CSCI 420 Computer Graphics
Lecture 12

# Texture Mapping

Texture Mapping + Shading
Filtering and Mipmaps
Non-color Texture Maps
[Angel Ch. 7]

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# Texture Mapping

- A way of adding surface details

- Two ways can achieve the goal:
  - Model the surface with more polygons
    - » Slows down rendering speed
    - » Hard to model fine features
  - Map a texture to the surface
    - » This lecture
    - » Image complexity does not affect complexity of processing

- Efficiently supported in hardware

# Trompe L'Oeil ("Deceive the Eye")

Jesuit Church, Vienna, Austria

- Windows and columns in the dome are painted, not a real 3D object
- Similar idea with texture mapping:

Rather than modeling the intricate 3D geometry, replace it with an image !

# Map textures to surfaces

an image

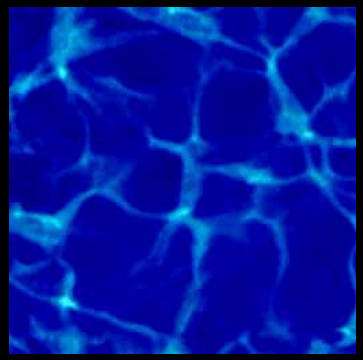
texture map

image mapped
to a 3D polygon

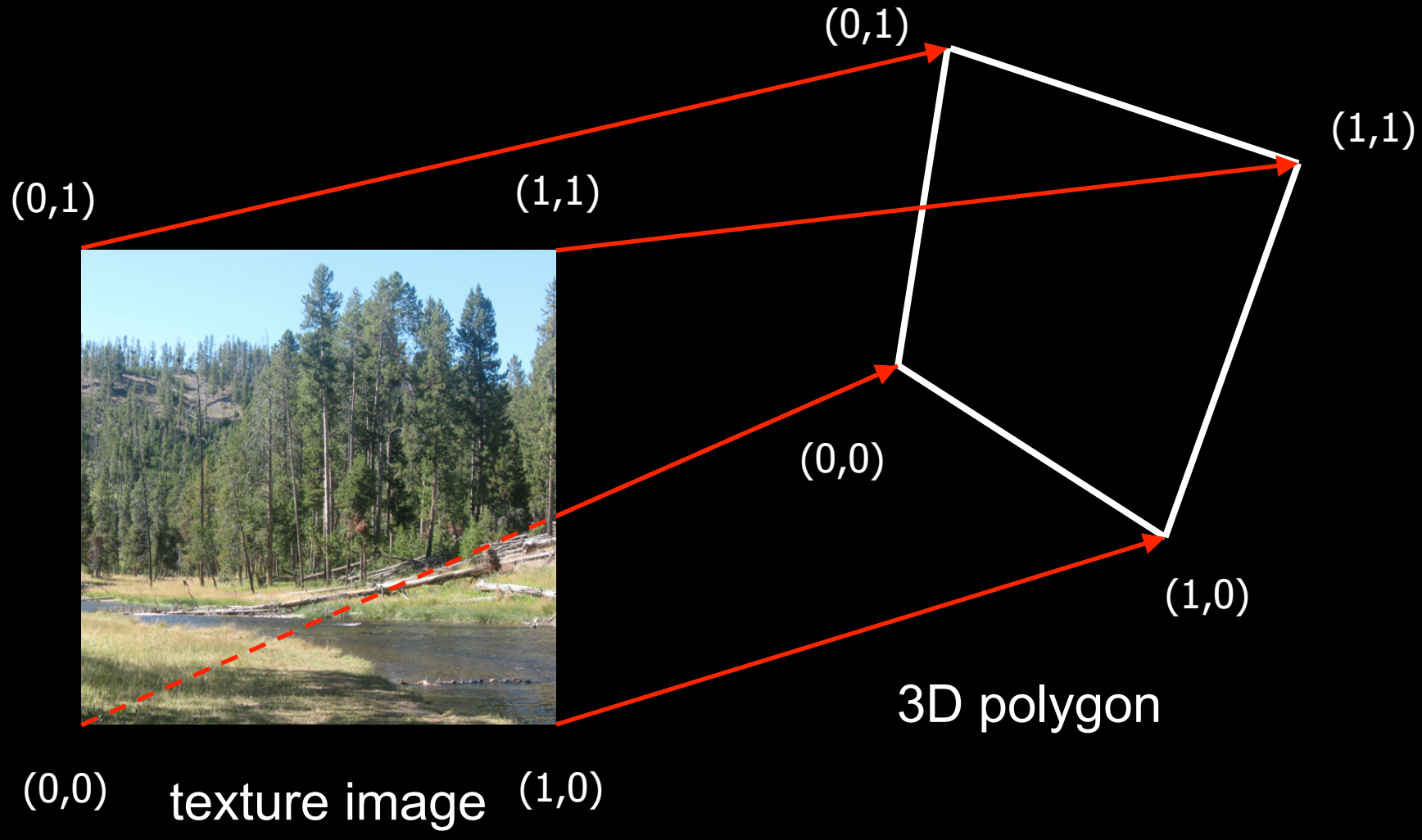
The polygon can have arbitrary size, shape and 3D position

# The texture

- Texture is a bitmap image
  - Can use an image library to load image into memory
  - Or can create images yourself within the program
- 2D array:
  unsigned char texture[height][width][4]
- Or unrolled into 1D array:
  unsigned char texture[4*height*width]
- Pixels of the texture are called *texels*
- Texel coordinates (s,t) scaled to [0,1] range



# Texture map



# Texture map

(0,1) (1,1)

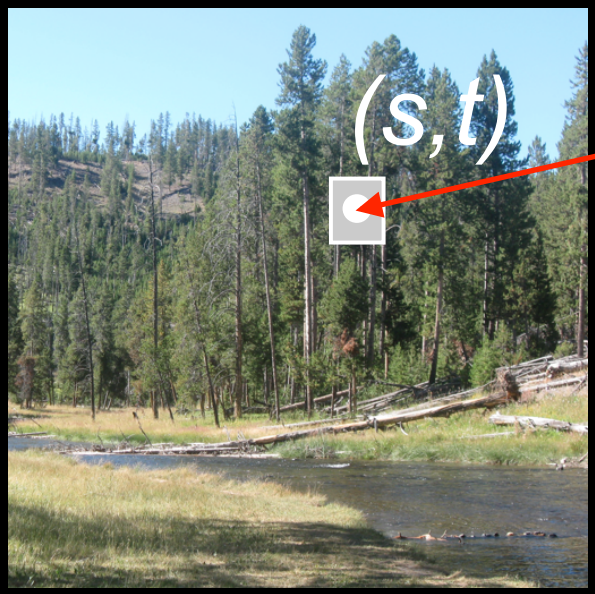
(0,0) texture image (1,0)

(0,1) (1,1)

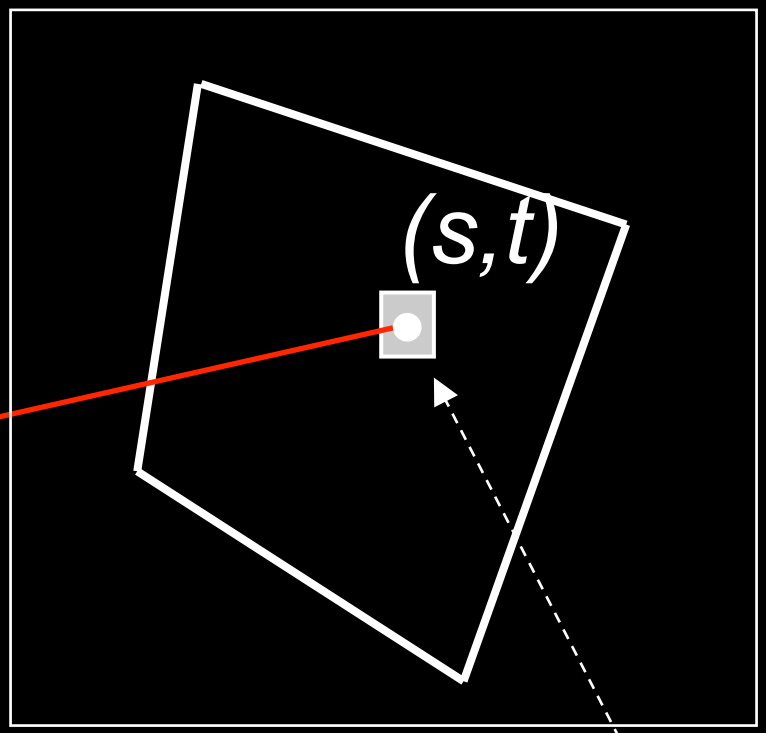
(0,0) (1,0)

