Computer Graphics
CS 543 – Lecture 8 (Part 2)
Texturing

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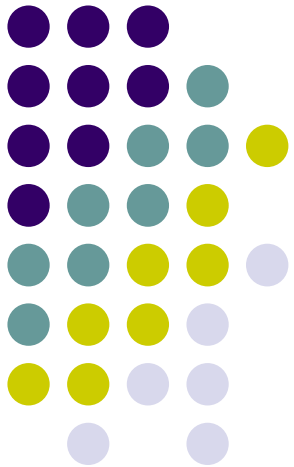
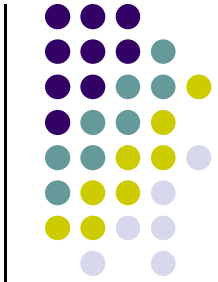
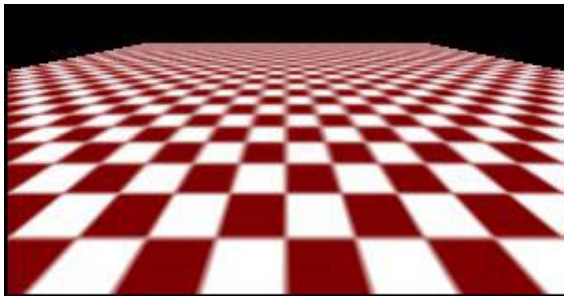
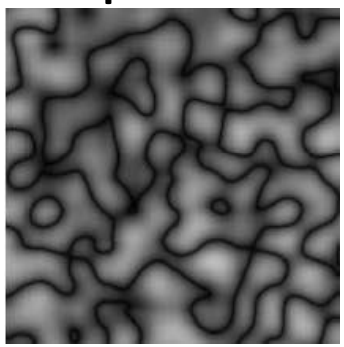


The Limits of Geometric Modeling



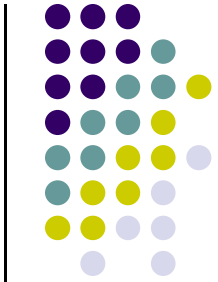
- Although graphics cards can render over 10 million polygons per second, that number is insufficient for many phenomena
  - Clouds
  - Grass
  - Terrain
  - Skin
- Computationally inexpensive way to add details





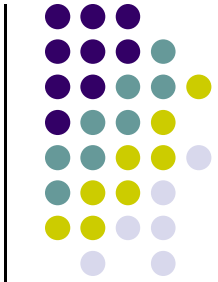
Complexity of images does
Not affect the complexity
Of geometry processing
(transformation, clipping…)

Modeling an Orange



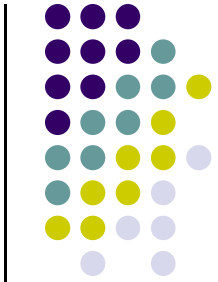
- Consider problem of modeling an orange (the fruit)
- Start with an orange-colored sphere
  - Too simple
- Replace sphere with a more complex shape
  - Does not capture surface characteristics (small dimples)
  - Takes too many polygons to model all the dimples

Modeling an Orange (2)

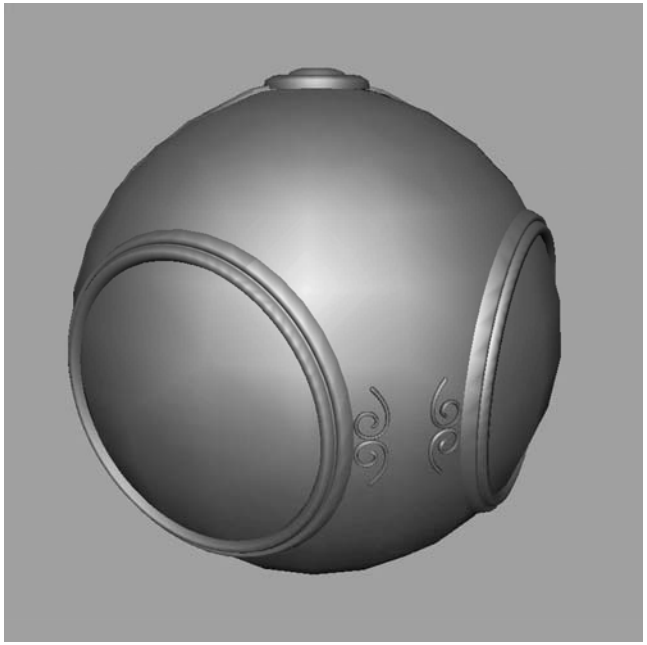


- Take a picture of a real orange, scan it, and “paste” onto simple geometric model
  - Known as texture mapping
- Still might not be sufficient because resulting surface will be smooth
  - Simulate surface roughness: bump mapping

Three Types of Mapping



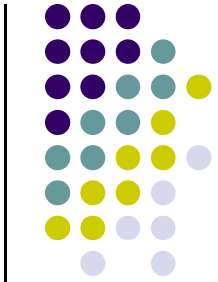
- Texture Mapping
  - Paste image onto polygon



geometric model

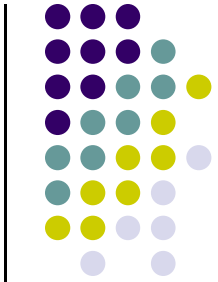
texture mapped

Three Types of Mapping

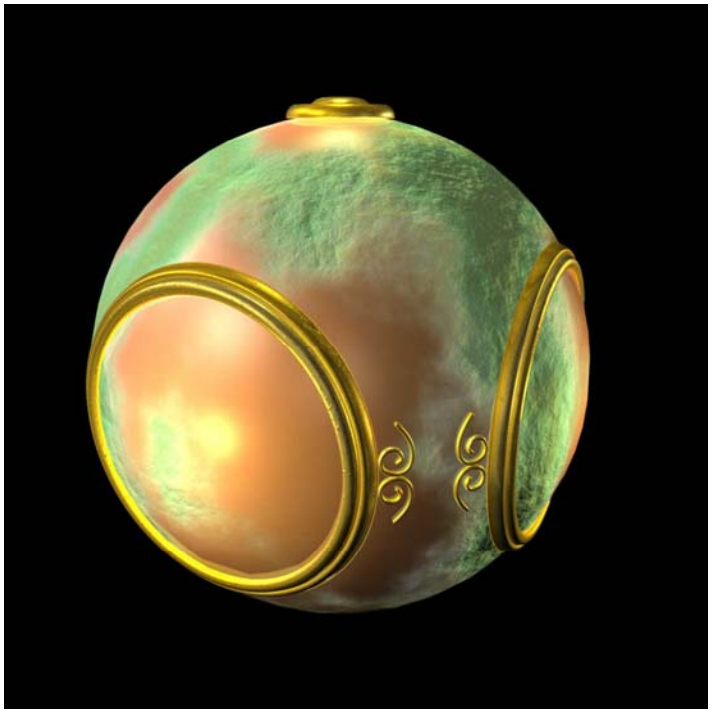


- Environment (reflection mapping)
  - Uses picture of the sky/environment for texture maps

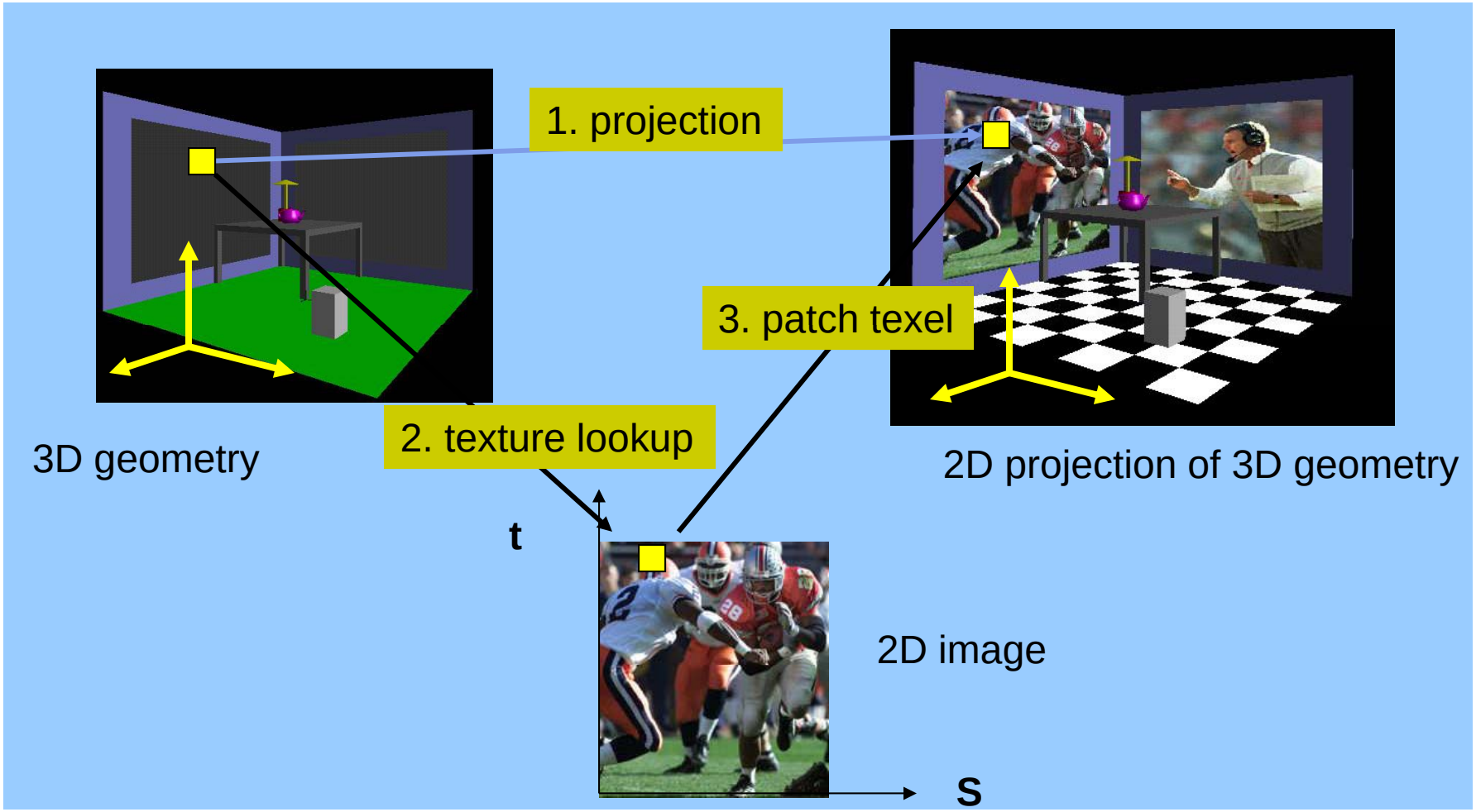
Three Types of Mapping



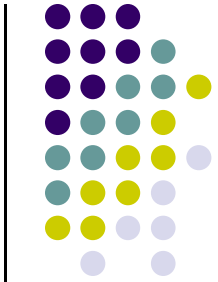
- Bump mapping
  - Alters normal vectors during rendering process to simulate surface roughness



