EECS 487: Interactive Computer Graphics

Lecture 24:
- Texture Mapping

Texture Mapping

What is texture mapping

Texture mapping in OpenGL
- texture-coordinates arrray

Automatic texture coordinates generation

Perspective-correct interpolation

Multitexture and Light Map

Texture mapping in GLSL

Texture Mapping

What determines the "look" of a pixel?

Often results in 3D objects that look like "plastic objects floating in free space"

"If it looks like computer graphics, it is not good computer graphics"
– Jeremy Birn

Surface Detail

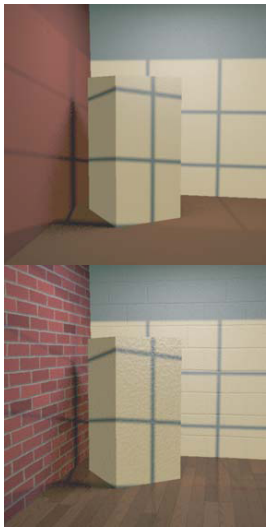
How to make 3D objects look less like "plastic objects floating in free space"?
- add surface detail
- but surface details are too expensive to do geometrically, too much geometric detail to model:

Texture Mapping

Instead, "glue on" a 2D image that captures the surface detail of the object; modify the surface properties used in lighting computation without changing the underlying geometry, providing an illusion of detail

- combine fragment color with a lookup value, or
- compute fragment color based on a lookup value

⇒Image complexity doesn't increase processing complexity



Yuo8

Texture Mapping

Texture map: an array of values loaded from a file and stored in texture memory

- can be 1D, 2D, or 3D
- a unit of texture element is called a texel

Simplest case, texels contain scalar values:

- image texturing: surface color (RGB(A))

More generally, texels can also contain vectors:

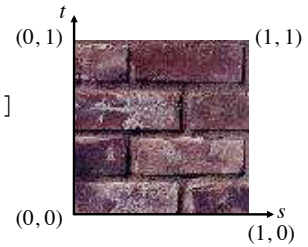
- bump mapping: surface normals, to simulate apparent roughness
- environment mapping: reflection vectors, to simulate shiny and glossy surfaces

Procedural texture: instead of relying on a pre-computed lookup table, texturing can also be done algorithmically

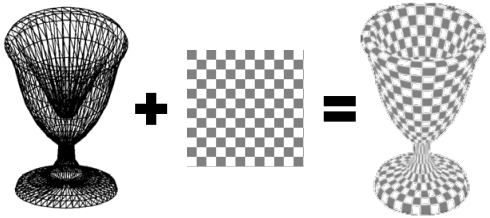
2D Texture Map

Texture is a 2D raster image:
`texture[width(s)][height(t)]`
of type RGB(A)

Texture coordinate (s, t) parameterized to $[0, 1]$ range



Can be scaled to cover many different surfaces of arbitrary size and shape



Hanrahan

Image-Based Rendering

Texture mapping in the extreme: using photos as textures to render dominant surfaces in scene

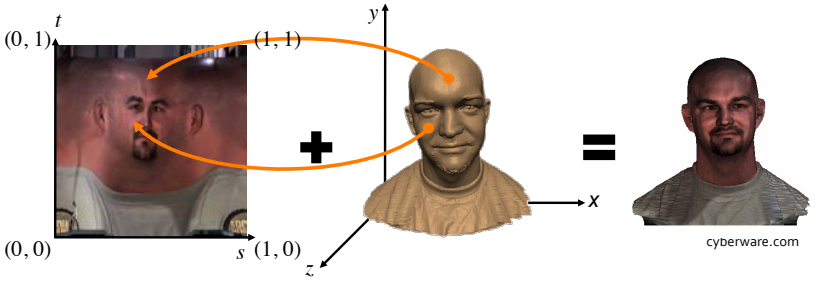
What You See Is ALL You Get
(but that may be all you need)

debevec.org

2D Texture Mapping

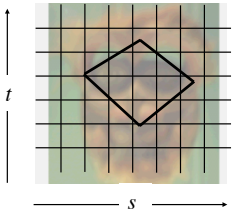
Establish a mapping between surface point and texture

When shading a particular surface point
- look up corresponding texel in the texture image
- final color of point will be a function of the texel

