Materials

UCSD CSE 167
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Can we build a general function for describing reflection?
Bidirectional Reflectance Distribution Function (BRDF)

\[ f(v, l) \]
Bidirectional Reflectance Distribution Function (BRDF)

\[ f(v, l) \]

if it also describes refraction/transmission, then it’s a Bidirectional Scattering Distribution Function (BSDF)
if it only describes transmission, then it’s a Bidirectional Transmission Distribution Function (BTDF)
BSDFs describe reflection/transmission properties

\[ f(v, l) \]

beautiful illustrations from Jonathan Dupuy
BSDFs describe reflection/transmission properties

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BSDFs describe reflection/transmission properties

\[ f(\mathbf{v}, \mathbf{l}) \]

beautiful illustrations from Jonathan Dupuy
BSDFs describe reflection/transmission properties

\[ f(v, l) \]

beautiful illustrations from Jonathan Dupuy
BRDF is a 4D function

\[ f(v, l) = f(v_{\theta}, v_{\phi}, l_{\theta}, l_{\phi}) \]
Reciprocity of BRDFs

\[ f(v, l) = f(l, v) \]
Energy conservation of BRDFs

for all view directions $v$, the total reflected energy over all incoming light direction $l$ should be less or equal than what comes in
Energy conservation of BRDFs

for all view directions $\mathbf{v}$, the total reflected energy over all incoming light direction $\mathbf{l}$ should be less or equal than what comes in

$$\int f(\mathbf{v}, \mathbf{l})(\mathbf{l} \cdot \mathbf{n})\,d\mathbf{l} \leq 1 \quad \text{for all } \mathbf{v}$$

$dl$ is an infinitesimal area on a unit sphere

$dl = \sin \theta d\theta d\phi$

(will talk more about this in 168)
Isotropic BRDFs vs anisotropic BRDFs

- isotropic BRDFs: reduces 4D BRDFs to 3D by only considering differences in azimuth angles

\[ f(v_\theta, v_\phi, l_\theta, l_\phi) = f(v_\theta, l_\theta, v_\phi - l_\phi) \]
Isotropic BRDFs vs anisotropic BRDFs

isotropic: circular highlights

anisotropic: “directional” highlights
How to obtain a BRDF?

• we can actually measure it!
How to obtain a BRDF?

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robot arm for BSDF measurement @ UCSD

https://cseweb.ucsd.edu/~ravir/nearfield.pdf
How to obtain a BRDF?

- we can actually measure it!

the robot arm in action @ EPFL

video from Wenzel Jakob

https://rgl.epfl.ch/pages/lab/pgII
The MERL BRDF data [Matusik 2003]

most popular data
100 isotropic BRDFs

warning: not a perfect dataset!
lots of camera artifacts
(defocus/bokeh/lens flare)
EPFL material data [2018]

50 isotropic BRDFs
12 anisotropic BRDFs
(probably much higher quality than MERL)

Q: what are the downsides of measured BRDFs?
Downsides of measured BRDFs

- capturing is time consuming
- very few of them
- does not support texturing

can’t support spatially varying roughness with measured BSDF
Remedy: let’s fit a model to the data!

\[ f(l, v) = \text{some parametric function} \]
The Lambertian BRDF

(we usually exclude the cosine term $\mathbf{n} \cdot \mathbf{l}$ from the BRDF)

$$f(\mathbf{v}, \mathbf{l}) = \frac{K_d}{\pi}$$
The Lambertian BRDF

(we usually exclude the cosine term $\mathbf{n} \cdot \mathbf{l}$ from the BRDF)

\[ f(\mathbf{v}, \mathbf{l}) = \frac{K_d}{\pi} \]

- it is reciprocal

\[ f(\mathbf{v}, \mathbf{l}) = f(\mathbf{l}, \mathbf{v}) \]
The Lambertian BRDF

(we usually exclude the cosine term $\mathbf{n} \cdot \mathbf{l}$ from the BRDF)

$$f(\mathbf{v}, \mathbf{l}) = \frac{K_d}{\pi}$$

- it is reciprocal
- it is energy conserving

$$\int f(\mathbf{v}, \mathbf{l})(\mathbf{l} \cdot \mathbf{n}) \, d\mathbf{l} \leq 1$$

if $K_d \leq 1$
The Phong BRDF

some variants divide the $K_s$ term by $\mathbf{n} \cdot \mathbf{l}$

$$f(\mathbf{v}, \mathbf{l}) = K_d + K_s \left( \max (\mathbf{v} \cdot \mathbf{r}, 0) \right)^\alpha$$

$r$ is mirror reflection direction

$$\mathbf{r} = -\mathbf{l} + 2 (\mathbf{l} \cdot \mathbf{n}) \mathbf{n}$$
The Phong BRDF

\[ f(v, l) = K_d + K_s \left( \max (v \cdot r, 0) \right)^\alpha \]