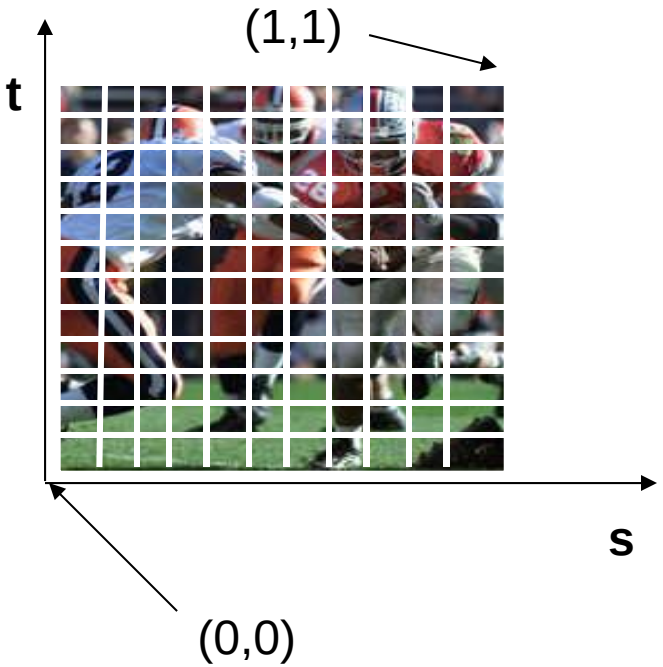
Texture Mapping



Texture Representation



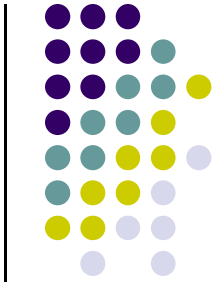
- ✓ Bitmap (pixel map) textures (supported by OpenGL)
- Procedural textures (used in advanced rendering programs)



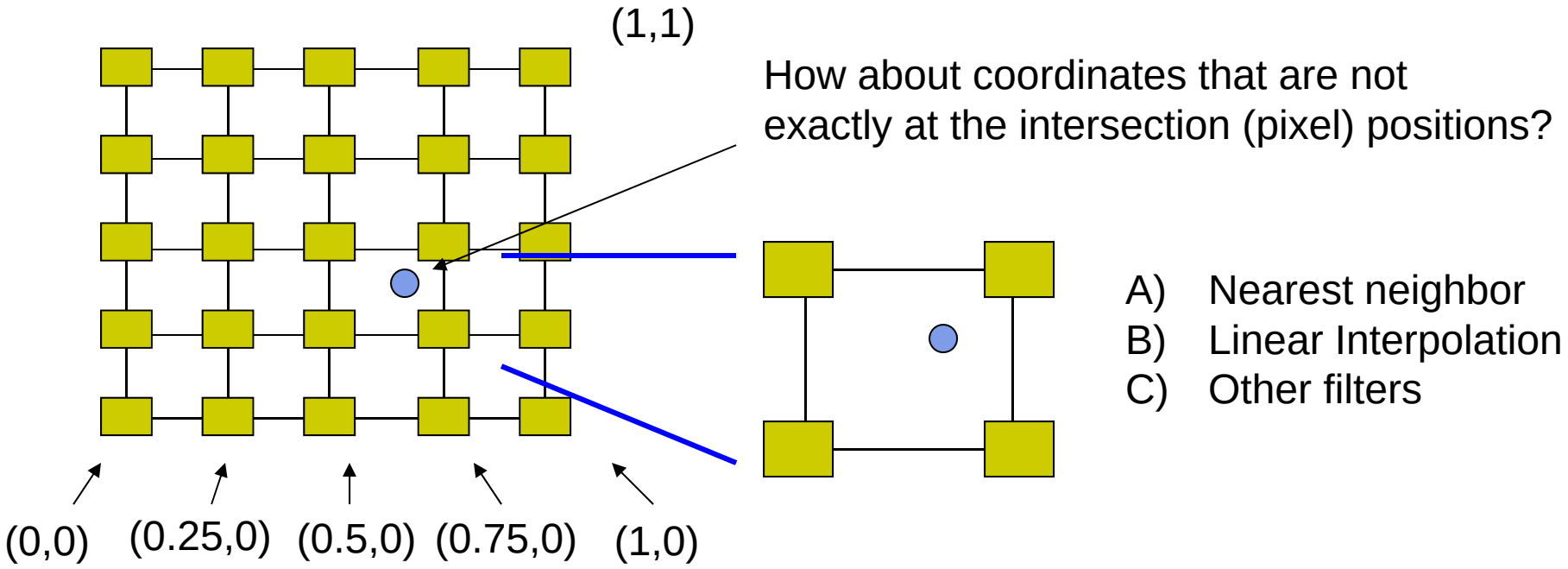
Bitmap texture:

- A 2D image - represented by 2D array texture[height][width]
- Each pixel (or called **texel**) by a unique pair texture coordinate (s, t)
- The s and t are usually normalized to a [0,1] range
- For any given (s,t) in the normalized range, there is also a unique image value (i.e., a unique [red, green, blue] set)

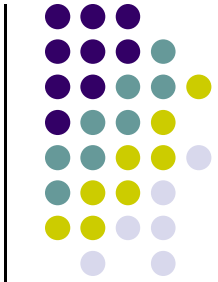
Texture Value Lookup



- For given texture coordinates (s,t), we can find a unique image value from the texture map



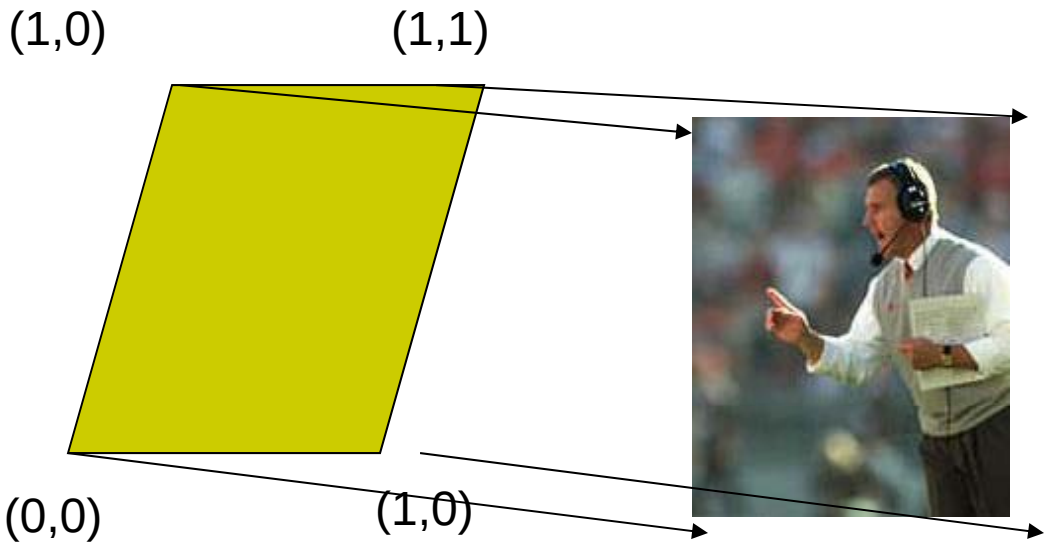
Map textures to surfaces



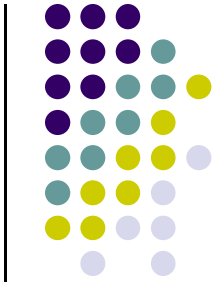
- Establish mapping from texture to surfaces (polygons):

  - Application program needs to specify texture coordinates for each corner of the polygon

