Shading

CS 432/637 Interactive Computer Graphics
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Objectives

- Learn to shade objects so their images appear three-dimensional
- Introduce the types of light-material interactions
- Build a simple reflection model—the Phong model—that can be used with real-time graphics hardware

Why we need shading

- Suppose we build a model of a sphere using many polygons and color it with one color. We get something like

  - But we want

Shading

- Why does the image of a real sphere look like this?

  - Light-material interactions cause each point to have a different color or shade
  - Need to consider
    - Light sources
    - Material properties
    - Location of viewer
    - Surface orientation

Scattering

- Light strikes A
  - Some scattered
  - Some absorbed
- Some of scattered light strikes B
  - Some scattered
  - Some absorbed
- Some of this scattered light strikes A and so on

Rendering Equation

- The infinite scattering and absorption of light can be described by the rendering equation
  - Cannot be solved in general
  - Ray tracing is a special case for perfectly reflecting surfaces
- Rendering equation is global and includes
  - Shadows
  - Multiple scattering from object to object
Global Effects

- translucent surface
- shadow
- multiple reflection

Local vs Global Rendering

- Correct shading requires a global calculation involving all objects and light sources
  - Incompatible with pipeline model which shades each polygon independently (local rendering)
- However, in computer graphics, especially real time graphics, we are happy if things “look right”
  - There are many techniques for approximating global effects

Light-Material Interaction

- Light that striking an object is partially absorbed and partially scattered (reflected)
- The amount reflected determines the color and brightness of the object
  - A surface appears red under white light because the red component of the light is reflected and the rest is absorbed
- The reflected light is scattered in a manner that depends on the smoothness and orientation of the surface

Light Sources

- General light sources are difficult to work with because we must integrate light coming from all points on the source

Simple Light Sources

- Point source
  - Model with position and color
  - Distant source = infinite distance away (parallel)
- Spotlight
  - Restrict light from ideal point source
- Ambient light
  - Same amount of light everywhere in scene
  - Can model contribution of many sources and reflecting surfaces

Surface Types

- The smoother a surface, the more reflected light is concentrated in the direction a perfect mirror would reflected the light
- A very rough surface scatters light in all directions

- smooth surface
- rough surface
Phong Model

- A simple model that can be computed rapidly
- Has three components
  - Diffuse
  - Specular
  - Ambient
- Uses four vectors
  - To light source
  - To viewer
  - Normal
  - Perfect reflector

Ideal Reflector

- Normal is determined by local orientation
- Angle of incidence = angle of reflection
- The three vectors must be coplanar

\[ r = 2 (l \cdot n) n - l \]

Lambertian Surface

- Perfectly diffuse reflector
- Light scattered equally in all directions
- Amount of light reflected is proportional to the vertical component of incoming light
  - reflected light \( \sim \cos \theta_i \)
  - \( \cos \theta_i = l \cdot n \) if vectors normalized
  - There are also three coefficients, \( k_r, k_g, k_b \) that show how much of each color component is reflected

\[ I_r = I_i k_r \cos \theta \]

Specular Surfaces

- Most surfaces are neither ideal diffusers nor perfectly specular (ideal reflectors)
- Smooth surfaces show specular highlights due to incoming light being reflected in directions concentrated close to the direction of a perfect reflection

Modeling Specular Reflections

- Phong proposed using a term that dropped off as the angle between the viewer and the ideal reflection increased

\[ I_r = I_i \cos \phi \text{ (shininess coefficient)} \]

\[ \phi \text{ (shininess coefficient)} \]

\[ I_i \text{ (incoming intensity)} \]

\[ I_r \text{ (reflected intensity)} \]

\[ k_r \text{ (absorption coefficient)} \]
The Shininess Coefficient

- Values of $\alpha$ between 100 and 200 correspond to metals
- Values between 5 and 10 give surfaces that look like plastic

$\cos \phi$

90
90

$+2$

$+5$

$-2$

$-5$

Ambient Light

- Ambient light is the result of multiple interactions between (large) light sources and the objects in the environment
- Amount and color depend on both the color of the light(s) and the material properties of the object
- Add $k_a l_a$ to diffuse and specular terms

