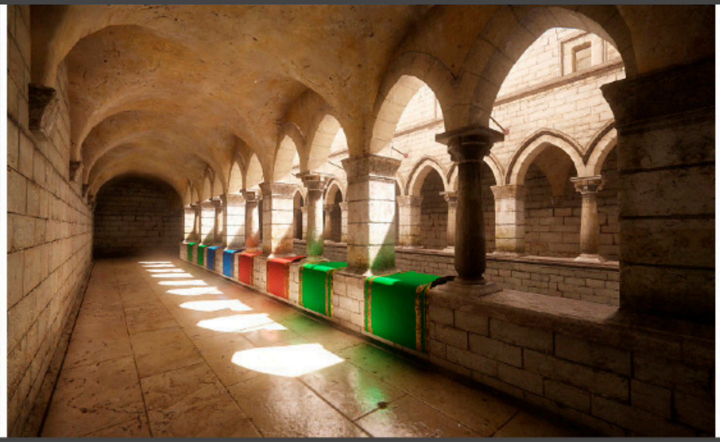
Real-Time High Quality Rendering

GAMES202, Lingqi Yan, UC Santa Barbara

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

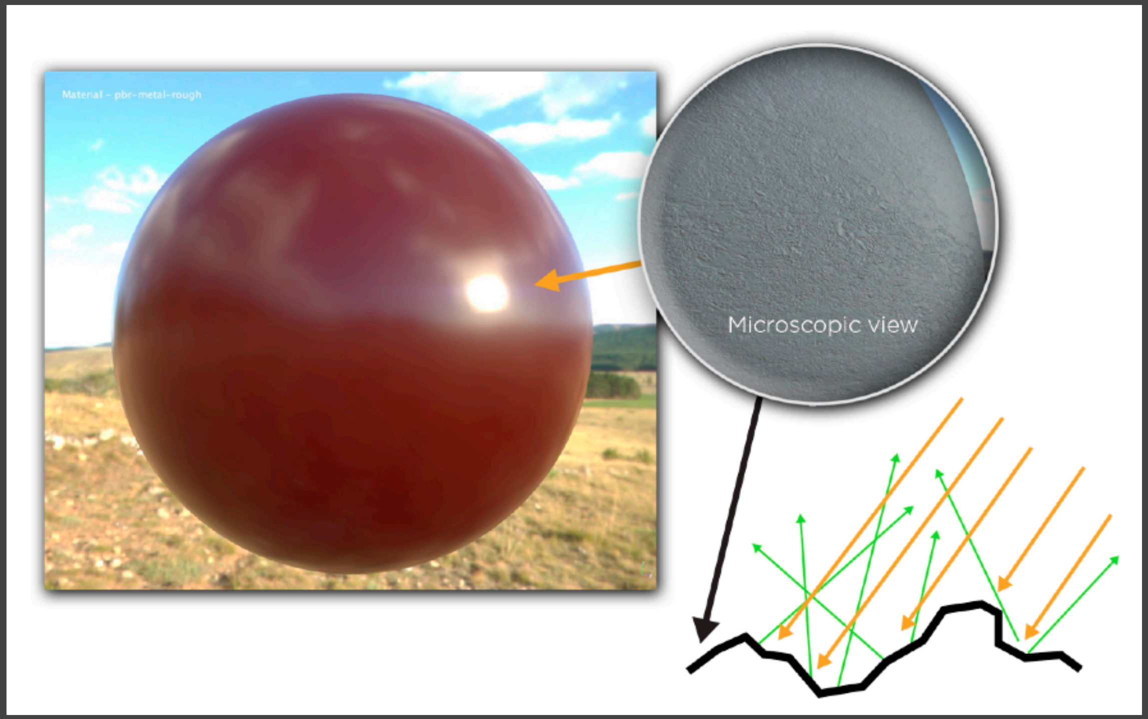
- Real-Time Physically-Based Materials
  - Microfacet BRDF
  - Disney principled BRDF
- Shading with microfacet BRDFs under polygonal lighting
  - Linearly Transformed Cosines (LTC)

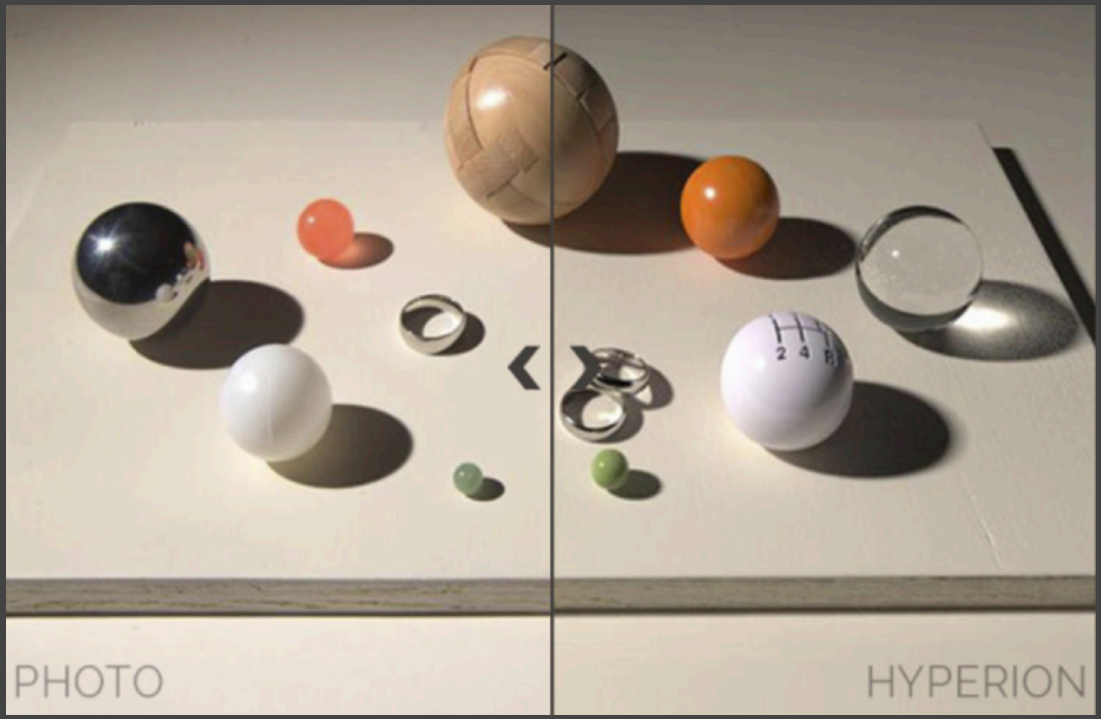
PBR and PBR Materials

- 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 :)

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]

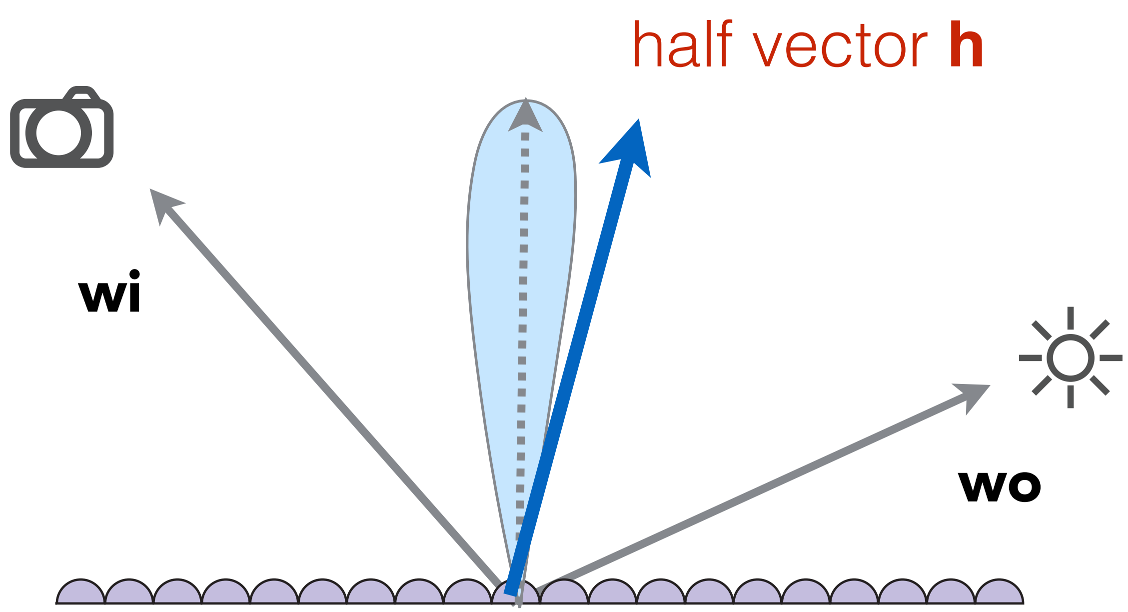
PBR Materials in RTR

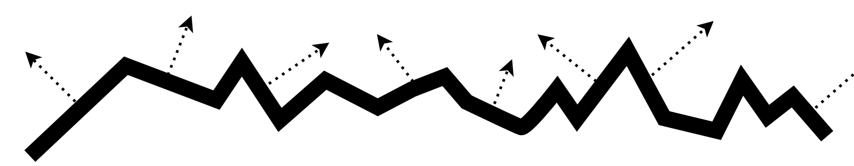
- PBR materials in RTR
  - **For surfaces**, mostly just
    microfacet models (used wrong so not PBR) and
    Disney principled BRDFs (artist friendly but still not PBR)
  - **For volumes**, mostly focused on fast and approximate
    single scattering and multiple scattering
    (for cloud, hair, skin, 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 wi to wo?
(hint: microfacets are mirrors)