- it is reciprocal
- it is not energy conserving

\[ r = -l + 2(l \cdot n) n \]
The modified Phong BRDF

some variants divide the $K_s$ term by $\mathbf{n} \cdot \mathbf{l}$

$$f(\mathbf{v}, \mathbf{l}) = \frac{K_d}{\pi} + K_s \frac{\alpha + 2}{2\pi} \left( \max (\mathbf{v} \cdot \mathbf{r}, 0) \right)^\alpha$$

- it is reciprocal
- it is energy conserving

$r$ is mirror reflection direction

$$\mathbf{r} = -\mathbf{l} + 2(\mathbf{l} \cdot \mathbf{n}) \mathbf{n}$$

Using the Modified Phong Reflectance Model for Physically Based Rendering

Eric P. Lafortune
Yves D. Willems
An issue of Phong BRDF (and it’s modified version)

\[ f(v, l) = K_d + K_s \left( \max(v \cdot r, 0) \right)^\alpha \]

\( v \cdot r \) can never go larger than 90 degrees!

\( r \) is mirror reflection direction

this leads to a sharp stop
idea: use the dot product between “half vector” $\mathbf{h}$ and normal $\mathbf{n}$

$$h = \frac{\mathbf{v} + \mathbf{l}}{\| \mathbf{v} + \mathbf{l} \|}$$
Blinn-Phong BRDF

idea: use the dot product between “half vector” $h$ and normal $n$

$$h = \frac{v + l}{\|v + l\|}$$

observation: when $v = r \rightarrow h = n$
Blinn-Phong BRDF

some variants divide the $K_s$ term by $n \cdot l$

$$f(v, l) = K_d + K_s (h \cdot n)^\alpha$$

(energy conserved version exists, but is often too dark)

$$h = \frac{v + l}{\|v + l\|}$$

observation: when $v = r \implies h = n$
Phong vs Blinn-Phong

https://learnopengl.com/Advanced-Lighting/Advanced-Lighting
Phong vs Blinn-Phong

Using R

Using H

http://theinstructionlimit.com/isotropic-specular-reflection-models-comparison
Phong vs Blinn-Phong

Blinn Phong models the long tail behavior of the sunset much better

http://theinstructionlimit.com/isotropic-specular-reflection-models-comparison
Phong vs Blinn-Phong

Blinn–Phong

Phong

Blinn–Phong
(higher exponent)

https://en.wikipedia.org/wiki/Blinn%E2%80%93Phong_reflection_model
Most popular BRDF: microfacet BRDFs

- assumption: surfaces are made of infinitely many little mirrors (microfacets)
- flat microsurfaces correspond to shiny surfaces
- bumpy microsurfaces correspond to rough surfaces

introduced to graphics by Blinn, popularized by Cook-Torrance

A Reflectance Model for Computer Graphics
ROBERT L. COOK
Lucasfilm Ltd.
and
KENNETH E. TORRANCE
Cornell University
Microfacet BRDFs make heavy use of half vectors

given a view direction $\mathbf{v}$ and a light direction $\mathbf{l}$, only microfacets with normal $\mathbf{h} = \frac{\mathbf{v} + \mathbf{l}}{\| \mathbf{v} + \mathbf{l} \|}$ will reflect light

"micro normal"

"macro normal"

figure inspired by Eric Heitz https://jcgt.org/published/0003/02/03/
Microfacet BRDFs fit well to MERL measured data!

measured (nickel material)  microfacet  Phong-like BRDF

from Ngan et al. “Experimental Analysis of BRDF Models”
http://people.csail.mit.edu/addy/research/ngan05_brdf_eval.pdf
Another factor: viewing angle can determine specularity!

more specular

less specular
Fresnel equation predicts the ratio of reflection/refraction

- it’s an electromagnetic phenomenon

\[
F = R_s^2 + R_p^2
\]

\[
R_s = \frac{\tan(\theta - \theta')}{\tan(\theta + \theta')}
\]

\[
R_p = -\frac{\sin(\theta - \theta')}{\sin(\theta + \theta')}
\]

from energy conservation & light wave oscillation direction

Graphics people use Schlick’s approximation

\[ F \approx \text{color} + (1 - \text{color})(1 - \cos \theta)^5 \]
Graphics people use Schlick’s approximation

\[ F \approx \text{color} + (1 - \text{color})(1 - \cos \theta)^5 \]

metal becomes colorless/white at grazing angle
We can use $F$ to weigh between diffuse and specular BRDFs

from CSE 168 HW3
Combining multiple BRDFs

\[ f(v, l) = \sum_i w_i f_i(v, l) \]
BRDF modeling is active research!

- we don’t really know how to model these materials

strongly anisotropic but “hazy”

iridescence?

???
(butterfly wings)

awesome material images from Jonathan Dupuy & Wenzel Jakob

https://rgl.epfl.ch/pages/lab/pgII
Next: color