

15-462 Computer Graphics I
Lecture 7

Lighting and Shading

Light Sources
Phong Illumination Model
Normal Vectors
[Angel, Ch. 6.1-6.4]

February 12, 2002
Frank Pfenning
Carnegie Mellon University
<http://www.cs.cmu.edu/~fp/courses/graphics/>

Remarks About Assignment 2

- Remember that object transformations are applied in the reverse order in which they appear in the code!
- Remember that transformation matrices are multiplied on the right and executed from right to left: $(R S T)v = R (S (T v))$!
- Look at the model solution (when it is out) and make sure you understand it before the midterm

02/12/2002

15-462 Graphics I

2

Outline

- Light Sources
- Phong Illumination Model
- Normal Vectors

02/12/2002

15-462 Graphics I

3

Lighting and Shading

- Approximate physical reality
- Ray tracing:
 - Follow light rays through a scene
 - Accurate, but expensive (off-line)
- Radiosity:
 - Calculate surface inter-reflection approximately
 - Accurate, especially interiors, but expensive (off-line)
- Phong Illumination model (this lecture):
 - Approximate only interaction light, surface, viewer
 - Relatively fast (on-line), supported in OpenGL

02/12/2002

15-462 Graphics I

4

Radiosity Example



Restaurant Interior. Guillermo Leal, Evolucion Visual

02/12/2002

15-462 Graphics I

5

Raytracing Example



Martin Moeck,
Siemens Lighting

02/12/2002

15-462 Graphics I

6

Light Sources and Material Properties

- Appearance depends on
 - Light sources, their locations and properties
 - Material (surface) properties
 - Viewer position
- Ray tracing: from viewer into scene
- Radiosity: between surface patches
- Phong Model: at material, from light to viewer

02/12/2002

15-462 Graphics I

7

Types of Light Sources

- Ambient light: no identifiable source or direction
- Point source: given only by point
- Distant light: given only by direction
- Spotlight: from source in direction
 - Cut-off angle defines a cone of light
 - Attenuation function (brighter in center)
- Light source described by a luminance
 - Each color is described separately
 - $I = [I_r \ I_g \ I_b]^T$ (I for intensity)
 - Sometimes calculate generically (applies to r, g, b)

02/12/2002

15-462 Graphics I

8

Ambient Light

- Global ambient light
 - Independent of light source
 - Lights entire scene
- Local ambient light
 - Contributed by additional light sources
 - Can be different for each light and primary color
- Computationally inexpensive

$$I_a = \begin{bmatrix} I_{ar} \\ I_{ag} \\ I_{ab} \end{bmatrix}$$

02/12/2002

15-462 Graphics I

9

Point Source

- Given by a point p_0
- Light emitted equally in all directions

$$I(p_0) = \begin{bmatrix} I_r(p_0) \\ I_g(p_0) \\ I_b(p_0) \end{bmatrix}$$

- Intensity decreases with square of distance

$$I(p, p_0) = \frac{1}{|p - p_0|^2} I(p_0)$$

02/12/2002

15-462 Graphics I

10

Limitations of Point Sources

- Shading and shadows inaccurate
- Example: penumbra (partial "soft" shadow)
- Similar problems with highlights
- Compensate with attenuation

$$\frac{1}{(a + bd + cd^2)} \quad \begin{array}{l} d = \text{distance } |p - p_0| \\ a, b, c \text{ constants} \end{array}$$

- Softens lighting
- Better with ray tracing
- Better with radiosity



02/12/2002

15-462 Graphics I

11

Distant Light Source

- Given by a vector v
- Simplifies some calculations
- In OpenGL:
 - Point source $[x \ y \ z \ 1]^T$
 - Distant source $[x \ y \ z \ 0]^T$



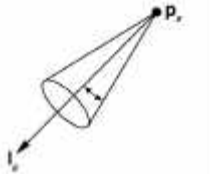
02/12/2002

15-462 Graphics I

12

Spotlight

- Most complex light source in OpenGL
- Light still emanates from point
- Cut-off by cone determined by angle θ