Fresnel term

shadowing-masking term

distribution of normals

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

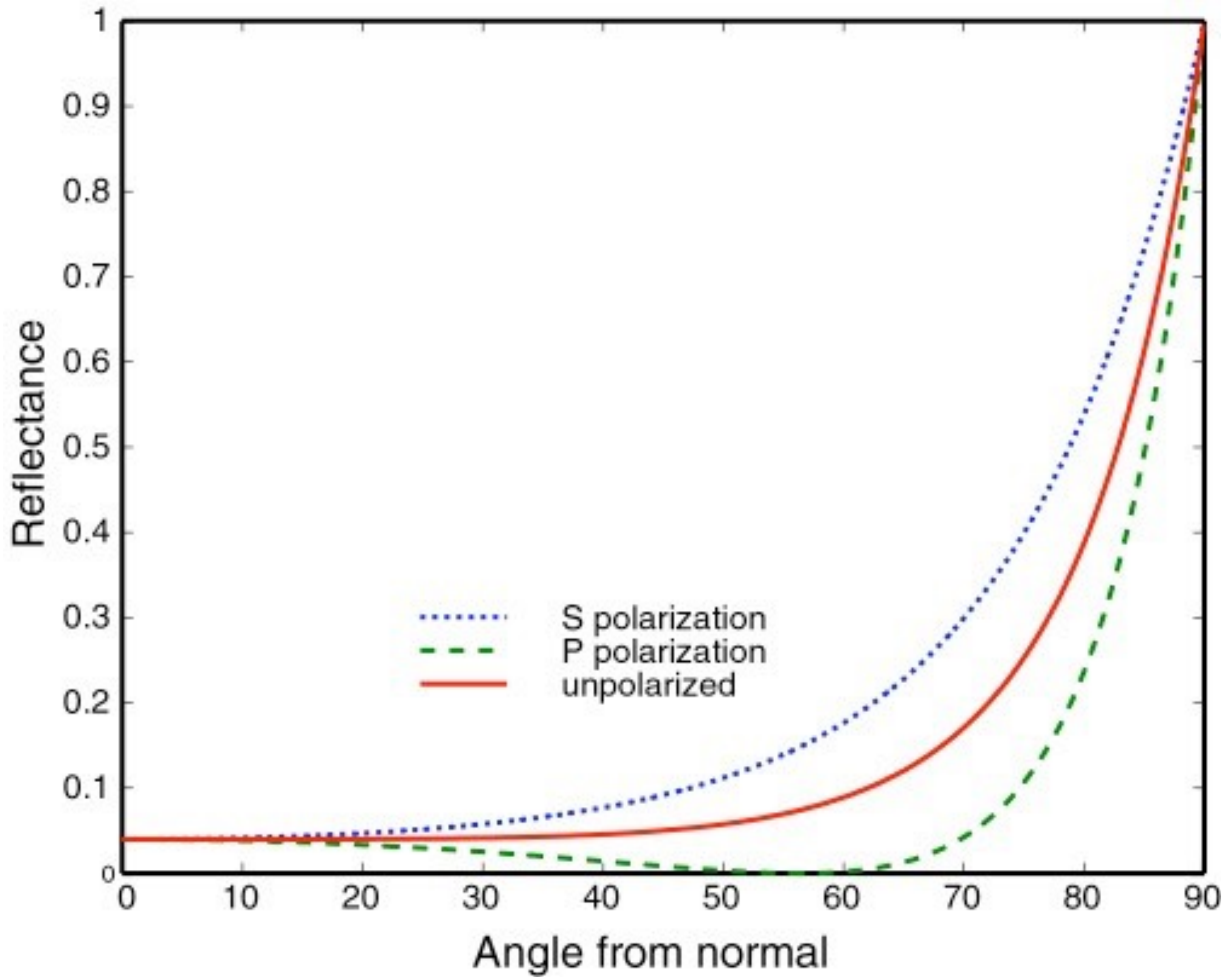
The Fresnel Term

Reflectance depends on incident angle (and polarization of light)

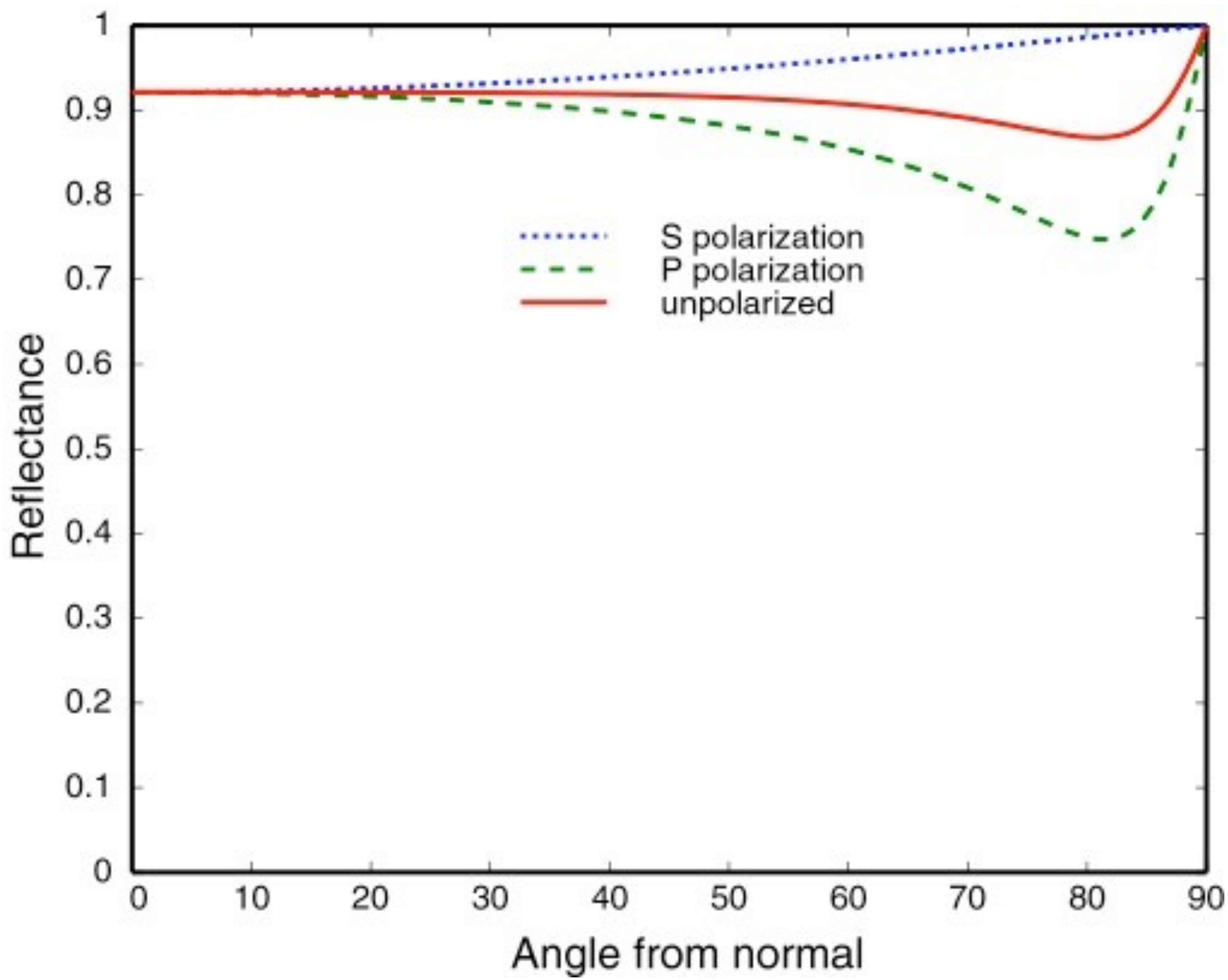
This example: reflectance increases with grazing angle

[Lafortune et al. 1997]

Fresnel Term (Dielectric, $\eta=1.5$)



Fresnel Term (Conductor)



Fresnel Term — Formulae

Accurate: need to consider polarization

$$R_{\mathrm{s}} = \left|\frac{n_1\cos\theta_{\mathrm{i}} - n_2\cos\theta_{\mathrm{t}}}{n_1\cos\theta_{\mathrm{i}} + n_2\cos\theta_{\mathrm{t}}}\right|^2 = \left|\frac{n_1\cos\theta_{\mathrm{i}} - n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2}}{n_1\cos\theta_{\mathrm{i}} + n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2}}\right|^2,$$

$$R_{\mathrm{p}} = \left|\frac{n_1\cos\theta_{\mathrm{t}} - n_2\cos\theta_{\mathrm{i}}}{n_1\cos\theta_{\mathrm{t}} + n_2\cos\theta_{\mathrm{i}}}\right|^2 = \left|\frac{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2} - n_2\cos\theta_{\mathrm{i}}}{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2} + n_2\cos\theta_{\mathrm{i}}}\right|^2.$$

$$R_{\mathrm{eff}} = \frac{1}{2}\left(R_{\mathrm{s}} + R_{\mathrm{p}}\right).$$

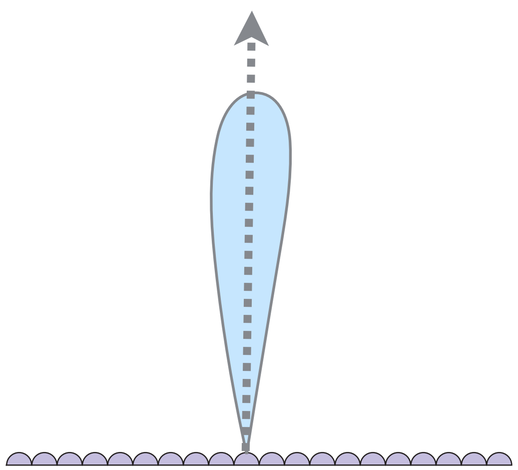
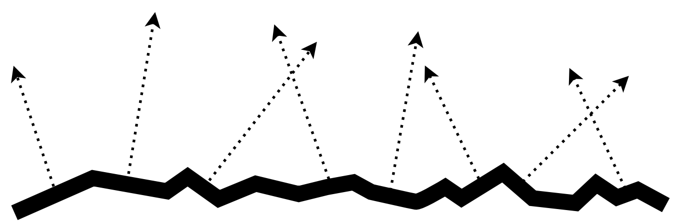
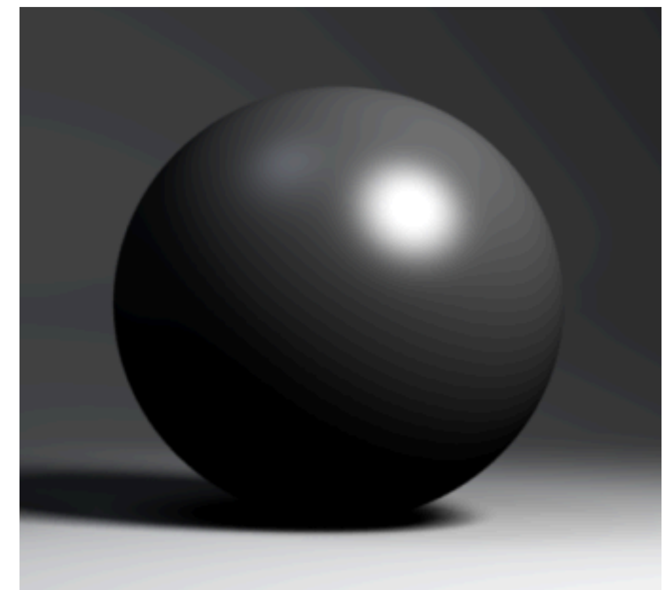
Approximate: Schlick’s approximation