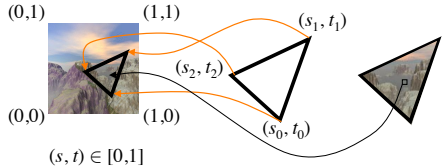


Texture Coordinates

Assign texture coordinates to each vertex
- 1, 2, 3, or 4 texture dimensions per vertex
- index into the texture image, to retrieve texel corresponding to the vertex



Texture coordinates
- manually specified by programmer or automatically generated for every vertex
- interpolated during rasterization
- texturing itself done during fragment processing



Texture Mapping in OpenGL

1. Create a texture object:
   `glGenTextures(), glBindTexture()`
2. Specify a texture for that object: `glTexImage2D()`
   - optional:
     - `gluScaleImage() // if dimensions are not powers of 2`
     - `glPixelStore*() // specify data format`
3. Specify wrapping and filtering modes: `glTexParameter*()`
4. Specify how the texture is to be applied to each pixel:
   `glTexEnv*()`
5. Enable texture mapping: `glEnable(GL_TEXTURE_2D)`
6. Render the scene, supplying both geometric and texture coordinates: `glTexCoord2f()`

Creating a Texture Object

As with other OpenGL objects, first generate texture object handles*:

```
int tods[N];
glGenTextures(N, tods)
// N is the number of texture objects to be allocated
// tods is an array to store the handles
```

Next, specify (by handle) which particular texture object to use for which type of texture and make it "current"

```
glBindTexture(GL_TEXTURE_2D, tods[i]);
```

*texture handle == texture name == texture ID

Specify the Texture Image

Specify the texture image to use:

```
glTexImage2D(target, level, component,
             width, height, border,
             format, type, teximage)
```

with:

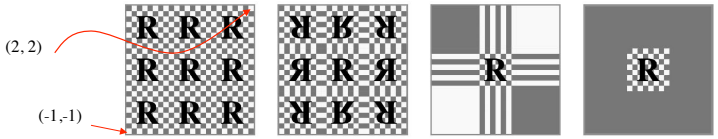
- `target`: `GL_TEXTURE_2D` (or cube faces or others)
- `level`: mipmap level, 0 if not mipmapping
- `component`: `GL_RGB` or `GL_RGBA`
- `width`: width of image, must be $2^n + 2^b$, where n is actual width of image, and b is size of border
- `height`: height of the image, must be $2^m + 2^b$
- `border`: whether image has border, must be 0 or 1
- `format`: format of pixel data, `GL_RGB` or `GL_RGBA`
- `type`: data type of pixel data, `GL_UNSIGNED_BYTE`, `GL_FLOAT`, etc.
- `teximage`: pointer to image in memory or offset if pixel buffer object is used

Surface Larger than Texture

What if surface maps to $(s, t) > 1.0$ or < 0.0 ?

Alternatives:

repeat/wrap/tile mirror clamp to edge clamp (to border)



To repeat textures, use the fractional part of vertex coordinates as texture coordinates, for example: $5.3 \rightarrow 0.3$

In OpenGL use `glTexParameter*()` to specify alternative

Setting Texture Parameters

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

where

- `target` is `GL_TEXTURE_2D`
- `pname` is a parameter name that you want to change:
  - `GL_TEXTURE_WRAP_T`
  - `GL_TEXTURE_WRAP_S`
  - `GL_TEXTURE_MIN_FILTER`
  - `GL_TEXTURE_MAG_FILTER`
- `param` is the parameter value to change to

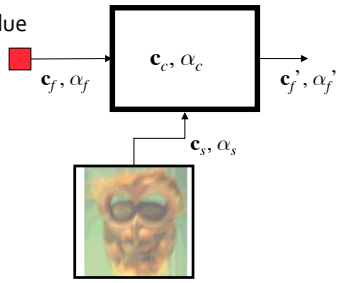
For example:

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

Texture Application Mode

`glTexEnv*()`: tell OpenGL how each texture shall be combined with pre-existing fragment color

