BRDF Evolution

- BRDFs have evolved historically
- 1970’s: Empirical models
  - Phong’s illumination model
- 1980s:
  - Physically based models
  - Microfacet models (e.g. Cook Torrance model)
- 1990’s
  - Physically-based appearance models of specific effects (materials, weathering, dust, etc)
- Early 2000’s
  - Measurement & acquisition of static materials/lights (wood, translucence, etc)
- Late 2000’s
  - Measurement & acquisition of time-varying BRDFs (ripening, etc)

Physically-Based Shading Models

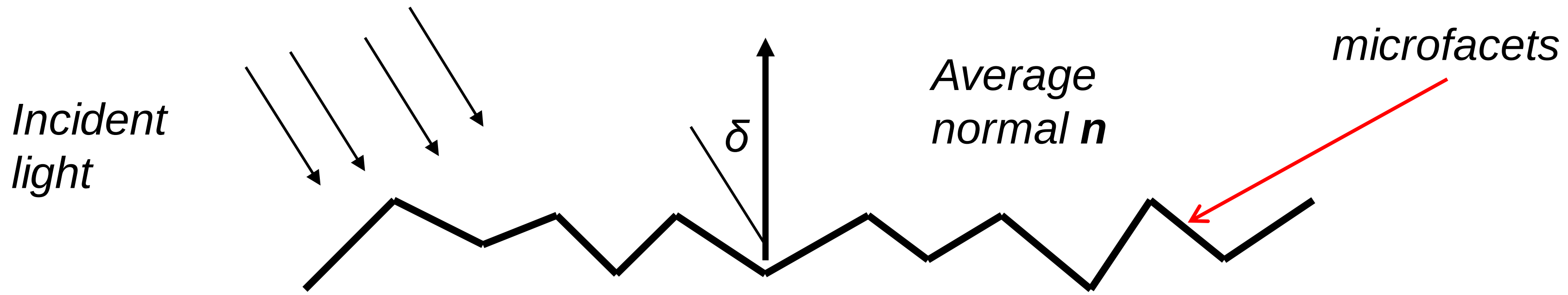
- Phong model produces pretty pictures
- **Cons:** empirical (fudged?) ($cos^{\alpha}\phi$), plastic look
- Shaders can implement better lighting/shading models
- Trend towards Physically-based lighting models
- Physically-based?
  - Based on physics of light, interactions with actual surface
  - Use Optics/Physics theories
- Classic: Cook-Torrance shading model (TOGS 1982)

Cook-Torrance Shading Model

- Ambient and diffuse terms same as Phong
- New, better specular component than ($cos^{\alpha}\phi$),

$$\cos^{\alpha}\phi \rightarrow \frac{F(\phi,\eta)DG}{(\mathbf{n}\cdot\mathbf{v})}$$

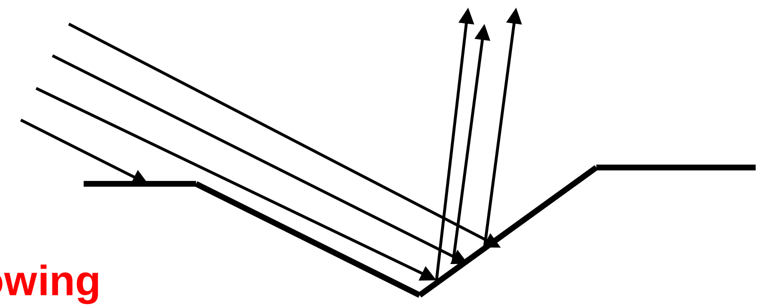
- **Idea:** surfaces has small V-shaped **microfacets (grooves)**



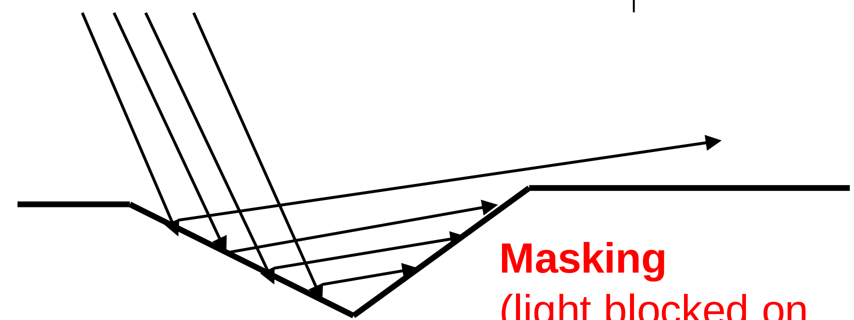
- Many grooves at each surface point
- **Distribution term D:** Grooves facing a direction contribute
- E.g. half of grooves face 30 degrees, etc
- **F term:** what fraction of light bounces off, depends on material, angle

Self-Shadowing (G Term)

- Grooves on very rough surface may block other grooves (shadowing & masking)



Shadowing
(light blocked on way into groove)

