Lecture 10:
Basics of Materials and Lighting

Interactive Computer Graphics
Stanford CS248, Winter 2022
Things you know so far!

- Representing geometry
  - As triangle meshes, subdivision surfaces, implicit surfaces, etc.

- Visibility and occlusion
  - Rasterization: determining what point on what triangle covers a sample
  - Ray tracing: determining what triangle a ray hits

- Today: basics of lights and materials
  - Computing the “appearance” of the surface at a point
“Shading” in drawing

- Depicting the appearance of the surface
- Due to factors like surface material, lighting conditions
Lighting

Credit: ETC

Credit: Pixar
Lighting

Credit: Wikipedia
(Nasir ol Molk Mosque)
Lighting

Portrait Lighting Cheat Sheet

0°  45°  90°  135°  180°  225°  270°  315°

Flash @ 45°
Down

Flash @ 90°

Flash @ 45°
Up

Credit: Platon
Materials: diffuse
Materials: plastic
Materials: red semi-gloss paint
Materials: Ford mystic lacquer paint
Materials: mirror
Materials: gold
Renderer measures light energy along a ray
Renderer measures light energy along a ray

Shading the surface point is computing the amount of light reflected off point toward the camera.
Multiple light sources

Appearance of surface is brighter, because it’s now reflecting light from three sources.
Mini-tutorial on radiometry
(much more in CS348B)
Electromagnetic radiation

Light is electromagnetic radiation that is visible to eye
What do lights do?

- Physical process converts input energy into photons
  - Each photon carries a small amount of energy

- Over some amount of time, light fixture consumes some amount of energy, Joules
  - Some input energy is turned into heat, some into visible photons

- Energy of photons hitting an object ~ exposure
  - Film, sensors, sunburn, solar panels, ...

- In graphics we generally assume "steady state" process
  - Rate of energy consumption = power, Watts (Joules/second)
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- In graphics we generally assume “steady state” process
  - Rate of energy consumption = power, Watts (Joules/second)
Measuring illumination: radiant flux (power)

- Given a sensor, we can count how many photons reach it
  - Over a period of time, gives the power received by the sensor

- Given a light, consider counting the number of photons emitted by it
  - Over a period of time, gives the power emitted by the light

- Energy carried by a photon:

  \[ Q = \frac{hc}{\lambda} \]

  \[ h \approx 6.626 \times 10^{-34} \ [m^2 \text{kg/s}] \]
Measuring illumination: radiant flux (power)

- Radiant Flux (power): energy per unit time (Watts) received by the sensor (or emitted by the light)

\[ \Phi = \lim_{\Delta \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt} \left[ \frac{J}{s} \right] \]

- Time integral of flux is total radiant energy

\[ Q = \int_{t_0}^{t_1} \Phi(t) \, dt \]
Spectral power distribution

Describes distribution of energy by wavelength
Spectral power distribution

Describes distribution of energy by wavelength
“Cool” vs. “Warm” white light LED

Credit: https://www.ledholidaylighting.com/LED-faq.aspx
Measuring illumination: irradiance

- Radiant Flux ($\Phi$): time density of energy (power)
- Irradiance ($E$): area density of radiant flux

Given a sensor of with area $A$, we can consider the average flux over the entire sensor area:

$$\frac{\Phi}{A}$$
Measuring illumination: irradiance

- Radiant Flux ($\Phi$): time density of energy (power)
- Irradiance ($E$): area density of radiant flux

Given a sensor of with area $A$, we can consider the average flux over the entire sensor area:

$$\frac{\Phi}{A}$$

Irradiance ($E$) is given by taking the limit of area at a single point on the sensor:

$$E(p) = \lim_{\Delta \to 0} \frac{\Delta \Phi(p)}{\Delta A} = \frac{d\Phi(p)}{dA} \quad \left[ \frac{W}{m^2} \right]$$
Beam power in terms of irradiance

Consider beam with flux $\Phi$ incident on surface with area $A$

$$E = \frac{\Phi}{A}$$

$$\Phi = EA$$
Projected area

Consider beam with flux $\Phi$ incident on angled surface with area $A'$

$A = A' \cos \theta$

$A = \text{projected area of surface relative to direction of beam}$
Lambert’s Law

Irradiance at surface is proportional to cosine of angle between light direction and surface normal.

\[ A = A' \cos \theta \]

\[ E = \frac{\Phi}{A'} = \frac{\Phi \cos \theta}{A} \]
Why do we have seasons?