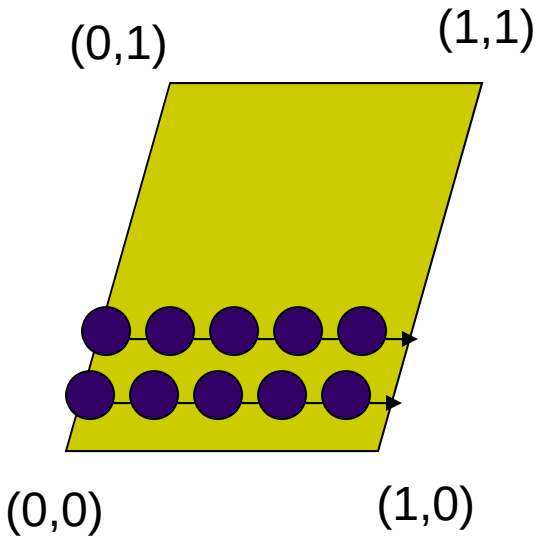
The polygon can be in an arbitrary size



Map textures to surfaces

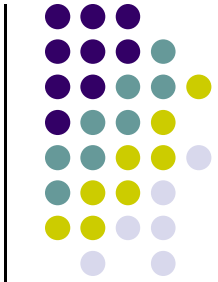


- Texture mapping is performed in rasterization



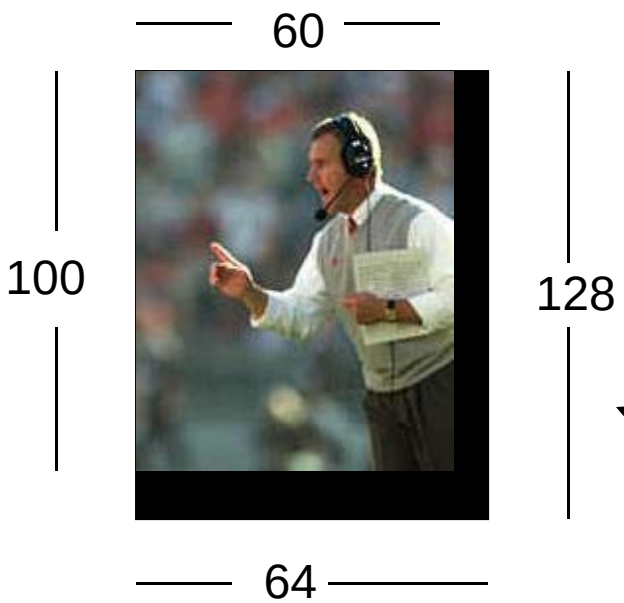
- For each pixel that is to be painted, its texture coordinates (s, t) are determined (interpolated) based on the corners' texture coordinates (why not just interpolate the color?)
- The interpolated texture coordinates are then used to perform texture lookup

Fix texture size



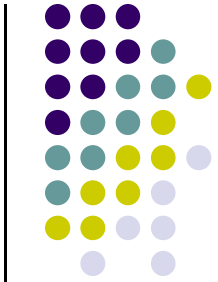
- If the dimensions of the texture map are not power of 2, you can

1) Pad zeros 2) Scale the Image

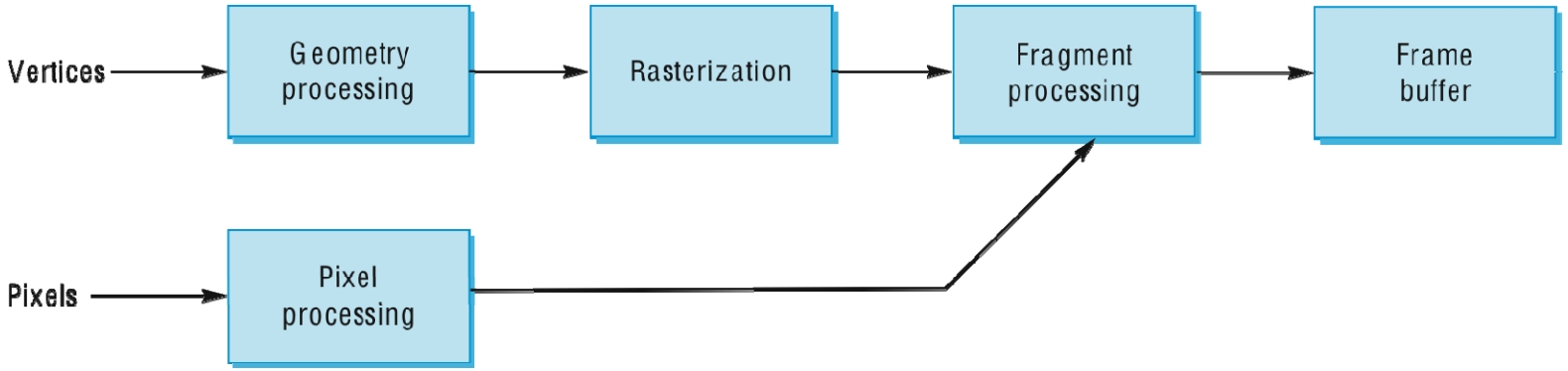


Remember to adjust the texture coordinates for your polygon corners – you don't want to Include black texels in your final picture

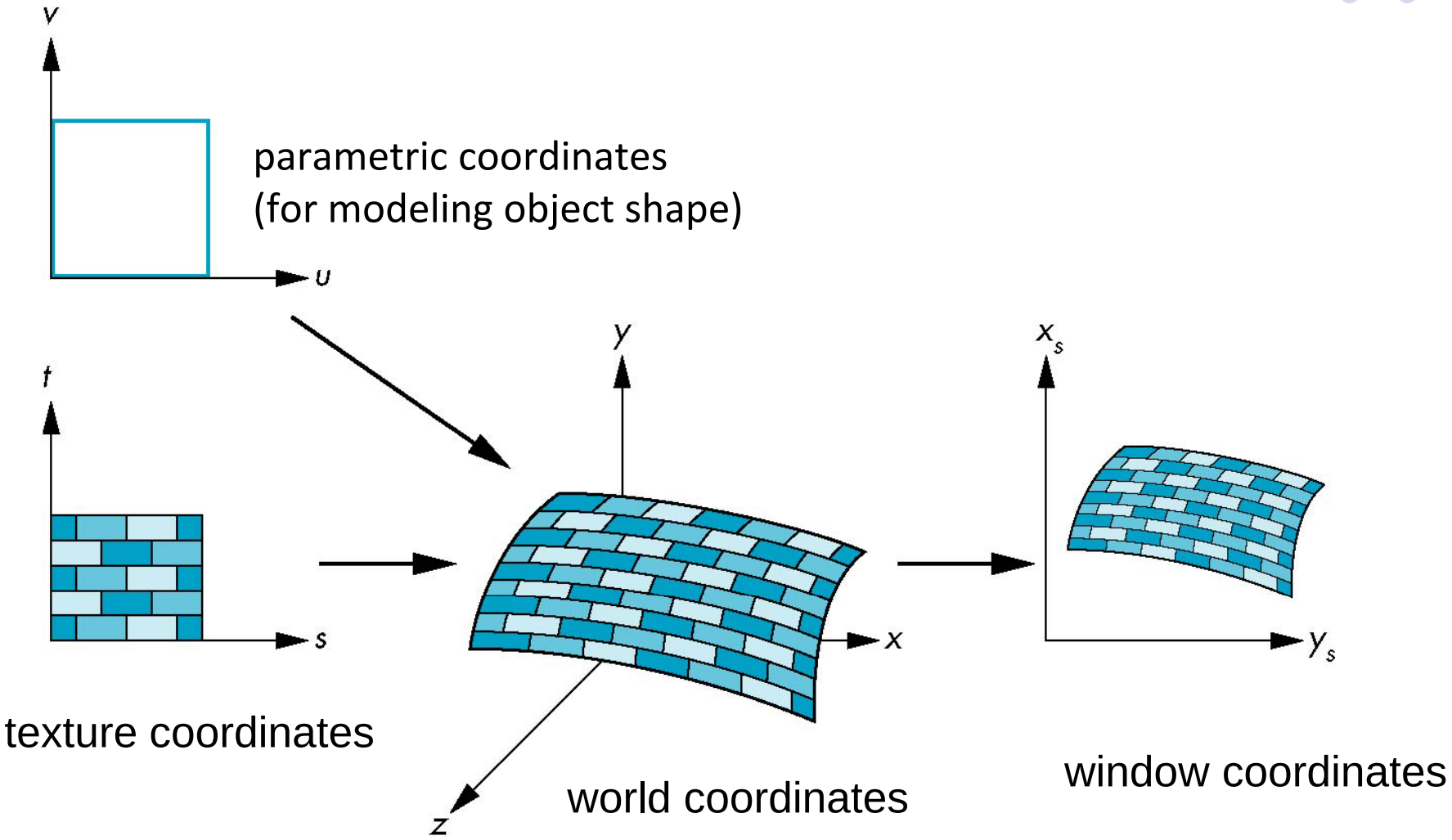
Where does mapping take place?



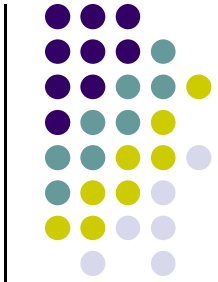
- Mapping techniques are implemented at the end of the rendering pipeline
  - Very efficient because few polygons make it past the clipper



Texture Mapping



Mapping Functions



- Basic problem is how to find the maps
- Consider mapping from texture coordinates to a point a surface
- Appear to need three functions

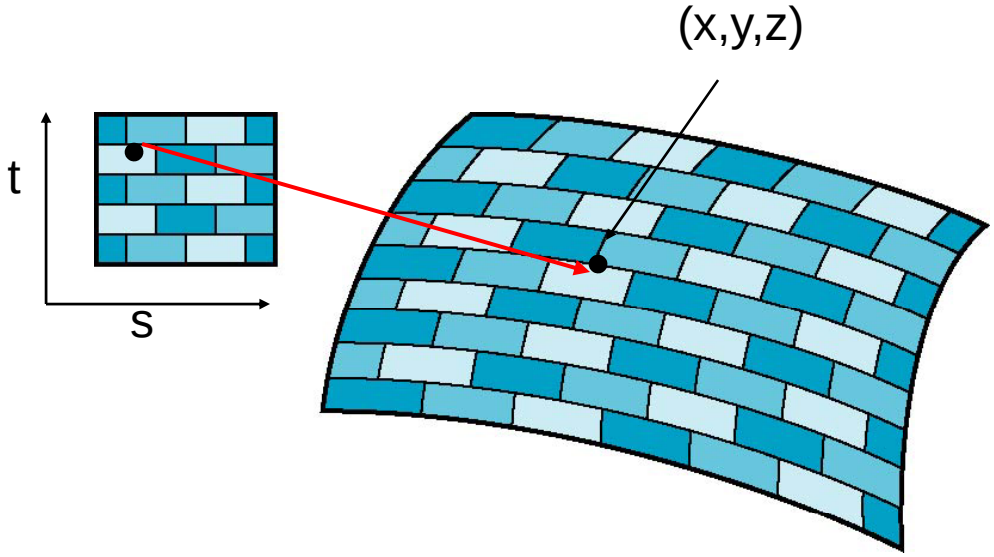
  $x = x(s,t)$

  $y = y(s,t)$

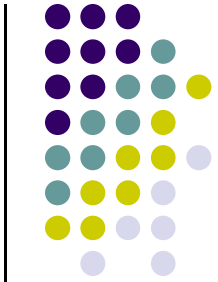
  $z = z(s,t)$

- But we really want

to go the other way



Backward Mapping

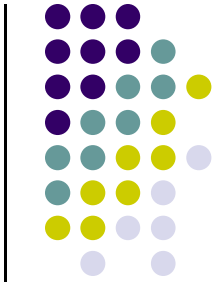


- We really want to go backwards
  - Given a pixel, we want to know to which point on an object it corresponds
  - Given a point on an object, we want to know to which point in the texture it corresponds
- Need a map of the form