3D polygon

# Texture coordinates



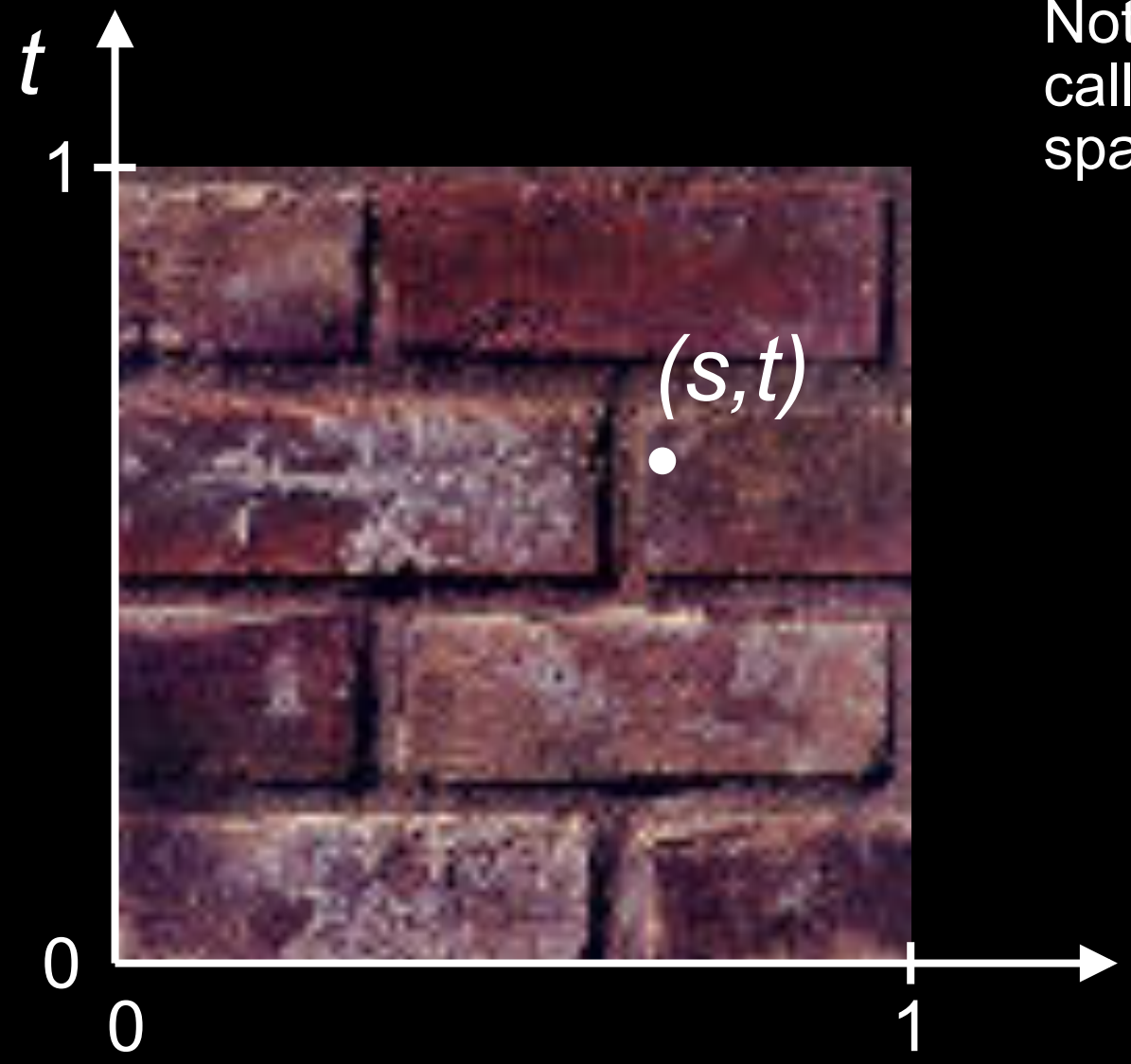

texture image




screen image

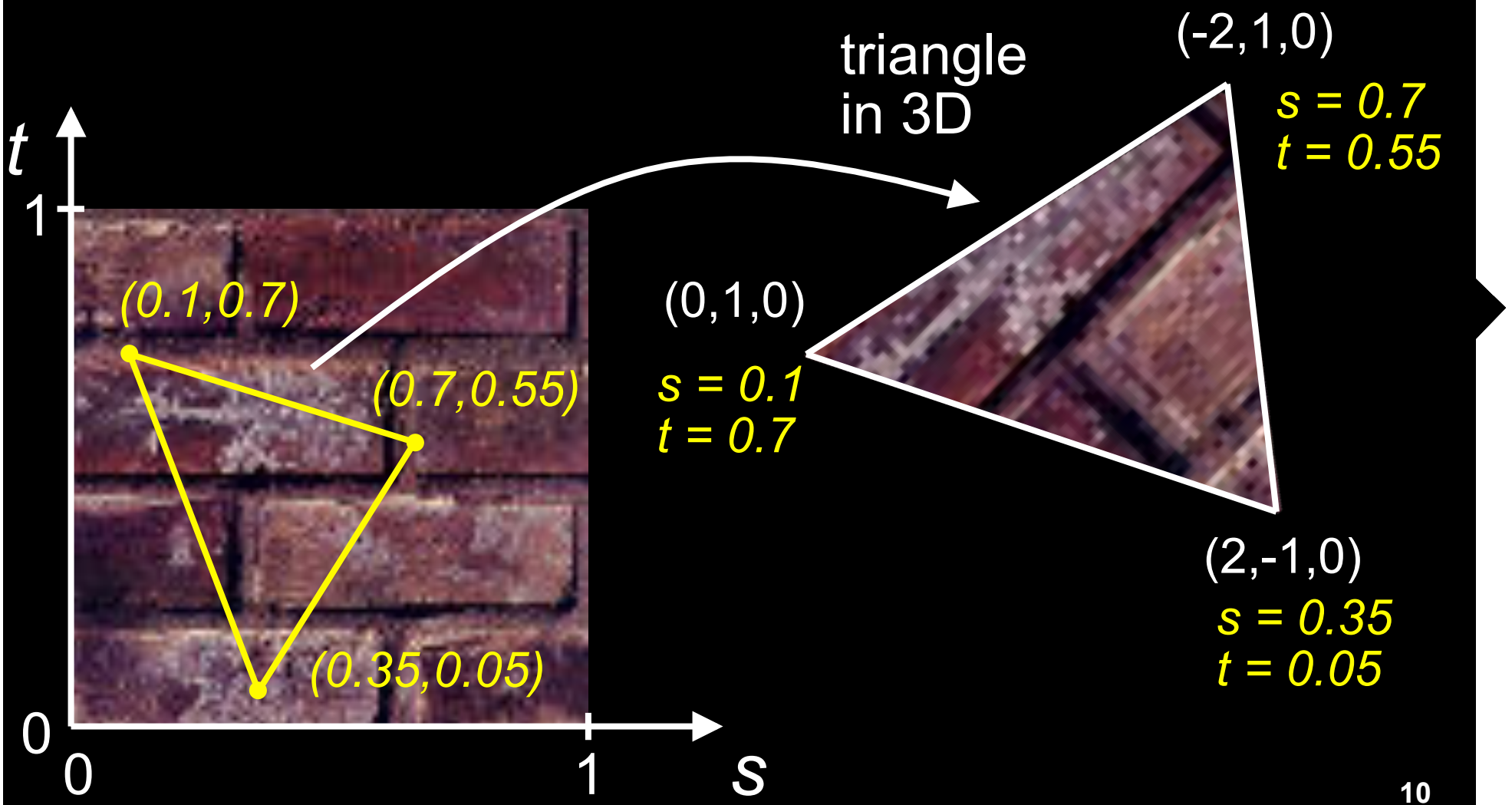
For each pixel, lookup into the texture image to obtain color.