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

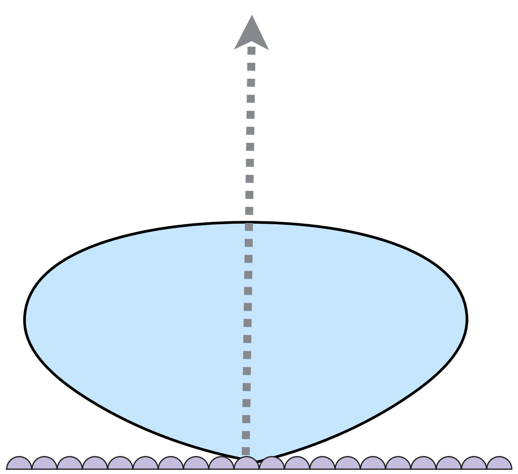
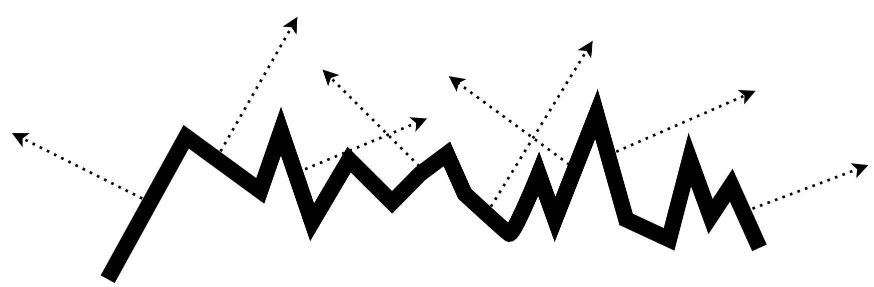
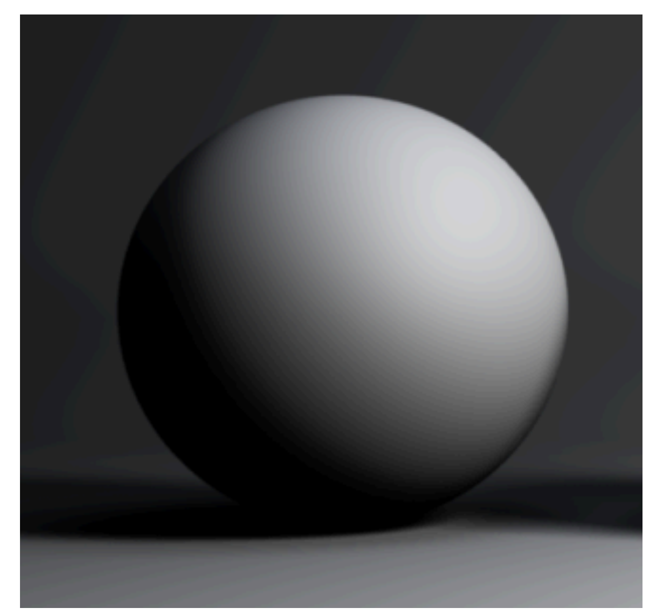
$$R_0 = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

Normal Distribution Function (NDF)

- Key: the distribution of microfacets' normals
  - Concentrated <==> glossy

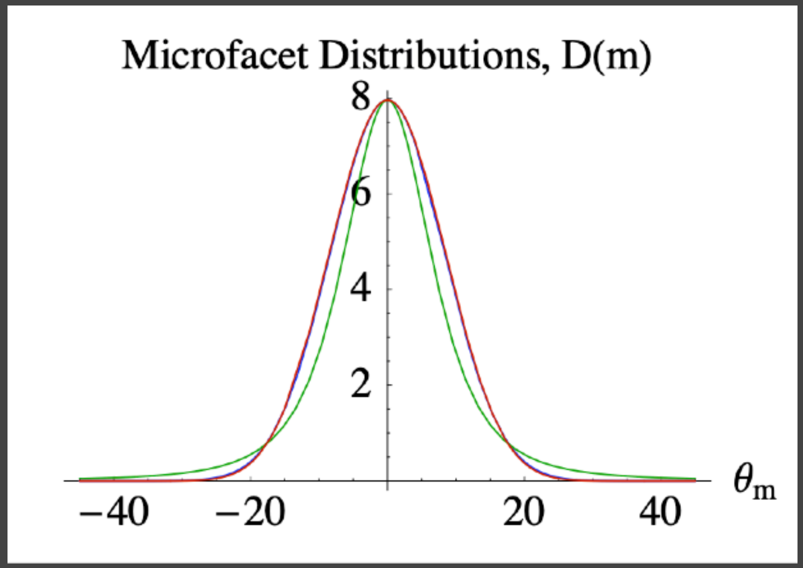




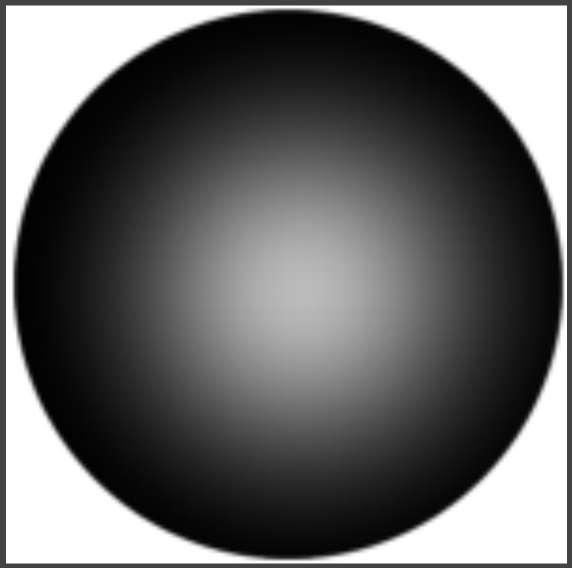
  - Spread <==> diffuse

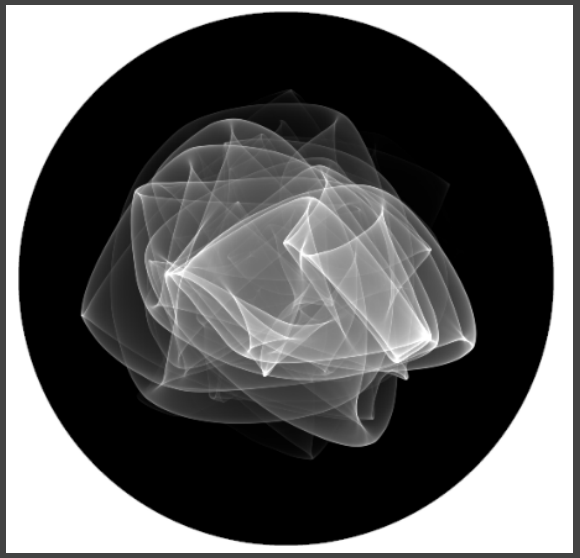




Normal Distribution Function (NDF)

- 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, …]



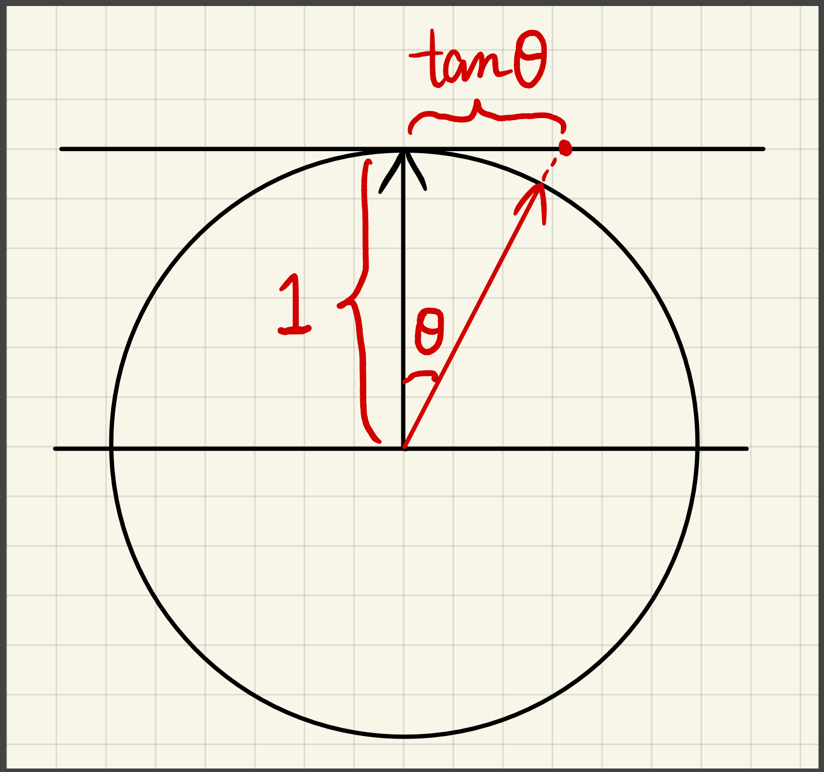




Normal Distribution Function (NDF)

