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CPT205 Computer Graphics

Texture Mapping

Lecture 10

2022-23

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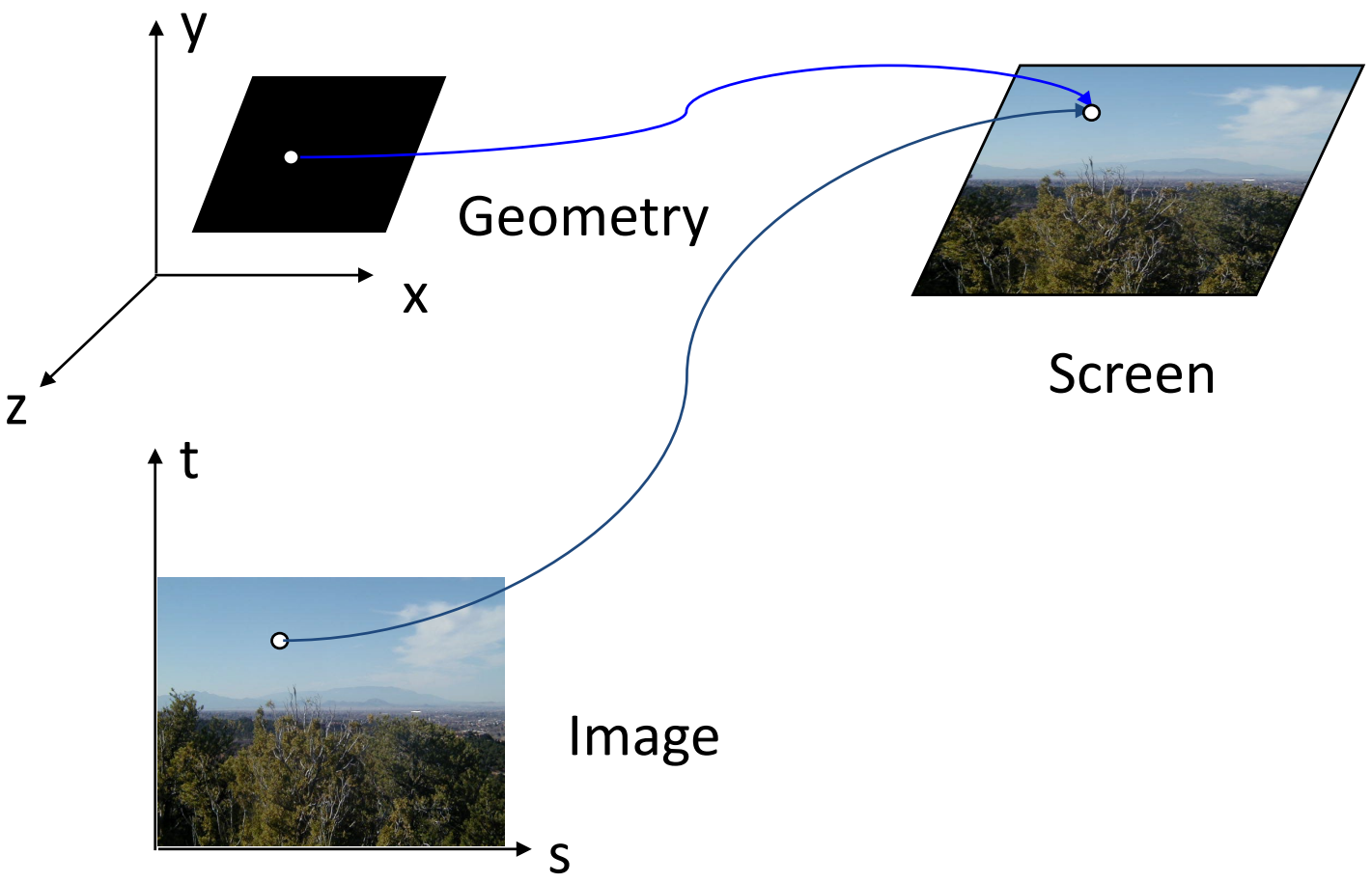
Topics for today

- Concepts
- Types of texture mapping
- Specifying the texture
- Magnification and minification
- Multiple levels of detail
- Modes, filtering and wrapping
- Steps in texture mapping
- OpenGL functions

Concepts of texture mapping (1)

- Although graphics cards can render over 10 million polygons per second, this may be insufficient or there could be alternative way to process phenomena, e.g. clouds, grass, terrain and skin.
- A common method for adding detail to an object is to map patterns onto the geometric description of the object.
  The method for incorporating object detail into a scene is called texture mapping or pattern mapping.
- What makes texture mapping tricky is that a rectangular texture can be mapped to nonrectangular regions, and this must be done in a reasonable way.
- When a texture is mapped, its display on the screen might be distorted due to various transformations applied – rotations, translations, scaling and projections.

Concepts of texture mapping (2)



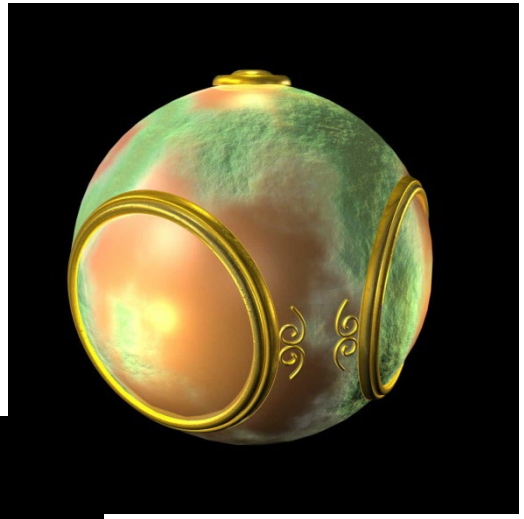
Types of texture mapping (1)

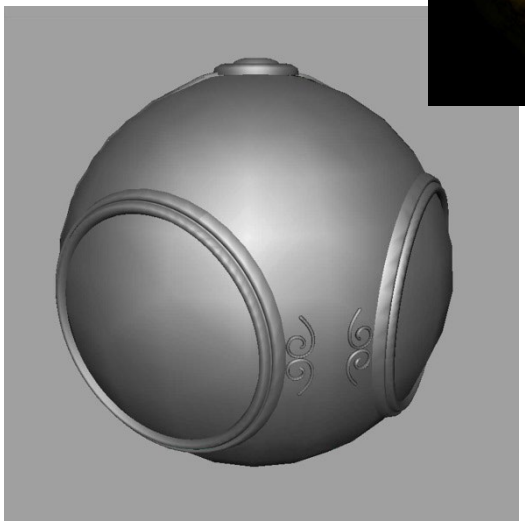
- Texture Mapping
  - Uses images to fill inside of polygons
- Environment (reflection) mapping
  - Uses a picture of the environment for texture maps
  - Allows simulation of highly specular surfaces
- Bump mapping
  - Emulates altering normal vectors during the rendering process

Types of texture mapping (2)

Texture mapped

Bump mapped





Geometric model

Environment mapped

Specifying the texture (1)

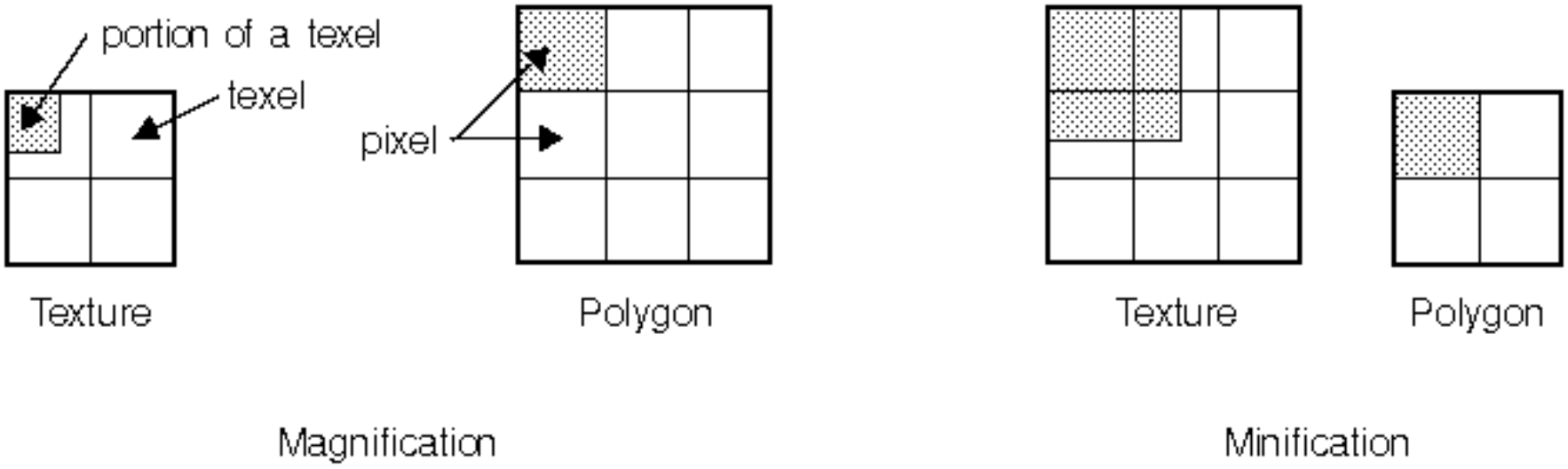
- There are two common types of texture:
  - image: a 2D image is used as the texture.
  - procedural: a program or procedure generates the texture.
- The texture can be defined as one-dimensional, two-dimensional or three-dimensional patterns.