# The “st” coordinate system



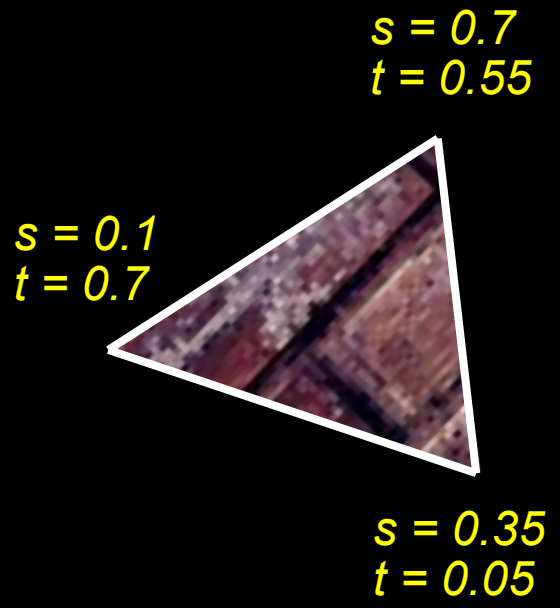

Note: also called “uv” space

# Texture mapping: key slide



# Specifying texture coordinates in OpenGL (core profile)

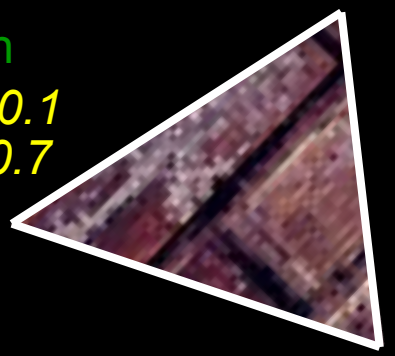
- Use VBO
- Either create a separate VBO for texture coordinates, or put them with vertex positions into one VBO



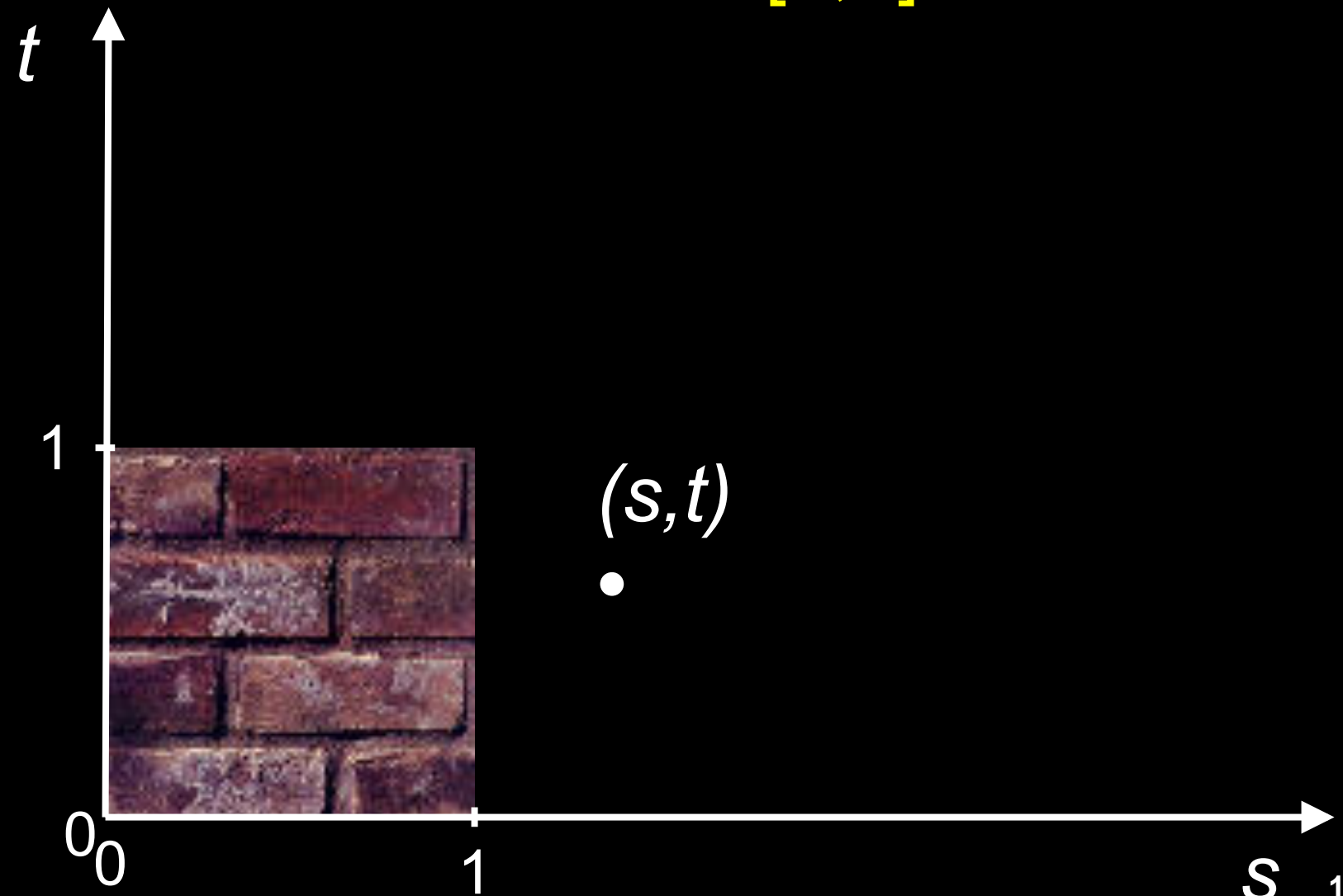
# Specifying texture coordinates in OpenGL (compatibility profile)

- Use glTexCoord2f(s,t)
- State machine: Texture coordinates remain valid until you change them
- Example (from the previous slide) :

```
glEnable(GL_TEXTURE_2D); // turn texture mapping on
glBegin(GL_TRIANGLES);
  glTexCoord2f(0.35,0.05); glVertex3f(2.0,-1.0,0.0);
  glTexCoord2f(0.7,0.55); glVertex3f(-2.0,1.0,0.0);
  glTexCoord2f(0.1,0.7); glVertex3f(0.0,1.0,0.0);
glEnd();
glDisable(GL_TEXTURE_2D); // turn texture mapping off
```