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

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

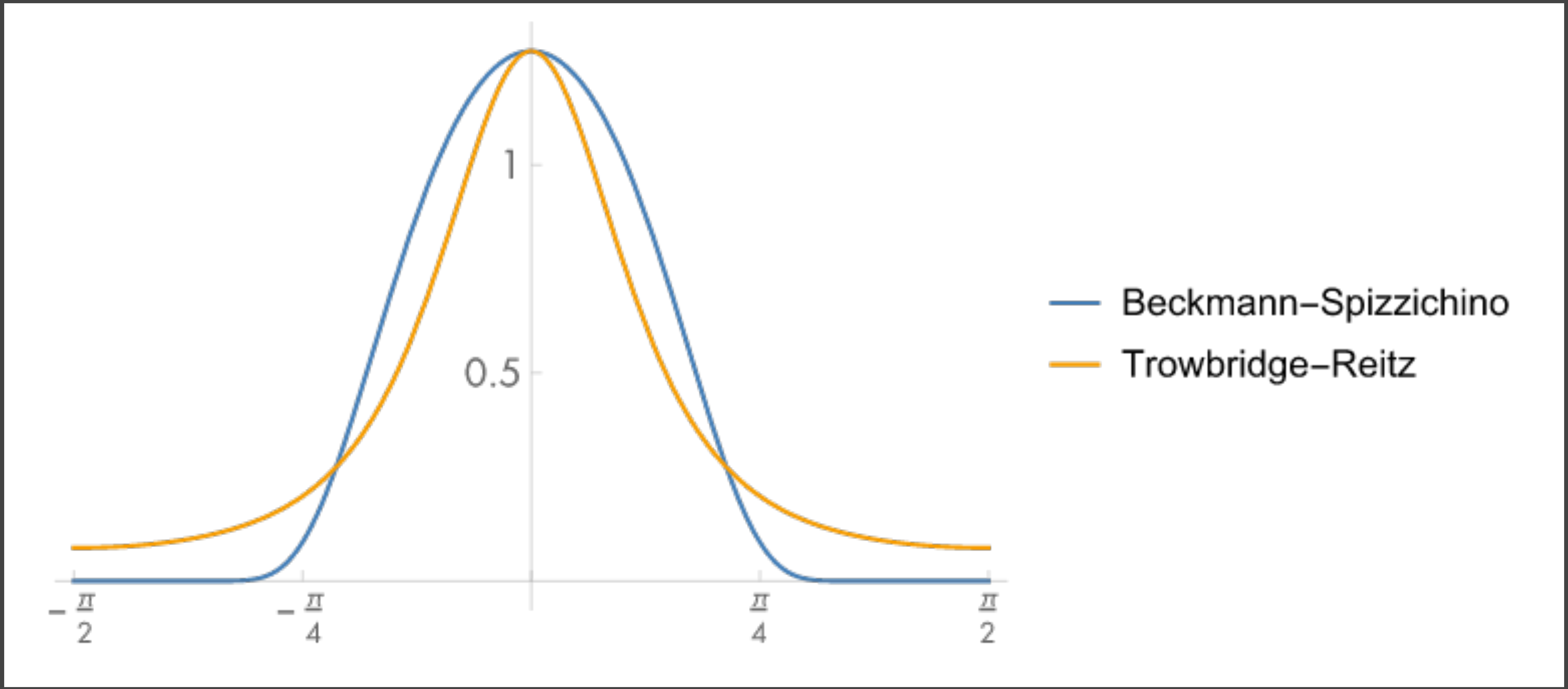


α: roughness of the surface (the smaller, the more like mirror/specular)

θ_h: angle between half vector h and normal n

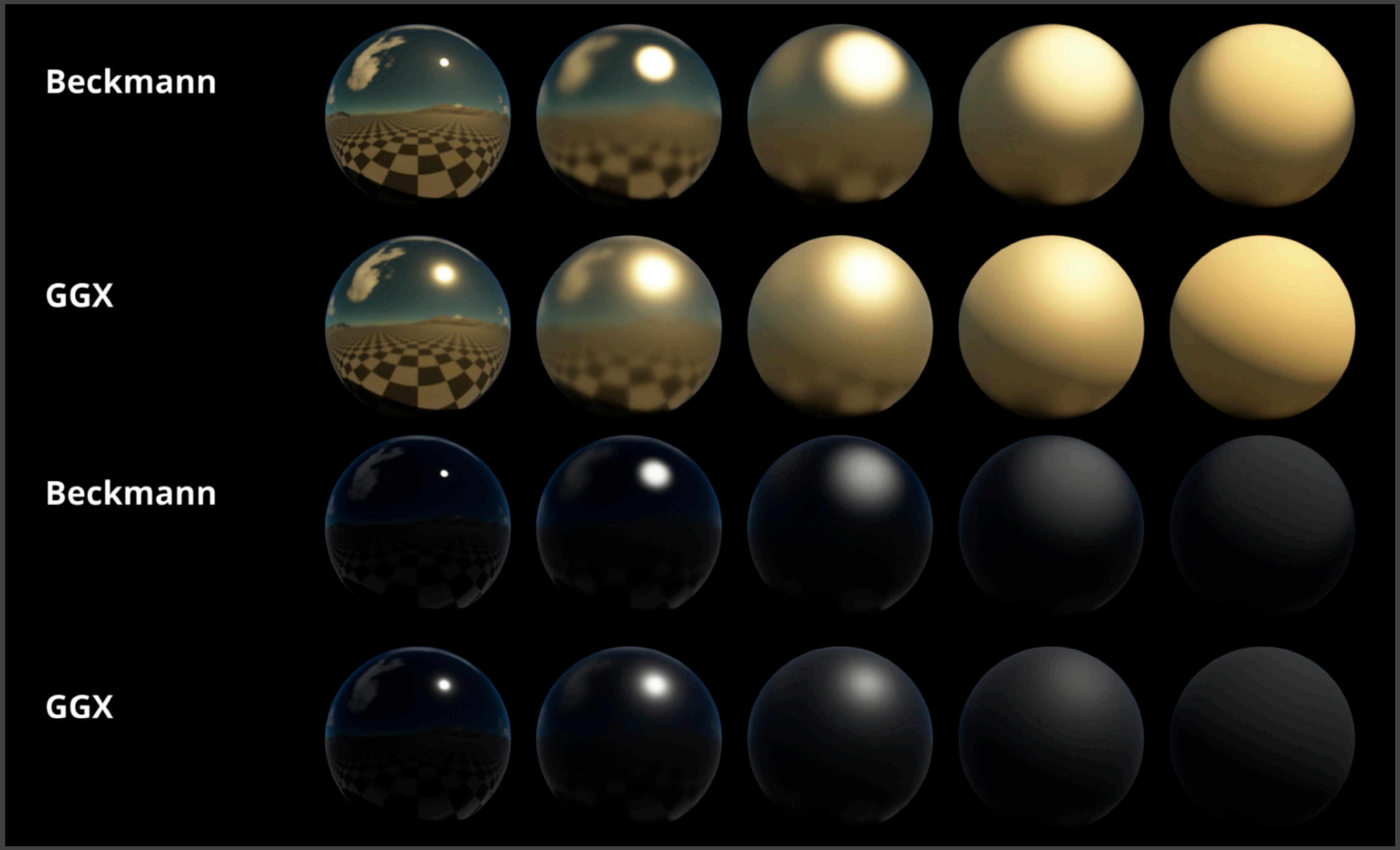
Normal Distribution Function (NDF)

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



Normal Distribution Function (NDF)