Ambient Light reflection coef intensity of ambient light

Our Three Basic Components of Illumination

Diffuse Specular Ambient

Combined for the Final Result

Distance Terms

- The light from a point source that reaches a surface is inversely proportional to the square of the distance between them
- We can add a factor of the form $1/(a + b + c d^2)$ to the diffuse and specular terms
- The constant and linear terms soften the effect of the point source

Light Sources

- In the Phong Model, we add the results from each light source
- Each light source has separate diffuse, specular, and ambient terms to allow for maximum flexibility even though this form does not have a physical justification
- Separate red, green, and blue components
- Hence, 9 coefficients for each point source

$I_{dr}, I_{dg}, I_{db}, I_{sr}, I_{sg}, I_{sb}, I_{ar}, I_{ag}, I_{ab}$
Material Properties

- Material properties match light source properties
  - Nine absorption coefficients
    - $k_{d1}$, $k_{d2}$, $k_{d3}$, $k_{d4}$, $k_{s1}$, $k_{s2}$, $k_{s3}$, $k_{s4}$
  - Shininess coefficient $\alpha$

Adding up the Components

For each light source and each color component, the Phong model can be written (without the distance terms) as

$$I = k_d I_d \cdot n + k_s I_s (v \cdot r) \alpha + k_a I_a$$

For each color component we add contributions from all light sources.

Too Intense

With multiple light sources, it is easy to generate values of $I > 1$
One solution is to set the color value to be $MIN(I, 1)$
- An object can change color, saturating towards white
  Ex. $(0.1, 0.4, 0.8) + (0.5, 0.5, 0.5) = (0.6, 0.9, 1.0)$
- Another solution is to renormalize the intensities to vary from 0 to 1 if one $I > 1$.
  - Requires calculating all $I$'s before rendering anything.
  - No over-saturation, but image may be too bright, and contrasts a little off.
  - Image-processing on image to be rendered (with original $I$'s) will produce better results, but is costly.

Modified Phong Model

- The specular term in the Phong model is problematic because it requires the calculation of a new reflection vector and view vector for each vertex
- Blinn suggested an approximation using the halfway vector that is more efficient

Using the halfway vector

- Replace $(v \cdot r)^\beta$ by $(n \cdot h)^\beta$
  - $\beta$ is chosen to match shininess
- Note that halfway angle is half of angle between $r$ and $v$ if vectors are coplanar
- Resulting model is known as the modified Phong or Blinn lighting model
  - Specified in OpenGL standard

The Halfway Vector

- $h$ is normalized vector halfway between $l$ and $v$
$$h = (l + v) / |l + v|$$
Example

Only differences in these teapots are the parameters in the modified Phong model.

Computation of Vectors

- I and v are specified by the application
- Can compute r from I and n
- Problem is determining n
- For simple surfaces n can be determined, but how we determine n differs depending on underlying representation of surface
- OpenGL leaves determination of normal to application
  - Exception for GLU quadrics and Bezier surfaces which are deprecated

Computing Reflection Direction

- Angle of incidence = angle of reflection
- Normal, light direction and reflection direction are coplaner
- Want all three to be unit length

\[ r = 2(l \cdot n) n - l \]

Plane Normals

- Equation of plane: ax+by+cz+d = 0
- From Chapter 3 we know that plane is determined by three points p_0, p_1, p_3 or normal n and p_0
- Normal can be obtained by

\[ n = (p_2 - p_0) \times (p_3 - p_0) \]

Normal to Sphere

- Implicit function f(x,y,z)=0
- Normal given by gradient
- Sphere f(p)=p dot p - 1
- \[ n = [\partial f/\partial x, \partial f/\partial y, \partial f/\partial z]^T = p \]