- `GL_REPLACE`: texture color replaces fragment color
  $\mathbf{c}_f' = \mathbf{c}_s, \alpha_f' = \alpha_s$
- `GL_ADD`: $\mathbf{c}_f' = \mathbf{c}_f + \mathbf{c}_s, \alpha_f' = \alpha_f + \alpha_s$
- `GL_MODULATE`: multiply texture and fragment color
  $\mathbf{c}_f' = \mathbf{c}_f * \mathbf{c}_s, \alpha_f' = \alpha_f * \alpha_s$
- `GL_BLEND`: use texture value as blending value to blend fragment color and a predetermined color
  $\mathbf{c}_f' = (1 - \mathbf{c}_s) * \mathbf{c}_f + \mathbf{c}_s * \mathbf{c}_c, \alpha_f' = \alpha_f * \alpha_s$
- `GL_DECAL`: replace fragment color with texture color if texel is opaque
  $\mathbf{c}_f' = (1-\alpha_s) * \mathbf{c}_f + \alpha_s * \mathbf{c}_s, \alpha_f' = \alpha_f$



Example: Diffuse Shading and Texture

Want: texture appear to be shaded, allowing for the perception of shape

- modulate texture only with diffuse light
  - color the polygon white and light it normally
  - use `glTexEnvi(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_MODULATE);`
  - texture color is multiplied by surface (fragment) color, lowering texture brightness

Problem: modulating texture by light only makes it darker, we lost specular highlights!

Solution:

- separate out specular component as a secondary color

Setting Up Texture (in `init()`)

```
/* First, read in the image file */
assert(fp = fopen("wood.ppm","rb"));
fscanf(fp,"%*s %*d %*d %*d%*c");
for (i = 0 ; i < 256 ; i++)
   for (j = 0 ; j < 256 ; j++)
      for (k = 0 ; k < 3 ; k++) // RGB
         fscanf(fp,"%c",&(teximage[i][j][k]));
fclose(fp);

/* Then set up the texture */
int tod;
glGenTextures(1, &tod);
glBindTexture(GL_TEXTURE_2D, tod);
glTexImage2D(GL_TEXTURE_2D,0,GL_RGB, 256, 256, 0, GL_RGB,
             GL_UNSIGNED_BYTE, teximage);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_NEAREST);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_NEAREST);
```

Rendering with Texture (in `display()`)

```
/* Also note some effort to find the error if any */

glTexEnvf(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_REPLACE);
glEnable(GL_TEXTURE_2D);
glColor3f(1.0,1.0,1.0);
err = glGetError(); assert(err == GL_NO_ERROR);
glBegin(GL_POLYGON);
   glTexCoord2f(1.0, 1.0); glVertex3f(0.5, 0.5, 0.0);
   glTexCoord2f(0.0,1.0); glVertex3f(-0.5, 0.5, 0.0);
   glTexCoord2f(0.0,0.0); glVertex3f(-0.5, -0.5, 0.0);
   glTexCoord2f(1.0,0.0); glVertex3f(0.5, -0.5, 0.0);
glEnd();
err = glGetError(); assert(err == GL_NO_ERROR);
glDisable(GL_TEXTURE_2D); // state machine!
```

Rendering with Different Textures

```
// in init():
glGenTextures(2, textures);
glBindTexture(GL_TEXTURE_2D, textures[0]);
glTexParameteri(…); … ; glTexImage2D(GL_TEXTURE_2D,…);

glBindTexture(GL_TEXTURE_2D, textures[1]);
glTexParameteri(…); … ; glTexImage2D(GL_TEXTURE_2D,…);

// in display():
glBindTexture(GL_TEXTURE_2D, textures[0]);
glBegin(...);
   glTexCoord (...);
   glVertex (...);
glEnd (...);

glBindTexture (GL_TEXTURE_2D, textures[1]);
glBegin (...);
   glTexCoord (...);
   glVertex (...);
glEnd (...);
```

Texture-Coordinates Array

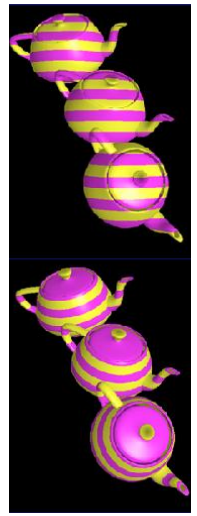
When a vertex array is used, texture coordinates corresponding to the vertices must be provided in a texture-coordinates array (see Lab6)

```
// texcoords must have a 1-1 mapping with vertices
float vertices[][] = { { 0.5, 0.5, 0.0 },
  {-0.5, 0.5, 0.0 }, {-0.5, -0.5, 0.0 },
  {0.5, -0.5, 0.0 } };
float texcoords[][] = { { 1.0, 1.0 },
  { 0.0, 1.0 }, { 0.0, 0.0 }, { 1.0, 0.0 } };

glEnableClientState(GL_VERTEX_ARRAY);
glVertexPointer(3, GL_FLOAT, 0, vertices);
glEnableClientState(GL_TEXTURE_COORD_ARRAY);
glTexCoordPointer(2, GL_FLOAT, 0, texcoords);
```

