Topics

Texture mapping in OpenGL

Mapping

Modify color in fragment processing after rasterization

Three Major Mapping Methods

- **Texture Mapping**
  - Uses images to fill inside of polygons
- **Environment (reflection mapping)**
  - Uses a picture of the environment for texture maps of reflection surface
  - Allows simulation of highly specular surfaces
- **Bump mapping**
  - Emulates altering normal vectors during the rendering process

Texture Mapping

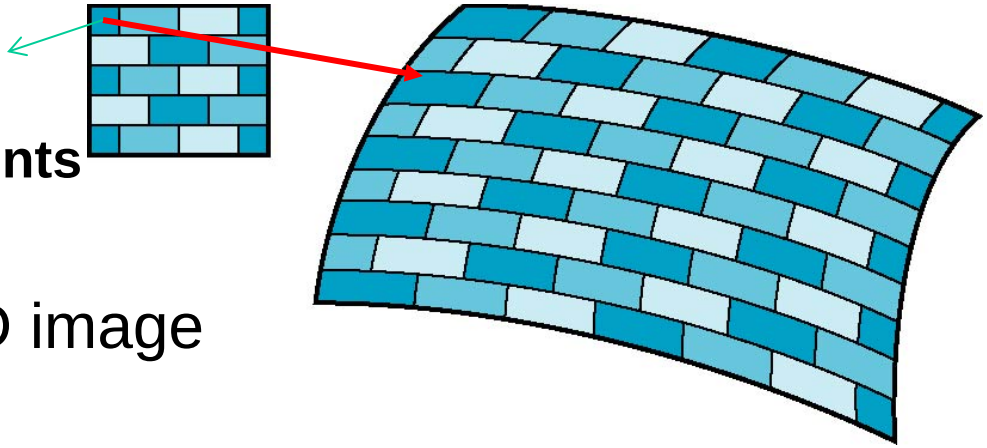
Textures are stored in images - 2D arrays.

Each element is called a ***texel***

The idea is simple---map an image to a surface or map every texel to a point on a geometric object