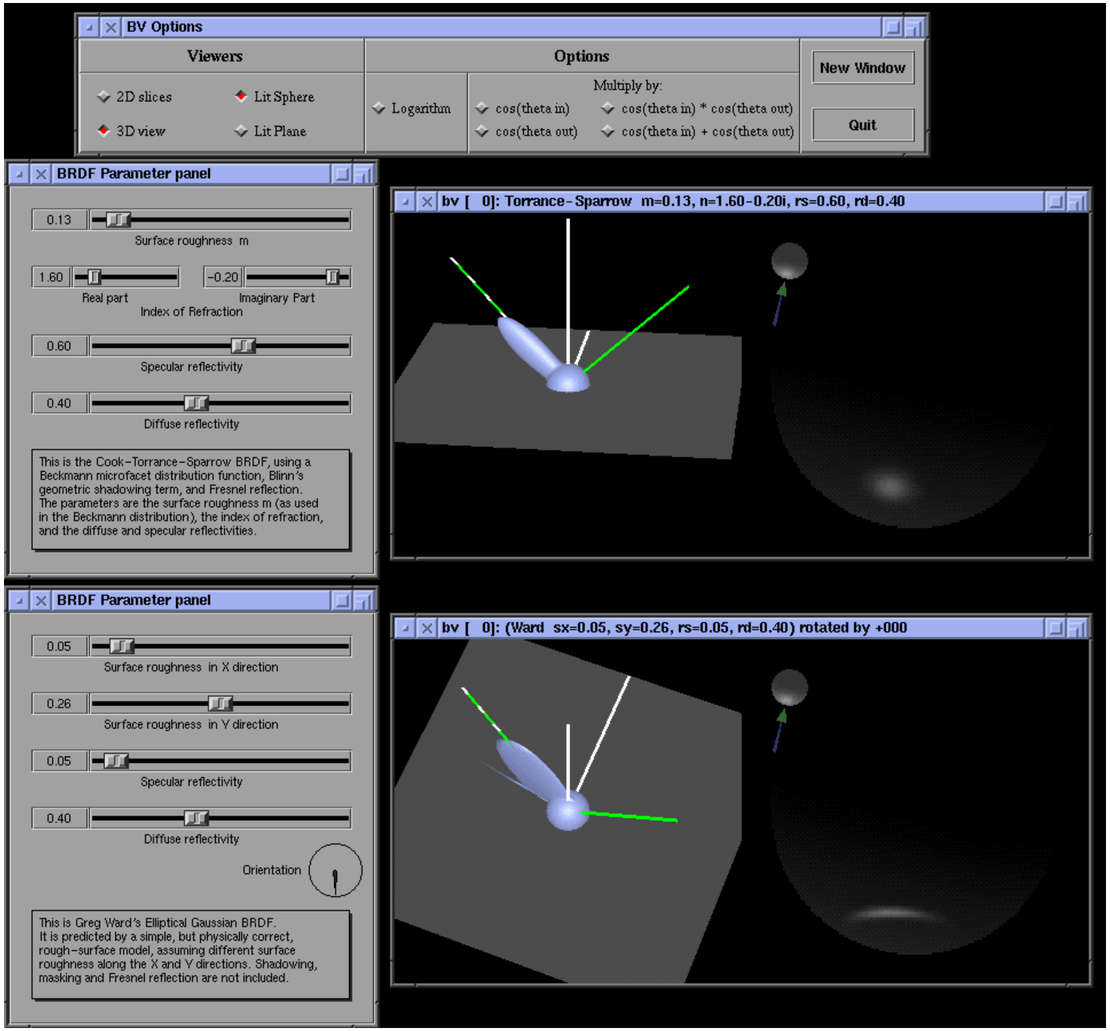


Masking
(light blocked on way out of groove)

$$\cos^{\alpha}\phi \rightarrow \frac{F(\phi,\eta)D\boxed{G}}{(\mathbf{n}\cdot\mathbf{v})}$$

BV BRDF (Surface Material) Viewer

Tool to visualize distribution of light bounce



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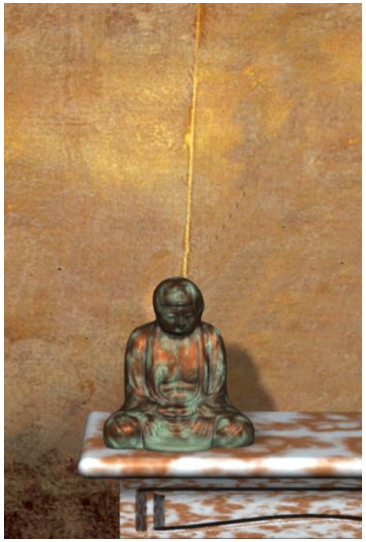
Appearance Example: Weathering

- Analytic model for weathering of stone, metals



Weathered Stone

Metallic Patina
(Weathering Effect)

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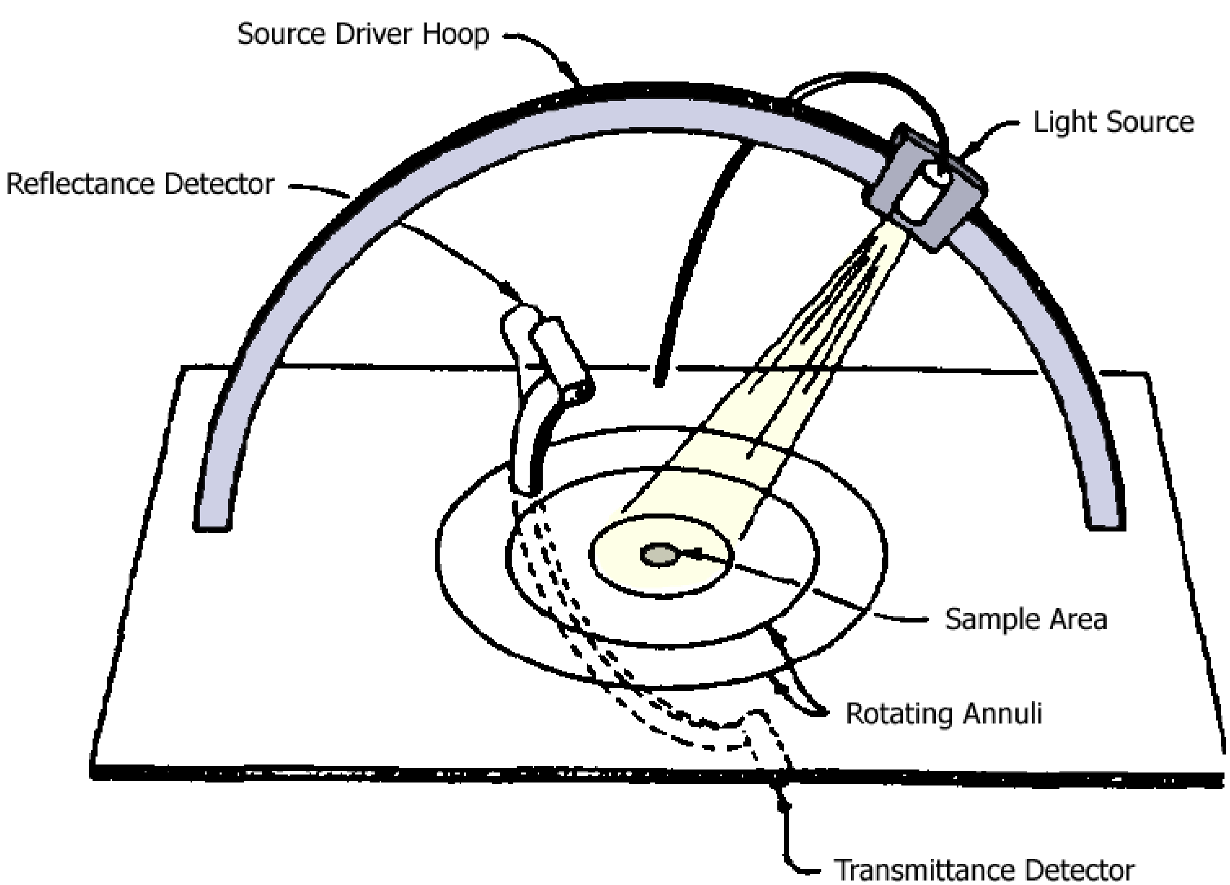
Measuring BRDFs (Surface Material)



