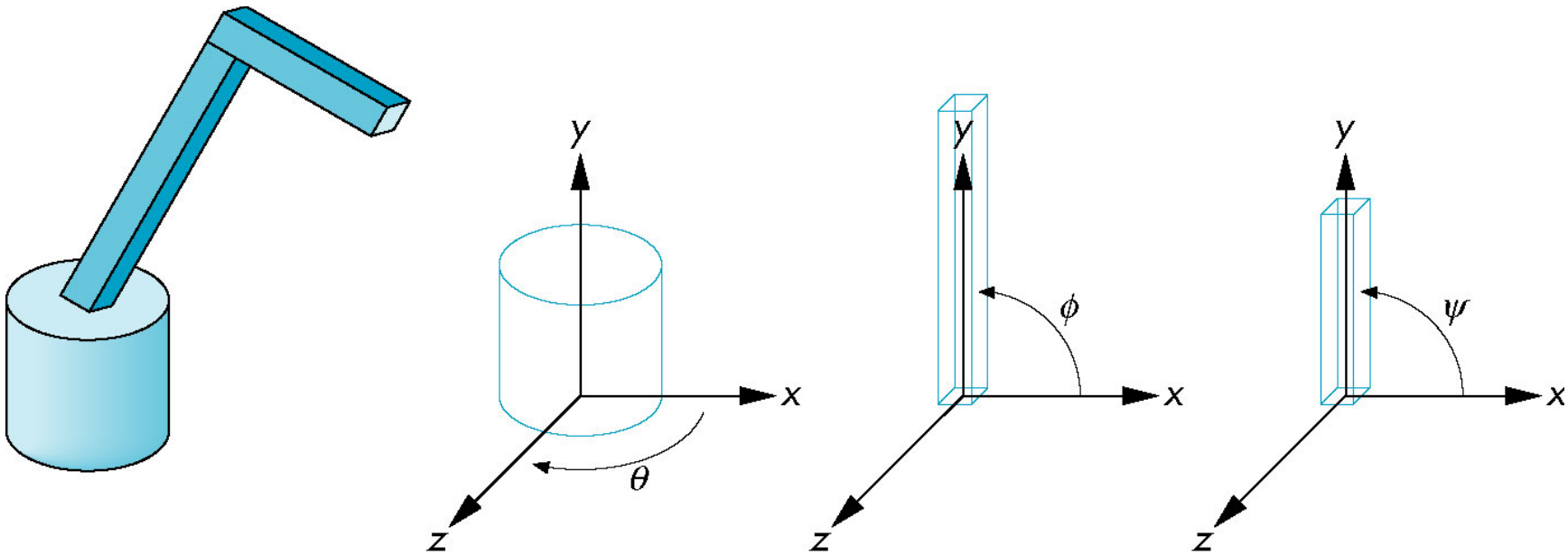
DAG Model

All the wheels are identical

Not much different than dealing with a tree



Robot Arm

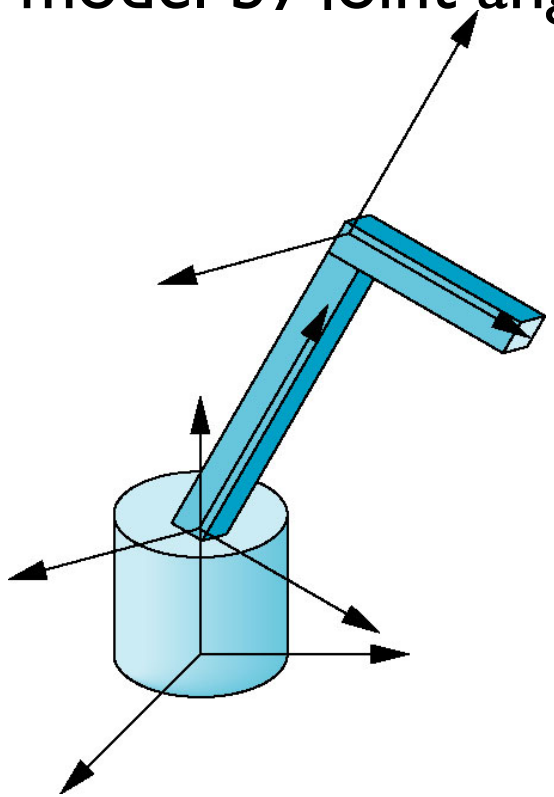


robot arm

parts in their own coodinate systems

Articulated Models

- Parts connected at joints
- Specify state of model by joint angles

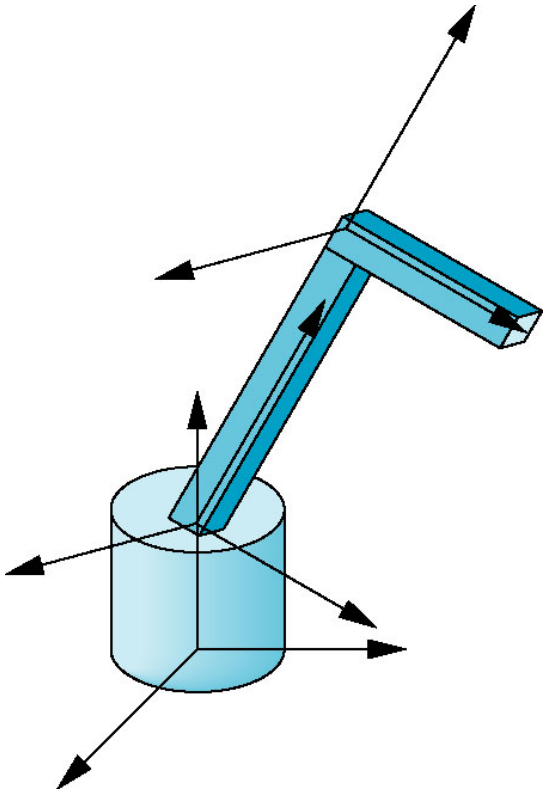


Relationships - Composition

- Base
- Lower Arm
- Upper Arm

Base

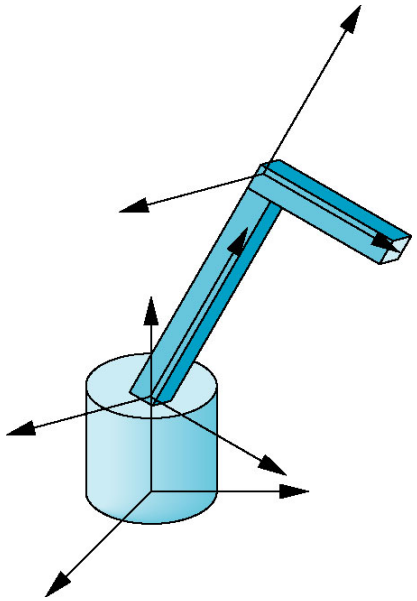
- Single angle determines position
- Is cylinder



Lower Arm

Attached to base

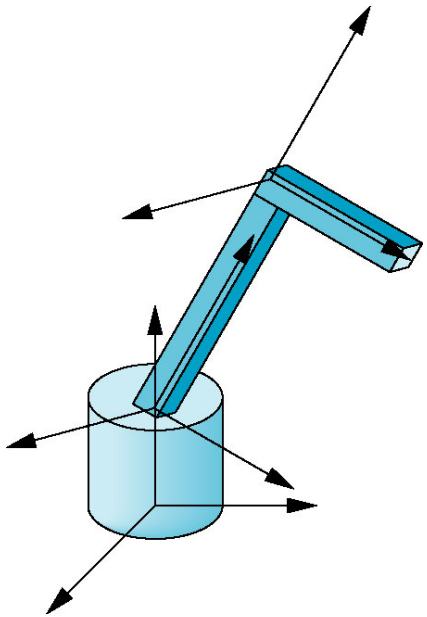
- Position depends on rotation of base
- Also translate relative to base, rotate about connecting joint
- Is cube



Upper Arm

Upper arm attached to lower arm

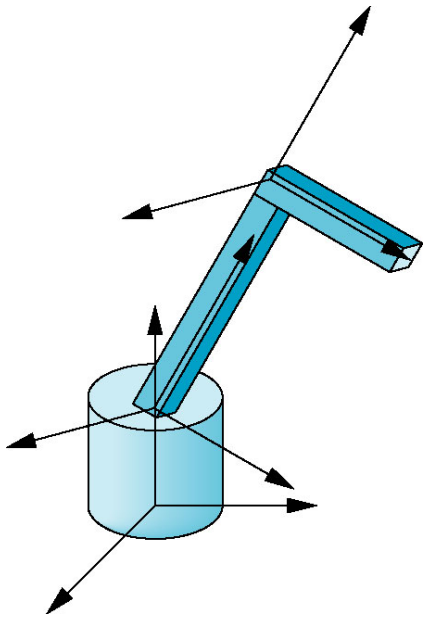
- Its position depends on both base and lower arm
- Translate relative to lower arm and rotate about joint connecting to lower arm



Upper Arm

Upper arm attached to lower arm

- Its position depends on both base and lower arm
- Translate relative to lower arm and rotate about joint connecting to lower arm



Do the same …

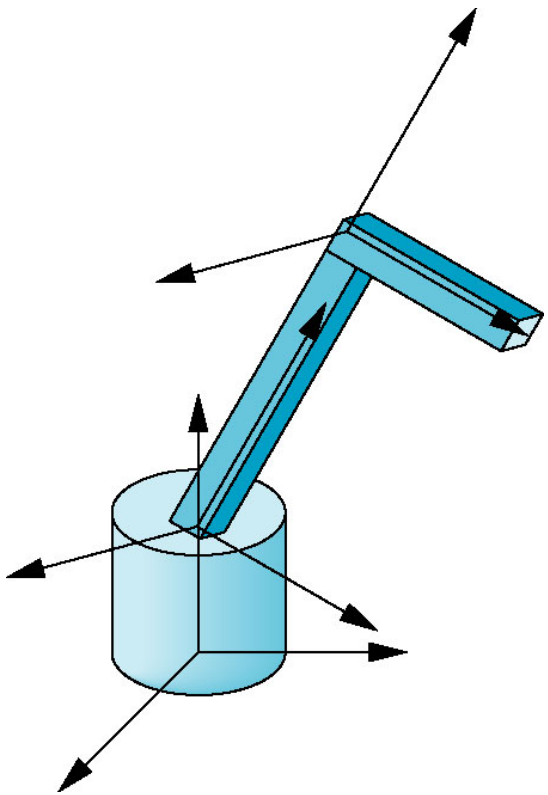

Pluto
Neptune
Uranus
Saturn
Jupiter
Mars
Moon
Earth
Venus
Mercury

Required Matrices

Base

Rotation of base: $\mathbf{R}_b$

– Apply $\mathbf{M} = \mathbf{R}_b$ to base

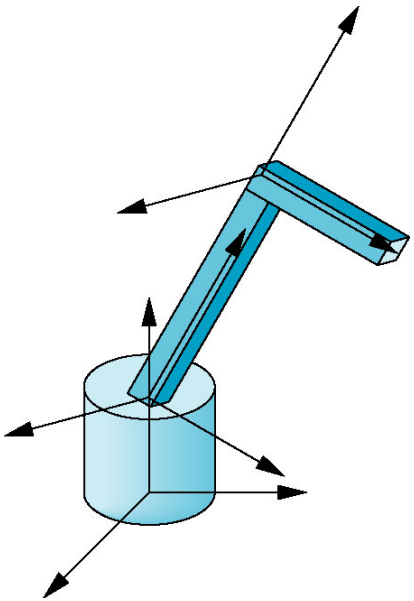


Lower Arm

Translate lower arm <u>relative</u> to base: $\mathbf{T}_{lu}$

Rotate lower arm around joint: $\mathbf{R}_{lu}$

– Apply $\mathbf{M} = \mathbf{R}_b \, \mathbf{T}_{lu} \, \mathbf{R}_{lu}$ to lower arm

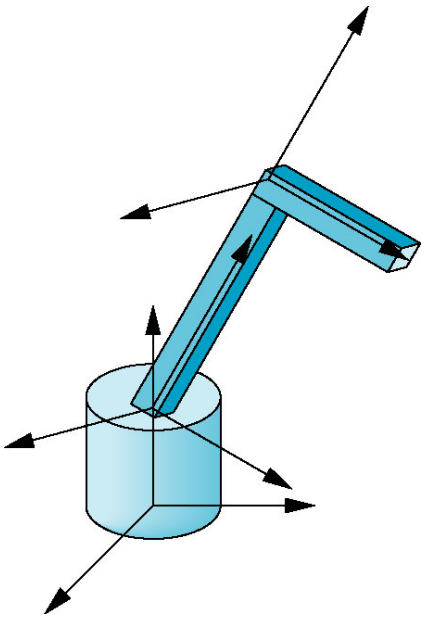


Upper Arm

Translate upper arm <u>relative</u> to upper arm: $\mathbf{T}_{uu}$

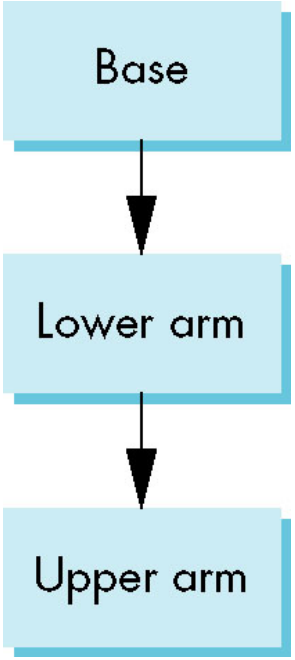
Rotate upper arm around joint: $\mathbf{R}_{uu}$

– Apply $\mathbf{M} = \mathbf{R}_b \, \mathbf{T}_{lu} \, \mathbf{R}_{lu} \, \mathbf{T}_{uu} \, \mathbf{R}_{uu}$ to upper arm



Simple Robot

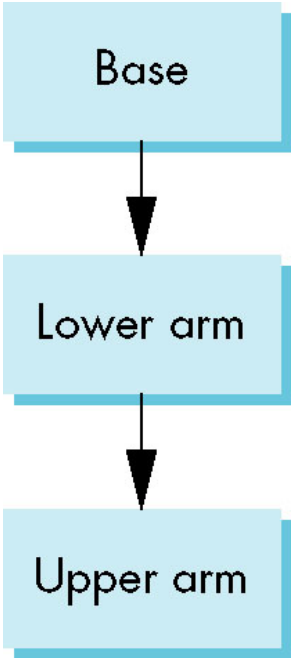
```
mat4 ctm;
robot_arm()
{
    ctm = RotateY(theta);
    base();
    ctm *= Translate(0.0, h1, 0.0);
    ctm *= RotateZ(phi);
    lower_arm();
    ctm *= Translate(0.0, h2, 0.0);
    ctm *= RotateZ(psi);
    upper_arm();
}
```



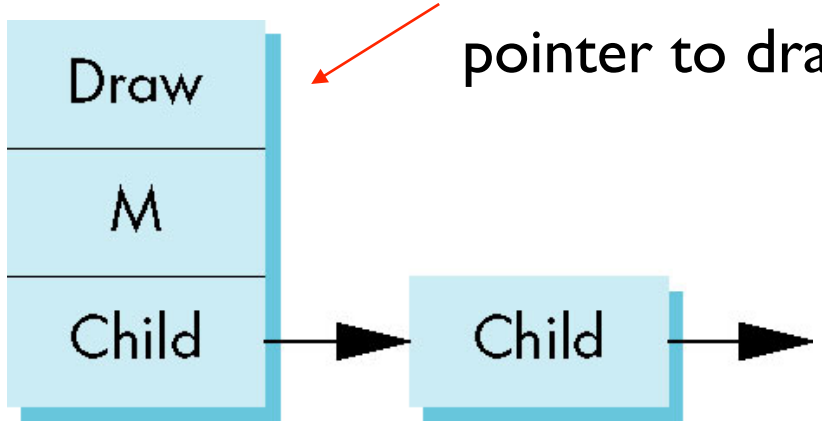
Tree Model of Robot

Code shows relationships between parts of model

– Can change shape/texture w/o altering relationships



Possible Node Structure



Code for drawing part or pointer to drawing function

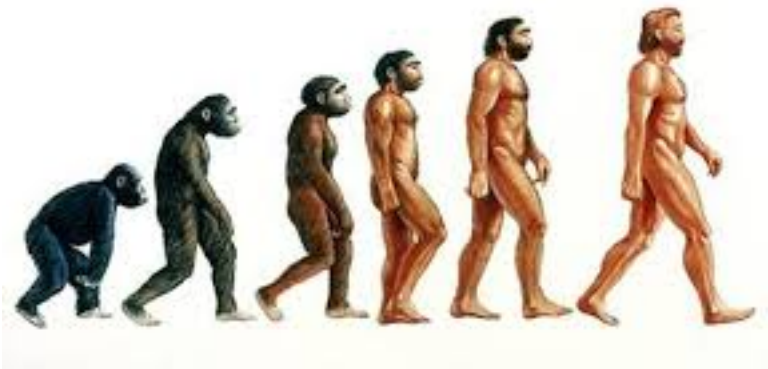
linked list of pointers to children

matrix relating node to parent

Do the same …


Pluto
Neptune
Uranus
Saturn
Jupiter
Mars
Moon
Earth
Venus
Mercury

Generalizations



Generalizations

- Need to deal with multiple children
  - How do we represent a more general tree?
  - How do we traverse such a data structure?
- Animation
  - How to use dynamically?
  - Can we create and delete nodes during execution?

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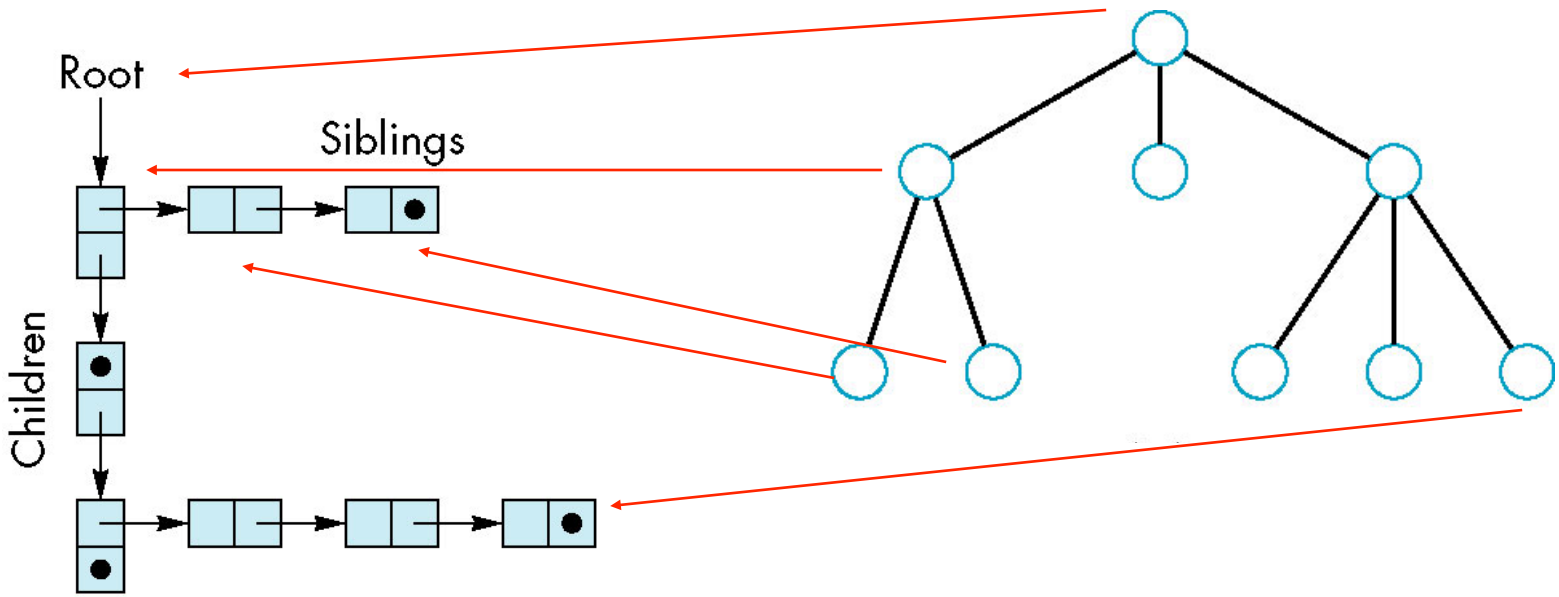
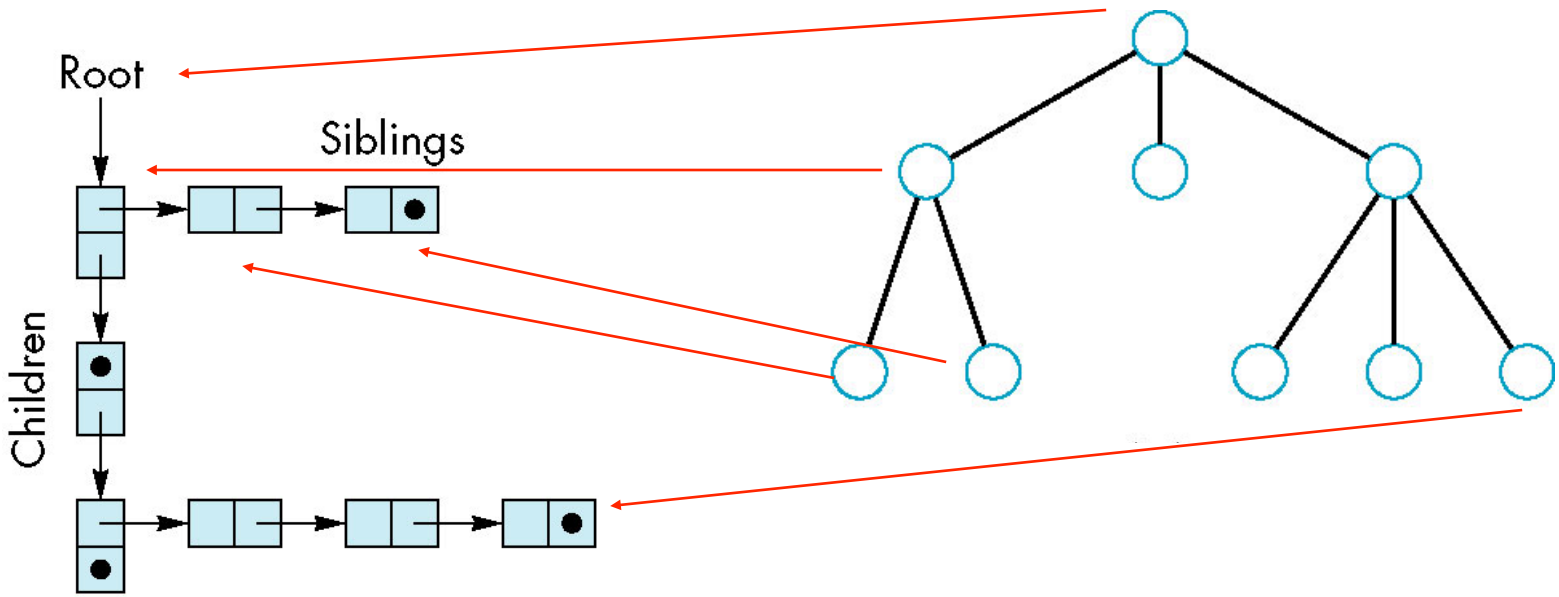
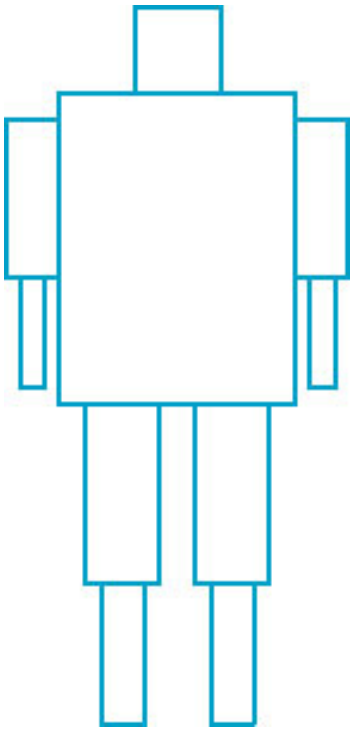
Breadth-First Tree

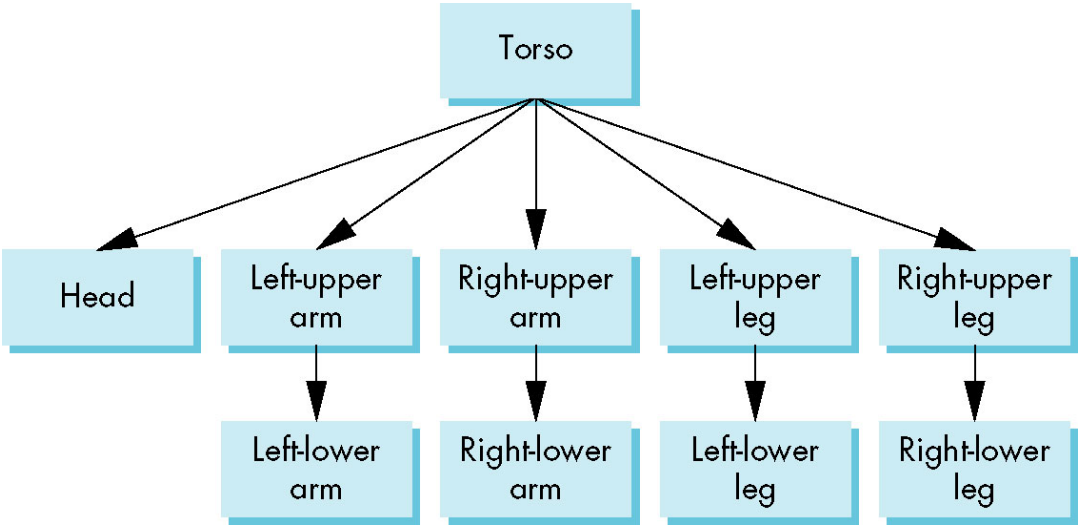


Solar System ?



Humanoid Figure

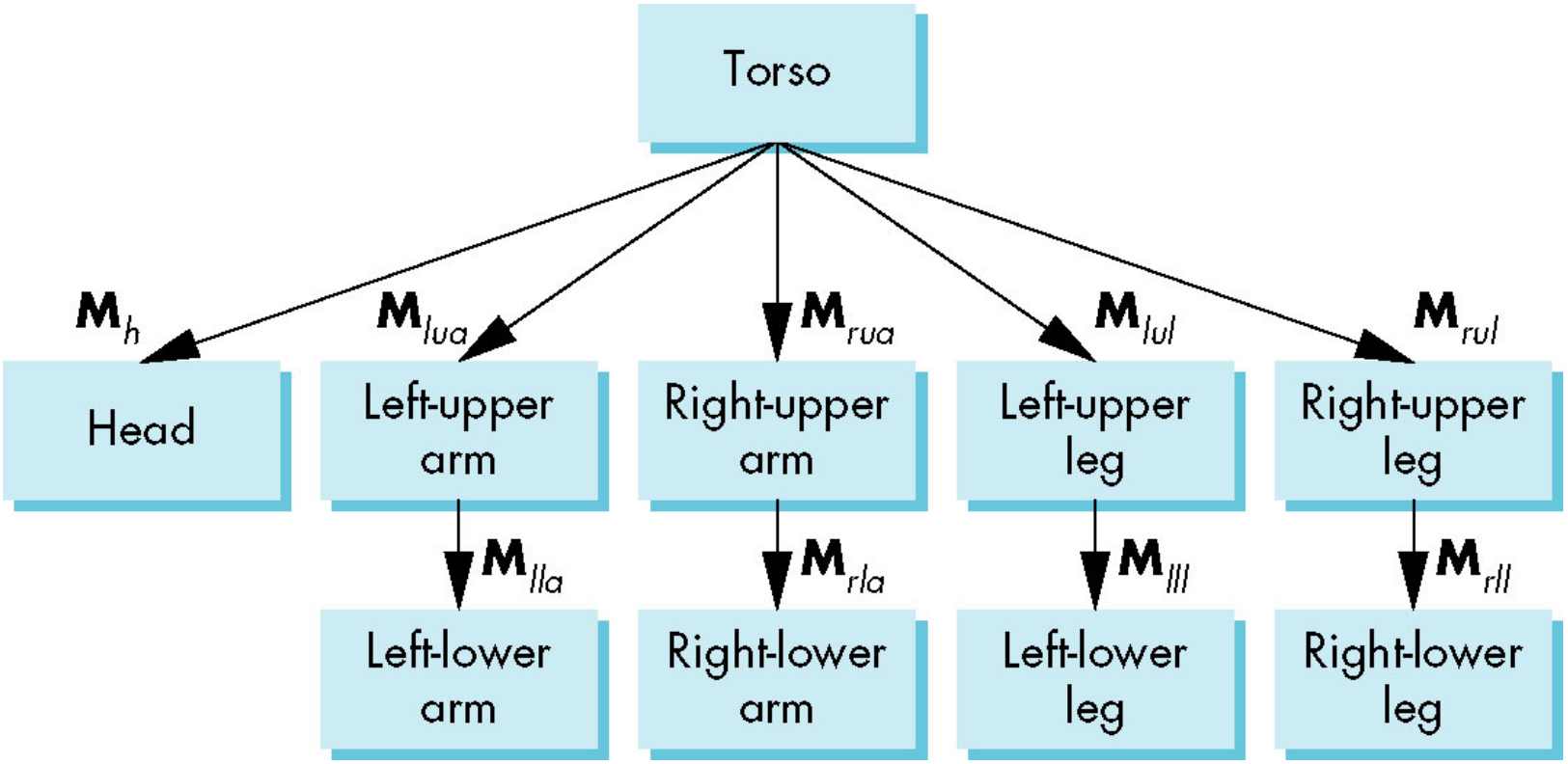




Building the Model

- Implementation using quadrics: ellipsoids and cylinders
- Access parts through functions
  - torso()
  - left_upper_arm()
- Matrices describe position of node with respect to parent
  - $\mathbf{M}_{lla}$ positions leftlowerleg with respect to leftupperarm

Matrices Tree



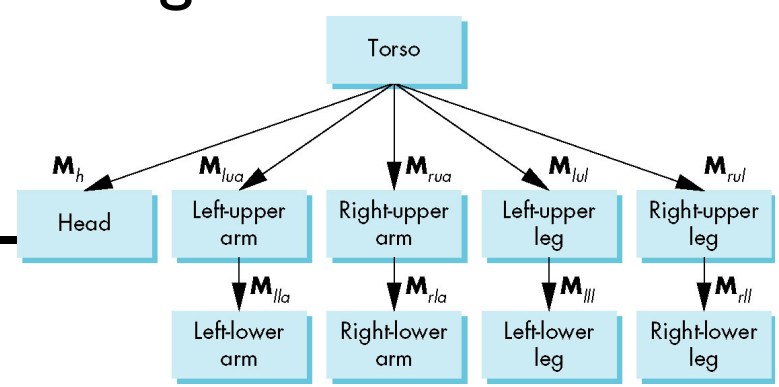
Display and Traversal

- The position determined by 11 joint angles (two for the head and one for each other part)
- Display of the tree requires a *graph traversal*
  - Visit each node once
  - Display function at each node pertaining to part
  - Applying correct transformation matrix for position and orientation

Transformation Matrices

10 relevant matrices

- **M** positions and orients entire figure through the torso which is the root node
- $\mathbf{M}_h$ positions head with respect to torso
- $\mathbf{M}_{lua}$, $\mathbf{M}_{rua}$, $\mathbf{M}_{lul}$, $\mathbf{M}_{rul}$ position arms and legs with respect to torso
- $\mathbf{M}_{lla}$, $\mathbf{M}_{rla}$, $\mathbf{M}_{lll}$, $\mathbf{M}_{rll}$ position lower parts of limbs with respect to corresponding upper limbs



Stack-based Traversal

- Set model-view matrix to **M** and draw torso
- Set model-view matrix to $\mathbf{MM}_h$ and draw head
- For left-upper arm need $\mathbf{MM}_{lua}$ and so on

- No need recomputing $\mathbf{Mm}_{lua}$
  - Use the matrix stack to store **M** and other matrices in tree traversal

Old Style GL Code

```
figure() {
   PushMatrix()
   torso();
   Rotate (…);
   head();
   PopMatrix();
   PushMatrix();
   Translate(…);
   Rotate(…);
   left_upper_arm();
   PopMatrix();
   PushMatrix();
```

save present model-view matrix

update model-view matrix for head

recover original model-view matrix

save it again

update model-view matrix for left upper arm

recover and save original model-view matrix again

rest of code

Tree Data Structure

- Represent tree and algorithm to traverse tree
- We will use a *left-child right sibling* structure
  - Uses linked lists
  - Each node in data structure is two pointers
  - Left: next node
  - Right: linked list of children

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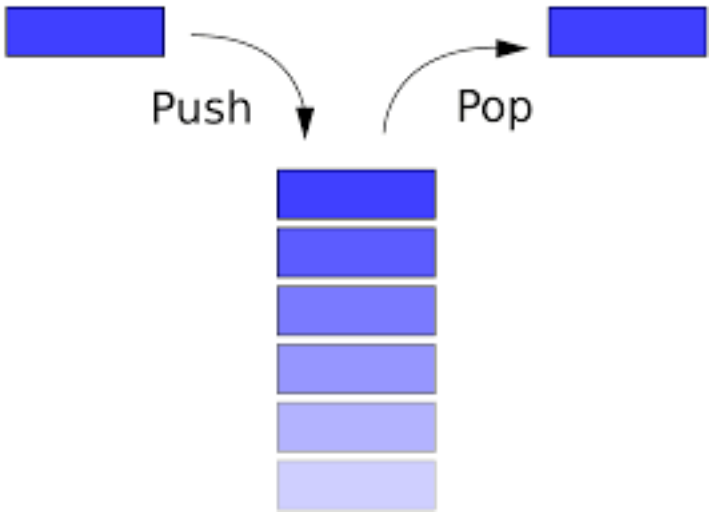
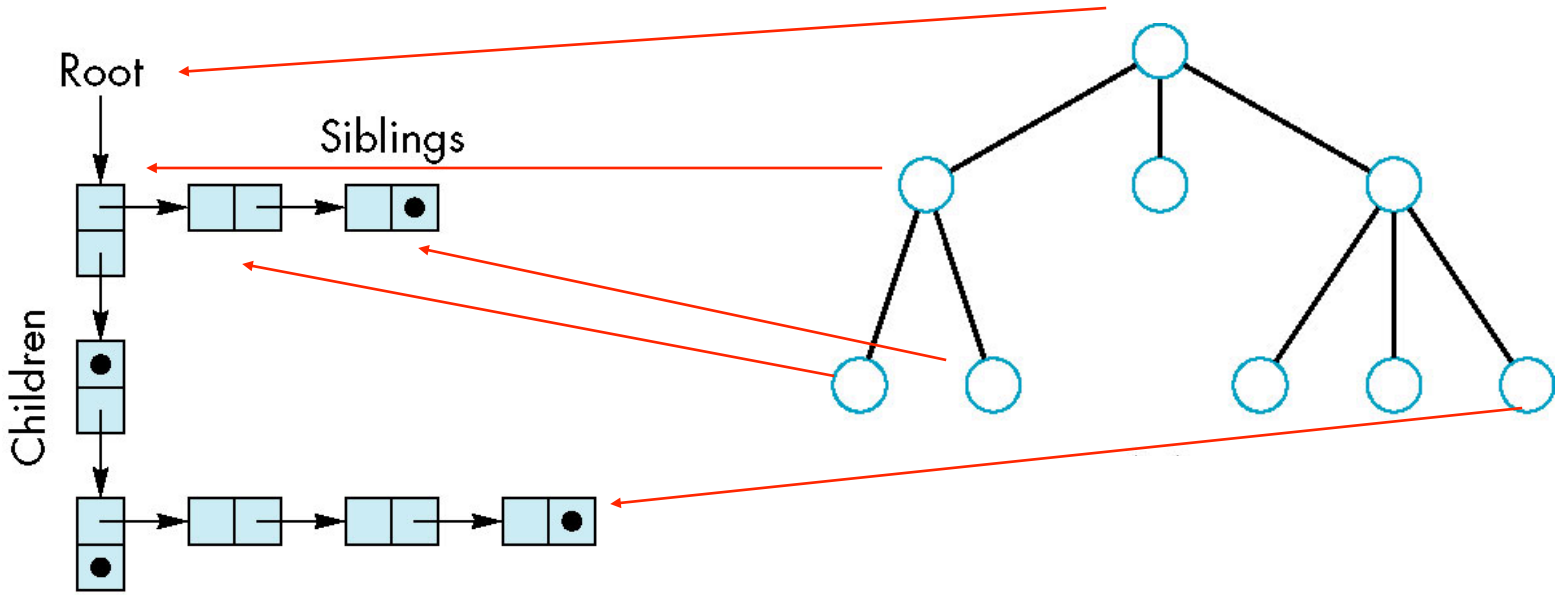
In GLSL