02/12/2002

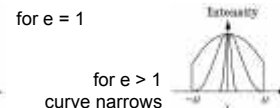
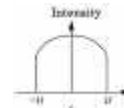
15-462 Graphics I

13

Spotlight Attenuation

- Spotlight is brightest along I_s
- Vector v with angle ϕ from p to point on surface
- Intensity determined by $\cos \phi$
- Corresponds to projection of v onto I_s
- Spotlight exponent e determines rate

$$I = \cos^e(\phi) = (v \cdot I_s)^e \quad \text{Diagram correction } [u = \theta, f = \phi]$$



02/12/2002

15-462 Graphics I

14

Outline

- Light Sources
- Phong Illumination Model
- Normal Vectors

02/12/2002

15-462 Graphics I

15

Phong Illumination Model

- Calculate color for arbitrary point on surface
- Compromise between realism and efficiency
- Local computation (no visibility calculations)
- Basic inputs are material properties and I , n , v :

I = vector to light source
 n = surface normal
 v = vector to viewer
 r = reflection of I at p
 (determined by I and n)



02/12/2002

15-462 Graphics I

16

Basic Calculation

- Calculate each primary color separately
- Start with global ambient light
- Add reflections from each light source
- Clamp to $[0, 1]$
- Reflection decomposed into
 - Ambient reflection
 - Diffuse reflection
 - Specular reflection
- Based on ambient, diffuse, and specular lighting and material properties

02/12/2002

15-462 Graphics I

17

Ambient Reflection

- Intensity of ambient light uniform at every point
- Ambient reflection coefficient k_a , $0 \leq k_a \leq 1$
- May be different for every surface and r, g, b
- Determines reflected fraction of ambient light
- L_a = ambient component of light source
- Ambient intensity $I_a = k_a L_a$
- Note: L_a is not a physically meaningful quantity

02/12/2002

15-462 Graphics I

18

Diffuse Reflection

- Diffuse reflector scatters light
- Assume equally all direction
- Called Lambertian surface
- Diffuse reflection coefficient k_d , $0 \leq k_d \leq 1$
- Angle of incoming light still critical



02/12/2002

15-462 Graphics I

19

Lambert's Law

- Intensity depends on angle of incoming light

- Recall

\mathbf{l} = unit vector from light

\mathbf{n} = unit surface normal

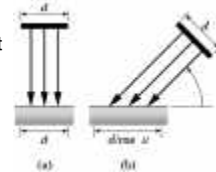
θ = angle to normal

- $\cos \theta = \mathbf{l} \cdot \mathbf{n}$

- $I_d = k_n (\mathbf{l} \cdot \mathbf{n}) L_d$

$$I_d = \frac{k_d}{a + bq + cq^2} (\mathbf{l} \cdot \mathbf{n}) L_d$$

q = distance to light source,
 L_d = diffuse component of light



02/12/2002

15-462 Graphics I

20

Specular Reflection

- Specular reflection coefficient k_s , $0 \leq k_s \leq 1$
- Shiny surfaces have high specular coefficient
- Used to model specular highlights
- Do not get mirror effect (need other techniques)



specular reflection



specular highlights

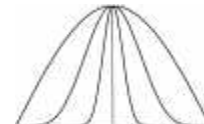
02/12/2002

15-462 Graphics I

21

Shininess Coefficient

- L_s is specular component of light
- \mathbf{r} is vector of perfect reflection of \mathbf{l} about \mathbf{n}
- \mathbf{v} is vector to viewer
- ϕ is angle between \mathbf{v} and \mathbf{r}
- $I_s = k_s L_s \cos^\alpha \phi$
- α is shininess coefficient
- Compute $\cos \phi = \mathbf{r} \cdot \mathbf{v}$
- Requires $|\mathbf{r}| = |\mathbf{v}| = 1$
- Multiply distance term



