Johns Hopkins
Engineering for Professionals

605.767 Applied Computer Graphics

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Module 3B
Advanced Reflection Models

Advanced Reflection Models

- Local reflection models
    - BRDF
        - Physically based models
        - Microfacet geometry
        - Fresnel reflectance
        - Cook and Torrance

Local Reflection Models

- Considerable research has been performed to improve local reflection models
  - Phong model (and variations) has remained the “standard” in most graphics pipeline implementations
    - Due to its simplicity
  - With the introduction of programmability in the graphics pipeline other local reflection models are gaining use
- Global illumination solutions (e.g., ray tracing) also use local reflection models internally
  - Local model is used at each point to calculate any direct illumination seen at that point
  - These have more flexibility in how the model is integrated
    - Software techniques

Shading Equation

- Section 5.1 - 5.3 discusses light sources, materials, sensor (viewer model) and shading
  - Develops a shading equation
    - Include diffuse and specular terms (no ambient)
  - Uses irradiance rather than an “ad-hoc” brightness value that the Blinn-Phong model uses
    - Moller, Haines, Hoffman, 3rd Edition Section 5.5, (omitted in 4th Edition)

$$L_0(v) = \left(\frac{c_{diff}}{\pi} + \frac{m+8}{8\pi}\cos^m\theta_h c_{spec}\right) \otimes E_L \cos\theta_i$$

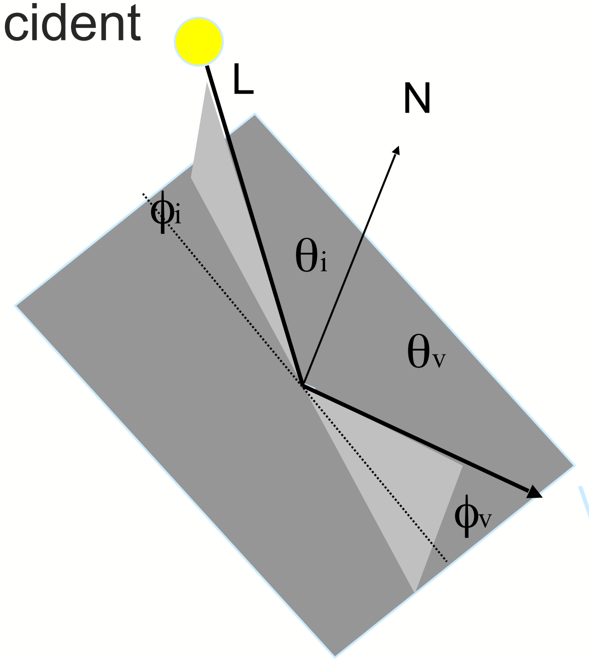
E_L is the light source irradiance – multiplied by cos theta to indicate how much strikes the surface
c_{diff} and c_{spec} are the material diffuse and specular reflection “colors”
m is the material smoothness (corresponds to shininess in Blinn-Phong model)
θ_h indicates the halfway vector between the view direction and the light direction
$\otimes$ indicates multiplication by a vector of RGB terms
Note that cos terms are clamped so values do not fall below 0

Blinn-Phong Model: $L_0(v) = \left(\cos\theta_i c_{diff} + \cos^m\theta_h c_{spec}\right) \otimes B_L \qquad B_L = \frac{E_L}{\pi}$

Lacks the (m+8)/m factor and specular term is not modulated by cos

Bidirectional Reflectivity Distribution Function (BRDF)

- The **bidirectional reflectivity distribution function** (BRDF) models incident light (direction) to outgoing light (direction)
  - $BRDF = f(\lambda, \varphi_i, \theta_i, \varphi_v, \theta_v) = f(\lambda, L, V)$
    - Where λ is the light wavelength
      - Represented using RGB color
    - φ_i, θ_i is the incoming light direction
    - φ_v, θ_v is the outgoing light direction
      - Reflected towards the view position
  - Produces a unit-less value that is relative energy reflected in outgoing direction given an input direction
  - Figure 9.17 (7.15 3rd edition) in Haines and Moller
- Simplifying assumption – hue and saturation remain constant
  - Even though some materials change color depending on incoming light direction



Bidirectional Reflectivity Distribution Function (BRDF)

- BRDF describes how incoming and outgoing radiant energy is related
  - Does not explain how materials physically interact with light
  - However, BRDF can be used to describe material properties
- **Helmholtz reciprocity**
  - Input and output angles can be switched and the result is equal
- Figure 9.18 (7.17 3rd edition) shows sample BRDFs
  - Diffuse – simple hemisphere
  - Phong specular: adds an elongated protrusion along the reflected angle
  - Several other models shown as well
- Further info:
  - http://www.cs.princeton.edu/~smr/cs348c-97/surveypaper.html
  - http://developer.download.nvidia.com/assets/gamedev/docs/BRDFIntro.pdf