Texture Coordinates Autogen

How do we "paste" a 2D texture image onto a 3D object?



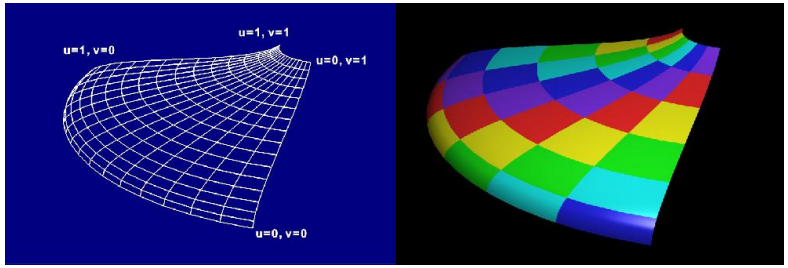
Non-parametrically
- texture size and orientation are fixed in world coordinates
- gives a "projector" effect: object "swims" through texture

Parametrically
- texture size and orientation tied to object, in object coordinates
- map object coordinates to texture coordinates

Wolfe97

Parametric Mapping

Mapping for parametric surfaces is easy: map surface parameters directly to texture coordinates: $u \rightarrow s$, $v \rightarrow t$



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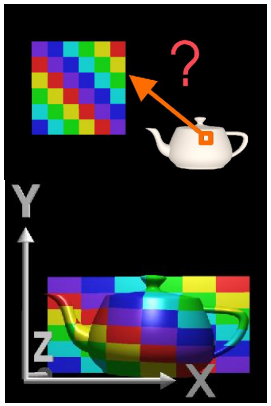
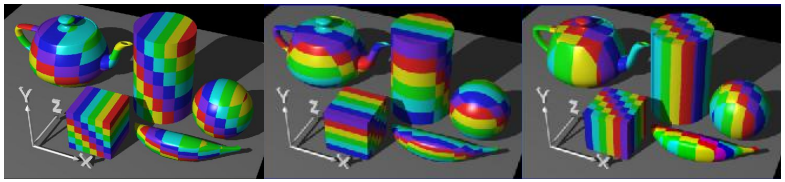
Planar Mapping

How do we map to polygonal meshes?



Planar/orthographic map:
- simply remove one of the object's coordinates to project onto that coordinate plane
- the texture is constant in one direction (z, x, y)



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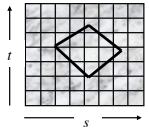
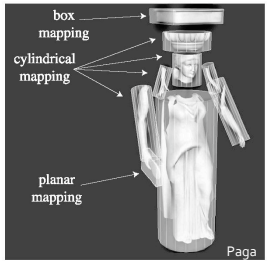
Texture Mapping with an Intermediate Surface



Two-stage mapping

1. map the texture to a simple intermediate surface (cube, cylinder, sphere)
2. map the intermediate surface (with the texture) onto the surface being rendered



Surface (θ, h)

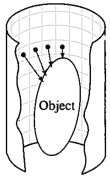
$$s = \frac{r}{c}(\theta - \theta_0),$$

$$t = \frac{1}{d}(h - h_0),$$

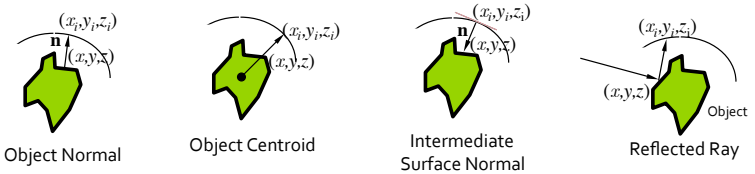
r: radius of cylinder,

c, d: scaling factors,

θ_0, h_0: position the texture on the cylinder



Intermediate to Object Mapping



	Plane	Cylinder	Sphere	Box
Object Normal	-	✗	ok	ok
Object Centroid	-	✗	✗	✗
Intermediate Surface Normal	slide projector	shrinkwrap	-	ok
Reflected ray	EM	EM	EM	EM