However, there are 3 or 4 coordinate systems involved

Texels:
texture elements

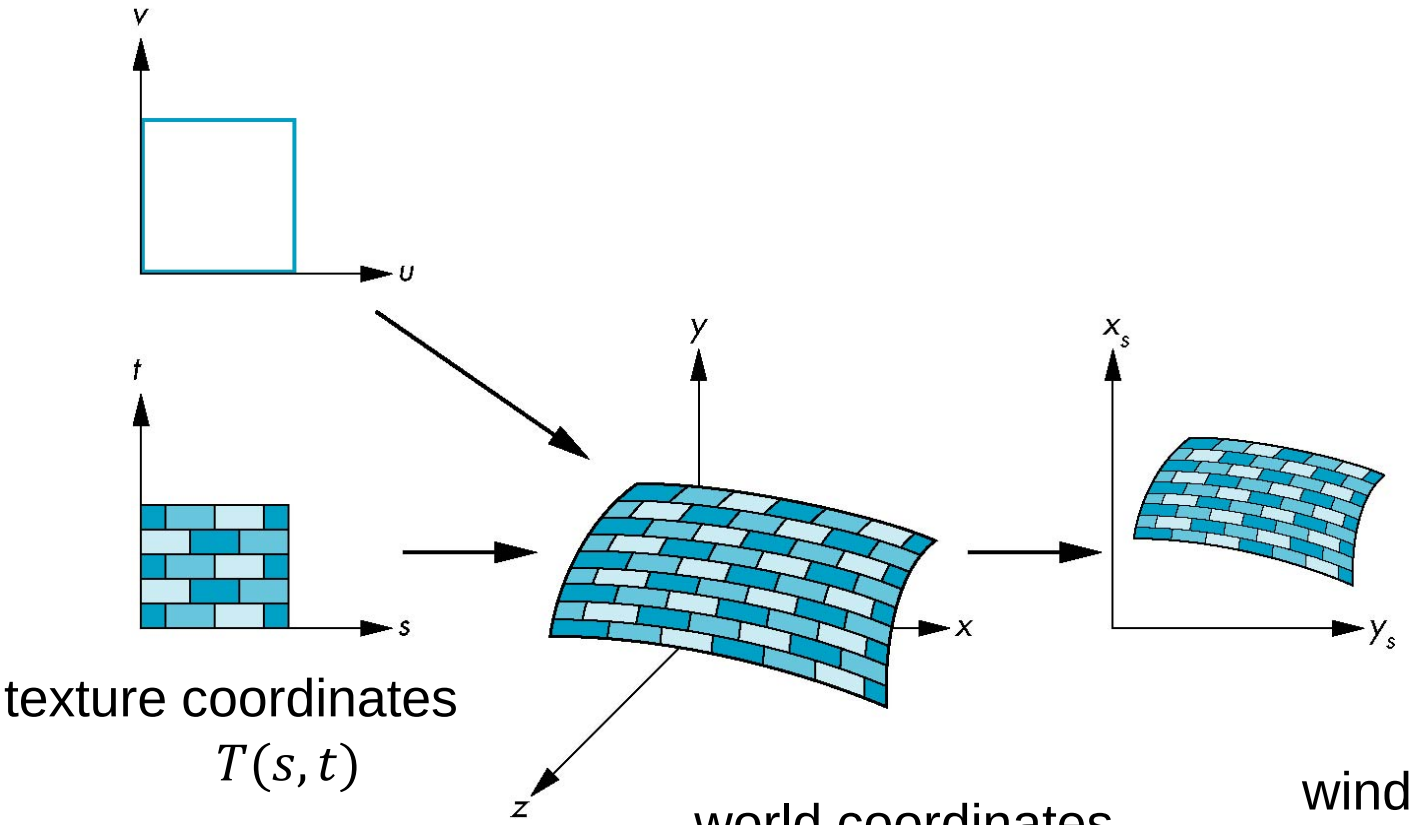


2D image

3D surface

Texture Mapping

parametric coordinates



texture coordinates
$T(s,t)$

world coordinates

window coordinates

Backward Mapping

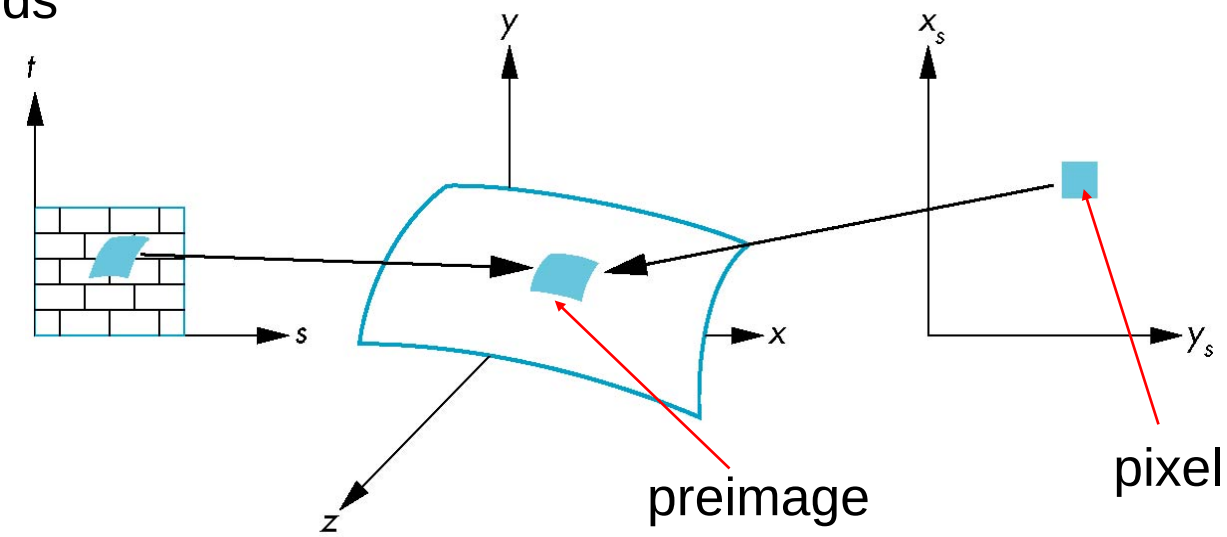
We really want to go backwards

- Given a pixel, we want to know to which point on an object it corresponds, the preimage (inverse) of a pixel
- Given a point on an object, we want to know to which point in the texture it corresponds

Backward mapping

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

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



Such functions are difficult to find in general

Two-part mapping

One solution to the mapping problem is to first map the texture to a simple intermediate surface, e.g., a sphere, cylinder, or cube

