Lecture 10:
Real-Time Physically-Based Materials
(surface models)
Announcements

• Correction: 2/3 contents covered after today’s lecture!

• GAMES202 homework late submission is open now!

• GAMES101 graders
  - Now we have a few applications for graders!
  - Will soon reach out to get started!

• GAMES101 now has 599K views on Bilibili!
Last Lecture

• Real-Time Global Illumination (screen space cont.)
  - Screen Space Directional Occlusion (SSDO)
  - Screen Space Reflection (SSR)

• Real-Time Physically-Based Materials
Today

• Real-Time Physically-Based Materials
  - Microfacet BRDF
  - Disney principled BRDF

• Shading with microfacet BRDFs under polygonal lighting
  - Linearly Transformed Cosines (LTC)
PBR and PBR Materials

- Physically-Based Rendering (PBR)
  - Everything in rendering should be physically based
  - Materials, lighting, camera, light transport, etc.
  - Not just materials, but usually referred to as materials :)

- PBR materials in RTR
  - The RTR community is much behind the offline community
  - “PB” in RTR is usually not actually physically based :)

Lingqi Yan, UC Santa Barbara
PBR Materials in RTR

- **PBR materials in RTR**
  - For surfaces, mostly just microfacet models (used wrong so not PBR) and Disney principled BRDFs (artist friendly but still not PBR)
PBR Materials in RTR

- **PBR materials in RTR**
  - **For surfaces**, mostly just microfacet models and Disney principled BRDFs
  - **For volumes**, mostly focused on fast and approximate single scattering and multiple scattering (for cloud, hair, skin, etc.)

[Lara Croft from the Tomb Raidar series]
PBR Materials in RTR

• PBR materials in RTR
  - **For surfaces**, mostly just microfacet models (used wrong so not PBR) and Disney principled BRDFs (artist friendly but still not PBR)
  - **For volumes**, mostly focused on fast and approximate single scattering and multiple scattering (for cloud, hair, skin, etc.)
    - Usually not much new theory, but a lot of implementation hacks*
    - Still, performance (speed) is the key factor to consider
Recap: Microfacet BRDF
Microfacet BRDF

- What kind of microfacets reflect \( \mathbf{w}_i \) to \( \mathbf{w}_o \)?
  (hint: microfacets are mirrors)

\[
f(i, o) = F(i, h) \cdot G(i, o, h) \cdot D(h) \cdot 4(n, i)(n, o)
\]
The Fresnel Term

Reflectance depends on incident angle (and polarization of light)

This example: reflectance increases with grazing angle

[Lafortune et al. 1997]
Fresnel Term (Dielectric, $\eta = 1.5$)
Fresnel Term (Conductor)
Fresnel Term — Formulae

Accurate: need to consider polarization

\[
R_s = \left| \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} \right|^2 = \left| \frac{n_1 \cos \theta_i - n_2 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta_i \right)^2}}{n_1 \cos \theta_i + n_2 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta_i \right)^2}} \right|^2,
\]

\[
R_p = \left| \frac{n_1 \cos \theta_t - n_2 \cos \theta_i}{n_1 \cos \theta_t + n_2 \cos \theta_i} \right|^2 = \left| \frac{n_1 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta_i \right)^2} - n_2 \cos \theta_i}{n_1 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta_i \right)^2} + n_2 \cos \theta_i} \right|^2.
\]

Approximate: Schlick’s approximation

\[
R(\theta) = R_0 + (1 - R_0)(1 - \cos \theta)^5
\]

\[
R_0 = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2
\]

\[
R_{\text{eff}} = \frac{1}{2} \left( R_s + R_p \right).
\]
Normal Distribution Function (NDF)

• Key: the distribution of microfacets’ normals
  • Concentrated $\leftrightarrow$ glossy
  • Spread $\leftrightarrow$ diffuse
Normal Distribution Function (NDF)

- The Normal Distribution Function (NDF)
  - Note: has nothing to do with the normal distribution in stats
  - Various models to describe it
    - Beckmann, GGX, etc.
  - Detailed models [Yan 2014, 2016, 2018, …]
Normal Distribution Function (NDF)

- Beckmann NDF
  - Similar to a Gaussian
  - But defined on the slope space

\[
D(h) = \frac{e^{-\frac{\tan^2 \theta_h}{\alpha^2}}}{\pi \alpha^2 \cos^4 \theta_h}
\]

\(\alpha\): roughness of the surface (the smaller, the more like mirror/specular)
\(\theta_h\): angle between half vector \(h\) and normal \(n\)
Normal Distribution Function (NDF)

- GGX (or Trowbridge-Reitz) [Walter et al. 2007]
  - Typical characteristic: long tail!
Normal Distribution Function (NDF)

• Comparison: Beckmann vs. GGX

https://planetside.co.uk/news/terragen-4-5-release/
Normal Distribution Function (NDF)

- Extending GGX [by Brent Burley from WDAS]
  - GTR (Generalized Trowbridge-Reitz)
  - Even longer tails
Shadowing-Masking Term