Parametric Form

- For sphere
  \[ x = r(u,v) = u \sin v \quad y = r(u,v) = u \cos v \quad z = r(u,v) = w, \text{ or } u \sin u \]
  \[ \frac{\partial p}{\partial u} = \left[ \frac{\partial x}{\partial u}, \frac{\partial y}{\partial u}, \frac{\partial z}{\partial u} \right]^T \]
  \[ \frac{\partial p}{\partial v} = \left[ \frac{\partial x}{\partial v}, \frac{\partial y}{\partial v}, \frac{\partial z}{\partial v} \right]^T \]
- Tangent plane determined by vectors
- Normal given by cross product

\[ n = \frac{\partial p}{\partial u} \times \frac{\partial p}{\partial v} \]
General Case

- We can compute parametric normals for other simple cases
  - Quadrics
  - Parametric polynomial surfaces
  - Bezier surface patches (Chapter 10)

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

OpenGL shading

- Need
  - Normals
  - Material properties
  - Lights
- State-based shading functions have been deprecated (glNormal, glMaterial, glLight)
- Get computed in application or send attributes to shaders

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 preserved length
- GLSL has a normalization function

Specifying a Point Light Source

- For each light source, we can set its position and an RGBA for the diffuse, specular, and ambient components
  
  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);
Distance and Direction

- The source colors are specified in RGBA
- 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
- The coefficients in distance terms are usually quadratic \(1/(a+b*d+c*d^2)\) where d is the distance from the point being rendered to the light source

Spotlights

- Derive from point source
  - Direction
  - Cutoff
  - Attenuation Proportional to \(\cos^\alpha\)

Global Ambient Light

- Ambient light depends on the color of light sources
  - A red light in a white room will cause a red ambient term that disappears when the light is turned off
- A global ambient term is often helpful for testing

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

- Material properties should match the terms in the light model
- Reflectivities
- \(w\) component gives opacity

\[
\begin{align*}
\text{vec4 ambient} &= \text{vec4}(0.2, 0.2, 0.2, 1.0); \\
\text{vec4 diffuse} &= \text{vec4}(1.0, 0.8, 0.0, 1.0); \\
\text{vec4 specular} &= \text{vec4}(1.0, 1.0, 1.0, 1.0); \\
\text{GLfloat shine} &= 100.0
\end{align*}
\]

Front and Back Faces

- Every face has a front and back
- For many objects, we never see the back face so we don’t care how or if it’s rendered
- If it matters, we can handle in shader

back faces not visible
back faces visible
Transparency

- Material properties are specified as RGBA values
- The A value can be used to make the surface translucent
- The default is that all surfaces are opaque regardless of A
- Later we will enable blending and use this feature

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)

Polygon Normals

- Triangles have a single normal
  - Shades at the vertices as computed by the Phong model can almost be the same
  - Identical for a distant viewer (default) or if there is no specular component
- Consider model of sphere
  - Want different normals at each vertex

Smooth Shading

- We can set a new normal at each vertex
  - Easy for sphere model
  - If centered at origin \( n = \mathbf{p} \)
- Now smooth shading works
- Note silhouette edge

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
  \[
  n = \frac{(\mathbf{n}_1 + \mathbf{n}_2 + \mathbf{n}_3 + \mathbf{n}_4)}{|\mathbf{n}_1 + \mathbf{n}_2 + \mathbf{n}_3 + \mathbf{n}_4|}
  \]

Normal for Triangle

\[
\text{plane } \mathbf{n} \cdot (\mathbf{p} - \mathbf{p}_0) = 0 \\
\mathbf{n} = (\mathbf{p}_2 - \mathbf{p}_0) \times (\mathbf{p}_1 - \mathbf{p}_0) \\
\text{normalize } \mathbf{n} \leftarrow \mathbf{n} / |\mathbf{n}| \\
\mathbf{p}_0
\]

Note that right-hand rule determines outward face
Simple Mesh Format (SMF)

- Michael Garland
  http://graphics.cs.uiuc.edu/~garland/
- Triangle data
  - List of 3D vertices
  - List of references to vertex array
define faces (triangles)
- Vertex indices begin at 1

```
#SMF 1.0
#vertices 5
v 2.0 0.0 2.0
v 0.0 0.0 2.0
v -2.0 0.0 -2.0
v 0.0 0.0 -2.0
v -2.0 0.0 2.0

#indices 6
f 1 2 3
f 1 3 4
f 2 4 5
f 2 5 6
f 3 6 7
f 3 7 8
f 4 8 9
f 4 9 1
```

