Texture Mapping

CS 432 Interactive Computer Graphics
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Objectives

• Introduce Mapping Methods
  - Texture Mapping
  - Environment Mapping
  - Bump Mapping

• Consider basic strategies
  - Forward vs backward mapping
  - Point sampling vs area averaging
The Limits of Geometric Modeling

• Although graphics cards can render over 20 million polygons per second, that number is insufficient for many phenomena
  - Clouds
  - Grass
  - Terrain
  - Skin
Modeling an Orange

- Consider the problem of modeling an orange (the fruit)
- Start with an orange-colored sphere
  - Too simple
- Replace sphere with a more complex shape
  - Does not capture surface characteristics (small dimples)
  - Takes too many polygons to model all the dimples
Modeling an Orange (2)

• Take a picture of a real orange, scan it, and “paste” onto simple geometric model
  - This process is known as texture mapping

• Still might not be sufficient because resulting surface will be smooth
  - Need to change local shape
  - Bump mapping
Three Types of Mapping

• 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
Texture Mapping

geometric model

texture mapped
Environment Mapping
Bump Mapping
Where does mapping take place?

- Mapping techniques are implemented at the end of the rendering pipeline
  - Very efficient because few polygons make it past the clipper
Is it simple?

• Although the idea is simple---map an image to a surface---there are 3 or 4 coordinate systems involved.
Coordinate Systems

• Parametric coordinates
  - May be used to model curves and surfaces

• Texture coordinates
  - Used to identify points in the image to be mapped

• Object or World Coordinates
  - Conceptually, where the mapping takes place

• Window Coordinates
  - Where the final image is really produced
Texture Mapping

parametric coordinates

texture coordinates

world coordinates

window coordinates
Mapping Functions

• Basic problem is how to find the maps
• Consider mapping from texture coordinates to a point a surface
• Appear to need three functions
  \[ x = x(s, t) \]
  \[ y = y(s, t) \]
  \[ z = z(s, t) \]
• 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: map to cylinder
parametric cylinder

\[ x = r \cos 2\pi u \]
\[ y = r \sin 2\pi u \]
\[ z = v/h \]

maps rectangle in u,v space to cylinder of radius r and height h in world coordinates

\[ s = u \]
\[ t = v \]

maps from texture space
We can use 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 environment maps
Second Mapping

- Map from intermediate object to actual object
  - Normals from intermediate to actual
  - Normals from actual to intermediate
  - Vectors from center of intermediate
Aliasing

- Point sampling of the texture can lead to aliasing errors

![Diagram showing point samples in u,v (or x,y,z) space and their corresponding points in texture space. The diagram illustrates how point samples can miss blue stripes.](image-url)
Area Averaging

A better but slower option is to use area averaging.

Note that preimage of pixel is curved.
Go to ART Texture Mapping slides
WebGL Texture Mapping
Objectives

• Introduce WebGL texture mapping
  - two-dimensional texture maps
  - assigning texture coordinates
  - forming texture images
Basic Strategy

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
   • wrapping, filtering
Texture Mapping
Texture Example

• The texture (below) is a 256 x 256 image that has been mapped to a rectangular polygon which is viewed in perspective.
Texture Mapping and the WebGL Pipeline

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

![Diagram of the WebGL pipeline with vertices, geometry pipeline, image, texel pipeline, and fragment processor.](image)
• Define a texture image from an array of texels (texture elements) in CPU memory
• Use an image in a standard format such as JPEG
  - Scanned image
  - Generate by application code
• WebGL 1 only supports 2 dimensional texture maps
  - Dimensions should be power of 2 for mip-mapping
• These restrictions removed in WebGL 2, and now supports many texture types
• We’ll still focus on 2D textures
Define Image as a Texture

```javascript
gl.texImage2D( target, level, internalformat, 
              w, h, border, format, type, texels );
```

target: type of texture, e.g. `gl.TEXTURE_2D`
level: used for mipmapping (discussed later)
internalformat: elements per texel
w, h: width and height of texels in pixels
border: width of the border. Must be 0.
format: must be the same as internalformat
type: data type of texel data
texels: source of texel data

```javascript
glTexImage2D( gl.TEXTURE_2D, 0, gl.RGBA, 512, 512, 0, gl.RGBA, gl.UNSIGNED_BYTE, my_texels );
```
A Checkerboard Image

```javascript
var image1 = new Uint8Array(4*texSize*texSize);
    for ( var i = 0; i < texSize; i++ ) {
        for ( var j = 0; j < texSize; j++ ) {
            var patchx = Math.floor(i/(texSize/numChecks));
            var patchy = Math.floor(j/(texSize/numChecks));
            if (patchx%2 ^ patchy%2) c = 255;
            else c = 0;
            //c = 255*(((i & 0x8) == 0) ^ ((j & 0x8) == 0))
            image1[4*i*texSize+4*j] = c;
            image1[4*i*texSize+4*j+1] = c;
            image1[4*i*texSize+4*j+2] = c;
            image1[4*i*texSize+4*j+3] = 255;
        }
    }
```
function loadTexture(url) {
    let texture = gl.createTexture();
    let image = new Image();
    // put in placeholder image data until actual image loads.
    configureTexture(texture, null);

