Shading in OpenGL

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Objectives

• Introduce the OpenGL shading methods
  - per vertex vs per fragment shading
  - Where to carry out
• Discuss polygonal shading
  - Flat
  - Smooth
    • Gouraud shading
    • Phong shading
Shading Principles

• Shading simulates how objects reflect light
  - material composition of object
  - light’s color and position
  - global lighting parameters

• Usually implemented in
  - vertex shader for faster speed
    • Gouraud shading
  - fragment shader for nicer shading
    • Phong shading
OpenGL shading

- Need to specify:
  - Normals
  - Material properties
  - Lights
- Get computed values in application or send attributes to shaders
Surface Normals

• Normals define how a surface reflects light
  - Application usually provides normals as a vertex attribute
  - Current normal is used to compute vertex’s color
  - Use unit normals for proper lighting
    • scaling affects a normal’s length
Normal for Triangle

plane \quad \mathbf{n} \cdot (\mathbf{p} - \mathbf{p}_0) = 0

\mathbf{n} = (\mathbf{p}_1 - \mathbf{p}_0) \times (\mathbf{p}_2 - \mathbf{p}_0)

normalize \mathbf{n} \quad \leftarrow \quad \mathbf{n}/|\mathbf{n}|

Note that right-hand rule determines outward face
Specifying a Point Light Source

• For each light source, we can set an RGBA for the diffuse, specular, and ambient components, and XYZW for the position

```cpp
vec4 diffuse0 = vec4(1.0, 0.0, 0.0, 1.0);
vec4 ambient0 = vec4(1.0, 0.0, 0.0, 1.0);
vec4 specular0 = vec4(1.0, 0.0, 0.0, 1.0);
vec4 light0_pos = vec4(1.0, 2.0, 3.0, 1.0);
```

• The position is given in homogeneous coordinates
  - If w = 1.0, we are specifying a finite location
  - If w = 0.0, we are specifying a parallel source with the given direction vector
Spotlights

• Derive from point source
  - Direction
  - Cutoff
  - Attenuation Proportional to $\cos^\alpha \phi$
Moving Light Sources

• Light sources are geometric objects whose positions or directions are affected by the model-view matrix
• Depending on where we place the position (direction) setting function, we can
  - Move the light source(s) with the object(s)
  - Fix the object(s) and move the light source(s)
  - Fix the light source(s) and move the object(s)
  - Move the light source(s) and object(s) independently
Material Properties (1)

• Define the surface properties of a primitive

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuse</td>
<td>Base object color</td>
</tr>
<tr>
<td>Specular</td>
<td>Highlight color</td>
</tr>
<tr>
<td>Ambient</td>
<td>Low-light color</td>
</tr>
<tr>
<td>Emission</td>
<td>Glow color</td>
</tr>
<tr>
<td>Shininess</td>
<td>Surface smoothness</td>
</tr>
</tbody>
</table>

- you can have separate materials for front and back
Material Properties (2)

• Material properties should match the terms in the light model

• Specifies amount of reflected light
  - An object appears red because it reflects red component of light

• w component gives opacity

```cpp
vec4 ambient = vec4(0.2, 0.2, 0.2, 1.0);
vec4 diffuse = vec4(1.0, 1.0, 1.0, 1.0);
GLfloat shine = 100.0
```
Flat Shading

- Use triangle normal across all fragments of triangle
- One color per triangular facet
Smooth Shading

• Set a new normal at each vertex
• Easy for sphere model
  - If centered at origin $\mathbf{n} = \mathbf{p}$
• Note *silhouette edges*
Gouraud Shading

- Computes a color for each vertex using:
  - Surface normals
  - Diffuse and specular reflections
  - Viewer’s position and viewing direction
  - Ambient light
  - Emission

- Vertex colors are interpolated across polygons by the rasterizer
  - *Phong shading* does the same computation per pixel, interpolating the normal across the polygon
    - more accurate results
Polygonal Shading

- In per vertex shading, shading calculations are done for each vertex
  - Vertex colors become vertex shades and can be sent to the vertex shader as a vertex attribute
  - Alternately, we can send the parameters to the vertex shader and have it compute the shade
- By default, vertex shades are interpolated across an object if passed to the fragment shader as a varying variable (smooth shading)
- We can also use uniform variables to shade with a single shade (flat shading)
Mesh Shading

• The previous example is not general because we knew the normal at each vertex analytically.