Specifying the texture (2)

- Texture functions in a graphics package often allow the number of colour components for each position in a pattern to be specified as an option.
- For example each colour definition in a texture pattern could consist of four RGBA components, three RGB components, a single intensity value for a shade of blue, an index into a colour table, or a single luminance value (a weighted average of the RGB components of a colour).
- The individual values in a texture array are often called *texels* (texture elements).

Magnification and minification (1)

- Depending on the texture size, the distortion and the size of the screen image, a texel may be mapped to more than one pixel (called *magnificatio*n), and a pixel may be covered by multiple texels (called *minification*).

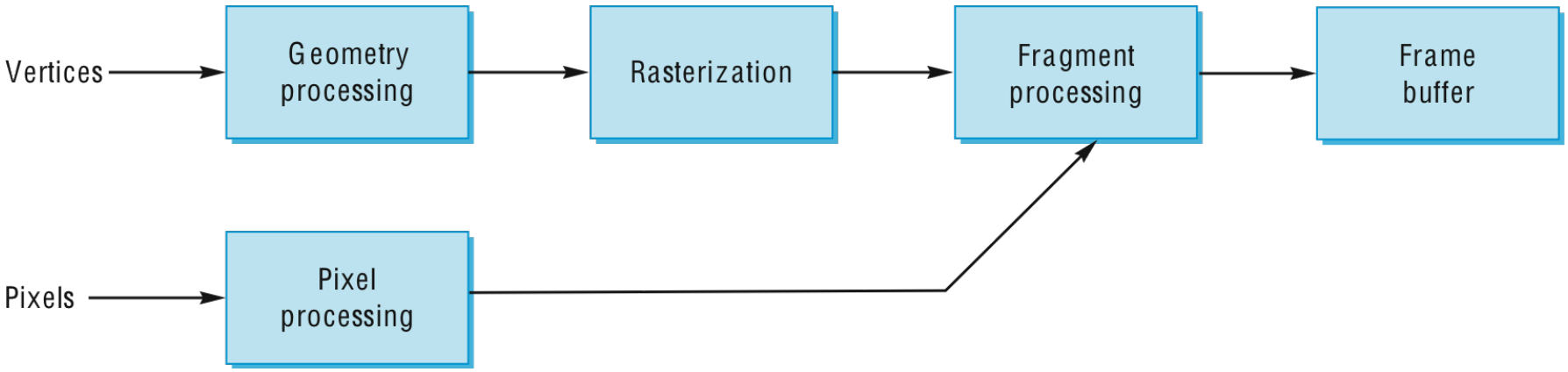


Magnification and minification (2)

- Since the texture is made up of discrete texels, filtering operations must be performed to map texels to pixels.
- For example, if many texels correspond to a pixel, they are averaged down to fit; if texel boundaries fall across pixel boundaries, a weighted average of the applicable texels is performed.
- Because of these calculations, texture mapping can be computationally expensive, which is why many specialised graphics systems include hardware support for texture mapping.

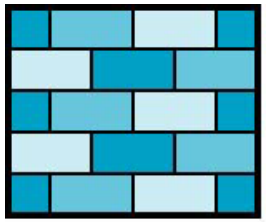
Where does it take place?

- Texture mapping techniques are implemented at the end of the rendering pipeline.
- It is very efficient because a few polygons make it past the clipper.

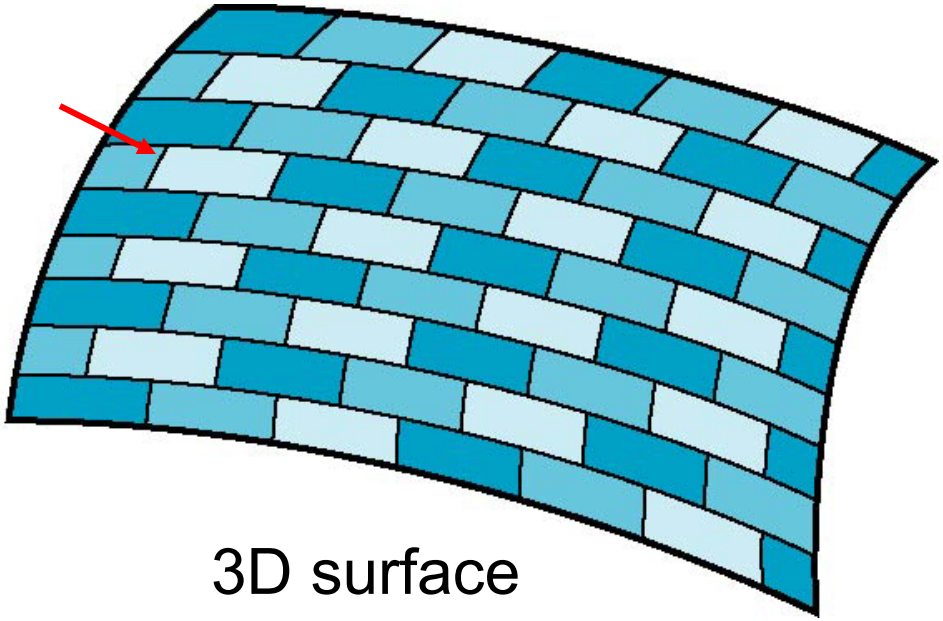


Is it simple?

Although the idea is simple, mapping an image to a surface, 3 or 4 coordinate systems are involved.