    image.addEventListener("error", (event) => {
        console.log(`error evt: ${JSON.stringify(event)}`);
    });
    image.addEventListener("load", (event) => {
        configureTexture(texture, image);
        window.requestAnimationFrame(render);
    });
    image.crossOrigin = "Anonymous";
    image.src = url + "?dont-use-cache";

    return texture;
}
Mapping a Texture

• Based on parametric texture coordinates
• Specify as a 2D vertex attribute
• Interpolated by the rasterizer

Texture Space

Object Space

(s, t) = (0.2, 0.8)

(0.4, 0.2)

(0.8, 0.4)
Cube Example

```javascript
var texCoord = [
    vec2(0, 0),
    vec2(0, 1),
    vec2(1, 1),
    vec2(1, 0)
];

function quad(a, b, c, d) {
    pointsArray.push(vertices[a]);
    colorsArray.push(vertexColors[a]);
    texCoordsArray.push(texCoord[0]);

    pointsArray.push(vertices[b]);
    colorsArray.push(vertexColors[a]);
    texCoordsArray.push(texCoord[1]);

    // etc
```
Interpolation

WebGL uses interpolation to find proper texels from specified texture coordinates

Can be distortions

- Good selection of tex coordinates
- Poor selection of tex coordinates
- Texture stretched over trapezoid showing effects of bilinear interpolation
Using Texture Objects

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 per vertex
   - coordinates can also be generated
Texture Parameters

• WebGL 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 allows us to use textures at multiple resolutions
  - Environment parameters determine how texture mapping interacts with shading
Wrapping Mode

Clamping: if \( s, t > 1 \) use 1, if \( s, t < 0 \) use 0

Wrapping: use \( s, t \) modulo 1

\[
\text{gl.texParameteri}(\text{gl.TEXTURE}_2\text{D}, \\
\text{gl.TEXTURE_WRAP}_S, \text{gl.CLAMP})
\]

\[
\text{gl.texParameteri}(\text{gl.TEXTURE}_2\text{D}, \\
\text{gl.TEXTURE_WRAP}_T, \text{gl.REPEAT})
\]
Magnification and Minification

More than one texel can cover a pixel (minification) or more than one pixel can cover a texel (magnification)

Can use point sampling (nearest texel) or linear filtering (2 x 2 filter) to obtain texture values
Filter Modes

Modes determined by

```c
gl.texParameteri( target, type, mode )
```

```c
gl.texParameteri(gl.TEXTURE_2D, gl.TEXTURE_MAG_FILTER,
               gl.NEAREST);

gl.texParameteri(gl.TEXTURE_2D, gl.TEXTURE_MIN_FILTER,
               gl.LINEAR);
```
Mipmapped Textures

- Allows for prefiltered texture maps of decreasing resolutions
- Lessens interpolation errors for smaller textured objects
- Declare mipmap level during texture definition
  
  ```javascript
  gl.texImage2D( gl.TEXTURE_*D, level, ... )
  ```
- Have WebGL make your mipmap with
  