Murray-Coleman and Smith Gonioreflectometer. (Copied and Modified from [Ward92]).

Measured BRDF (Surface Material) Samples

- Mitsubishi Electric Research Lab (MERL)

http://www.merl.com/brdf/

- Wojciech Matusik
- MIT PhD Thesis
- 100 Samples

BRDF (Surface Material) Evolution

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Time-varying BRDF (Surface Material)

- BRDF: How different materials reflect light
- Time varying?: how reflectance changes over time
- 

References

- Interactive Computer Graphics (6th edition), Angel and Shreiner
- Computer Graphics using OpenGL (3rd edition), Hill and Kelley

Computer Graphics (4731)
Lecture 17: Texturing

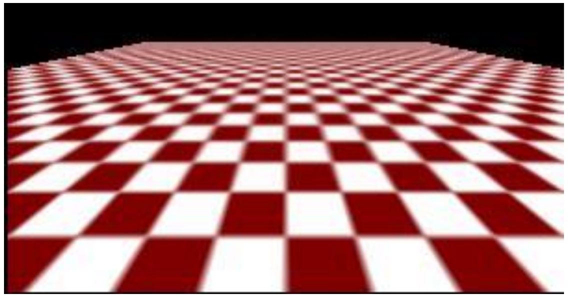
Prof Emmanuel Agu

Computer Science Dept.

Worcester Polytechnic Institute (WPI)

The Limits of Geometric Modeling

- Although graphics cards can render over 10 million polygons per second
- Many phenomena even more detailed
  - Clouds
  - Grass
  - Terrain
  - Skin
- **Images:** Computationally inexpensive way to add details



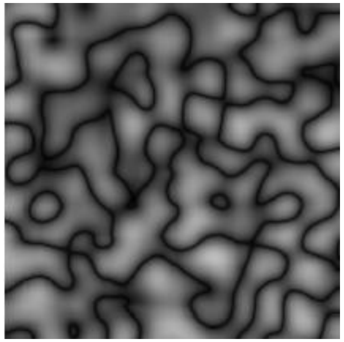
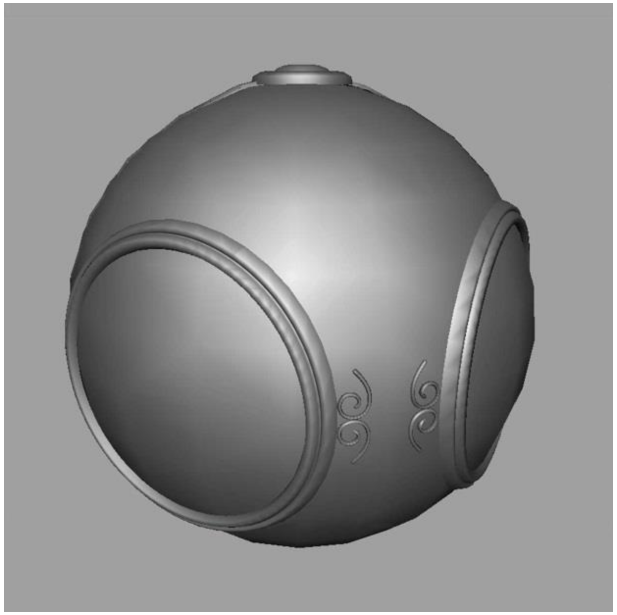


Image complexity does not affect the complexity of geometry processing (transformation, clipping…)

Textures in Games

- Mostly made of textures except foreground characters that require interaction
- Even details on foreground texture (e.g. clothes) is texture