Blinn&Newell76

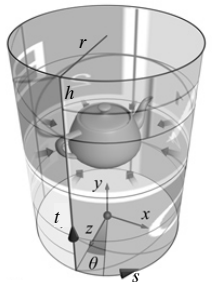
Cylindrical Map

Object coordinate (x, y, z) is converted to $(r(adius), \theta, h(eight))$

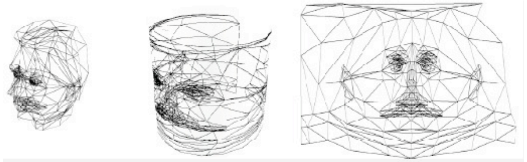
For texture mapping, θ is converted into s-coordinate and h is converted into t-coordinate

This wraps the texture map around the object

Useful for faces



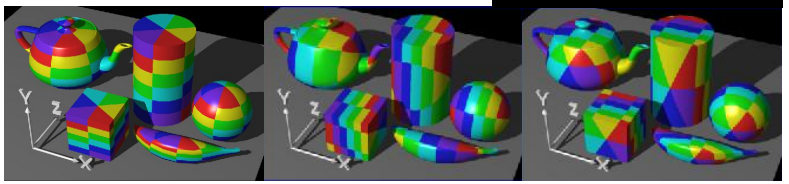
TP3



Schulze

Cylindrical Map

At minimum and maximum extents of the cylinder, the texture gets pinched together



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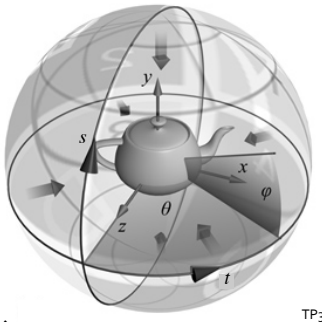
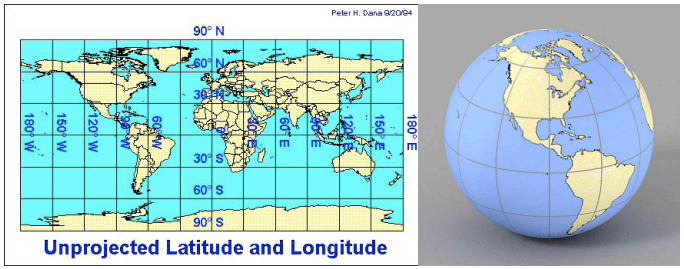
Spherical Map

Convert from (x, y, z) to spherical coordinates (θ, φ)

Longitude (φ) is converted into s-coordinate, latitude (θ) is converted into t-coordinate (note z is not pointing up in image)

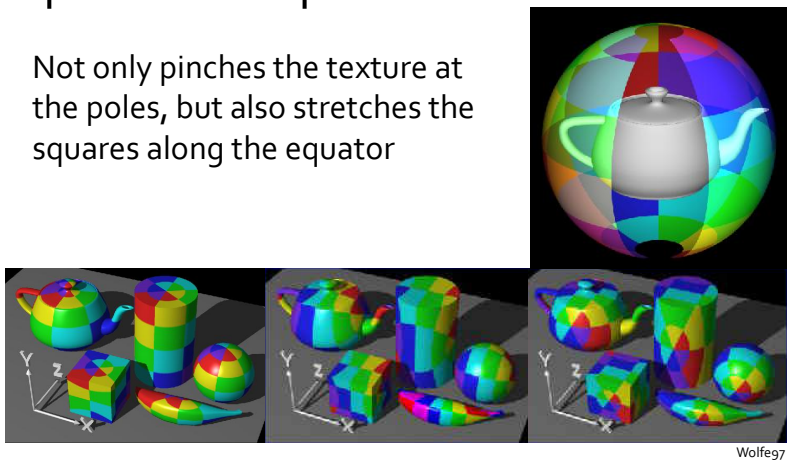


TP3



Spherical Map

Not only pinches the texture at the poles, but also stretches the squares along the equator