In GLSL

Still Use



Left-Child Right-Sibling Tree



Tree node Structure

At each node

- Pointer to sibling
- Pointer to child
- Pointer to a function that draws the object represented by the node
- Homogeneous coordinate matrix to multiply on the right of the current model-view matrix
  - Represents changes going from parent to node
  - In OpenGL this matrix is a 1D array storing matrix by columns

C

```
typedef struct treenode
{
   mat4 m;
   void (*f)();
   struct treenode *sibling;
   struct treenode *child;
} treenode;
```

torso and head nodes

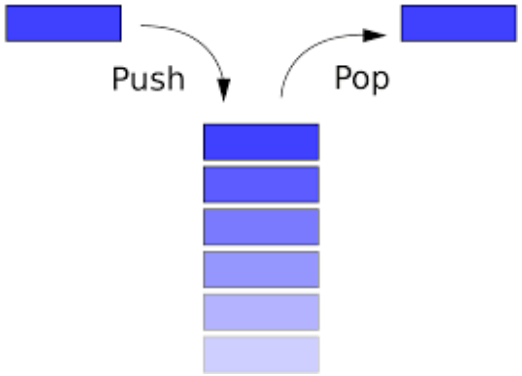
```
treenode torso_node, head_node, lua_node, … ;
torso_node.m = RotateY(theta[0]);
torso_node.f = torso;
torso_node.sibling = NULL;
torso_node.child =  &head_node;

 head_node.m = translate(0.0, TORSO_HEIGHT
    +0.5*HEAD_HEIGHT, 0.0)*RotateX(theta[1])*RotateY(theta[2]);
head_node.f = head;
head_node.sibling = &lua_node;
head_node.child = NULL;
```

Notes

- Position determined by 11 joint angles in theta[11]
- Animate by changing angles and redisplaying
- Form required matrices using Rotate and Translate

Preorder Traversal

```
void traverse(treenode* root)
{
   if(root==NULL) return;
   mvstack.push(model_view);
   model_view = model_view*root->m;
   root->f();
   if(root->child!=NULL) traverse(root->child);
   model_view = mvstack.pop();
   if(root->sibling!=NULL) traverse(root->sibling);
}
```



Notes

- Save model-view matrix before multiplying it by node matrix
  - Updated matrix applies to children but not to siblings
- Traversal applies to any left-child right-sibling tree
  - Particular tree encoded in definition of individual nodes
- Order of traversal matters given state changes in the functions

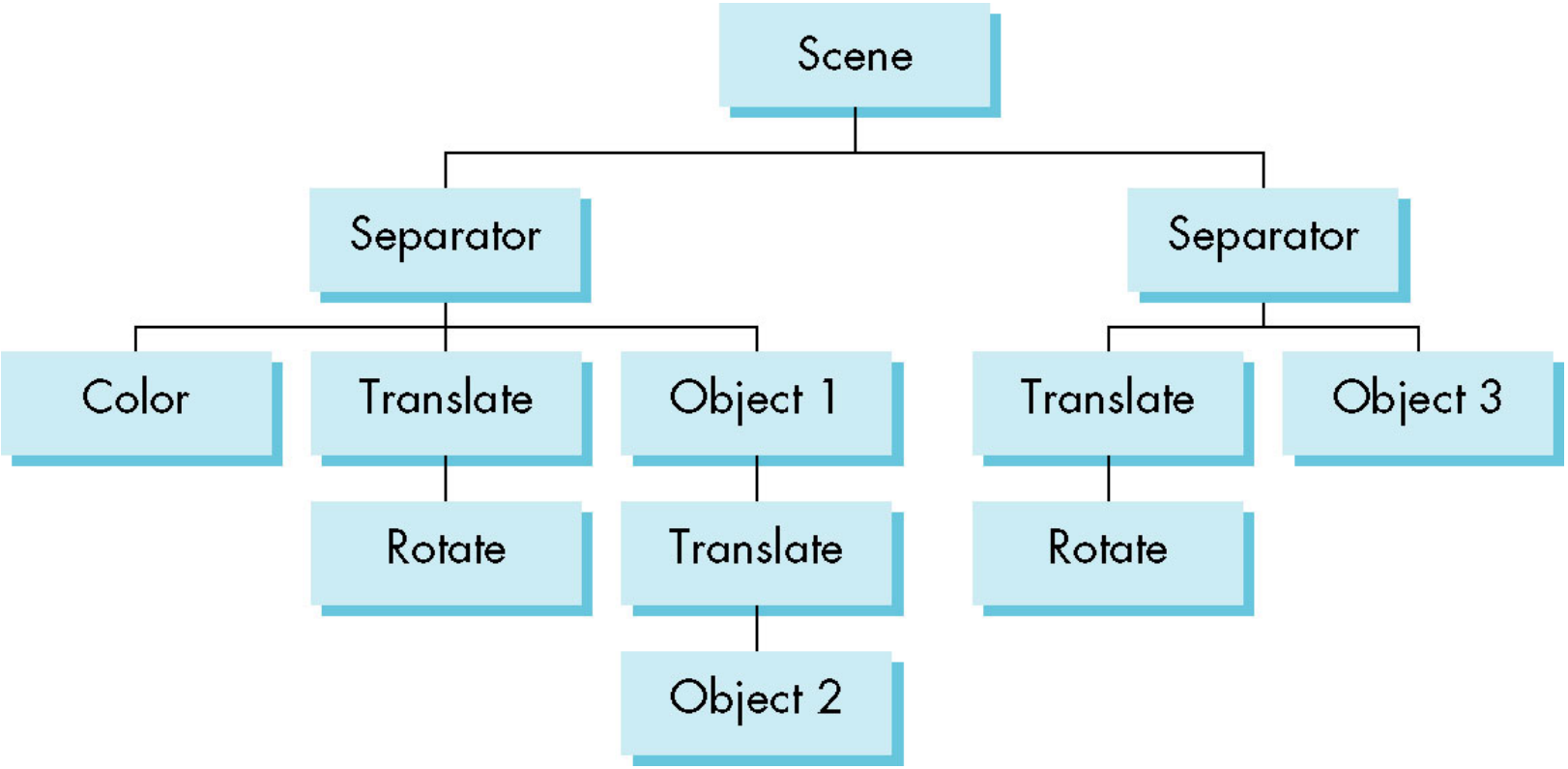
Dynamic Trees

Use pointers, the structure can be dynamic

```
typedef treenode *tree_ptr;
tree_ptr torso_ptr;
torso_ptr = malloc(sizeof(treenode));
```

Definition of nodes and traversal are essentially the same as before but we can add and delete nodes during execution

The Real Thing



As Opposed

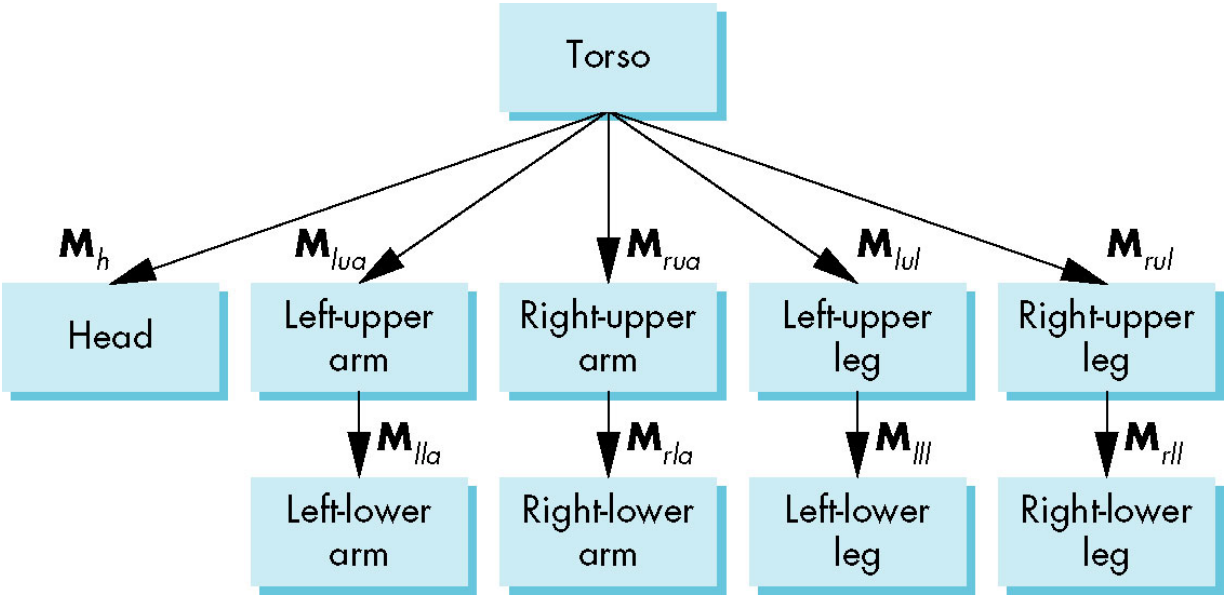

Torso
$\mathbf{M}_h$
$\mathbf{M}_{lua}$
$\mathbf{M}_{rua}$
$\mathbf{M}_{lul}$
$\mathbf{M}_{rul}$
Head
Left-upper arm
Right-upper arm
Left-upper leg
Right-upper leg
$\mathbf{M}_{lla}$
$\mathbf{M}_{rla}$
$\mathbf{M}_{lll}$
$\mathbf{M}_{rll}$
Left-lower arm
Right-lower arm
Left-lower leg
Right-lower leg

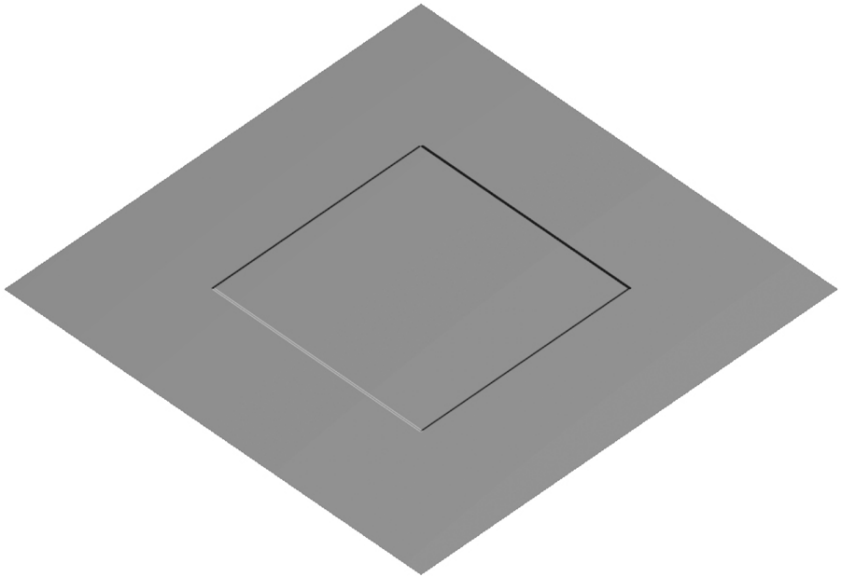
Image Processing

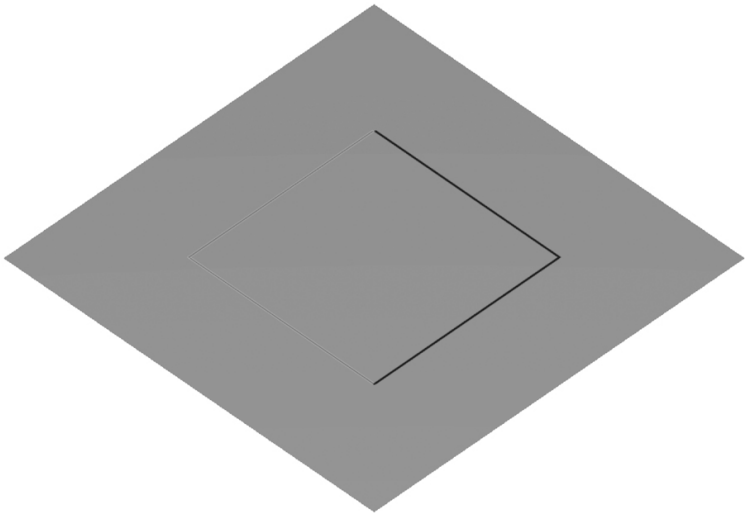
- Suppose that we start with a function $d(u,v)$
- We can sample it to form an array $D=[d_{ij}]$
- Then $\partial d/\partial u \approx d_{ij} - d_{i-1,j}$

  and $\partial d/\partial v \approx d_{ij} - d_{i,j-1}$
- **Embossing**: multipass approach using floating point buffer

Example

Single Polygon and a Rotating Light Source





How to do this?

- The problem is that we want to apply the perturbation at all points on the surface
- Cannot solve by vertex lighting (unless polygons are very small)
- Really want to apply to every fragment
- Can't do that in fixed function pipeline
- But can do with a fragment program!!

Compositing & Blending

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A

- Blending for translucent surfaces
- Compositing images
- Antialiasing

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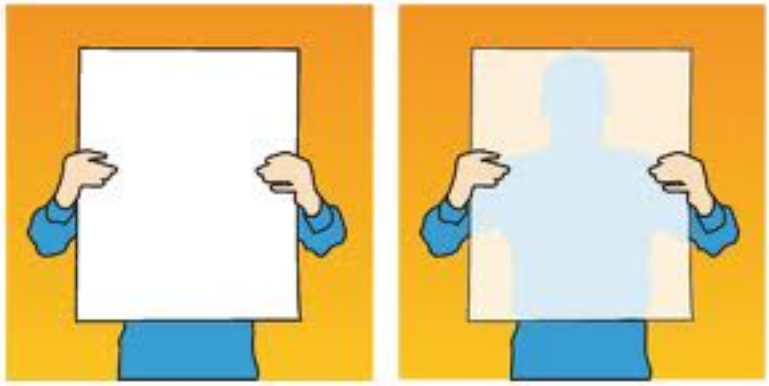
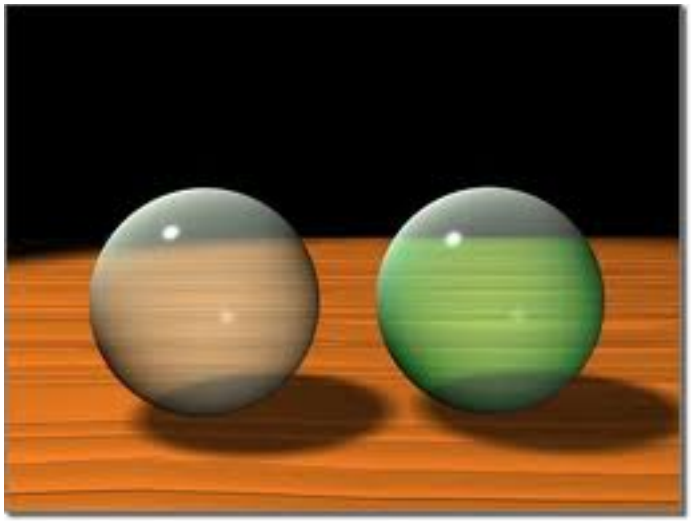
A



High opacity

Low opacity

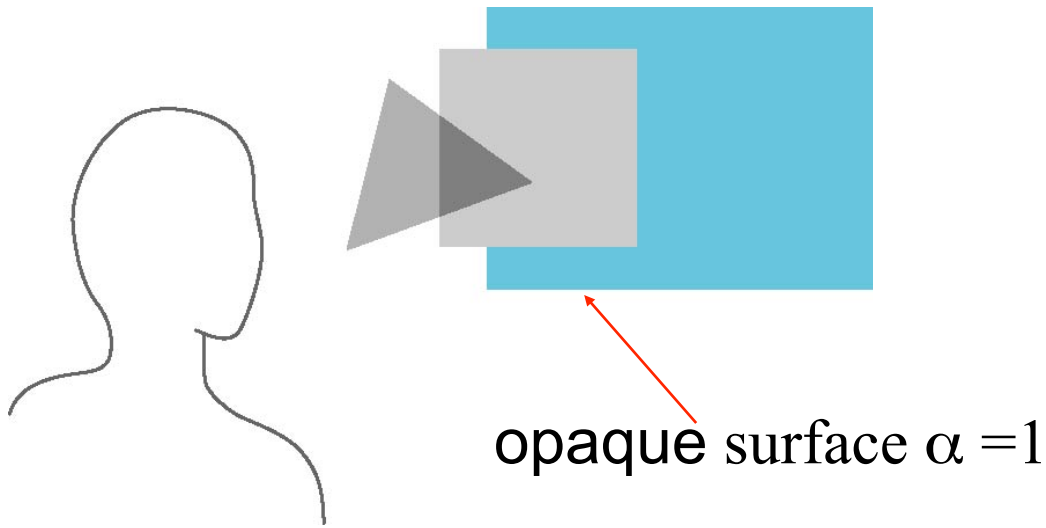
A



A

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

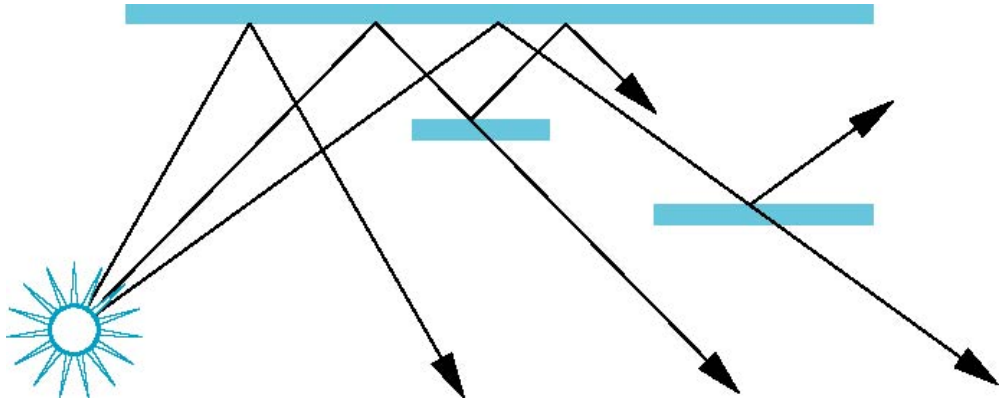
  translucency = 1 – opacity (α)



Physical Models

Translucency in a physically correct manner is difficult

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



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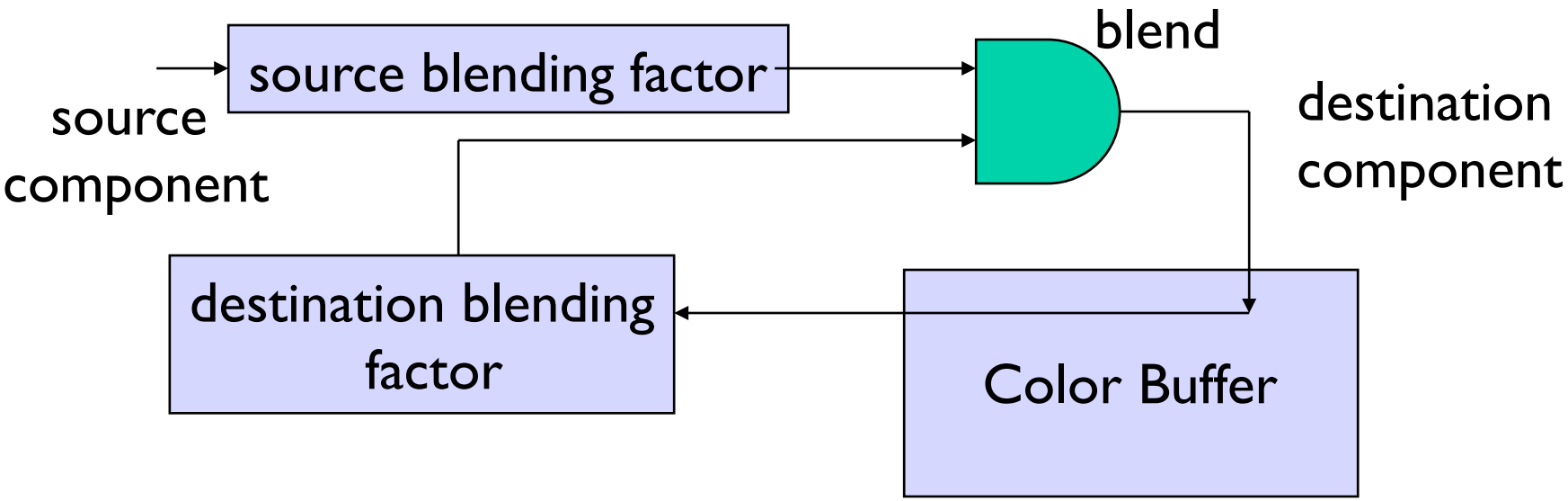
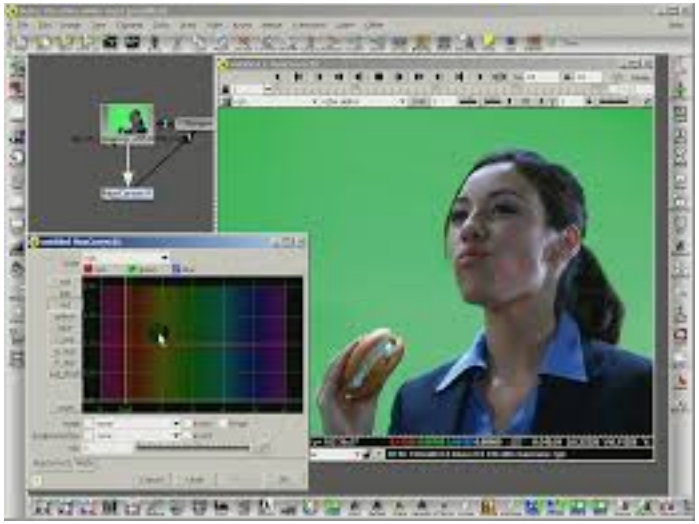
Compositing Operation

Rendering Model

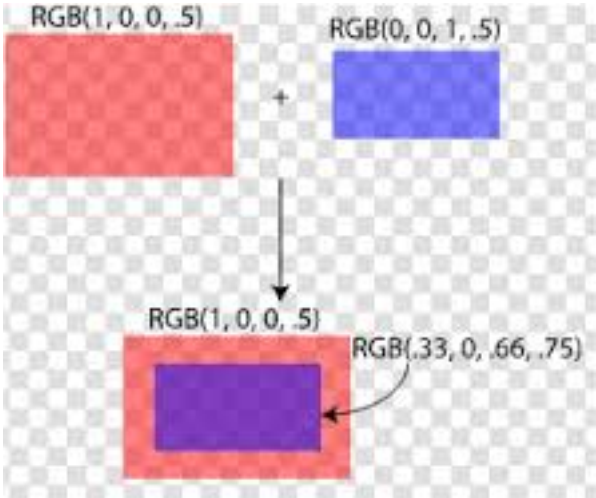
- Use A component of RGBA (or RGBa) color for opacity
- During rendering expand to use RGBA values



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

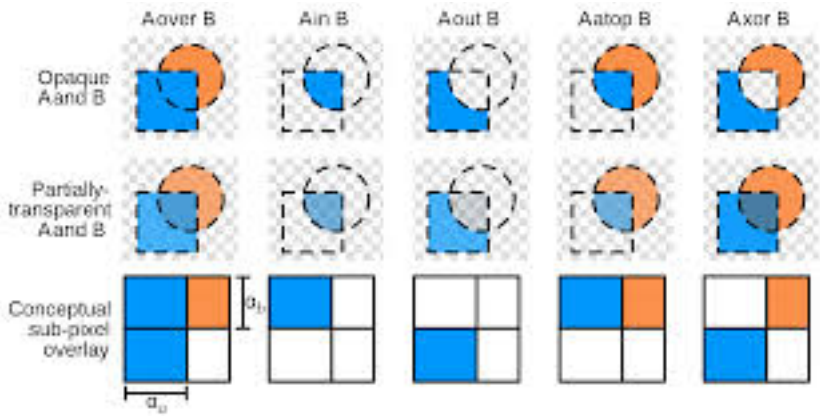
GL_ZERO, GL_ONE

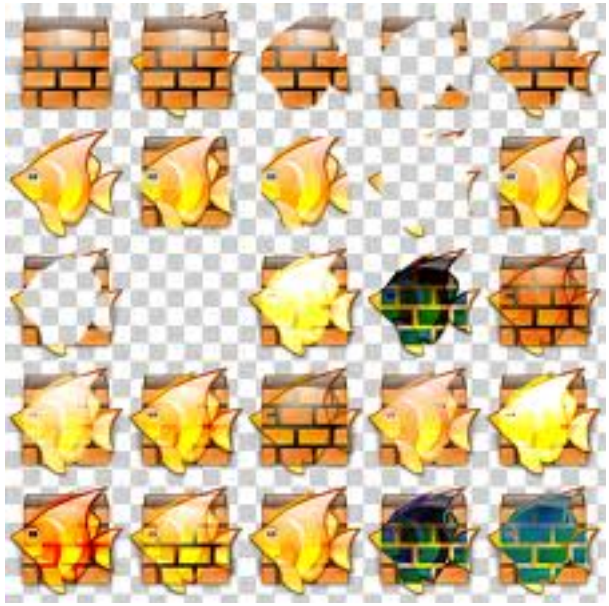
GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA

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

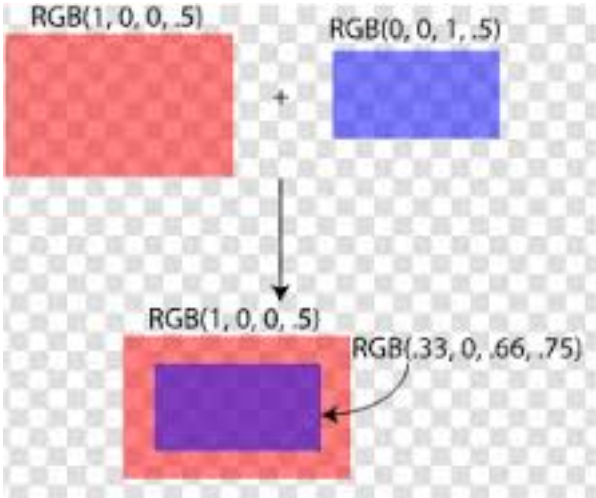


Example

- 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

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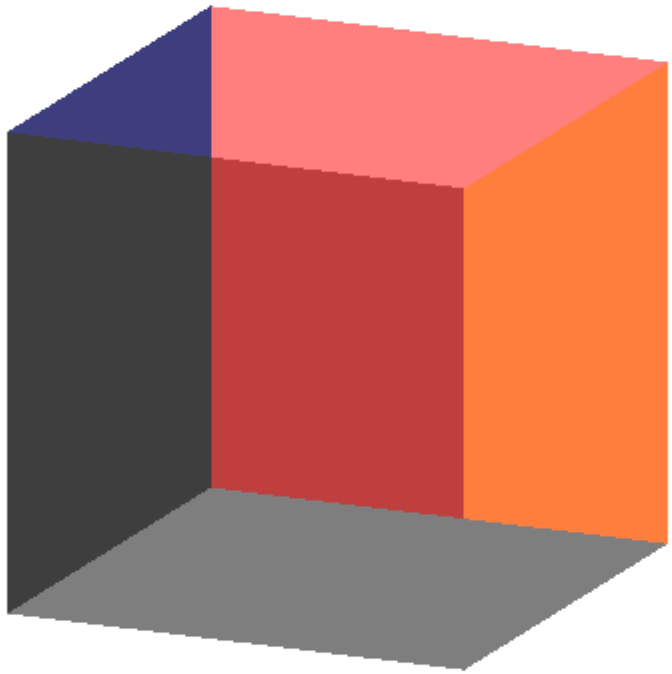
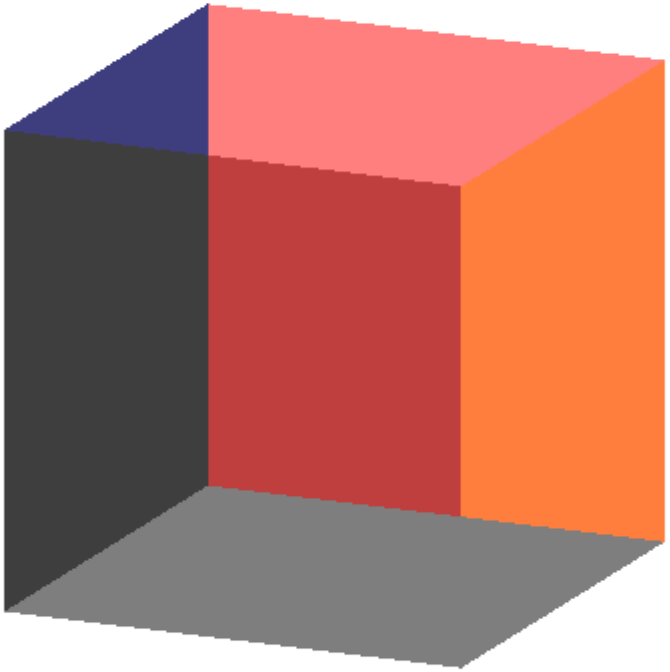
Order Dependency



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

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Fog

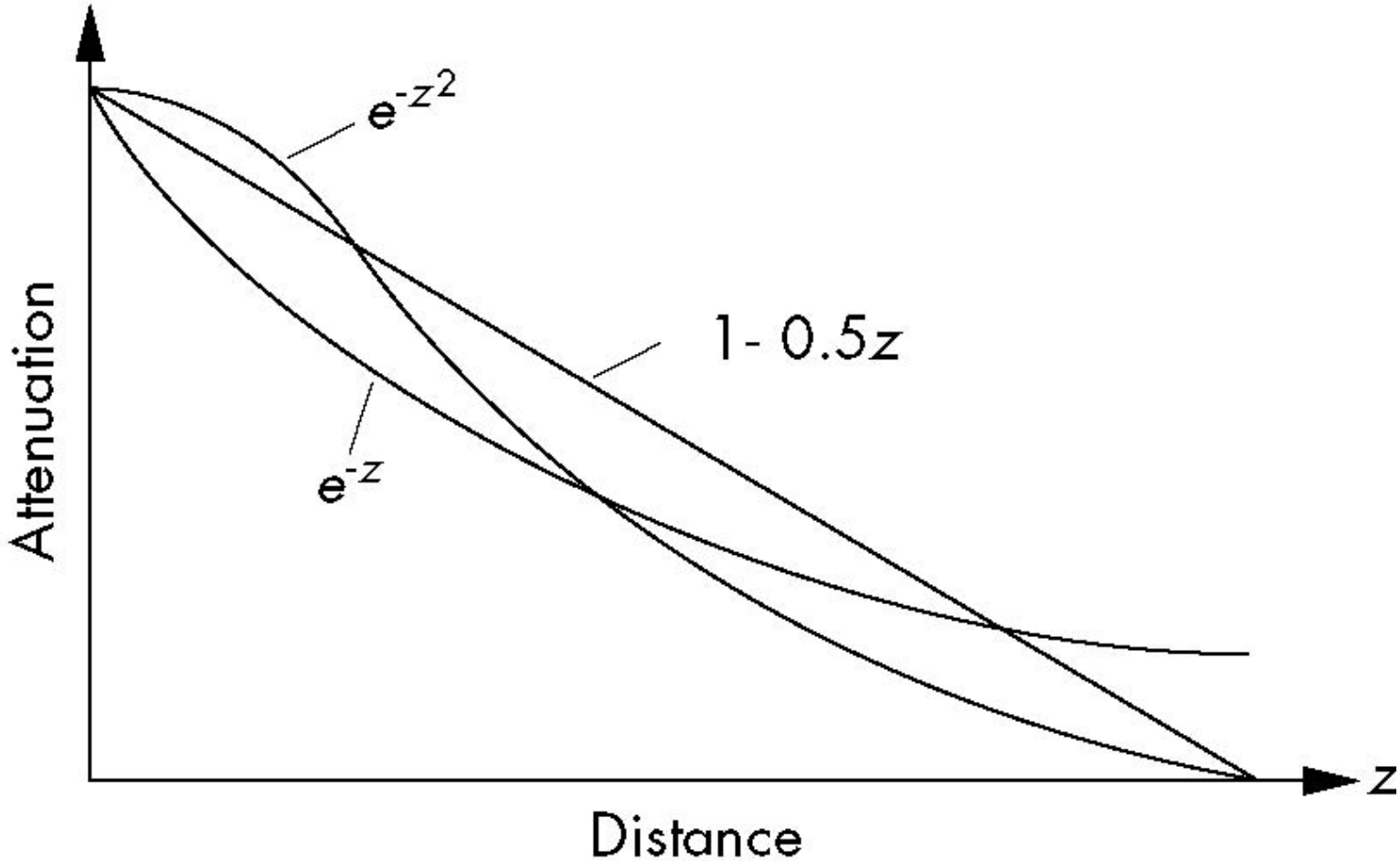
Simulate Fog

- 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)

F - Fog Functions



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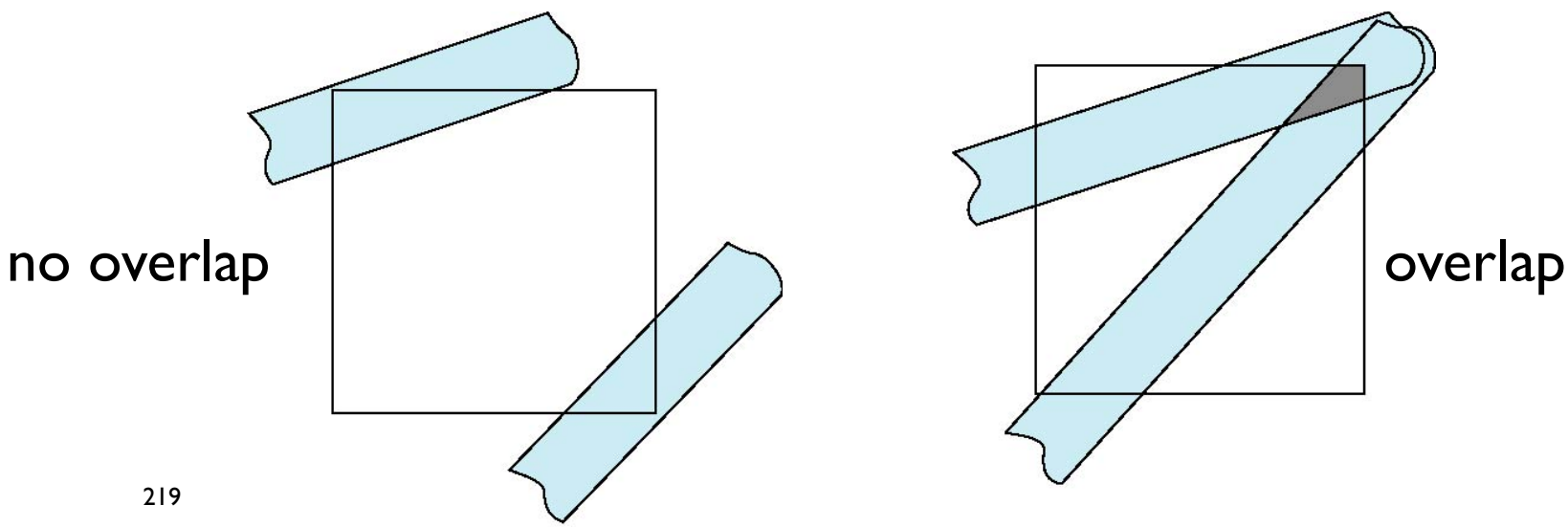
Antialiasing