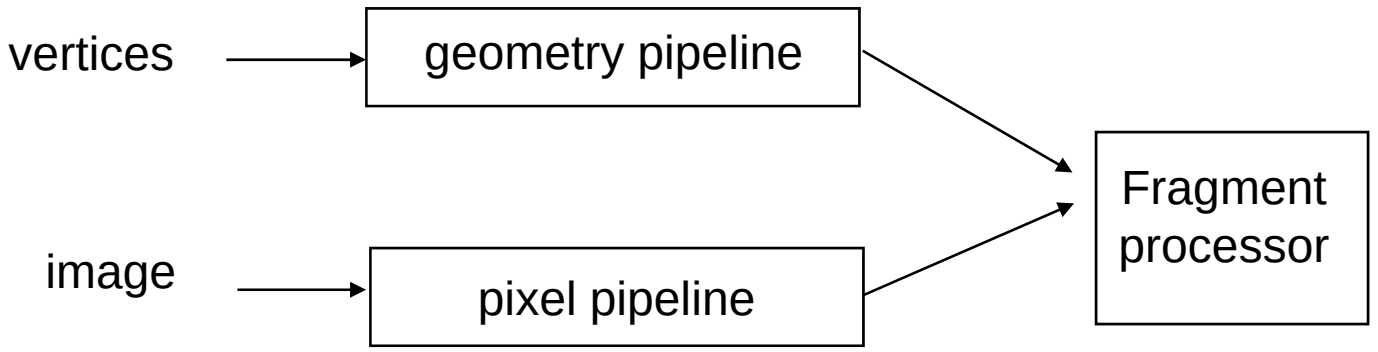
  $s = s(x,y,z)$

  $t = t(x,y,z)$
- Such functions are difficult to find in general

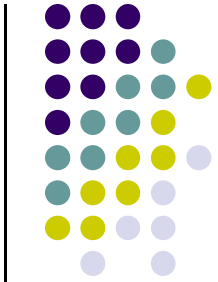
Texture Mapping and the OpenGL Pipeline



- Images and geometry flow through separate pipelines that join during fragment processing
  - "complex" textures do not affect geometric complexity



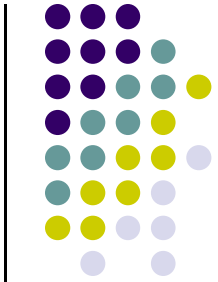
Basic Stragegy



Three steps to applying a texture

1. specify the 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

Specifying a Texture Image

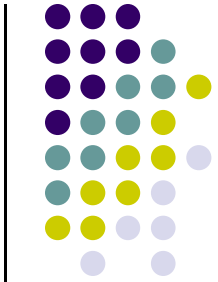


- Define a texture image from an array of *texels* (texture elements) in CPU memory

  `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

Define Image as 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 (discussed later)

components: elements per texel

w, h: width and height of **texels** in pixels

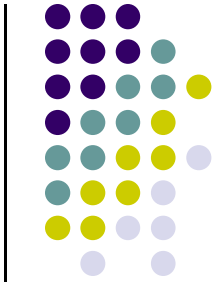
border: used for smoothing (discussed later)