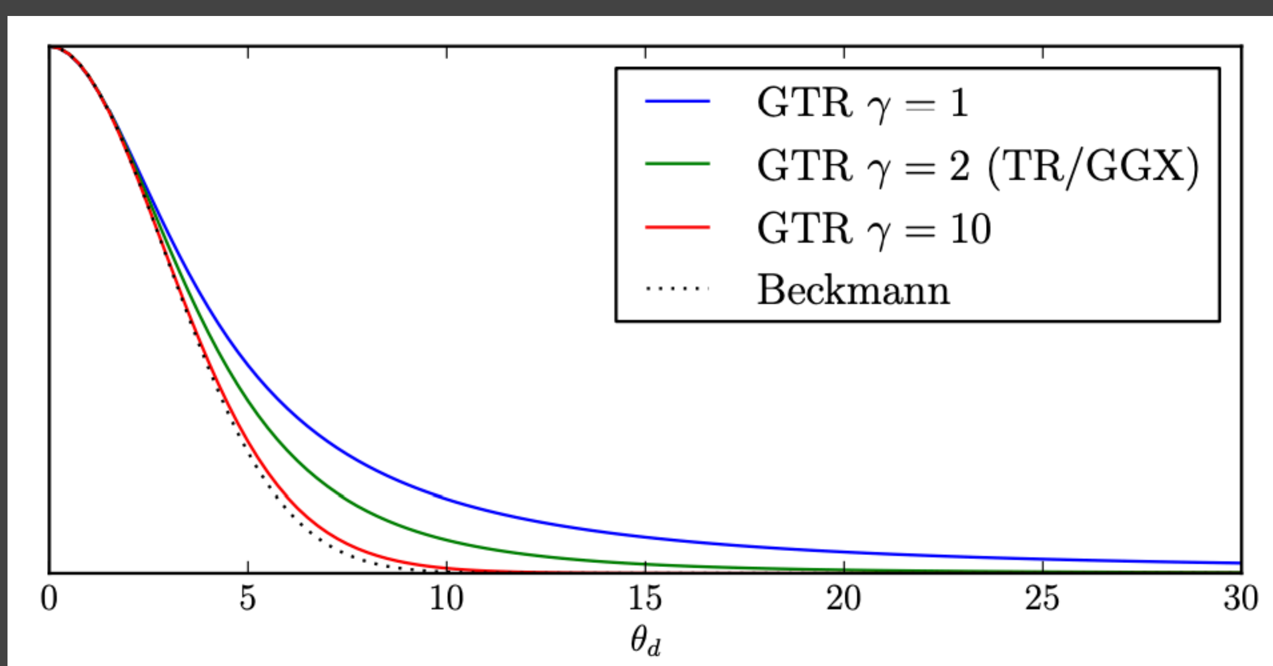
- Comparison: Beckmann vs. GGX



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

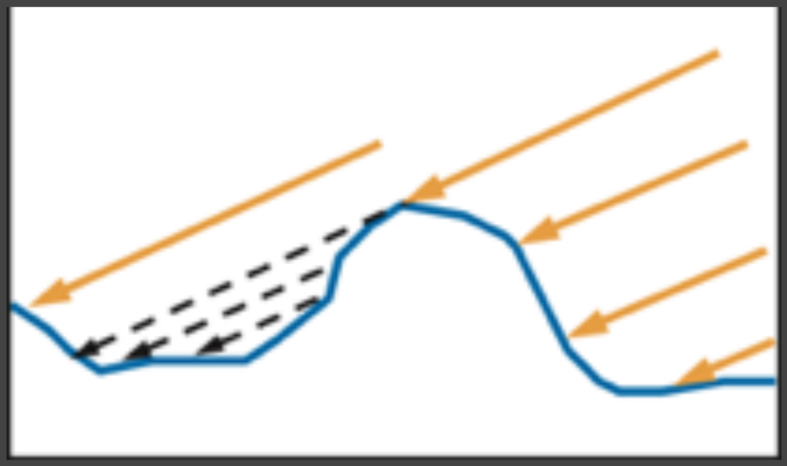


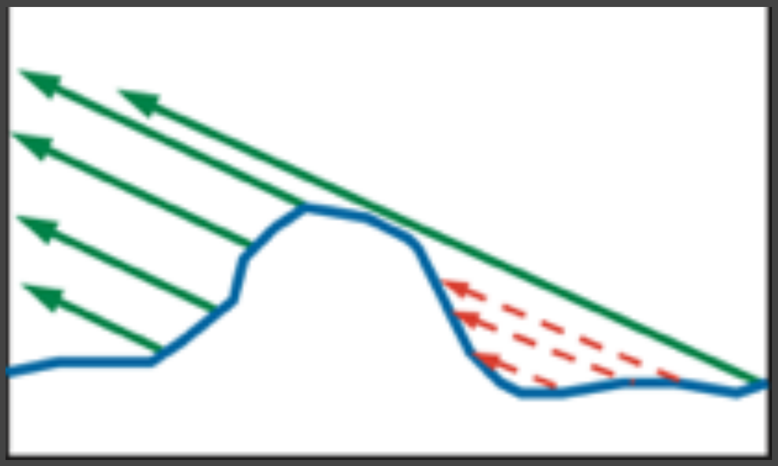
Shadowing-Masking Term

- Or, the geometry term G

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

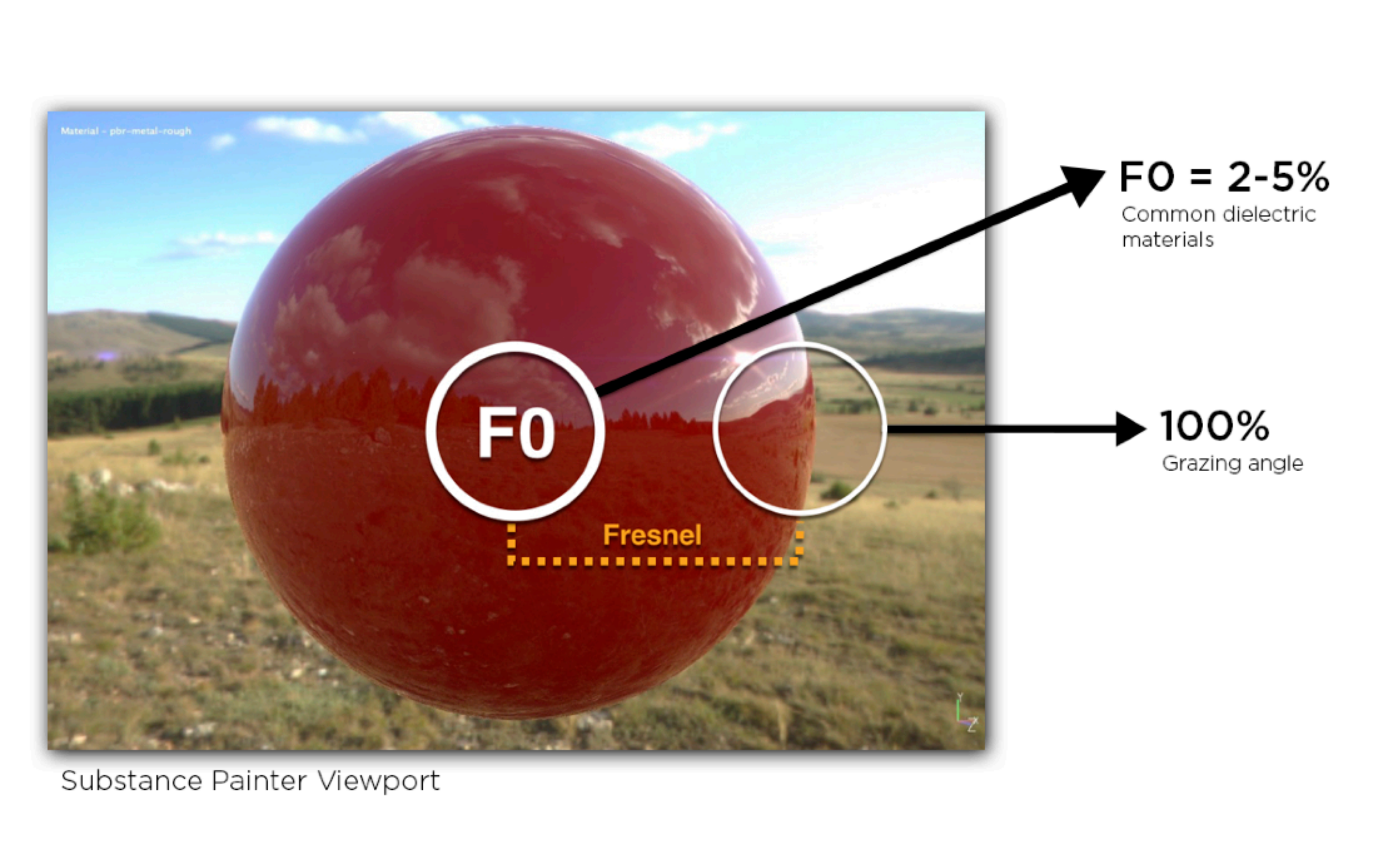
  - Account for self-occlusion of microfacets
  - Shadowing — light, masking — eye
  - Provide darkening esp. around grazing angles





Shadowing-Masking Term

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



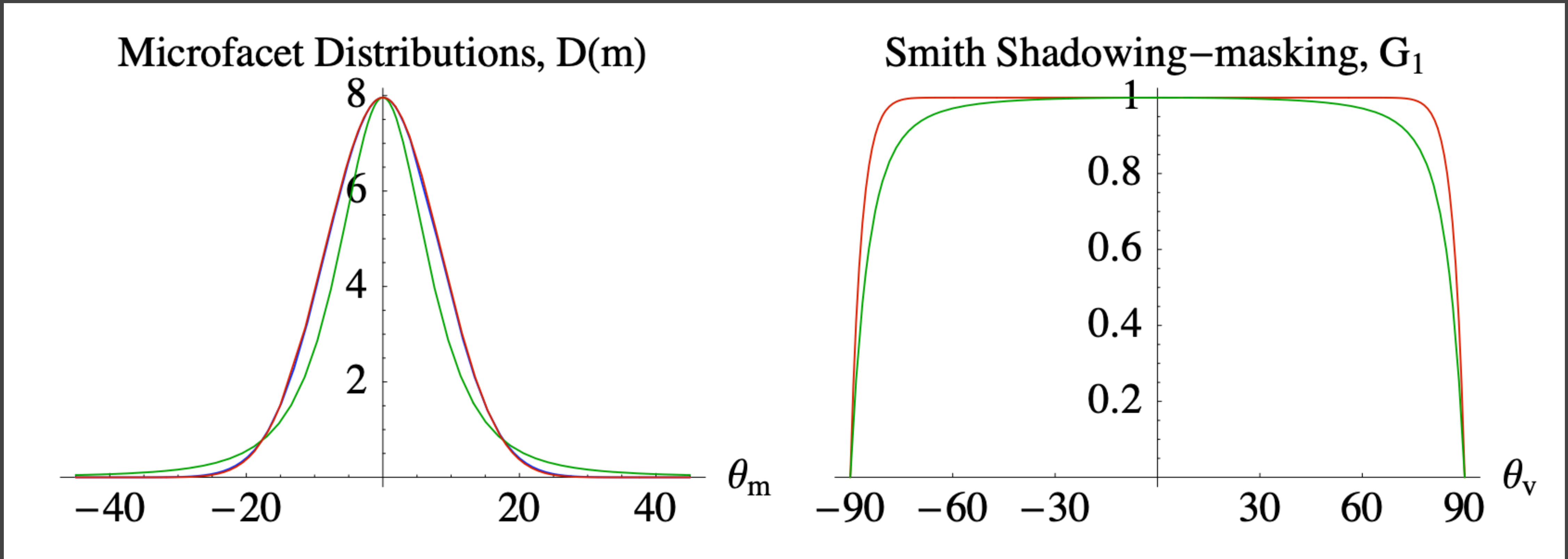
$$f(i,o) = \frac{F(i,h)G(i,o,h)D(h)}{4(n,i)(n,o)}$$

Can be arbitrarily bright
around grazing angles!