Complications with BRDF

- Isotropic surfaces (independent of direction)
  - BRDF shape is independent of incoming azimuth angle
- Anisotropic surface (directionally dependent)
  - Surface retains coherent patterns
    - e.g., brushed aluminum with patterns from a milling machine
    - Magnitude of the specular lobe depends on whether incoming light is aligned with the grain of the surface
- Where do we get the “actual” BRDF from?
  - Data available for some materials (mainly metals) but not complete
    - Using methods of taking direct measurements to form BRDFs
- At what scale should we represent the BRDF?
  - Over entire surface? Should it include imperfections such as scratches?
- How do we represent the BRDF?
  - Empirical model – imitates light-object interaction
    - Phong method uses mathematical function to represent the specular lobe
  - Physical model
    - Cook and Torrance - statistical distribution to represent surface geometry

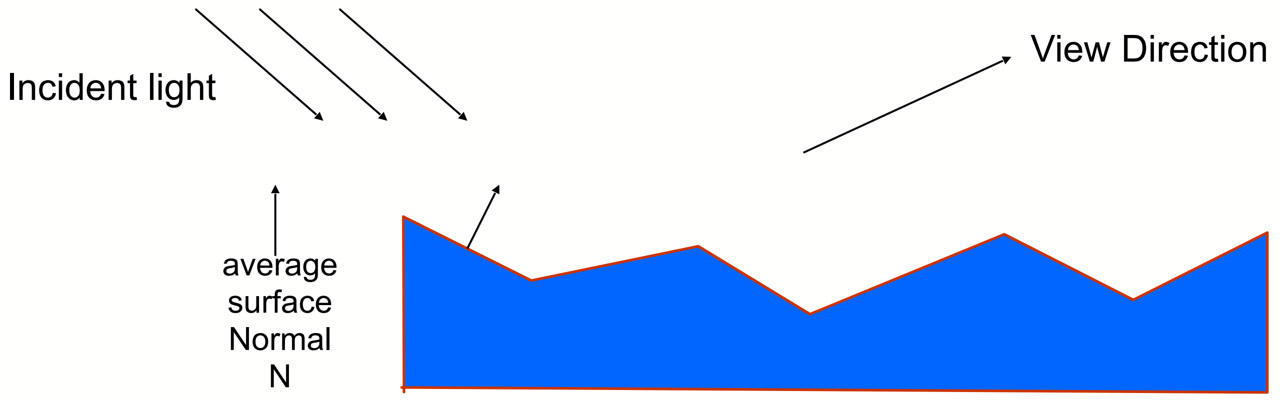
Physically Based Specular Reflection

- Phong model fails to account for 2 important aspects of specular reflection
  - Intensity varies with angle of incidence of light
    - Usually increases when light is nearly parallel to surface
  - Highlight color depends on material and can vary with angle of incidence
- 1977 - Jim Blinn proposed a physically simulated specular component
- 1982 - Cook and Torrance extended this model
  - Based on method proposed by Torrance and Sparrow in 1967
    - Applied physicists
  - Often used to simulate the reflectance from metals and plastics
  - Accounts for the spectral composition of highlights
    - Dependency on material type and angle of incidence
  - Depends on multiple factors (D, G, F)
    - Explained in the next few slides

$$R_s(\lambda) = \frac{DGF}{N \cdot V}$$

Microfacet Geometry

- Surfaces are not perfect mirrors in reality
- A physically based approach models the surface as microfacets
  - Each microfacet is a perfect reflecting surface, i.e., a mirror
    - Orientated at random angles relative to the average surface normal
- Only the microfacets oriented in a direction that reflects light towards the viewer contribute to specular reflection
    - Need to find the fraction (D) of microfacets that are oriented in this direction



Distribution of Microfacet Orientations

- Torrance and Sparrow (1967) used a simple Gaussian distribution

$$D = e^{-(\alpha m)^2} \qquad \alpha = \cos^{-1}(N \cdot H)$$

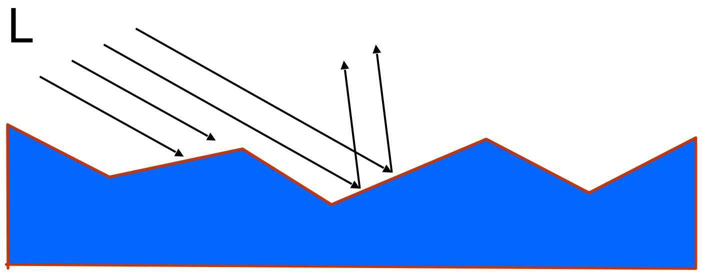
  - m is standard deviation of the distribution (property of the material)
- Cook and Torrance

