Shading

CS 537 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 strikes 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
**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

\[ r = 2 \left( \frac{l \cdot n}{n} \right) n - l \]

**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 \( \sim \cos \theta \)
  - \( \cos \theta = l \cdot n \) if vectors normalized
- There are also three coefficients, \( k_r, k_b, k_g \), that show how much of each color component is reflected

**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
The Shininess Coefficient

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

\[
\cos^\alpha \phi
\]

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 $k_a I_a$ to diffuse and specular terms

Our Three Basic Components of Illumination

- Diffuse
- Specular
- Ambient

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 $1/(a + bd + cd^2)$ to the diffuse and specular terms
- The constant and linear terms soften the effect of the point source

Combined for the Final Result

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: $k_{d}$, $k_{a}$, $k_{s}$, $k_{r}$, $k_{g}$, $k_{b}$, $k_{t}$, $k_{h}$, $k_{w}$
- 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.

The Halfway Vector

- $h$ is normalized vector halfway between $I$ and $v$

$$h = (I + v) / |I + v|$$

Using the halfway vector

- Replace $(v \cdot r)^\alpha$ 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
Example

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

Computation of Vectors

- $l$ and $v$ are specified by the application
- Can compute $r$ from $l$ 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 $p_0, p_2, p_3$ or normal $n$ and $p_0$
- Normal can be obtained by

\[ n = (p_2-p_0) \times (p_1-p_0) \]

Normal to Sphere

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

Parametric Form

- For sphere
  \[ x = u \cos v \sin u \]
  \[ y = u \sin v \cos u \]
  \[ z = u \sin u \]
- Tangent plane determined by vectors

\[ \frac{\partial p}{\partial u} = [\partial x/\partial u, \partial y/\partial u, \partial z/\partial u]^T \]
\[ \frac{\partial p}{\partial v} = [\partial x/\partial v, \partial y/\partial v, \partial z/\partial v]^T \]
- 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 preserve 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

```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);
```
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 \( \frac{1}{(a+b+cd+cd^2)} \) 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 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

```
vec4 ambient = vec4(0.2, 0.2, 0.2, 1.0);
vec4 diffuse = vec4(1.0, 0.8, 0.0, 1.0);
vec4 specular = vec4(1.0, 1.0, 1.0, 1.0);
GLfloat shine = 100.0;
```

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 \( \mathbf{n} = \mathbf{p} \)
- 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

\[
\mathbf{n} = \frac{1}{4} (\mathbf{n}_1 + \mathbf{n}_2 + \mathbf{n}_3 + \mathbf{n}_4) / |\mathbf{n}_1 + \mathbf{n}_2 + \mathbf{n}_3 + \mathbf{n}_4|
\]

Note that right-hand rule determines outward face

Normal for Triangle

\[
\mathbf{n} \cdot (\mathbf{p} - \mathbf{p}_0) = 0
\]

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

normalize \( \mathbf{n} \leftarrow \mathbf{n} / |\mathbf{n}| \)
Simple Mesh Format (SMF)

- Michael 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 -1.0 0.0 2.0
v 1.0 0.0 -2.0
v -0.0 0.0 -3.0
v -2.0 0.0 2.0

#Triangles 6
v 1 3 4
t 1 3 4
v 1 4 2
t 1 4 2
t 1 2 6
v 5 6 8
t 5 6 8
t 5 8 7
v 3 7 8
t 3 7 8
t 3 8 4
v -1 -1 1
t -1 -1 1
v 1 1 1
t 1 1 1
f 1 3 4
f 1 4 2
f 5 6 8
f 5 8 7
f 1 2 6
f 3 7 8
f 3 8 4
```

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

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 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

Adding up the Components

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

\[ I = k_d I_d + k_l (\mathbf{n} \cdot \mathbf{r}) + k_a I_a \]

For each color component we add contributions from all light sources
Vertex Lighting Shaders I
(Gouraud shading)

// 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;

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;
}

Fragment Lighting Shaders I
(Phong Shading)

// 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 vec3 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;
}

Vertex Lighting Shaders II

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;
}

Fragment Lighting Shaders II

void main()
{
    frag_color = vec4(color, 1.0);
}
// fragment shader
// per-fragment interpolated values from the vertex shader
in vec3 fN;
in vec3 fL;
in vec3 fE;
out frag_color;
uniform vec3 AmbientProduct, DiffuseProduct, SpecularProduct;
uniform mat4 ModelView;
uniform float Shininess;

// 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);

frag_color = vec4(ambient + diffuse + specular, 1.0);