2D image

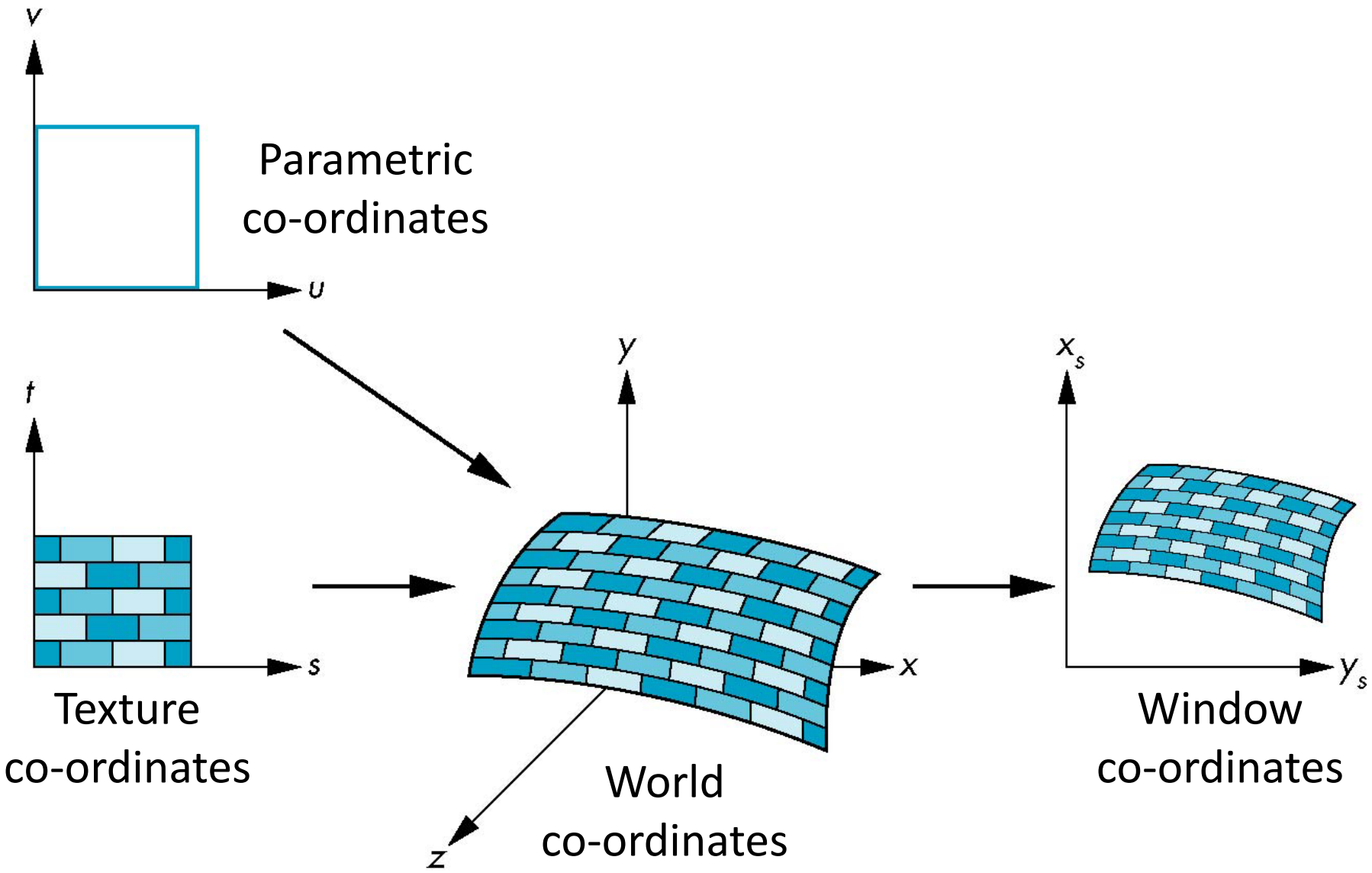


3D surface

Co-ordinate systems for texture mapping

- Parametric co-ordinates
  may be used to model curves and surfaces
- Texture co-ordinates
  used to identify points in the image to be mapped
- Object or world co-ordinates
  conceptually, where the mapping takes place
- Window co-ordinates
  where the final image is finally produced

Co-ordinate systems for texture mapping

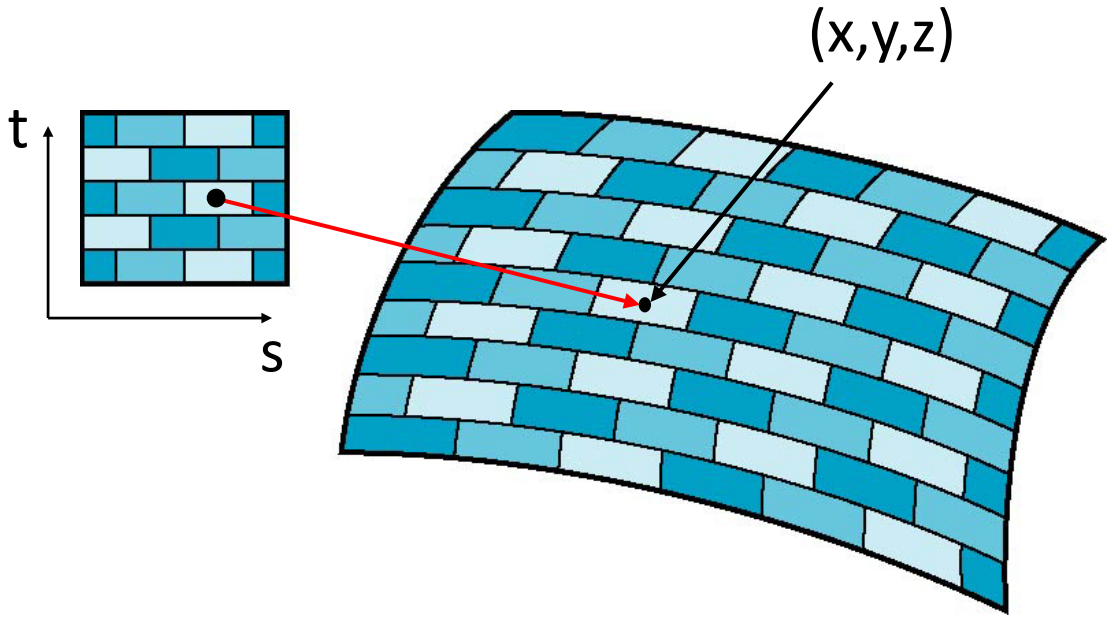


Co-ordinate systems for texture mapping

- The basic problem is how to find the maps.
- Consider mapping from texture co-ordinates to a point on a surface.
- Apparently three functions are needed

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

- But we really want to go the other way.



Backward mapping

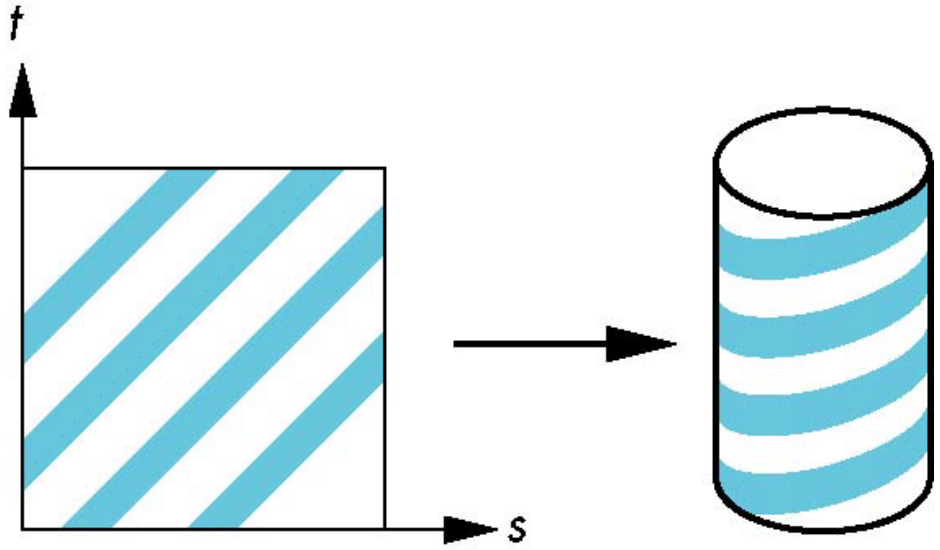
- We really want to go backwards:
  - Given a pixel, we want to know to which point on an object it corresponds.
  - Given a point on an object, we want to know to which point in the texture it corresponds.
- Need a map of the form:

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

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

Two-part mapping

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



Cylindrical mapping

A parametric cylinder

$x = r*\cos(2\pi*u)$

$y = r*\sin(2\pi*u)$

$z = v*h$

maps a rectangle in the (u,v) space to the cylinder of radius r and height h in the world co-ordinates

$s = u$

$t = v$

maps from the texture space.