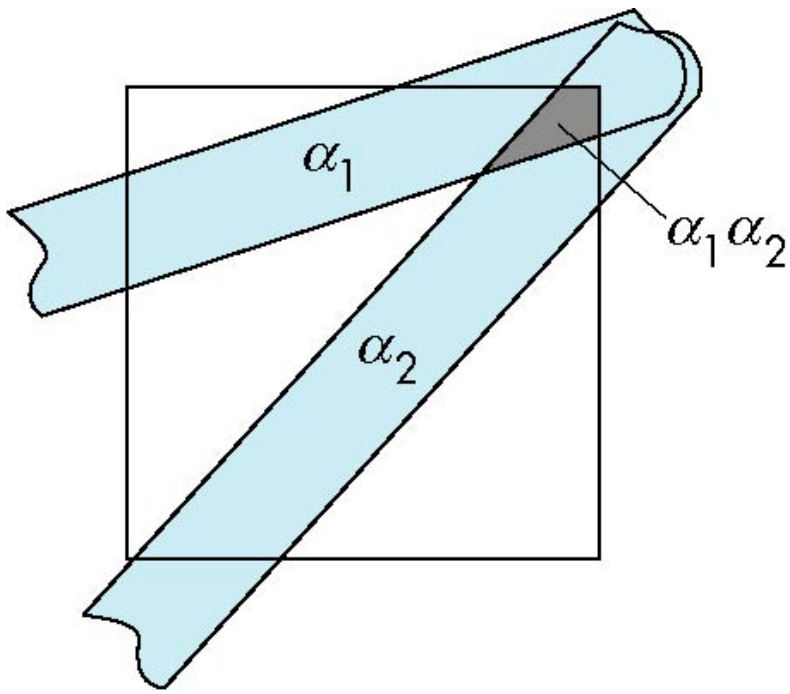
Color a pixel by adding fraction of color to frame buffer

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



Area Averaging

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



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
- *Accumulation 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

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

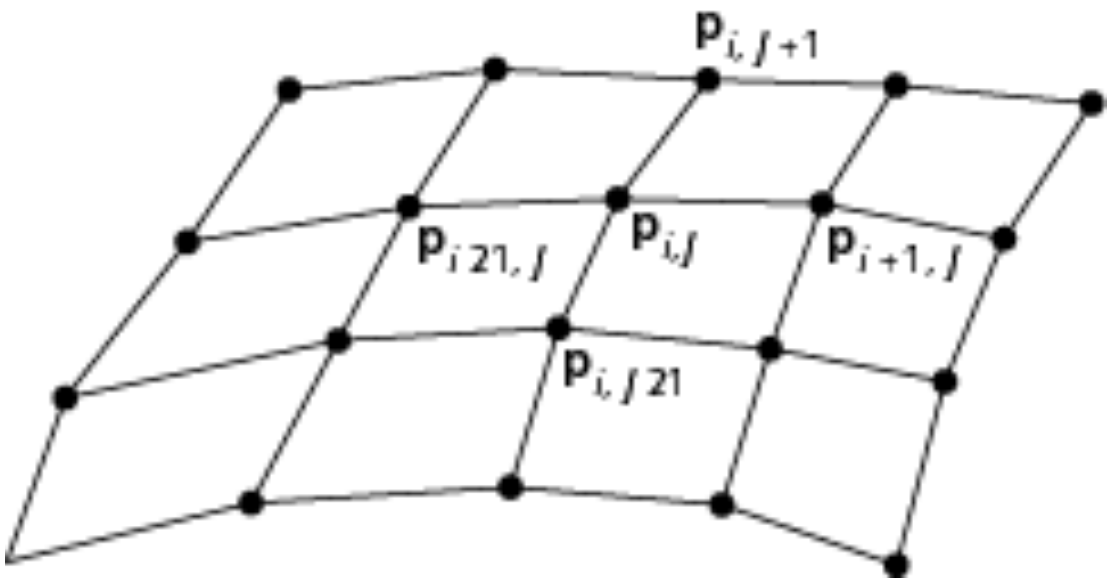
  $\mathbf{g} = (0, -g, 0)$

- 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 ($d = \|\mathbf{p} - \mathbf{q}\|$) 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

$\mathbf{d}/|\mathbf{d}|$ is a unit vector pointed from **p** to **q**

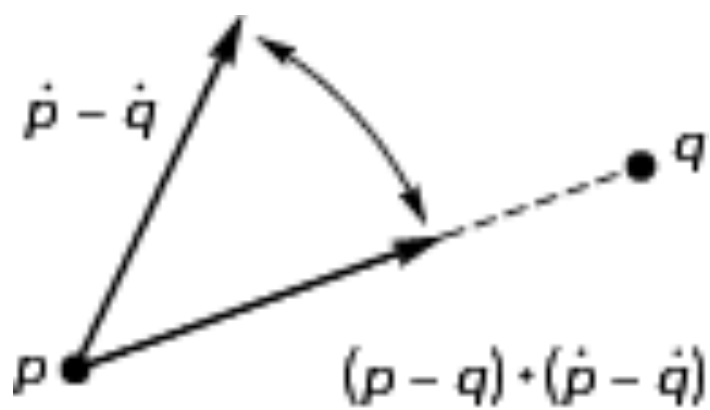
Each interior point in mesh has four forces applied to it

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

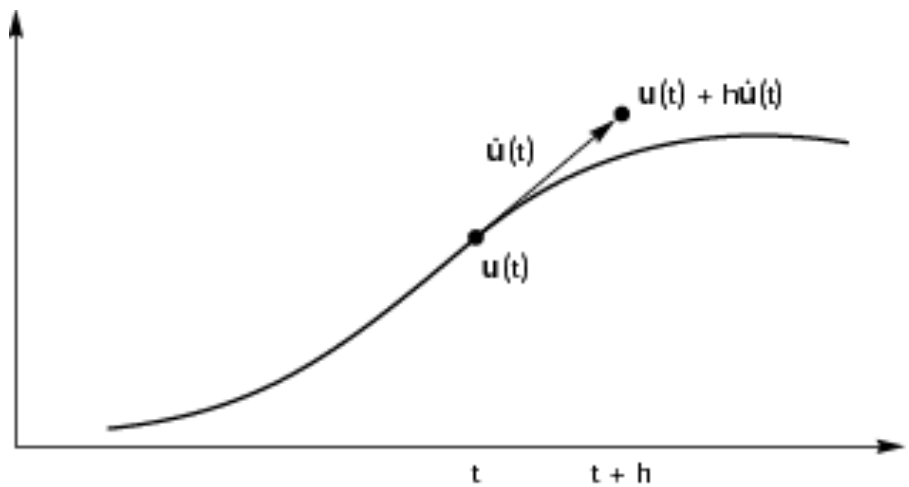
$$\mathbf{f} = -k_r \mathbf{d}/|\mathbf{d}|^3$$

- 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

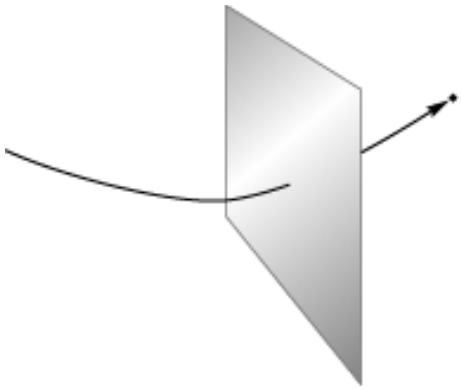
But requires two function evaluations per step

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



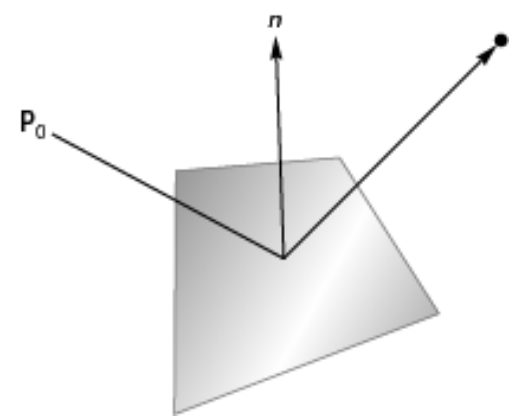
Collisions

Once we detect a collision, we can calculate new path

Use coefficient of resititution

Reflect vertical component

May have to use partial time step

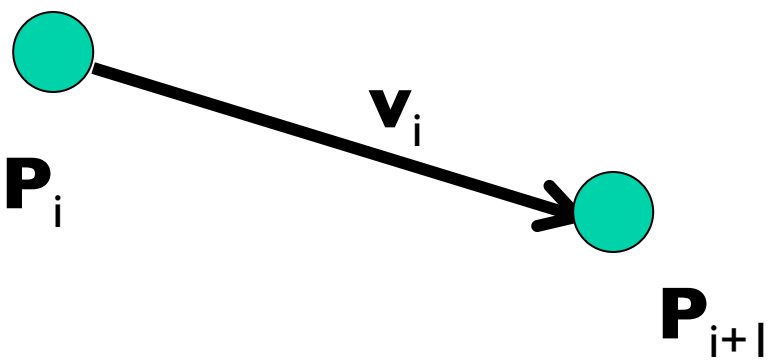


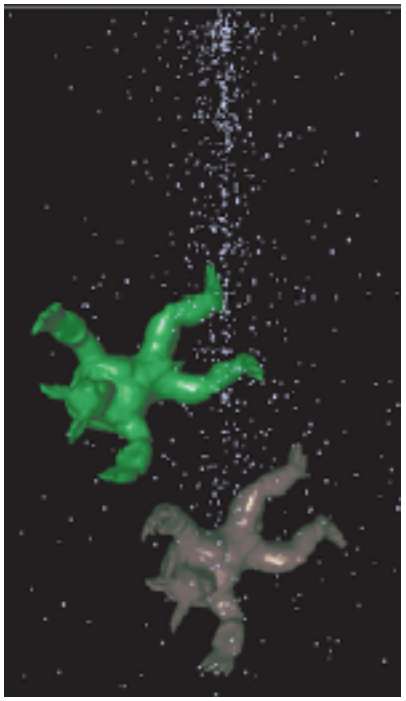
Example

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

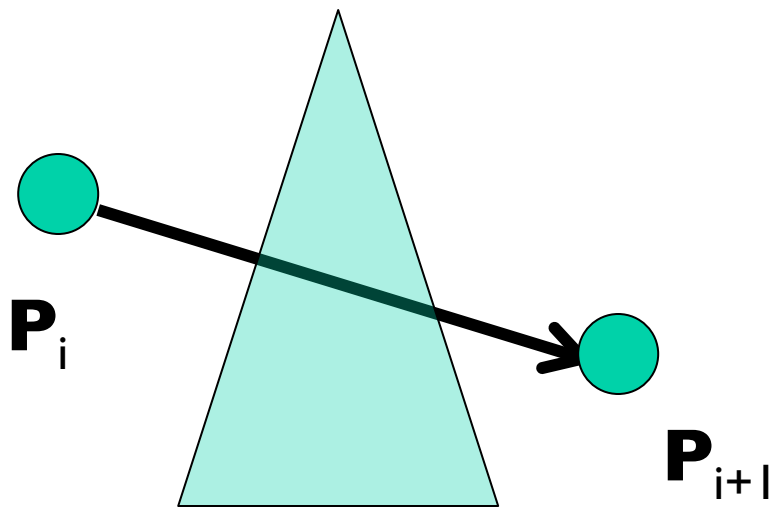
$\mathbf{v}_i = d\mathbf{p}_i /dt = \mathbf{p}_i' = (dx_i /dt, dy_i /dt\ , z_i /dt)$

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





Collision ?



Problem:
Triangle & Ray Distinct Objects

Ray/Triangle Intersection

Fast, Minimum Storage Ray/Triangle Intersection

Tomas Möller
Prosolvia Clarus AB
Chalmers University of Technology
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Ben Trumbore
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Cornell University
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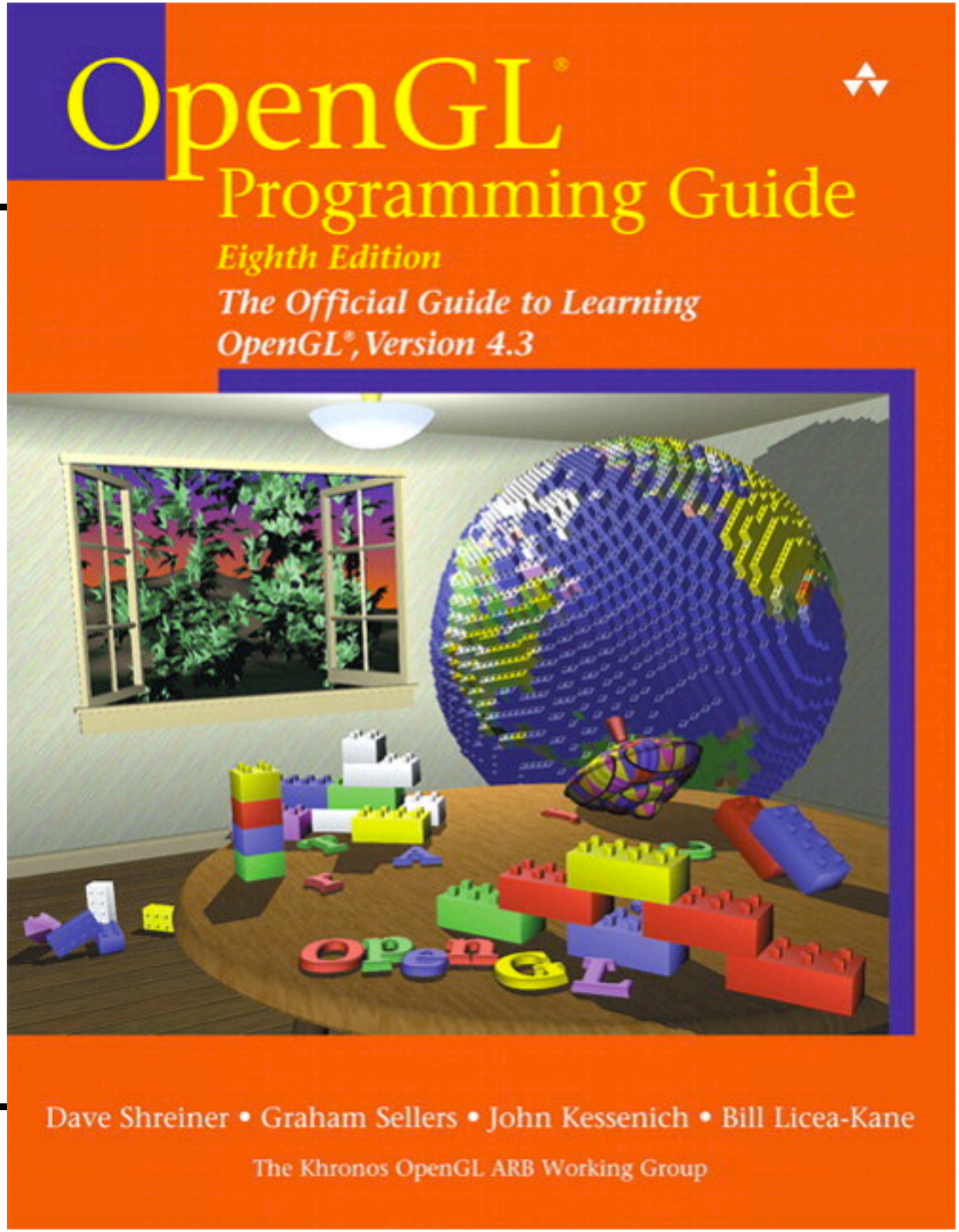
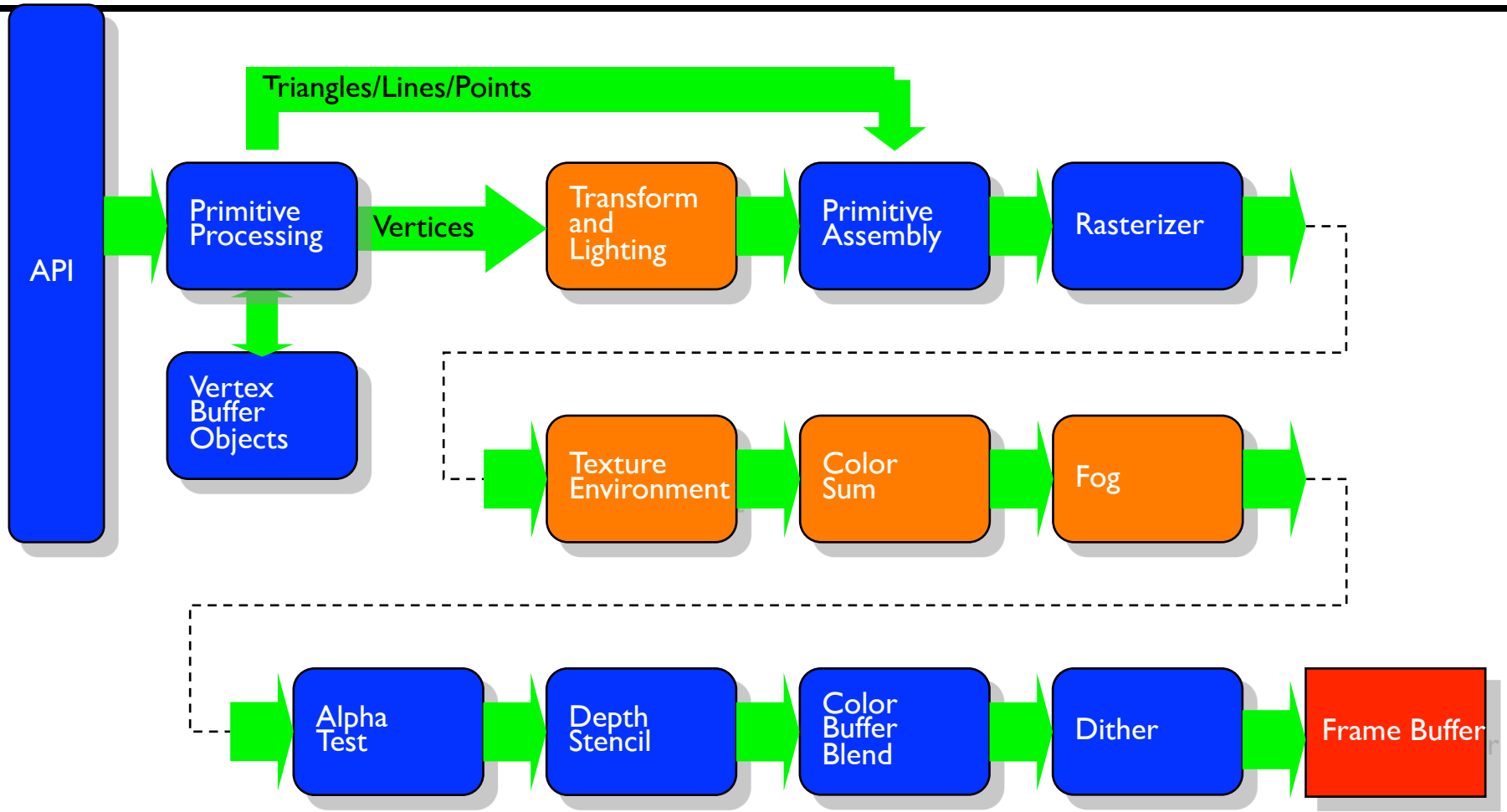
Advanced Features of GLSL
TF - Transform Feedback
TBO – Texture Buffer Obejct

Chapter 5

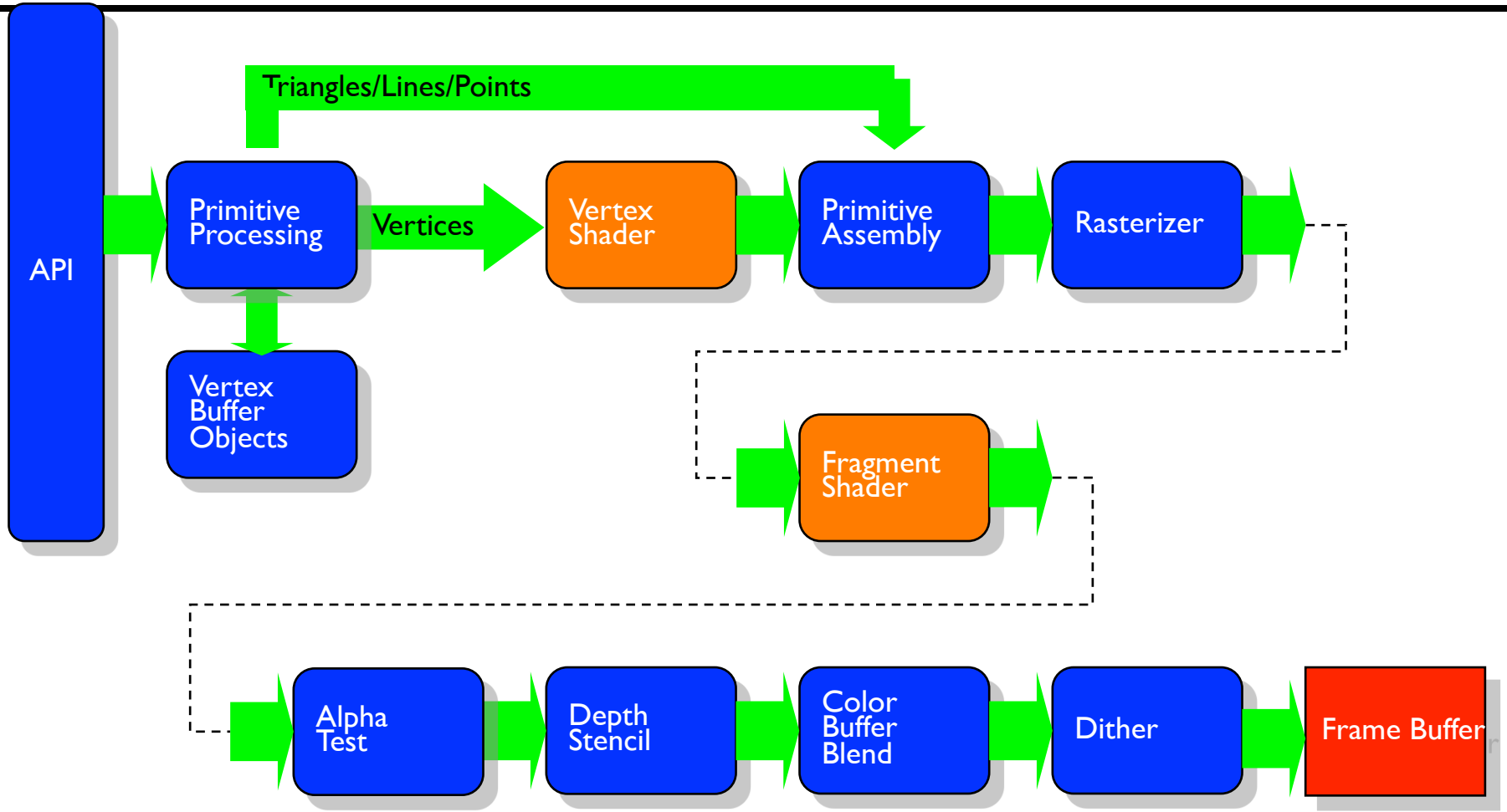


THE OHIO STATE UNIVERSITY
DEPARTMENT OF
COMPUTER SCIENCE
AND ENGINEERING

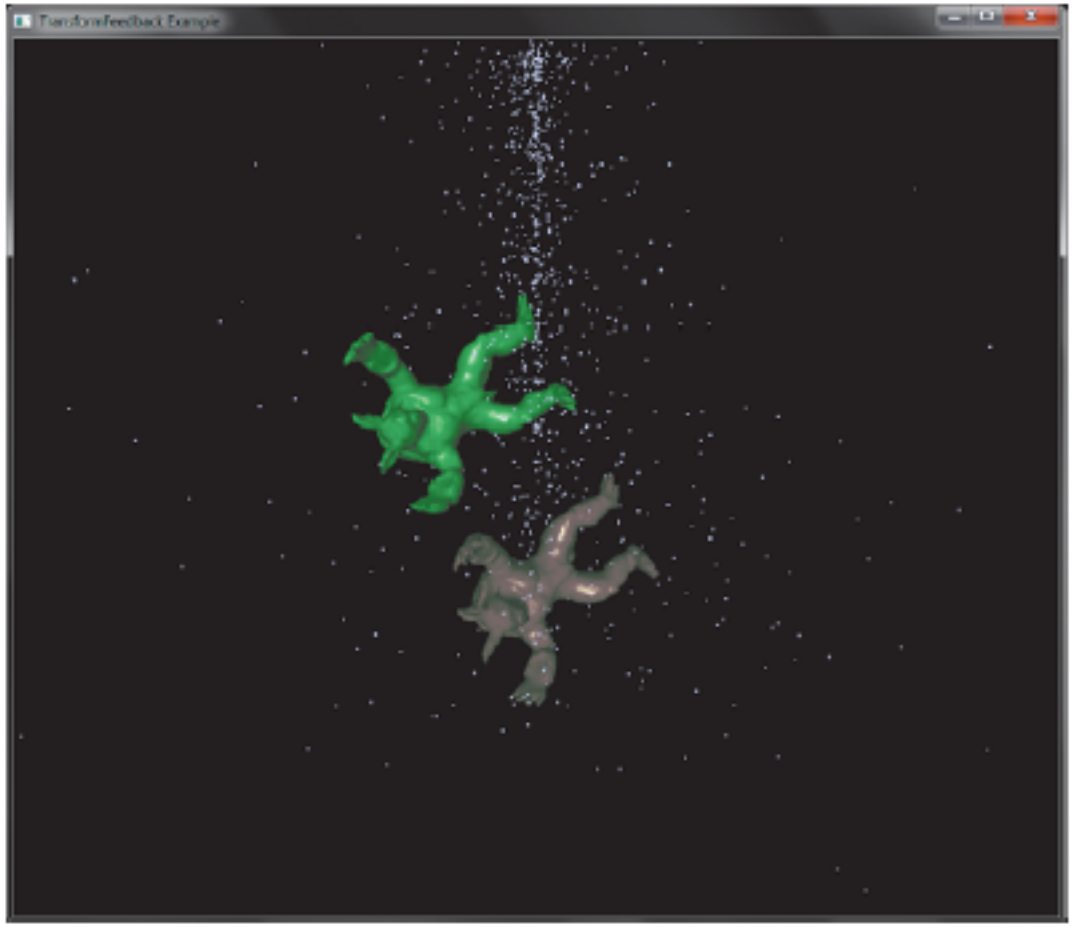
Fixed Functionality Pipeline



Programmable Shader Pipeline



Back2Particles



Schema

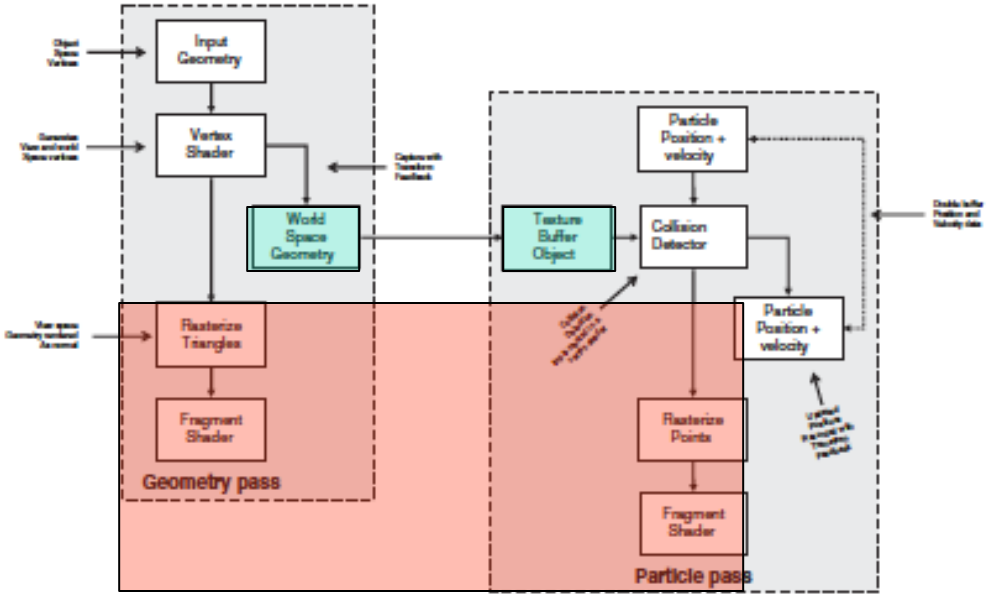


Figure 5.19 Schematic of the particle system simulator

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

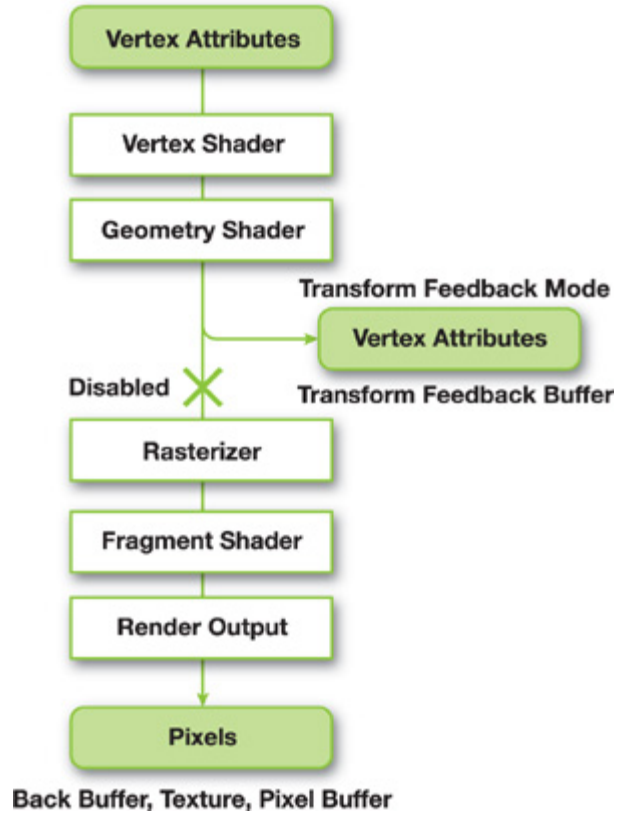
```
void glTransformFeedbackVaryings(GLuint program,
                                 GLsizei count,
                                 const GLchar ** varyings,
                                 GLenum bufferMode);
```

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

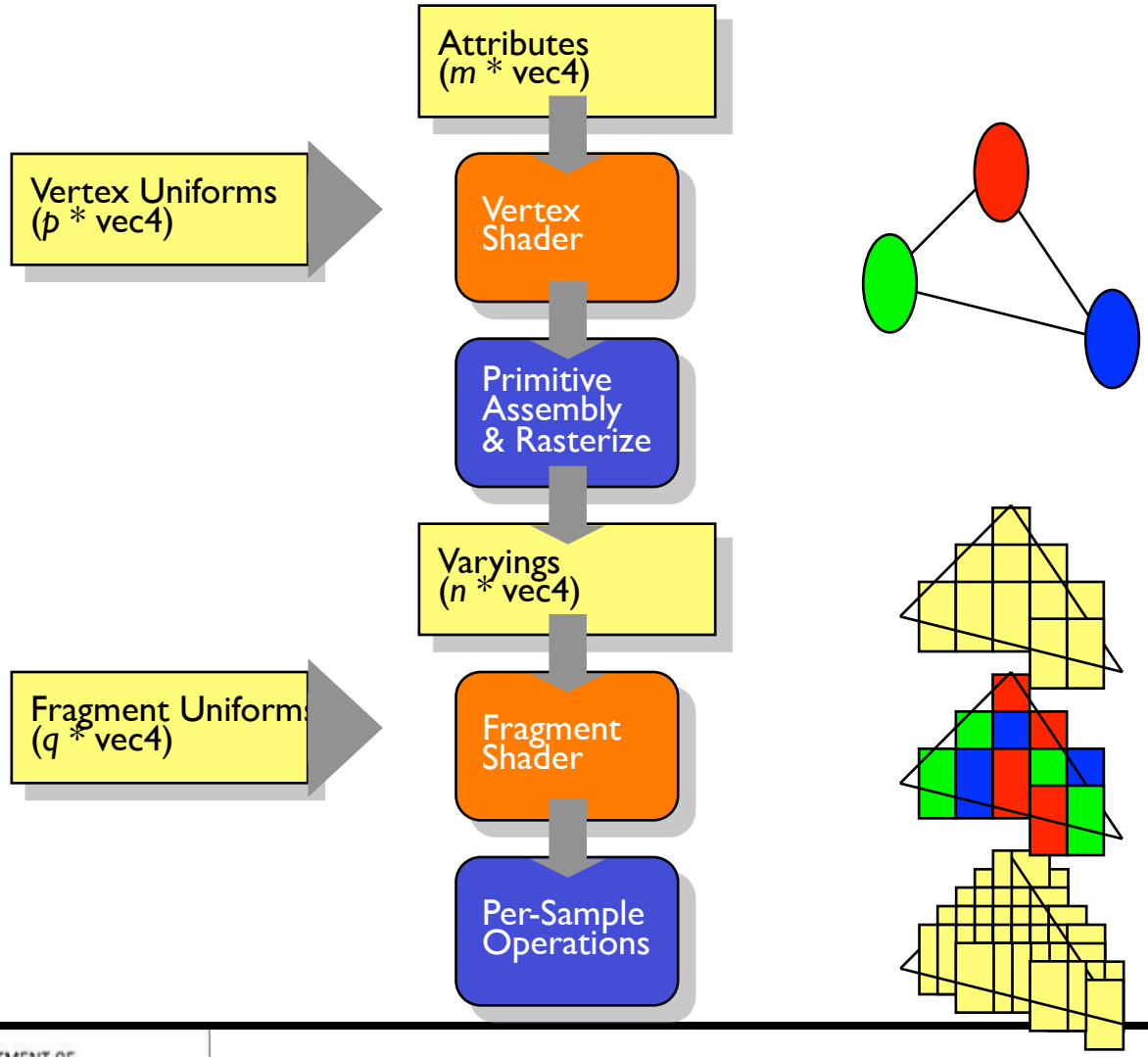
http://www.youtube.com/watch?v=SiCq8ETTqRk