Shadowing-Masking Term

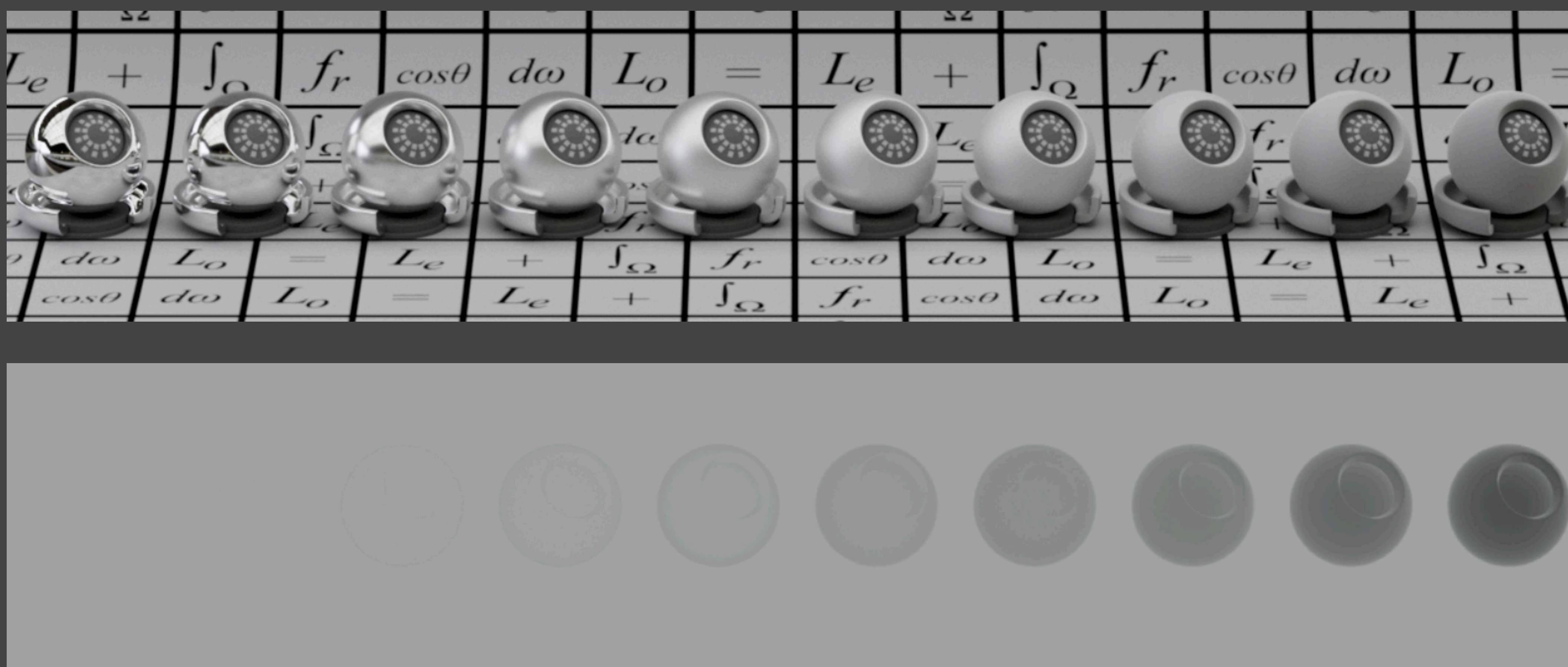
- A commonly used shadowing-masking term
  - The Smith shadowing-masking term
  - Decoupling shadowing and masking

$$G(\mathbf{i},\mathbf{o},\mathbf{m}) \approx G_1(\mathbf{i},\mathbf{m})G_1(\mathbf{o},\mathbf{m})$$



Multiple Bounces

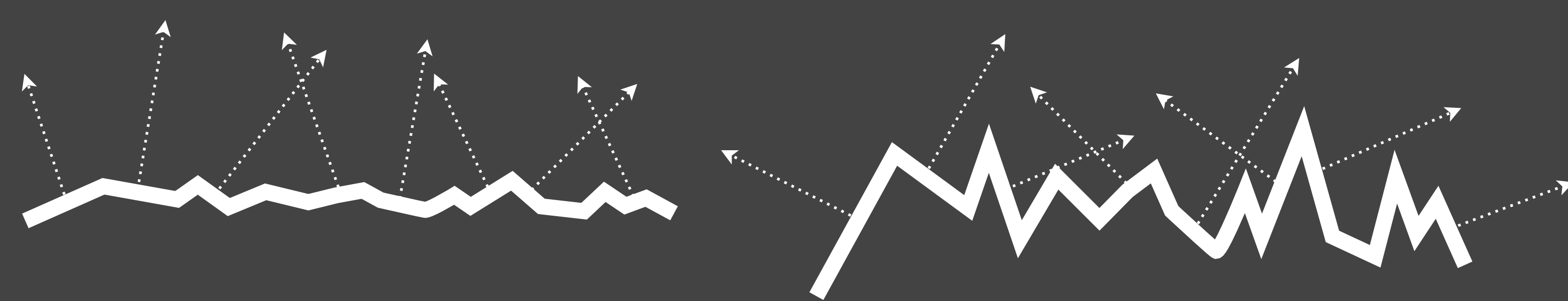
- Missing energy!
  - Especially prominent when roughness is high (why?)



https://fpsunflower.github.io/ckulla/data/s2017_pbs_imageworks_slides_v2.pdf

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,

$$f_{\mathrm{ms}}(\mu_o, \mu_i) = \frac{(1 - E(\mu_o))(1 - E(\mu_i))}{\pi(1 - E_{\mathrm{avg}})}, \quad E_{\mathrm{avg}} = 2\int_0^1 E(\mu)\,\mu\, d\mu$$

- FYI, validation:

$$\begin{aligned}
E_{\mathrm{ms}}(\mu_o) &= \int_0^{2\pi}\int_0^1 f_{\mathrm{ms}}(\mu_o, \mu_i, \phi)\mu_i d\mu_i d\phi \\
&= 2\pi \int_0^1 \frac{(1 - E(\mu_o))(1 - E(\mu_i))}{\pi(1 - E_{\mathrm{avg}})}\mu_i d\mu_i \\
&= 2\frac{1 - E(\mu_o)}{1 - E_{\mathrm{avg}}}\int_0^1 (1 - E(\mu_i))\ \mu_i\, d\mu_i \\
&= \frac{1 - E(\mu_o)}{1 - E_{\mathrm{avg}}}(1 - E_{\mathrm{avg}}) \\
&= 1 - E(\mu_o)
\end{aligned}$$

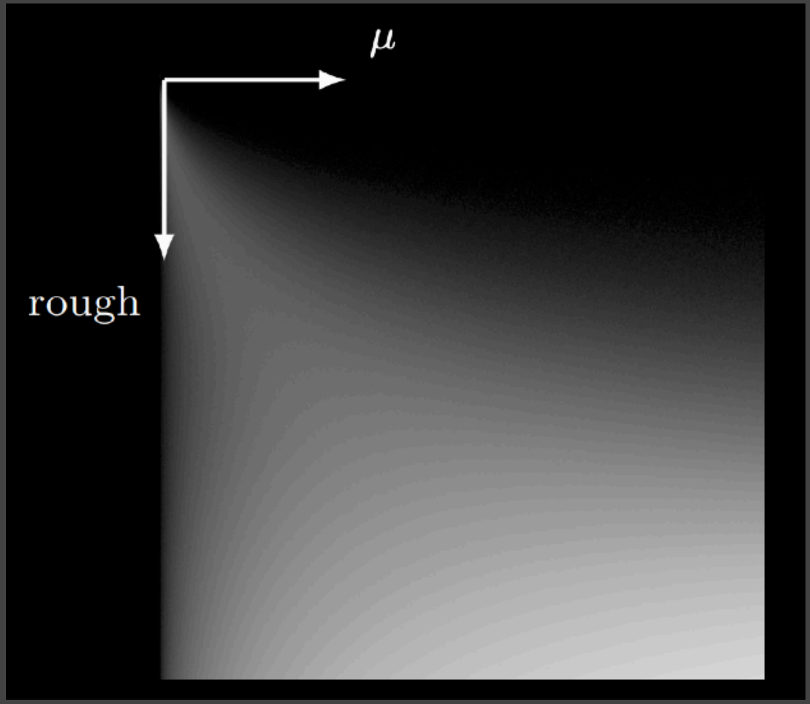
https://fpsunflower.github.io/ckulla/data/s2017_pbs_imageworks_slides_v2.pdf

The Kulla-Conty Approximation

- But neither $E(\mu)$ nor $E_{avg} = 2\int_0^1 E(\mu)\mu \, \mathrm{d}\mu$ are analytic

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

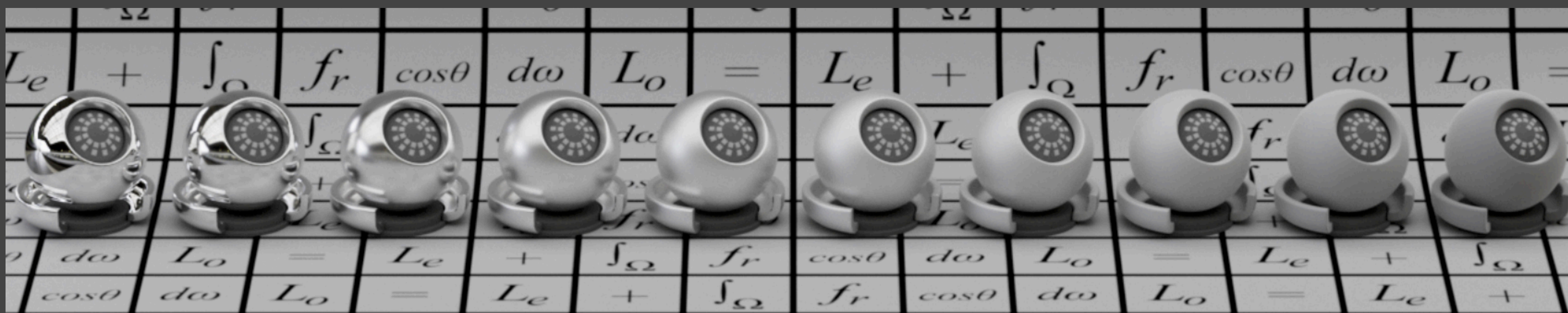
- Dimension / parameters of $E(\mu)$ and E_{avg}?
  - $E(\mu)$: roughness & μ [therefore, a 2D table]
  - E_{avg}: just roughness [therefore, a 1D table]