Spherical mapping

We can map a parametric sphere

$x = r*\cos(2\pi*u)$

$y = r*\sin(2\pi*u)*\cos(2\pi*v)$

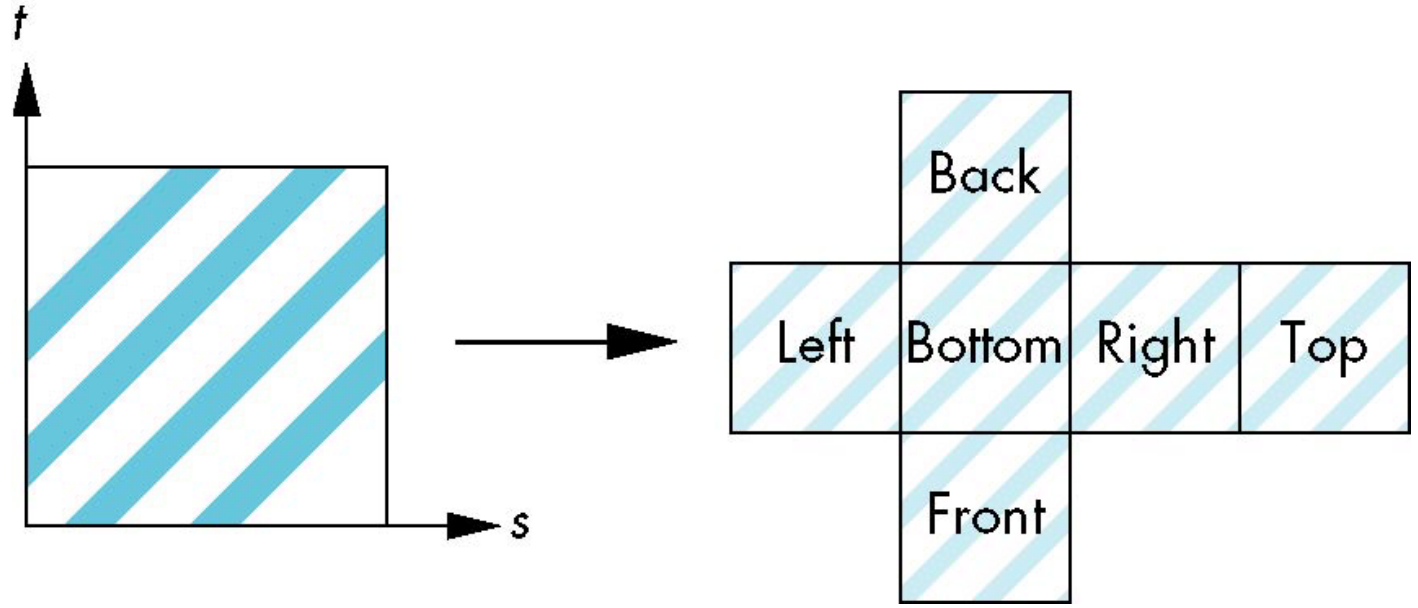
$z = r*\sin(2\pi*u)*\sin(2\pi*v)$

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

Spheres are used in environmental maps.

Box mapping

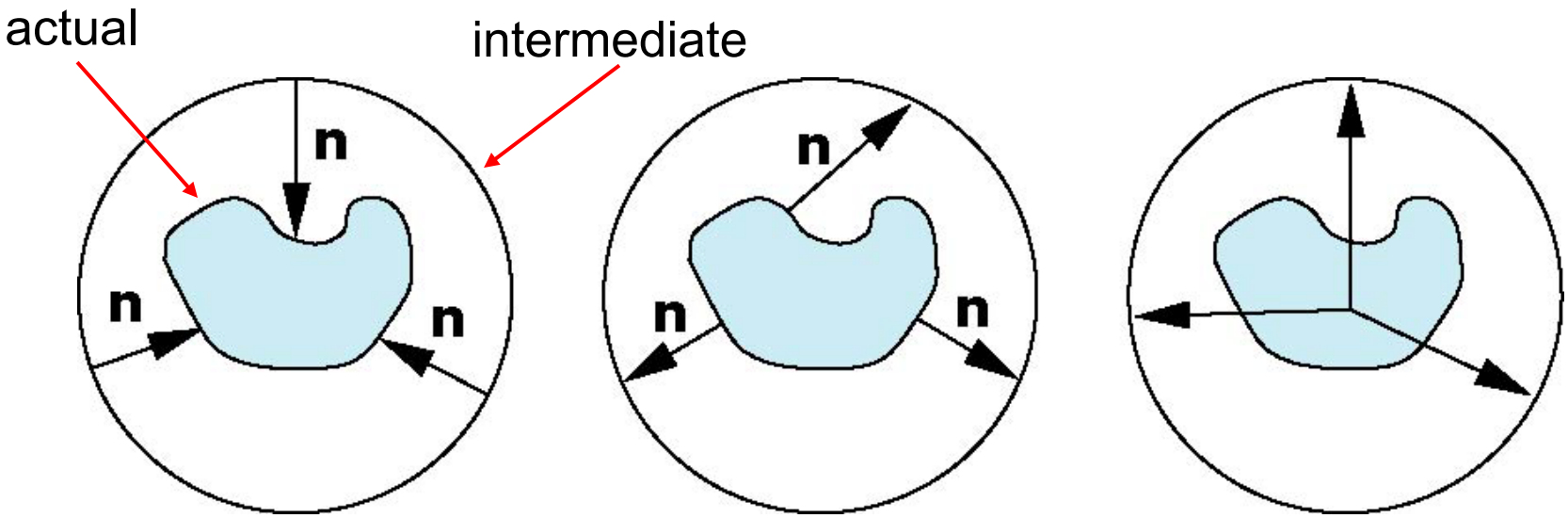
- Easy to use with simple orthographic projection
- Also used in environmental maps



Second mapping

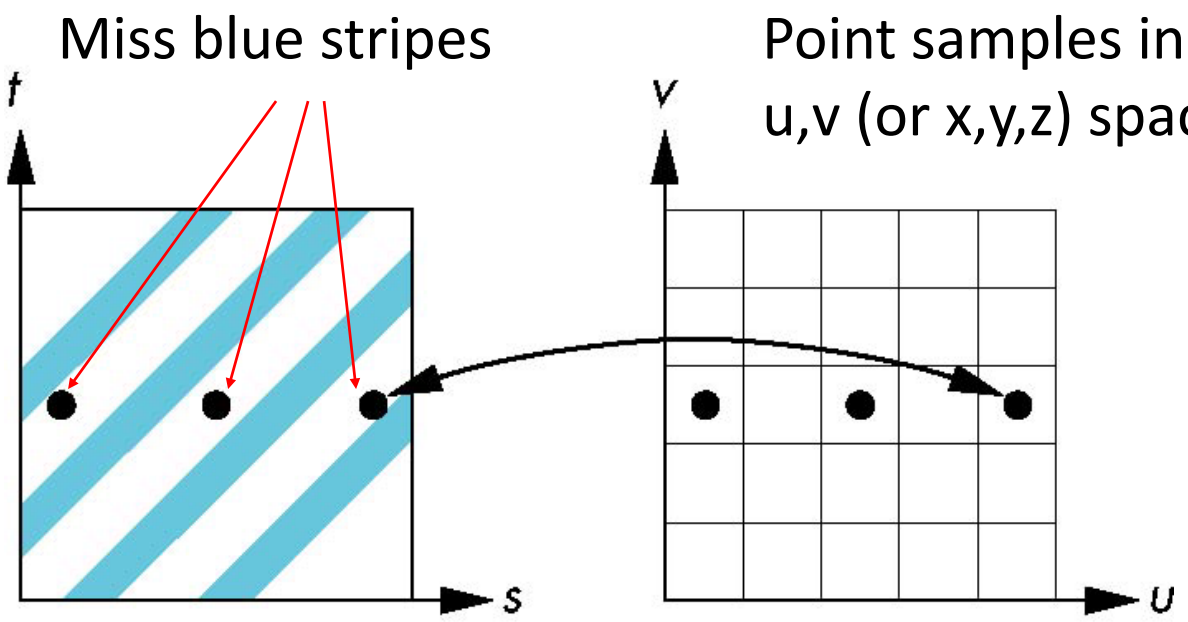
Mapping from an intermediate object to an actual object

- Normals from the intermediate to actual objects
- Normals from the actual to intermediate objects
- Vectors from the centre of the intermediate object