format and type: describe texels

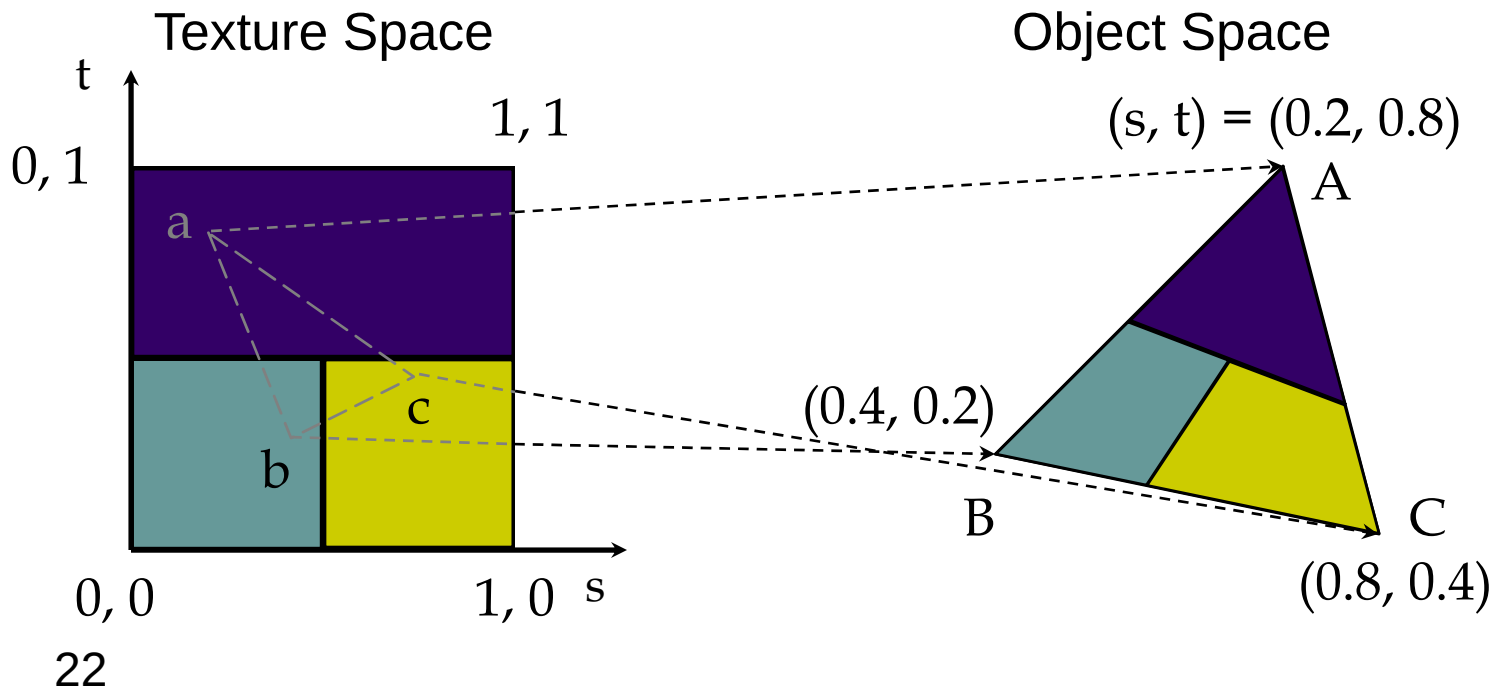
texels: pointer to texel array

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

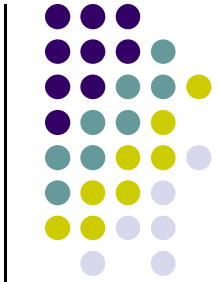
Mapping a Texture



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

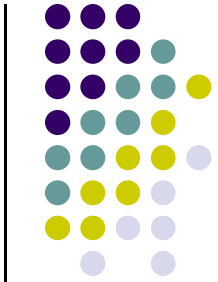


Typical Code



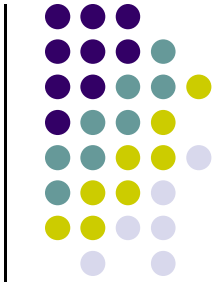
```
offset = 0;
GLuint vPosition = glGetAttribLocation( program, "vPosition" );
glEnableVertexAttribArray( vPosition );
glVertexAttribPointer( vPosition, 4, GL_FLOAT, GL_FALSE,
   0,BUFFER_OFFSET(offset) );

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

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

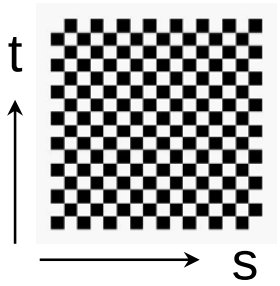
Wrapping Mode



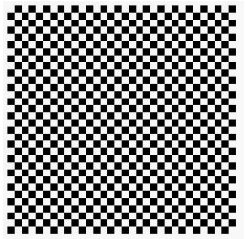
Clamping: if s,t > 1 use 1, if s,t <0 use 0

Wrapping: use s,t modulo 1

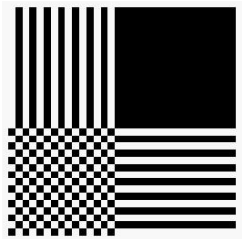
```
glTexParameteri( GL_TEXTURE_2D,
      GL_TEXTURE_WRAP_S, GL_CLAMP )
glTexParameteri( GL_TEXTURE_2D,
      GL_TEXTURE_WRAP_T, GL_REPEAT )
```



texture

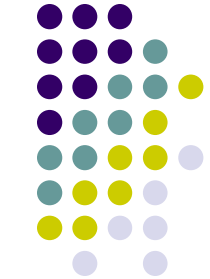


GL_REPEAT wrapping



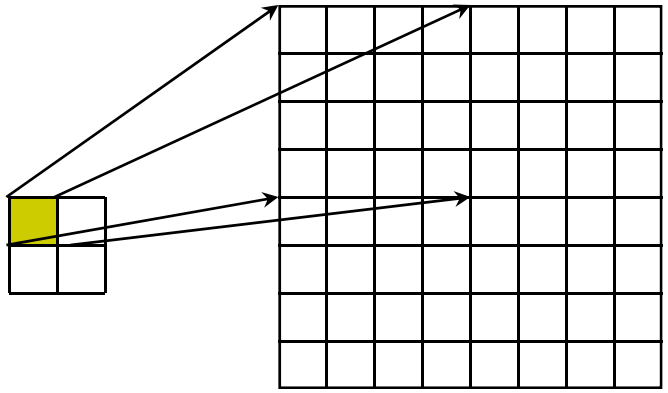
GL_CLAMP wrapping

Magnification and Minification



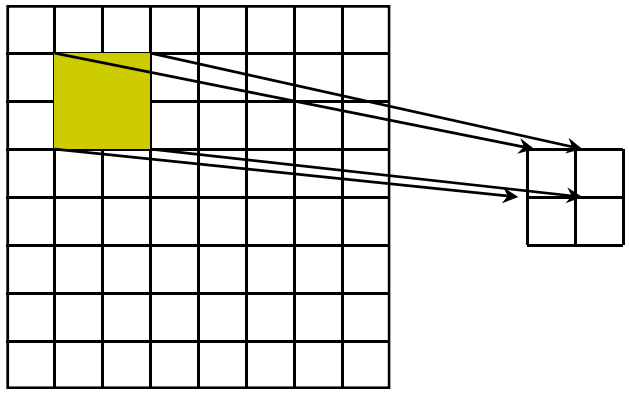
More than one texel can cover a pixel (*minification*) or more than one pixel can cover a texel (*magnification*)

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



Texture Polygon

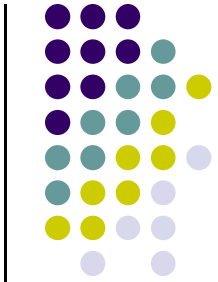
Magnification



Texture Polygon

Minification

Filter Modes

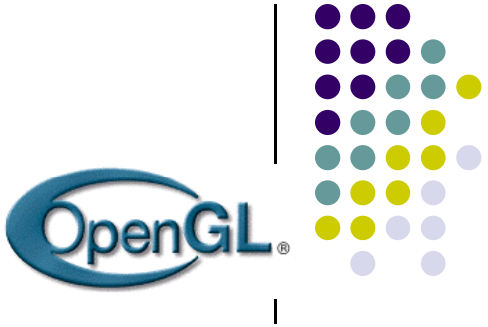


Modes determined by

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

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

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

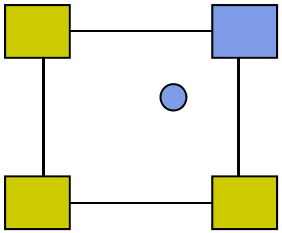
Note that linear filtering requires a border of an extra texel for filtering at edges (border = 1)



Texture mapping parameters

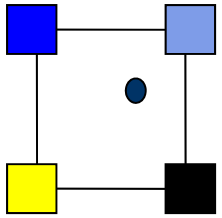
- OpenGL texture filtering:

1) Nearest Neighbor (lower image quality)



glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_NEAREST);

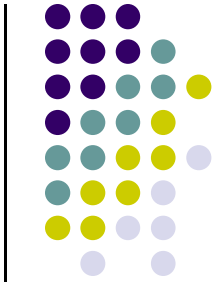
2) Linear interpolate the neighbors (better quality, slower)



glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR)

Or GL_TEXTURE_MAX_FILTER

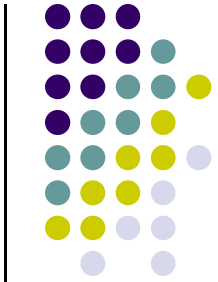
Mipmapped Textures



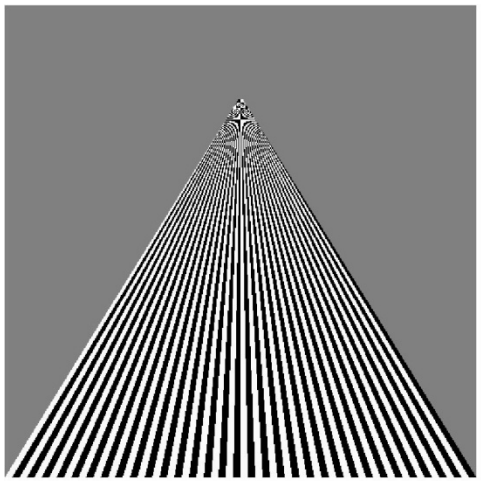
- *Mipmapping* allows for prefiltered texture maps of decreasing resolutions
- Lessens interpolation errors for smaller textured objects
- Declare mipmap level during texture definition

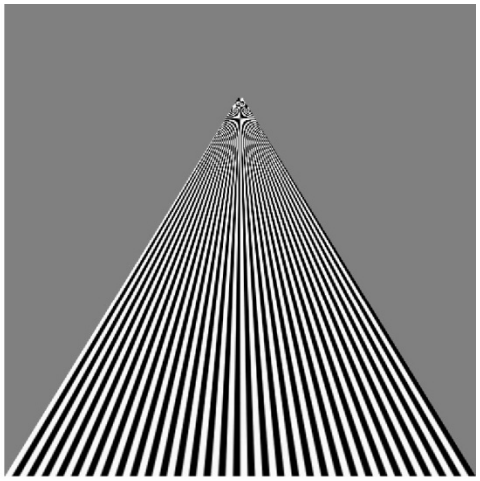
```
glTexImage2D( GL_TEXTURE_*D, level, … )
```

Example



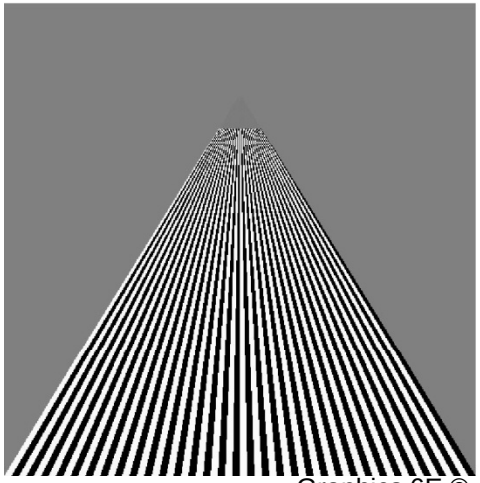
point sampling

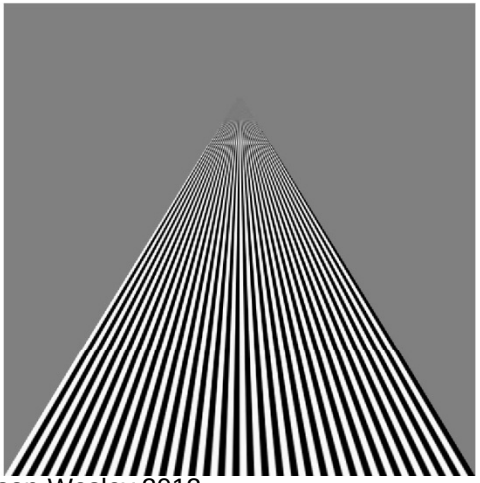




linear filtering

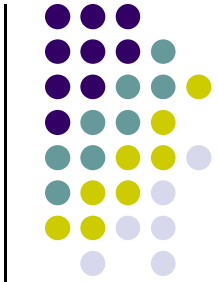
mipmapped point sampling





mipmapped linear filtering

Texture Functions



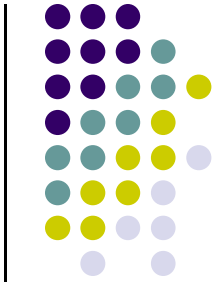
- Controls how texture is applied
  - **`glTexEnv{fi}[v]( GL_TEXTURE_ENV, prop, param )`**
- **`GL_TEXTURE_ENV_MODE`** modes
  - **`GL_MODULATE:`** multiply texture and object color
  - **`GL_BLEND:`** linear combination of texture and object color
  - **`GL_REPLACE:`** use only texture color
  - **`GL(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE);`**
- E.g: glTexEnvf(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_REPLACE);

Enable (Disable) Textures

- Enable texture – glEnable(GL_TEXTURE_2D)
- Disable texture – glDisable(GL_TEXTURE_2D)

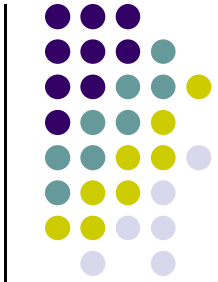
- Remember to disable texture mapping when you draw non-textured polygons

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

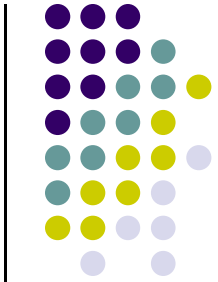
Applying Textures



- Textures are applied during fragments 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 );
}
```