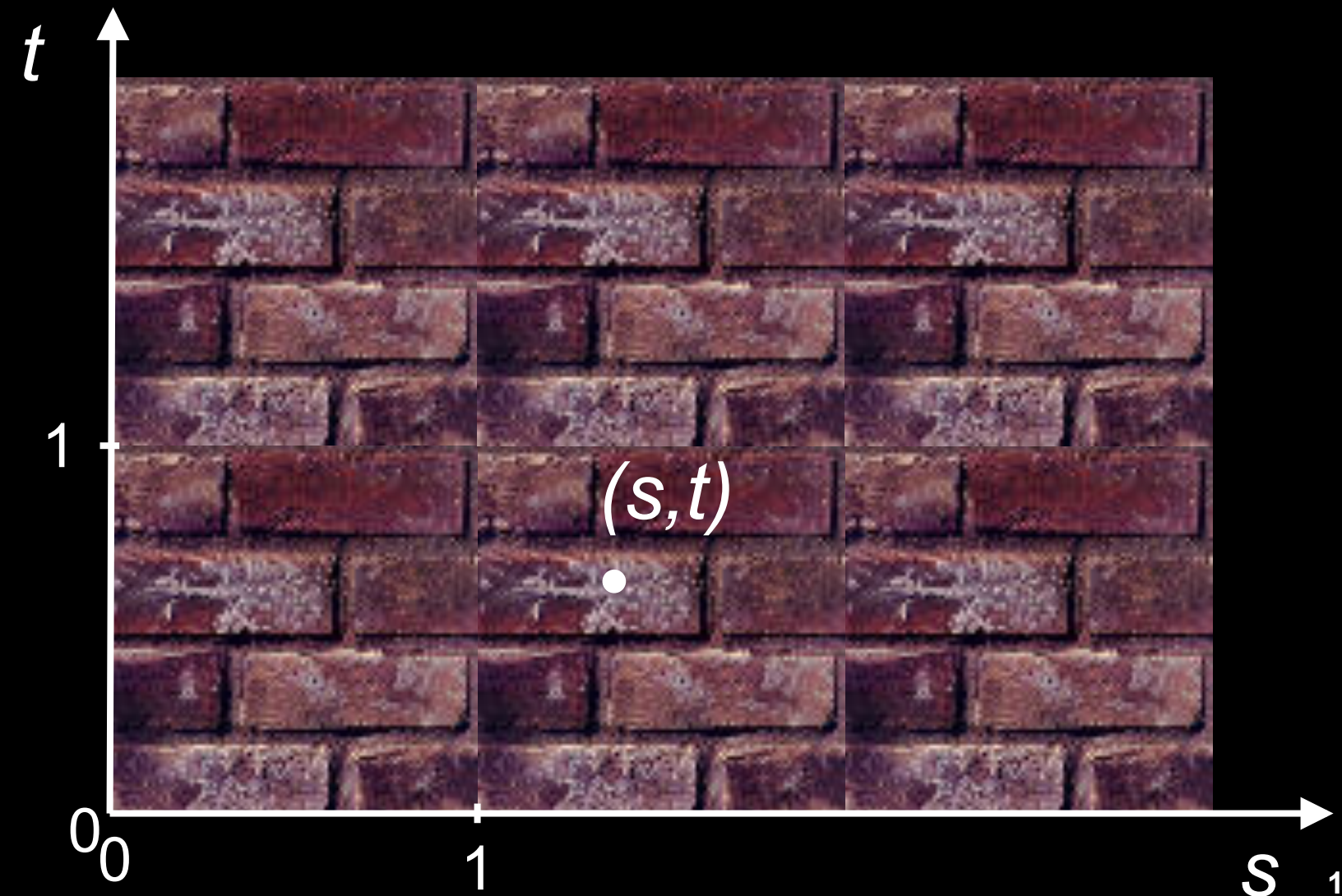


# What if texture coordinates are outside of [0,1] ?



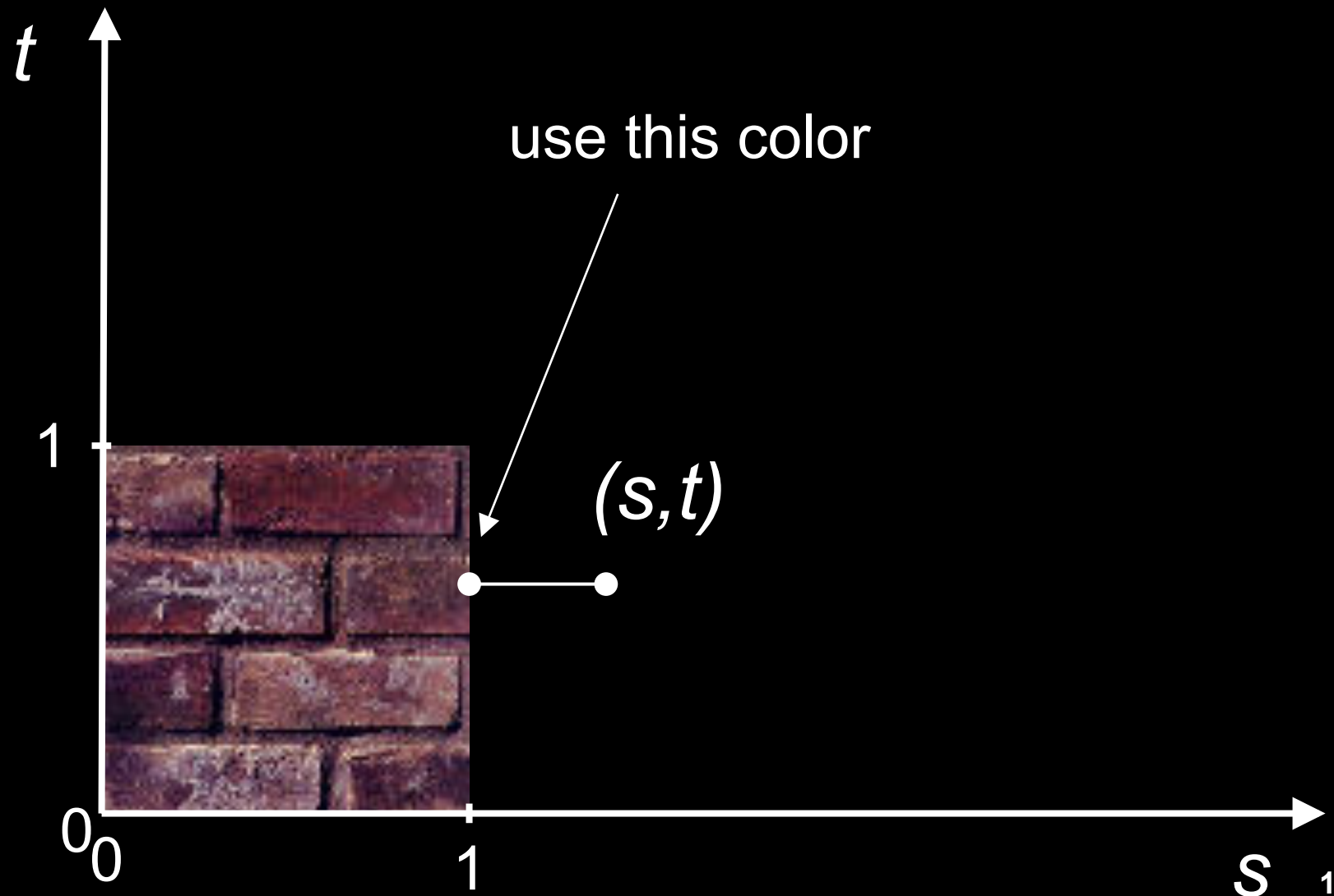
# Solution 1: Repeat texture

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

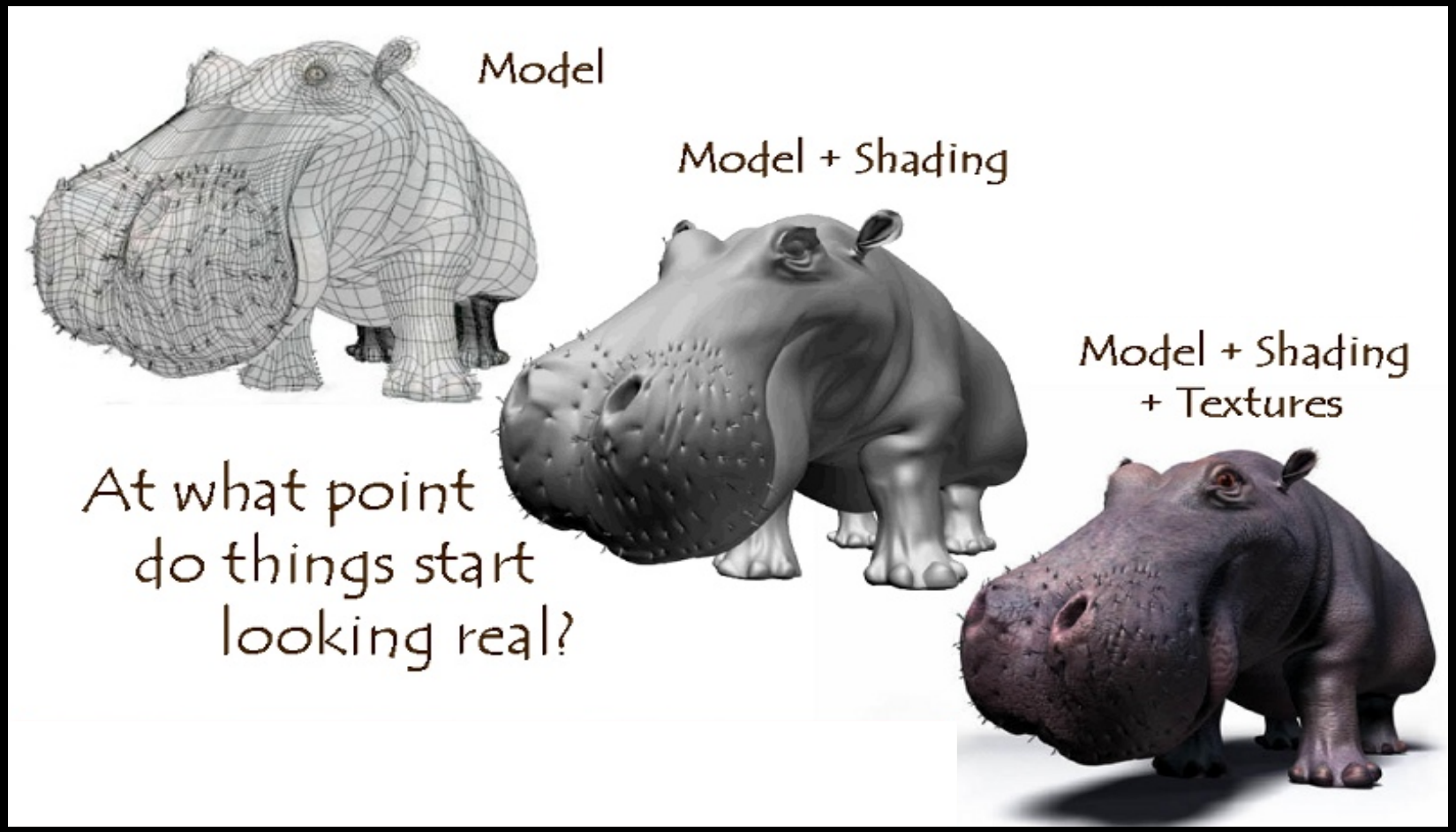


# Solution 2: Clamp to [0,1]

glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_CLAMP_TO_EDGE)
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_CLAMP_TO_EDGE)



# Combining texture mapping and shading



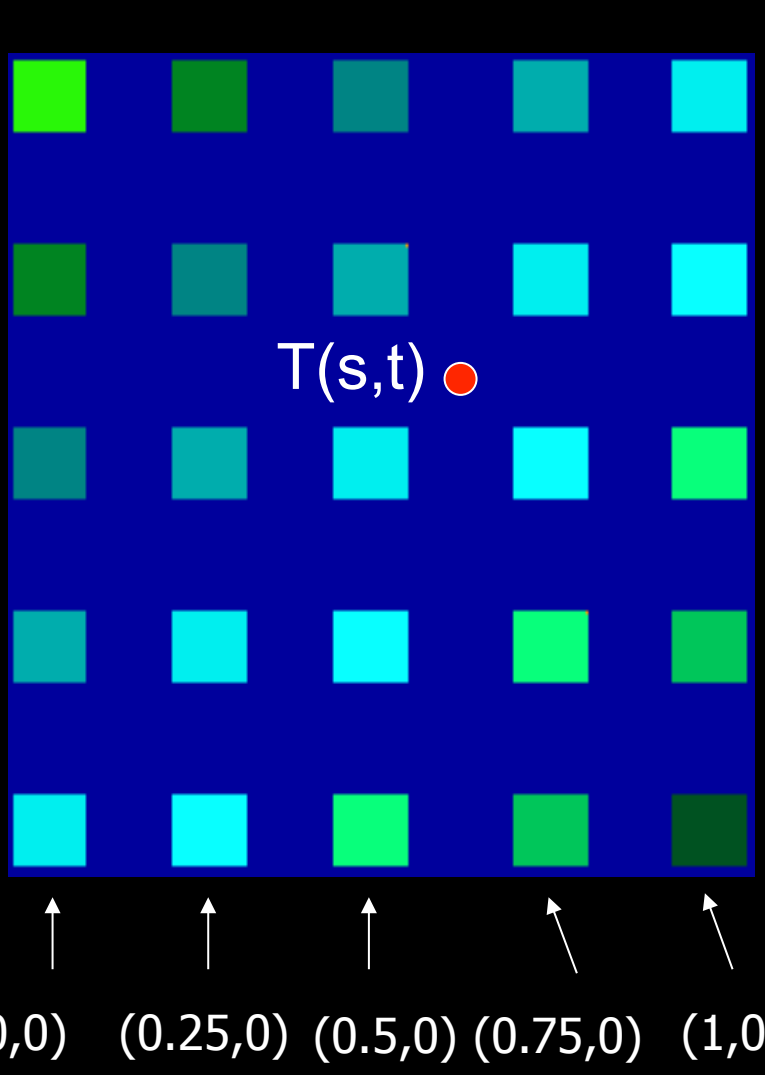

Source: Jeremy Birn

# Outline

- Introduction
- Filtering and Mipmaps
- Non-color texture maps
- Texture mapping in OpenGL