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

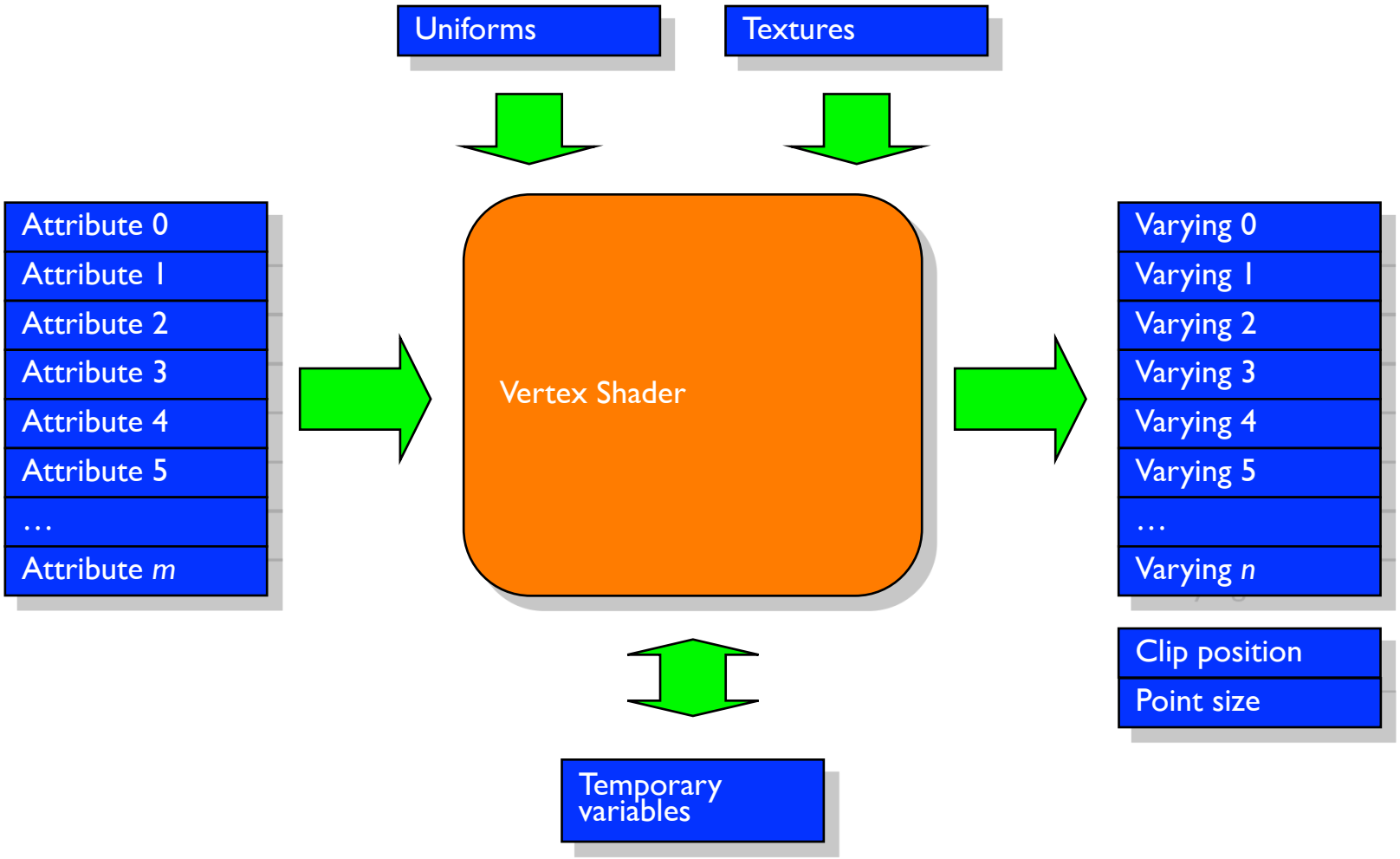
http://www.youtube.com/watch?v=E636tYOxoVI

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

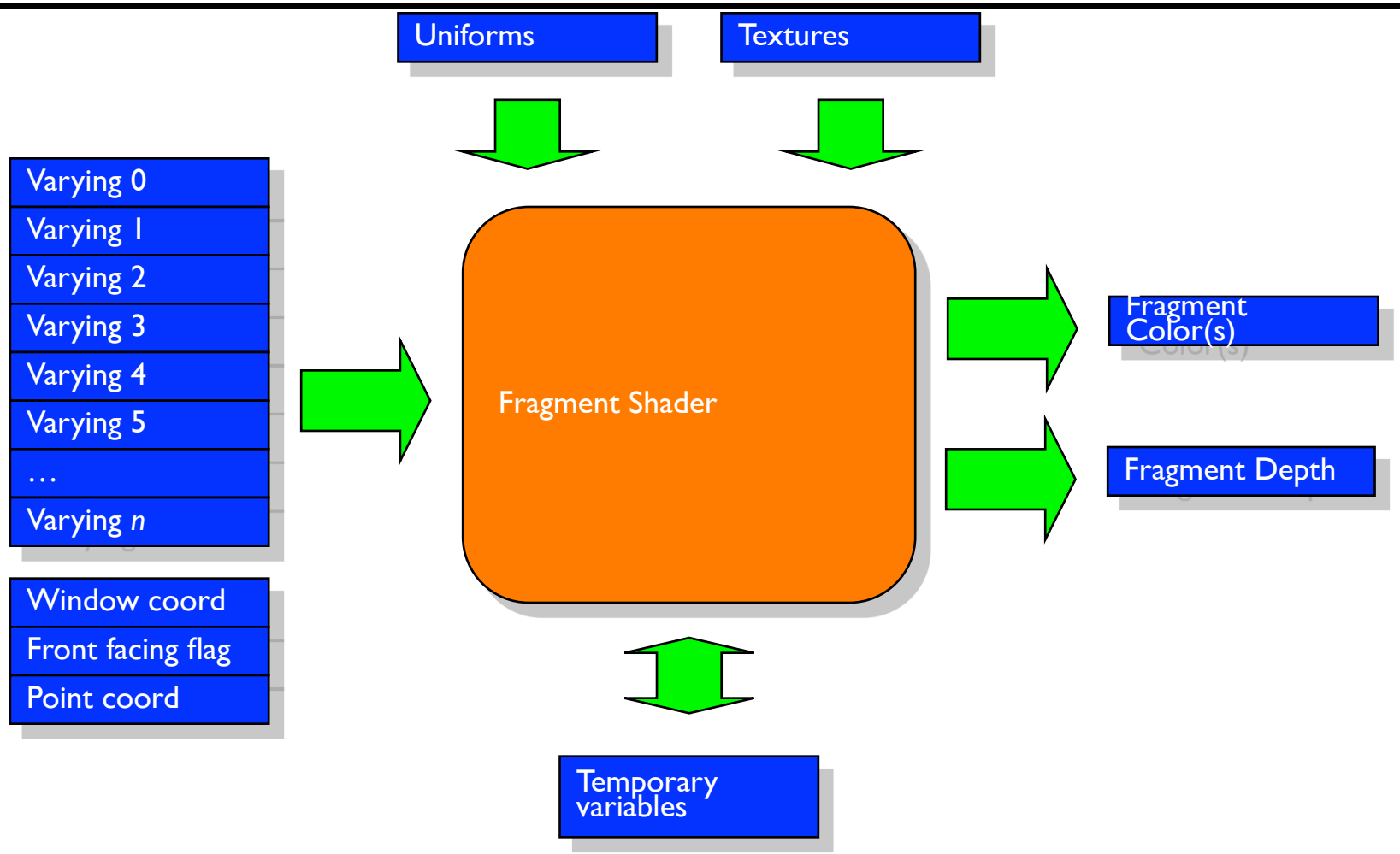
Programmer's Model



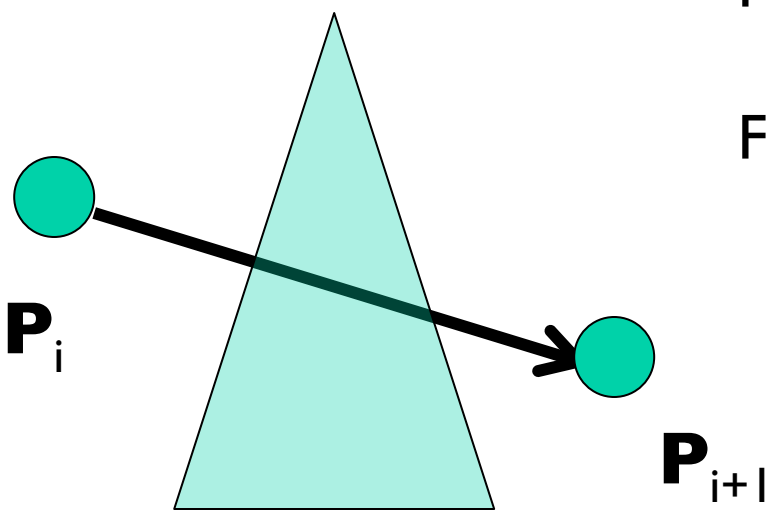
Vertex Shader Environment



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

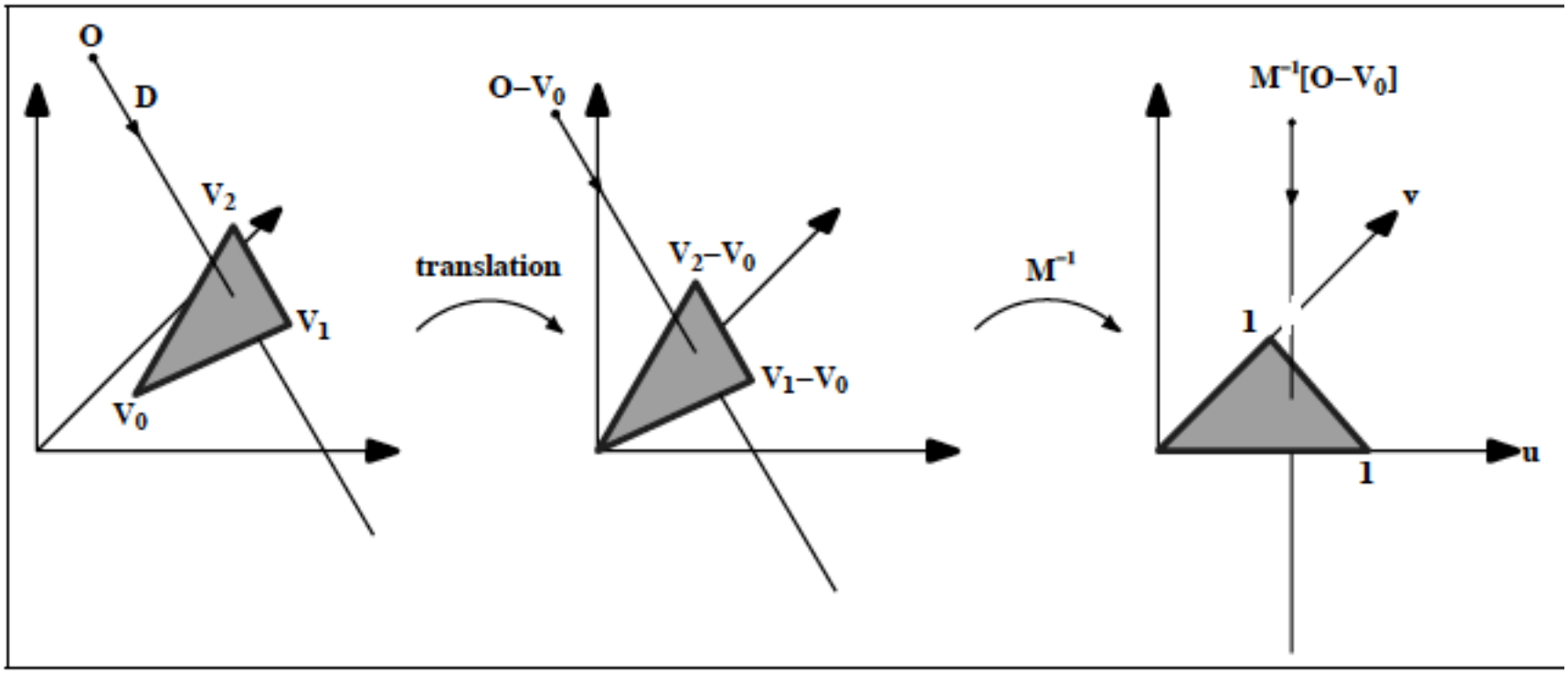


Figure 1: Translation and change of base of the ray origin.

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

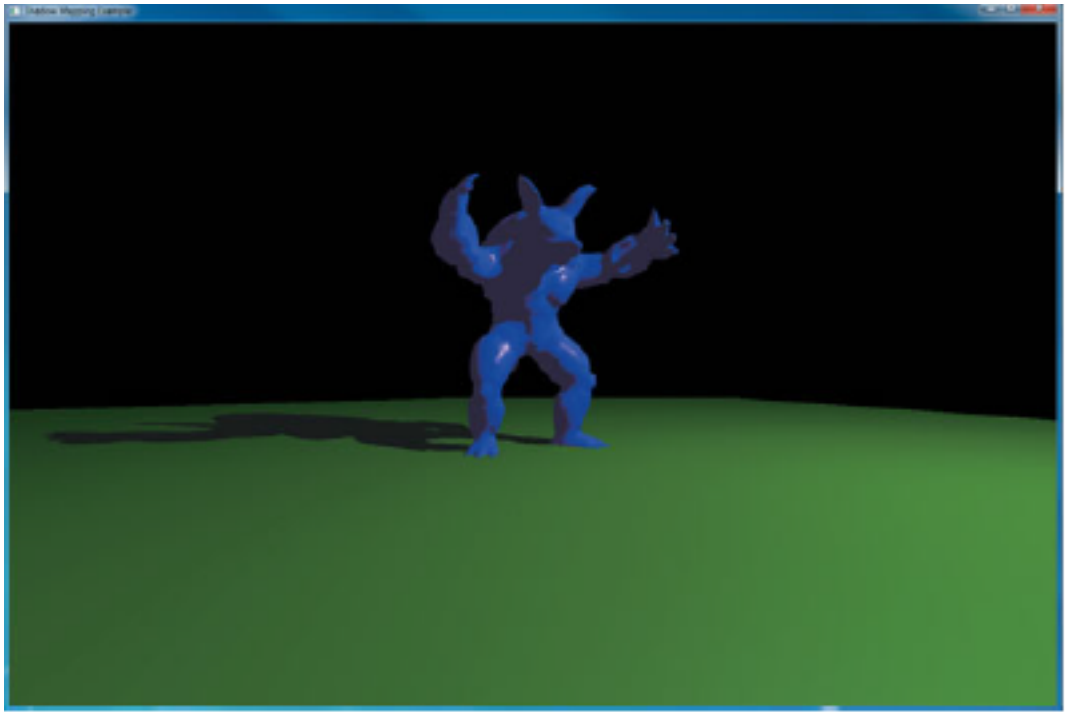
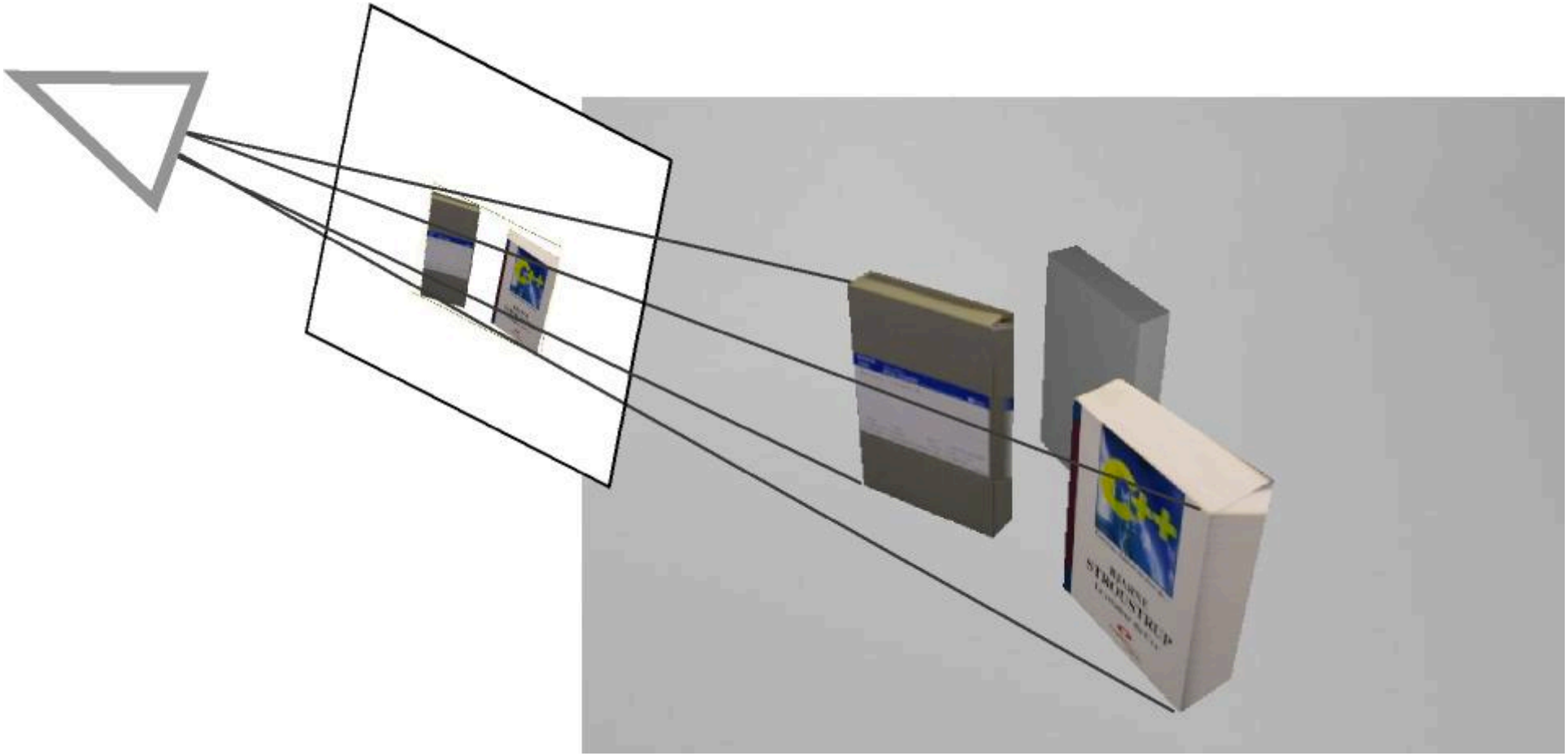
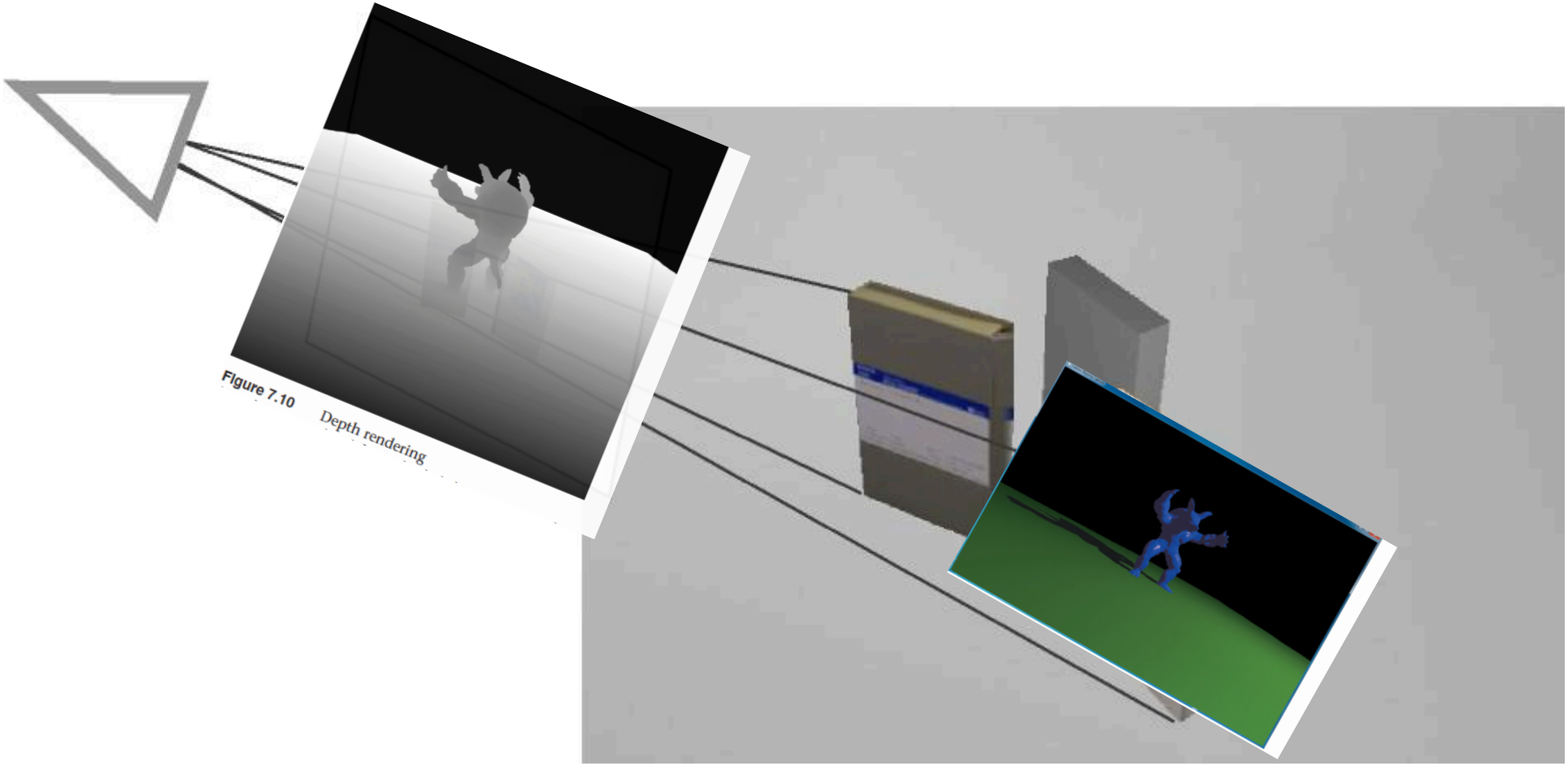


Figure 7.11 Final rendering of shadow map

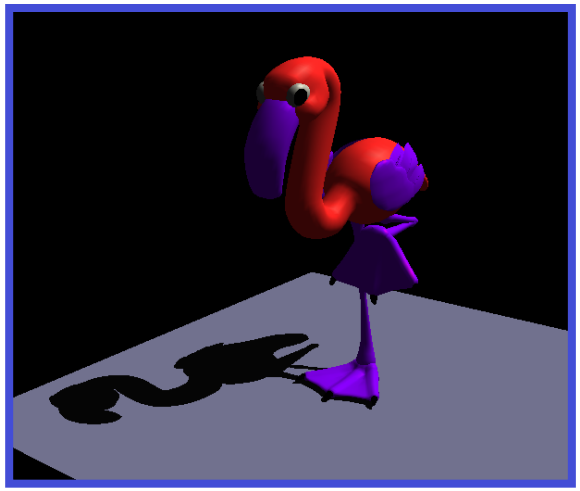
Shadows & Textures ?



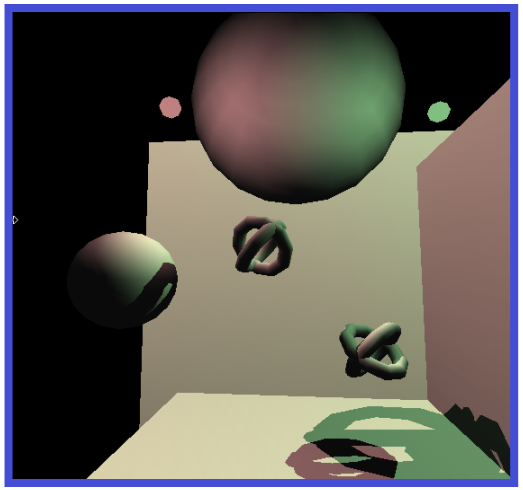
Shadows & Textures ?



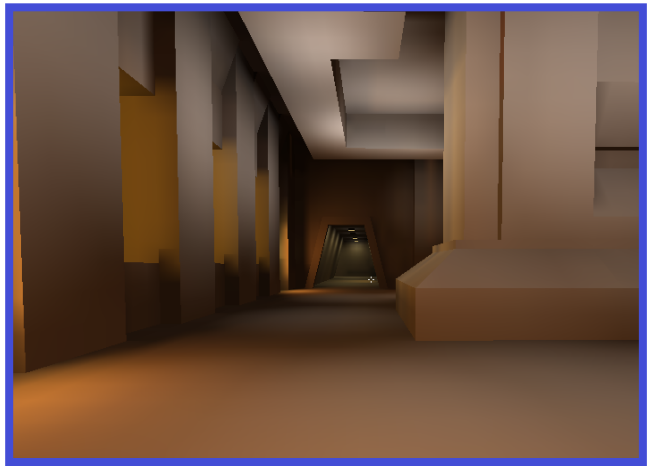
Real-time Shadow Techniques



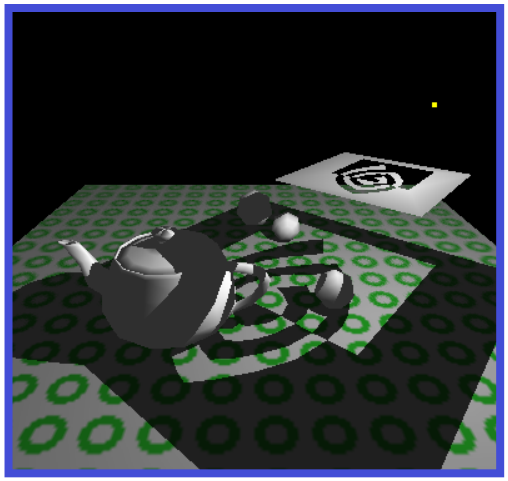
Projected planar shadows



Shadow volumes



Light maps



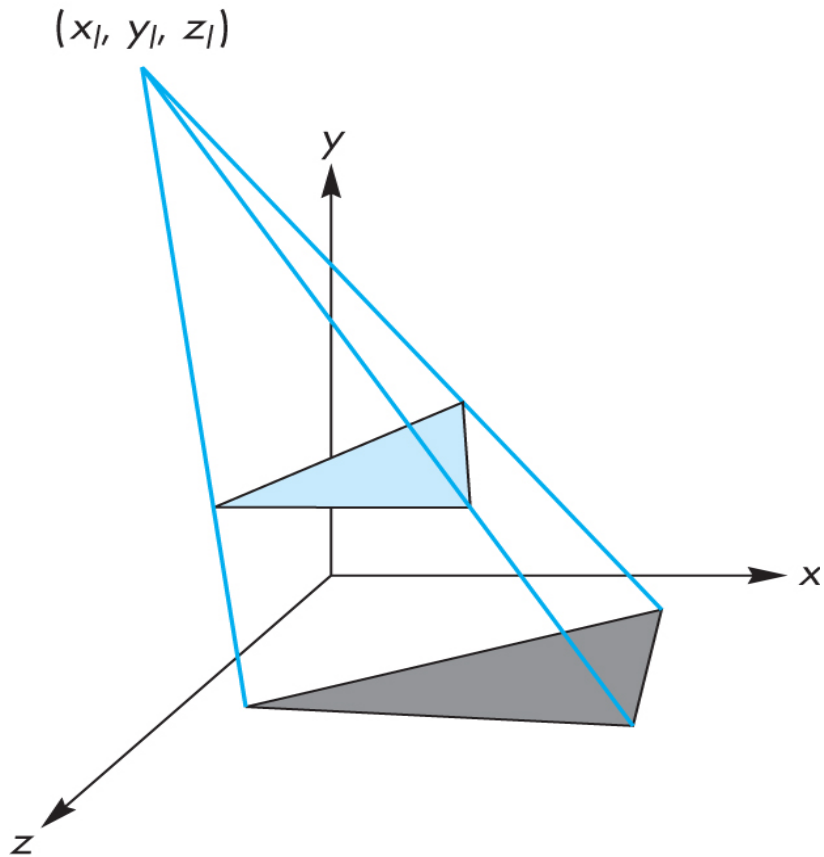
Hybrid approaches

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

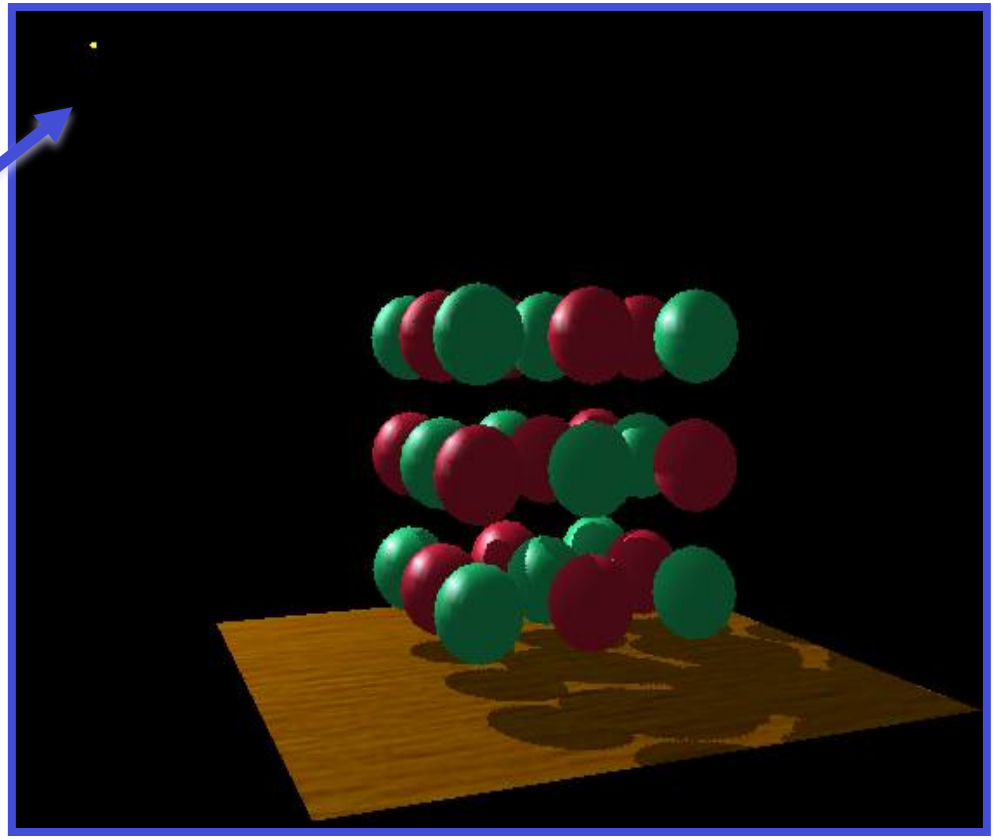


Projective Shadows

- 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

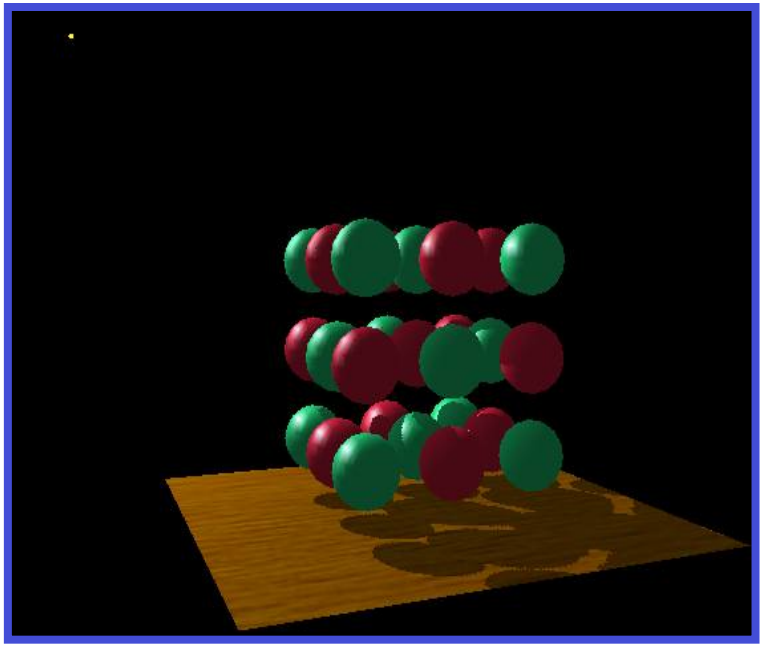
Visualizing Shadow Mapping

the point light source

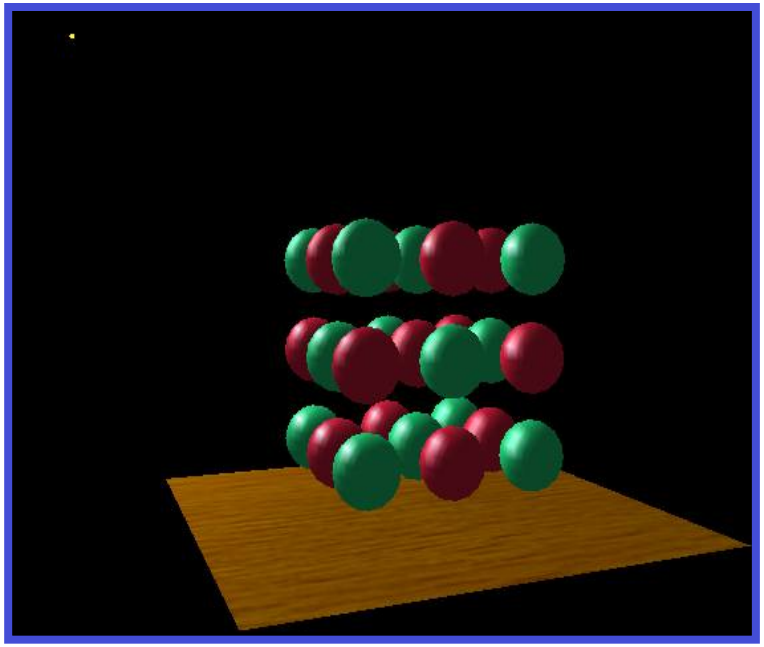


Visualizing Shadow Mapping

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

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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

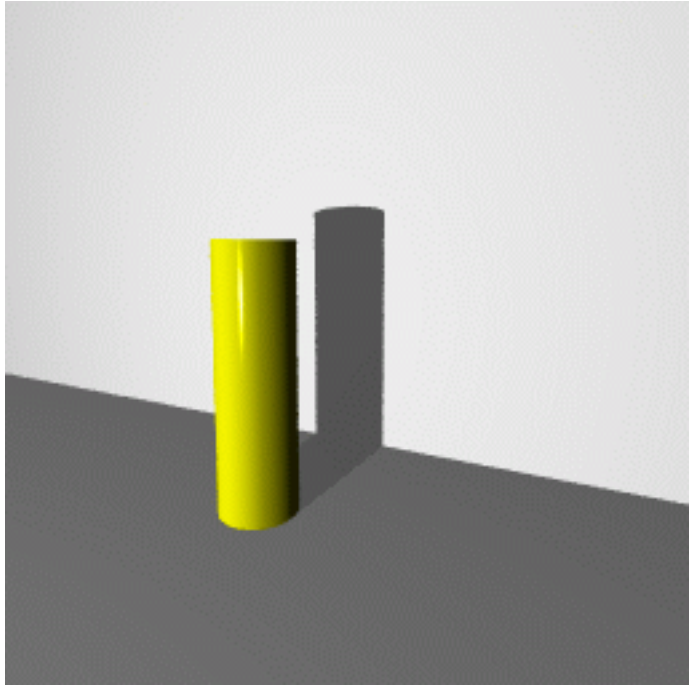
$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & \frac{1}{-y_l} & 0 & 0 \end{bmatrix}$$

