News

- homework correction: questions 13-16 should use:
  - unit square has points A=(0,0,0,1), B=(0,1,0,1), C=(0,1,1,1), D=(0,0,1,1) in world coordinates
Review: Illumination

- transport of energy from light sources to surfaces & points
  - includes *direct* and *indirect illumination*

Images by Henrik Wann Jensen
Review: Light Sources

- directional/parallel lights
  - point at infinity: \((x, y, z, 0)^T\)

- point lights
  - finite position: \((x, y, z, 1)^T\)

- spotlights
  - position, direction, angle

- ambient lights
Review: Light Source Placement

- geometry: positions and directions
  - standard: world coordinate system
    - effect: lights fixed wrt world geometry
  - alternative: camera coordinate system
    - effect: lights attached to camera (car headlights)
Types of Reflection

- **specular** (a.k.a. *mirror* or *regular*) reflection causes light to propagate without scattering.

- **diffuse** reflection sends light in all directions with equal energy.

- **mixed** reflection is a weighted combination of specular and diffuse.
Types of Reflection

- *retro-reflection* occurs when incident energy reflects in directions close to the incident direction, for a wide range of incident directions.

- *gloss* is the property of a material surface that involves mixed reflection and is responsible for the mirror-like appearance of rough surfaces.
Reflectance Distribution Model

- most surfaces exhibit complex reflectances
  - vary with incident and reflected directions.
  - model with combination

specular + glossy + diffuse = reflectance distribution
Surface Roughness

- at a microscopic scale, all real surfaces are rough
- cast shadows on themselves
- “mask” reflected light:
Surface Roughness

- notice another effect of roughness:
  - each “microfacet” is treated as a perfect mirror.
  - incident light reflected in different directions by different facets.
  - end result is mixed reflectance.
    - smoother surfaces are more specular or glossy.
    - random distribution of facet normals results in diffuse reflectance.
Physics of Diffuse Reflection

- ideal diffuse reflection
  - very rough surface at the microscopic level
    - real-world example: chalk
  - microscopic variations mean incoming ray of light equally likely to be reflected in any direction over the hemisphere
- what does the reflected intensity depend on?
Lambert’s Cosine Law

- ideal diffuse surface reflection
  - the energy reflected by a small portion of a surface from a light source in a given direction is proportional to the cosine of the angle between that direction and the surface normal

- reflected intensity
  - independent of viewing direction
  - depends on surface orientation wrt light

- often called Lambertian surfaces
intuitively: cross-sectional area of the “beam” intersecting an element of surface area is smaller for greater angles with the normal.
Computing Diffuse Reflection

- angle between surface normal and incoming light is **angle of incidence**: 
  \[ I_{\text{diffuse}} = k_d I_{\text{light}} \cos \theta \]

- in practice use vector arithmetic 
  \[ I_{\text{diffuse}} = k_d I_{\text{light}} (\mathbf{n} \cdot \mathbf{l}) \]

\( k_d \): diffuse component
”surface color”
Diffuse Lighting Examples

- Lambertian sphere from several lighting angles:

- need only consider angles from 0° to 90°
  - why?

- demo: Brown exploratory on reflection
Specular Reflection

- shiny surfaces exhibit specular reflection
  - polished metal
  - glossy car finish

- specular highlight
  - bright spot from light shining on a specular surface

- view dependent
  - highlight position is function of the viewer’s position
Physics of Specular Reflection

- at the microscopic level a specular reflecting surface is very smooth

- thus rays of light are likely to bounce off the microgeometry in a mirror-like fashion

- the smoother the surface, the closer it becomes to a perfect mirror
Optics of Reflection

- reflection follows *Snell’s Law:*
  - incoming ray and reflected ray lie in a plane with the surface normal
  - angle the reflected ray forms with surface normal equals angle formed by incoming ray and surface normal

\[ \theta_{\text{light}} = \theta_{\text{reflection}} \]
Non-Ideal Specular Reflectance

- Snell’s law applies to perfect mirror-like surfaces, but aside from mirrors (and chrome) few surfaces exhibit perfect specularity.
- How can we capture the “softer” reflections of surface that are glossy, not mirror-like?
- One option: model the microgeometry of the surface and explicitly bounce rays off of it.
- Or…
Empirical Approximation

- we expect most reflected light to travel in direction predicted by Snell’s Law

- but because of microscopic surface variations, some light may be reflected in a direction slightly off the ideal reflected ray

- as angle from ideal reflected ray increases, we expect less light to be reflected
Empirical Approximation