Higher α is narrower

02/12/2002

15-462 Graphics I

22

Summary of Phong Model

- Light components for each color:
 - Ambient (L_a), diffuse (L_d), specular (L_s)
- Material coefficients for each color:
 - Ambient (k_a), diffuse (k_d), specular (k_s)
- Distance q for surface point from light source

$$I = \frac{1}{a + bq + cq^2} (k_d L_d (\mathbf{l} \cdot \mathbf{n}) + k_s L_s (\mathbf{r} \cdot \mathbf{v})^\alpha) + k_a L_a$$

\mathbf{l} = vector from light

\mathbf{n} = surface normal

\mathbf{r} = \mathbf{l} reflected about \mathbf{n}

\mathbf{v} = vector to viewer

02/12/2002

15-462 Graphics I

23

Outline

- Light Sources
- Phong Illumination Model
- Normal Vectors

02/12/2002

15-462 Graphics I

24

Normal Vectors

- Summarize Phong

$$I = \frac{1}{a + bq + cq^2} (k_d L_d (l \cdot n) + k_s L_s (r \cdot v)^\alpha) + k_a L_a$$

- Surface normal n is critical
 - Calculate $l \cdot n$
 - Calculate r and then $r \cdot v$
- Must calculate and specify the normal vector
 - Even in OpenGL!
- Two examples: plane and sphere

02/12/2002

15-462 Graphics I

25

Normals of a Plane, Method I

- Method I: given by $ax + by + cz + d = 0$
- Let p_0 be a known point on the plane
- Let p be an arbitrary point on the plane
- Recall: $u \cdot v = 0$ iff u orthogonal v
- $n \cdot (p - p_0) = n \cdot p - n \cdot p_0 = 0$
- Consequently $n_0 = [a \ b \ c]^T$
- Normalize to $n = n_0 / |n_0|$

02/12/2002

15-462 Graphics I

26

Normals of a Plane, Method II

- Method II: plane given by p_0, p_1, p_2
- Points may not be collinear
- Recall: $u \times v$ orthogonal to u and v
- $n_0 = (p_1 - p_0) \times (p_2 - p_0)$
- Order of cross product determines orientation
- Normalize to $n = n_0 / |n_0|$

02/12/2002

15-462 Graphics I

27

Normals of Sphere

- Implicit Equation $f(x, y, z) = x^2 + y^2 + z^2 - 1 = 0$
- Vector form: $f(p) = p \cdot p - 1 = 0$
- Normal given by gradient vector

$$n_0 = \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial z} \end{bmatrix} = \begin{bmatrix} 2x \\ 2y \\ 2z \end{bmatrix} = 2p$$

- Normalize $n_0 / |n_0| = 2p / 2 = p$

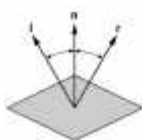
02/12/2002

15-462 Graphics I

28

Angle of Reflection

- Perfect reflection: angle of incident equals angle of reflection
- Also: l, n , and r lie in the same plane
- Assume $|l| = |n| = 1$, guarantee $|r| = 1$



$$l \cdot n = \cos \theta = n \cdot r$$

$$r = \alpha l + \beta n \quad \text{Solution: } \alpha = -1 \text{ and } \beta = 2(l \cdot n)$$

$$r = 2(l \cdot n)n - l$$

Perhaps easier geometrically

02/12/2002

15-462 Graphics I

29

Summary: Normal Vectors

- Critical for Phong model (diffuse and specular)
- Must calculate accurately (even in OpenGL)
- Pitfalls
 - Not unit length
 - How to set at surface boundary?
- Omitted
 - Refraction of transmitted light (Snell's law)
 - Halfway vector (yet another optimization)

02/12/2002

15-462 Graphics I

30

Summary

- Light Sources
- Phong Illumination Model
- Normal Vectors

02/12/2002

15-462 Graphics I

31

Preview

- Polygonal shading
- Lighting and shading in OpenGL
- [Demo]
- Moving and stationary light sources

02/12/2002

15-462 Graphics I

32

Announcements

- Assignment 2 back Thursday
- Check out model solution (before midterm)
- Assignment 3 due a week from Thursday

02/12/2002

15-462 Graphics I

33