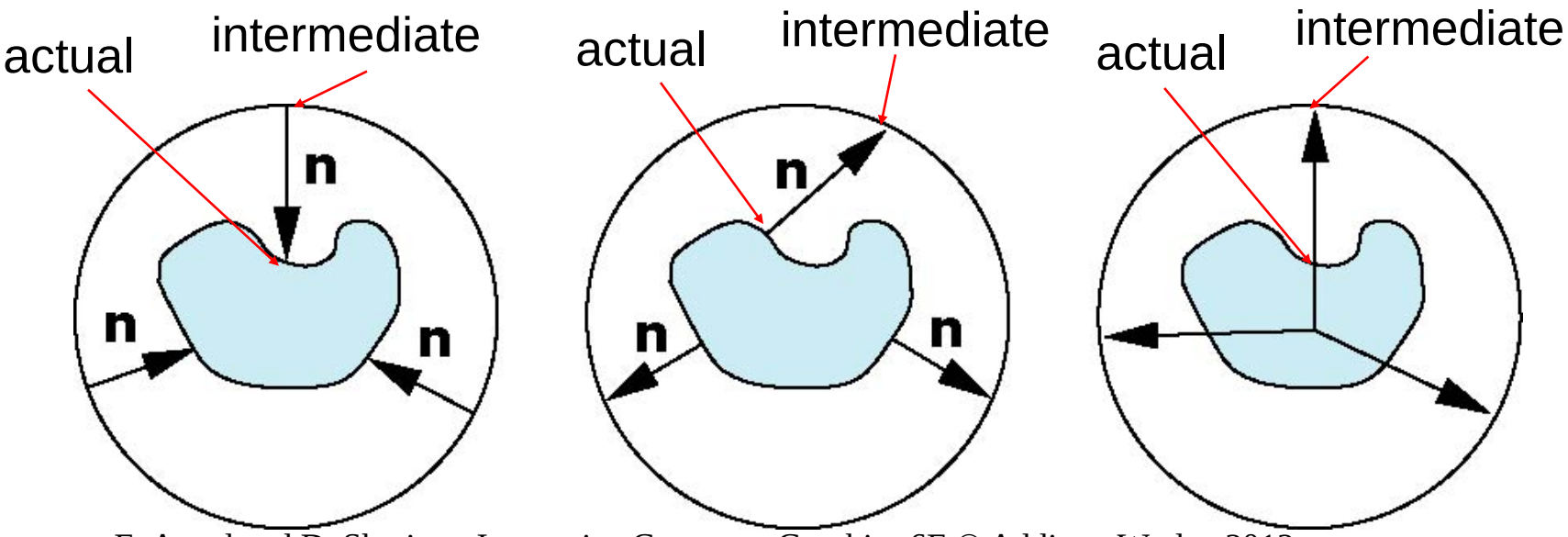
First mapping can be

- Cylindrical mapping
- Spherical mapping
- Box mapping

Second Mapping: From Intermediate Object to Actual Object

Three strategies:

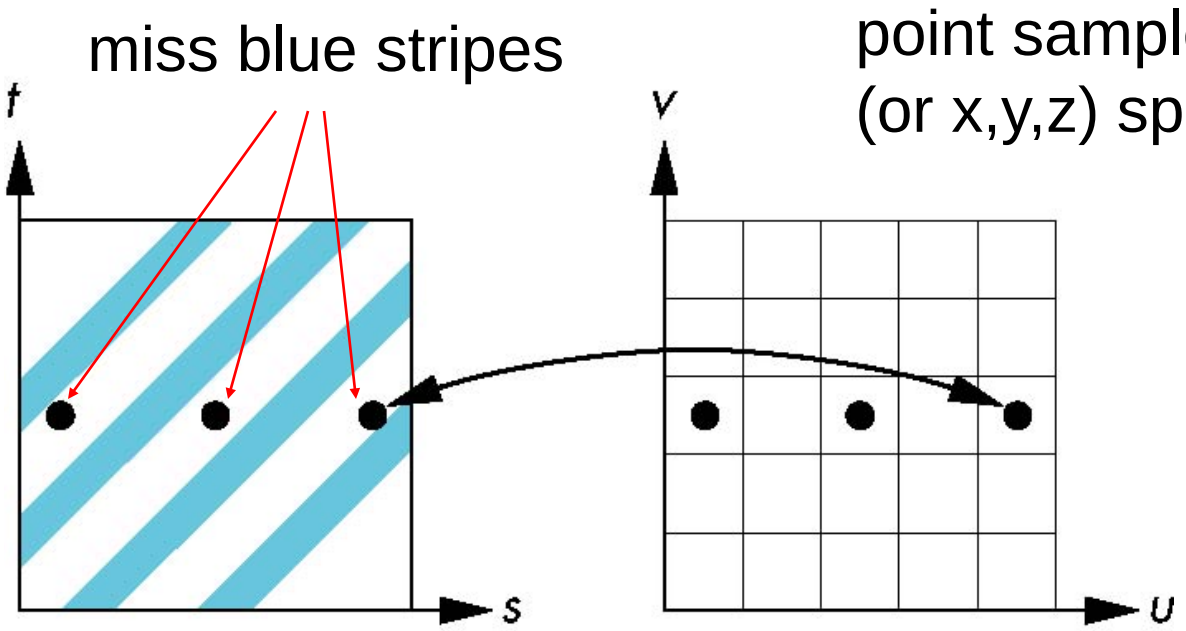
- from intermediate, along normal of intermediate until intersect with the object
- from object, along normal of the object until intersect with the intermediate
- Vectors from center of intermediate/object, intersect the object and the intermediate