  ```javascript
  gl.generateMipmap()
  ```
Example

point sampling

linear filtering

mipmapped point sampling

mipmapped linear filtering
function configureTexture(texture, image) {
    gl.bindTexture(gl.TEXTURE_2D, texture);
    if (image) {
        gl.pixelStorei(gl.UNPACK_FLIP_Y_WEBGL, true);
        gl.texImage2D(gl.TEXTURE_2D, 0, gl.RGBA, gl.RGBA, 
                       gl.UNSIGNED_BYTE, image);
        gl.generateMipmap(gl.TEXTURE_2D);
    } else {
        let pixel = new Uint8Array([0, 0, 150, 255]);  // dark blue pixel
        gl.texImage2D(gl.TEXTURE_2D, 0, gl.RGBA, 1, 1, 0, 
                      gl.RGBA, gl.UNSIGNED_BYTE, pixel);
    }
}
Texture Object II

```c
gl.texParameteri( gl.TEXTURE_2D, gl.TEXTURE_MIN_FILTER,
                gl.NEAREST_MIPMAP_LINEAR );
gl.texParameteri( gl.TEXTURE_2D, gl.TEXTURE_MAG_FILTER,
                gl.NEAREST );
gl.texParameteri( gl.TEXTURE_2D, gl.TEXTURE_WRAP_S,
                gl.REPEAT );
gl.texParameteri( gl.TEXTURE_2D, gl.TEXTURE_WRAP_T,
                gl.REPEAT );
gl.activeTexture(gl.TEXTURE0);
gl.uniform1i(gl.getUniformLocation(program, "utexture"), 0);
```
Other Texture Features

• Environment Maps
  - Start with image of environment through a wide angle lens
    • Can be either a real scanned image or an image created in WebGL
  - Use this texture to generate a spherical map
  - Alternative is to use a cube map

• Multitexturing
  - Apply a sequence of textures through cascaded texture units
Using Textures

• Texture value may be used in ANY of the components of the shading formula

• For example
  - Diffuse color
  - Specular color
  - Ambient color
  - Shininess
  - Normals
  - Alpha

• Or as a decal, or mask or blended in
Typical Code

• Application sending texture coordinates

```javascript
var aPosition = gl.getAttribLocation( program, "aPosition" );
gl.enableVertexAttribArray( aPosition );
gl.vertexAttribPointer( aPosition, 4, gl.FLOAT, false, 0, 0 );

gl.bindBuffer( gl.ARRAY_BUFFER, tBuffer );

var aTexCoord = glGetAttribLocation( program, "aTexCoord" );
gl.enableVertexAttribArray( aTexCoord );
gl.vertexAttribPointer( aTexCoord, 2, gl.FLOAT, false, 0, 0 );
```
Vertex Shader

• Usually vertex shader will output texture coordinates to be rasterized
• Must do all other standard tasks too
  - Compute vertex position
  - Compute vertex color or normal if needed

```cpp
in vec4 aPosition;    //vertex position in object coordinates
in vec4 aColor;        //vertex color from application
in vec2 aTexCoord; //texture coordinate from application

out vec4 vcolor;        //output color to be interpolated
out vec2 vtexCoord;  //output tex coordinate to be interpolated
```
Applying Textures

• Texture can be applied in many ways
  - texture fully determines color
  - modulates a computed color
  - used as diffuse color during Phong shading

• Fixed function pipeline has a function glTexEnv to set mode
  - deprecated
  - can get all desired functionality via fragment shader

• Can also use multiple texture units
Applying Textures

- Textures are applied during fragments shading by a **sampler**
- Samplers return a color from a texture object
- This example modulates vcolor from rasterizer

```glsl
in vec4 vcolor; // color from rasterizer
in vec2 vtexCoord; // texture coordinate from rasterizer
uniform sampler2D utexture; // texture object from application
out vec4 fcolor;

void main() {
    fcolor = vcolor * texture( utexture, vtexCoord );
}
```

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Reflection and Environment Maps
Objectives

• Texture Mapping Applications
• Reflection (Environment) Maps
  - Cube Maps
  - Spherical Maps
• Bump Maps
Mapping Variations

smooth shading

environment
mapping

bump mapping
Environment Mapping

• Environmental (reflection) mapping is a way to create the appearance of highly reflective surfaces without ray tracing which requires global calculations.

• Introduced in movies such as The Abyss and Terminator 2.

• Prevalent in video games.

• It is a form of texture mapping.
Reflecting the Environment
Mapping to a Sphere
Hemisphere Map as a Texture

• If we map all objects to hemisphere, we cannot tell if they are on the sphere or anywhere else along the reflector
• Use the map on the sphere as a texture that can be mapped onto the object
• Can use other surfaces as the intermediate
  - Cube maps
  - Cylinder maps
Cube Map
Indexing into Cube Map

- Compute \( R = 2(N \cdot V)N - V \)
- Object at origin
- Use largest magnitude component of \( R \) to determine face of cube
- Other two components give texture coordinates
WebGL Implementation

• WebGL supports only cube maps
  - desktop OpenGL also supports sphere maps
• First must form map
  - Use images from a real camera
  - Form images with WebGL
• Texture map it to object
We can form a cube map texture by defining six 2D texture maps that correspond to the sides of a box. Supported by WebGL through cubemap sampler (samplerCube)

```glsl```
vec4 texColor = texture(mycube, texcoord);
```glsl```

