EECS 487: Interactive Computer Graphics

Lecture 24:
- Texture Mapping

Texture Mapping

What is texture mapping

Texture mapping in OpenGL
- texture-coordinates array

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:

O'Brien

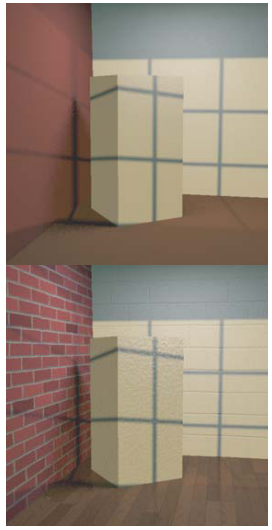
Texture Mapping

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



Yu08

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

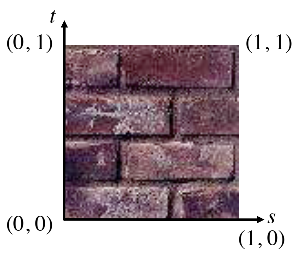
Procedural texture: instead of relying on a pre-computed lookup table, texturing can also be done algorithmically

2D Texture Map

Texture is a 2D raster image:

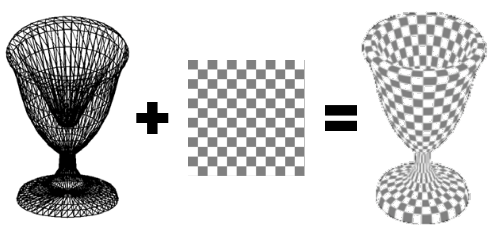
`texture[width(s)][height(t)]`

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



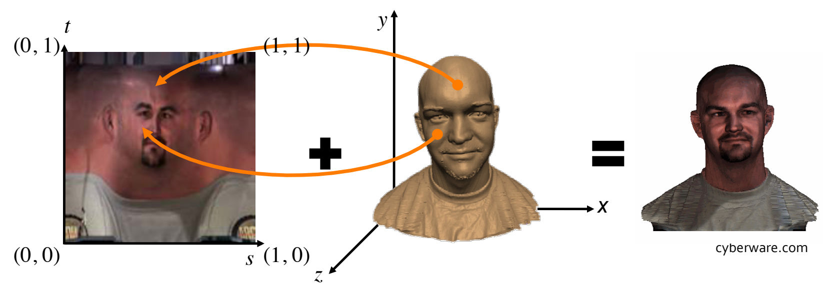
Hanrahan

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



cyberware.com

Image-Based Rendering

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

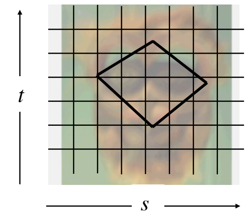
What You See Is ALL You Get
(but that may be all you need)

Original photograph with marked edges | Recovered model | Model edges projected onto photograph | Synthetic rendering

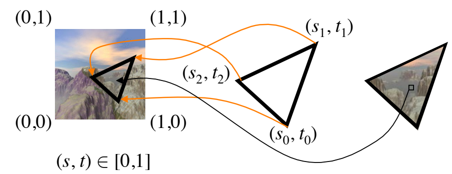
debevec.org

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 descriptors*:

```
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 descriptor == texture handle == texture name == texture ID

Specify the Texture Image

Specify the texture image to use:

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

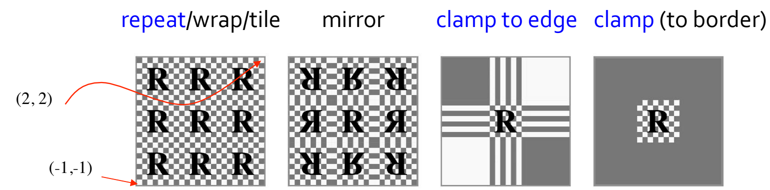
with:

- `target`: `GL_TEXTURE_2D` (or cube faces or others)
- `level`: mipmap level, 0 if not mipmapping
- `internalFormat`: `GL_RGB` or `GL_RGBA`, or a compressed format
- `width`: width of image, including border
- `height`: height of the image, including border
- `border`: whether image has border, must be 0 or 1
- `format`: format of image's pixel data, `GL_RGB` or `GL_RGBA`
- `type`: data type of pixel data, `GL_UNSIGNED_BYTE`, `GL_FLOAT`, etc.
- `teximage`: pointer to image 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:



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

Akenine-Moller02

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

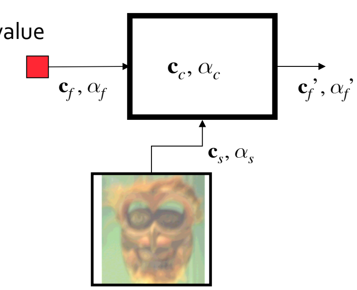
For example:

```
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 Lab 6)

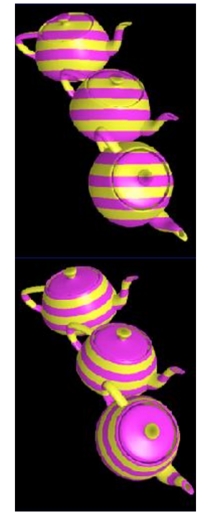
```
// texcoords must have a 1-1 mapping with vertices
float vertices[][] = { { 0.5, 0.5, 0.0 },
  {-0.5, 0.5, 0.0 }, {-0.5, -0.5, 0.0 },
  {0.5, -0.5, 0.0 } };
float texcoords[][] = { { 1.0, 1.0 },
  { 0.0, 1.0 }, { 0.0, 0.0 }, { 1.0, 0.0 } };

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?

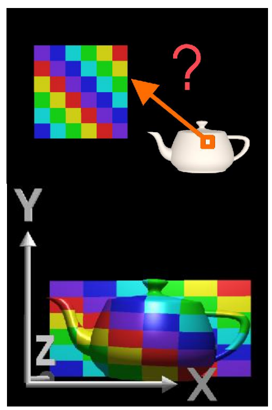
Non-parametrically
- texture size and orientation are fixed in world coordinates
- gives a "projector" effect: object "swims" through texture

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



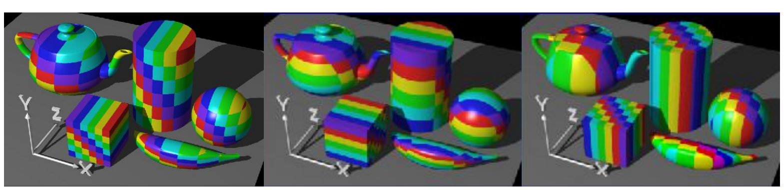
Wolfe97

Planar Mapping



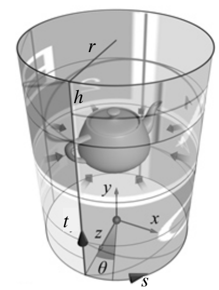
How do we map to polygonal meshes?

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)



Wolfe97

Cylindrical Map



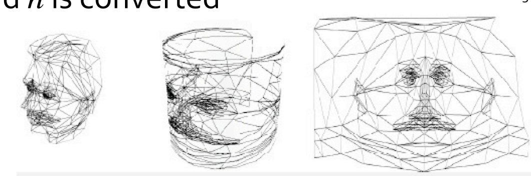
TP3

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

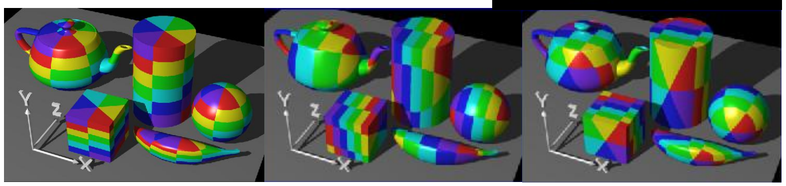
Useful for faces



Schulze

Cylindrical Map

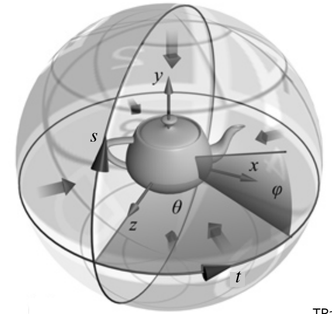
At minimum and maximum extents of the cylinder, the texture gets pinched together



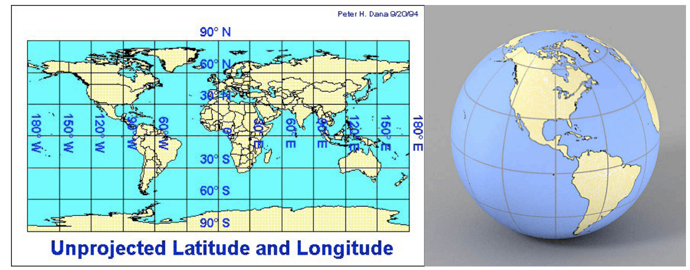
Wolfe97

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)

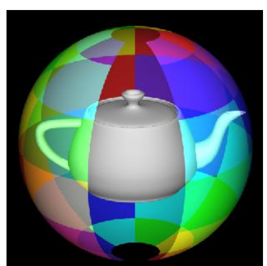


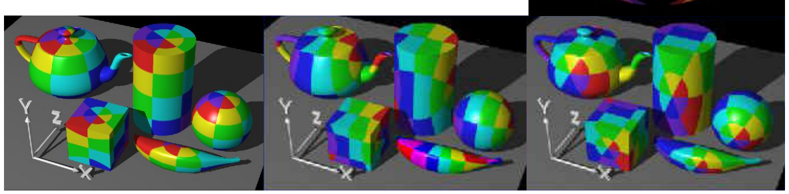
TP3