Aliasing

Backward mapping for the centers of pixels

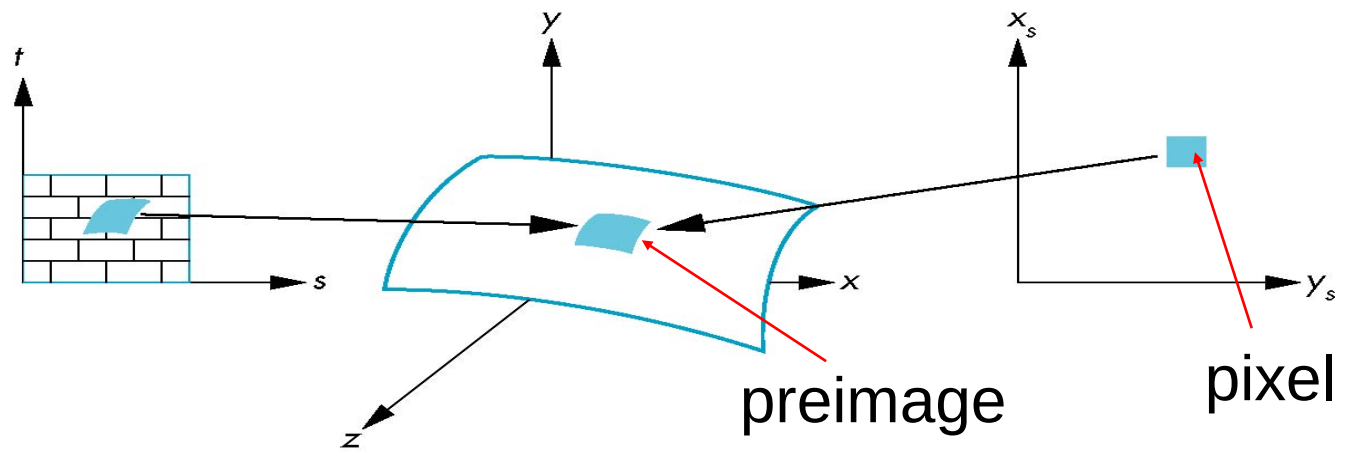
Point sampling of the texture/object can lead to aliasing errors



Area Averaging

A better but slower option is to use ***area averaging*** of the texture map over the preimage

Cannot handle high-frequency components, e.g., the stripe pattern – sampling at higher frequencies