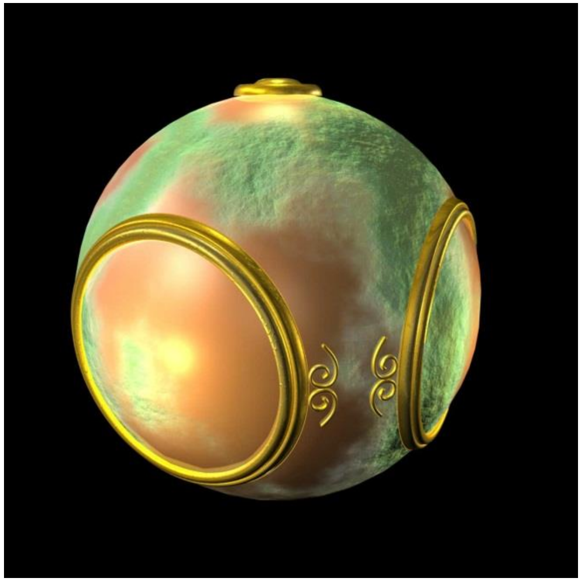
Types of Texturing



1. geometric model

2. texture mapped
Paste image (marble)
onto polygon

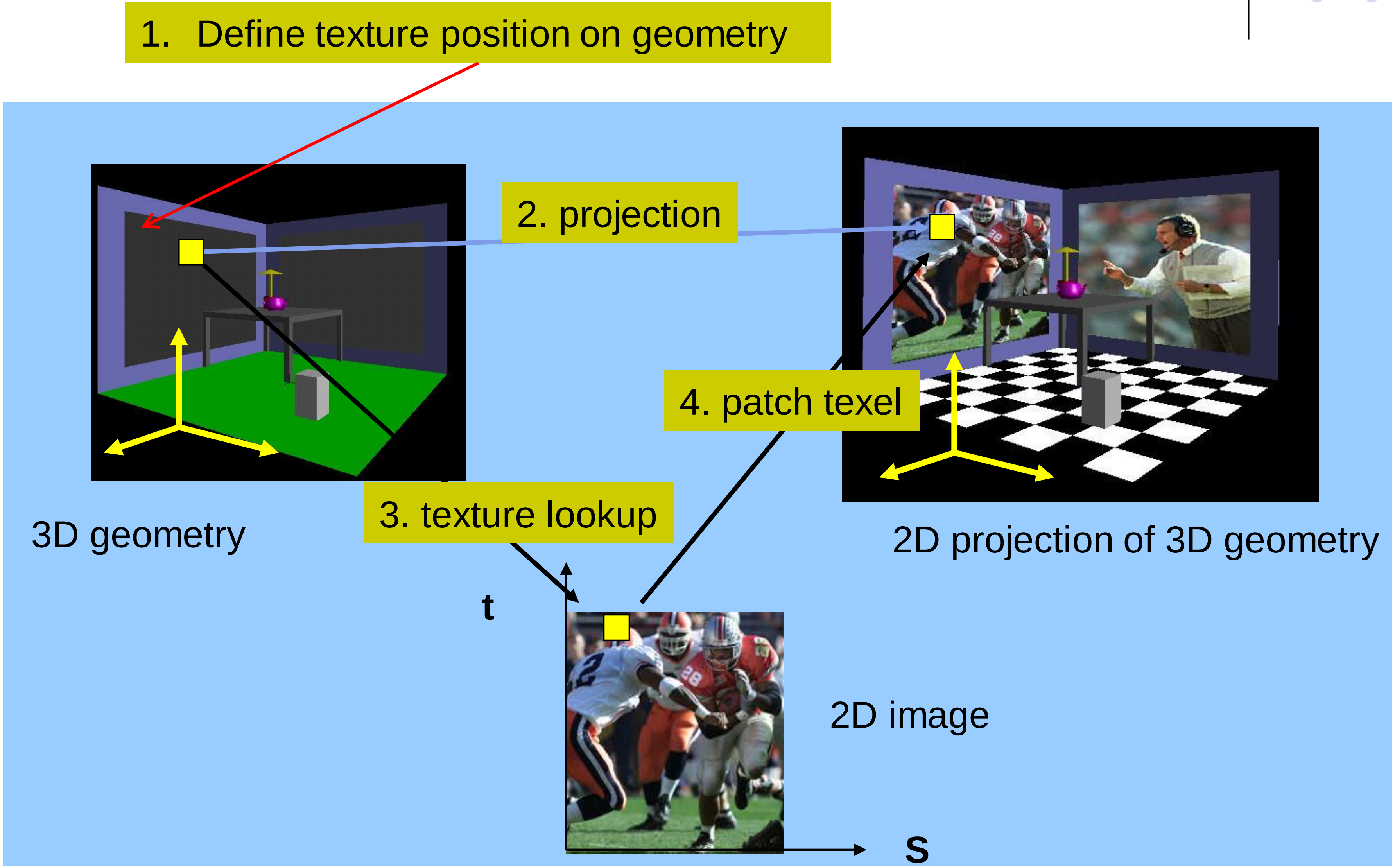
Types of Texturing



3. Bump mapping
Simulate surface roughness
(dimples)

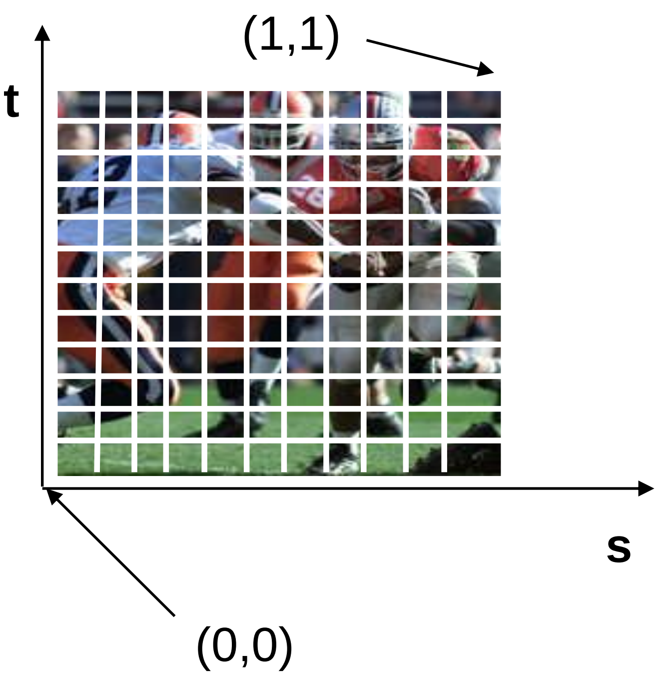
4. Environment mapping
Picture of sky/environment
over object

Texture Mapping



Texture Representation

- **Bitmap (pixel map) textures:** images (jpg, bmp, etc) loaded
- **Procedural textures:** E.g. fractal picture generated in OpenGL program
- Textures applied in shaders



Bitmap texture:

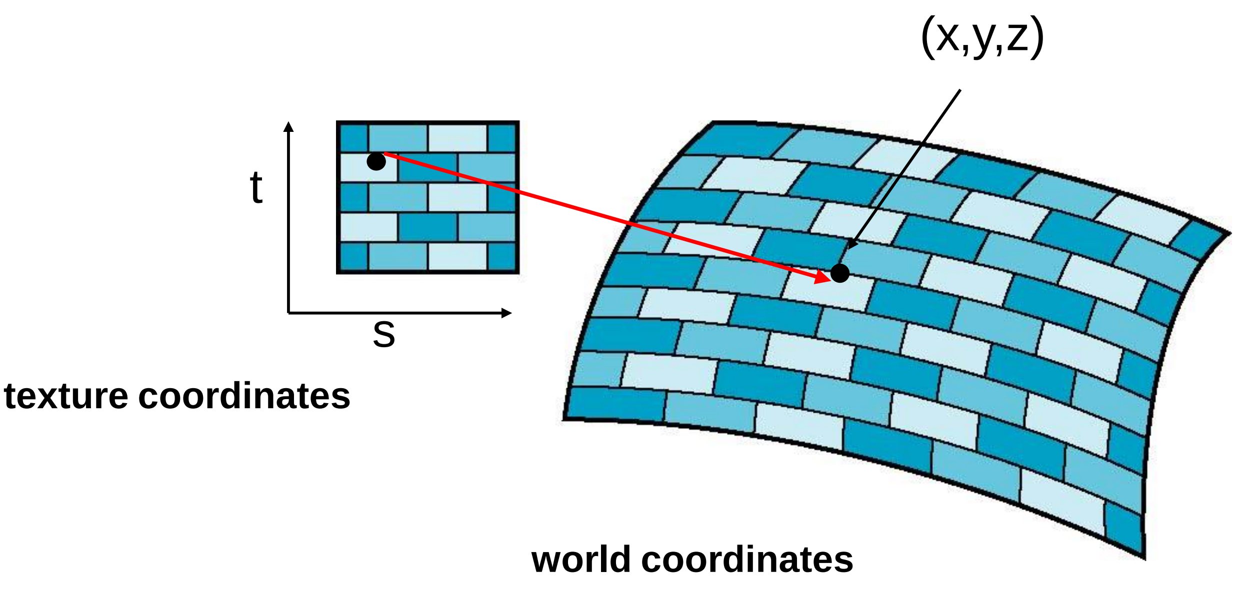
- 2D image - 2D array **texture[height][width]**
- Each element (or **texel**) has coordinate (s, t)
- s and t normalized to [0,1] range
- Any (s,t) => [red, green, blue] color

Texture Mapping

- Map? Each (x,y,z) point on object, has corresponding (s, t) point in texture

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

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



6 Main Steps to Apply Texture

1. Create texture object
2. Specify the texture
   - Read or generate image
   - assign to texture (hardware) unit
   - enable texturing (turn on)
3. Assign texture (corners) to Object corners
4. Specify texture parameters
   - wrapping, filtering
5. Pass textures to shaders
6. Apply textures in shaders

Step 1: Create Texture Object

- OpenGL has **texture objects** (multiple objects possible)
  - 1 object stores 1 texture image + texture parameters
- First set up texture object

```
GLuint mytex[1];
glGenTextures(1, mytex);                 // Get texture identifier
glBindTexture(GL_TEXTURE_2D, mytex[0]); // Form new texture object
```

- Subsequent texture functions use this object
- Another call to **`glBindTexture`** with new name starts new texture object

Step 2: Specifying a Texture Image

- Define picture to paste onto geometry
- Define texture image as array of ***texels*** in CPU memory

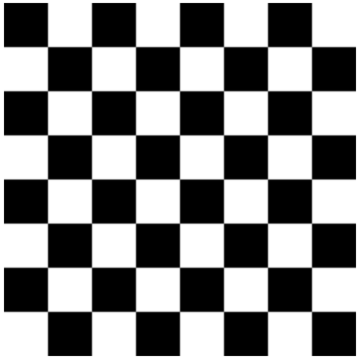
```
Glubyte my_texels[512][512][3];
```

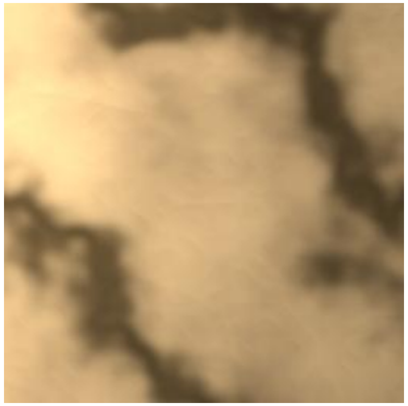
- Read in scanned images (jpeg, png, bmp, etc files)
  - If uncompressed (e.g bitmap): read from disk
  - If compressed (e.g. jpeg), use third party libraries (e.g. Qt, devil) to uncompress + load

bmp, jpeg, png, etc

Step 2: Specifying a Texture Image

- Procedural texture: generate pattern in application code





- Enable texture mapping
  - `glEnable(GL_TEXTURE_2D)`
  - OpenGL supports 1-4 dimensional texture maps

Specify Image as a Texture

Tell OpenGL: this image is a texture!!

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

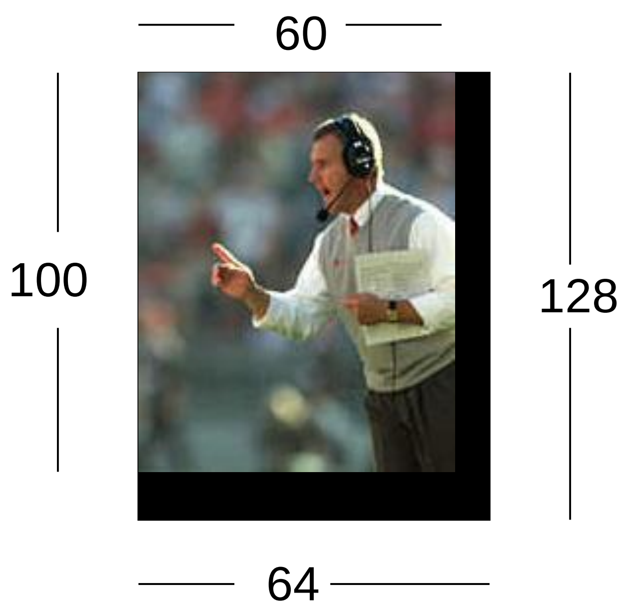
- `target:` type of texture, e.g. `GL_TEXTURE_2D`
- `level:` used for mipmapping (0: highest resolution. More later)
- `components:` elements per texel
- `w, h:` width and height of `texels` in pixels
- `border:` used for smoothing (discussed later)
- `format,type:` describe texels
- `texels:` pointer to texel array

Example:

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

Fix texture size

- OpenGL textures must be power of 2
- If texture dimensions not power of 2, either
  1) Pad zeros 2) Scale the Image



