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 :)

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PBR Materials in RTR

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  - 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

- **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 Raider 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 $w_i$ to $w_o$? (hint: microfacets are mirrors)

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

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

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

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 $\iff$ glossy
  - Spread $\iff$ 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,

\[
f_{ms}(\mu_0, \mu_i) = \frac{(1 - E(\mu_0))(1 - E(\mu_i))}{\pi(1 - E_{avg})}, \quad E_{avg} = 2 \int_0^1 E(\mu) \mu \ d\mu
\]

• FYI, validation:

\[
E_{ms}(\mu_0) = \int_0^{2\pi} \int_0^1 f_{ms}(\mu_0, \mu_i, \phi) \mu_i \ d\mu_i \ d\phi
\]
\[
= 2\pi \int_0^1 \frac{(1 - E(\mu_0))(1 - E(\mu_i))}{\pi(1 - E_{avg})} \mu_i \ d\mu_i
\]
\[
= 2 \frac{1 - E(\mu_0)}{1 - E_{avg}} \int_0^1 (1 - E(\mu_i)) \mu_i \ d\mu_i
\]
\[
= \frac{1 - E(\mu_0)}{1 - E_{avg}} (1 - E_{avg})
\]
\[
= 1 - E(\mu_0)
\]

The Kulla-Conty Approximation

- But neither $E(\mu)$ nor $E_{\text{avg}} = 2\int_{0}^{1} E(\mu)\mu \, d\mu$ are analytic

- But we already know what to do!
  - Hint: in split sum, how do we deal with a difficult integral?
  - Precompute / tabulate!

- Dimension / parameters of $E(\mu)$ and $E_{\text{avg}}$?
  - $E(\mu)$: roughness & $\mu$ [therefore, a 2D table]
  - $E_{\text{avg}}$: just roughness [therefore, a 1D table]

\[ E(\mu) \]
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 Fresnel (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 NOT participate in further bounces)
The Kulla-Conty Approximation

• Therefore, the proportion of energy (color) that

  - You can directly see: \( F_{\text{avg}}E_{\text{avg}} \)

  - After one bounce then be seen: \( F_{\text{avg}}(1 - E_{\text{avg}}) \cdot F_{\text{avg}}E_{\text{avg}} \)

  - ...

  - After \( k \) bounces then be seen: \( F_{\text{avg}}^k(1 - E_{\text{avg}})^k \cdot F_{\text{avg}}E_{\text{avg}} \)

• Adding everything up, we have the color term

  - Which will be directly multiplied on the uncolored additional BRDF
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?
Disney’s Principled BRDF
Why is it needed?

• Motivation
  - No physically-based materials are good at rep. all real materials
    - e.g. lacking diffuse term in most microfacet models
  - Physically-based materials are not artist friendly
    - e.g. “the complex index of refraction n-ik”

• High level design goal
  - Art directable, not necessarily physically correct
  - But again, referred to as PBR in real-time rendering…
What is “principled”?

• The BRDF is designed with a few important principles
  - Intuitive rather than physical parameters should be used.
  - There should be as few parameters as possible.
  - Parameters should be zero to one over their plausible range.
  - Parameters should be allowed to be pushed beyond their plausible range where it makes sense.
  - All combinations of parameters should be as robust and plausible as possible.
How does it work?

- A table showing the effects of **individual** parameters
Pros and Cons

• Easy-to-understand / control

• A wide range of materials in a single model

• Open source implementation is available

• Not physically based
  – But is it a big problem?
  – Academia vs. industry

• Huge parameter space
Questions?
Shading Microfacet Models using Linearly Transformed Cosines (LTC)
Linearly Transformed Cosines

• Solves the shading of microfacet models
  - Mainly on GGX, though others are also fine
  - No shadows
  - Under polygon shaped light
Linearly Transformed Cosines

• Key idea
  - Given the viewing direction, any outgoing 2D BRDF lobe can be transformed to a cosine
  - The shape of the light can also be transformed along
  - Integrating the transformed light on a cosine lobe can be analytical
Next Lecture

• More Real-Time Physically-Based Materials!

Thank you!