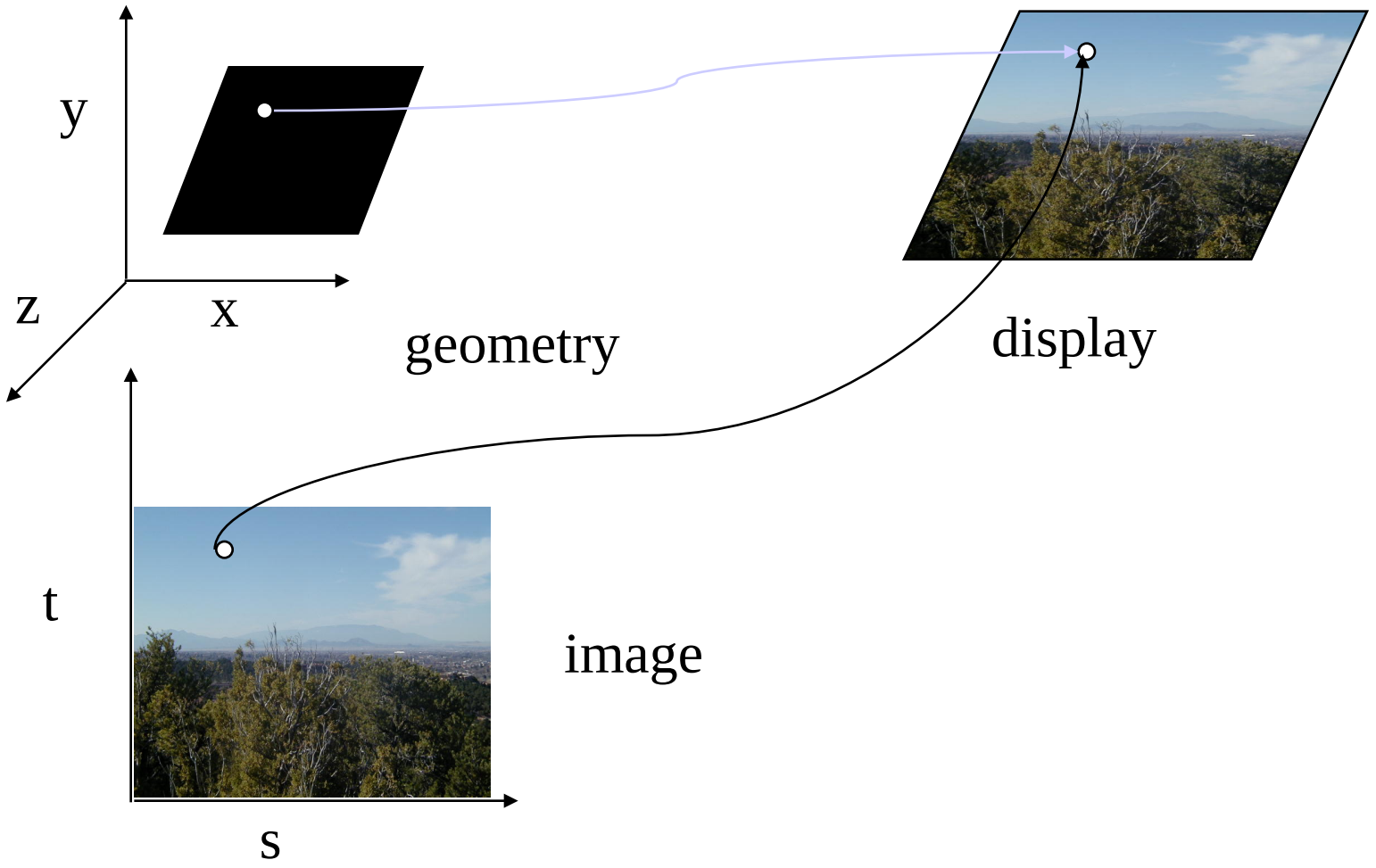
OpenGL Texture Mapping

Texture mapping is part of fragment processing

Three steps to applying a texture

1. Generate the texture map
   - read or generate image
   - assign to texture
   - enable texturing
2. assign texture coordinates to vertices
   - Texture coordinates can be interpolated
   - Proper mapping function is left to application
3. specify texture parameters
   - wrapping, filtering

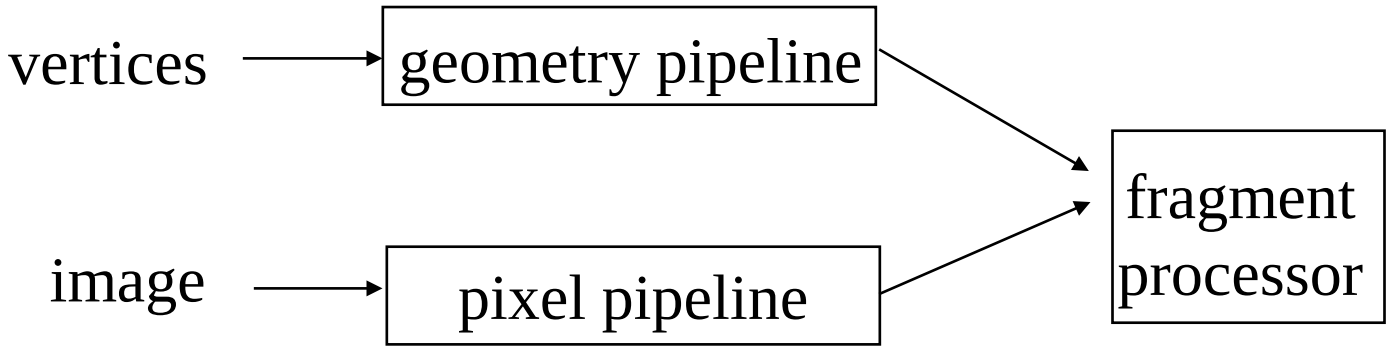
Texture Mapping



Texture Mapping and the OpenGL Pipeline

Images and geometry flow through separate pipelines that join during fragment processing

- "complex" textures do not affect geometric complexity



Shader-based OpenGL Texture Mapping

- Create a ***texture object*** and load texel data into the texture object
- Associate texture coordinates with vertices of object
- Associate a ***texture sampler*** with each texture map
- Get the texel values from the texture sampler from shader

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Create Texture Objects

```
GLuint textures[# of texture objects];
```

- Create texture objects and return n unused names for texture objects

```
void glGenTextures(GLsizei n, GLuint *textures);
```