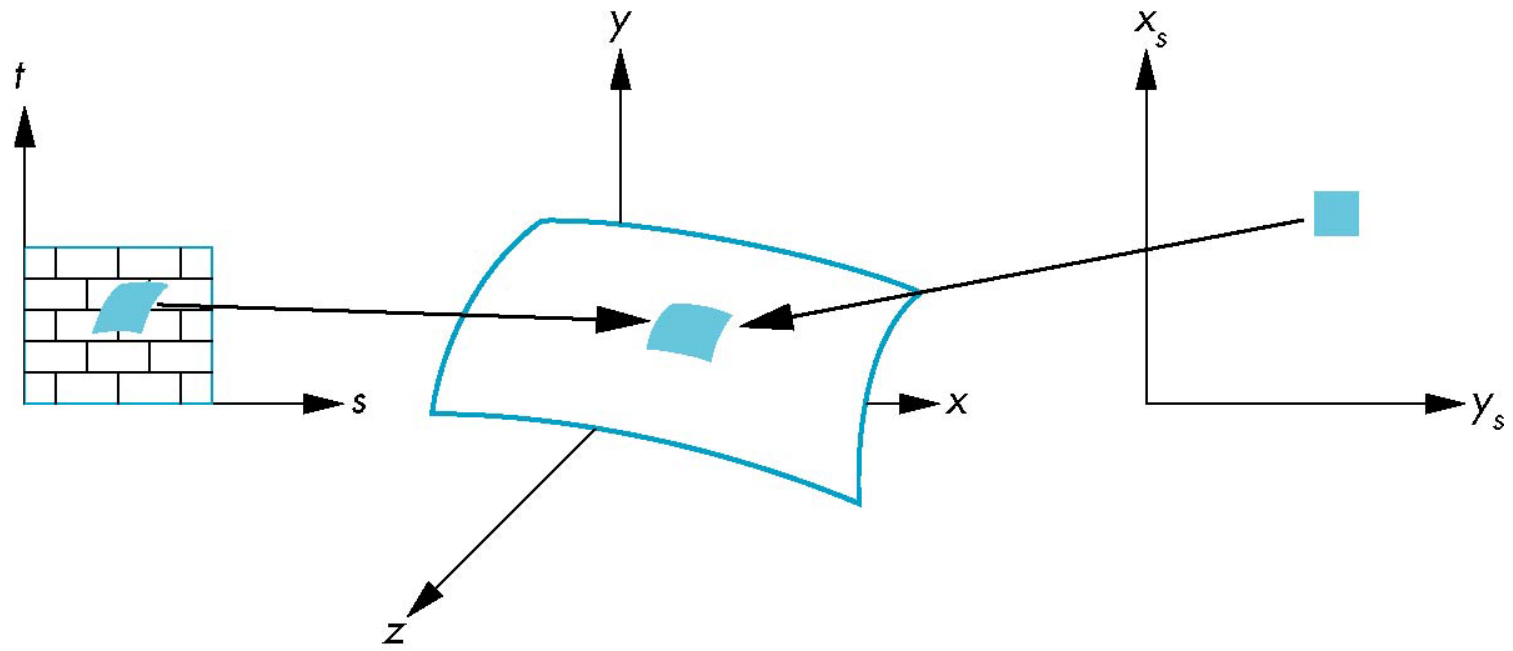
Aliasing

- Point sampling of the texture can lead to aliasing errors



Area averaging

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



Note that the *pre-image* of the pixel is curved.

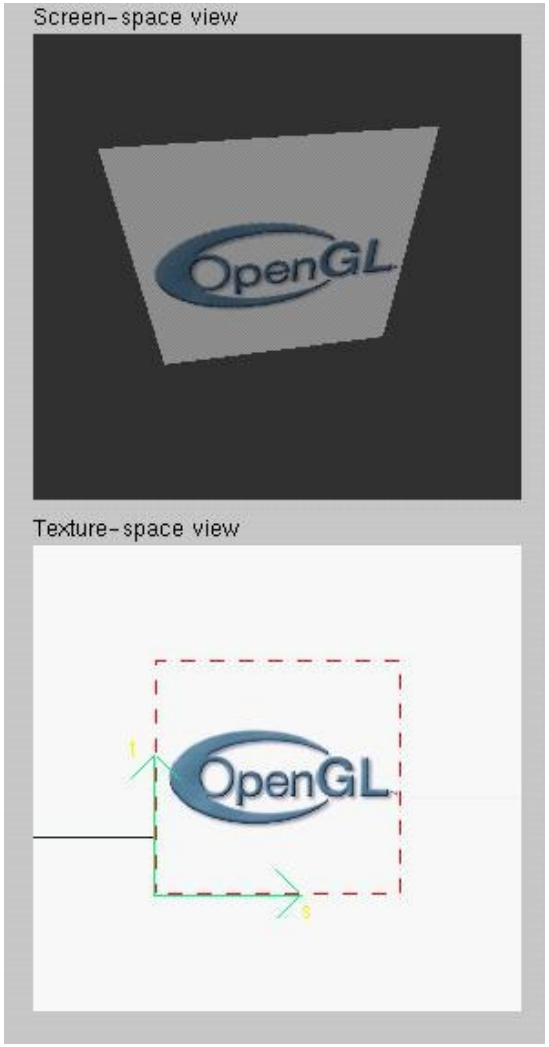
OpenGL steps in texture mapping

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
   - mode
   - filtering
   - wrapping

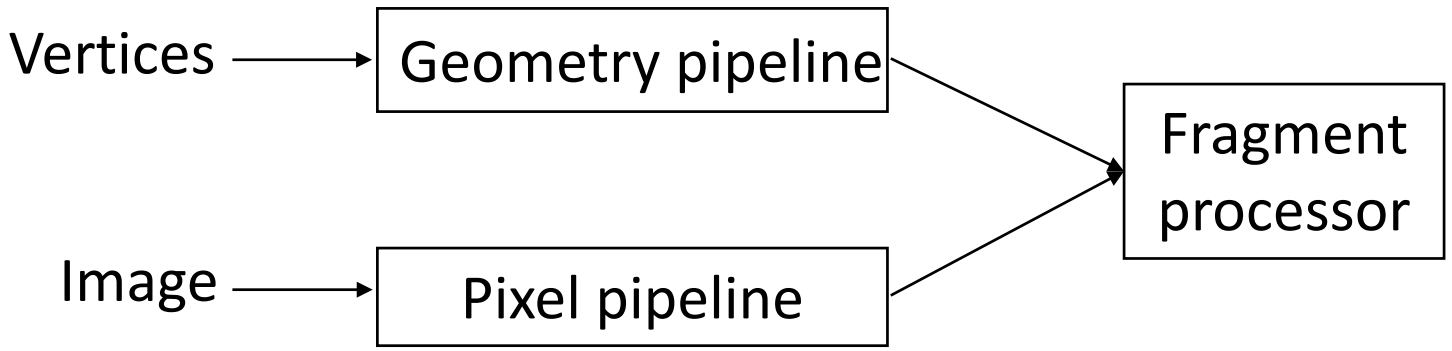
Texture example

The texture is a 256 x 256 image that has been mapped to a rectangular polygon which is viewed in perspective.



Texture mapping and the OpenGL pipeline

- The images and geometry flow through separate pipelines that join during fragment processing.
- "Complex" textures do not affect geometric complexity.



Specifying a texture image

- Define a texture image from an array of *texels* (texture elements) in CPU memory
  - **`Glubyte my_texels[512][512][4];`**
- Define a texture as any other pixel map
  - Scanned image
  - Generate by an application program
- Enable texture mapping
  - **`glEnable(GL_TEXTURE_2D)`**
  - OpenGL supports 1-4 dimensional texture maps

Defining image as a texture (1)

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

`target`: type of texture, e.g. **`GL_TEXTURE_2D`**

`level`: used for mipmapping (0 for only one/top resolution – to be discussed shortly)

`components`: colour elements per texel - an integer from 1 to 4 indicating which of the R, G, B and A components are selected for modulating or blending. A value of 1 selects the R component, 2 selects the R and A components, 3 selects R, G and B, and 4 selects R, B, G and A.

Defining image as a texture (2)

`w` and **`h`**: width and height of the image in pixels.

`border`: used for smoothing (discussed shortly), which is usually 0.

Both **`w`** and **`h`** must have the form $2^{m} + 2\mathbf{b}$, where **`m`** is an integer and **`b`** is the value of **`border`** though they can have different values. The maximum size of a texture map depends on the implementation of OpenGL, but it must be at least 64 × 64 (or 66 × 66 with borders).

Defining image as a texture (3)

`format` and **`type`**: describe the format and data type of the texture image data. They have the same meaning with **`glDrawPixels()`**. In fact, texture data has the same format as the data used by **`glDrawPixels()`**.

The **`format`** parameter can be **`GL_COLOR_INDEX`**, **`GL_RGB`**, **`GL_RGBA`**, **`GL_RED`**, **`GL_GREEN`**, **`GL_BLUE`**, **`GL_ALPHA`**, **`GL_LUMINANCE`**, or **`GL_LUMINANCE_ALPHA`** – i.e., the same formats available for **`glDrawPixels()`** with the exceptions of **`GL_STENCIL_INDEX`** and **`GL_DEPTH_COMPONENT`**.

Similarly, the **`type`** parameter can be **`GL_BYTE`**, **`GL_UNSIGNED_BYTE`**, **`GL_SHORT`**, **`GL_UNSIGNED_SHORT`**, **`GL_INT`**, **`GL_UNSIGNED_INT`**, **`GL_FLOAT`**, or **`GL_BITMAP`**.