Spherical Map

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





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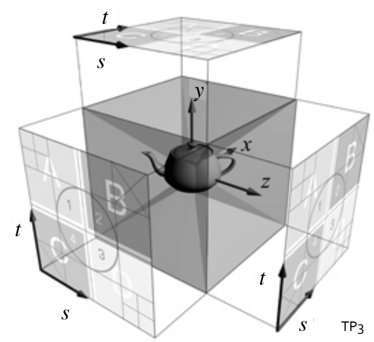
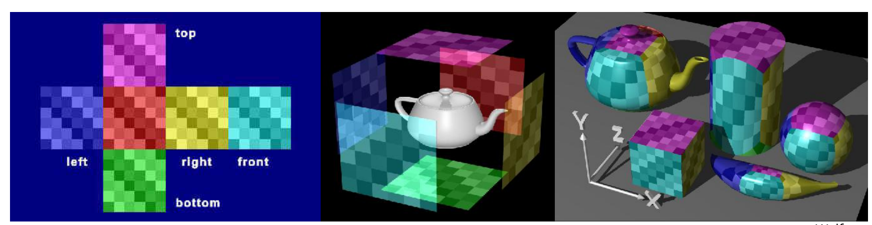
Cube/Box Map

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



TP3



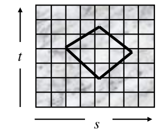
Wolfe97

Generating Texture Coordinates

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

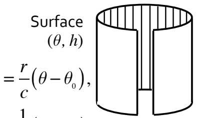
- based on distance of vertex from a given plane in either
  - object-coordinates (`GL_OBJECT_LINEAR`): texture attached to object, or
  - eye-coordinates (`GL_EYE_LINEAR`): object appears swimming in texture, e.g., to render an oil drill, as it goes deeper into ground, it changes color

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



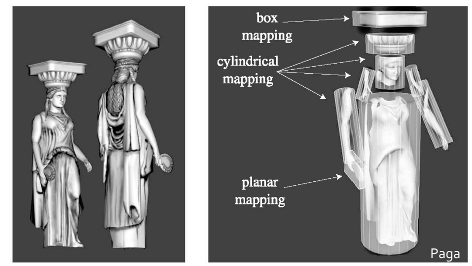
$s = \frac{r}{c}(\theta - \theta_0)$,

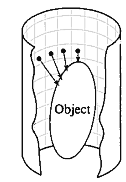
$t = \frac{1}{d}(h - h_0)$,

r: radius of cylinder,

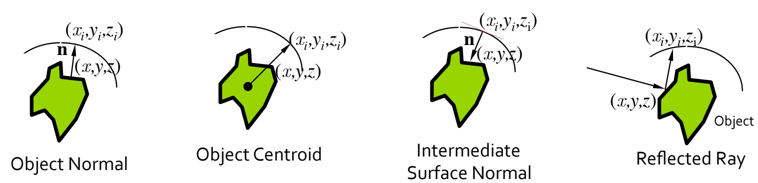
c, d: scaling factors,

θ_0, h_0: position the texture on the cylinder





Intermediate to Object Mapping



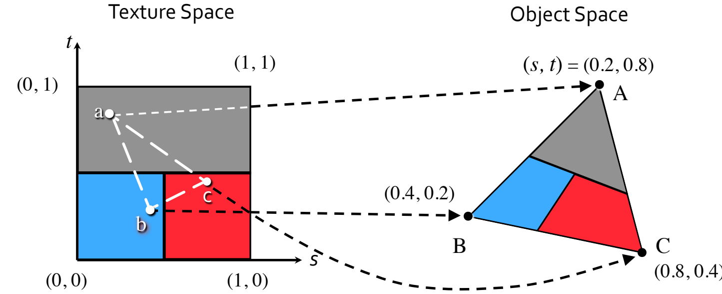
	Plane	Cylinder	Sphere	Box
Object Normal	-	✗	ok	ok
Object Centroid	-	✗	✗	✗
Intermediate Surface Normal	slide projector	shrinkwrap	-	ok
Reflected ray	EM	EM	EM	EM

Blinn&Newell76

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:

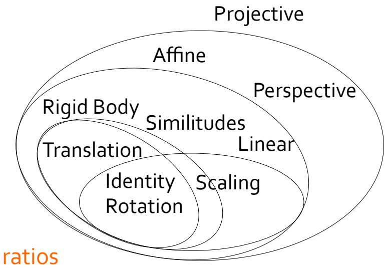
- angles, length ratios

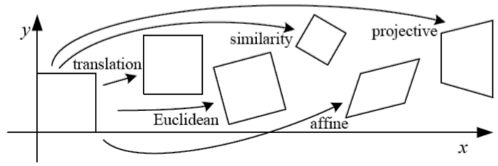
Affine:

- parallel lines, length ratios, area ratios

Perspective: not

- collinearity, cross-ratios

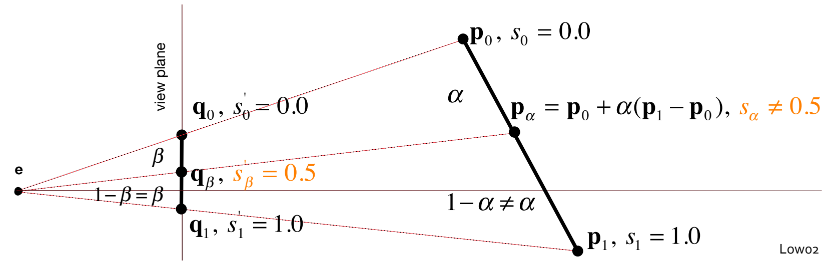




DeMenthon
Durand08

Linear Interpolation in Perspective

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



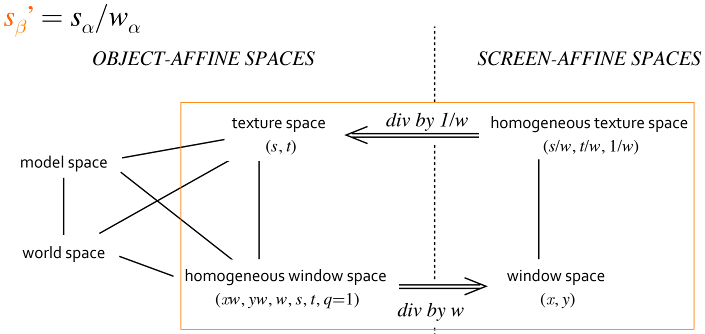
Lowo2

Solution?

Perspective-correct Interpolation

Instead of interpolating the parameter s' after perspective divide, do the perspective divide on the interpolated s and interpolated homogenous coordinate w:

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



Heckbert89

Bilinear Interpolation

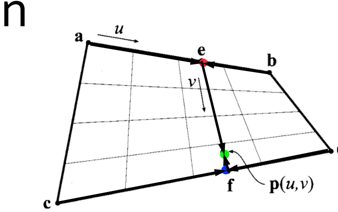
Linear interpolation in 2D:

$$\mathbf{e} = (1-u)\mathbf{a} + u\mathbf{b}$$

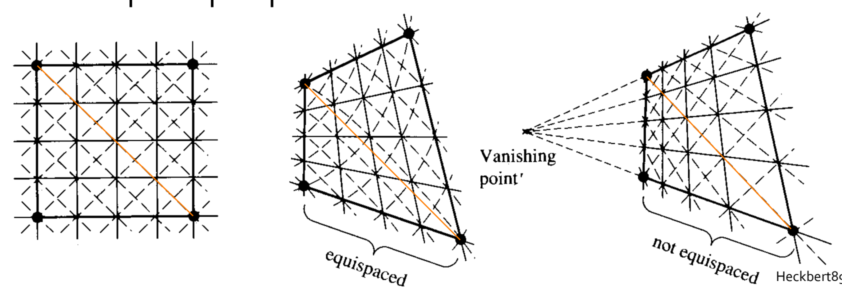
$$\mathbf{f} = (1-u)\mathbf{c} + u\mathbf{d}$$

$$\mathbf{p}(u,v) = (1-v)\mathbf{e} + v\mathbf{f}$$

$$= (1-u)(1-v)\mathbf{a} + u(1-v)\mathbf{b} + (1-u)v\mathbf{c} + uv\mathbf{d}$$



Also requires perspective correction:



Heckbert89

Bilinear Interpolation in Perspective

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

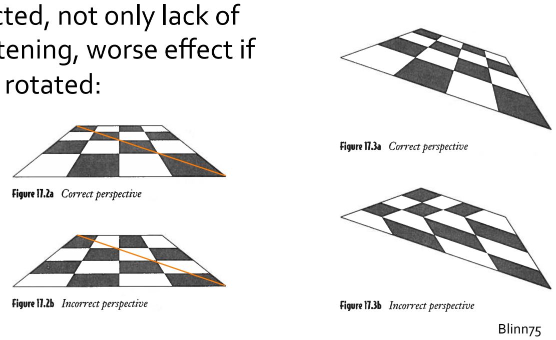


Figure 17.2a *Correct perspective*

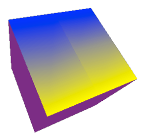
Figure 17.2b *Incorrect perspective*

Figure 17.3a *Correct perspective*