Texture coordinates must be 3D - usually are given by the vertex location so we don’t need to compute separate tex coords.
Environment Maps with Shaders

- Environment maps are usually computed in world coordinates which can differ from object coordinates because of the modeling matrix.
  - May have to keep track of modeling matrix and pass it to the shaders as a uniform variable.
- Can also use reflection map or refraction map for effects such as simulating water.
Issues

• Must assume environment is very far from object (equivalent to the difference between near and distant lights)
• Object cannot be concave (no self reflections possible)
• No reflections between objects
• Need a reflection map for each object
• Need a new map if viewer moves
Forming Cube Map

• Use six cameras, each with a 90 degree angle of view
vs Cube Image
Doing it in WebGL

```javascript
gl.textureMap2D(
    gl.TEXTURE_CUBE_MAP_POSITIVE_X,
    level, rows, columns, border, gl.RGBA,
    gl.UNSIGNED_BYTE, image1)
```

- Same for other five images
- Make one texture object out of the six images
Example

• Consider rotating cube inside a cube that reflects the color of the walls
• Each wall is a solid color (red, green, blue, cyan, magenta, yellow)
  - Each face of room can be a texture of one texel

```javascript
var red = new Uint8Array([255, 0, 0, 255]);
var green = new Uint8Array([0, 255, 0, 255]);
var blue = new Uint8Array([0, 0, 255, 255]);
var cyan = new Uint8Array([0, 255, 255, 255]);
var magenta = new Uint8Array([255, 0, 255, 255]);
var yellow = new Uint8Array([255, 255, 0, 255]);
```
Texture Object

cubeMap = gl.createTexture();
gl.bindTexture(gl.TEXTURE_CUBE_MAP, cubeMap);
gl.texImage2D(gl.TEXTURE_CUBE_MAP_POSITIVE_X, 0, gl.RGBA,
1, 1, 0, gl.RGBA, gl.UNSIGNED_BYTE, red);
gl.texImage2D(gl.TEXTURE_CUBE_MAP_NEGATIVE_X, 0, gl.RGBA,
1, 1, 0, gl.RGBA, gl.UNSIGNED_BYTE, green);
gl.texImage2D(gl.TEXTURE_CUBE_MAP_POSITIVE_Y, 0, gl.RGBA,
1, 1, 0, gl.RGBA, gl.UNSIGNED_BYTE, blue);
gl.texImage2D(gl.TEXTURE_CUBE_MAP_NEGATIVE_Y, 0, gl.RGBA,
1, 1, 0, gl.RGBA, gl.UNSIGNED_BYTE, cyan);
gl.texImage2D(gl.TEXTURE_CUBE_MAP_POSITIVE_Z, 0, gl.RGBA,
1, 1, 0, gl.RGBA, gl.UNSIGNED_BYTE, yellow);
gl.texImage2D(gl.TEXTURE_CUBE_MAP_NEGATIVE_Z, 0, gl.RGBA,
1, 1, 0, gl.RGBA, gl.UNSIGNED_BYTE, magenta);
gl.activeTexture(gl.TEXTURE0);
gl.uniform1i(gl.getUniformLocation(program, "texMap"),0);
in vec4 aPosition;
in vec4 aNormal;
out vec3 vR;
uniform mat4 modelViewMatrix;
uniform mat4 projectionMatrix;
uniform vec3 theta;
void main()
{
    vec3 angles = radians( theta );
    // compute rotation matrices rx, ry, rz here
    mat4 ModelViewMatrix = modelViewMatrix*rz*ry*rx;
    gl_Position = projectionMatrix*ModelViewMatrix*aPosition;
    vec4 eyePos  = ModelViewMatrix*aPosition;
    vec4 N = ModelViewMatrix*aNormal;
    vR = reflect(eyePos.xyz, N.xyz);
}
precision mediump float;

in vec3 vR;
out vec4 fcolor
uniform samplerCube texMap;

void main()
{
    R = normalize(vR);
    vec4 texColor = texture(texMap, R);
    fcolor = texColor;
}
Sphere Mapping

• Original environmental mapping technique proposed by Blinn and Newell based in using lines of longitude and latitude to map parametric variables to texture coordinates

• OpenGL supports sphere mapping which requires a circular texture map equivalent to an image taken with a fisheye lens
Sphere Map
Bump Maps

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Objectives

- Introduce bump mapping
Modeling an Orange

• Consider modeling an orange
• Texture map a photo of an orange onto a surface
  - Captures dimples
  - Will not be correct if we move viewer or light
  - We have shades of dimples rather than their correct orientation
• Ideally we need to perturb normal across surface of object and compute a new color at each interior point
Bump Mapping (Blinn)