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



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

Shadows

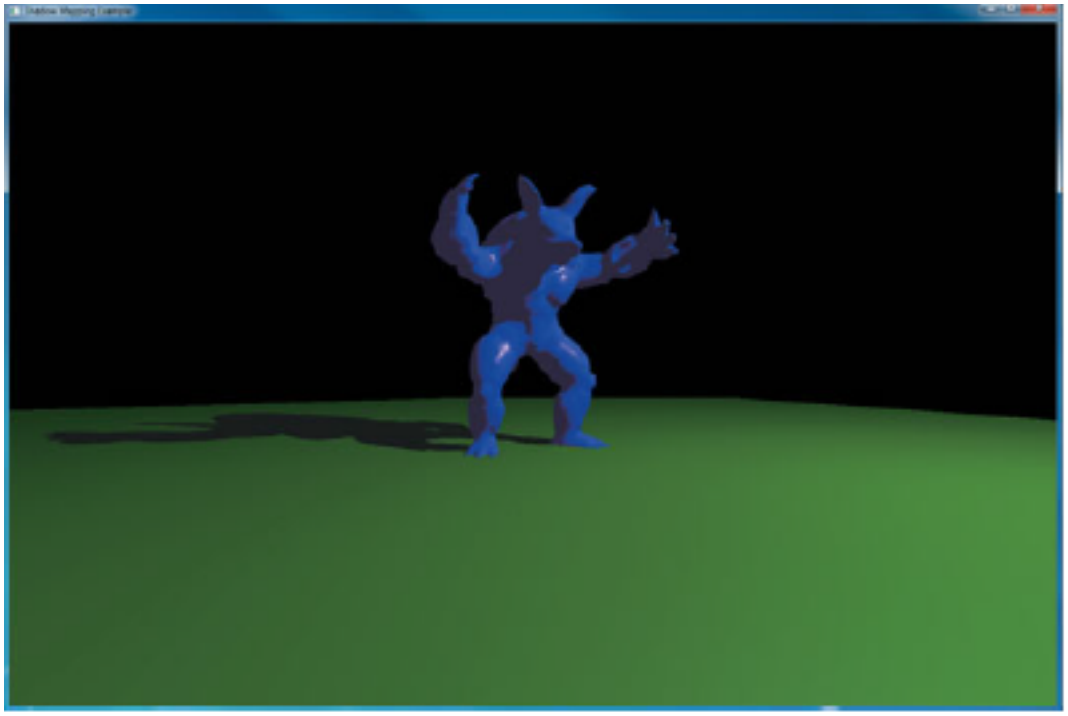
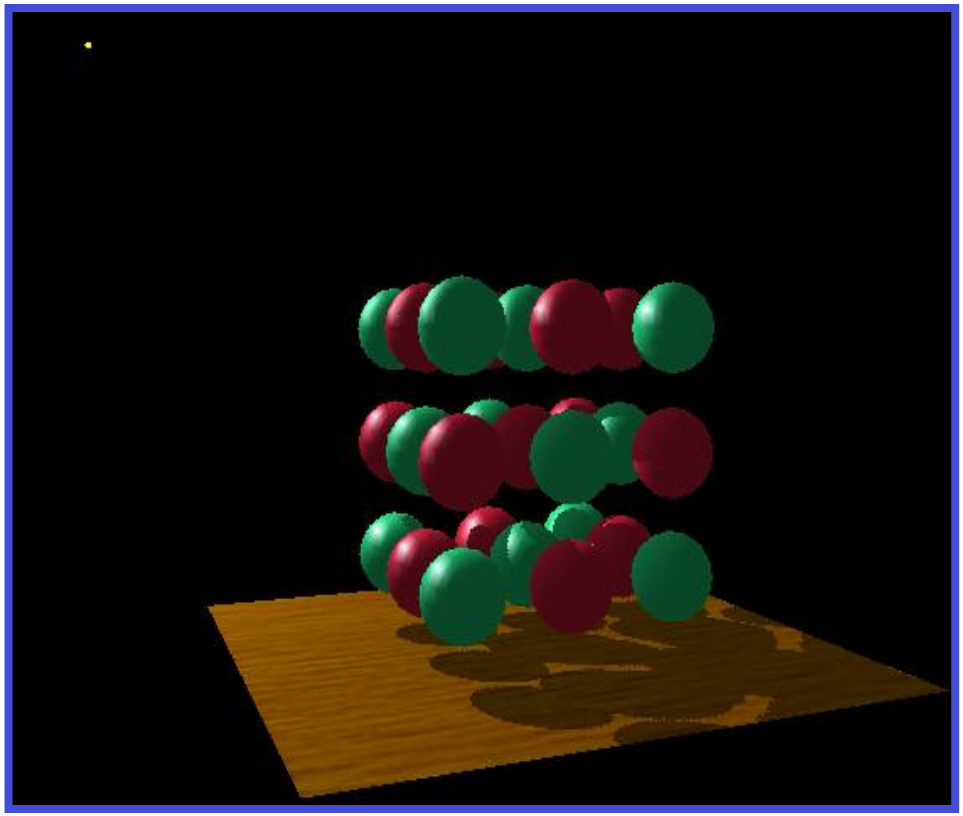


Figure 7.11 Final rendering of shadow map

Visualizing Shadow Mapping

Scene with shadows

Notice how specular highlights never appear in shadows



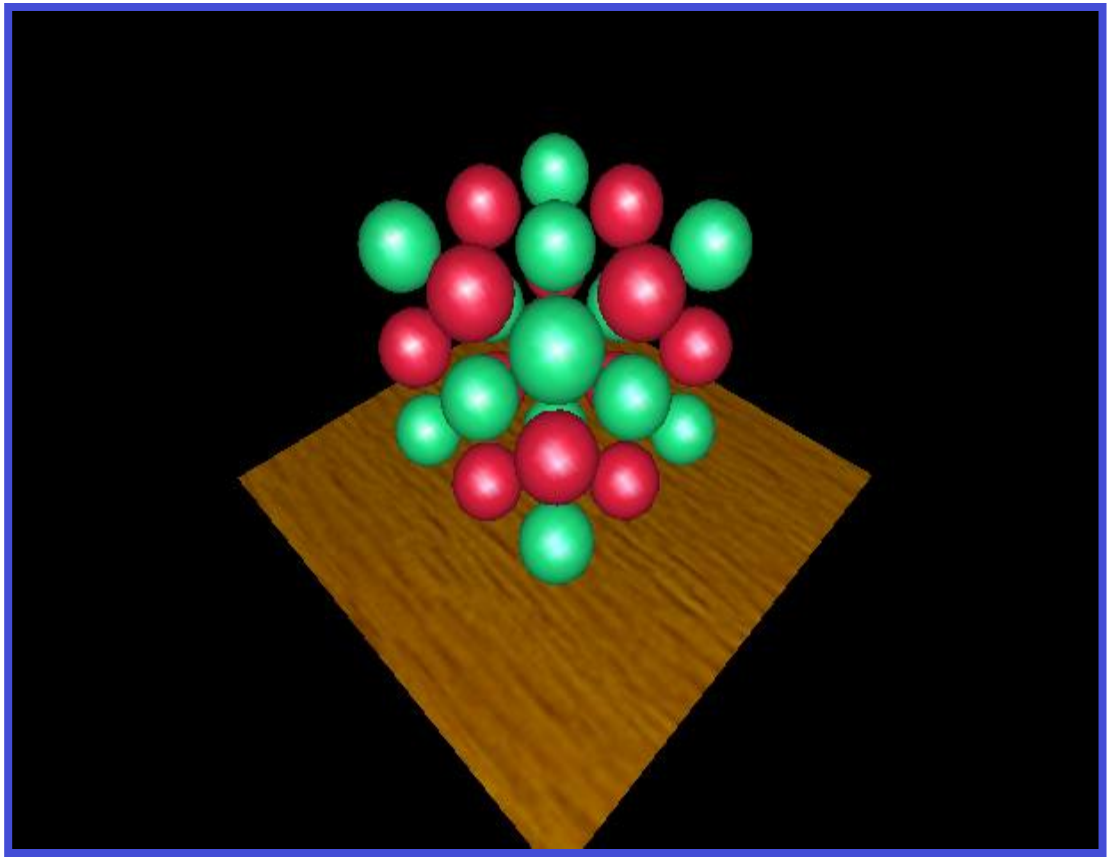
Notice how curved surfaces cast shadows on each other

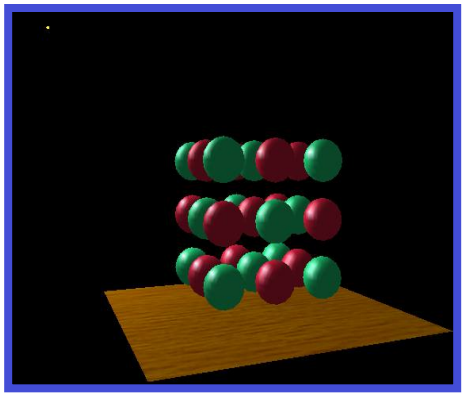
Applications Side

- 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

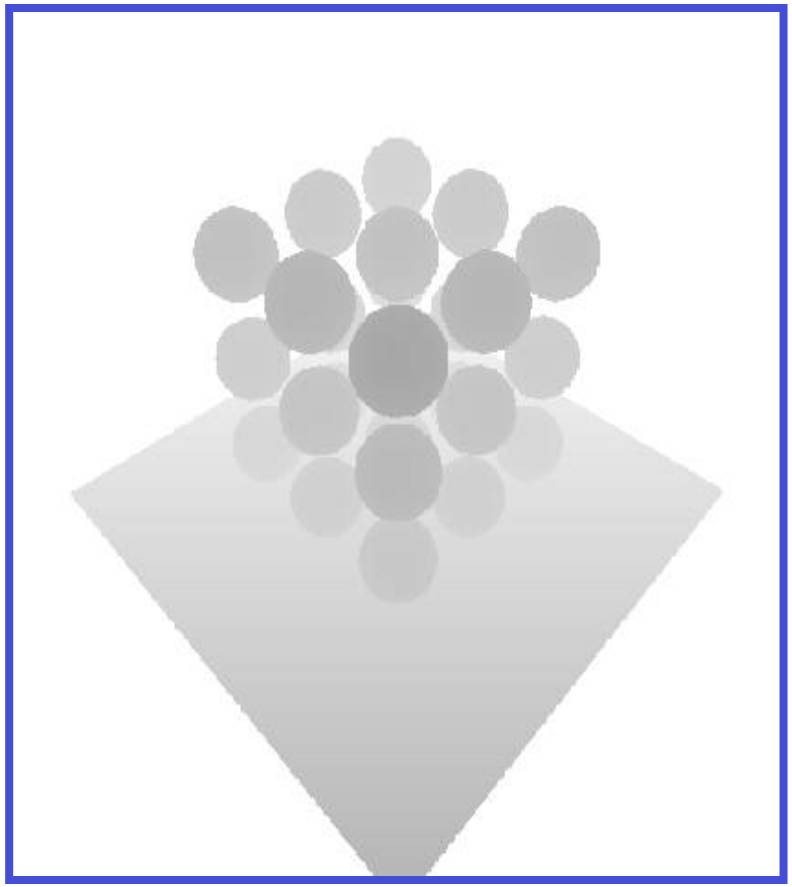


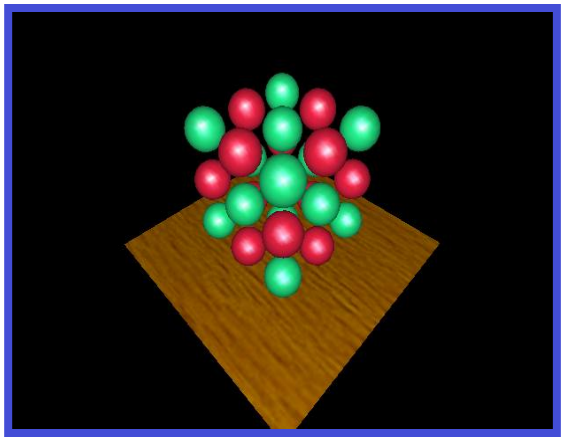


FYI: from the eye's point-of-view again

Visualizing Shadow Mapping

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

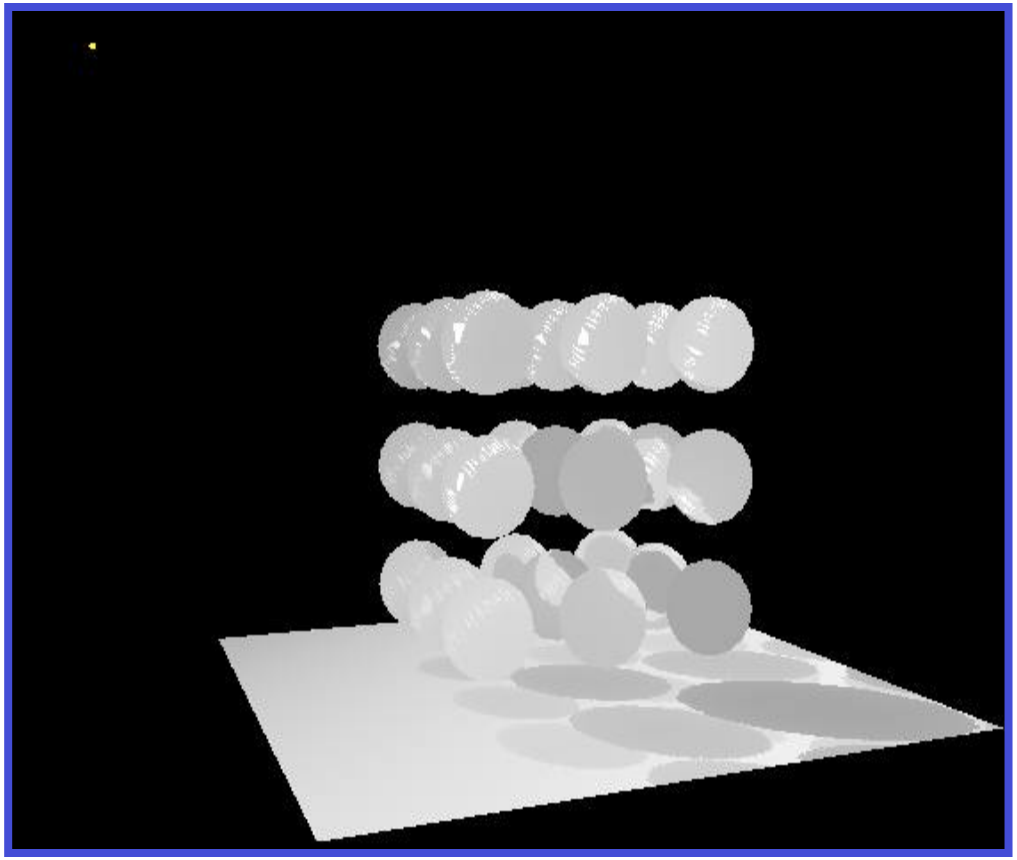


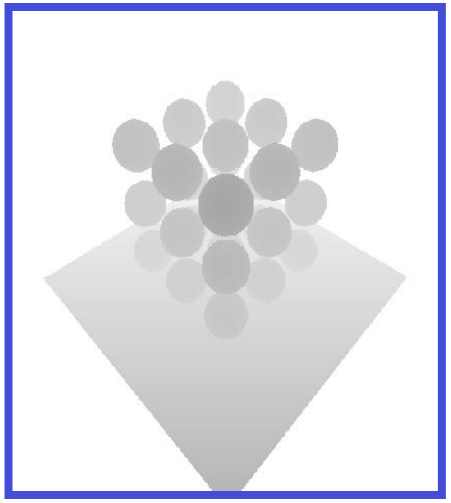


FYI: from the light's point-of-view again

Visualizing Shadow Mapping

Projecting the depth map onto the eye's view

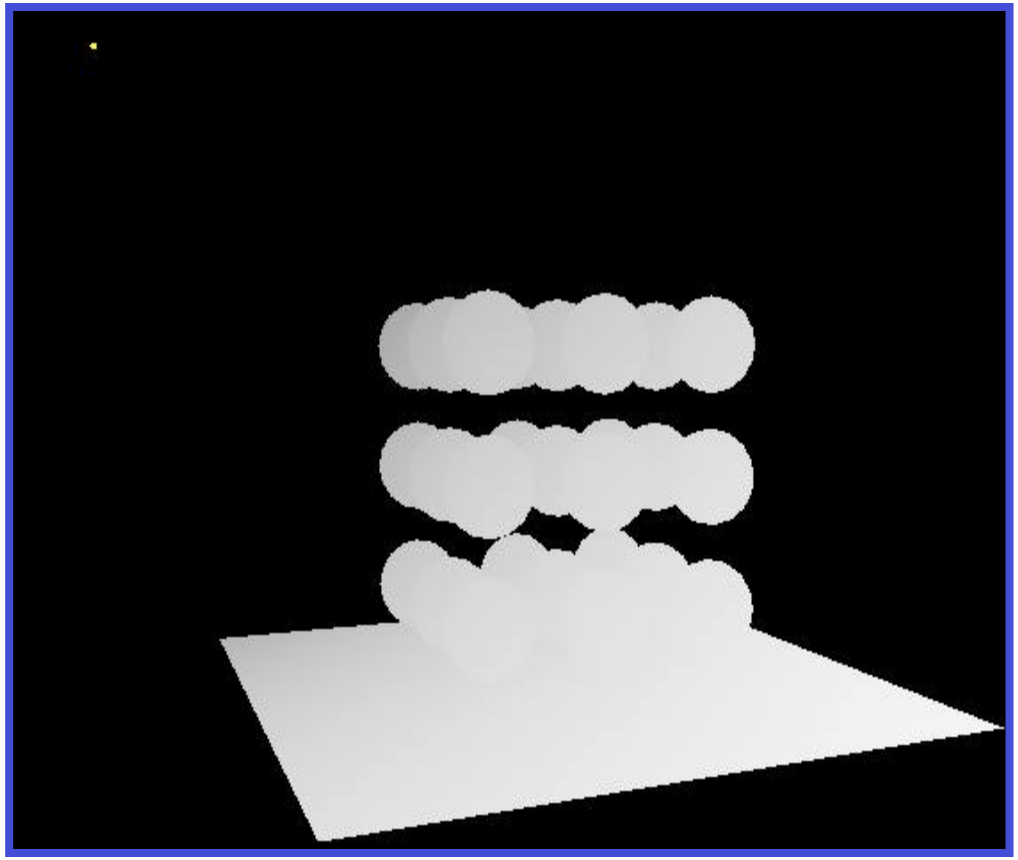




FYI: depth map for light's point-of-view again

Visualizing Shadow Mapping

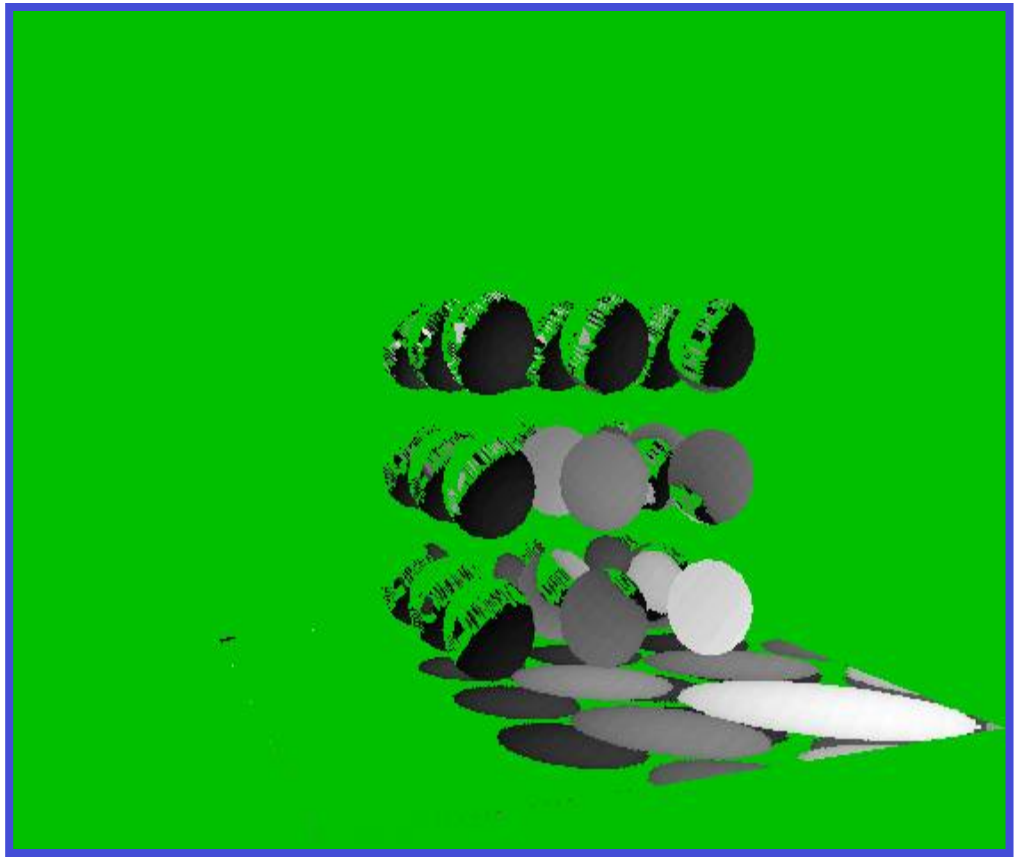
Projecting light's planar distance onto eye's view



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

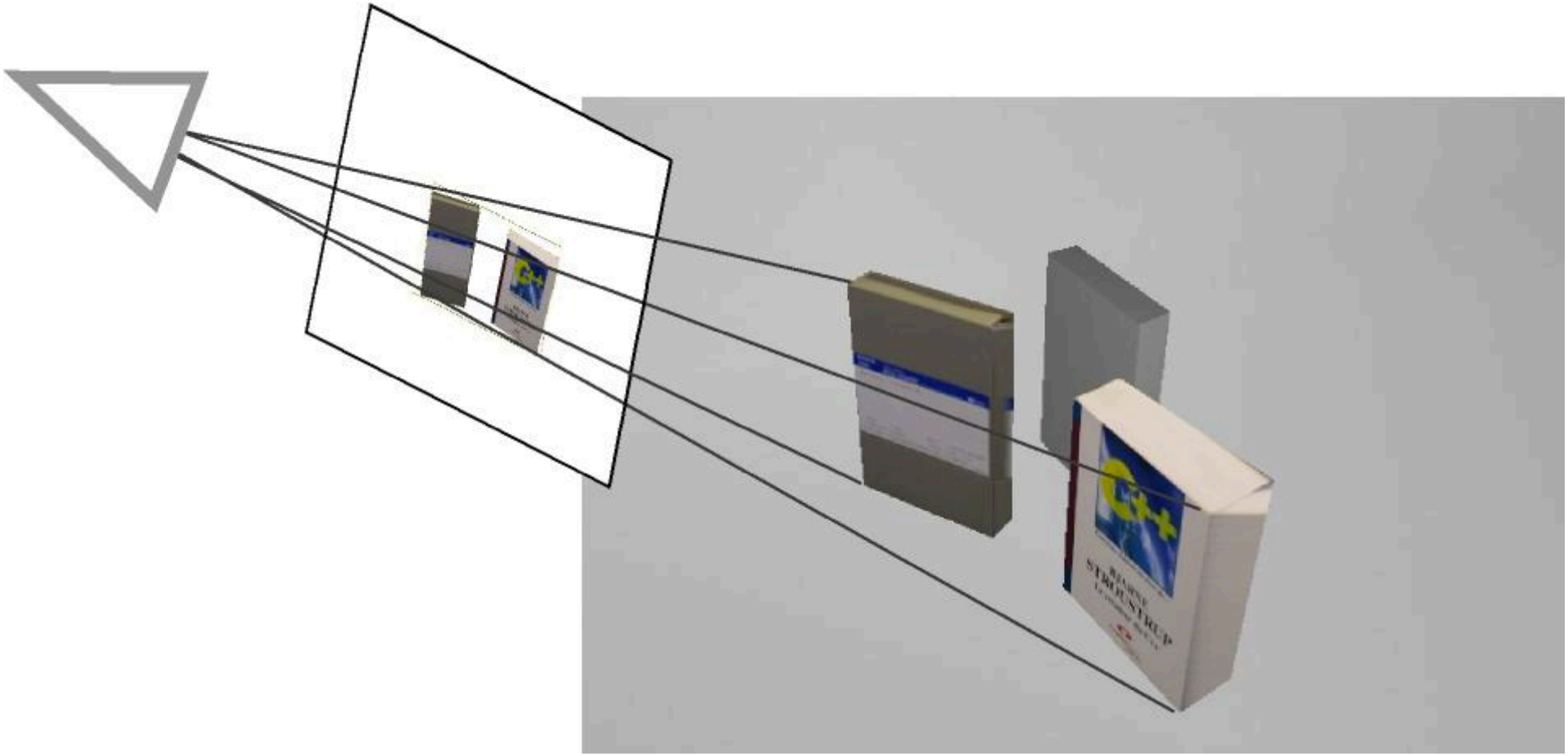


Non-green is where shadows should be

Generalized Shadows

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

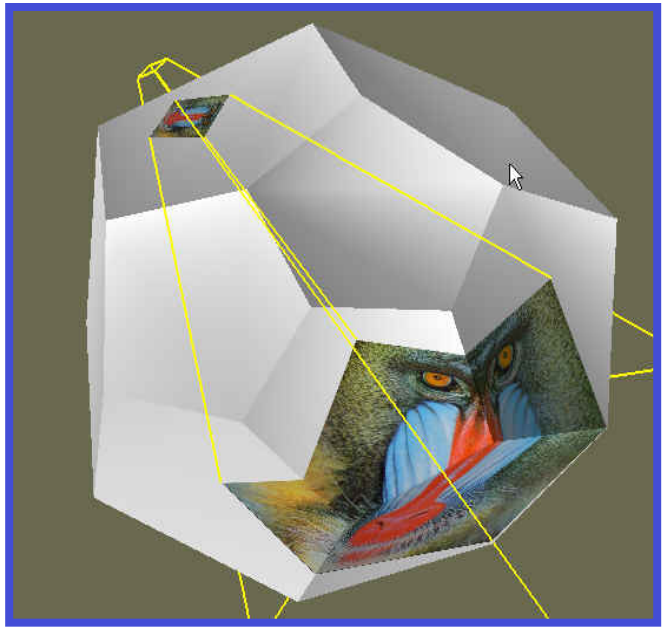
Projective Textures



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);

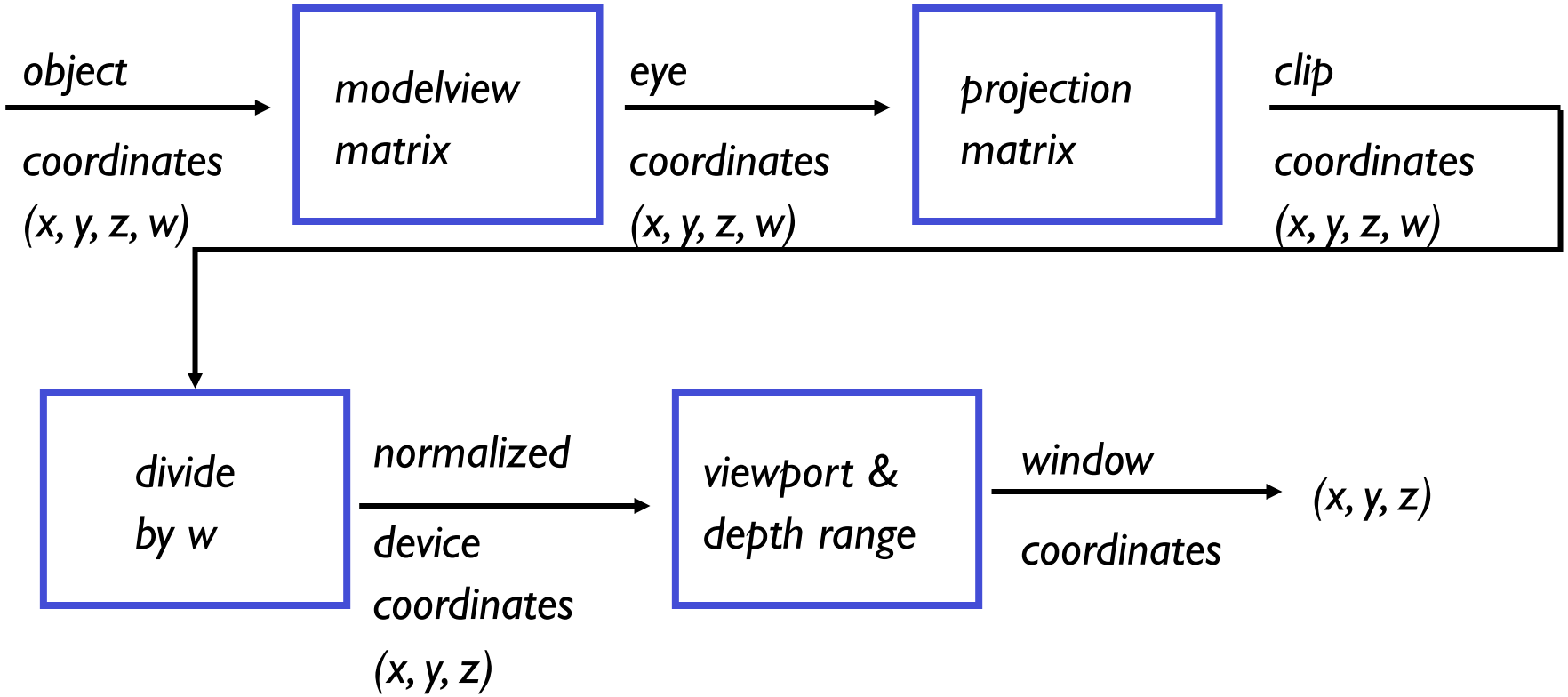
Check

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

```
glFramebufferTexture(GL_FRAMEBUFFER,
GL_DEPTH_STENCIL_ATTACHMENT, depth_texture, 0);
```

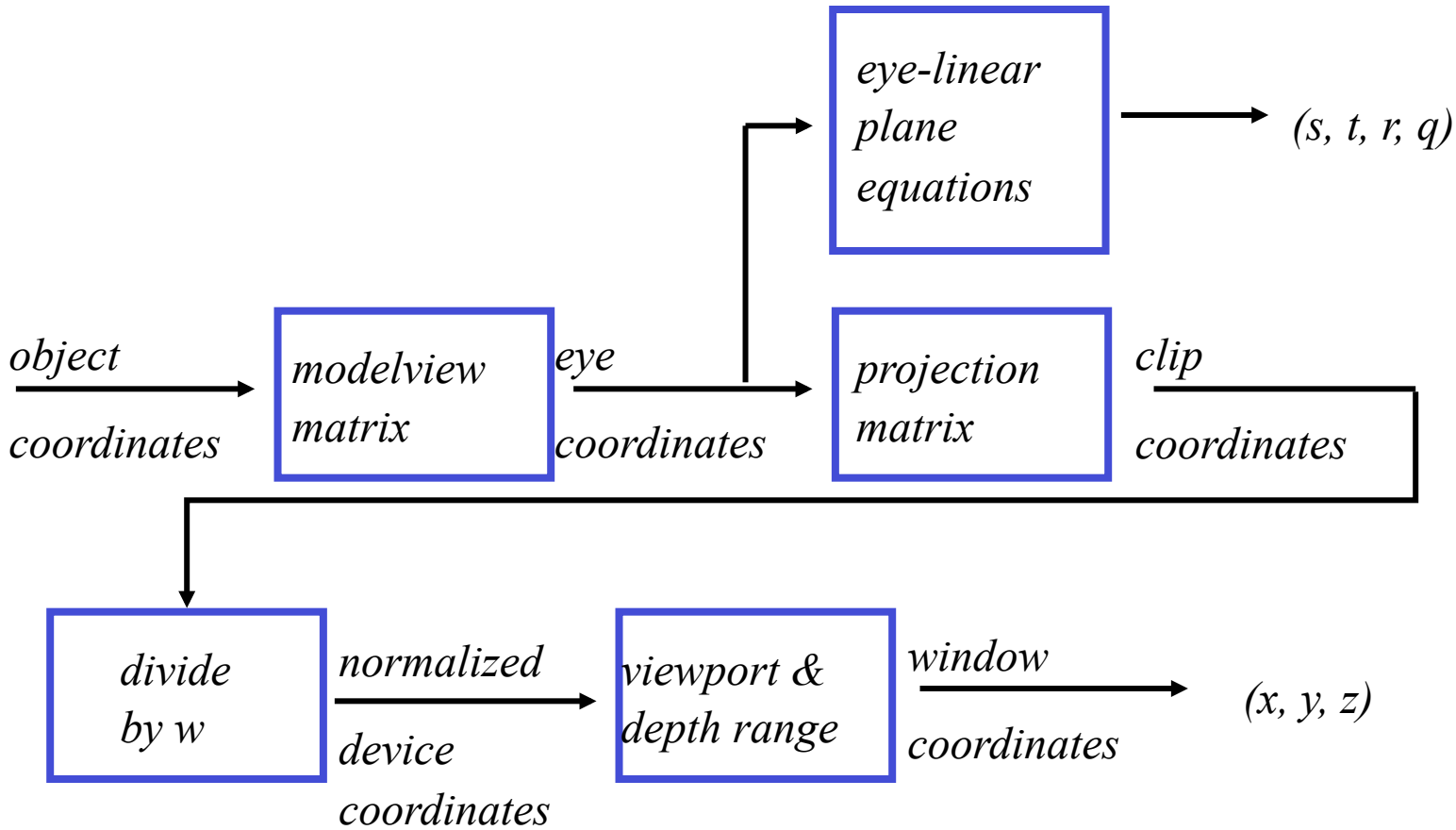
Vertex Coordinate Transform

From object to window coordinates



Eye Linear Texture Coordinate

Generating texture coordinates from eye-space



Transforms

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

Map Use

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

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

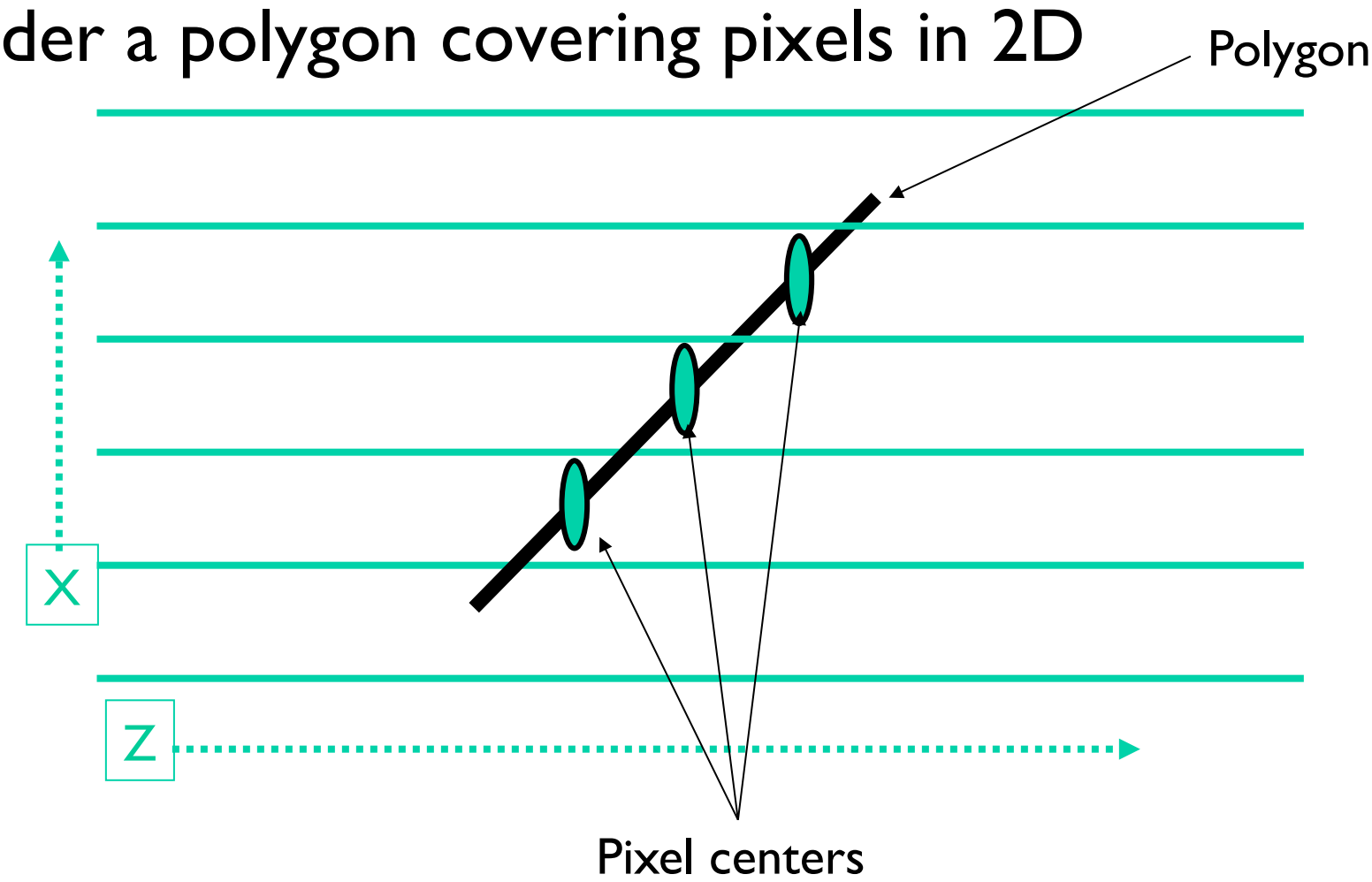
- Two Issues
  - Constructing the depth map
    - use existing hardware depth buffer
    - use glPolygonOffset to offset depth value back
    - read back the depth buffer contents
  - Depth map can be copied to a 2D texture
    - unfortunately, depth values tend to require more precision than 8-bit typical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