$$D = \frac{e^{-\left(\frac{\tan\delta}{m}\right)^2}}{4m^2\cos^4(\delta)}$$

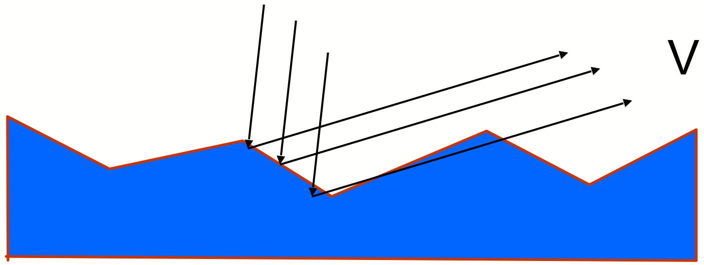
  - Statistical model of the microfacet variation in the halfway-vector H direction
  - D = number of facets oriented correctly to the viewer
  - Based on a Beckman distribution function
  - Consistent with the surface variations of rough surfaces
  - δ the angle between N and H
  - m is a measure of the roughness of the surface
    - Root-mean-square slope of the microfacets
      - Large m indicates steep slopes and the reflections spread out over the surface
    - m near 0.2 indicates a nearly smooth surface
    - m near 0.6 indicates a rough surface

Specular Reflection from Microfacet Surface

- Specular reflection from this surface depends on three factors:
  - Number of facets oriented correctly to the viewer (D)
  - Shadowing and masking
    - Incident light may be shadowed
    - Reflected light may be masked
  - Fresnel's reflectance equations
    - Predict intensity/color change depending on angle of incidence
- Assumptions:
  - Microfacets are larger than the wavelength of light in size
  - Diameter of the light beam such that it intersects a large number of microfacets
    - To be statistically correct



Shadowing



Masking

Shadowing and Masking Effects

- Interference occurs when viewing vector (V) or light orientation vector (L) approach the mean surface
  - Geometry of the microfacets
  - Shadowing – incident light is obstructed by other facets
  - Masking – reflected light is trapped (hits other facets)
  - Geometrical attenuation factor G
    - Value from 0 to 1 representing the proportionate amount of light remaining after the masking or shadowing has taken place
- Blinn described dependence of this ratio on L, V, H
  - Masking $$G_m = \frac{2(N \cdot H)(N \cdot V)}{V \cdot H}$$
  - Shadowing $$G_s = \frac{2(N \cdot H)(N \cdot L)}{V \cdot H}$$
  - G is the minimum of G_s and G_m: $G = \min\{1, G_s, G_m\}$

Fresnel Reflectance

- **Fresnel reflectance** (F)
  - Accounts for the change of highlight color with changes to angle L
  - The fraction of light incident on a facet that is reflected rather than absorbed
  - Important for **dielectric** (nonconductive) materials such as plastic, glass, water
    - More reflective at grazing angles
- Fresnel reflection depends on index of refraction and the incident angle

$$F = \frac{1}{2}\frac{(g-c)^2}{(g+c)^2}\left(1 + \frac{[c(g+c)-1]^2}{[c(g-c)-1]^2}\right)$$

$$c = V \cdot H$$

Measure of view and light angles

$$g = \sqrt{\mu^2 + c^2 - 1}$$

  - For many materials, index of refraction varies with wavelength
    - So you can get color changes in specular regions
- Fresnel effect also explains why most surfaces approximate mirror reflectors when the light strikes them at a grazing angle

Glare Term

- Another pure geometric term accounts for the glare effect
  - As the angle between N and V approaches 90 one sees more and more glare
    - Observer sees more microfacets
- Accounted for by term: $\dfrac{1}{N \cdot V}$
- Increase in area of microfacets seen by viewer is inversely proportional to the angle between the viewing direction and surface normal
  - Effect is countered by the masking effect

Cook and Torrance Reflection Model (1982)

- Specular term: $$R_s(\lambda) = \frac{DGF}{N \cdot V}$$
  - D = proportion of microfacets aligned to view
  - G = fraction of light remaining that is not shadowed or masked
  - F = Fresnel term
  - $N \cdot V$ = glare effect term
  - In practice, R_s is calculated for red, green, blue
  - Note it depends on angle of incidence and angle of view
- Specular term is combined with a uniform diffuse term:
- $BRDF = sR_s + dR_d$ (where s + d = 1)
  - For metals: d = 0, s = 1
    - Specular term controls color for metals – contrast this to Phong model
  - For shiny plastics: d = 0.9, s = 0.1
    - Its BRDF does not depend on the incoming azimuth

Other Reflection Models

- Well-known Models
  - Ward
    - Models anisotropic materials
  - Schlick's approximation
    - Approximates the BRDF of metallic surfaces
  - He, Torrance, Sillion, Greenberg (HTSG)
    - Simulates many physical phenomena
- Types of BRDFs
  - Various distribution models of microfacets
  - Isotropic vs. Anisotropic
  - Material-specific
    - Cloth
    - Sub-surface Scattering