Defining image as a texture (4)

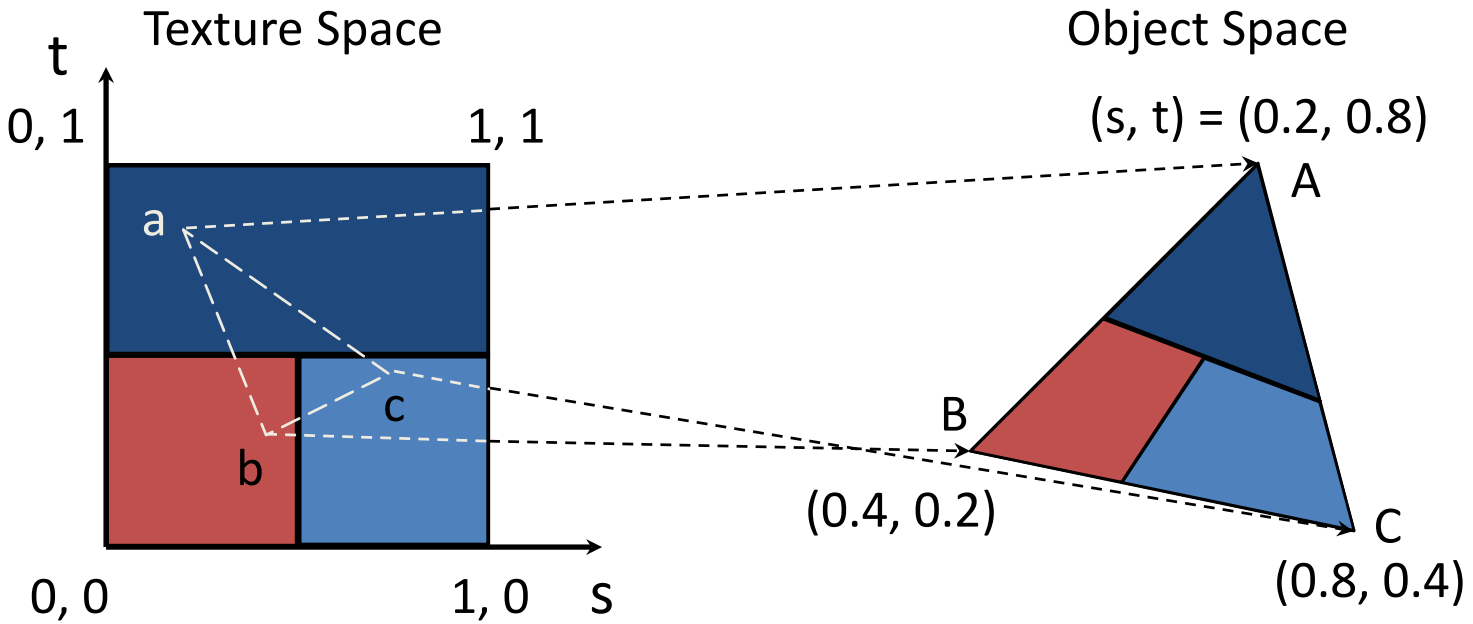
`texels:` pointer to the texel array which contains the texture-image data. This data describes the texture image itself as well as its border.

For example:

```
glTexImage2D(GL_TEXTURE_2D, 0, 3, 514, 514, 1,
  GL_RGB, GL_UNSIGNED_BYTE, my_texels);
```

Mapping a texture

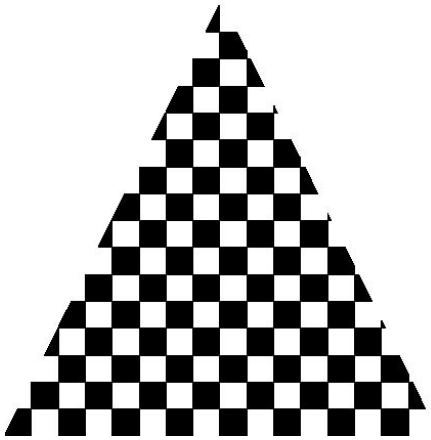
Based on parametric texture co-ordinates, **`glTexCoord*()`** is specified at each vertex.



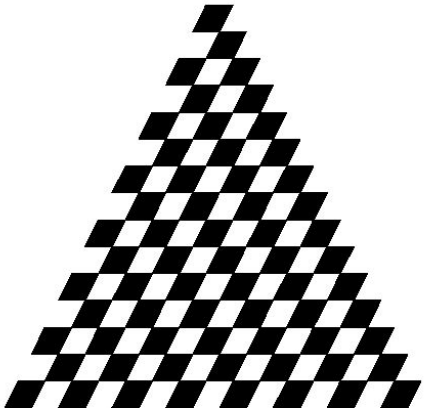
Interpolation

- OpenGL uses interpolation to find proper texels from specified texture coordinates.
- There can be distortions.

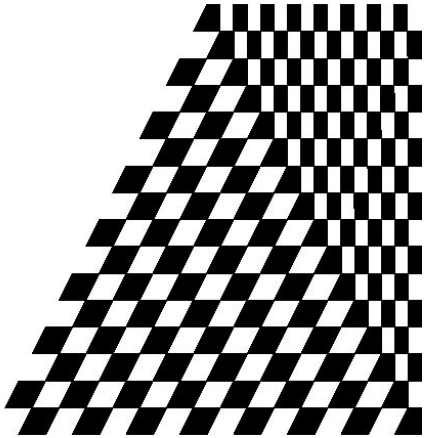
Good selection of texture co-ordinates



Poor selection of texture co-ordinates



Texture stretched over trapezoid showing effects of bilinear interpolation



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* (discussed shortly) allows us to use textures of multiple resolutions.
- *Mode/environment parameters* determine how texture mapping interacts with shading.

Repeating and clamping textures (1)

- We can assign texture co-ordinates outside the range [0,1] and have them either clamp or repeat in the texture map.
- With repeating textures, if we have a large plane with texture co-ordinates running from 0.0 to 10.0 in both directions, for example, we will get 100 copies of the texture tiled together on the screen. During repeating, the integer part of texture co-ordinates is ignored, and copies of the texture map tile the surface.
- For most applications of repeating, the texels at the top of the texture should match those at the bottom, and similarly for the left and right edges.

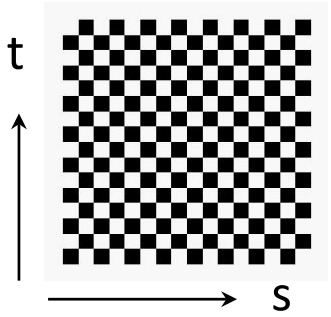
Repeating and clamping textures (2)

- The other possibility is to clamp the texture co-ordinates: any values greater than 1.0 are set to 1.0, and any values less than 0.0 are set to 0.0.
- Clamping is useful when a single copy of the texture is to appear on a large surface. If the surface-texture co-ordinates range from 0.0 to 10.0 in both directions, one copy of the texture appears in the lower corner of the surface. The rest of the surface is painted with the texture border colours as needed.

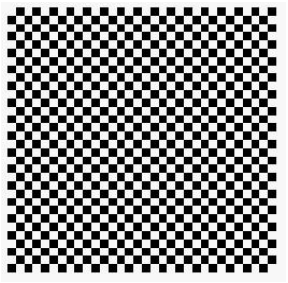
Repeating and clamping textures (4)

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

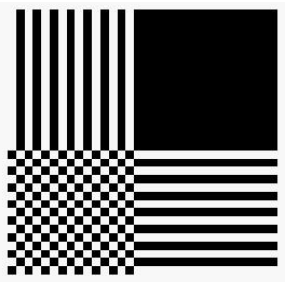
```
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S,
                GL_CLAMP)
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T,
                GL_REPEAT)
```