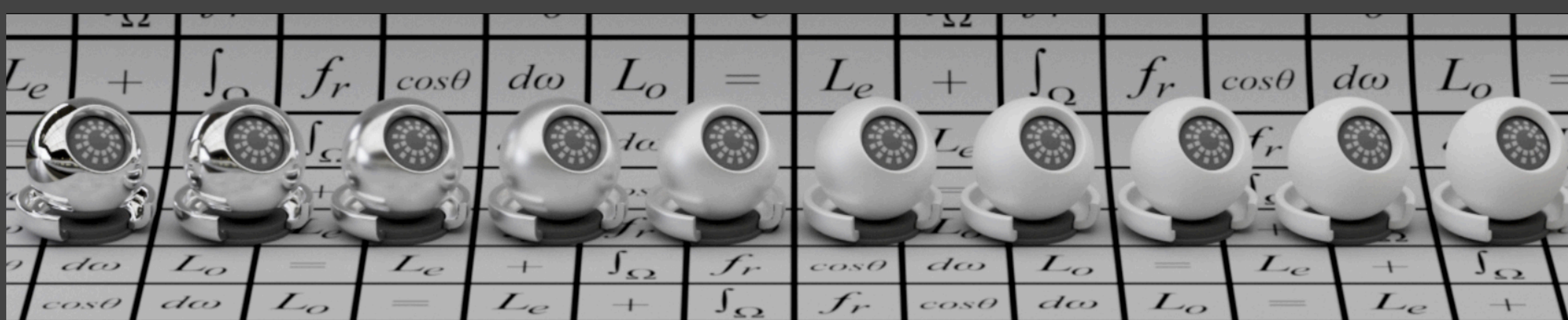


Precomputed table for $E(\mu)$

The Kulla-Conty Approximation

- Results





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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)

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

[Therefore, just a number]

- And recall that E_{avg} is how much energy that you can see (i.e., will **NOT** participate in further bounces)

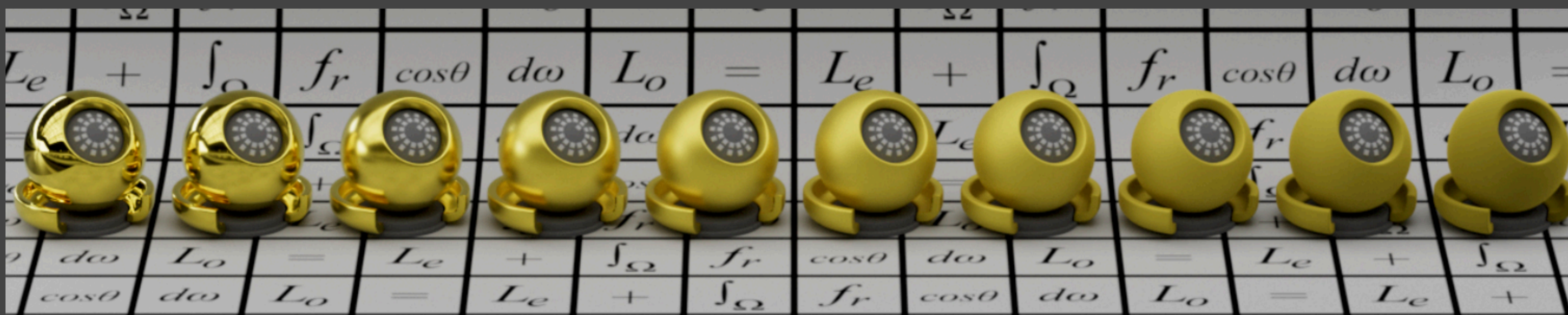
The Kulla-Conty Approximation

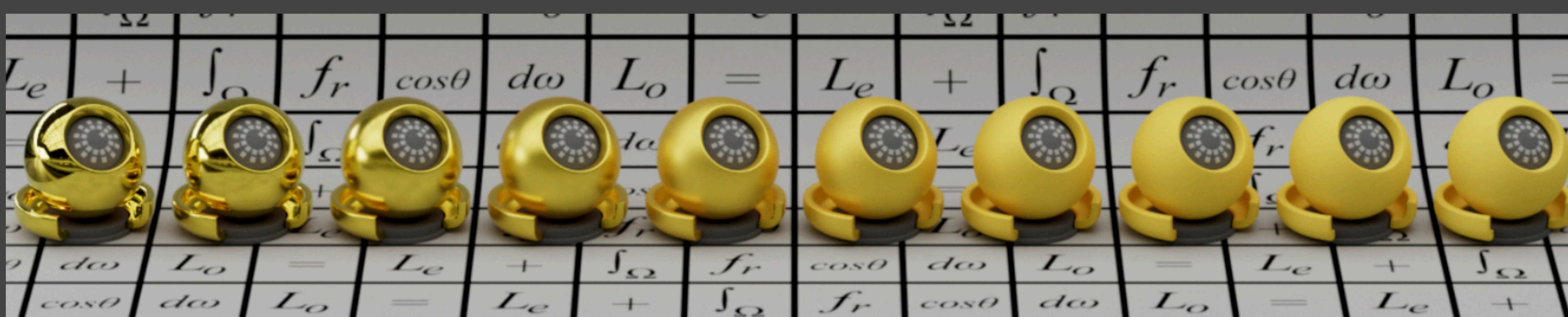
- Therefore, the proportion of energy (color) that
  - You can directly see: $F_{avg}E_{avg}$
  - After one bounce then be seen: $F_{avg}(1 - E_{avg}) \cdot F_{avg}E_{avg}$
  - …
  - After k bounces then be seen: $F_{avg}^k(1 - E_{avg})^k \cdot F_{avg}E_{avg}$
- Adding everything up, we have the color term
  - Which will be directly multiplied on the uncolored **additional BRDF**

$$\frac{F_{\mathrm{avg}}E_{\mathrm{avg}}}{1 - F_{\mathrm{avg}}\left(1 - E_{\mathrm{avg}}\right)}$$

The Kulla-Conty Approximation

- Results





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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?

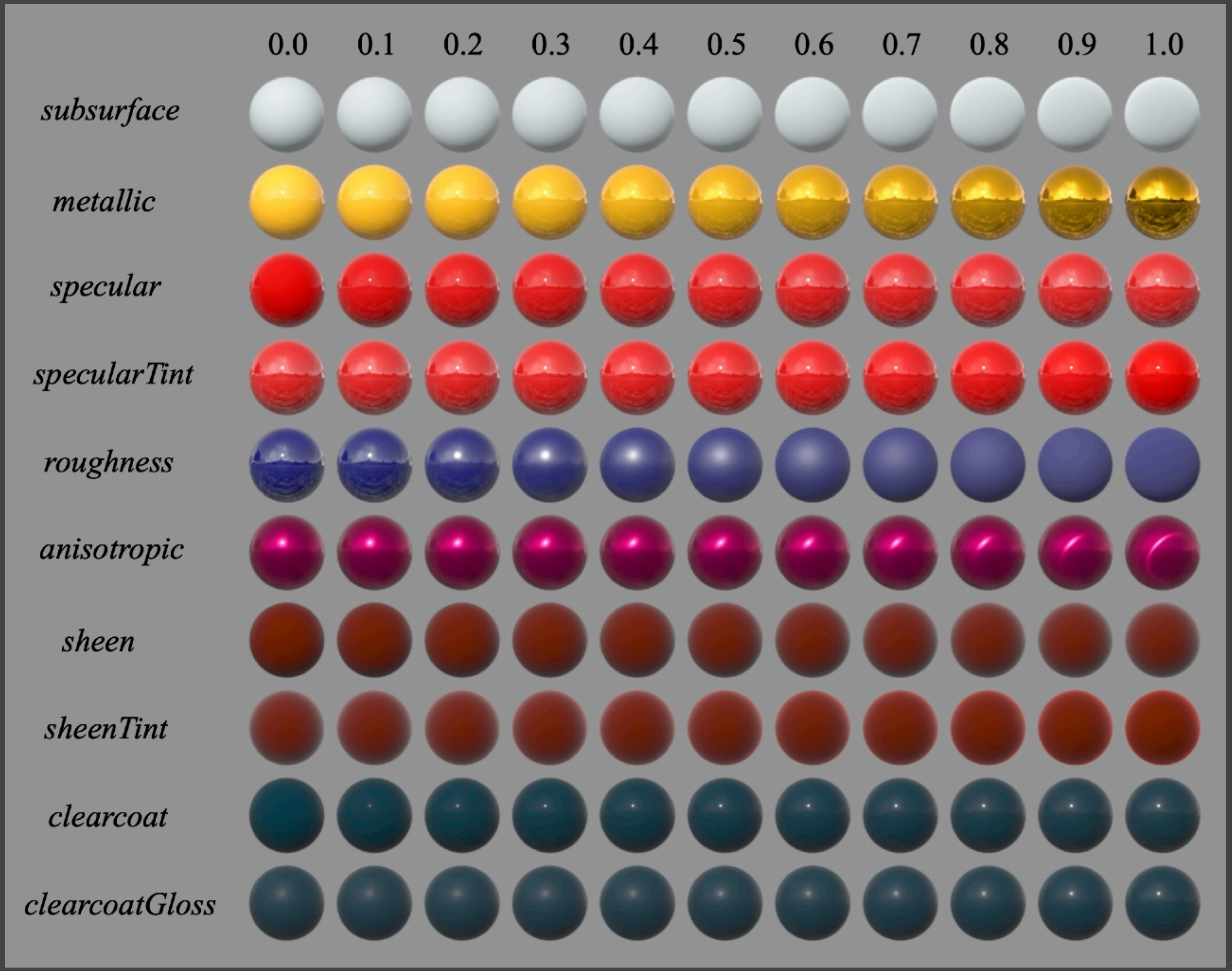
- Motivation
  - No physically-based materials are good at rep. all real materials
    - e.g. lacking diffuse term in most microfacet models
  - Physically-based materials are not artist friendly
    - e.g. “the complex index of refraction n-ik”
- High level design goal
  - Art directable, not necessarily 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