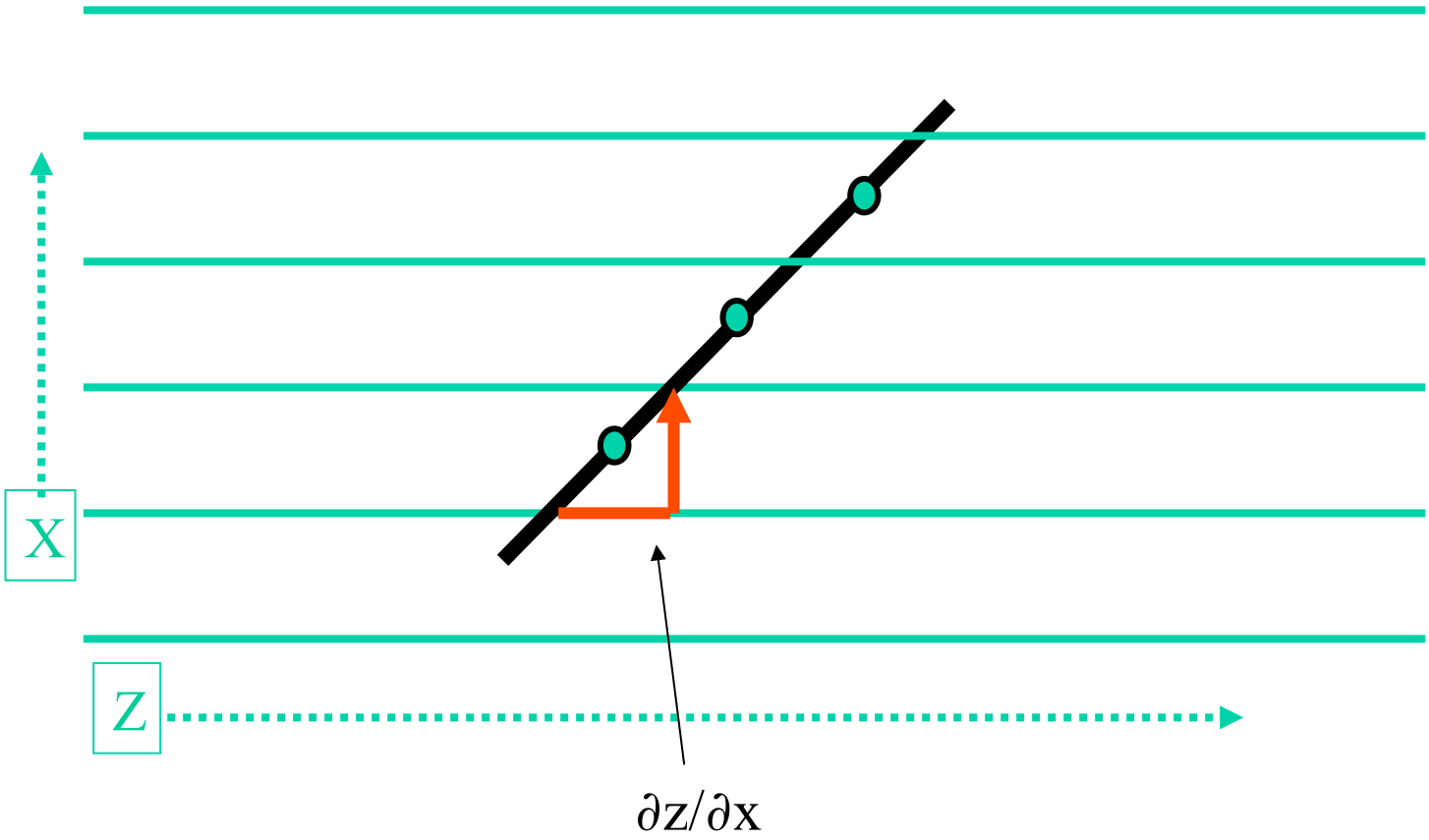
In Pictures - Pixel Centers

Consider a polygon covering pixels in 2D



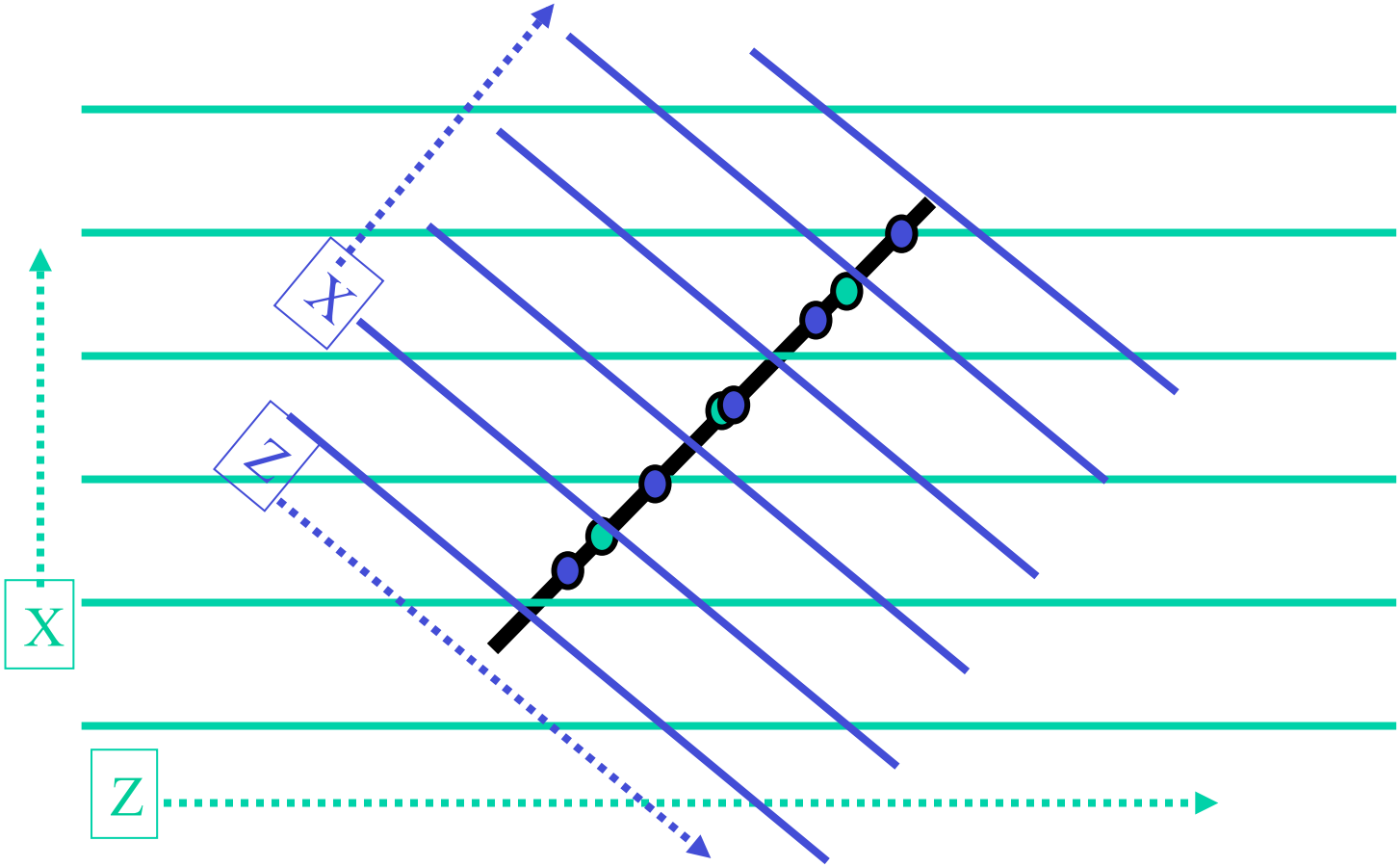
In Pictures - Pixel Centers

Change of Z with respect to X



In Pictures - Pixel Centers

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



glPolygonOffset's Slope

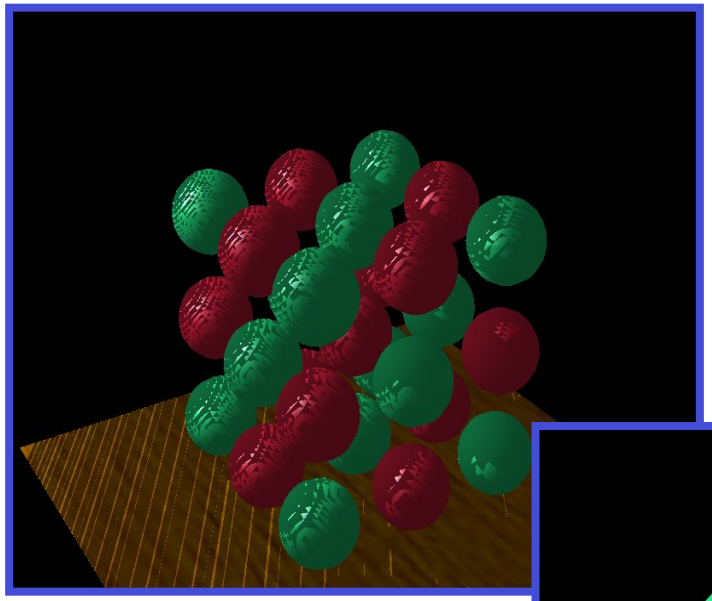
- Pixel center is re-sampled to another grid
  - For example, the shadow map texture's grid!
- The re-sampled depth could be off by

  $+/-0.5\ \partial z/\partial x$ and $+/-0.5\ \partial z/\partial y$
- The maximum absolute error would be

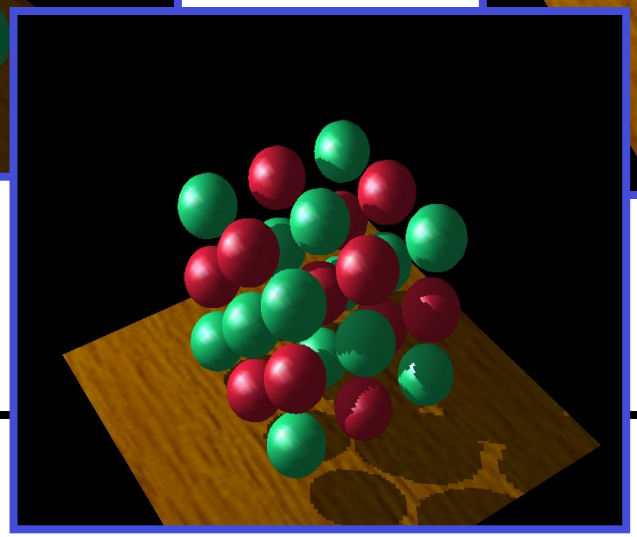
  $|\ 0.5\ \partial z/\partial x\ | + |\ 0.5\ \partial z/\partial y\ | \approx \max(\ |\ \partial z/\partial x\ |\ ,\ |\ \partial z/\partial y\ |\ )$
  - This assumes the two grids have pixel footprint area ratios of 1.0
  - Otherwise, we might need to scale by the ratio
- Exactly what polygon offset's "slope" depth bias does

Results

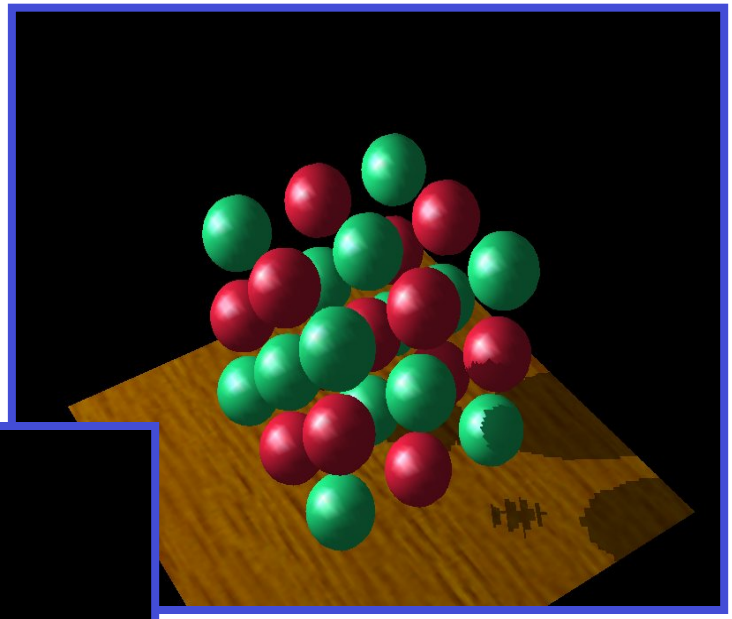
How much polygon offset bias depends



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

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

Map Use

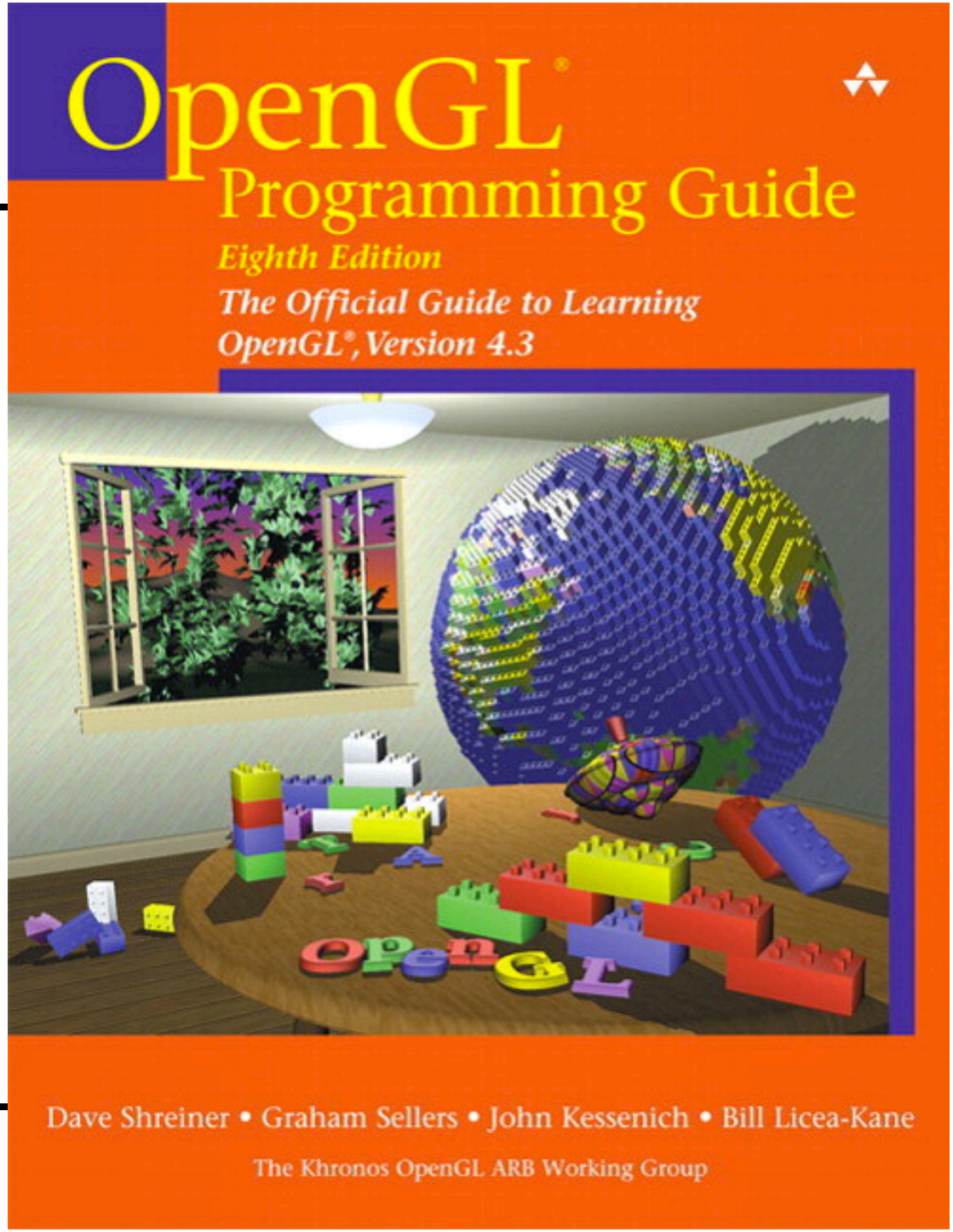
$$\begin{bmatrix} s \\ t \\ r \\ q \end{bmatrix} = \underbrace{\begin{bmatrix} 1/2 & & & 1/2 \\ & 1/2 & & 1/2 \\ & & 1/2 & 1/2 \\ & & & 1 \end{bmatrix} \begin{bmatrix} \textit{Light} \\ \textit{frustum} \\ \textit{(projection)} \\ \textit{matrix} \end{bmatrix} \begin{bmatrix} \textit{Light} \\ \textit{view}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

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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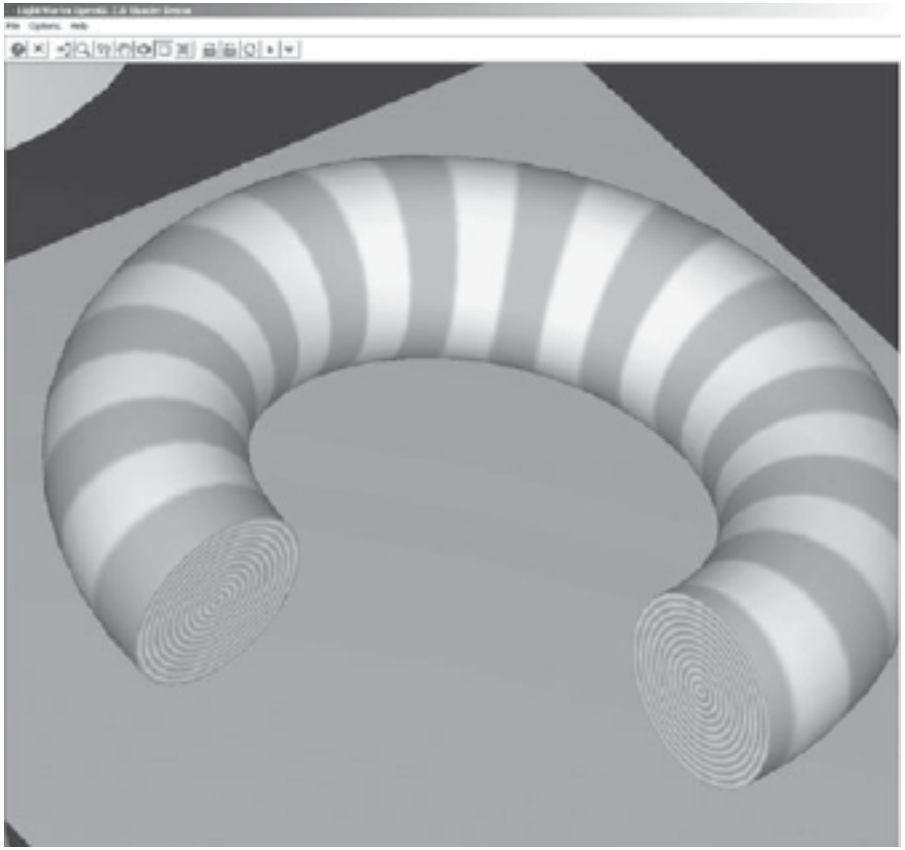
Procedural Texturing

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;
}
```

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).)

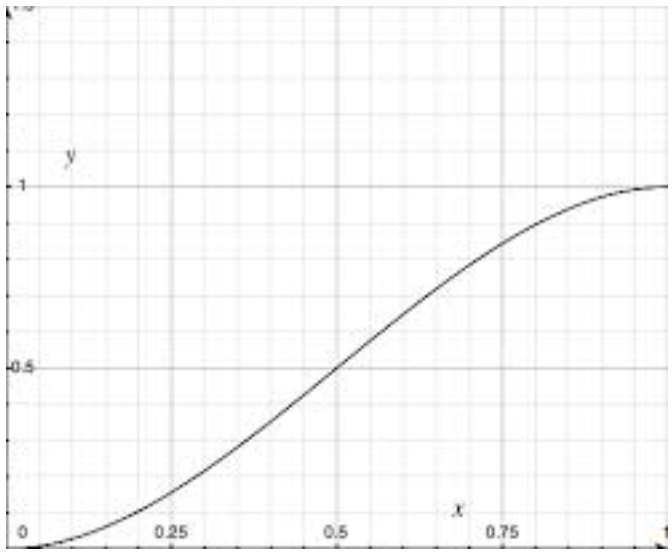
Fragment Shader

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

Hermite



$$2t^3 - 3t^2 + 1$$

The Brick Wall

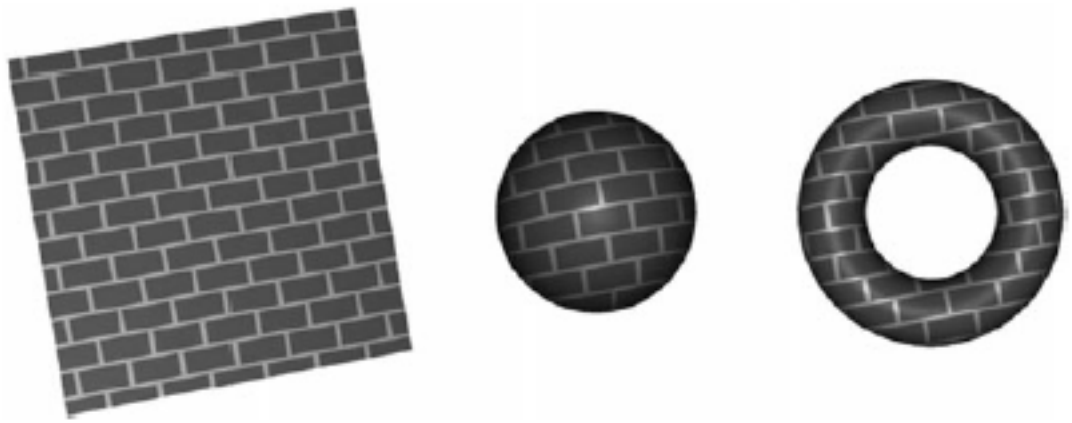


Figure 8.3 Brick patterns
(A flat polygon, a sphere, and a torus rendered with the brick shaders.)

Example 8.3 Vertex Shader for Drawing Bricks

```
#version 330 core

in vec4       MCvertex;
in vec3       MCnormal;

uniform mat4 MVMatrix;
uniform mat4 MVPMatrix;
uniform mat3 NormalMatrix;
uniform vec3 LightPosition;

const float SpecularContribution = 0.3;
const float DiffuseContribution  = 1.0 - SpecularContribution;

out float     LightIntensity;
out vec2      MCposition;

void main()
{
    vec3 ecPosition = vec3(MVMatrix * MCvertex);
    vec3 tnorm      = normalize(NormalMatrix * MCnormal);
    vec3 lightVec   = normalize(LightPosition - ecPosition);
    vec3 reflectVec = reflect(-lightVec, tnorm);
    vec3 viewVec    = normalize(-ecPosition);
    float diffuse   = max(dot(lightVec, tnorm), 0.0);
```

Bricks – Vertex Shader

```
    float spec       = 0.0;

    if (diffuse > 0.0)
    {
         spec = max(dot(reflectVec, viewVec), 0.0);
         spec = pow(spec, 16.0);
    }

    LightIntensity   = DiffuseContribution * diffuse +
                       SpecularContribution * spec;

    MCposition       = MCvertex.xy;
    gl_Position      = MVPMatrix * MCvertex;
}
```

Example 8.4 Fragment Shader for Drawing Bricks

```
#version 330 core

uniform vec3 BrickColor, MortarColor;
uniform vec2 BrickSize;
uniform vec2 BrickPct;

in vec2  MCposition;
in float LightIntensity;

out vec4 FragColor;

void main()
{
    vec3 color;
    vec2 position, useBrick;

    position = MCposition / BrickSize;

    if (fract(position.y * 0.5) > 0.5)
        position.x += 0.5;

    position = fract(position);
    useBrick = step(position, BrickPct);

    color  = mix(MortarColor, BrickColor, useBrick.x * useBrick.y);
    color *= LightIntensity;

    FragColor = vec4(color, 1.0);
}
```

Lattice

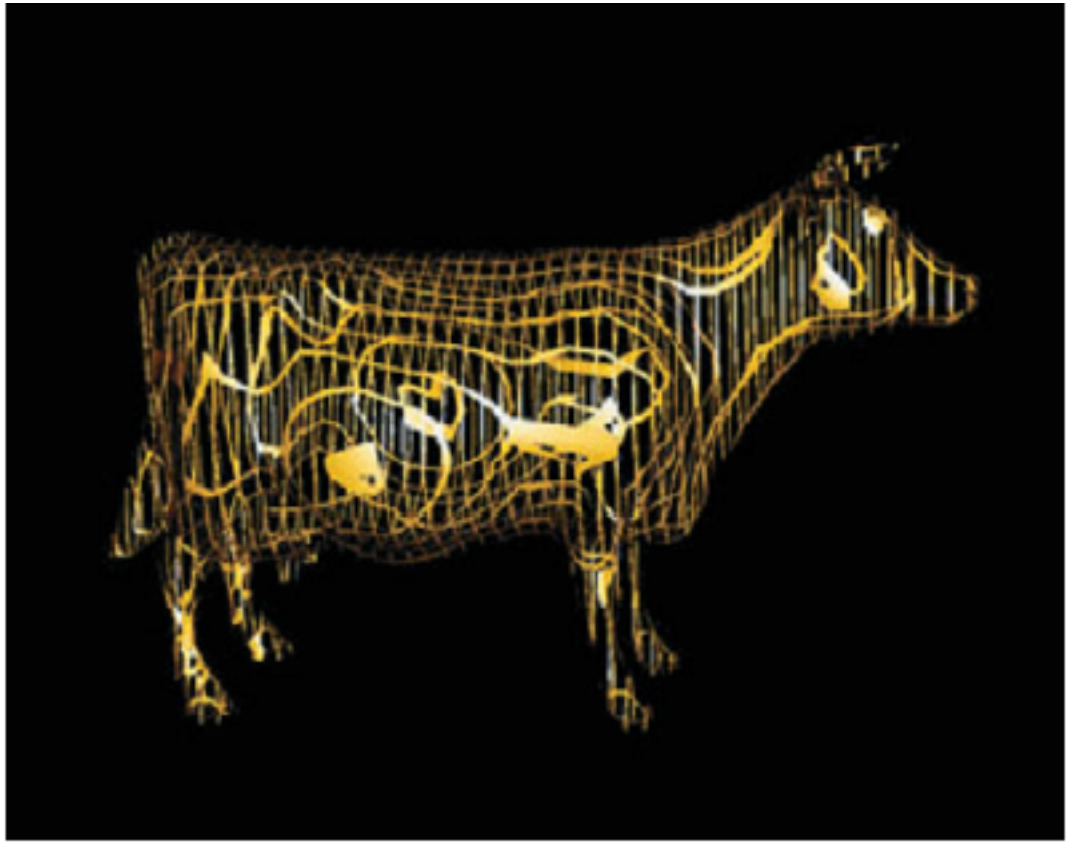


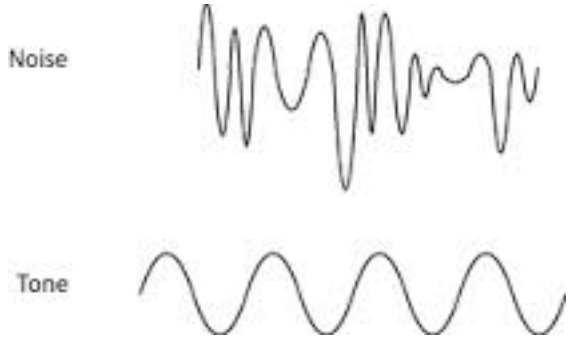
Figure 8.7 The lattice shader applied to the cow model (3Dlabs, Inc.)

Discarding Cow Parts

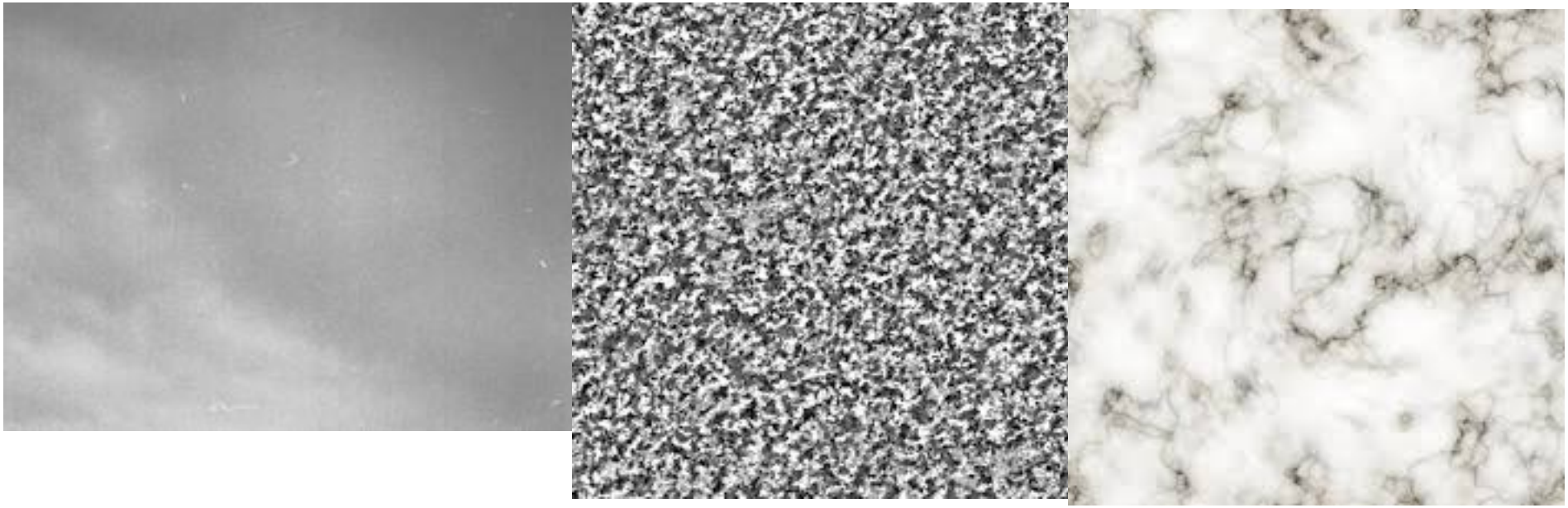
Example 8.8 Fragment Shader for Procedurally Discarding Part of an Object