Earth’s axis of rotation: ~23.5° off axis

[Image credit: Pearson Prentice Hall]
Irradiance falloff with distance

Assume light is emitting flux $\Phi$ in a uniform angular distribution
Irradiance falloff with distance

Assume light is emitting flux $\Phi$ in a uniform angular distribution

Compare irradiance at surface of two spheres:

$$E_1 = \frac{\Phi}{4\pi r_1^2}$$

$$E_2 = \frac{\Phi}{4\pi r_2^2}$$

$$\frac{E_2}{E_1} = \frac{r_1^2}{r_2^2}$$
Why does a room get darker farther from a light source?
Measuring illumination: radiance

- Radiance (L) is the solid angle density of irradiance (irradiance per unit direction)

In other words, radiance is energy along a ray defined by origin point \( p \) and direction \( \omega \)
How much light hits the surface at point p

(irradiance at point p)
How much light hits the surface at point $p$  
(irradiance at point $p$)

$L_i \cos \theta_i$
How much light hits the surface at point \( p \)?
(from multiple light sources)

(irradiance at point \( p \))

\[
\sum_i L_i \cos \theta_i
\]
Types of lights

- **Attenuated omnidirectional point light**
  (emits equally in all directions, intensity falls off with distance as $1/r^2$)

- **Infinite directional light**
  (infinitely far away, all points in scene receive light with radiance $L$ from direction $d$)

$$L = \frac{\Phi}{r^2}$$
Point light with shadows

Image credit: https://forum.reallusion.com/PrintTopic231048.aspx
Spot light

Does not emit equally in all directions… intensity falls off in directions away from main spotlight direction

\[ w = \text{normalize}(p - p_L) \]

\[ L(w) = \begin{cases} 0 & \text{if } w \cdot d > \cos \theta \\ L_0 & \text{otherwise} \end{cases} \]

Or, if spotlight intensity falls off from direction \( d \)

\[ L(w) \approx w \cdot d \]
Spot light
Environment light (represented by texture map)

Pixel \((x,y)\) stores radiance \(L\) from direction \((\phi, \theta)\)
Review of spherical coordinates

\( (r, \theta, \varphi) \)
So far... we’ve discussed how to compute the light arriving at a surface point (radiance along incoming ray)

But goal is to compute what fraction of that light is reflected toward a camera!
Recall: how much light hits the surface at point p?

(irradiance at point p)

\[ \sum_{i} L_i \cos \theta_i \]
How much light is REFLECTED from \( p \) toward \( p_0 \)?

\[
L(p, \omega_o) = \sum_i f_p(\omega, \omega_i, \omega_o) L_i \cos \theta_i
\]

\[
\omega_o = \text{normalize}(p_0 - p)
\]
Bidirectional reflectance distribution function (BRDF)

- Gives fraction of light arriving at surface point $P$ from direction $\omega_i$ is reflected in the direction $\omega_o$

$$f(p, \omega_i, \omega_o)$$
Reflection models

- *Reflection* is the process by which light incident on a surface interacts with the surface such that it leaves on the incident (same) side without change in frequency.
- Choice of reflection function determines surface appearance.
What is this material?

Light is scattered equally in all directions
Diffuse / Lambertian material

Uniform colored diffuse BRDF
Albedo (fraction of light reflected) is same for all surface points $p$

Textured diffuse BRDF
Albedo is spatially varying, and is encoded in texture map.

[Mitsuba renderer, Wenzel Jakob, 2010]
What is this material?
Glossy material (BRDF)

Copper

Aluminum

[Mitsuba renderer, Wenzel Jakob, 2010]
What is this material?
Perfect specular reflection
Perfect specular reflection
Calculating direction of specular reflection

\[ \theta = \theta_o = \theta_i \]

\[ \omega_o + \omega_i = 2 \cos \theta \vec{n} = 2(\omega_i \cdot \vec{n})\vec{n} \]

\[ \omega_o = -\omega_i + 2(\omega_i \cdot \vec{n})\vec{n} \]

Top-down view (looking down on surface)

\[ \phi_o = (\phi_i + \pi) \mod 2\pi \]
How might you render a specular surface

- Compute direction from surface point $p$ to camera = $w_o$
- Given normal at $p$, compute reflection direction $w_i$
- Light reflected in direction $w_o$ is light arriving from direction $w_i$
- How do you measure light arriving from $w_i$?

One idea...
look up amount in environment map!
(more on this later)

Pixel (x,y) stores radiance $L$ from direction $(\phi, \theta)$
Some basic reflection functions

- **Ideal specular**
  Perfect mirror

- **Ideal diffuse**
  Uniform reflection in all directions

- **Glossy specular**
  Majority of light distributed in reflection direction

- **Retro-reflective**
  Reflects light back toward source

Diagrams illustrate how incoming light energy from given direction is reflected in various directions.
More complex materials

Isotropic / anisotropic materials (BRDFs)

Key: directionality of underlying surface

Isotropic

Anisotropic

Surface (normals)

BRDF (fix $\omega_i$, vary $\omega_o$)
Anisotropic BRDFs

Reflection depends on azimuthal angle $\phi$

\[ f_r(\theta_i, \phi_i; \theta_r, \phi_r) \neq f_r(\theta_i, \theta_r, \phi_r - \phi_i) \]

Results from oriented microstructure of surface, e.g., brushed metal
Anisotropic BRDF: Nylon

[Westin et al. 1992]
Anisotropic BRDF: Velvet

[Westin et al. 1992]
Anisotropic BRDF: Velvet

[https://www.youtube.com/watch?v=2hjoW8TYTd4]
Anisotropic BRDF: Velvet

[https://www.youtube.com/watch?v=2hjoW8YTd4]
What is this material?
Ideal reflective / refractive material (BxDF *)

Air ↔ water interface

Air ↔ glass interface (with absorption)

*X stands in for reflectance “r”, scattering, transmission, etc.*
Transmission

In addition to reflecting off surface, light may be transmitted through surface.