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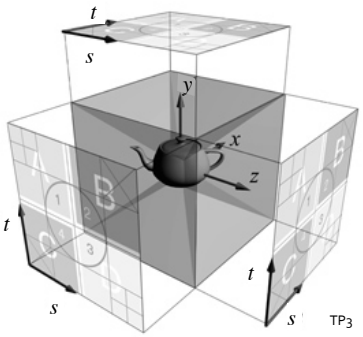
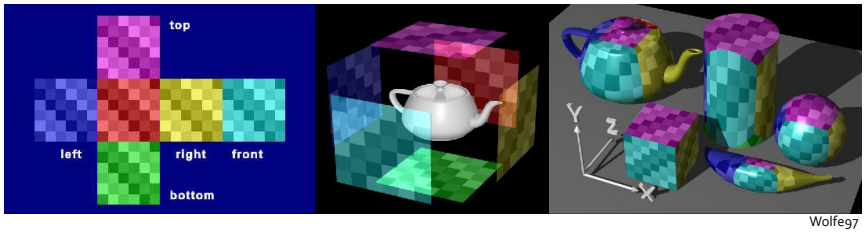
Cube/Box Map

Use six planar maps, one for each face of the cube



TP3



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Generating Texture Coordinates

OpenGL can generate texture coordinates automatically using `glTexGen*()`

- based on distance of vertex from a given plane in either
  - object-coordinates (`GL_OBJECT_LINEAR`): texture attached to object, or
  - eye-coordinates (`GL_EYE_LINEAR`): object appears swimming in texture, e.g., to render an oil drill, as it goes deeper into ground, it changes color

Generating Texture Coordinates

For environment mapping (in eye-coordinates):

- by sphere mapping:

```
// insert where the texture is created
glTexGeni(GL_S,GL_TEXTURE_GEN_MODE,GL_SPHERE_MAP);
glTexGeni(GL_T,GL_TEXTURE_GEN_MODE,GL_SPHERE_MAP);
glEnable(GL_TEXTURE_GEN_S);
glEnable(GL_TEXTURE_GEN_T);
```

- or by cube mapping:
  - load six images, one for each face with: `glTexImage2D(target)`
  - texture coordinates generated using

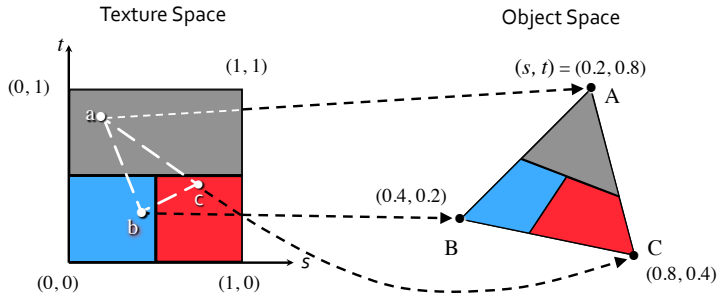
```
glTexGen*(…,GL_TEXTURE_GEN_MODE,GL_REFLECTION_MAP);
glEnable(GL_TEXTURE_CUBE_MAP);
glEnable(GL_TEXTURE_GEN_S);
glEnable(GL_TEXTURE_GEN_T);
glEnable(GL_TEXTURE_GEN_R);
```

Function deprecated

Rasterizing Texture Coordinates

When rasterizing primitives:

- assign texture coordinates to each vertex
- within a triangle, use linear interpolation (barycentric coordinates!)



Akenine-Möller02

Perspective Projection

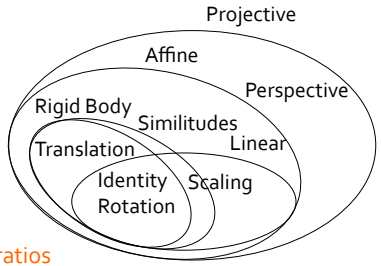
Characteristics preserved:

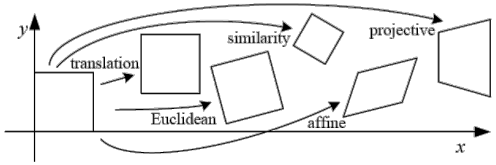
Rigid body/Euclidean:
- angles, lengths, areas