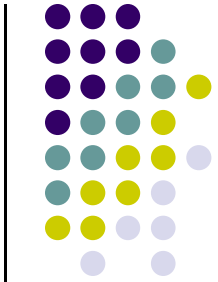
Vertex Shader



- 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

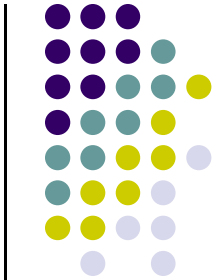
```
in vec4 vPosition; //vertex position in object coordinates
in vec4 vColor;  //vertex color from application
in vec2 vTexCoord; //texture coordinate from application

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

Adding Texture Coordinates



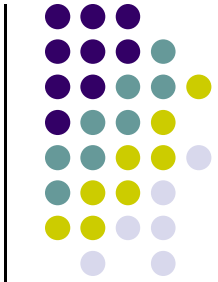
```
void quad( int a, int b, int c, int d )
{
    quad_colors[Index] = colors[a];
    points[Index] = vertices[a];
    tex_coords[Index] = vec2( 0.0, 0.0 );
    index++;
   quad_colors[Index] = colors[b];
    points[Index] = vertices[b];
    tex_coords[Index] = vec2( 0.0, 1.0 );
    Index++;

// other vertices
}
```

Texture Object



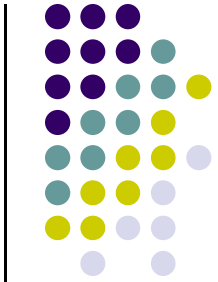
```
GLuint textures[1];
 glGenTextures( 1, textures );

 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 );
```

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 );
```

Other Stuff



- Wrapping texture onto curved surfaces. E.g. cylinder, can, etc

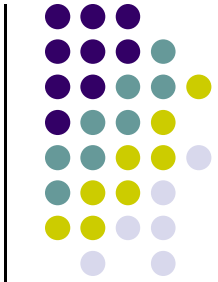
$$s = \frac{\theta - \theta_a}{\theta_b - \theta_a} \qquad t = \frac{z - z_a}{z_b - z_a}$$

- Wrapping texture onto sphere

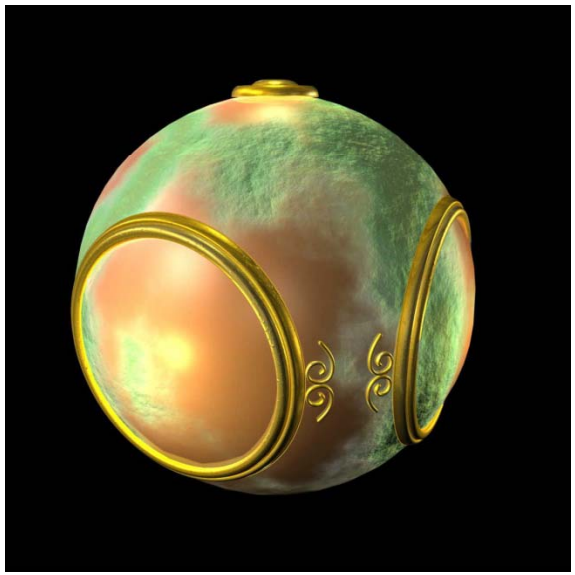
$$s = \frac{\theta - \theta_a}{\theta_b - \theta_a} \qquad s = \frac{\phi - \phi_a}{\phi_b - \phi_a}$$

- Bump mapping: perturb surface normal by a quantity proportional to texture

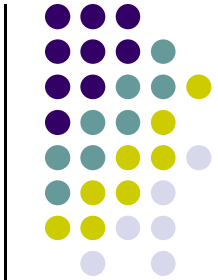
Bump Mapping



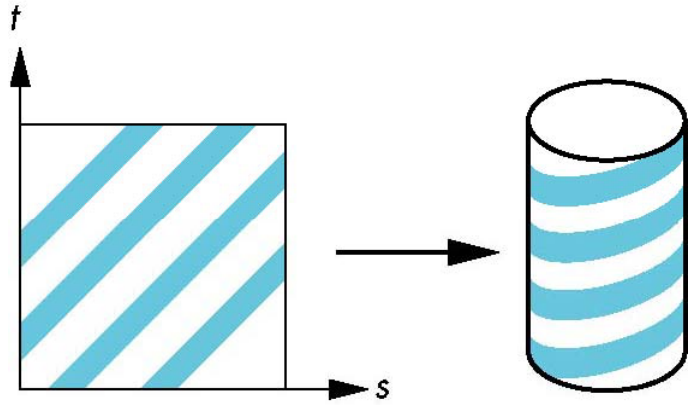
- Perturb normal for each fragment
- Store perturbation as textures



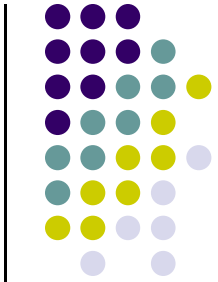
Two-part mapping



- One solution to mapping problem is to first map texture to a simple intermediate surface
- Example: map to cylinder



Cylindrical Mapping



parametric cylinder

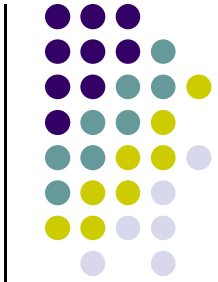
$$x = r \cos 2\pi u$$
$$y = r \sin 2\pi u$$
$$z = v/h$$

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



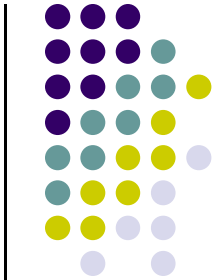
We can use a parametric sphere

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

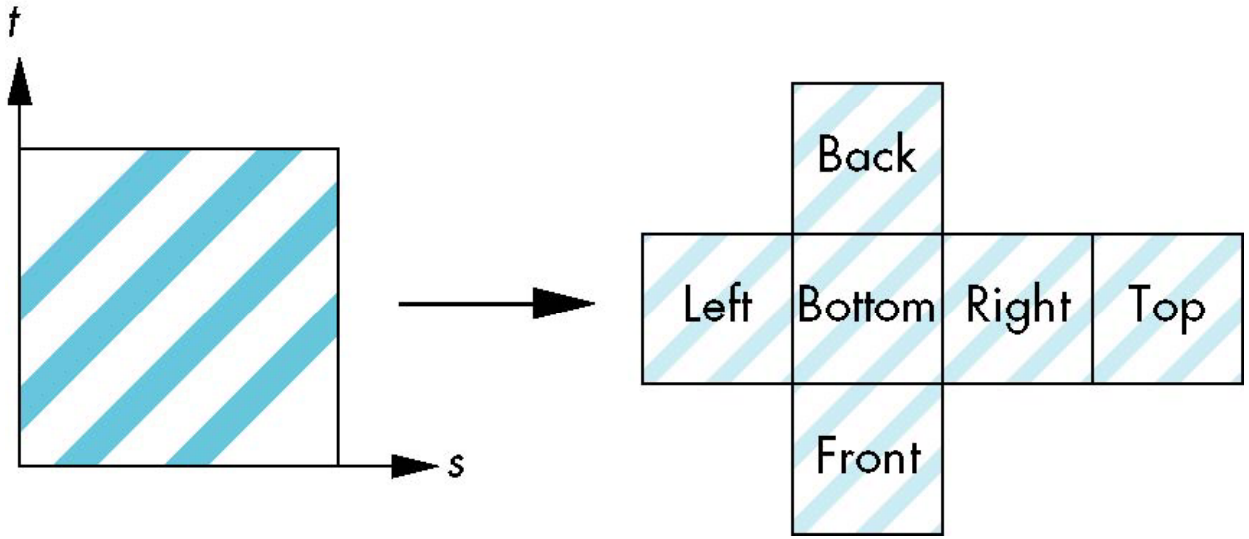
in a similar manner to the cylinder
but have to decide where to put
the distortion

Spheres are used in environmental maps

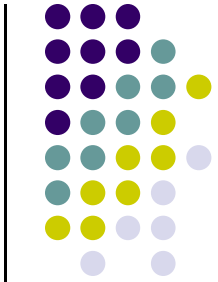
Box Mapping



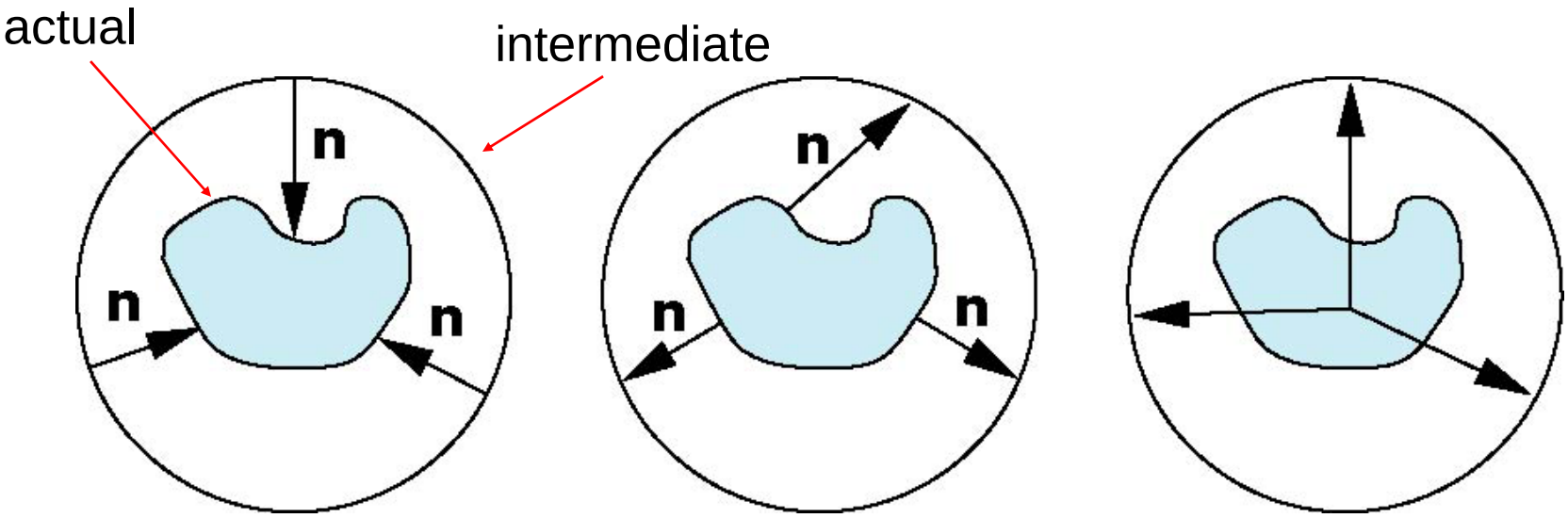
- Easy to use with simple orthographic projection
- Also used in environment maps