Light refracts when it enters a new medium.
Snell’s Law

Transmitted angle depends on index of refraction of medium incident ray is in and index of refraction of medium light is entering.

\[ \eta_i \sin \theta_i = \eta_t \sin \theta_t \]

<table>
<thead>
<tr>
<th>Medium</th>
<th>(\eta^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>1.0</td>
</tr>
<tr>
<td>Air (sea level)</td>
<td>1.00029</td>
</tr>
<tr>
<td>Water (20°C)</td>
<td>1.333</td>
</tr>
<tr>
<td>Glass</td>
<td>1.5-1.6</td>
</tr>
<tr>
<td>Diamond</td>
<td>2.42</td>
</tr>
</tbody>
</table>

* index of refraction is wavelength dependent (these are averages)
Fresnel reflection

Many real materials: reflectance increases w/ viewing angle

[Lafortune et al. 1997]
Snell + Fresnel: example

Refraction (Snell’s Law)

Reflection (Fresnel)
Subsurface scattering

- Visual characteristics of many surfaces caused by light entering at different points than it exits
  - Violates a fundamental assumption of the BRDF
  - Need to generalize scattering model (BSSRDF)

* BSSRDF = bidirectional subsurface scattering reflectance distribution function
Translucent materials: Jade
Translucent materials: skin
Translucent materials: leaves
BRDF
BSSRDF
(models subsurface scattering of light)
Parameters to Disney BRDF

- **specularTint**: a concession for artistic control that tints incident specular towards the base color. Grazing specular is still achromatic.
- **roughness**: surface roughness, controls both diffuse and specular response.
- **anisotropic**: degree of anisotropy. This controls the aspect ratio of the specular highlight. (0 = isotropic, 1 = maximally anisotropic).
- **sheen**: an additional grazing component, primarily intended for cloth.
- **sheenTint**: amount to tint sheen towards base color.
- **clearcoat**: a second, special-purpose specular lobe.
- **clearcoatGloss**: controls clearcoat glossiness (0 = a “satin” appearance, 1 = a “gloss” appearance).

Rendered examples of the effect of each of our parameters are shown in Figure 16.
Pattern generation vs. BRDF

In practice, it is convenient to separate computation of spatially varying BRDF parameters (like albedo, shininess, etc.) from the reflectance function itself.

Example 1: albedo value at surface point is given by expression combining multiple textures.

Example 2: Different textures defining different spatially varying BRDF input parameters.
Unity’s shader graph
Fragment processing stage of graphics pipeline evaluates surface appearance

* Several stages of the modern OpenGL pipeline are omitted

“Computing color of surface at coverage point” = simulation of lighting and materials
GLSL shader programs

Define behavior of vertex processing and fragment processing stages of pipeline
Describe operation on a single vertex (or single fragment)

Example GLSL fragment shader program

```
uniform sampler2D myTexture;
uniform vec3 lightDir;  // light direction
uniform vec3 Li;        // light intensity

in vec2 uv;
in vec3 norm;
out vec4 fragColor;

void diffuseShader() {
    vec3 kd = texture(myTexture, uv);
    vec3 in_light = Li * clamp(dot(-lightDir, norm), 0.0, 1.0);
    fragColor = vec4(kd * in_light, 1.0);
}
```

Shader function executes once per "fragment".

Outputs color of surface at sample point corresponding to fragment.
(this shader performs a texture lookup to obtain the surface's material color at this point, then performs a simple lighting computation)

Program parameters

- `uniform sampler2D myTexture;`
- `uniform vec3 lightDir;  // light direction`
- `uniform vec3 Li;        // light intensity`

Per-fragment attributes

- `in vec2 uv;`
- `in vec3 norm;`
- `out vec4 fragColor;`

Sample surface albedo (reflectance color) from texture

- `vec3 kd = texture(myTexture, uv);`
- `vec3 in_light = Li * clamp(dot(-lightDir, norm), 0.0, 1.0);`
- `fragColor = vec4(kd * in_light, 1.0);`

Diffuse BRDF: \( f(\omega_o, \omega_i) = kd \)
 incoming light reflected equally in all directions
 (fraction reflected = kd)
Appearance of a surface is determined by:
- The amount of light reaching the surface from different directions
  - Surface irradiance: the amount of light arriving at a surface point
  - Radiance: the amount of light arriving at a surface point from a given direction
- The reflectance properties of the surface:
  - BRDF(w_i,w_o): the fraction of light from direction w_i reflected in direction w_o

CS348B covers the physics of lighting and material models in great detail!
Acknowledgements

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