Texture mapping is a computer graphics operation in which a separate image, referred to as the texture, is stretched onto a piece of 3D geometry and follows it however it is transformed. This image is also known as a texture map.

This can be most any image. Some graphics hardware requires the image’s pixel dimensions to be a power of two. (This restriction has been lifted on most graphics cards, but just to be safe, . . .) The X and Y dimensions do not need to be the same power of two, just a power of two. So, a 128x512 image would be OK, a 129x511 image might not.

The mapping between the geometry of the 3D object and the S and T of the texture image works like this:

Enable texture mapping:
```c
glEnable( GL_TEXTURE_2D );
```

Draw your polygons, specifying s and t at each vertex:
```c
glBegin( GL_POLYGON );
glTexCoord2f( s0, t0 );
glNormal3f( nx0, ny0, nz0 );
glVertex3f( x0, y0, z0 );
glTexCoord2f( s1, t1 );
glNormal3f( nx1, ny1, nz1 );
glVertex3f( x1, y1, z1 );
. . .
glEnd( );
```

If this geometry is static (i.e., will never change), it is a good idea to put this all into a display list.

Disable texture mapping:
```c
glDisable( GL_TEXTURE_2D );
```
Or, for a sphere, you do the same thing you did for the plane, only the interpolated variables are angular (spherical) coordinates instead of linear coordinates:

\[
\begin{align*}
    s &= \frac{\theta - (-\pi)}{2\pi} \\
    t &= \frac{\phi - (-\pi/2)}{\pi}
\end{align*}
\]

The Sphere code does it like this:

\[
\begin{align*}
    s &= \frac{(\text{lng} + \pi)}{2\pi} \\
    t &= \frac{(\text{lat} + \pi/2)}{\pi}
\end{align*}
\]

Using a Texture: How do you know what (s,t) to assign to each vertex?

Uh-oh. Now what? Here's where it gets tougher….

You really are at the mercy of whoever did the modeling and assigned the s,t coordinates…

Be careful where s abruptly transitions from 1. back to 0.

unsigned char *BmpToTexture( char *, int *, int * );

unsigned char *Texture;

•••

Texture = BmpToTexture( "filename.bmp", &width, &height );

This function is found in your sample code. The BMP file filename.bmp needs to be created by something that writes uncompressed 24-bit color BMP files, or converted to the uncompressed BMP format by a tool such as ImageMagick's convert, Adobe Photoshop, or GIMP.

Note: this function should be called once, and called from InitGraphics() function. Do not call it in the Display() function.

Define the texture wrapping parameters. This will control what happens when a texture coordinate is greater than 1.0 or less than 0.0:

\[
\begin{align*}
    \text{glTexParameteri}( \text{GL_TEXTURE_2D}, \text{GL_TEXTURE_WRAP_S}, \text{wrap} ); \\
    \text{glTexParameteri}( \text{GL_TEXTURE_2D}, \text{GL_TEXTURE_WRAP_T}, \text{wrap} );
\end{align*}
\]

where wrap is:

- **GL_REPEAT** specifies that this pattern will repeat (i.e., wrap-around) if transformed texture coordinates less than 0.0 or greater than 1.0 are encountered.
- **GL_CLAMP** specifies that the pattern will "stick" to the value at 0.0 or 1.0.
Define the texture filter parameters. This will control what happens when a texture is scaled up or down.

```c
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, filter);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, filter);
```

where `filter` is:

- **GL_NEAREST** specifies that point sampling is to be used when the texture map needs to be magnified or minified.

- **GL_LINEAR** specifies that bilinear interpolation among the four nearest neighbors is to be used when the texture map needs to be magnified or minified.

### Texture Filtering

<table>
<thead>
<tr>
<th>GL_NEAREST</th>
<th>GL_LINEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnified</td>
<td>Minified</td>
</tr>
</tbody>
</table>

This tells OpenGL what to do with the texel colors when it gets them:

```c
glTexEnvf(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, mode);
```

There are several modes that can be used. Two of the most useful are:

- **GL_REPLACE** specifies that the 3-component texture will be applied as an opaque image on top of the polygon, replacing the polygon’s specified color.

- **GL_MODULATE** specifies that the 3-component texture will be applied as piece of colored plastic on top of the polygon. The polygon’s specified color “shines” through the plastic texture. This is very useful for applying lighting to textures: paint the polygon white with lighting and let it shine up through a texture.