# Texture interpolation

5 x 5 texture



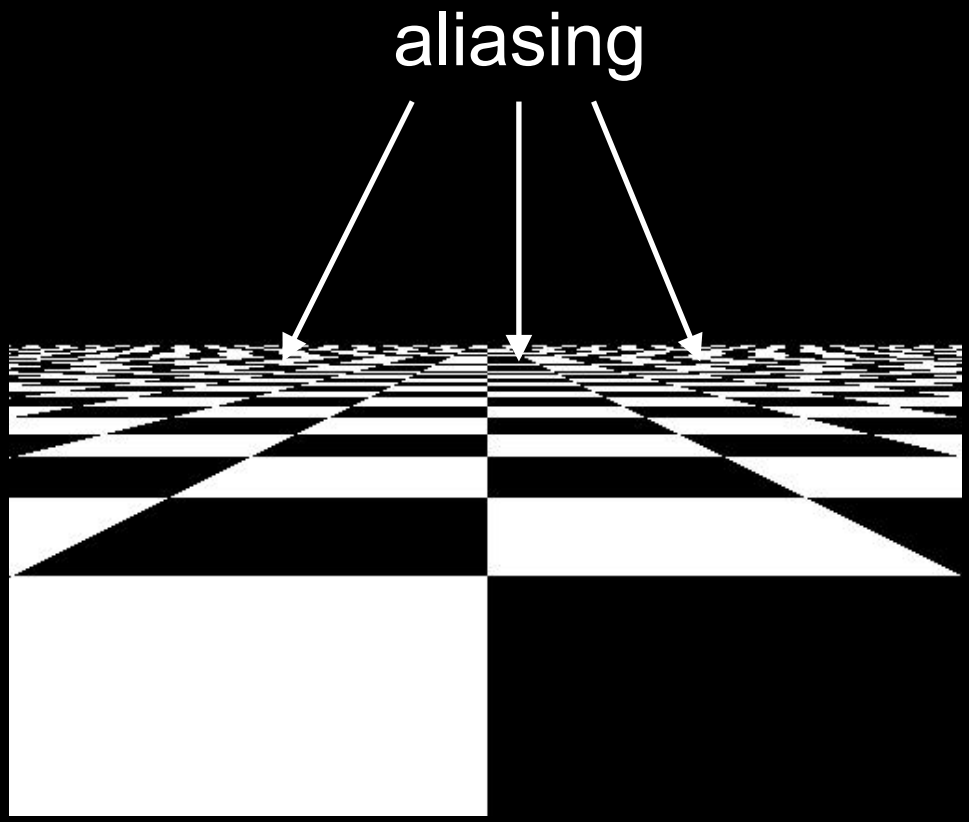

(s,t) coordinates typically not directly at pixel in the texture, but in between

# Texture interpolation

- (s,t) coordinates typically not directly at pixel in the texture, but in between
- Solutions:
  - Use the nearest neighbor to determine color
    - » Faster, but worse quality
    - » glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_NEAREST);
  - Linear interpolation
    - » Incorporate colors of several neighbors to determine color
    - » Slower, better quality
    - » glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR)