• For polygonal models, Gouraud proposed we use the average of the normals around a mesh vertex:

\[ \mathbf{n} = \frac{\mathbf{n}_1 + \mathbf{n}_2 + \mathbf{n}_3 + \mathbf{n}_4}{|\mathbf{n}_1 + \mathbf{n}_2 + \mathbf{n}_3 + \mathbf{n}_4|} \]
Gouraud and Phong Shading

• Gouraud Shading
  - Find average normal at each vertex (vertex normals)
  - Apply Phong illumination equation at each vertex
  - Interpolate vertex shades across each polygon

• Phong shading
  - Find vertex normals
  - Interpolate vertex normals across edges
  - Interpolate edge normals across polygon
  - Apply modified Phong model at each fragment
Comparison

• If the polygon mesh approximates surfaces with a high curvatures, Phong shading may look smooth while Gouraud shading may show edges.

• Phong shading requires much more work than Gouraud shading:
  - Until recently not available in real time systems
  - Now can be done using fragment shaders

• Both need data structures to represent meshes so we can obtain vertex normals.
Normalization

- Cosine terms in lighting calculations can be computed using dot product
- Unit length vectors simplify calculation
- Usually we want to set the magnitudes to have unit length but
  - Length can be affected by transformations
  - Note that scaling does not preserve length
- GLSL has a normalization function
Gouraud Shading: Vertex Shader(1)

// Vertex Shader

in vec4 vPosition;
in vec3 vNormal;
out vec4 color;  // vertex shade

// light and material properties
uniform vec4 AmbientProduct, DiffuseProduct, SpecularProduct;
uniform mat4 ModelView;
uniform mat4 Projection;
uniform vec4 LightPosition;
uniform float Shininess;
void main()
{
    // transform vertex position into eye coordinates
    vec3 pos = (ModelView * vPosition).xyz;

    vec3 L = normalize( LightPosition.xyz - pos );
    vec3 E = normalize( -pos );
    vec3 H = normalize( L + E );

    // transform vertex normal into eye coordinates
    vec3 N = normalize( ModelView*vec4(vNormal, 0.0) ).xyz;
Gouraud Shading: Vertex Shader (3)

    // compute terms in the illumination equation
    // ambient lighting term
    vec4 ambient = AmbientProduct;

    // diffuse lighting term
    float Kd = max( dot(L, N), 0.0 );
    vec4 diffuse = Kd*DiffuseProduct;

    // specular lighting term
    float Ks = pow( max(dot(N, H), 0.0), Shininess );
    vec4 specular = Ks * SpecularProduct;
    if( dot(L, N) < 0.0 ) specular = vec4(0.0, 0.0, 0.0, 1.0);

    // add lighting terms to form color
    color = ambient + diffuse + specular;
    color.a = 1.0;

    gl_Position = Projection * ModelView * vPosition;
Gouraud Shading: Fragment Shader

// Fragment Shader
in vec4 color;

void main()
{
    gl_FragColor = color;
}

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// Vertex Shader
in vec4 vPosition;
in vec3 vNormal;

// output values that will be interpolated per-fragment
out vec3 fN;
out vec3 fE;
out vec3 fL;

uniform mat4 ModelView;
uniform vec4 LightPosition;
uniform mat4 Projection;
void main() {
    fN = vNormal;
    fE = vPosition.xyz;
    fL = LightPosition.xyz;

    if( LightPosition.w != 0.0 ) {
        fL = LightPosition.xyz - vPosition.xyz;
    }

    gl_Position = Projection*ModelView*vPosition;
}
Phong Shading: Fragment Shader (1)

// Fragment Shader

// per-fragment interpolated values from the vertex shader
in vec3 fN;
in vec3 fL;
in vec3 fE;

uniform vec4 AmbientProduct, DiffuseProduct, SpecularProduct;
uniform mat4 ModelView;
uniform vec4 LightPosition;
uniform float Shininess;

void main()
{
    // normalize the input lighting vectors
    vec3 N = normalize(fN);
    vec3 E = normalize(fE);
    vec3 L = normalize(fL);
}
vec3 H = normalize( L + E );
vec4 ambient = AmbientProduct;

float Kd = max(dot(L, N), 0.0);
vec4 diffuse = Kd*DiffuseProduct;

float Ks = pow(max(dot(N, H), 0.0), Shininess);
vec4 specular = Ks*SpecularProduct;