Texture



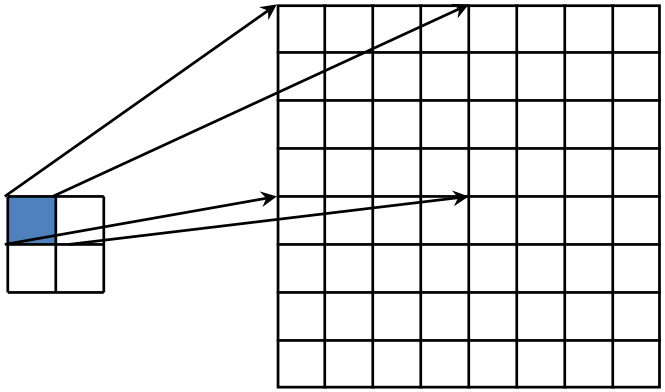
GL_REPEAT
wrapping



GL_CLAMP
wrapping

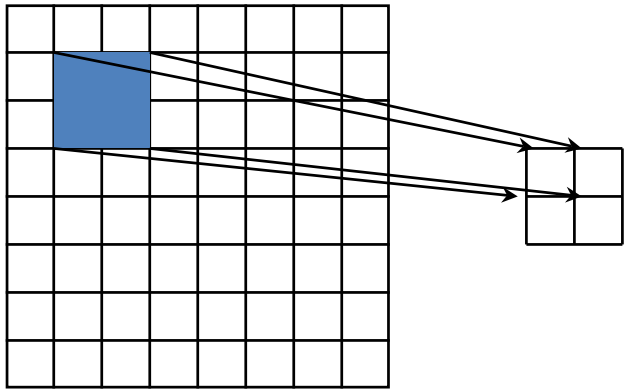
Minification and magnification

- More than one pixel can cover a texel (*magnification*) or more than one texel can cover a pixel (minification).
- We can use point sampling (nearest texel) or linear filtering to obtain texture values.



Texture Polygon

Magnification



Texture Polygon

Minification

Controlling filtering (1)

- OpenGL allows us to specify any of several filtering options to determine the calculations. The options provide different trade-offs between speed and image quality. We can specify the filtering methods for magnification and minification independently.
- OpenGL can make a choice between magnification and minification that in most cases gives the best result possible. The following lines are examples of how to use **`glTexParameter*()`** to specify the magnification and minification filtering methods:

```
glTexParameteri(GL_TEXTURE_2D,
                GL_TEXTURE_MAG_FILTER, GL_NEAREST);
glTexParameteri(GL_TEXTURE_2D,
                GL_TEXTURE_MIN_FILTER, GL_LINEAR);
```

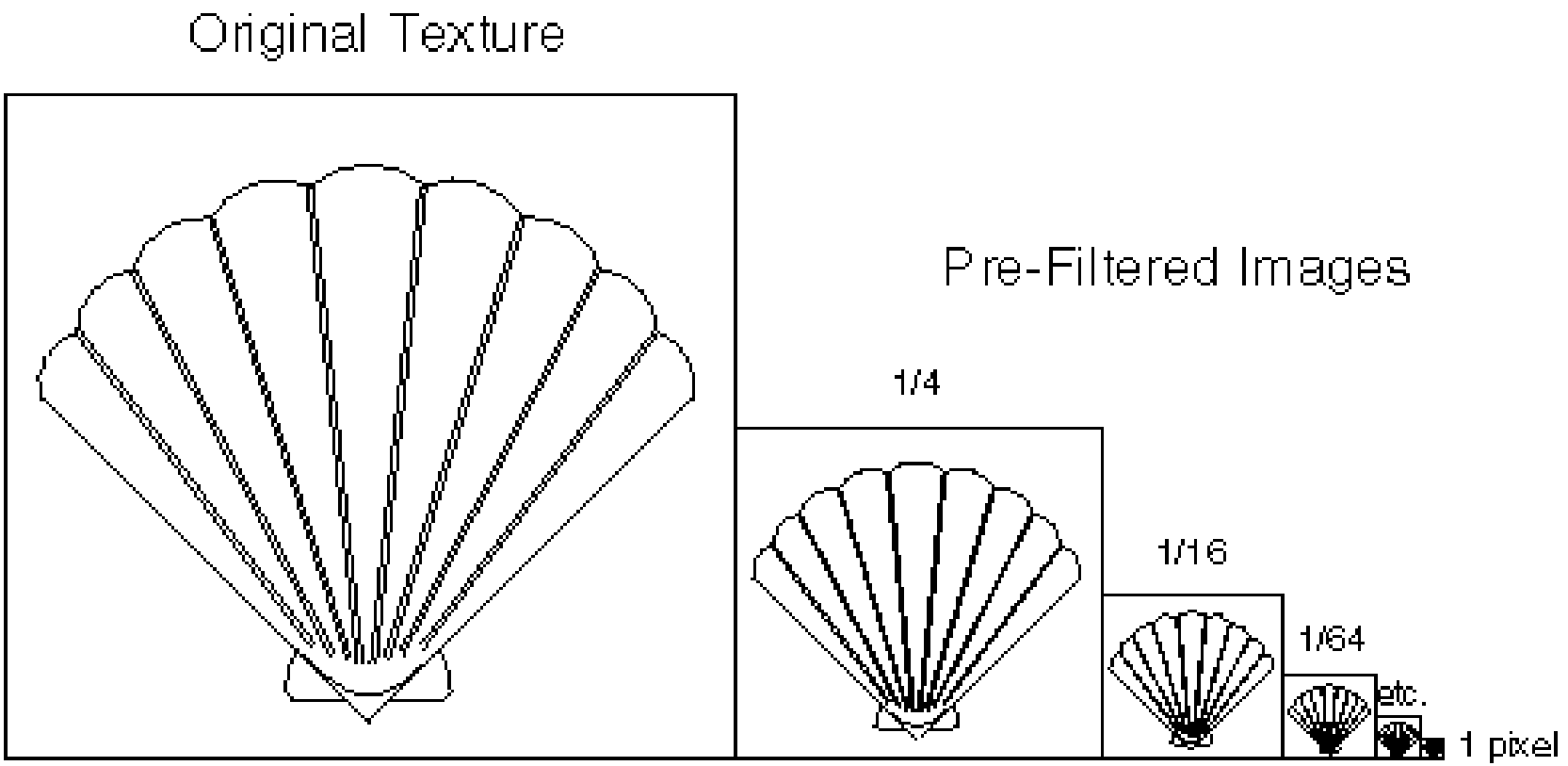
Controlling filtering (2)

- The second argument is either **`GL_TEXTURE_MAG_FILTER`** or **`GL_TEXTURE_MIN_FILTER`** to indicate whether we are specifying the filtering method for magnification or minification. The third argument specifies the filtering method.
- Note that linear filtering requires a border of an extra texel for filtering at edges (border = 1).

Multiple levels of detail (1)

- Textured objects can be viewed, like any other objects in a scene, at different distances from the viewpoint. In a dynamic scene, as a textured object moves further from the viewpoint, the texture map must decrease in size along with the size of the projected image.
- To accomplish this, OpenGL has to filter the texture map down to an appropriate size for mapping onto the object, without introducing visually disturbing artefact.
- To avoid such artefact, we can specify a series of pre-filterred texture maps of decreasing resolutions, called *mipmaps*, as shown on the next slide.

Multiple levels of detail (2)



Multiple levels of detail (3)

- OpenGL automatically determines which texture map to use based on the size (in pixels) of the object being mapped.
- With this approach, the level of detail in the texture map is appropriate for the image that is drawn on the screen - as the image of the object gets smaller, the size of the texture map decreases.
- Mipmapping requires some extra computation to reduce interpolation errors, but, when it is not used, textures that are mapped onto smaller objects might shimmer and flash as the objects move.

Multiple levels of detail (4)

- To use mipmapping, we provide all sizes of the texture in powers of 2 between the largest size and a 1×1 map.
- For example, if the highest-resolution map is 64×16, we must also provide maps of size 32×8, 16×4, 8×2, 4×1, 2×1 and 1×1.
- The smaller maps are typically filtered and averaged-down versions of the largest map in which each texel in a smaller texture is an average of the corresponding four texels in the larger texture.
- OpenGL does not require any particular method for calculating the smaller maps, so the differently sized textures could be totally unrelated.