Similitudes/similarity:
- angles, length ratios

Affine:
- parallel lines, length ratios, area ratios

Perspective: not
- collinearity, cross-ratios

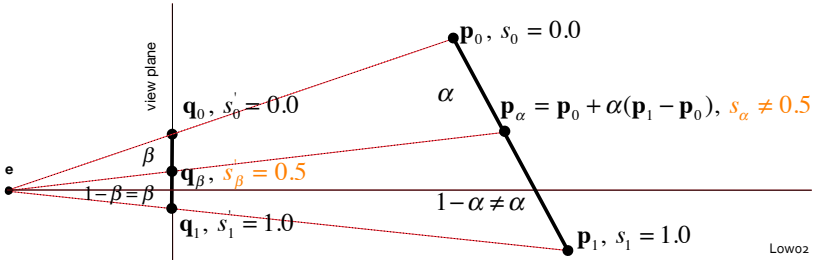




DeMenthon Durando8

Linear Interpolation in Perspective

Linear interpolation in screen coordinates is not equal to linear interpolation in eye coordinates!



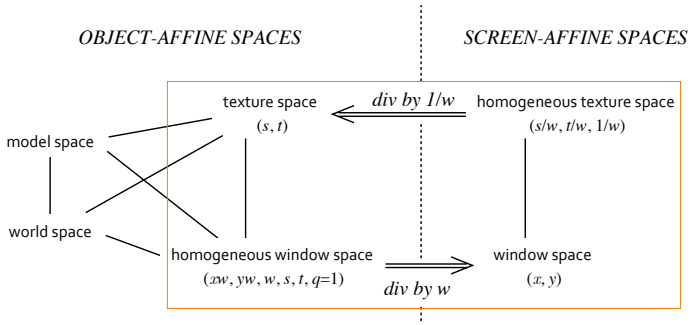
Lowo2

Solution?

Perspective-correct Interpolation

Instead of interpolating s', interpolate $s = s'w$, $w = 1/z$

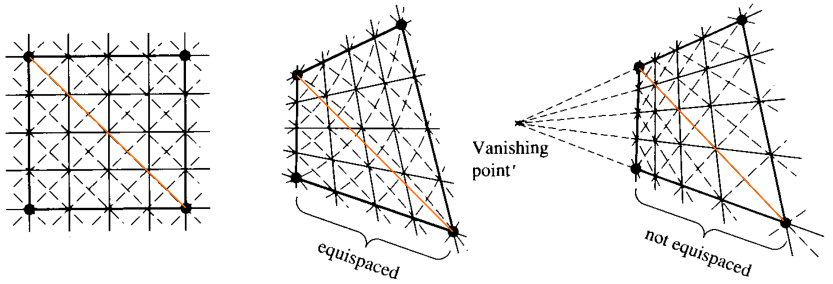
- $s_\alpha = lerp(s_0, s_1)$
- $w_\alpha = lerp(w_0, w_1)$
- $s_\beta' = s_\alpha / w_\alpha$



Heckbert89

Bilinear Interpolation

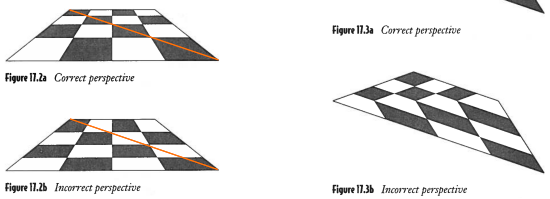
Also requires perspective correction:



Heckbert89

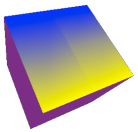
Bilinear Interpolation in Perspective

Uncorrected, not only lack of foreshortening, worse effect if square is rotated:



Blinn75

Effect is most visible on texture mapping, but also presents in color shading, though generally tolerated



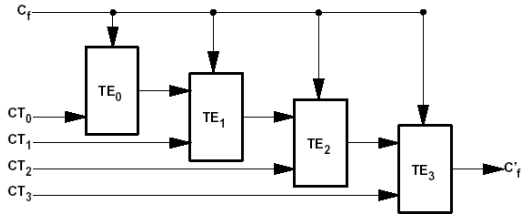
Perspective-correct interpolation in OpenGL:

```
glHint(GL_PERSPECTIVE_CORRECTION_HINT, GL_NICEST);
```