6 Main Steps. Where are we?

1. Create texture object
2. Specify the texture
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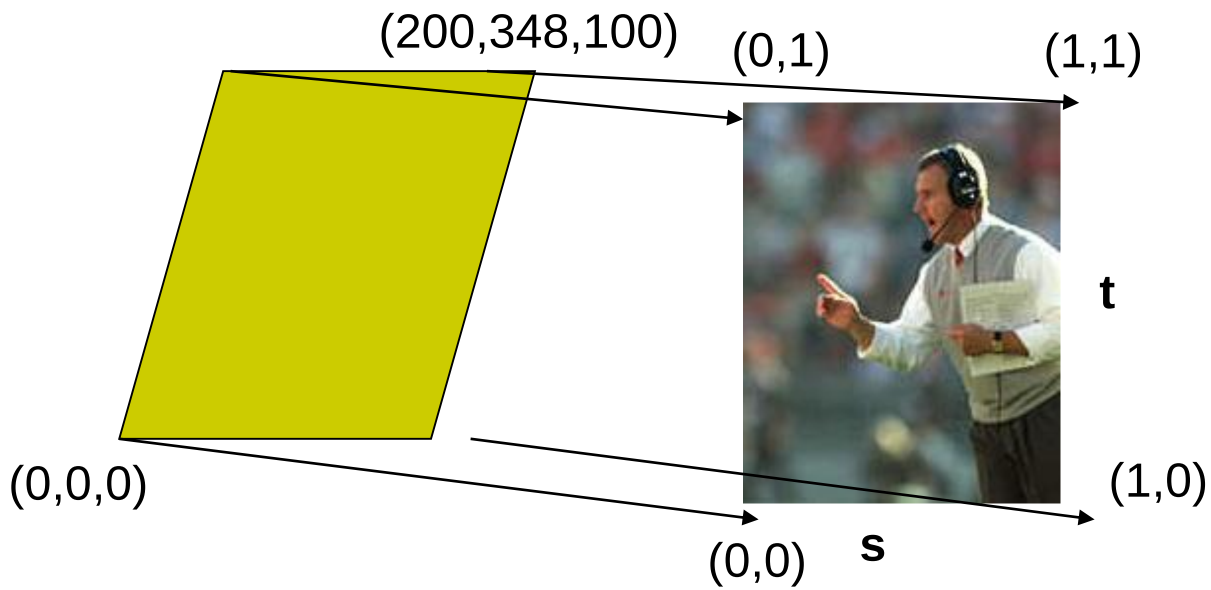
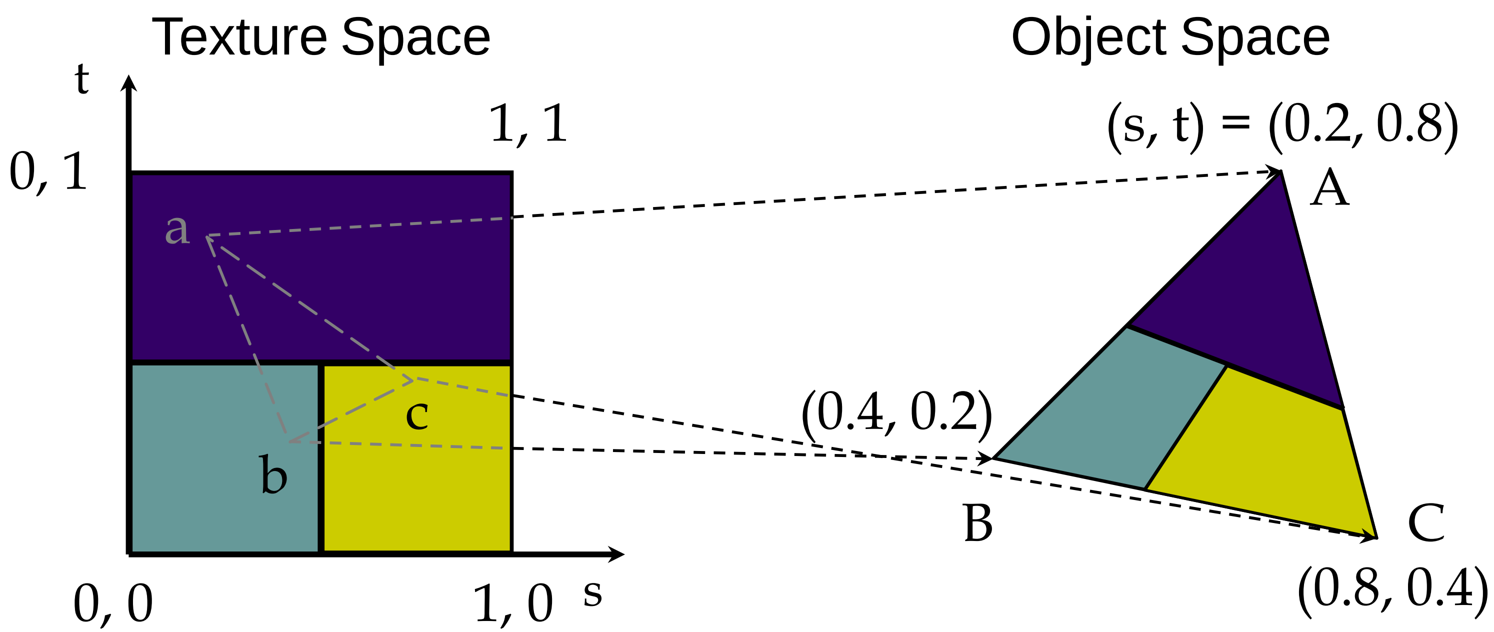
Step 3: Assign Object Corners to Texture Corners

- Each object corner (x,y,z) => image corner (s, t)
  - E.g. object (200,348,100) => (1,1) in image
- Programmer establishes this mapping