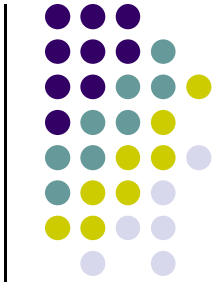
Second Mapping



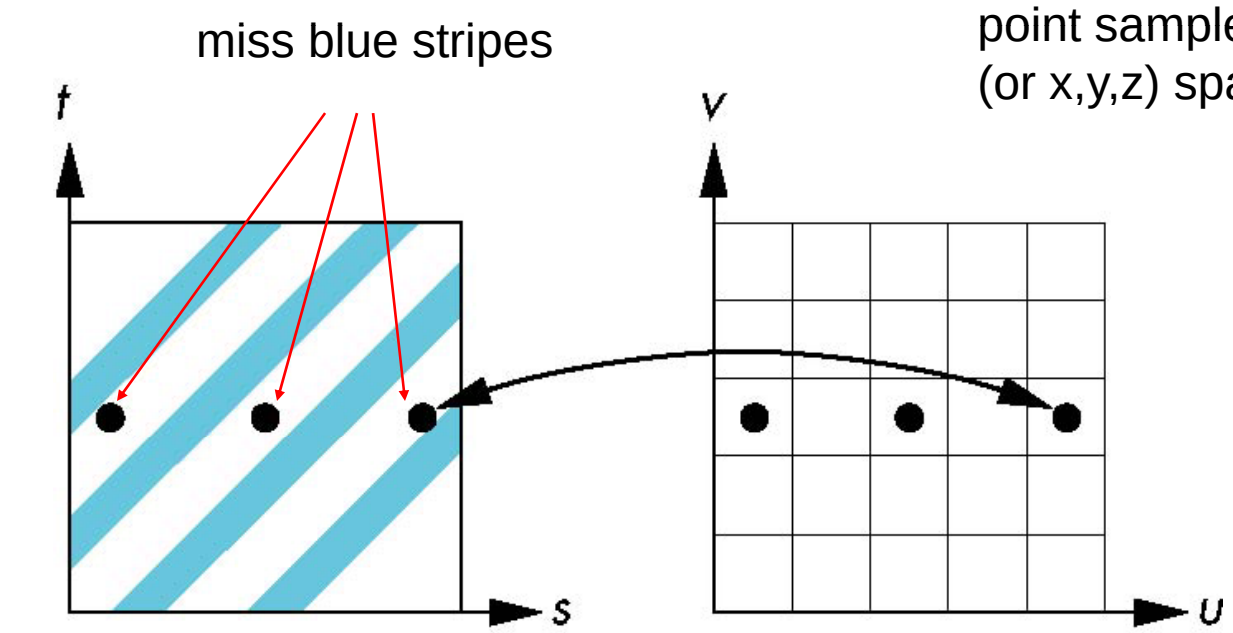
- Map from intermediate object to actual object



Aliasing

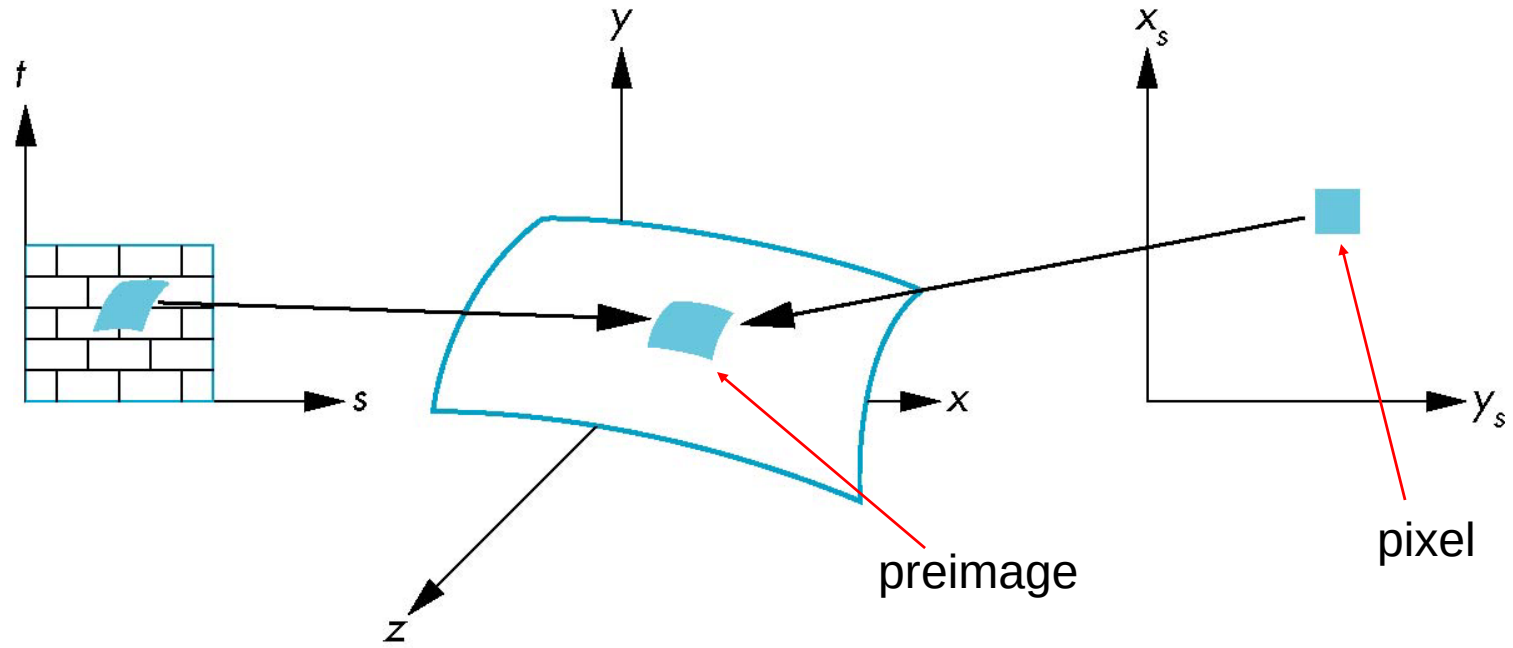


- Point sampling of the texture can lead to aliasing errors



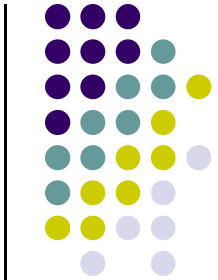
Area Averaging

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



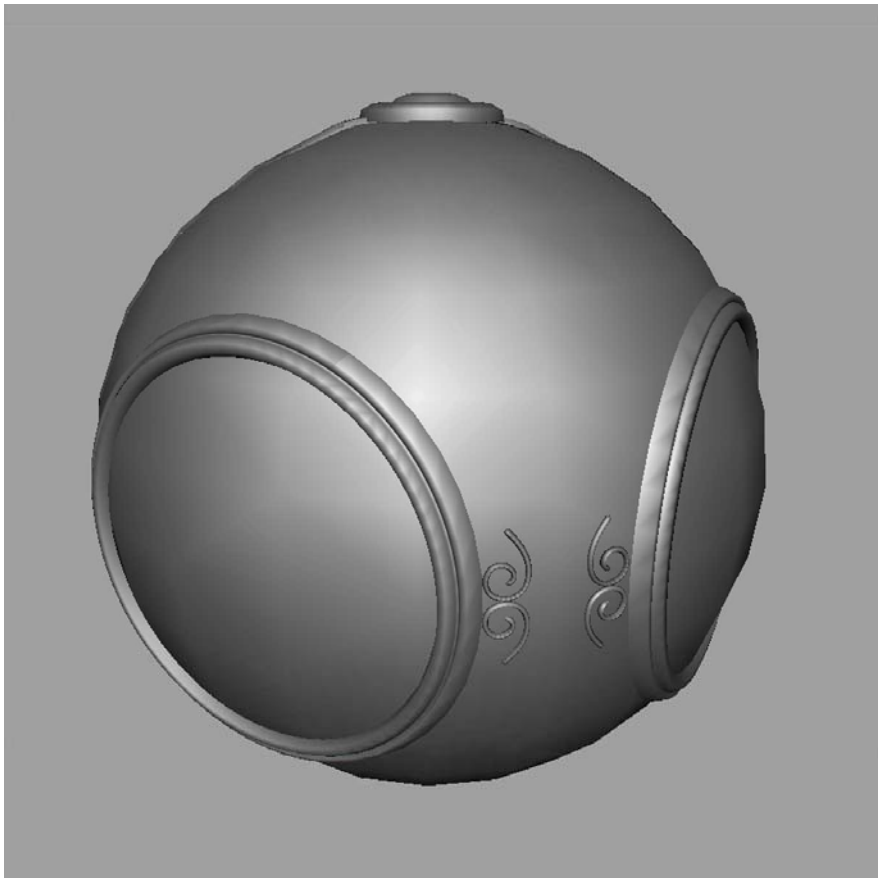
Note that *preimage* of pixel is curved

Introduction



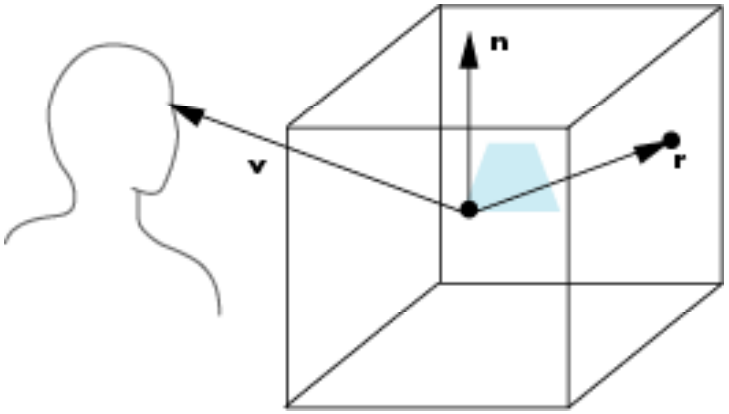
- Environmental mapping is way to create the appearance of highly reflective surfaces without ray tracing which requires global calculations
- Examples: The Abyss, Terminator 2
- Is a form of texture mapping
  - Supported by OpenGL and Cg