Figure 17.3b *Incorrect perspective*

Blinn75

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



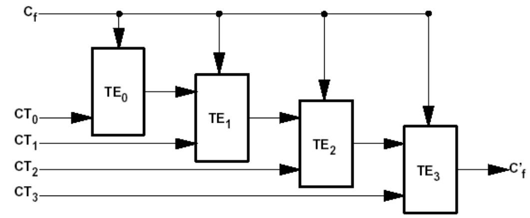
Perspective-correct interpolation in OpenGL:

```
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 texture binding to be encapsulated into a single texture context/ environment

In OpenGL, there are only a fixed, pre-determined number (≥ 80) of texture units and they are not dynamic OpenGL objects

To select a particular texture unit, use `glActiveTexture()`

- after which calls to `glBindTexture()`, affect only the selected texture unit

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, tbods[0]);
glEnable(GL_TEXTURE_2D);

// bind and enable texture unit 1
glActiveTexture(GL_TEXTURE1);
glBindTexture(GL_TEXTURE_2D, tbods[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 unit is passed, as a `uniform` variable, from application to shaders as a texture `sampler`

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

Example: to pass texture unit 0 from application to shader as a `sampler`, 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
```

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);
}
```

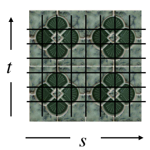
Texture Lookup in GLSL 1.2

```
// 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 GLSL 1.3+ 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);
```