```
in vec3 DiffuseColor;
in vec3 SpecularColor;
in vec2 TexCoord

out vec3 FragColor;

uniform vec2  Scale;
uniform vec2  Threshold;
uniform vec3  SurfaceColor;

void main()
{
        float ss = fract(TexCoord.s * Scale.s);
        float tt = fract(TexCoord.t * Scale.t);

        if ((ss > Threshold.s) && (tt > Threshold.t))
            discard;

        vec3 finalColor = SurfaceColor * DiffuseColor + SpecularColor;
        FragColor = vec4(finalColor, 1.0);
}
```

Noise



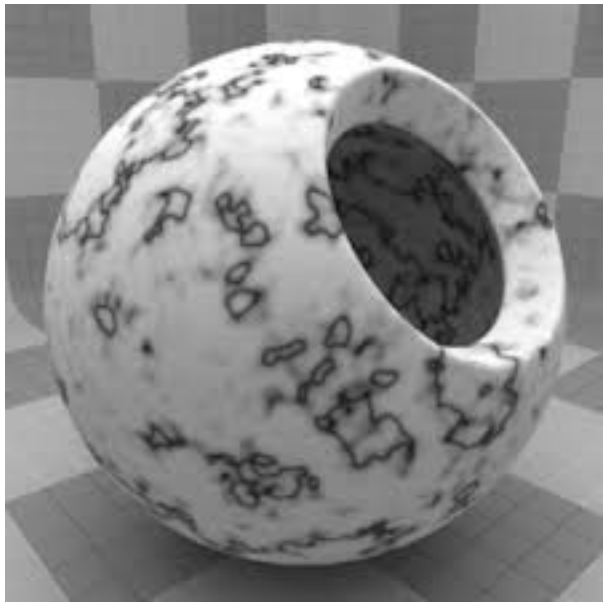
Noise Textures



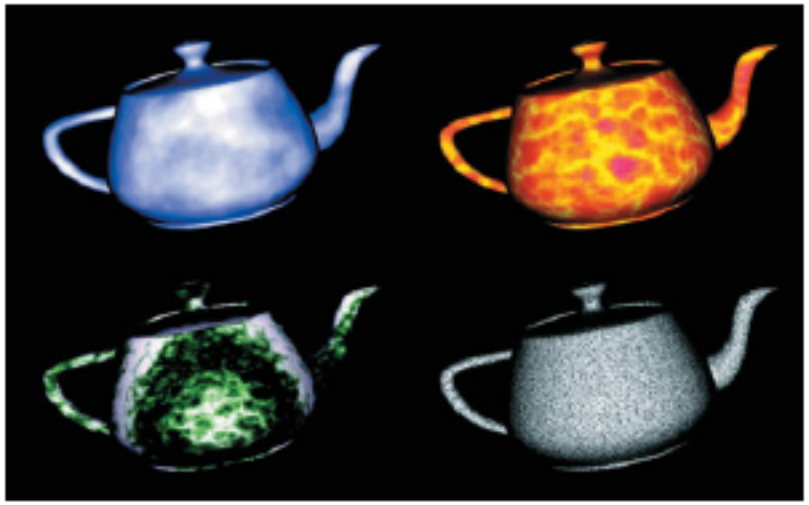
Noise is Seasoning

- It does not show any obvious regular or repeated patterns.
- It is a continuous function, and its derivative is also continuous. That is, there are no sudden steps or sharp bends, only smooth variation, and zooming in to smaller and smaller scales still shows only smooth variation.
- It is a function that is repeatable across time (i.e., it generates the same value each time it is presented with the same input).
- It has a well-defined range of output values (usually the range is $[-1, 1]$ or $[0, 1]$).
- It is a function whose small-scale form is roughly independent of large-scale position (there is an underlying frequency to variation, or statistical character, that is the same everywhere).
- It is a function that is isotropic (its statistical character is the same in all directions).
- It can be defined for 1, 2, 3, 4, or even more dimensions.
- It is fast to compute for any given input.

Noisy Texture on Surfaces



RedBook



Discrete Noise

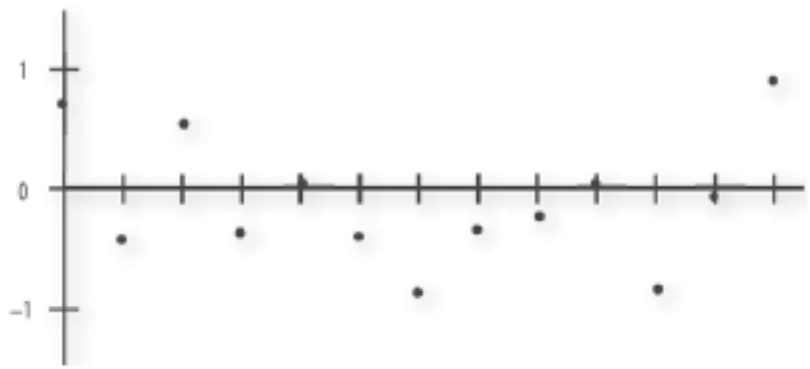


Figure 8.21 A discrete 1D noise function

Continuous Noise

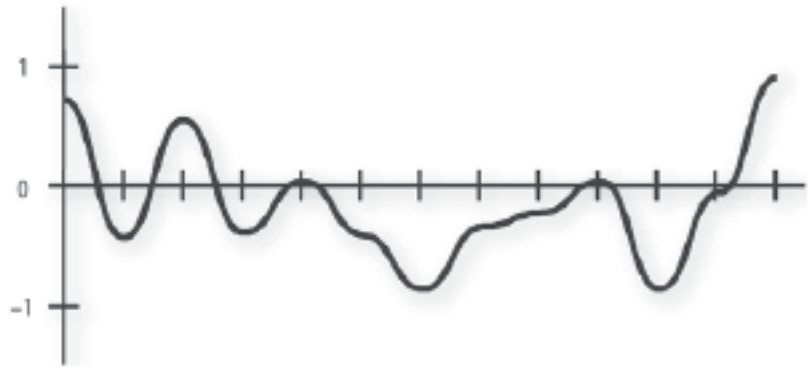
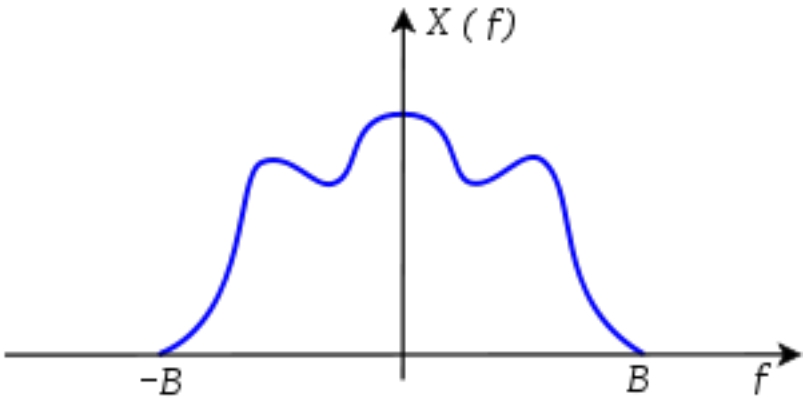
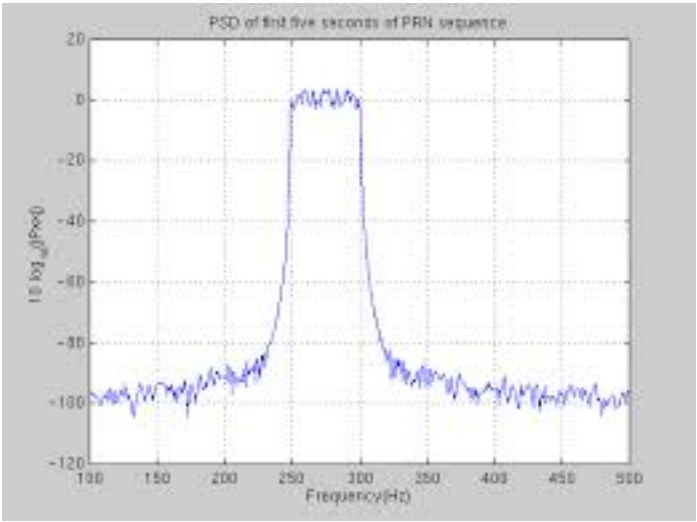


Figure 8.22 A continuous 1D noise function

Interpolation

Bandlimited Noise





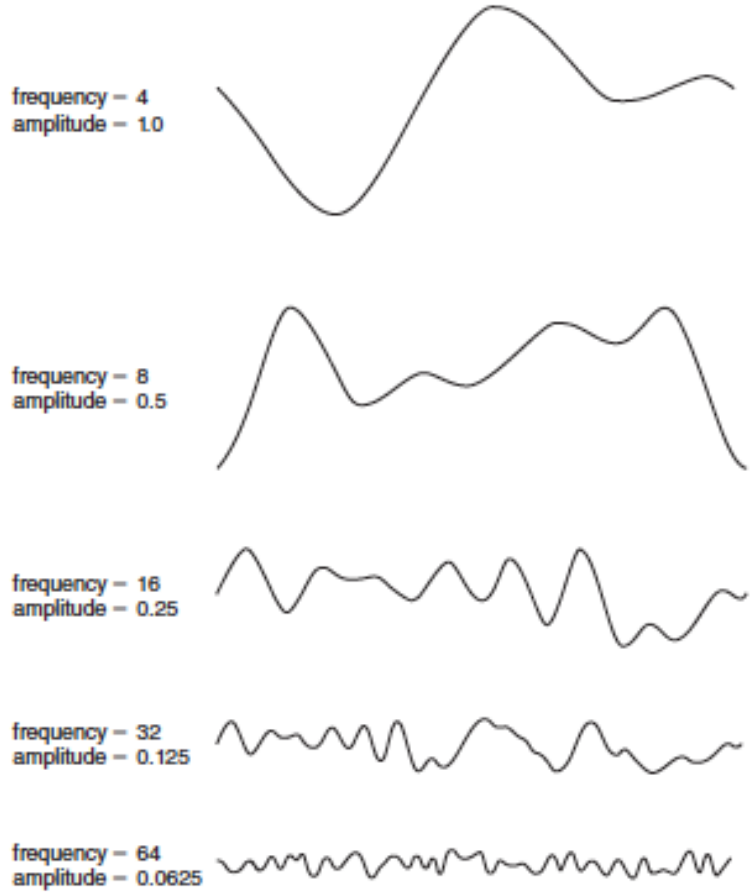


Figure 8.23 Varying the frequency and the amplitude of the noise function

Making Synthetic Noise

$$fnoise(x) = \sum_{i=0}^{octaves-1} \alpha^i \cdot noise(2^i \cdot x)$$

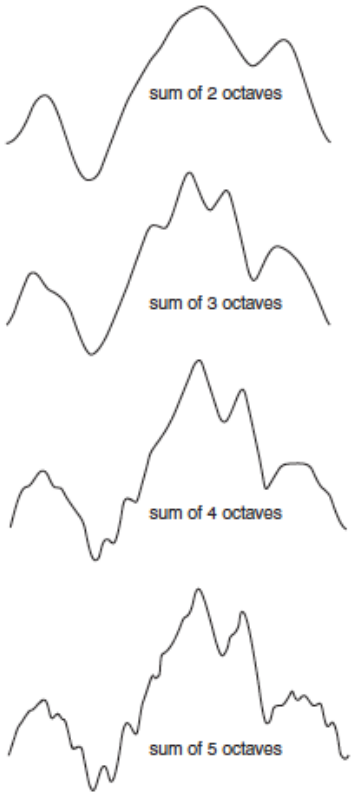


Figure 8.24 Summing noise functions
(Shows the result of summing noise functions of different amplitude and frequency.)

2D

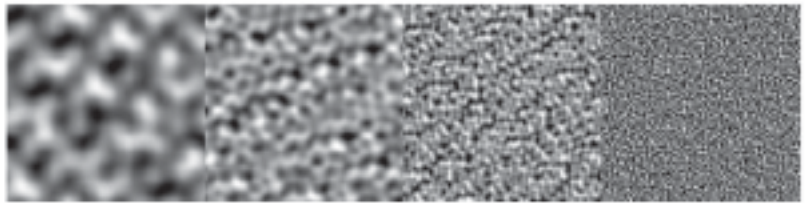


Figure 8.25 Basic 2D noise, at frequencies 4, 8, 16, and 32 (contrast enhanced)

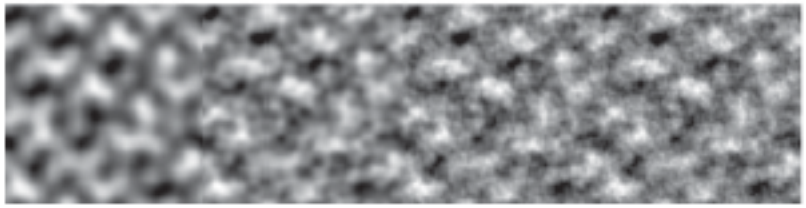


Figure 8.26 Summed noise, at 1, 2, 3, and 4 octaves (contrast enhanced)

3D, nD

$$fnoise(x) = \sum_{i=0}^{octaves-1} \alpha^i \cdot noise(2^i \cdot x)$$

Example 8.14 C function to Generate a 3D Noise Texture

```
int noise3DTexSize = 128;

GLuint noise3DTexName = 0;
GLubyte *noise3DTexPtr;

void make3DNoiseTexture(void)
{
    int f, i, j, k, inc;
    int startFrequency = 4;
    int numOctaves = 4;
    double ni[3];
    double inci, incj, inck;
    int frequency = startFrequency;
    GLubyte *ptr;
    double amp = 0.5;

    if ((noise3DTexPtr = (GLubyte *) malloc(noise3DTexSize *
                                            noise3DTexSize *
                                            noise3DTexSize * 4))
         == NULL)
    {
        fprintf(stderr,
                "ERROR: Could not allocate 3D noise texture\n");
        exit(1);
    }

    for (f = 0, inc = 0; f < numOctaves;
         ++f, frequency *= 2, ++inc, amp *= 0.5)
    {
        setNoiseFrequency(frequency);
        ptr = noise3DTexPtr;
        ni[0] = ni[1] = ni[2] = 0;

        inci = 1.0 / (noise3DTexSize / frequency);
        for (i = 0; i < noise3DTexSize; ++i, ni[0] += inci)
        {
            incj = 1.0 / (noise3DTexSize / frequency);
            for (j = 0; j < noise3DTexSize; ++j, ni[1] += incj)
            {
                inck = 1.0 / (noise3DTexSize / frequency);
                for (k = 0; k < noise3DTexSize;
                     ++k, ni[2] += inck, ptr += 4)
                {
                    *(ptr+inc) = (GLubyte)(((noise3(ni)+1.0) * amp)
                                           * 128.0);
                }
            }
        }
    }
}
```

Repeatability

Example 8.15 A Function for Activating the 3D Noise Texture

```
void init3DNoiseTexture()
{
    glGenTextures(1, & noise3DTexName);

    glActiveTexture(GL_TEXTURE6);
    glBindTexture(GL_TEXTURE_3D, noise3DTexName);
    glTexParameterf(GL_TEXTURE_3D, GL_TEXTURE_WRAP_S, GL_REPEAT);
    glTexParameterf(GL_TEXTURE_3D, GL_TEXTURE_WRAP_T, GL_REPEAT);
    glTexParameterf(GL_TEXTURE_3D, GL_TEXTURE_WRAP_R, GL_REPEAT);
    glTexParameterf(GL_TEXTURE_3D, GL_TEXTURE_MAG_FILTER, GL_LINEAR);
    glTexParameterf(GL_TEXTURE_3D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);

    glTexImage3D(GL_TEXTURE_3D, 0, GL_RGBA, noise3DTexSize,
                 noise3DTexSize, noise3DTexSize, 0, GL_RGBA,
                 GL_UNSIGNED_BYTE, noise3DTexPtr);
}
```

Noise in GLSL

Example 8.16 Cloud Vertex Shader

```
#version 330 core

uniform mat4 MVMatrix;
uniform mat4 MVPMatrix;
uniform mat3 NormalMatrix;

uniform vec3 LightPos;
uniform float Scale;

in  vec4  MCvertex;
in  vec3  MCnormal;

out float LightIntensity;
out vec3  MCposition;

void main()
{
   vec3 ECposition = vec3(MVMatrix * MCVertex);
   MCposition       = vec3(MCVertex) * Scale;
   vec3 tnorm      = normalize(vec3(NormalMatrix * MCNormal));
   LightIntensity   = dot(normalize(LightPos - ECposition), tnorm);
   LightIntensity  *= 1.5;
   gl_Position      = MVPMatrix * MCVertex;
}
```

Fragment Shader

Example 8.17 Fragment Shader for Cloudy Sky Effect

```
#version 330 core

uniform sampler3D Noise;
uniform vec3 SkyColor;        // (0.0, 0.0, 0.8)
uniform vec3 CloudColor;      // (0.8, 0.8, 0.8)

in  float LightIntensity;
in  vec3  MCposition;

out vec4  FragColor;
```

Chapter 8: Procedural Texturing

```
void main()
{
   vec4 noisevec = texture(Noise, MCposition);

   float intensity = (noisevec[0] + noisevec[1] +
                      noisevec[2] + noisevec[3] + 0.03125) * 1.5;

   vec3 color = mix(SkyColor, CloudColor, intensity) *
                  LightIntensity;
   FragColor = vec4(color, 1.0);
}
```

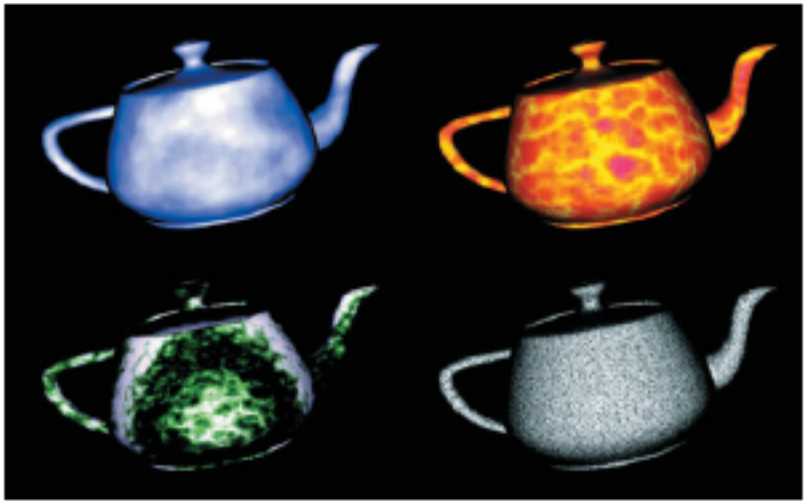


Figure 8.27 Teapots rendered with noise shaders
(Clockwise from upper left: a cloud shader that sums four octaves of noise and uses a blue-to-white color gradient to code the result; a sun surface shader that uses the absolute value function to introduce discontinuities (turbulence); a granite shader that uses a single high-frequency noise value to modulate between white and black; a marble shader that uses noise to modulate a sine function to produce alternating "veins" of color. (3Dlabs, Inc.))

Turbulence

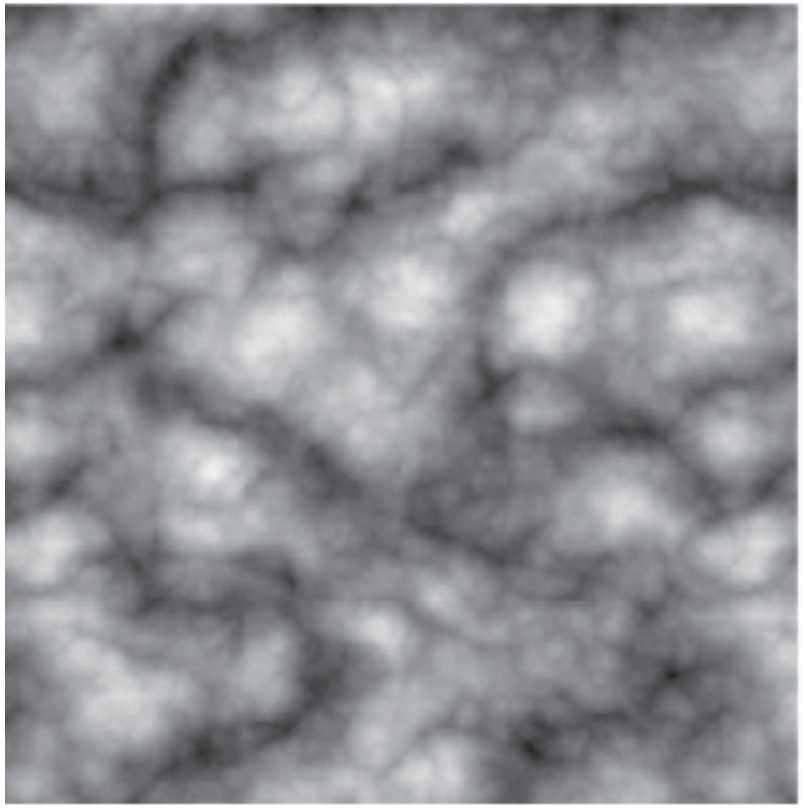


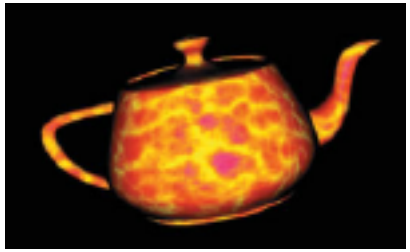
Figure 8.28 Absolute value noise or "turbulence"

Sun Surface

Example 8.18 Sun Surface Fragment Shader

```
#version 330 core

in float LightIntensity;
in vec3 MCposition;

uniform sampler3D Noise;
uniform vec3  Color1;        // (0.8, 0.7, 0.0)
uniform vec3  Color2;        // (0.6, 0.1, 0.0)
uniform float NoiseScale;    // 1.2

out vec4 FragColor;

void main()
{
    vec4 noisevec = texture(Noise, MCposition * NoiseScale);

    float intensity = abs(noisevec[0] - 0.25) +
                      abs(noisevec[1] - 0.125) +
                      abs(noisevec[2] - 0.0625) +
                      abs(noisevec[3] - 0.03125);

    intensity = clamp(intensity * 6.0, 0.0, 1.0);
    vec3 color = mix(Color1, Color2, intensity) * LightIntensity;
    FragColor = vec4(color, 1.0);
}
```

We can achieve an effect that looks like a pit of hot molten lava or the surface of the sun by using the same vertex shader as the cloud shader and a slightly different fragment shader. The main difference is that we scale each noise value and shift it over so that it is centered at 0; then we take its absolute value. After summing the values, we scale the result again to occupy nearly the full range of [0, 1]. We clamp this value and use it to mix between yellow and red to get the result shown in Figure 8.27 (see Example 8.18). This technique can be extended to change the results over time, using another dimension of noise for time, resulting in animation of the effect.

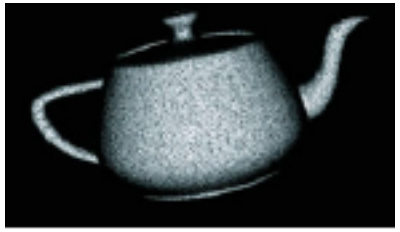


Granite

With noise, it's also easy just to try to make stuff up. In this example, we want to simulate a grayish rocky material with small black specks. To generate a relatively high-frequency noise texture, we use only the fourth component (the highest frequency one). We scale it by an arbitrary amount to provide an appropriate intensity level and then use this value for each of the red, green, and blue components. The shader in Example 8.20 generates an appearance similar to granite, as shown in Figure 8.27.

Example 8.20 Granite Fragment Shader

```
#version 330 core

uniform sampler3D Noise;
uniform float NoiseScale;

in float LightIntensity;
in vec3  MCposition;

out vec4 FragColor;

void main()
{
   vec4 noisevec   = texture(Noise, NoiseScale * MCposition);
   float intensity = min(1.0, noisevec[3] * 18.0);
   vec3 color      = vec3(intensity * LightIntensity);
   FragColor       = vec4(color, 1.0);
}
```

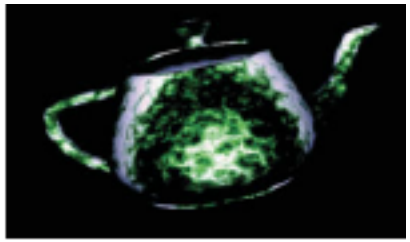


Marble

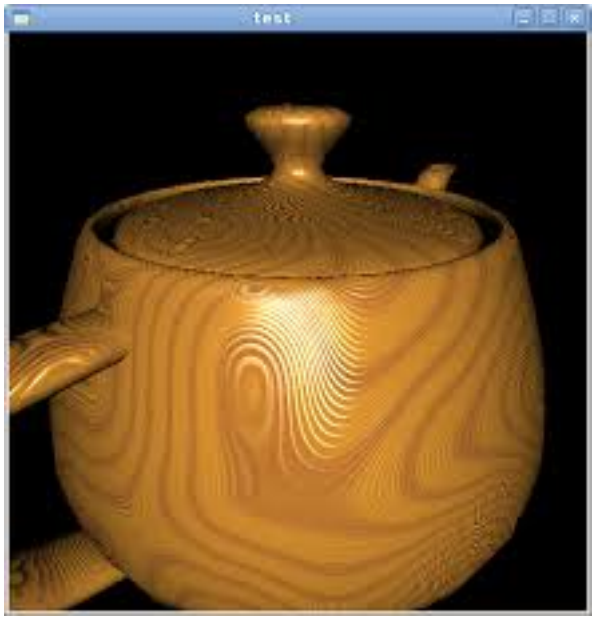
Example 8.19 Fragment Shader for Marble

```
#version 330 core

uniform sampler3D Noise;
uniform vec3 MarbleColor;
uniform vec3 VeinColor;

in float LightIntensity;
in vec3  MCposition;

out vec4 FragColor;


void main()
{
   vec4 noisevec = texture(Noise, MCposition);
   float intensity = abs(noisevec[0] - 0.25) +
                     abs(noisevec[1] - 0.125) +
                     abs(noisevec[2] - 0.0625) +
                     abs(noisevec[3] - 0.03125);
   float sineval = sin(MCposition.y * 6.0 + intensity * 12.0)
                       * 0.5 + 0.5;
   vec3 color    = mix(VeinColor, MarbleColor, sineval)
                       * LightIntensity;
   FragColor     = vec4(color, 1.0);
}
```

Yet another variation on the noise function is to use it as part of a periodic function such as sine. By adding noise to the input value for the sine function, we get a "noisy" oscillating function. We use this to create a look similar to the alternating color veins of some types of marble. Example 8.19 shows the fragment shader to do it. Again, we use the same vertex shader. Results of this shader are also shown in Figure 8.27.



Wood



Wood

LightPos	0.0, 0.0, 4.0
Scale	2.0
LightWood	0.6, 0.3, 0.1
DarkWood	0.4, 0.2, 0.07
RingFreq	4.0
LightGrains	1.0
DarkGrains	0.0
GrainThreshold	0.5
NoiseScale	0.5, 0.1, 0.1
Noisiness	3.0
GrainScale	27.0

- Wood is composed of light and dark areas alternating in concentric cylinders surrounding a central axis.
- Noise is added to warp the cylinders to create a more natural-looking pattern.
- The center of the "tree" is taken to be the y axis.
- Throughout the wood, a high-frequency grain pattern gives the appearance of wood that has been sawed, exposing the open grain nature of the wood.

Wood

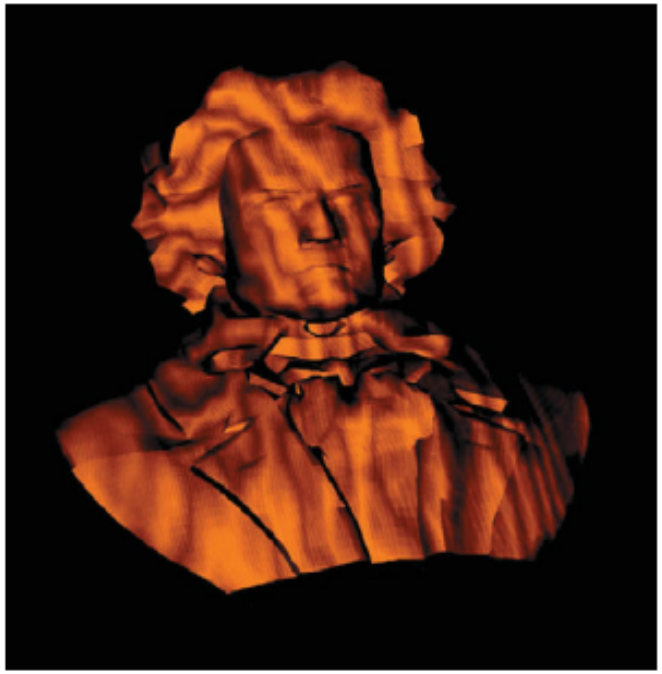


Figure 8.29 A bust of Beethoven rendered with the wood shader (3Dlabs, Inc.)

Example 8.21 Fragment Shader for Wood

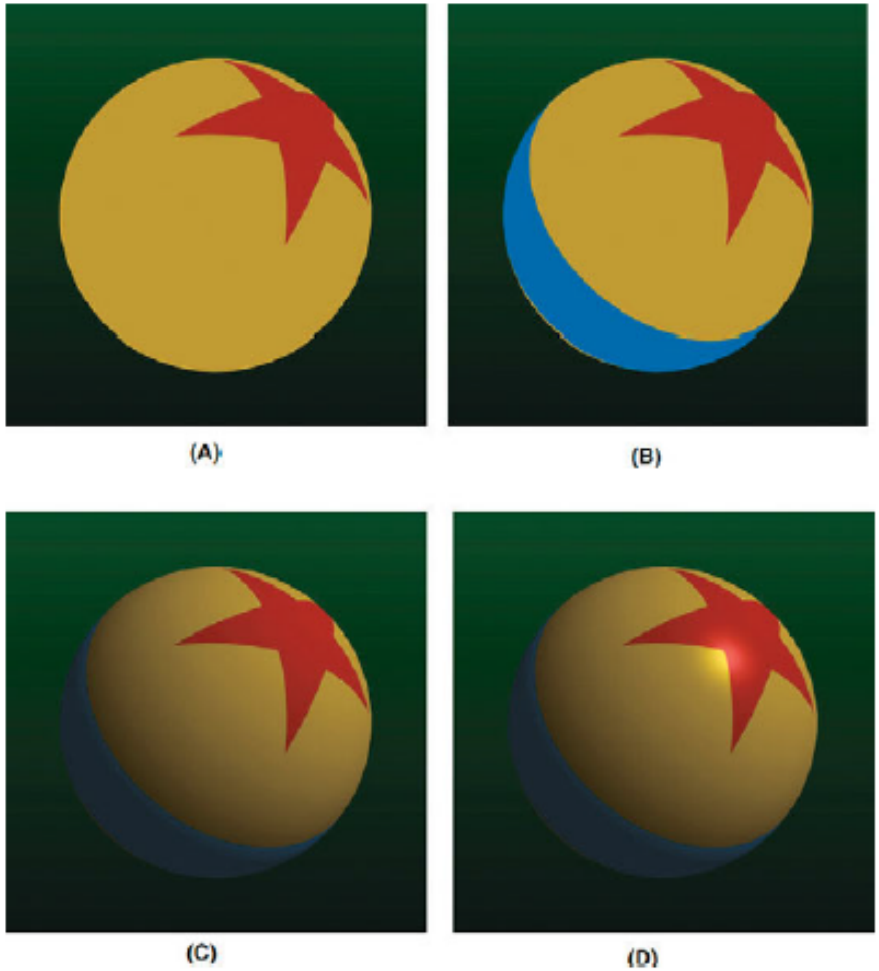
```
#version 330 core

uniform sampler3D Noise;
uniform vec3 LightWood;
uniform vec3 DarkWood;
uniform float RingFreq;
uniform float LightGrains;
uniform float DarkGrains;
uniform float GrainThreshold;
uniform vec3 NoiseScale;
uniform float Noisiness;
uniform float GrainScale;

in  float LightIntensity;
in  vec3  MCposition;

out vec4  FragColor;

void main()
{
   vec3 noisevec = vec3(texture(Noise, MCposition * NoiseScale) *
                                                  Noisiness);
   vec3 location = MCposition + noisevec;
   float dist = sqrt(location.x * location.x + location.z * location.z);
   dist *= RingFreq;
   float r = fract(dist + noisevec[0] + noisevec[1] + noisevec[2])
             * 2.0;
   if (r > 1.0)
       r = 2.0 - r;
   vec3 color = mix(LightWood, DarkWood, r);
   r = fract((MCposition.x + MCposition.z) * GrainScale + 0.5);
   noisevec[2] *= r;
   if (r < GrainThreshold)
       color += LightWood * LightGrains * noisevec[2];
   else
       color -= LightWood * DarkGrains * noisevec[2];
   color *= LightIntensity;
   FragColor = vec4(color, 1.0);
}
```

Wood

Example 8.21 Fragment Shader for Wood

```
#version 330 core

uniform sampler3D Noise;
uniform vec3 LightWood;
uniform vec3 DarkWood;
uniform float RingFreq;
uniform float LightGrains;
uniform float DarkGrains;
uniform float GrainThreshold;
uniform vec3 NoiseScale;
uniform float Noisiness;
uniform float GrainScale;

in  float LightIntensity;
in  vec3  MCposition;

out vec4  FragColor;

void main()
{
   vec3 noisevec = vec3(texture(Noise, MCposition * NoiseScale) *
                                                Noisiness);
   vec3 location = MCposition + noisevec;
   float dist = sqrt(location.x * location.x + location.z * location.z);
   dist *= RingFreq;
   float r = fract(dist + noisevec[0] + noisevec[1] + noisevec[2])
             * 2.0;
   if (r > 1.0)
       r = 2.0 - r;
   vec3 color = mix(LightWood, DarkWood, r);
   r = fract((MCposition.x + MCposition.z) * GrainScale + 0.5);
   noisevec[2] *= r;
   if (r < GrainThreshold)
       color += LightWood * LightGrains * noisevec[2];
   else
       color -= LightWood * DarkGrains * noisevec[2];
   color *= LightIntensity;
   FragColor = vec4(color, 1.0);
}
```

ToyBall



Fragment Shader - TB

Example 8.7 Fragment Shader for Drawing a Toy Ball

```
#version 330 core

uniform vec4  HalfSpace[5]; // half-spaces used to define star pattern
uniform float StripeWidth;
uniform float InOrOutInit;  // -3.0
uniform float FWidth;       // = 0.005

uniform vec4  StarColor;
uniform vec4  StripeColor;
uniform vec4  BaseColor;

uniform vec4  LightDir;     // light direction, should be normalized
uniform vec4  HVector;      // reflection vector for infinite light
```

ToyBall

Example 8.7 Fragment Shader for Drawing a Toy Ball

```
#version 330 core

uniform vec4  HalfSpace[5]; // half-spaces used to define star pattern
uniform float StripeWidth;
uniform float InOrOutInit;  // -3.0
uniform float FWidth;       // = 0.005

uniform vec4  StarColor;
uniform vec4  StripeColor;
uniform vec4  BaseColor;

uniform vec4  LightDir;     // light direction, should be normalized
uniform vec4  HVector;      // reflection vector for infinite light
```

Fragment Shader

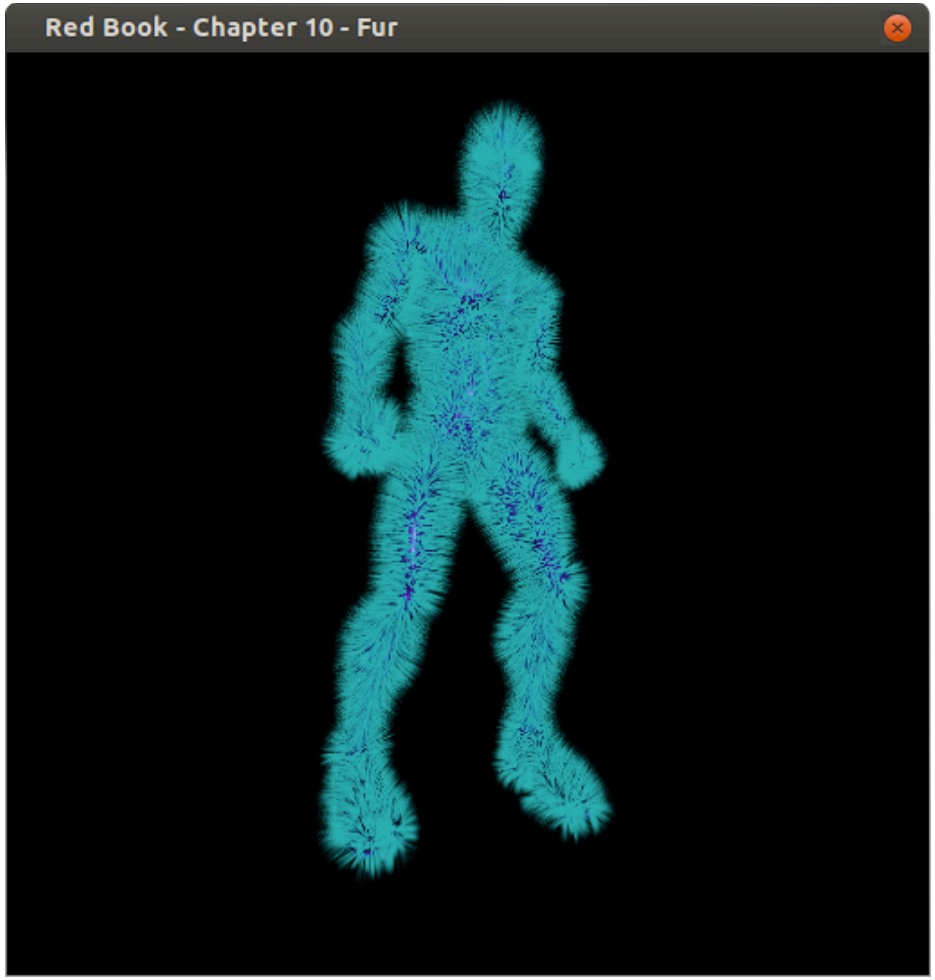
```
uniform vec4  SpecularColor;
uniform float SpecularExponent;

uniform float Ka;
uniform float Kd;
uniform float Ks;

      in vec4  ECPosition;   // surface position in eye coordinates
      in vec3  OCPosition;   // surface position in object coordinates
flat in vec4  ECBallCenter; // ball center in eye coordinates

out vec4 FragColor;

void main()
{
    vec3  normal;           // Analytically computed normal
    vec4  pShade;           // Point in shader space
    vec4  surfColor;        // Computed color of the surface
    float intensity;        // Computed light intensity
    vec4  distance;         // Computed distance values
    float inorout;          // Counter for classifying star pattern

    pShade.xyz  = normalize(OCPosition.xyz);
    pShade.w    = 1.0;

    inorout     = InOrOutInit;     // initialize inorout to -3.0

    distance[0] = dot(pShade, HalfSpace[0]);
    distance[1] = dot(pShade, HalfSpace[1]);
    distance[2] = dot(pShade, HalfSpace[2]);
    distance[3] = dot(pShade, HalfSpace[3]);