Multitexture Pipeline

Applying multiple textures to a single fragment

- applied one by one in a pipelined fashion
- each stage consists of a texture unit/environment
- allows for texture blending, for lighting effects, decals, compositing



C_f = fragment primary color input to texturing

C'_f = fragment color output from texturing

CT_i = texture color from texture lookup i

TE_i = texture environment i

Texture Units

A texture unit allows various texture settings to be encapsulated into a single texture context/ environment

There are only a fixed, pre-determined number of texture units and they are not OpenGL objects

Setting Up the Texture Units

To select a particular texture unit, use `glActiveTexture()`
- after which calls to `glBindTexture()`, `glTexImage*()`, `glTexParameter*()` affect only the selected texture unit

Each texture unit has its own texture state, which must be setup as shown earlier:
- allocate/assign texture object handle(s)
- load texture image(s)
- set texture wrapping and magnification/ minification filtering modes
- set texture combination mode
- set texture matrix stack (for transforming the texture)
- etc.

Using Multitexture Pipeline

```
// In init(), load images and initialize textures as before.
// In display():

// bind and enable texture unit 0
glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE_2D, textures[0]);
glEnable(GL_TEXTURE_2D);

// bind and enable texture unit 1
glActiveTexture(GL_TEXTURE1);
glBindTexture(GL_TEXTURE_2D, textures[1]);
glEnable(GL_TEXTURE_2D);

// specify two sets of texture coordinates per vertex
glBegin(GL_TRIANGLES);
   glColor3f(1.0f, 1.0f, 1.0f);

   glMultiTexCoord2f(GL_TEXTURE0, 0.0, 1.0);
   glMultiTexCoord2f(GL_TEXTURE1, 0.0, 1.0);
   glVertex3f(…);
   …
glEnd();
```

Texture `sampler`

A texture `sampler` corresponds to a texture unit, encapsulating a texture object with all its parameters and environment

Texture `sampler`s are passed from application to shaders as a `uniform` variable

Fragment shaders use `texture*()` to sample texture from `sampler*`

Example: to create `sampler` in the OpenGL application, assuming texture unit 0 has been set up as shown previously:

```
GLuint texid;

texid = glGetUniformLocation(myprog, "mytexture");

glUniform1i(texid,0)      // assign texture object and
                          // texture unit 0 to sampler
                          // assuming texture unit 0 has
                          // been set up as shown previously
```

Interpolated Texture Coordinates

```
// vertex shader: generally only worries about texcoords

uniform vec4 lightPos;
varying vec3 normal;
varying vec3 lightVec;
varying vec2 texcoord;

void main() {
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;

  texcoord = 0.01*gl_Vertex.xz;

  vec4 vert = gl_ModelViewMatrix * gl_Vertex;
  normal = gl_NormalMatrix * gl_Normal;
  lightVec = vec3(lightPos - vert);
}
```

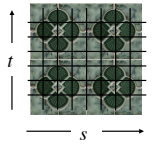
Texture Lookup in GLSL

```
// fragment shader

varying vec3 normal;
varying vec3 lightVec;
varying vec2 texcoord;

uniform sampler2D mytexture;

void main(){
       vec3 norm = normalize(normal);
       vec3 L = normalize(lightVec);
       vec4 color = texture2D(mytexture, texcoord);
       float NdotL = dot(L, norm);
       float diffuse = 0.5 * NdotL + 0.5;
       gl_FragColor = color*vec4(vec3(diffuse),1.0);
}
```



Texture Coordinates as Custom Vertex Attribute

```
attribute vec4 va_Position;
attribute vec2 va_TexCoords;
varying texcoords;

void
main(void)
{
  gl_Position = gl_ModelViewProjectionMatrix*va_Position;
  texcoords = va_TexCoords;
}
```

Application loads, compiles, and links shaders as usual

Then application gets the cva locations:

```
int vPos = glGetAttribLocation(pd, "va_Position");
int vTex = glGetAttribLocation(pd, "va_TexCoords");
```

Binding CVA with Data Stream

Setup vbo `GL_ARRAY_BUFFER` to include texture coordinates (see PA3)

Enable cva:

```
glEnableVertexAttribArray(vTex);
```

Then bind the cva to the vbo holding the data stream:

```
glVertexAttribPointer(vTex, 2, GL_FLOAT, GL_FALSE,
                      stride, offset);
```