Calculating Normals

- Create vector structure (for normals) same size as vertex structure
- For each face
  - Calculate unit normal
  - Add to normal structure using vertex indices
- Normalize all the normals

```
v -1 -1 -1
v 1 -1 -1
v 1 1 -1
v -1 1 -1
v 1 -1 1
v -1 -1 1
v 1 1 1
v -1 1 1

f 1 3 4
f 1 4 2
f 5 6 8
f 5 8 7
f 1 2 6
f 1 6 5
f 3 7 8
f 3 8 4
f 1 5 7
f 1 7 3
f 2 4 8
f 2 8 6
```

Gouraud and Phong Shading

- Gouraud Shading
  - Find average normal at each vertex (vertex normals)
  - Apply modified Phong model 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

Comparison

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

// Light and material properties. Light color * surface color
uniform vec3 AmbientProduct, DiffuseProduct, SpecularProduct;
uniform mat4 ModelView;
uniform mat4 Projection;
uniform vec3 LightPosition;
uniform float Shininess;

Vertex Lighting Shaders I (Gouraud shading)
void main() {
    // Transform vertex position into eye coordinates
    vec3 pos = (ModelView * vec4(vPosition,1.0)).xyz;

    // Light defined in camera frame
    vec3 L = normalize( LightPosition - 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;

    // Compute terms in the illumination equation
    vec3 ambient = AmbientProduct;
    float Kd = max( dot(L, N), 0.0 );
    vec3  diffuse = Kd*DiffuseProduct;
    float Ks = pow( max(dot(N, H), 0.0), Shininess );
    vec3  specular = Ks * SpecularProduct;
    if( dot(L, N) < 0.0 )  specular = vec4(0.0, 0.0, 0.0, 1.0);

    gl_Position = Projection * ModelView * vPosition;
    color = ambient + diffuse + specular;
}

void main() {
    // fragment shader
    in vec3 color;
    void main() {
        gl_FragColor = vec4(color, 1.0);
    }
}

// vertex shader
in vec3 vPosition;
in vec3 vNormal;
// output values that will be interpolated per-fragment
out vec3 fN;
out vec3 fE;
out vec3 fL;
uniform vec4 LightPosition;
uniform vec3 EyePosition;
uniform mat4 ModelView;
uniform mat4 Projection;

void main() {
    fN = vNormal;
    fE = EyePosition - vPosition.xyz;

    // Light defined in world coordinates
    if( LightPosition.w != 0.0 ) {
        fL = LightPosition.xyz - vPosition.xyz;
    } else {
        fL = LightPosition.xyz;
    }

    gl_Position = Projection*ModelView*vPosition;
}

// fragment shader
// per-fragment interpolated values from the vertex shader
in vec3 fN;
in vec3 fE;
in vec3 fL;
uniform vec3 AmbientProduct, DiffuseProduct, SpecularProduct;
uniform mat4 ModelView;
uniform float Shininess;

// Compute terms in the illumination equation
vec3 ambient = AmbientProduct;
float Kd = max( dot(L, N), 0.0 );
vec3  diffuse = Kd*DiffuseProduct;
float Ks = pow( max(dot(N, H), 0.0), Shininess );
vec3  specular = Ks * SpecularProduct;
if( dot(L, N) < 0.0 )  specular = vec4(0.0, 0.0, 0.0, 1.0);

gl_Position = Projection * ModelView * vPosition;

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

    float Kd = max(dot(L, N), 0.0);
    vec3 diffuse = Kd*DiffuseProduct;

    float Ks = pow(max(dot(N, H), 0.0), Shininess);
    vec3 specular = Ks*SpecularProduct;

    // discard the specular highlight if the light's behind the vertex
    if( dot(L, N) < 0.0 )
        specular = vec3(0.0, 0.0, 0.0);

    gl_FragColor = vec4(ambient + diffuse + specular, 1.0);
}