    //float FWidth = fwidth(pShade);
    distance    = smoothstep(-FWidth, FWidth, distance);

    inorout     += dot(distance, vec4(1.0));

    distance.x  = dot(pShade, HalfSpace[4]);
    distance.y  = StripeWidth - abs(pShade.z);
    distance.xy = smoothstep(-FWidth, FWidth, distance.xy);
    inorout     += distance.x;

    inorout     = clamp(inorout, 0.0, 1.0);

    surfColor   = mix(BaseColor, StarColor, inorout);
    surfColor   = mix(surfColor, StripeColor, distance.y);

    // Calculate analytic normal of a sphere
    normal      = normalize(ECPosition.xyz-ECBallCenter.xyz);

    // Per-fragment diffuse lighting
    intensity  = Ka; // ambient
    intensity += Kd * clamp(dot(LightDir.xyz, normal), 0.0, 1.0);
```

Chapter 8: Procedural Texturing

Fragment Shader

```
    surfColor *= intensity;

    // Per-fragment specular lighting
    intensity  = clamp(dot(HVector.xyz, normal), 0.0, 1.0);
    intensity  = Ks * pow(intensity, SpecularExponent);
    surfColor.rgb += SpecularColor.rgb * intensity;
    FragColor = surfColor;
}
```

Fur



Furry Again

Figure 1. Fur Rendered Using the Shells and Fins Technique

Chapter 10

Geometry Shaders

THE OHIO STATE UNIVERSITY
DEPARTMENT OF
COMPUTER SCIENCE
AND ENGINEERING

Another Resource

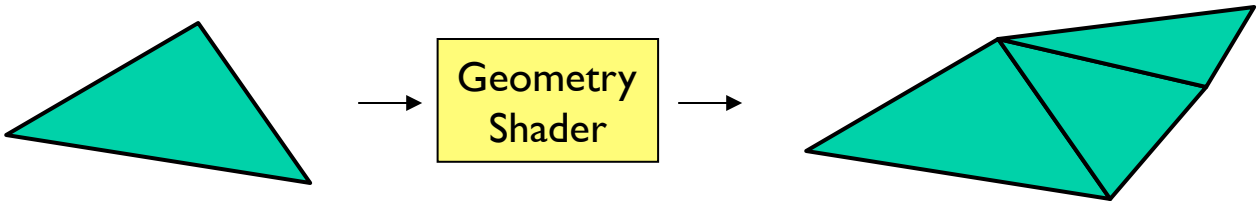
Section 4.6

developer.nvidia.com/object/gpu_programming_guide.html

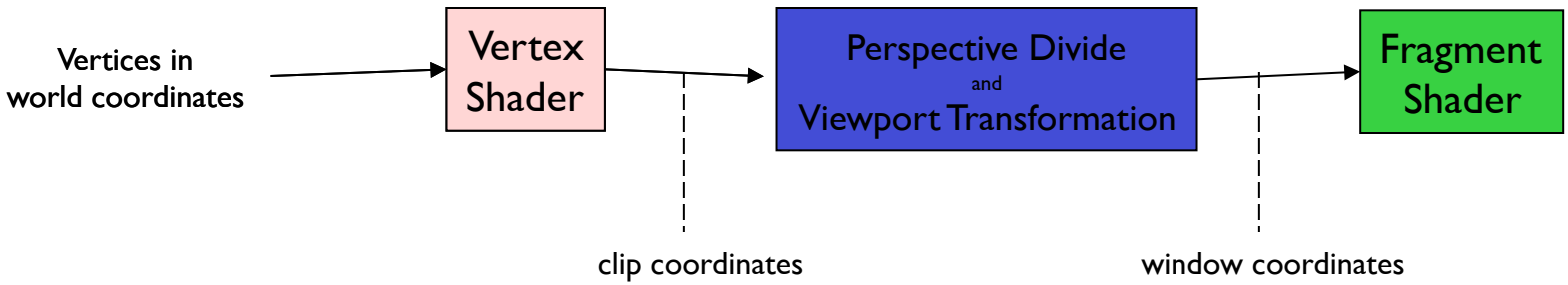
Yet Another Resource

Geometry Shaders

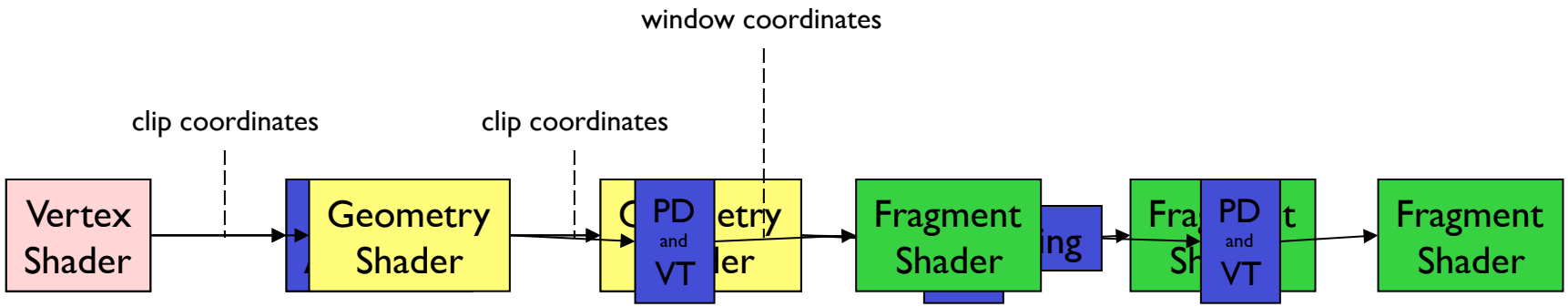
Create or destroy primitives on the GPU



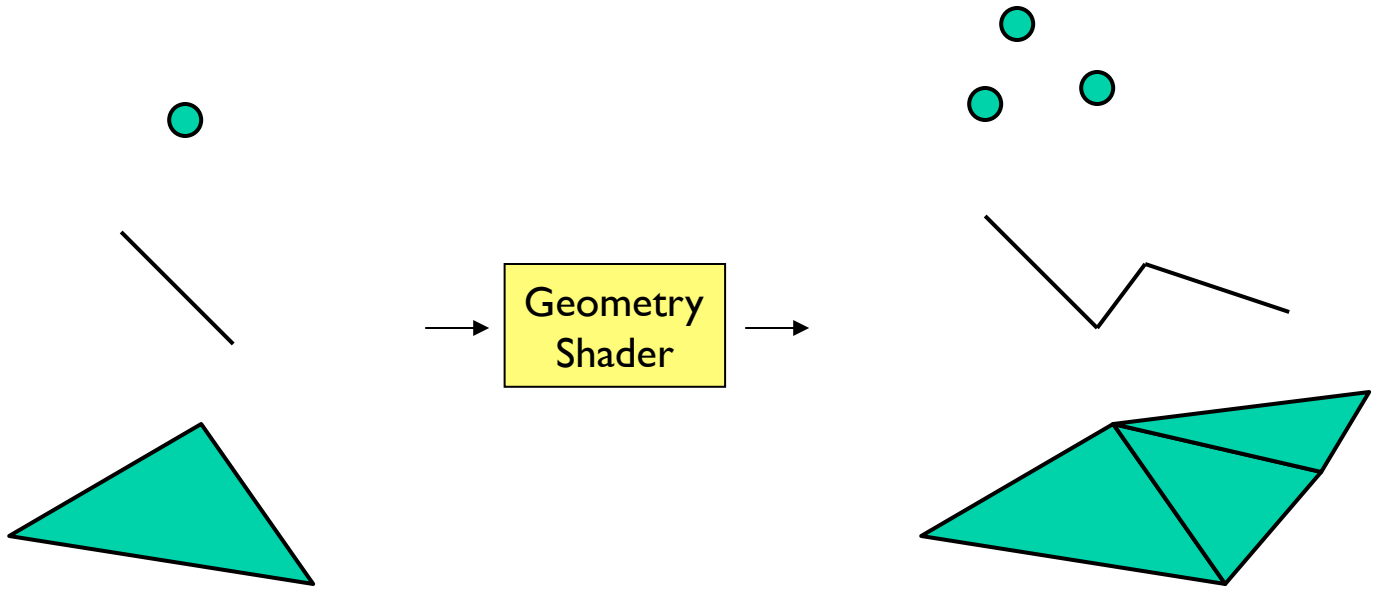
Geometry Shaders & Pipeline



Geometry Shaders & Pipeline



Primitive Types



Output primitives can be disconnected

Primitive Types

- Input Primitives
  - GL_POINTS
  - GL_LINES
  - GL_TRIANGLES
  - Adjacency
- Output Primitives
  - GL_POINTS
  - GL_LINE_STRIP
  - GL_TRIANGLE_STRIP

More Primitives

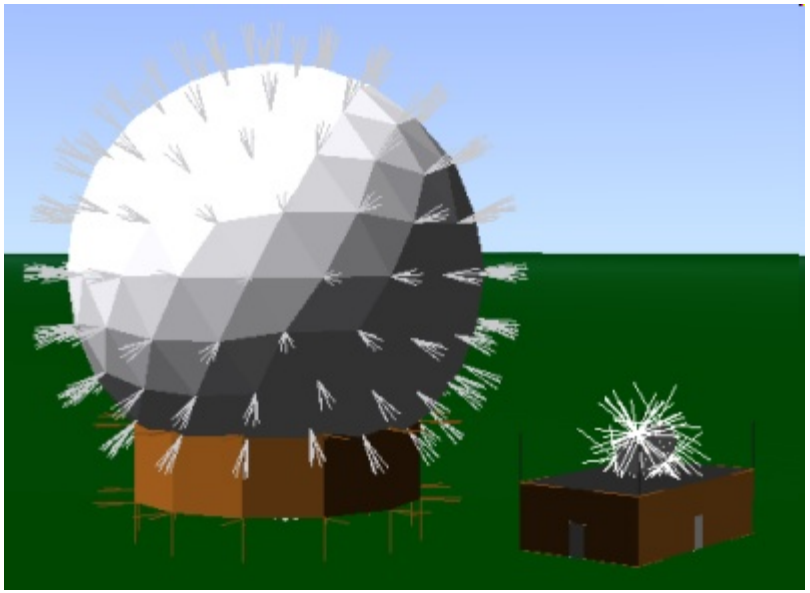
Table 10.1 Geometry Shader Primitive Types and Accepted Drawing Modes

Geometry Shader Primitive Type	Accepted Drawing Command Modes
`points`	GL_POINTS, GL_PATCHES[1]
`lines`	GL_LINES, GL_LINE_STRIP, GL_LINE_LOOP, GL_PATCHES[1]
`triangles`	GL_TRIANGLES, GL_TRIANGLE_STRIP GL_TRIANGLE_FAN, GL_PATCHES[1]
`lines_adjacency`[2]	GL_LINES_ADJACENCY, GL_LINE_STRIP_ADJACENCY
`triangles_adjacency`[2]	GL_TRIANGLES_ADJACENCY, GL_TRIANGLE_STRIP_ADJACENCY

Important …

Input primitive type is NOT same as output primitive type

blogs.agi.com/insight3d/index.php/2008/10/23/geometry-shader-for-debugging-normals/



Geometry Shaders

NOP – Do Nothing

Example 10.1 A Simple Pass-Through Geometry Shader

```
// This is a very simple pass-through geometry shader
#version 330 core

// Specify the input and output primitive types, along
// with the maximum number of vertices that this shader
// might produce. Here, the input type is triangles and
// the output type is triangle strips.
layout (triangles) in;
layout (triangle_strip, max_vertices = 3) out;

// Geometry shaders have a main function just
// like any other type of shader
```

NOP – Do Nothing

```
void main()
{
     int n;

     // Loop over the input vertices
     for (n = 0; n < gl_in.length(); n++)
     {
          // Copy the input position to the output
          gl_Position = gl_in[0].gl_Position;
          // Emit the vertex
          EmitVertex();
     }
     // End the primitive. This is not strictly necessary
     // and is only here for illustrative purposes.
     EndPrimitive();
}
```

Do Nothing

Example 10.5 A Geometry Shader that Drops Everything

```
#version 330 core

layout (triangles) in;
layout (triangle_strip, max_vertices = 3) out;

void main()
{
    /* Do nothing */
}
```

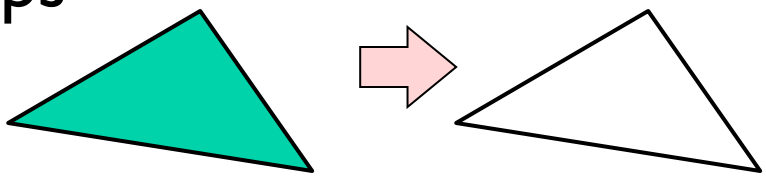
Do Filtering

Example 10.6 Geometry Shader Passing Only Odd-Numbered Primitives

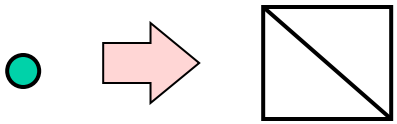
```
#version 330 core

layout (triangles) in;
layout (triangle_strip, max_vertices = 3) out;

void main()
{
    int n;

    // Check the LSB of the primitive ID.
    // If it's set, emit a primitive.
    if (gl_PrimitiveIDIn & 1)
    {
        for (n = 0; n < gl_in.length(); ++n)
        {
            gl_Position = gl_in[n].gl_Position;
            EmitVertex();
        }
        EndPrimitive();
    }
}
```

Other Possibilities

- Implement glPolygonMode
  - Triangles Points or Line Strips



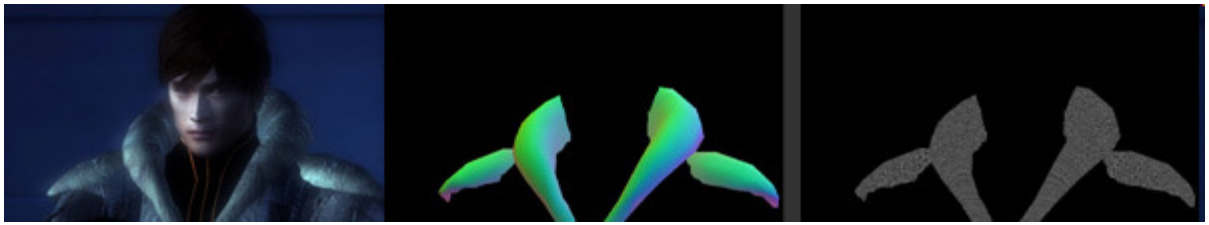
- Emulate GL_ARB_point_sprite
  - Points Triangle Strips



Applications

- Displacement Mapping
- Extrusions
  - Shadow volumes
  - Fins along silhouettes for fur rendering

Fur



color angle length

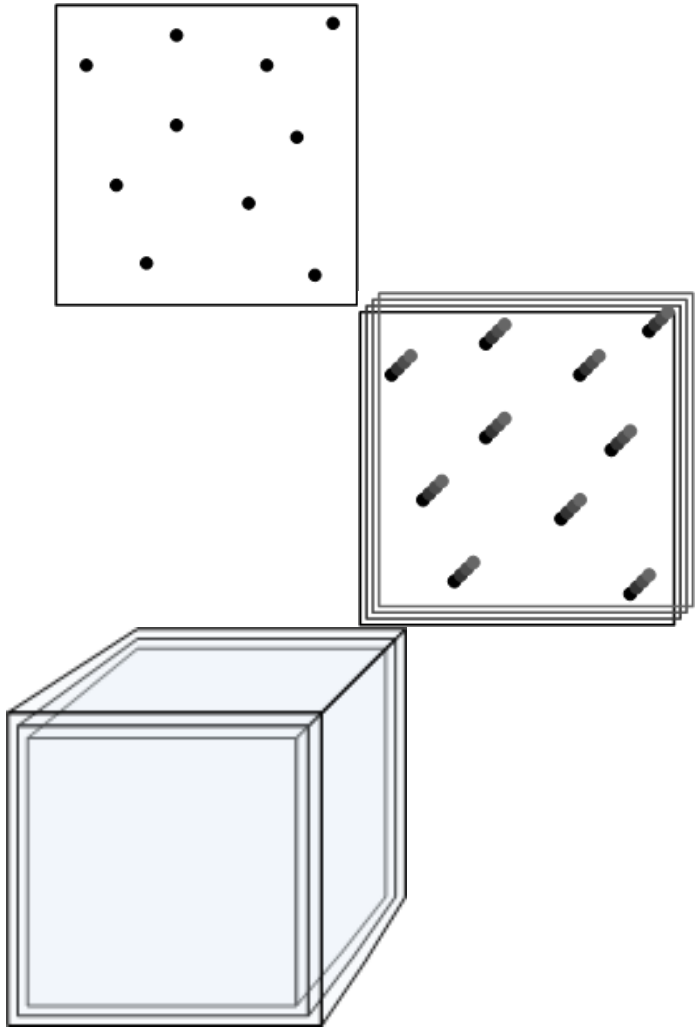
Images from meshula.net/wordpress/?p=124

Rendering Fur

- Rendering fur/hair hard given the number
- Geometry shader techniques used
  - Face performance issues
- Or render the fur as a set of *cross-sections*
- Layering cross-sections to form final effect

Fur Shells

- Create a texture for fur cross-section
  - Some randomly scattered pixels
- Render same geometry several times using texture
  - Use geometry shader
  - Only draw hairs, elsewhere transparent
- Each render of geometry slightly expanded
  - Layering fur cross-section over entire geometry



Fur Premise

Shells are rendered by extruding the model outwards and texturing it with progressively higher slices from a 3D fur texture

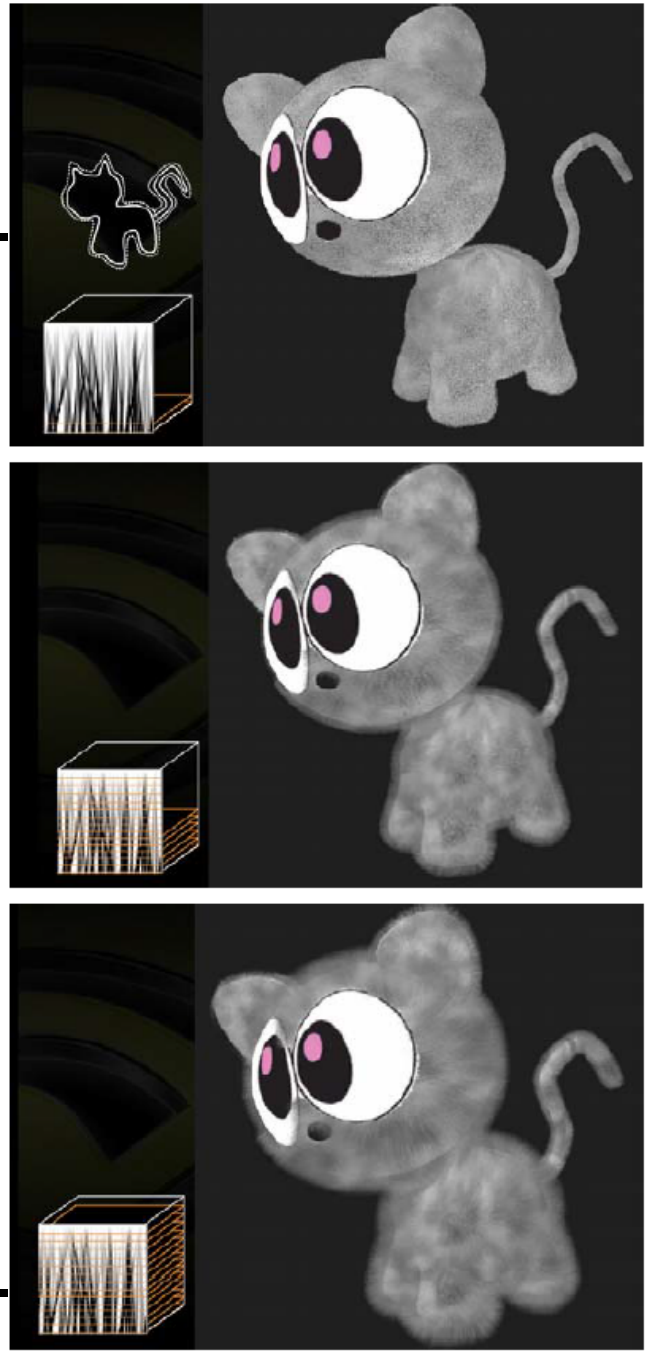
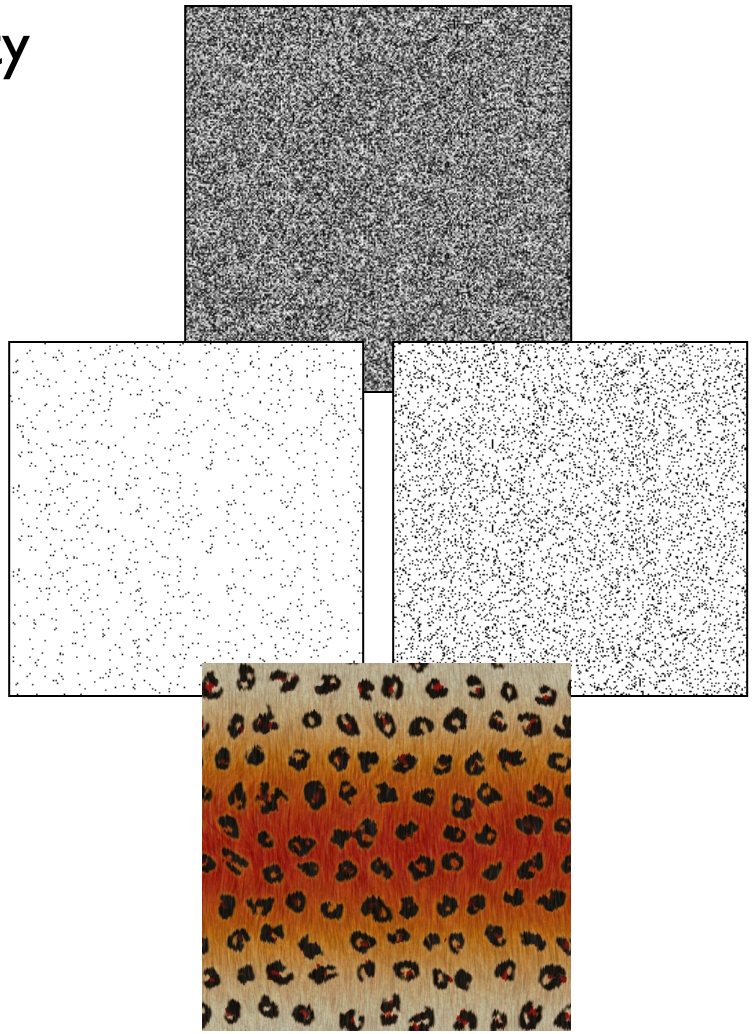


Figure 2. Rendering Shells

Creating Hairs

- Alter random pixels to change fur density
  - Implies new texture for each density
- Use noise texture for the hairs
- Compare the noise pixel to the density
  - If less, draw that pixel
  - Otherwise don't (discard)
- Hairs are colored & lit with a standard diffuse/specular map



Shadowing

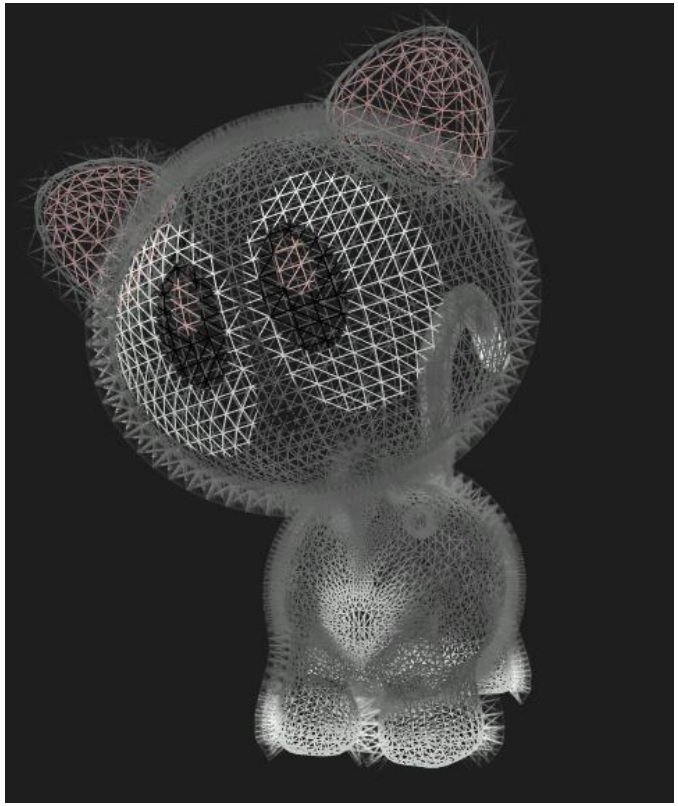
- Draw inner-most shell solid
- However, effect is not yet ideal:
  - Fur should cast shadows
  - Complex to do this properly
- Or make deeper shells darker
  - Reduce light received by lower shells
- Inner-most shell reduced by 0.5-0.75, outer-most shell unchanged

Varying Length & Density

- Vary overall length of hair by expanding shells
- Vary density with noise texture as described
- Both settings can be controlled *per-pixel* using another texture
  - Store a special texture containing per-pixel fur data:
    - Red component stores length
    - Green stores density
  - Use shader work to utilise data
- Define patches of long/thin/no hair

Fur & Geometry Shaders

- Shells generated using geometry shader
- F***ins*** sticking out at silhouette edges:
  - Improves fur silhouette where shells are less effective
  - Can reduce number of shells



In GLSL

Creating Geometry Shaders

GLuint glCreateShader(GLenum shaderType);

https://www.opengl.org/sdk/docs/man3/xhtml/glCreateShader.xml

http://cirl.missouri.edu/gpu/glsl_lessons/glsl_geometry_shader/

http://www.geeks3d.com/20111111/simple-introduction-to-geometry-shaders-glsl-opengl-tutorial-part1/

Details

Example 10.7 Fur Rendering Geometry Shader

```
// Fur rendering geometry shader
#version 330 core

// Triangles in, triangles out, large max_vertices as we're amplifying
layout (triangles) in;
layout (triangle_strip, max_vertices = 120) out;

uniform mat4 model_matrix;
uniform mat4 projection_matrix;

// The number of layers in the fur volume and the depth of the volume
uniform int fur_layers = 30;
uniform float fur_depth = 5.0;

// Input from the vertex shader
in VS_GS_VERTEX
{
   vec3 normal;
   vec2 tex_coord;
} vertex_in[];

// Output to the fragment shader
out GS_FS_VERTEX
{
   vec3 normal;
   vec2 tex_coord;
   flat float fur_strength;
} vertex_out;

void main()
{
   int i, layer;
   // The displacement between each layer
   float disp_delta = 1.0 / float(fur_layers);
   float d = 0.0;

   // For each layer...
   for (layer = 0; layer < fur_layers; layer++)
   {
       // For each incoming vertex (should be three of them)
       for (i = 0; i < gl_in.length(); i++) {
           // Get the vertex normal
```

```
            vec3 n = vertex_in[i].normal;
            // Copy it to the output for use in the fragment shader
            vertex_out.normal = n;
            // Copy the texture coordinate too - we'll need that to
            // fetch from the fur texture
            vertex_out.tex_coord = vertex_in[i].tex_coord;
            // Fur "strength" reduces linearly along the length of
            // the hairs
            vertex_out.fur_strength = 1.0 - d;
            // This is the core - displace each vertex along its normal
            // to generate shells
            position = gl_in[i].gl_Position +
                       vec4(n * d * fur_depth, 0.0);
            // Transform into place and emit a vertex
            gl_Position = projection_matrix * (model_matrix * position);
            EmitVertex();
        }
        // Move outwards by our calculated delta
        d += disp_delta;
        // End the "strip" ready for the next layer
        EndPrimitive();
    }
}
```

Frag Shader

Example 10.8 Fur Rendering Fragment Shader

```
// Fur rendering fragment shader
#version 330 core

// One output
layout (location = 0) out vec4 color;
```

Producing Primitives **529**

Frag Shader

```
// The fur texture
uniform sampler2D fur_texture;
// Color of the fur. Silvery gray by default...
uniform vec4 fur_color = vec4(0.8, 0.8, 0.9, 1.0);

// Input from the geometry shader
in GS_FS_VERTEX
{
   vec3 normal;
   vec2 tex_coord;
   flat float fur_strength;
} fragment_in;

void main()
{
   // Fetch from the fur texture. We'll only use the alpha channel
   // here, but we could easily have a color fur texture.
   vec4 rgba = texture(fur_texture, fragment_in.tex_coord);
   float t = rgba.a;
   // Multiply by fur strength calculated in the GS for the
   // current shell t *= fragment_in.fur_strength;
   // Scale fur color alpha by fur strength.
   color = fur_color * vec4(1.0, 1.0, 1.0, t);
}
```

Texture

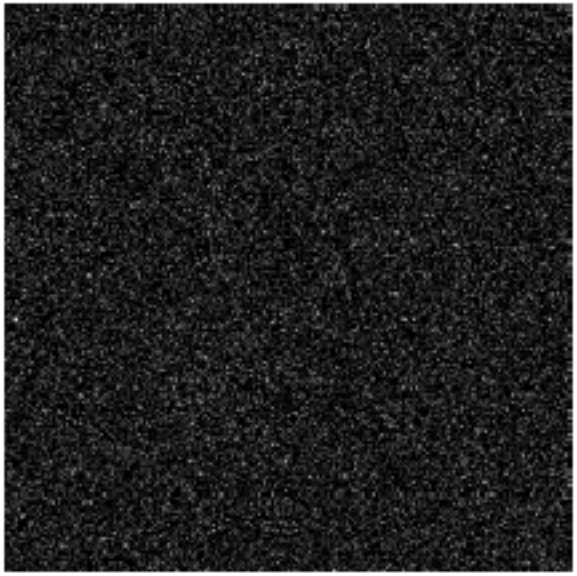


Figure 10.6 Texture used to represent hairs in the fur rendering example

Performance

Duplicates per-vertex operations for vertices shared by primitives

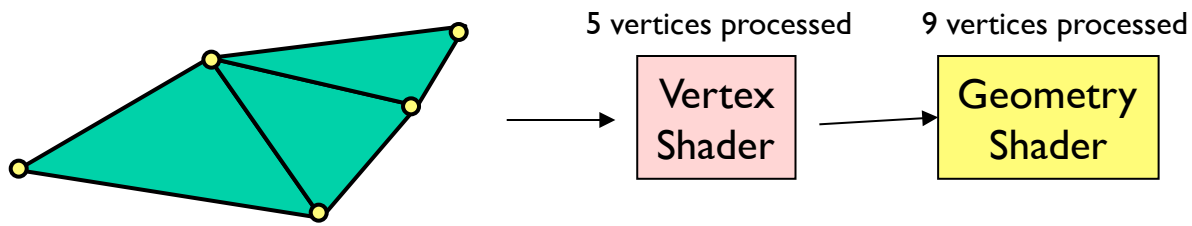
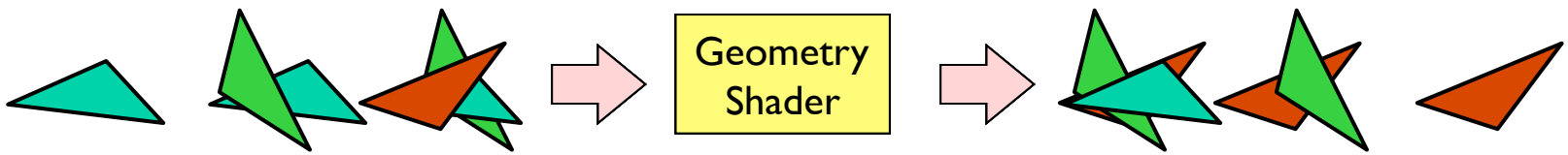


Table 10.2 Geometry Shader Primitives and the Vertex Count for Each

Primitive Type	Input Array Size
`points`	1
`lines`	2
`triangles`	3
`lines_adjacency`	4
`triangles_adjacency`	6

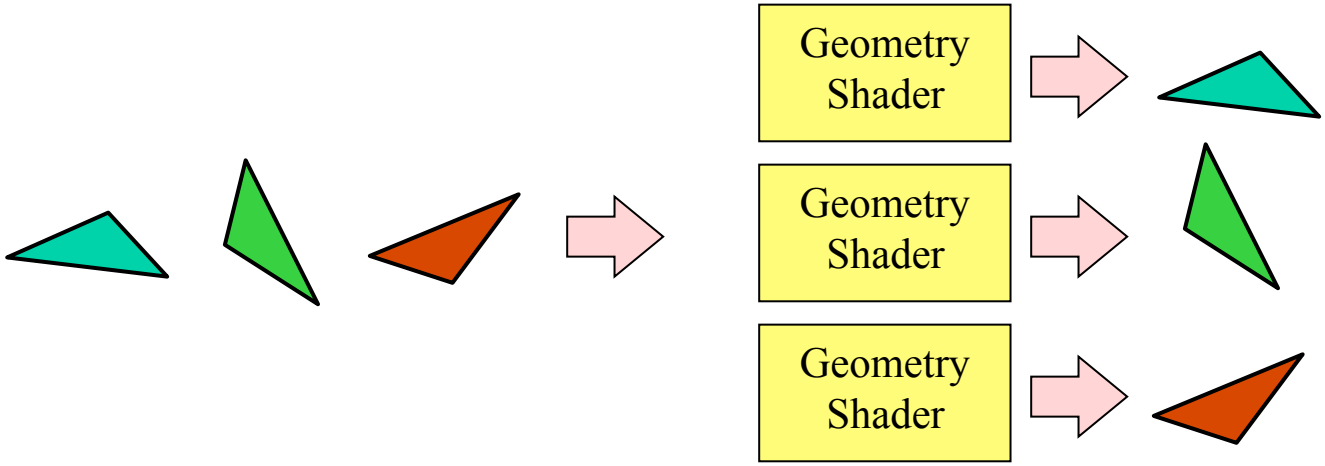
Performance

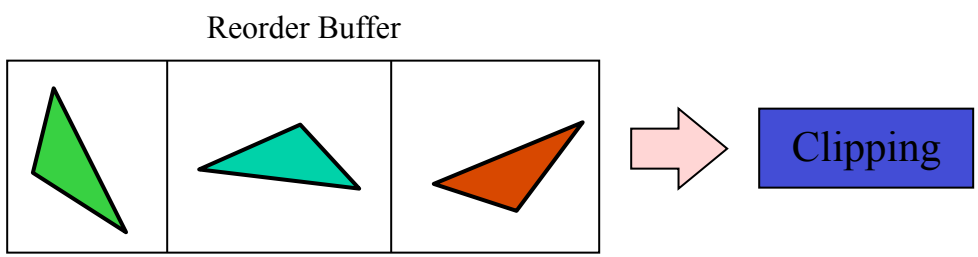
Must guarantee order in == order out



Performance

Order guarantee affects parallelism





Performance

Buffer size should support number of parallel threads

Performance

- Maximum number of vertices a GS will output:

  GEOMETRY_VERTICES_OUT_ARB

- Determines the speed of GS execution

- Make this and vertex sizes as small as possible

Performance

- Benefits
  - Reduces vertex buffer memory usage
    - Compute in GS, e.g. normals
    - Create more geometry
    - No need to duplicate (e.g. compared to equivalent VS implementation)
  - Less memory == less bus traffic
  - Reduces vertex attribute setup cost

Pros and Cons

- This is an effective, if simple technique:
  - Flexible
  - Decent looking
    - If you use enough shells or don't get too close
  - Can be efficient (low number of shells)

- However:
  - Can be slow if too many shells
  - Can look poor if too few
  - Can't manipulate hairs individually

- A good technique for short patches of hair or grass in a complex environment

This is The End

https://www.youtube.com/watch?v=JSUIQgEVDM4