// discard the specular highlight if the light
// is behind the vertex
if( dot(L, N) < 0.0 )
    specular = vec4(0.0, 0.0, 0.0, 1.0);

gl_FragColor = ambient + diffuse + specular;
gl_FragColor.a = 1.0;
}
Fragment Shaders

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Fragment Shader

• A shader that’s executed for each “potential” pixel
  - fragments still need to pass several tests before making it to the framebuffer

• There are lots of effects we can do in fragment shaders
  - Per-fragment lighting
  - Texture and bump Mapping
  - Environment (Reflection) Maps
Shader Examples

• Vertex Shaders
  - Moving vertices: height fields
  - Per vertex lighting: height fields
  - Per vertex lighting: cartoon shading

• Fragment Shaders
  - Per vertex vs. per fragment lighting: cartoon shader
  - Samplers: reflection Map
  - Bump mapping
Height Fields

- A height field is a function $y = f(x, z)$
  - $y$ represents height of point for a location in the $x$-$z$ plane
- Heights fields are usually rendered as a rectangular mesh of triangles or rectangles sampled from a grid
  - samples $y_{ij} = f(x_i, z_j)$
Displaying a Height Field

• First, generate a mesh data and use it to initialize data for a VBO

```c
float dx = 1.0/N, dz = 1.0/N;
for( int i = 0; i < N; i++ ) {
  float x = i*dx;
  for( int j = 0; j < N; j++ ) {
    float z = j*dz;
    float y = f( x, z );
    vertex[Index++] = vec3( x, y, z );
    vertex[Index++] = vec3( x, y, z + dz );
    vertex[Index++] = vec3( x + dx, y, z + dz );
    vertex[Index++] = vec3( x + dx, y, z );
  }
}
```

• Finally, display each quad using

```c
for( int i = 0; i < NumVertices ; i += 4 )
glDrawArrays( GL_LINE_LOOP, 4*i, 4 );
```
```glsl
in vec4 vPosition;
in vec4 vColor;

uniform float time; // in milliseconds
uniform mat4 ModelViewProjectionMatrix;

void main()
{
    vec4 v = vPosition;
    vec4 u = sin( time + 5*v );

    v.y = 0.1 * u.x * u.z;

    gl_Position = ModelViewProjectionMatrix * v;
}
```
Mesh Display
Adding Lighting

• Solid Mesh: create two triangles for each quad
• Display with
  \texttt{glDrawArrays(GL_TRIANGLES, 0, NumVertices);}
• For better looking results, add lighting
• We’ll do per-vertex lighting
  - leverage the vertex shader since we’ll also use it to vary the mesh in a time-varying way
uniform float time, shininess;
uniform vec4 vPosition, lightPosition, diffuseLight, specularLight;
uniform mat4 ModelViewMatrix, ModelViewProjectionMatrix, NormalMatrix;

void main()
{
    vec4 v = vPosition;
    vec4 u = sin( time + 5*v );
    v.y = 0.1 * u.x * u.z;

    gl_Position = ModelViewProjectionMatrix * v;

    vec4 diffuse, specular;
    vec4 eyePosition = ModelViewMatrix * vPosition;
    vec4 eyeLightPos = lightPosition;
Mesh Shader (2)

```cpp
vec3 N = normalize(NormalMatrix * Normal);
vec3 L = normalize(vec3(eyeLightPos - eyePosition));
vec3 E = -normalize(eyePosition.xyz);
vec3 H = normalize(L + E);

float Kd = max(dot(L, N), 0.0);
float Ks = pow(max(dot(N, H), 0.0), shininess);
diffuse = Kd*diffuseLight;
specular = Ks*specularLight;
color = diffuse + specular;
}
```
Shaded Mesh
Shadows

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Objectives

• Introduce Shadow Algorithms
• Expand to projective textures
Flashlight in the Eye Graphics

• When do we not see shadows in a real scene?
• When the only light source is a point source at the eye or center of projection
  - Shadows are behind objects and not visible
• Shadows are a global rendering issue
  - Is a surface visible from a source
  - May be obscured by other objects
Projective Shadows