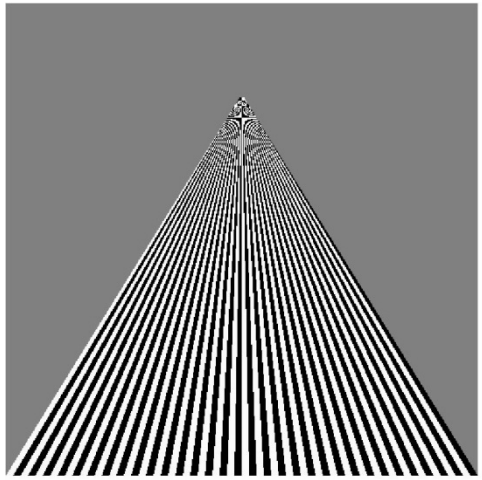
Multiple levels of detail (5)

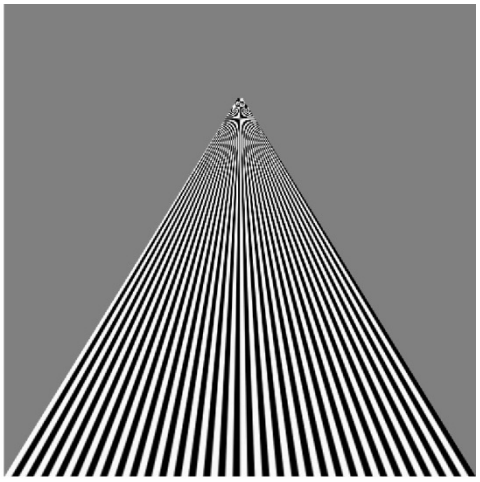
- Mipmapping level is declared during texture definition by calling **`glTexImage2D(GL_TEXTURE_*D, level, …)`** once for each resolution of the texture map, with different values for the **`level`**, **`width`**, **`height`** and **`image`** parameters.

- Starting with zero, **`level`** identifies which texture in the series is specified; with the previous example, the largest texture of size 64×16 would be declared with **`level`** = 0, the 32×8 texture with **`level`** = 1, and so on.
- In addition, for the mipmapped textures to take effect, we need to choose one of the appropriate filtering methods.

Mipmapped texture - example

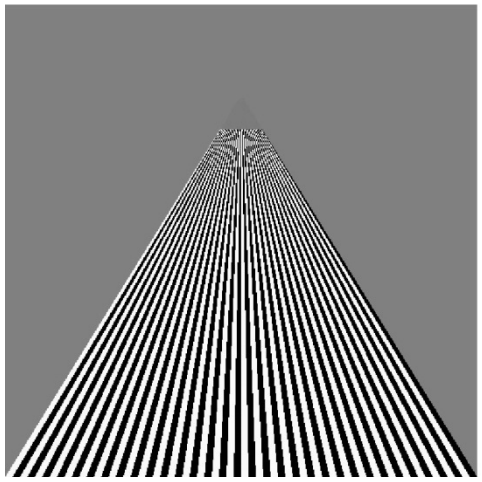
Point sampling

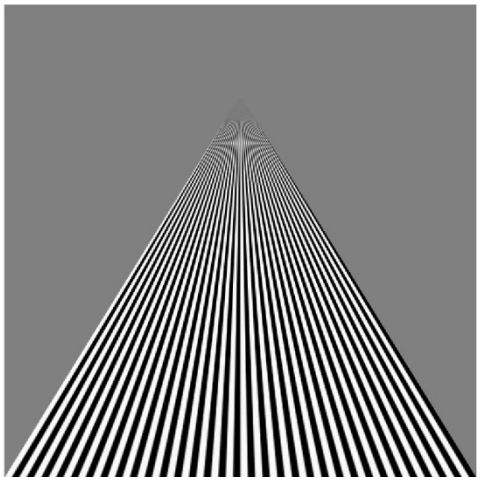




Linear filtering

Mipmapped point sampling





Mipmapped linear filtering

Texture mapping functions

- Control 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 colour

  `GL_REPLACE`: use only texture colour

- Set blend colour with **`GL_TEXTURE_ENV_COLOR`**

Modulating and blending (1)

We can choose one of three possible functions for computing the final RGBA value from the fragment colour and the texture-image data.

- simply use the texture colour as the final colour, called the *decal* mode, in which the texture is painted on top of the fragment, just as a decal would be applied.
- use the texture to *modulate*, or scale, the fragment colour, useful for combining the effects of lighting with texturing.
- a constant colour can be blended with the fragment colour, based on the texture value.

Modulating and blending (2)

- The values in the texture map can be used directly as colours to be painted on the surface being rendered. We can also use the values in the texture map to modulate the colour that the surface would be painted without texturing, or to blend the colour in the texture map with the non-textured colour of the surface.
- We can choose one of these three texturing functions by supplying the appropriate arguments to **`glTexEnv{if}{v}(GLenum target, GLenum pname, TYPEparam)`**, which sets the current texturing function.

Modulating and blending (3)

- The **`target`** must be **`GL_TEXTURE_ENV`**. If **`pname`** is **`GL_TEXTURE_ENV_MODE`**, **`TYPEparam`** can be **`GL_DECAL`**, **`GL_MODULATE`**, or **`GL_BLEND`**, to specify how texture values are to be combined with the colour values of the fragment being processed. In the decal mode and with a three-component texture, the texture colours replace the fragment colours.
- With either of the other two modes or with a four-component texture, the final colour is a combination of the texture and the fragment values. If **`pname`** is **`GL_TEXTURE_ENV_COLOR`**, **`TYPEparam`** is an array of four floating-point values representing the R, G, B and A components. These values are used only if the **`GL_BLEND`** texture function is specified as well.

Perspective correction hint

- Texture co-ordinate and colour interpolation
  - either linearly in the screen space
  - or using depth/perspective values (slower)
- Noticeable for polygons “on edge”

  `glHint(GL_PERSPECTIVE_CORRECTION_HINT, hint)`

  where **`hint`** is one of

  `GL_DONT_CARE`
  `GL_NICEST`
  `GL_FASTEST`

Generating texture co-ordinates (1)

- Texture co-ordinates are usually referred to as the *s, t, r* and *q* co-ordinates to distinguish them from object co-ordinates (*x, y, z* and *w*). For 2D textures, *s* and *t* are used. Currently, the *r* coordinate is ignored (although it might have meaning in the future). The *q* co-ordinate, like *w*, is typically given the value 1 and can be used to create homogeneous co-ordinates.
- We need to indicate how the texture should be aligned relative to the fragments to which it is to be applied. We can specify both texture co-ordinates and geometric co-ordinates as we specify the objects in the scene.
- The command to specify texture co-ordinates, **`glTexCoord*()`**, is similar to **`glVertex*()`**, **`glColor*()`** and **`glNormal*()`** - it comes in similar variations and is used in the same way between **`glBegin()`** and **`glEnd()`** pairs.

Generating texture co-ordinates (2)

- Usually, texture co-ordinate values range between 0 and 1.
- **`void glTexCoord{1234}{sifd}[v](TYPEcoords)`** sets the current texture co-ordinates (*s, t, r, q*).
- Subsequent calls to **`glVertex*()`** result in those vertices being assigned the current texture co-ordinates.
- Using **`glTexCoord2*()`** allows us to specify *s* and *t*; *r* and *q* are set to 0 and 1, respectively. We can supply the co-ordinates individually, or we can use the vector version of command to supply them in a single array. Texture co-ordinates are multiplied by the 4x4 texture matrix before any texture mapping occurs.

Generating texture co-ordinates (3)

- OpenGL can generate texture co-ordinates automatically

  `glTexGen{ifd}[v]()`

- Specify a plane

  generates texture coordinates based on the distance from the plane

- Generation modes

  `GL_OBJECT_LINEAR`
  `GL_EYE_LINEAR`
  `GL_SPHERE_MAP` (used for environmental maps)

Texture objects

- Texture is part of the OpenGL state
  - If we have different textures for different objects, OpenGL will be moving large amounts of data from the processor memory to the texture memory.
- Recent versions of OpenGL have *texture objects*
  - One image per texture object.
  - The texture memory can hold multiple texture objects.

Applying textures

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)

OpenGL functions

- **`glTexImage2D()`**: Defining image as texture (type, level and colour)
- **`glTexParameter*()`**: Specifying filtering and wrapping
- **`glTexEnv{fi}[v]()`**: Specifying modulating, blending or decal
- **`glHint()`**: Defining perspective correction hint
- **`glBindTexture()`**: Binding a named texture to a texturing target
- **`glTexCoord{1234}{sifd}{v}()`**: Specifying texture co-ordinates s and t while r is set to 0 and q to 1
- **`glTexGen{ifd}[v]()`**: Automatic generation of texture co-ordinates by OpenGL

Summary

- Why texture mapping is needed and how it works
- Techniques for texture mapping
  - Specifying the texture
  - Magnification and minification
  - Multiple levels of detail (mipmapping)
  - Modes and filtering
  - Wrapping
- Steps for texture mapping
- OpenGL functions