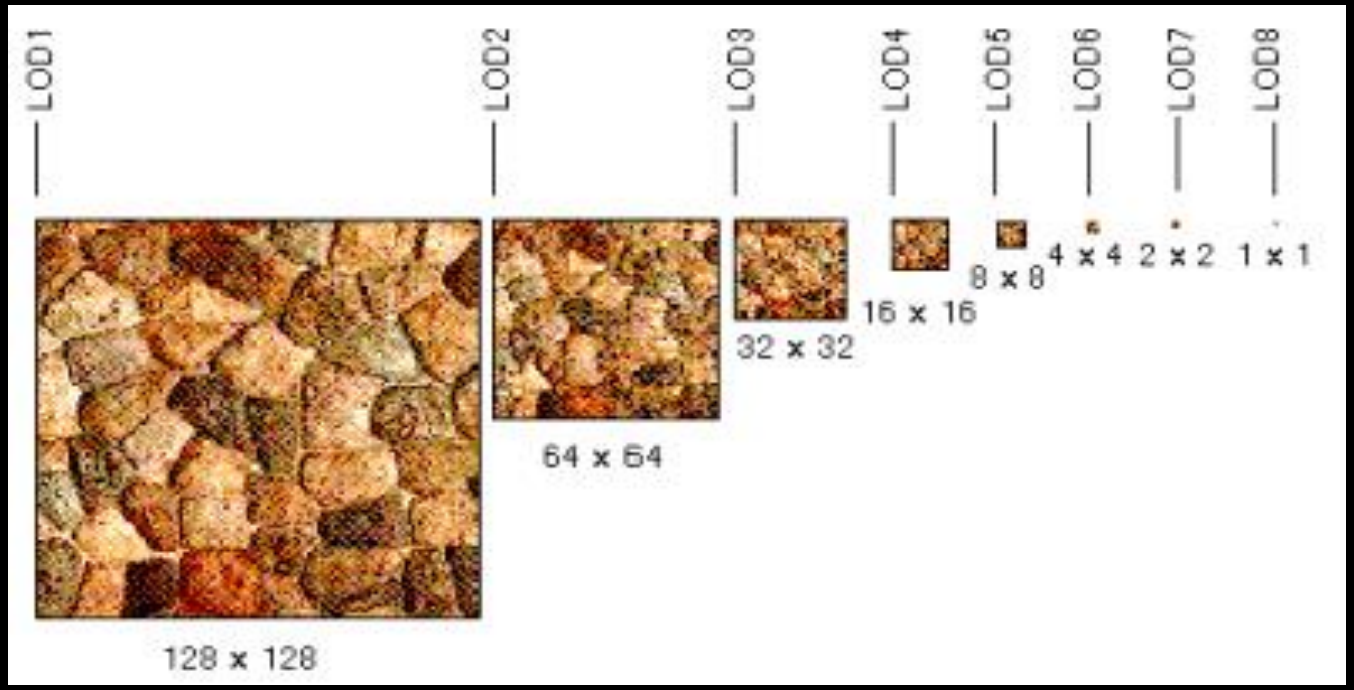
# Filtering

- Texture image is shrunk in distant parts of the image
- This leads to aliasing
- Can be fixed with *filtering*
  - bilinear in space
  - trilinear in space and level of detail (mipmapping)



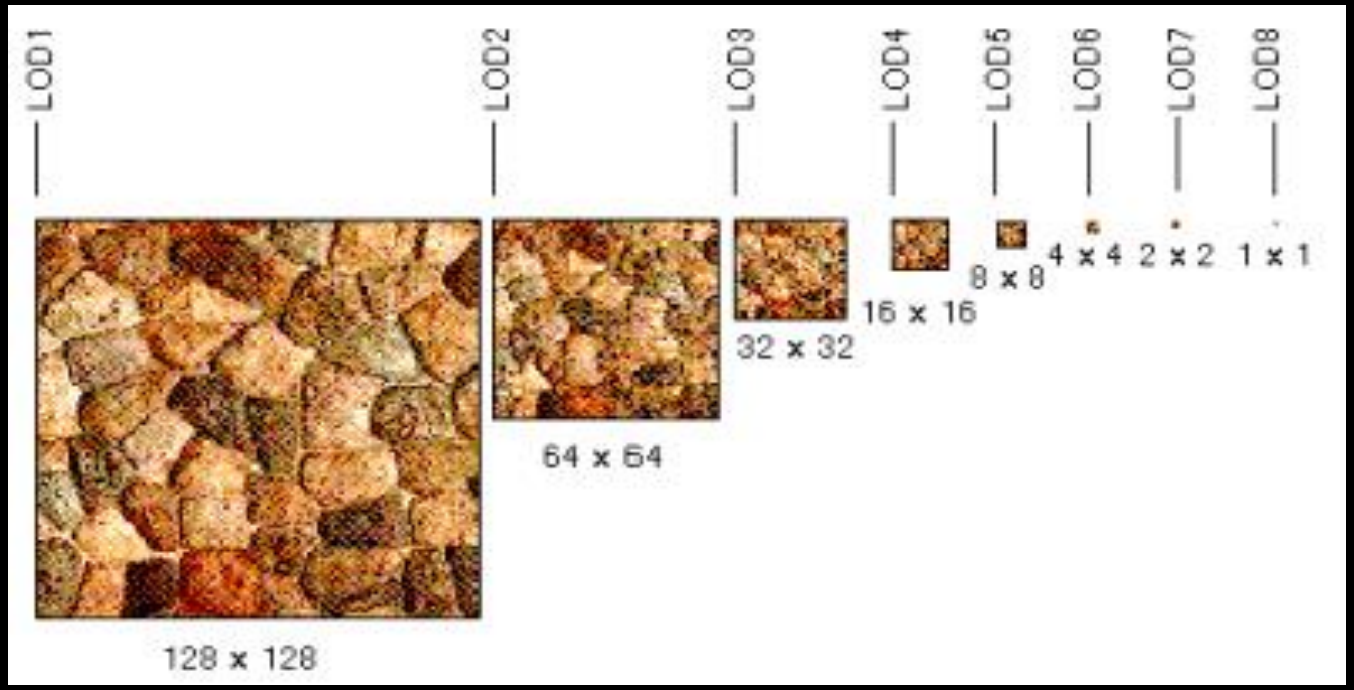
# Mipmapping

- Pre-calculate how the texture should look at various distances, then use the appropriate texture at each distance
- Reduces / fixes the aliasing problem



# Mipmapping

- Each mipmap (each image below) represents a level of depth (LOD).
- Decrease image 2x at each level



# Mipmapping in OpenGL

- Generate mipmaps automatically
  (for the currently bound texture):