Number of texture objects

Bind Texture Objects

```
void glBindTexture(GLenum target, GLuint texture);
```

Type and dimensionality of target, e.g., GL_TEXTURE_2D

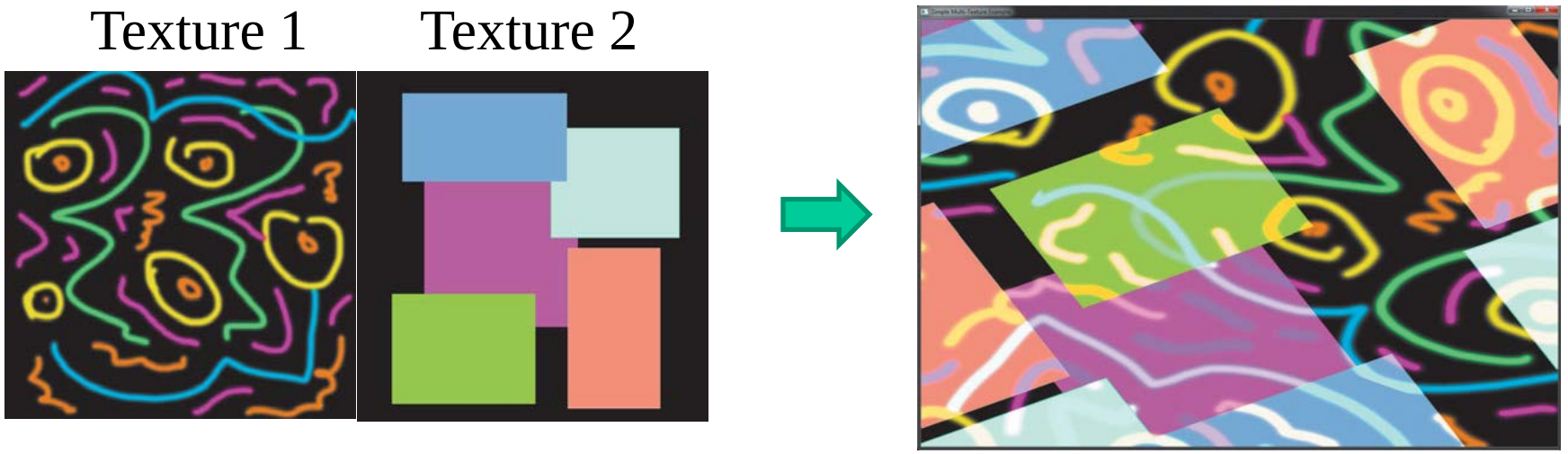
- Create a new texture object with the assigned name
- Bind an existing texture object and make it active.

Select Texture Units

In OpenGL, textures are bound to OpenGL context by ***texture units.***

The context can support multiple texture units – many textures can be bound to the same context at the same time

Texture 1 Texture 2



Shreiner et al: OpenGL Programming Guide (Version 4.3)

Select Texture Units

Step 1: select the (first) texture unit by

```
void glActiveTexture(GLenum texture);
```

A constant of the form $\mathrm{GL\_TEXTURE}i$, $i \in [0, \text{max \# of texture objects} - 1]$

If there is only one texture unit, use **GL_TEXTURE0**

Step 2: bind the texture object

```
void glBindTexture(GLenum target, GLuint texture);
```

For example,

```
glActiveTexture( GL_TEXTURE0 );
glBindTexture( GL_TEXTURE_2D, textures[0] );
```

Specifying a Texture Image

Define a texture image from an array of *texels* (texture elements) in CPU memory

- Generate by application code
- Load from scanned image

```
Glubyte my_texels[height][width][channel];
```

Example: Checkerboard Texture

```
GLubyte my_texels [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;
```

Bitwise XOR

Define Image as a Texture

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

- `target:` type of texture, e.g. `GL_TEXTURE_2D`
- `level:` used for mipmapping (discussed later), e.g., 0 w/o mipmap
- `Internal format:` format to store texture data, e.g., GL_RGB or GL_RGBA
- `w, h:` width and height of `texels` in pixels
- `border:` used for smoothing (discussed later)
- `format and type:` describe texels
- `texels:` pointer to texel array

For example,

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

Shader-based OpenGL Texture Mapping

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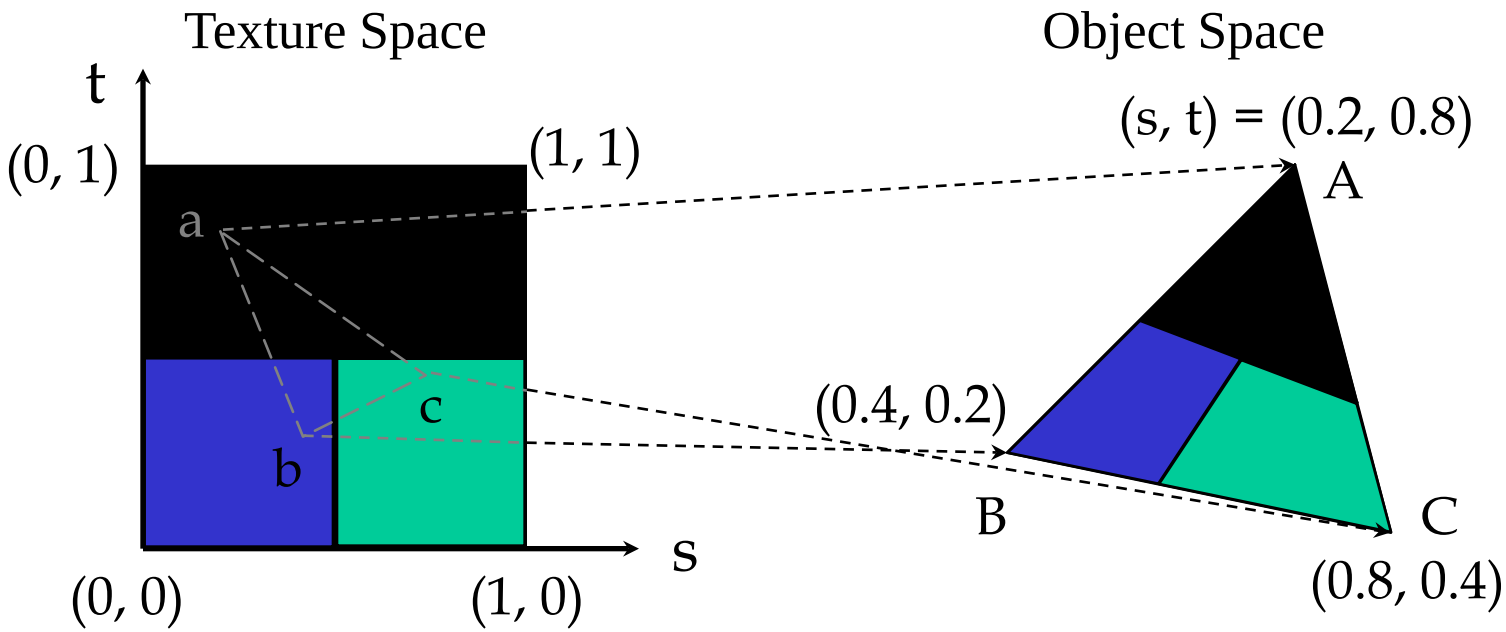
Mapping a Texture