• Oldest methods
  - Used in flight simulators to provide visual clues
• Projection of a polygon is a polygon called a shadow polygon
• Given a point light source and a polygon, the vertices of the shadow polygon are the projections of the original polygon’s vertices from a point source onto a surface
Shadow Polygon

\[(x_i, y_i, z_i)\]
Computing Shadow Vertex

1. Source at \((x_l, y_l, z_l)\)
2. Vertex at \((x, y, z)\)
3. Consider simple case of shadow projected onto ground at \((x_p, 0, z_p)\)
4. Translate source to origin with \(T(-x_l, -y_l, -z_l)\)
5. Perspective projection
   \[
   M = \begin{bmatrix}
   1 & 0 & 0 & 0 \\
   0 & 1 & 0 & 0 \\
   0 & 0 & 1 & 0 \\
   0 & \frac{1}{-y_l} & 0 & 0 \\
   \end{bmatrix}
   \]
6. Translate back
Shadow Process

1. Put two identical triangles and their colors on GPU (black for shadow triangle)
2. Compute two model-view matrices as uniforms
3. Send model-view matrix for original triangle
4. Render original triangle
5. Send second model-view matrix
6. Render shadow triangle
   - Note shadow triangle undergoes two transformations
   - Note hidden surface removal takes care of depth issues
Generalized Shadows

- Approach was OK for shadows on a single flat surface
- Note with geometry shader we can have the shader create the second triangle
- Cannot handle shadows on general objects
- Exist a variety of other methods based on same basic idea
- We’ll pursue methods based on projective textures
Image Based Lighting

• We can project a texture onto the surface in which case we are treating the texture as a “slide projector”

• This technique is the basis of projective textures and image based lighting

• Supported in OpenGL and GLSL through four-dimensional texture coordinates
4D Textures Coordinates

• Texture coordinates (s, t, r, q) are affected by a perspective division so the actual coordinates used are (s/q, t/q, r/q) or (s/q, t/q) for a two dimensional texture.

• GLSL has a variant of the function texture `textureProj` which will use the two- or three-dimensional texture coordinate obtained by a perspective division of a 4D texture coordinate a texture value from a sampler:

```glsl
color = textureProj(my_sampler, tex_coord)
```
Shadow Maps

• If we render a scene from a light source, the depth buffer will contain the distances from the source to each fragment.
• We can store these depths in a texture called a depth map or shadow map
• Note that although we don’t care about the image in the shadow map, if we render with some light, anything lit is not in shadow.
• Form a shadow map for each source
Final Rendering

• During the final rendering we compare the distance from the fragment to the light source with the distance in the shadow map.
• If the depth in the shadow map is less than the distance from the fragment to the source, the fragment is in shadow (from this source).
• Otherwise we use rendered color.
Application’s Side

• Start with vertex in object coordinates
• Want to convert representation to texture coordinates
• Form LookAt matrix from light source to origin in object coordinates (MVL)
• From projection matrix for light source (PL)
• From a matrix to convert from [-1, 1] clip coordinates to [0, 1] texture coordinates
• Concatenate to form object to texture coordinate matrix (OTC)
Vertex Shader

uniform mat4 modelview;
uniform mat4 projection;
uniform normalmatrix;        // for diffuse lighting
uniform mat4 otc;            // object to texture coordinate
uniform vec4 diffuseproduct; // diffuse light*diffuse reflectivity

in vec4 vPosition;
in vec4 normal;

out vec4 color;
out vec4 shadowCoord;

void main()
{
    // compute diffuse color as usual
    // using normal, normal matrix, diffuse product
    color = ...

    gl_Position = projection*modelview*vPosition;
    shadowCoord = OTC*vPosition;
}
textureProj function

- Application provides the shadow map as a texture object.
- The GLSL function `textureProj` compares the third value of the texture coordinate with the third value of the texture image.
- For nearest filtering of the texture object, `textureProj` returns 0.0 if the shadow map value is less than the third coordinate and 1.0 otherwise.
- For other filtering options, `textureProj` returns values between 0.0 and 1.0.
uniform sampler2DShadow ShadowMap;

in vec4 shadowCoord;
in vec4 Color;

main()
{
  // assume nearest sampling in ShadowMap
  float shadeFactor = textureProj(ShadowMap, ShadowCoord);
  gl_FragColor = vec4(shadeFactor*Color.rgb, Color.a)
}