- angular falloff

- how might we model this falloff?
Phong Lighting

- most common lighting model in computer graphics
  - (Phong Bui-Tuong, 1975)

\[ I_{\text{specular}} = k_s I_{\text{light}} (\cos \phi)^{n_{\text{shiny}}} \]

- \( n_{\text{shiny}} \): purely empirical constant, varies the rate of falloff
- no physical basis, works ok in practice
Phong Lighting: The $n_{\text{shiny}}$ Term

- Phong reflectance term drops off with divergence of viewing angle from ideal reflected ray

- *What does this term control, visually?*

Viewing angle – reflected angle
Phong Examples

varying $l$

varying $n_{\text{shiny}}$
Calculating Phong Lighting

- compute **cosine** term of Phong lighting with vectors

\[ I_{\text{specular}} = k_s I_{\text{light}} (v \cdot r)^{n_{\text{shiny}}} \]

- \( v \): unit vector towards viewer
- \( r \): ideal reflectance direction
- \( k_s \): specular component
  - highlight color

- how to efficiently calculate \( r \)?
Calculating The $R$ Vector

$$P = N \cos \theta = \text{projection of } L \text{ onto } N$$
Calculating The $\mathbf{R}$ Vector

$\mathbf{P} = \mathbf{N} \cos \theta = \text{projection of } \mathbf{L} \text{ onto } \mathbf{N}$

$\mathbf{P} + \mathbf{S} = \mathbf{R}$
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$P = N \cos \theta = \text{projection of } L \text{ onto } N$

$P + S = R$

$N \cos \theta + S = R$
Calculating The $R$ Vector

\[ P = N \cos \theta = \text{projection of } L \text{ onto } N \]
\[ P + S = R \]
\[ N \cos \theta + S = R \]
\[ S = P - L = N \cos \theta - L \]
Calculating The $R$ Vector

$P = N \cos \theta = \text{projection of } L \text{ onto } N$

$P + S = R$

$N \cos \theta + S = R$

$S = P - L = N \cos \theta - L$

$N \cos \theta + (N \cos \theta - L) = R$

$2 (N \cos \theta) - L = R$

$\cos \theta = N \cdot L$

$2 (N (N \cdot L)) - L = R$
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- $N$ and $R$ are unit length!
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Phong Lighting Model

- combine ambient, diffuse, specular components

\[ I_{\text{total}} = k_s I_{\text{ambient}} + \sum_{i=1}^{\text{#lights}} I_i (k_d (n \cdot l_i) + k_s (v \cdot r_i)^{n_{\text{shiny}}}) \]

- commonly called *Phong lighting*
  - once per light
  - once per color component
### Phong Lighting: Intensity Plots

<table>
<thead>
<tr>
<th>Phong</th>
<th>$\rho_{\text{ambient}}$</th>
<th>$\rho_{\text{diffuse}}$</th>
<th>$\rho_{\text{specular}}$</th>
<th>$\rho_{\text{total}}$</th>
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</thead>
<tbody>
<tr>
<td>$\phi_i = 60^\circ$</td>
<td><img src="image1" alt="Phong Lighting" /></td>
<td><img src="image2" alt="Phong Lighting" /></td>
<td><img src="image3" alt="Phong Lighting" /></td>
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<td>$\phi_i = 25^\circ$</td>
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<td>$\phi_i = 0^\circ$</td>
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<td><img src="image11" alt="Phong Lighting" /></td>
<td><img src="image12" alt="Phong Lighting" /></td>
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</tbody>
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Blinn-Phong Model

- variation with better physical interpretation
  - Jim Blinn, 1977
- $h$: halfway vector
- highlight occurs when $h$ near $n$

$$I_{out}(x) = k_s (h \cdot n)^{n_{shiny}} \cdot I_{in}(x); \text{with } h = (l + v)/2$$
Light Source Falloff

- quadratic falloff
  - brightness of objects depends on power per unit area that hits the object
  - the power per unit area for a point or spot light decreases quadratically with distance

\[
\text{Area } 4\pi r^2
\]

\[
\text{Area } 4\pi (2r)^2
\]
Light Source Falloff

- non-quadratic falloff
- many systems allow for other falloffs
- allows for faking effect of area light sources
- OpenGL / graphics hardware
  - $I_o$: intensity of light source
  - $x$: object point
  - $r$: distance of light from $x$

$$I_{in}(x) = \frac{1}{ar^2 + br + c} \cdot I_0$$
Lighting Review

- lighting models
  - ambient
    - normals don’t matter
  - Lambert/diffuse
    - angle between surface normal and light
  - Phong/specular
    - surface normal, light, and viewpoint