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

\[
\text{specular} + \text{glossy} + \text{diffuse} = \text{reflectance distribution}
\]

**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
Lambert’s Law

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:

\[ I_{\text{diffuse}} = k_d \cdot I_{\text{light}} \cdot \cos \theta \]

- in practice use vector arithmetic

\[ I_{\text{diffuse}} = k_d \cdot I_{\text{light}} \cdot (n \cdot l) \]

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
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

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?

Phong Examples

- varying \(I\)
- varying \(n_{\text{shiny}}\)
Calculating Phong Lighting

- compute cosine term of Phong lighting with vectors
  \[ I_{\text{specular}} = k_s I_{\text{light}} (\mathbf{v} \cdot \mathbf{r}) \]
  \[ n_{\text{shiny}} \]
  - \( \mathbf{v} \): unit vector towards viewer
  - \( \mathbf{r} \): ideal reflectance direction
  - \( k_s \): specular component
  - highlight color

- how to efficiently calculate \( \mathbf{r} \)?

Calculating The \( \mathbf{R} \) Vector

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

\[ \mathbf{S} = \mathbf{P} - \mathbf{L} = \mathbf{N} \cos \theta - \mathbf{L} \]

\[ \mathbf{S} = \mathbf{P} - \mathbf{L} = \mathbf{N} \cos \theta - \mathbf{L} \]
\[ \mathbf{N} \cos \theta + \mathbf{S} = \mathbf{R} \]
\[ 2 (\mathbf{N} \cos \theta - \mathbf{L}) = \mathbf{R} \]
\[ \cos \theta = \mathbf{N} \cdot \mathbf{L} \]
\[ 2 (\mathbf{N} (\mathbf{N} \cdot \mathbf{L})) - \mathbf{L} = \mathbf{R} \]
Phong Lighting: Intensity Plots

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>$\Omega_{ambient}$</th>
<th>$\Omega_{diffuse}$</th>
<th>$\Omega_{specular}$</th>
<th>$\Omega_{total}$</th>
</tr>
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<td>$60^\circ$</td>
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<td><img src="image2.png" alt="Image" /></td>
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<td><img src="image8.png" alt="Image" /></td>
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<tr>
<td>$0^\circ$</td>
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<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
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</tbody>
</table>

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
    - \(I_c\): 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