Step 3: Assigning Texture Coordinates

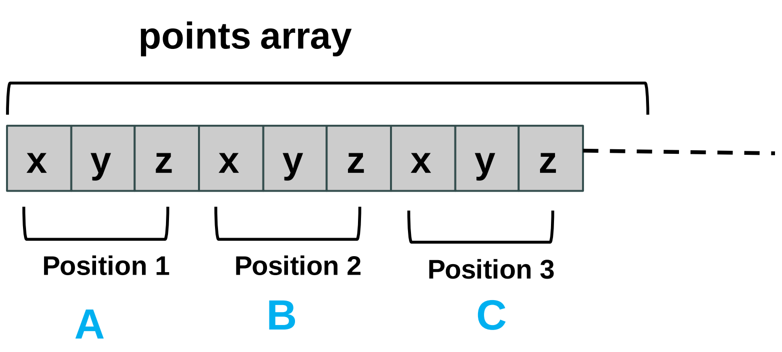
- After specifying corners, interior (s,t) ranges also mapped
- Example? Corners mapped below, abc subrange also mapped

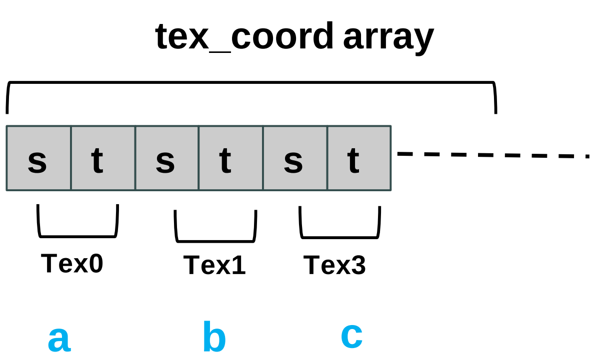


Step 3: Code for Assigning Texture Coordinates

- **Example:** Map a picture to a quad
- For each quad corner (vertex), specify
  - Vertex (x,y,z),
  - Corresponding corner of texture (s, t)
- May generate array of vertices + array of texture coordinates

```
points[i] = point3(2,4,6);
tex_coord[i] = point2(0.0, 1.0);
```

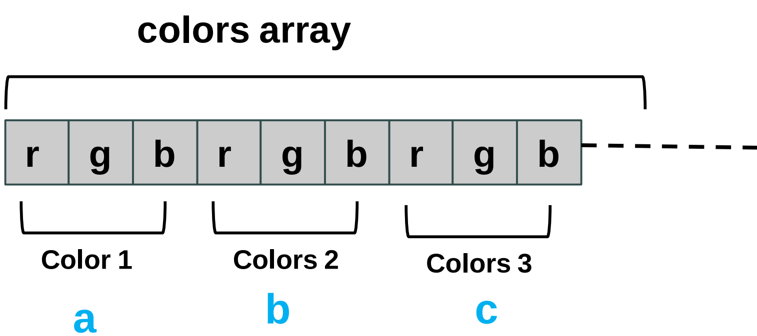


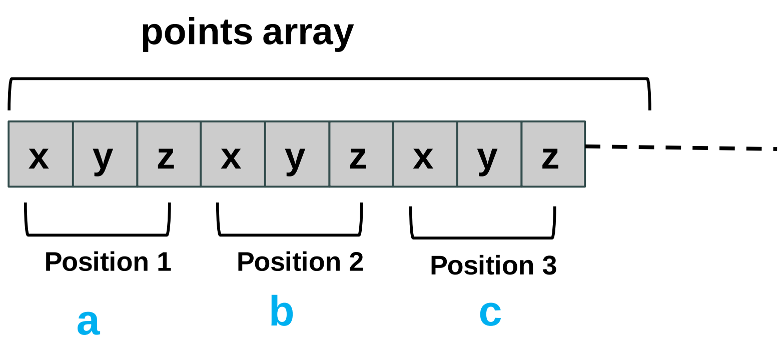


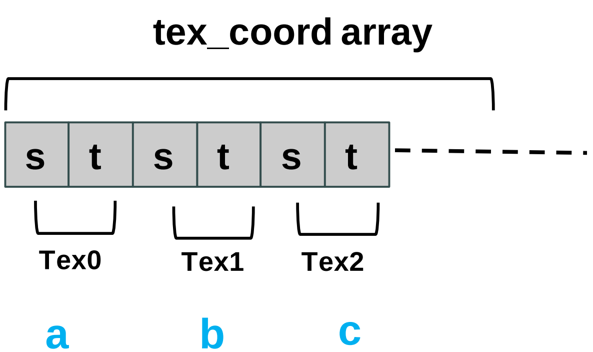
Step 3: Code for Assigning Texture Coordinates

```
void quad( int a, int b, int c, int d )
{
    quad_colors[Index] = colors[a];         // specify vertex color
    points[Index] = vertices[a];             // specify vertex position
    tex_coords[Index] = vec2( 0.0, 0.0 );   //specify corresponding texture corner
    index++;
   quad_colors[Index] = colors[b];
    points[Index] = vertices[b];
    tex_coords[Index] = vec2( 0.0, 1.0 );
    Index++;

// other vertices
}
```







Step 5: Passing Texture to Shader

- Pass vertex, texture coordinate data as vertex array
- Set texture unit

Variable names in shader

```
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) );

// Set the value of the fragment shader texture sampler variable
//   ("texture") to the appropriate texture unit.

glUniform1i( glGetUniformLocation(program, "texture"), 0 );
```

Step 6: Apply Texture in Shader (Vertex Shader)

- Vertex shader receives data, output texture coordinates to fragment shader

```
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


    texCoord = vTexCoord
    color = vColor
    gl_Position = modelview * projection * vPosition
```

Step 6: Apply Texture in Shader (Fragment Shader)