### Texture Environment

<table>
<thead>
<tr>
<th>GL_REPLACE</th>
<th>GL_MODULATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Show texture as an opaque image</td>
<td>Show texture as colored plastic</td>
</tr>
</tbody>
</table>

### Setting up the Texture

```c
int width, height;
unsigned char *Texture = BmpToTexture( "filename.bmp", &width, &height );
int level, ncomps, border;

GLenum format = GL_RGB; // or GL_RGBA
GLenum type = GL_UNSIGNED_BYTE;

// Set up the texture

GLuint textureID;

glGenTextures(1, &textureID);

// Set up the texture parameters

glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);

// Load the texture

glTexImage2D(GL_TEXTURE_2D, level, ncomps, width, height, border, format, type, Texture);

// Use the texture

glBindTexture(GL_TEXTURE_2D, textureID);
```

where:

- `level` is used with mip-mapping. Use 0 for now.

- `ncomps` number of components in this texture: 3 if using RGB, 4 if using RGBA.

- `width` width of this texture map, in pixels.

- `height` height of this texture map, in pixels.

- `border` width of the texture border, in pixels. Use 0 for now.

- `Texture` the name of an array of unsigned characters holding the texel colors.

This function physically transfers the array of texels from the CPU to the GPU and makes it the current active texture. You can get away with specifying this ahead of time only if you are using a single texture. If you are using multiple textures, you must make each current in `Display()` right before you need it. See the section below about binding textures.

### Texture Transformation

In addition to the Projection and ModelView matrices, OpenGL maintains a transformation for texture map coordinates S and T as well. You use all the same transformation routines you are used to: `glRotatef()`, `glScalef()`, `glTranslatef()`, but you must first specify the Matrix Mode:

```c
glMatrixMode(GL_TEXTURE);
```

The only trick to this is to remember that you are transforming the texture coordinates, not the texture image. Transforming the texture image forward is the same as transforming the texture coordinates backwards:

- **Scale**
  - Scale = 1: Texture stays the same.
  - Scale < 1: Texture becomes smaller.
  - Scale > 1: Texture becomes larger.

- **Angle**
  - Angle = 0: Texture stays the same.
  - Angle > 0: Texture rotates clockwise.
  - Angle < 0: Texture rotates counterclockwise.

### Texture Objects

The OpenGL `glTexImage2D` function doesn’t just use that texture, it downloads it from the CPU to the GPU, every time that call is made! After the download, this texture becomes the “current texture image”.

```c
GLuint textureID;

// Load the texture

glTexImage2D(GL_TEXTURE_2D, level, ncomps, width, height, border, format, type, Texture);

// Use the texture

glBindTexture(GL_TEXTURE_2D, textureID);
```

If your scene has only one texture, this is easy to manage. Just do it once and forget about it.

But, if you have several textures, all to be used at different times on different objects, it will be important to maximize the efficiency of how you create, store, and manage those textures. In this case you should bind texture objects.

Texture objects leave your textures on the graphics card and then re-uses them, which is always going to be faster than re-loading them.
Create a texture object by generating a texture name and then bind the texture object to the texture data and texture properties. The first time you execute `glBindTexture()`, you fill the texture object. Subsequent times you do this, you are making that texture object current. So, create global Texture IDs like this:

```c
GLuint Tex0, Tex1; // global variables
...
```

Then, at the end of `InitGraphics()` you add:

```c
int width, height;
unsigned char * TextureArray0 = BmpToTexture( "file.bmp", &width, &height );
glPixelStorei( GL_UNPACK_ALIGNMENT, 1 );
glGenTextures( 1, &Tex0 ); // assign binding "handles"
```

Later, before rendering, you make the texture current and set its parameters:

```c
// make the Tex0 texture current
// and set its parameters
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_CLAMP );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T,  GL_CLAMP );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );
glTexImage2D( GL_TEXTURE_2D, 0, 3, width, height, 0, GL_RGB, GL_UNSIGNED_BYTE, TextureArray0 );
```

Then, later on in `Display()`:

```c
// designate the Tex1 texture as the "current texture"
// and set its parameters
glBindTexture( GL_TEXTURE_2D, Tex1 );
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 );
glTexImage2D( GL_TEXTURE_2D, 0, 3, 512, 512, 0, GL_RGB, GL_UNSIGNED_BYTE, TextureArray1 );
```

Some Great Uses for Texture Mapping you have seen in the Movies

Disney

Pixar

Yes, I know, I know, these are older examples, but I especially like them because, at the time, the CG (and the textures) became part of the story-telling.

Bonus Topic: Procedural Texture Mapping

You can also create a texture from data on-the-fly. In this case, the fragment shader takes a grid of heights and uses cross-products to produce surface normal vectors for lighting.

Although this looks like an incredible amount of polygonal scene detail, the geometry for this scene consists of just a single quadrilateral.

We cover this more in the shaders course: CS 457/557
“Mandelzoom”:
In this case, the texture is a pure equation, so you never run out of resolution. (You do run out of floating-point precision, however.)

$z^2 + c \rightarrow z$

Bonus Topic: Procedural Texture Mapping

We cover this more in the shaders course: CS 457/557