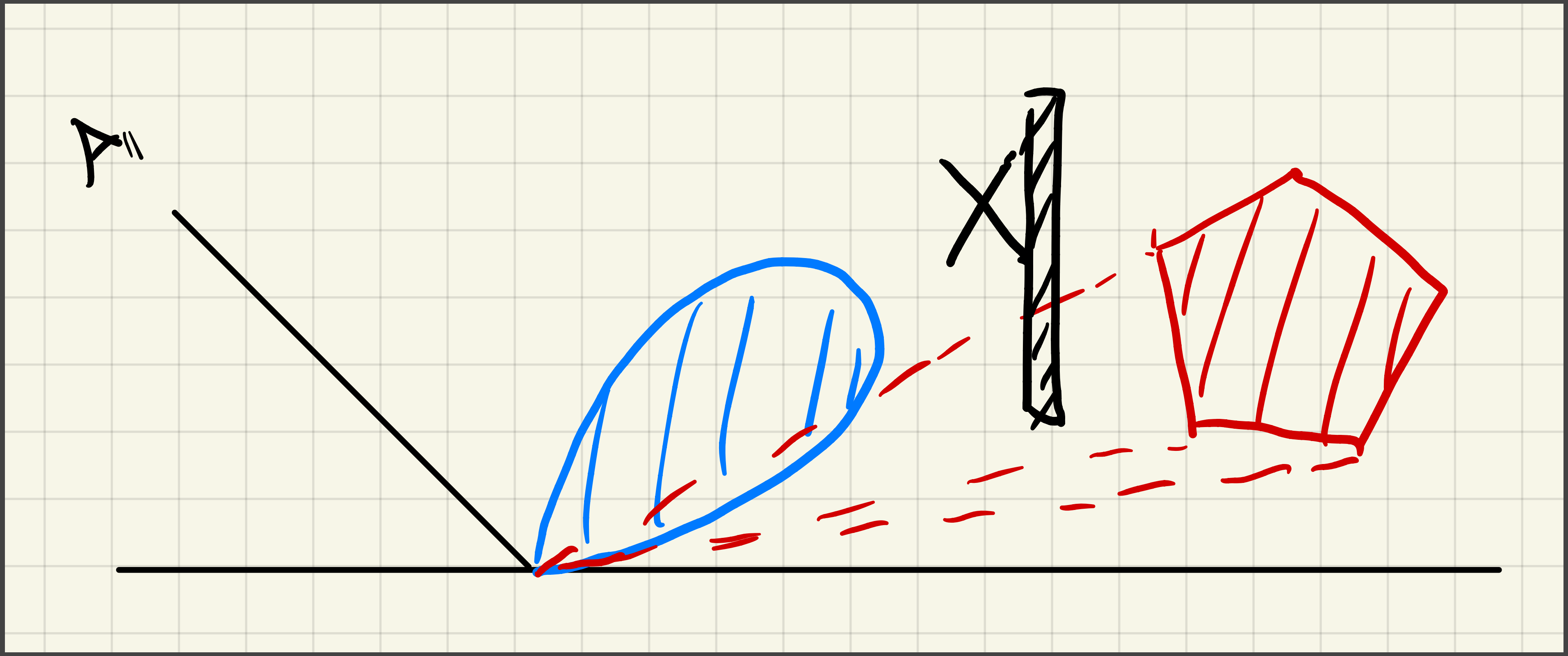
- Easy-to-understand / control
- A wide range of materials in a single model
- Open source implementation is available
- Not physically based
  - But is it a big problem?
  - Academia vs. industry
- Huge parameter space

Questions?

Shading Microfacet Models using Linearly Transformed Cosines (LTC)

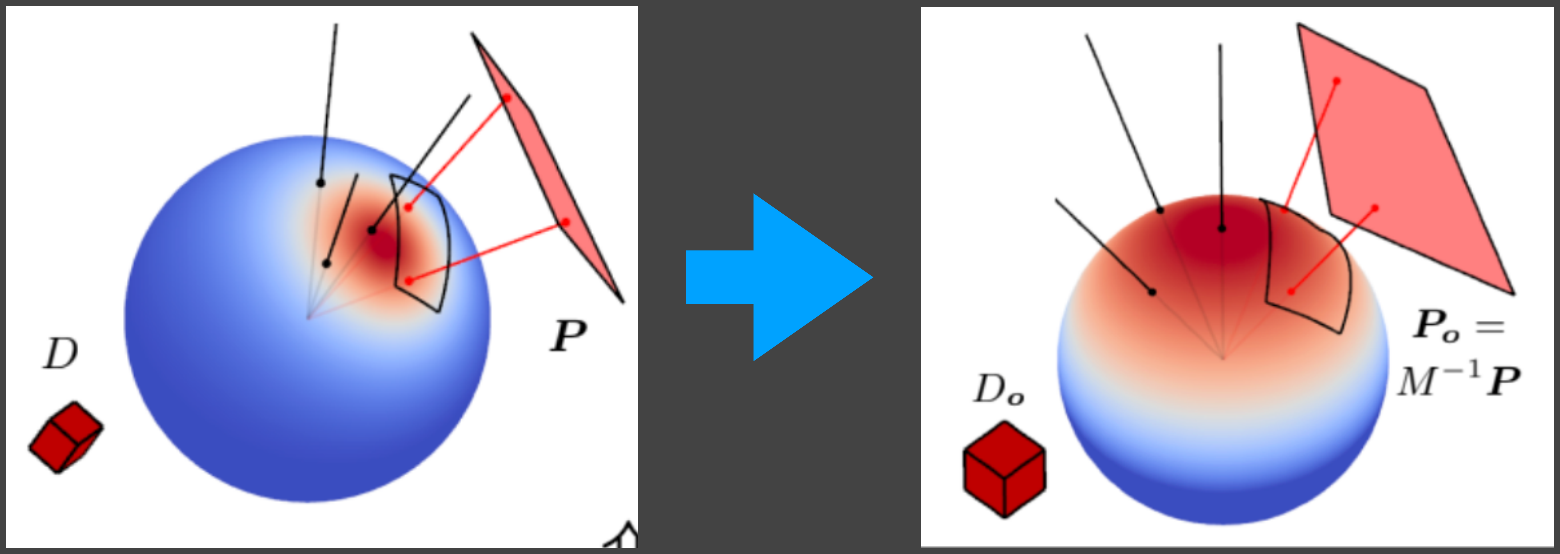
Linearly Transformed Cosines

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



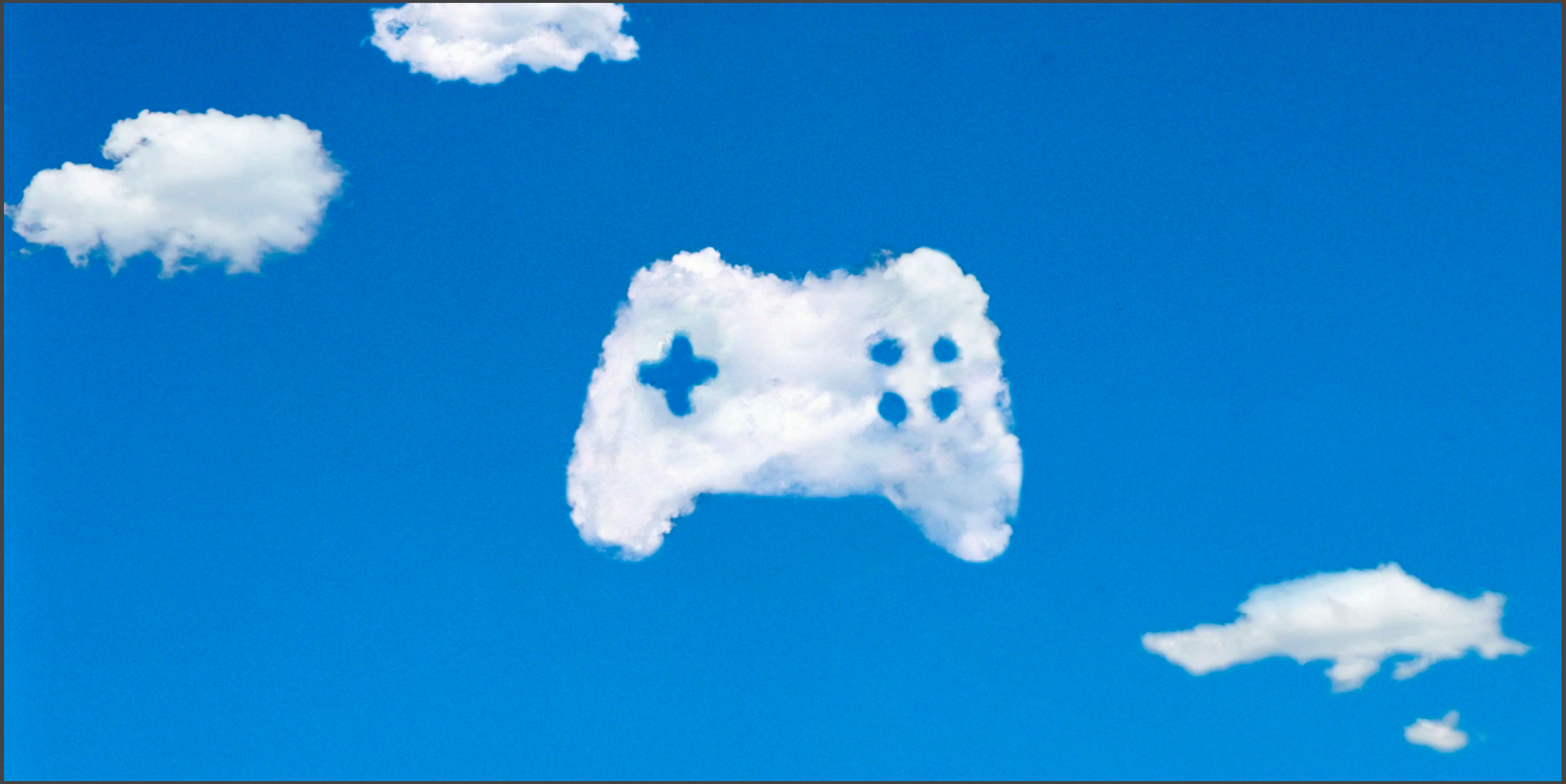
Linearly Transformed Cosines

- 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!



https://www.wired.com/story/cloud-gaming-infrastructure-arms-race/

Thank you!