In the 512x512 texture space, (0,0) corresponds to my_texels(0,0), and (1.0,1.0) corresponds to my_texels(511,511)



Adding Texture Coordinates

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

    points[Index] = vertices[b];
    tex_coords[Index] = vec2( 0.0, 1.0 );
    Index++;

// other vertices
}
```

Associate Texture Coordinates with Vertices of Object

Treat texture coordinates as a vertex attribute, similar to vertices and vertex colors.

Pass the vertex texture coordinates to the vertex shader.

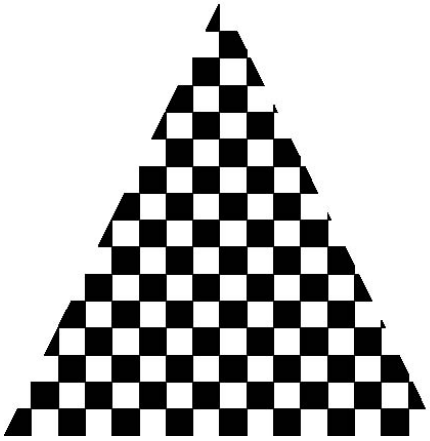
The rasterizer interpolates the vertex texture coordinates to fragment texture coordinates.

Interpolation

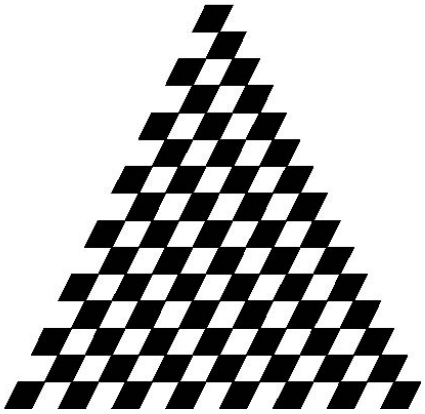
OpenGL uses interpolation to find proper texels from specified texture coordinates

Can be distortions

good selection
of texture coordinates



poor selection
of texture coordinates



Angel's Example Code

```
// 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(vertices) + sizeof(tex_coords),
                 NULL, GL_STATIC_DRAW );
```

Angel's Example Code

```
GLintptr offset = 0;

glBufferSubData( GL_ARRAY_BUFFER, offset, sizeof(vertices), vertices );

offset += sizeof(vertices);

glBufferSubData( GL_ARRAY_BUFFER, offset, sizeof(tex_coords),
tex_coords );
```

Angel's Example Code

```
// after load shaders, use the program

offset = 0;

GLuint vPosition = glGetAttribLocation( program, "vPosition" );

glEnableVertexAttribArray( vPosition );

glVertexAttribPointer( vPosition, 4, GL_FLOAT, GL_FALSE,
0,BUFFER_OFFSET(offset) );

offset += sizeof(vertices);

GLuint vTexCoord = glGetAttribLocation( program, "vTexCoord" );

glEnableVertexAttribArray( vTexCoord );

glVertexAttribPointer( vTexCoord, 2,GL_FLOAT,GL_FALSE, 0,
BUFFER_OFFSET(offset) );
```

Shader-based OpenGL Texture Mapping

- Create a ***texture object*** and load texel data into the texture object
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Applying Textures

Textures are read/applied during fragments shading by ***a sampler***, often in a fragment shader

A texture object has a built-in sampler object

Samplers return a texture color from a texture object

Set the value of the fragment shader texture sampler variable to the appropriate texture unit selected by calling glActiveTexture().

The selected texture unit

glUniform1i(glGetUniformLocation(program, "tex"), 0);

Fragment shader texture sampler variable

Shader-based OpenGL Texture Mapping

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Applying Textures: Vertex Shader

Usually vertex shader will output texture coordinates to be rasterized