- Or, the geometry term $G$
  - Account for self-occlusion of microfacets
  - Shadowing — light, masking — eye
  - Provide darkening esp. around grazing angles

\[ f(i, o) = \frac{F(i, h)G(i, o, h)D(h)}{4(n, i)(n, o)} \]
Shadowing-Masking Term

- Why is it important?
  - Suppose no G term, what will happen when the incident / outgoing is from grazing angle?

\[ f(i, o) = \frac{F(i, h)G(i, o, h)D(h)}{4(n, i)(n, o)} \]

Can be arbitrarily bright around grazing angles!
Shadowing-Masking Term

• A commonly used shadowing-masking term
  - The Smith shadowing-masking term
  - Decoupling shadowing and masking

\[ G(i, o, m) \approx G_1(i, m)G_1(o, m) \]
Multiple Bounces

• Missing energy!
  - Especially prominent when roughness is high (why?)

Multiple Bounces

- Missing energy!

- Adding back the missing energy?
  - Accurate methods exist [Heitz et al. 2016]
  - But can be too slow for RTR

- Basic idea
  - Being occluded == next bounce happening
The Kulla-Conty Approximation

• What’s the overall energy of an outgoing 2D BRDF lobe?

\[ E(\mu_o) = \int_0^{2\pi} \int_0^1 f(\mu_o, \mu_i, \phi)\mu_i d\mu_i d\phi \]

Note: \( \mu = \sin \theta \)

• Key idea

- We can design an additional lobe that integrates to \( 1 - E(\mu_o) \)
- The outgoing BRDF lobe can be different for different incident dir.
- Consider reciprocity, it should be* of the form

\[ c(1 - E(\mu_i))(1 - E(\mu_o)) \]
The Kulla-Conty Approximation

- Therefore,

\[ f_{ms}(\mu_0, \mu_i) = \frac{(1 - E(\mu_0))(1 - E(\mu_i))}{\pi (1 - E_{avg})} \]

\[ E_{avg} = 2 \int_{0}^{1} E(\mu) \mu \, d\mu \]

- FYI, validation:

\[ E_{ms}(\mu_o) = \int_{0}^{2\pi} \int_{0}^{1} f_{ms}(\mu_0, \mu_i, \phi) \mu_i \, d\mu_i \, d\phi \]

\[ = 2\pi \int_{0}^{1} \frac{(1 - E(\mu_0))(1 - E(\mu_i))}{\pi (1 - E_{avg})} \mu_i \, d\mu_i \]

\[ = 2 \frac{1 - E(\mu_o)}{1 - E_{avg}} \int_{0}^{1} (1 - E(\mu_i)) \, \mu_i \, d\mu_i \]

\[ = \frac{1 - E(\mu_o)}{1 - E_{avg}} (1 - E_{avg}) \]

\[ = 1 - E(\mu_o) \]

The Kulla-Conty Approximation

But \( E_{avg}(\mu_o) = 2 \int_0^1 E(\mu_i)\mu_i \, d\mu_i \) is still unknown (as analytic)

- But we already know what to do!
  - Hint: in split sum, how do we deal with a difficult integral?
  - Precompute / tabulate!
  - What’s the dimension of \( E_{avg} \)?
    - How many parameters are in \( E_{avg} \)?
  - Just \( \mu_o \) and roughness
The Kulla-Conty Approximation

• Results

The Kulla-Conty Approximation

• What if the BRDF has color?
  - Color == absorption == energy loss (as it should)
  - So we’ll just need to compute the overall energy loss

• Define the average Frensel (how much energy is reflected)

\[
F_{avg} = \frac{\int_0^1 F(\mu) \mu \, d\mu}{\int_0^1 \mu \, d\mu} = 2 \int_0^1 F(\mu) \mu \, d\mu
\]

• And recall that \( E_{avg} \) is how much energy that you can see
  (i.e., will \textbf{NOT} participate in further bounces)
The Kulla-Conty Approximation

• Therefore, the proportion of energy (color) that
  - You can directly see: $F_{avg}E_{avg}$
  - After one bounce then be seen: $F_{avg}(1 - E_{avg}) \cdot F_{avg}E_{avg}$
  - ...
  - After $k$ bounces then be seen: $F_{avg}^k(1 - E_{avg})^k \cdot F_{avg}E_{avg}$

• Adding everything up, we have the color term
  - Which will be directly multiplied on the uncolored additional BRDF

\[
\frac{F_{avg}E_{avg}}{1 - F_{avg}(1 - E_{avg})}
\]
The Kulla-Conty Approximation

• Results

However, An Undesirable Hack

• Combining a Microfacet BRDF with a **diffuse** lobe
  - Pervasively used in computer vision for material recognition
  - COMPLETELY WRONG
  - COULDN’T BE WORSE
  - I NEVER TAUGHT YOU SO

• Issues
  - Physically incorrect
  - Not energy preserving
    (fixed in Kulla-Conty)
    (can also be fixed in other ways)
Questions?
Next Lecture

• More Real-Time Physically-Based Materials!

Thank you!