- Textures applied in fragment shader
- 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 );
}
```

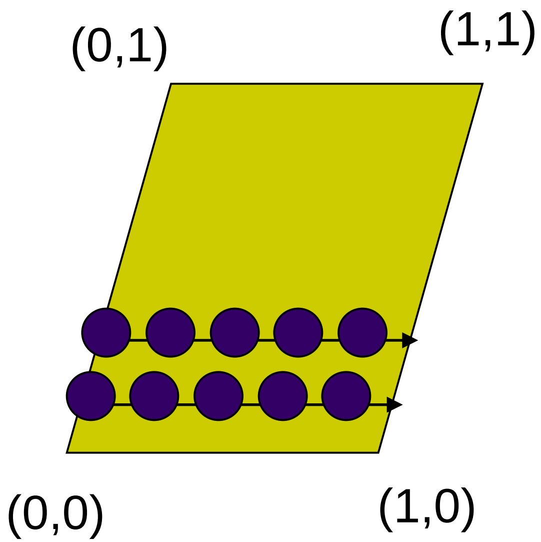
Output color Of fragment

Original color of object

Lookup color of texCoord (s,t) in texture

Map textures to surfaces

- Texture mapping is performed in rasterization

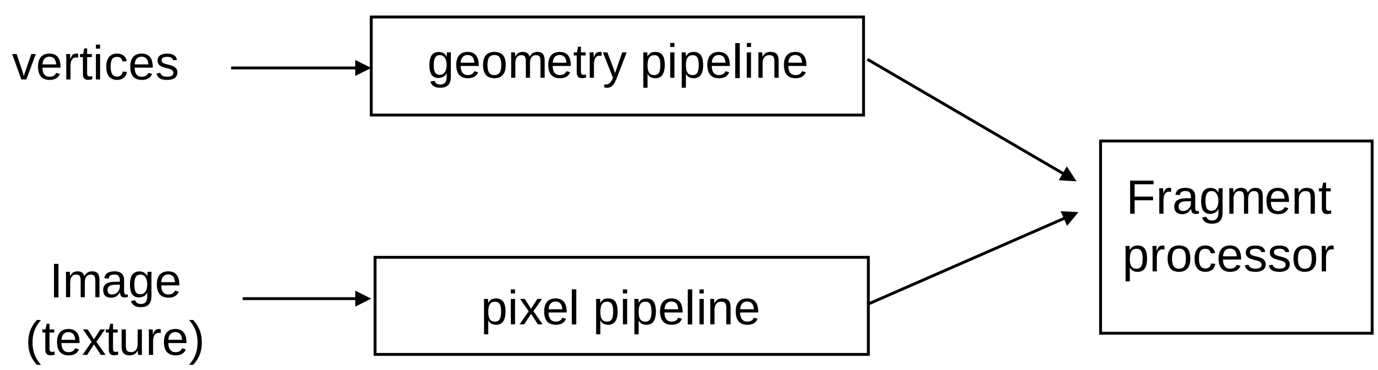


- For each pixel, its texture coordinates (s, t) interpolated based on corners' texture coordinates (why not just interpolate the color?)

- The interpolated texture (s,t) coordinates are then used to perform texture lookup

Texture Mapping and the OpenGL Pipeline

- Images and geometry flow through separate pipelines that join during fragment processing
  - Object geometry: geometry pipeline
  - Image: pixel pipeline
  - “complex” textures do not affect geometric complexity



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still haven't talked about setting texture parameters

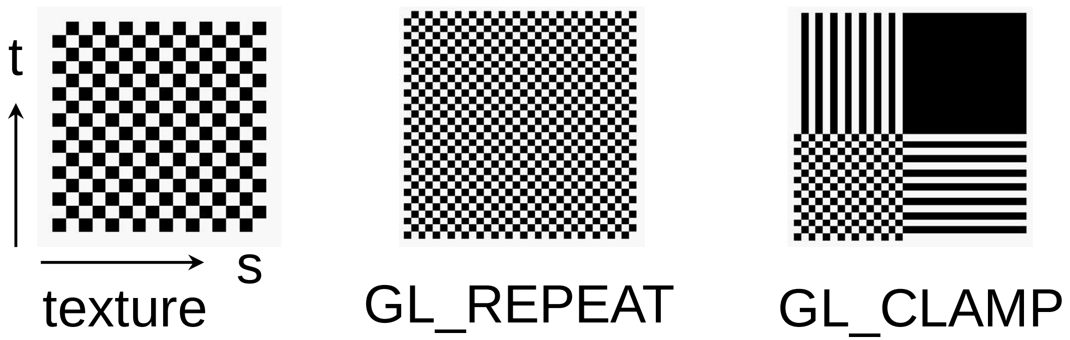
Step 4: Specify Texture Parameters

- Texture parameters control how texture is applied
  - **Wrapping parameters** used if s,t outside (0,1) range

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

    Wrapping: use s,t modulo 1

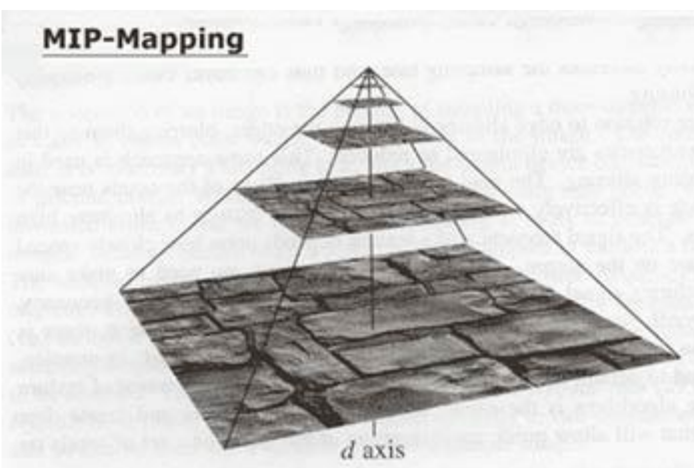
```
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_CLAMP )
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT )
```



Step 4: Specify Texture Parameters Mipmapped Textures

- Mipmapping pre-generates prefiltered (averaged) texture maps of decreasing resolutions
- Declare mipmap level during texture definition

```
glTexImage2D( GL_TEXTURE_*D, level, … )
```



References

- Angel and Shreiner, Interactive Computer Graphics, 6th edition
- Hill and Kelley, Computer Graphics using OpenGL, 3rd edition
- UIUC CS 319, Advanced Computer Graphics Course
- David Luebke, CS 446, U. of Virginia, slides
- Chapter 1-6 of RT Rendering
- Hanspeter Pfister, CS 175 Introduction to Computer Graphics, Harvard Extension School, Fall 2010 slides
- Christian Miller, CS 354, Computer Graphics, U. of Texas, Austin slides, Fall 2011
- Ulf Assarsson, TDA361/DIT220 - Computer graphics 2011, Chalmers Instititute of Tech, Sweden