- Consider a smooth surface
Rougher Version
Tangent Plane

\[ \mathbf{n}, \mathbf{p}_u, \mathbf{p}_v \]
Equations

\[ \mathbf{p}(u,v) = [x(u,v), y(u,v), z(u,v)]^T \]

\[ \mathbf{p}_u = [\partial x/ \partial u, \partial y/ \partial u, \partial z/ \partial u]^T \]

\[ \mathbf{p}_v = [\partial x/ \partial v, \partial y/ \partial v, \partial z/ \partial v]^T \]

\[ \mathbf{n} = \left( \mathbf{p}_u \times \mathbf{p}_v \right) / | \mathbf{p}_u \times \mathbf{p}_v | \]
Displacement Function

\[ p' = p + d(u,v) \textbf{n} \]

\( d(u,v) \) is the bump or displacement function

\[ |d(u,v)| \ll 1 \]
Perturbed Normal

\[ n' = p'_u \times p'_v \]

\[ p'_u = p_u + (\partial d/\partial u)n + d(u,v)\mathbf{n}_u \]

\[ p'_v = p_v + (\partial d/\partial v)n + d(u,v)\mathbf{n}_v \]

If \( d \) is small, we can neglect last term
Approximating the Normal

\[ \mathbf{n}' = \mathbf{p}'_u \times \mathbf{p}'_v \]

\[ \approx \mathbf{n} + (\partial d/\partial u)\mathbf{n} \times \mathbf{p}_v + (\partial d/\partial v)\mathbf{n} \times \mathbf{p}_u \]

The vectors \( \mathbf{n} \times \mathbf{p}_v \) and \( \mathbf{n} \times \mathbf{p}_u \) lie in the tangent plane.
Hence the normal is displaced in the tangent plane.
Must precompute the arrays \( \partial d/\partial u \) and \( \partial d/\partial v \).
Finally, we perturb the normal during shading.
• Suppose that we start with a function $d(u,v)$
• We can sample it to form an array $D = [d_{ij}]$
• Then $\frac{\partial d}{\partial u} \approx d_{ij} - d_{i-1,j}$
  and $\frac{\partial d}{\partial v} \approx d_{ij} - d_{i,j-1}$
• **Embossing**: multipass approach using floating point buffer
Example

Single Polygon and a Rotating Light Source
Biparametric Patch

- \((u,v)\) pair maps to a 3D point on patch
- Can use the same \((u,v)\) for texture lookup
Suggestions for HW8

• First add texture coordinates [u,v] to your vertices

• Just use the [u,v] pair used to compute the vertex on the Bezier patch

• Use a variant of the code in slides 34, 38, 47, 48, 52, 53, 55 to define and access your texture object in your application and fragment shader

• Note that the texture coordinates get passed through to the fragment shader, where they are used to sample the 2D texture
Suggestions for HW8

- To test if your texture coordinates are getting to the shaders properly, you can map the coordinates to the red & green channels of the fragment's color.
- This is one way to visualize the texture coordinates values.
- The color retrieved from the texture map should be used for the material’s diffuse color in your Phong shading calculation in your fragment shader.
- You will need to send the light’s diffuse color via a uniform variable, instead of diffuseProduct.
Suggestions for HW8

For 3D procedural texturing

• I would suggest that your mapping from 3D Cartesian space to RGB color space be based on a location specified in world, NOT camera, coordinates.

• So you will need to pass the location of the vertices in world coordinates to the fragment shader
Shader Code

```glsl
in vec4 aPosition;
out vec4 vPosition
uniform mat4 modelViewMatrix;
uniform mat4 projectionMatrix;

void main() {
    gl_Position = projectionMatrix * modelViewMatrix * aPosition;
vPosition = aPosition;
}
```

```glsl
precision mediump float;

in vec4 vPosition
out vec4 fColor;

void main()
{
    // assuming that model lies between -0.5 and 0.5
    fColor = vPosition + vec4(0.5, 0.5, 0.5, 0.0);
}
```
Suggestions for HW8

• Write your procedural texture function in your fragment shader based on the interpolated value of the vertex location
• The color computed by your procedure should be used for the material’s diffuse color in your Phong shading calculation in your fragment shader
• RGB colors should be between 0 and 1
• For the 3D procedural texturing you will need to change your vertex and fragment shaders. Very little of your HW6 application code will need to change (except sending the light diffuse color)