  Core profile:
  ```
  glGenerateMipmap(GL_TEXTURE_2D);
  ```

  Compatibility profile:
  ```
  gluBuild2DMipmaps(GL_TEXTURE_2D,
    components, width, height, format, type, data)
  ```

- Must also instruct OpenGL to use mipmaps:

  ```
  glTexParameteri(GL_TEXTURE_2D,
        GL_TEXTURE_MIN_FILTER,
        GL_LINEAR_MIPMAP_LINEAR)
  ```

# Outline

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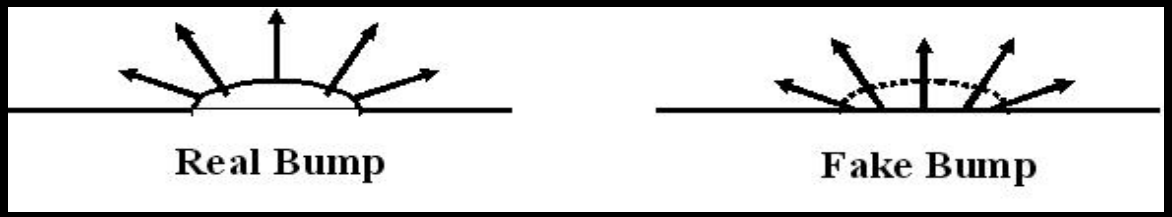
# Textures do not have to represent color

- Specularity (patches of shininess)
- Transparency (patches of clearness)
- Normal vector changes (bump maps)
- Reflected light (environment maps)
- Shadows
- Changes in surface height (displacement maps)

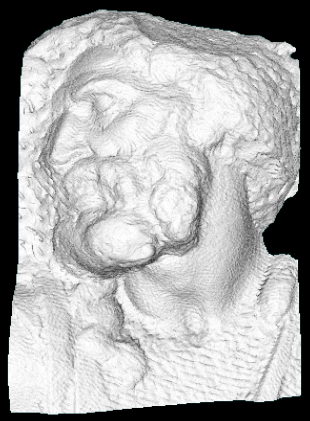
# Bump mapping

- How do you make a surface look *rough*?
  - Option 1: model the surface with many small polygons
  - Option 2: perturb the normal vectors before the shading calculation
    - » Fakes small displacements above or below the true surface
    - » The surface doesn't actually change, but shading makes it look like there are irregularities!
    - » A texture stores information about the "fake" height of the surface

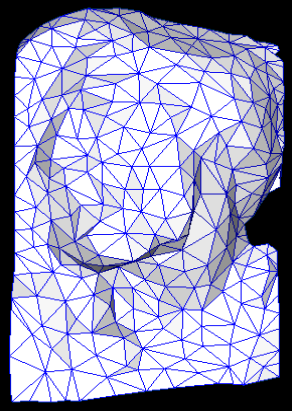


# Bump mapping

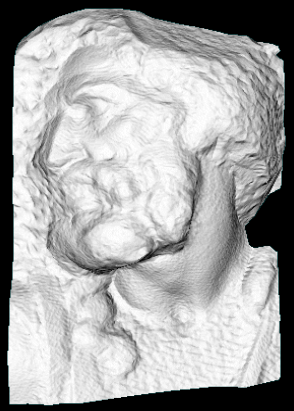
- We can perturb the normal vector without having to make any actual change to the shape.
- This illusion can be seen through—how?



Original model (5M)



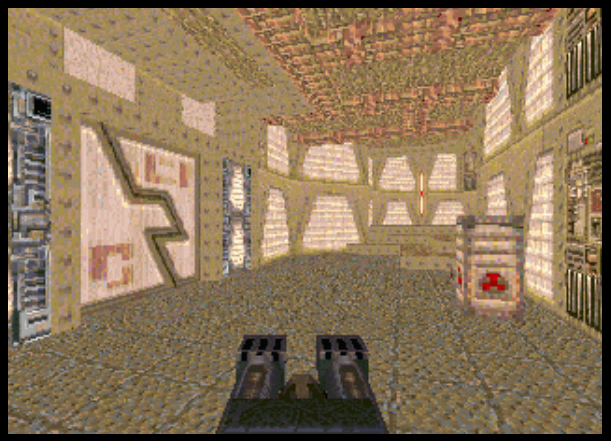
Simplified (500)



Simple model with bump map

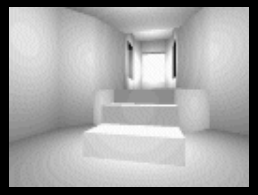
# Light Mapping

- *Quake* uses *light maps* in addition to texture maps. Texture maps are used to add detail to surfaces, and light maps are used to store pre-computed illumination. The two are multiplied together at run-time, and cached for efficiency.



Texture Map Only

Texture + Light Map



Light Map

# Outline

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# OpenGL Texture Mapping (Core Profile)

- During initialization:
  1. Read texture image from file into an array in memory, or generate the image using your program
  2. Initialize the texture (glTexImage2D)
  3. Specify texture mapping parameters:
     - » Repeat/clamp, filtering, mipmapping, etc.
  4. Make VBO for the texture coordinates
  5. Create VAO
- In display():
  1. Bind VAO
  2. Select the texture unit, and texture (using glBindTexture)
  3. Render (e.g., glDrawArrays)

# Read texture image from file into an array in memory

- Can use our ImageIO library

- ```
  ImageIO * imageIO = new ImageIO();
  if (imageIO->loadJPEG(imageFilename) != ImageIO::OK)
  {
     cout << “Error reading image “ << imageFilename << “.” << endl;
     exit(EXIT_FAILURE);
  }
  ```

- See starter code for hw2
  ```

# Initializing the texture

- Do once during initialization, for each texture image in the scene, by calling glTexImage2D
- The dimensions of texture images must be a multiple of 4 (Note: they do NOT have to be a power of 2)
- Can load textures dynamically if GPU memory is scarce:

  Delete a texture (if no longer needed) using glDeleteTextures

# glTexImage2D

- glTexImage2D(GL_TEXTURE_2D, level, internalFormat, width, height, border, format, type, data)

- GL_TEXTURE_2D: specifies that it is a 2D texture
- Level: used for specifying levels of detail for mipmapping (default: 0)
- InternalFormat
  - Often: GL_RGB or GL_RGBA
  - Determines how the texture is stored internally
- Width, Height
  - The size of the texture must be a multiple of 4
- Border (often set to 0)
- Format, Type
  - Specifies what the input data is (GL_RGB, GL_RGBA, …)
  - Specifies the input data type (GL_UNSIGNED_BYTE, GL_BYTE, …)
  - Regardless of Format and Type, OpenGL converts the data to internalFormat
- Data: pointer to the image buffer

# Texture Initialization

Global variable:

```
GLUint texHandle;
```

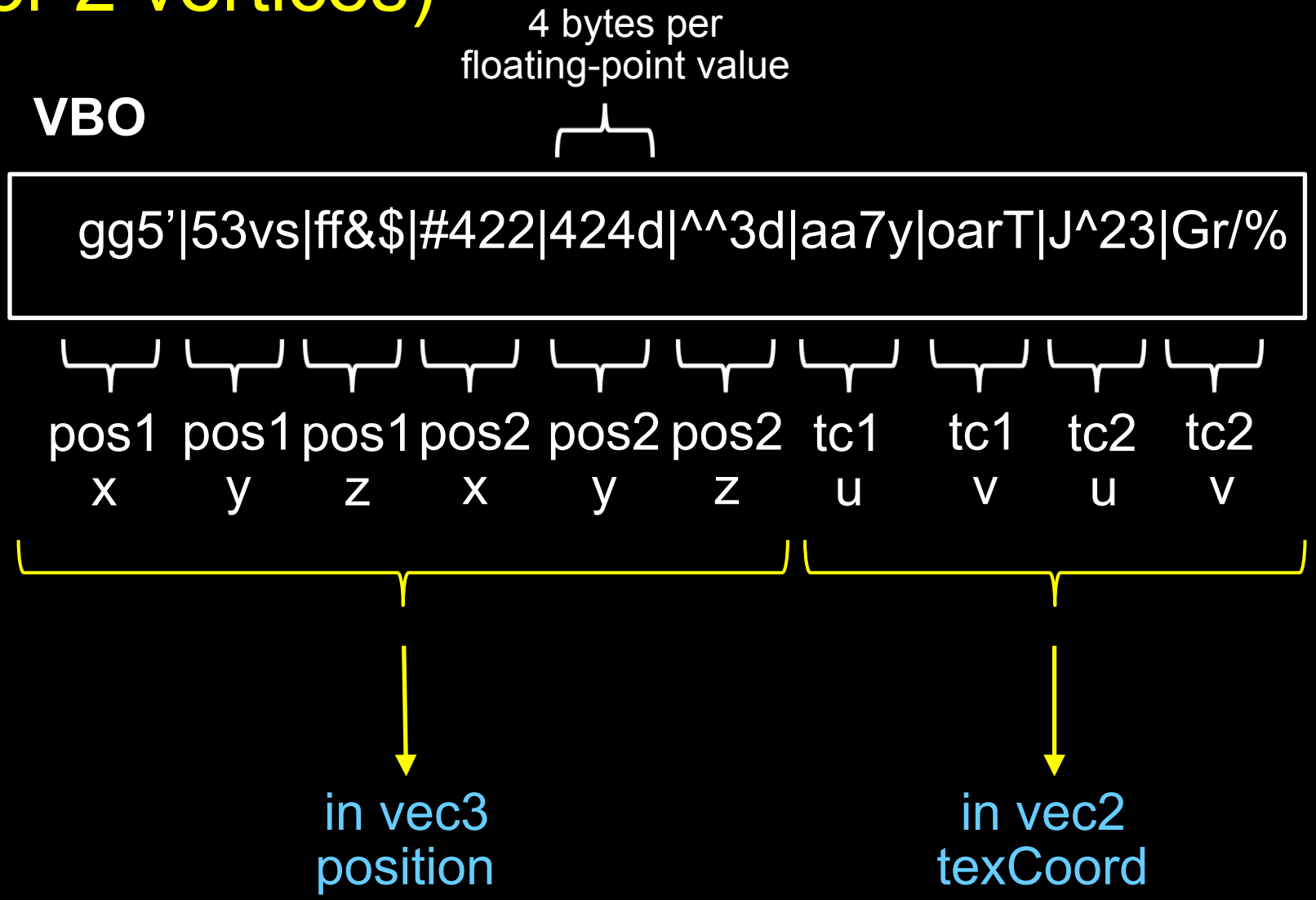
During initialization:

```
// create an integer handle for the texture
glGenTextures(1, &texHandle);

int code = initTexture("sky.jpg", texHandle);
if (code != 0)
{
  printf("Error loading the texture image.\n");
  exit(EXIT_FAILURE);
}
```

Function initTexture() is given in the starter code for hw2.

# VBO Layout: positions, texture coordinates (for 2 vertices)



# Texture Shader: Vertex Program

```
#version 150

in vec3 position;
in vec2 texCoord;

out vec2 tc;

uniform mat4 modelViewMatrix;
uniform mat4 projectionMatrix;

void main()
{
  // compute the transformed and projected vertex position (into gl_Position)
  gl_Position = projectionMatrix * modelViewMatrix * vec4(position, 1.0f);
  // pass-through the texture coordinate
  tc = texCoord;
}
```

input vertex position and texture coordinates

output texture coordinates; they will be passed to the fragment program (interpolated by hardware)

transformation matrices

# Texture Shader: Fragment Program

```
#version 150

in vec2 tc; // input tex coordinates (computed by the interpolator)
out vec4 c; // output color (the final fragment color)
uniform sampler2D textureImage; // the texture image

void main()
{
  // compute the final fragment color,
  // by looking up into the texture map
  c = texture(textureImage, tc);
}
```

# VAO code (“texCoord” shader variable)

During initialization:

```
glBindVertexArray(vao); // bind the VAO

// bind the VBO “buffer” (must be previously created)
glBindBuffer(GL_ARRAY_BUFFER, buffer);

// get location index of the “texCoord” shader variable
GLuint loc = glGetAttribLocation(program, “texCoord”);
glEnableVertexAttribArray(loc); // enable the “texCoord” attribute

// set the layout of the “texCoord” attribute data
const void * offset = (const void*) sizeof(positions);  GLsizei stride = 0;
glVertexAttribPointer(loc, 2, GL_FLOAT, GL_FALSE, stride, offset);
```

# Multitexturing

- The ability to use *multiple* textures simultaneously in a shader
- Useful for bump mapping, displacement mapping, etc.
- The different texture units are denoted by GL_TEXTURE0, GL_TEXTURE1, GL_TEXTURE2, etc.
- In simple applications (our homework), we only need one unit

```
void setTextureUnit(GLint unit)
{
  glActiveTexture(unit); // select the active texture unit
  // get a handle to the “textureImage” shader variable
  GLint h_textureImage = glGetUniformLocation(program, “textureImage”);
  // deem the shader variable “textureImage” to read from texture unit “unit”
  glUniform1i(h_textureImage, unit - GL_TEXTURE0);
}
```

# The display function

```
void display()
{
   // put all the usual code here (clear screen, set up camera, upload
   //   the modelview matrix and projection matrix to GPU, etc.)
   // …

  // select the active texture unit
  setTextureUnit(GL_TEXTURE0); // it is safe to always use GL_TEXTURE0
  // select the texture to use (“texHandle” was generated by glGenTextures)
  glBindTexture(GL_TEXTURE_2D, texHandle);

  // here, bind the VAO and render the object using the VAO (as usual)
  // …

  glutSwapBuffers();
}
```

# Texture mapping in OpenGL (Compatibility Profile)

- During your initialization:
  1. Read texture image from file into an array in memory, or generate the image using your program
  2. Specify texture mapping parameters
     - » Wrapping, filtering, etc.
  3. Initialize and activate the texture

- In display():
  1. Enable OpenGL texture mapping
  2. Draw objects: Assign texture coordinates to vertices
  3. Disable OpenGL texture mapping

# Enable/disable texture mode (Compatibility Profile)

- Must be done before rendering any primitives that are to be texture-mapped
- glEnable(GL_TEXTURE_2D)
- glDisable(GL_TEXTURE_2D)

- Successively enable/disable texture mode to switch between drawing textured/non-textured polygons

- Changing textures:
  - Only one texture is active at any given time (with OpenGL extensions, more than one can be used simultaneously; this is called *multitexturing*)
  - Use glBindTexture to select the active texture

# Rendering (compatibility profile)

```
void display()
{
  …
  // no modulation of texture color with lighting; use texture color directly
  glTexEnvf(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE,
    GL_REPLACE);

  // turn on texture mapping (this disables standard OpenGL lighting,
    unless in GL_MODULATE mode)
  glEnable(GL_TEXTURE_2D);

  (continues on next page)
```

# Rendering (compatibility profile) (part 2)

```
  glBegin(GL_QUADS); // draw a textured quad
    glTexCoord2f(0.0,0.0); glVertex3f(-2.0,-1.0,0.0);
    glTexCoord2f(0.0,1.0); glVertex3f(-2.0,1.0,0.0);
    glTexCoord2f(1.0,0.0); glVertex3f(0.0,1.0,0.0);
    glTexCoord2f(1.0,1.0); glVertex3f(0.0,-1.0,0.0);
  glEnd();

  // turn off texture mapping
  glDisable(GL_TEXTURE_2D);

  // draw some non-texture mapped objects
    (standard OpenGL lighting will be used if it is enabled)
  …
  // switch back to texture mode, etc.
  …
} // end display()
```

# Summary

- Introduction
- Filtering and Mipmaps
- Non-color texture maps
- Texture mapping in OpenGL