```
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
void main()
{
   color  = vColor;
   texCoord    = vTexCoord;
   gl_Position = vPosition;
}
```

Applying Textures in Fragment Shader

```
in vec4 color;  //color from rasterizer

in vec2 texCoord; //texture coordinate from rasterizer

uniform sampler2D tex; //texture object from application

void main()  {

    gl_FragColor = color * texture( tex, texCoord );

}
```

Type of sampler, e.g., sampler3D, samplerCube

Get texels from the sampler

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

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

Setting Texture Parameters

```
glTexParameteri(GLenum target, GLenum pname,Type param );
```

Can be f, fv, iv, etc.

- `target:` type of texture, e.g. `GL_TEXTURE_2D`
- `pname:` the symbolic name of a single-valued texture parameter, e.g., `GL_TEXTURE_WRAP_S` and `GL_TEXTURE_MIN_FILTER`
  - Need to run this function for every parameter
- `param:` the value of parameter

OpenGL manual for glTexParameter

https://www.opengl.org/sdk/docs/man4/html/glTexParameter.xhtml

Wrapping Mode

Valid range of texture coordinates: $0 \leq s, t \leq 1$

***Clamping mode*: if $s, t > 1$ use 1, if $s, t < 0$ use 0**

- Avoid wrapping artifacts for nonrepeated texture patterns

***Wrapping mode*: use s, t *modulo* 1**

- Preferred for repeated texture patterns, e.g., checkerboard

```
glTexParameteri(GL_TEXTURE_2D,GL_TEXTURE_WRAP_S,GL_CLAMP)

glTexParameteri(GL_TEXTURE_2D,GL_TEXTURE_WRAP_T,GL_REPEAT)
```

`GL_TEXTURE_WRAP_S(T)`: set texture coordinate *s (t)*

Parameters to choose: `GL_CLAMP`, `GL_CLAMP_TO_EDGE`, `GL_CLAMP_TO_BORDER`, `GL_MIRRORED_REPEAT`, `GL_REPEAT`, or `GL_MIRROR_CLAMP_TO_EDGE`.

Wrapping Mode

***Clamping mode*: if $s, t > 1$ use 1, if $s, t < 0$ use 0**

***Wrapping mode*: use s, t *modulo* 1**

Example: repeated texture patterns

Wrapping Mode

Example: nonrepeated texture

GL_REPEAT

GL_MIRRORED_REPEAT

GL_CLAMP_TO_EDGE

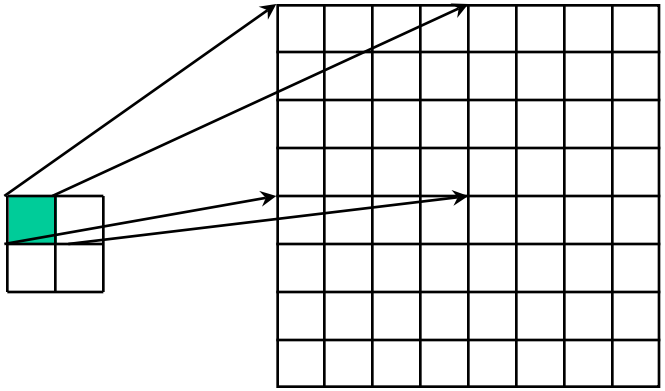
GL_CLAMP_TO_BORDER

https://open.gl/textures

Magnification and Minification

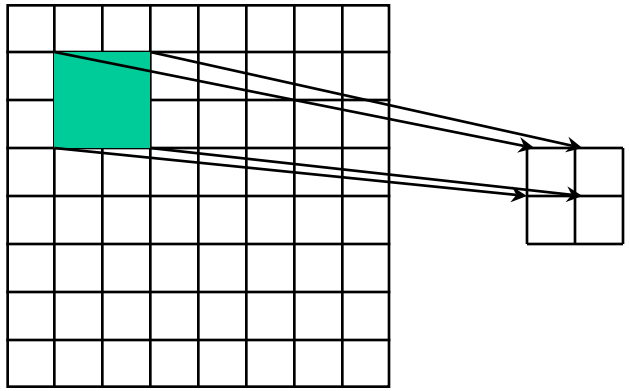
***Minification**:* more than one texel can cover a pixel
***Magnification**:* more than one pixel can cover a texel

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



Texture Polygon

Magnification



Texture Polygon

Minification

Magnification and Minification: Filter Modes

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

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

GL_NEAREST is faster, but causes jitter edge
GL_LINEAR is the default mode.

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