Example

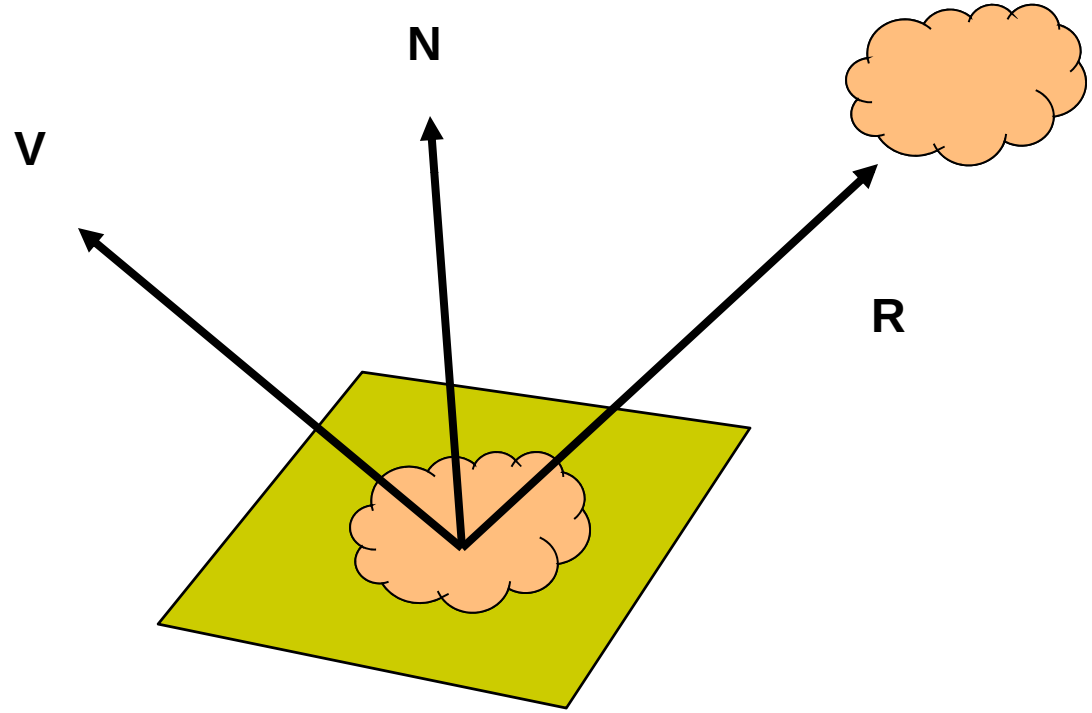


Environment Map

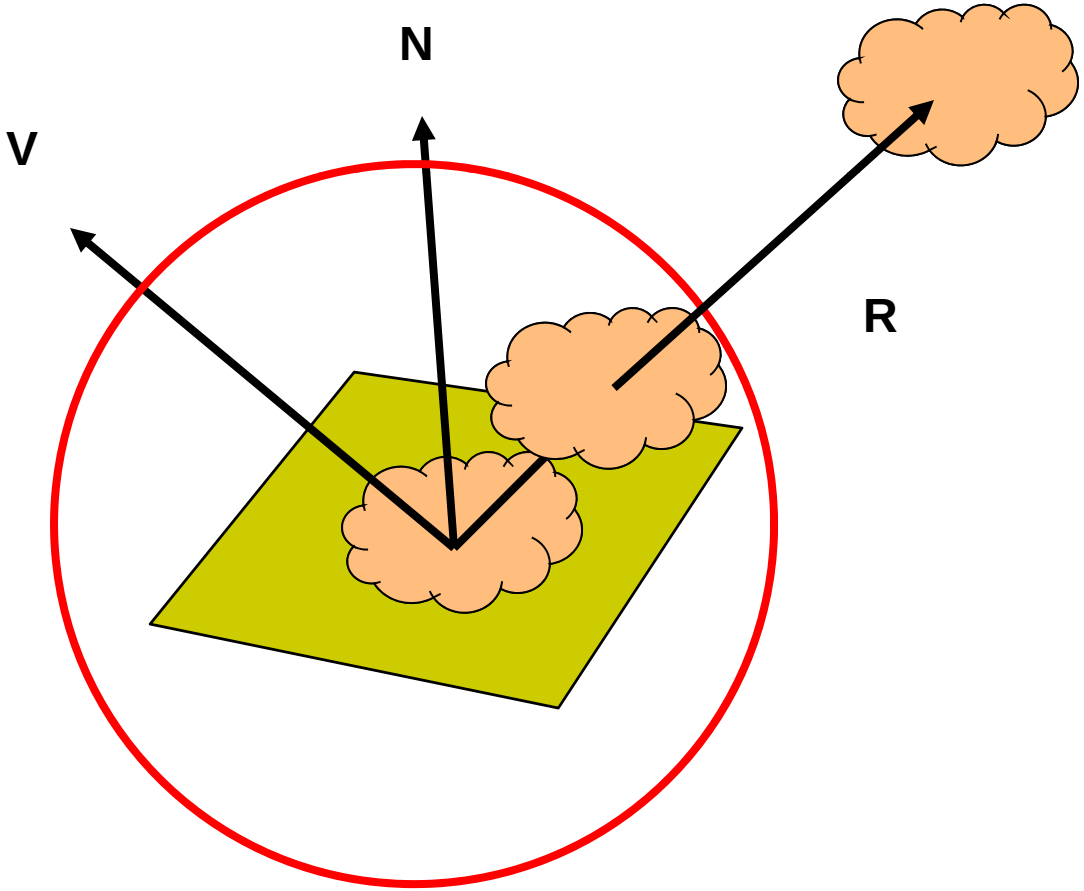
Use reflection vector to locate texture in cube map



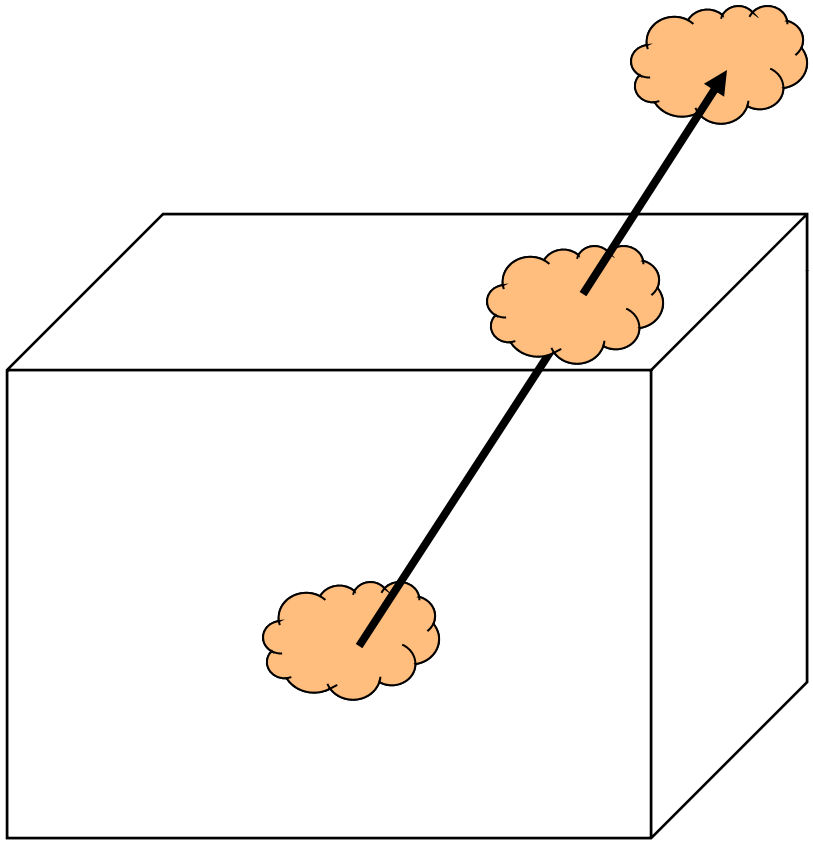
Reflecting the Environment



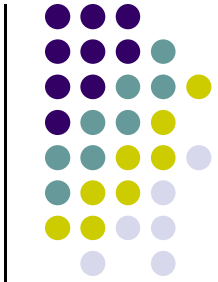
Mapping to a Sphere



Cube Map



Cube Maps

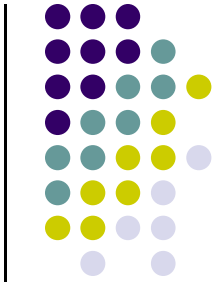


- We can form a cube map texture by defining six 2D texture maps that correspond to sides of a box
- Supported by OpenGL
- Also supported in GLSL through cubemap sampler

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

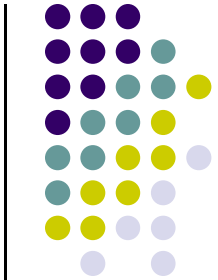
- Texture coordinates must be 3D

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

References



- Angel and Shreiner
- Hill and Kelley,