15. Physically Based Rendering

Advanced

Game Graphic Programming

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Introduction

Computer graphics have come a long way in recent years, and with the introduction of Physically Based Rendering (PBR), it's never been easier to create realistic 3D images and videos.

PBR?

- PBR is a method of rendering computer graphics that simulates the physical properties of light and materials, resulting in more accurate and realistic rendering outputs.

Phong lighting-based vs. PBR-based rendering?

- Phong lighting-based rendering is a traditional method of rendering 3D graphics that uses an ad-hoc model for simulating how light interacts with materials.
  - The function assumes that the amount of reflected light is mainly determined by ambient, diffuse, and specular under the cosine trajectory.
- PBR-based rendering considers the physical properties of materials and complex behavior of light.
  - Material: reflectance, transparency, and how light interacts with materials.
  - Light behavior: the effect of light penetrating a material, and scattering within or upon a material.

Introduction

Phong lighting-based vs. PBR-based rendering[cmp]

Overview

Principles of PBR

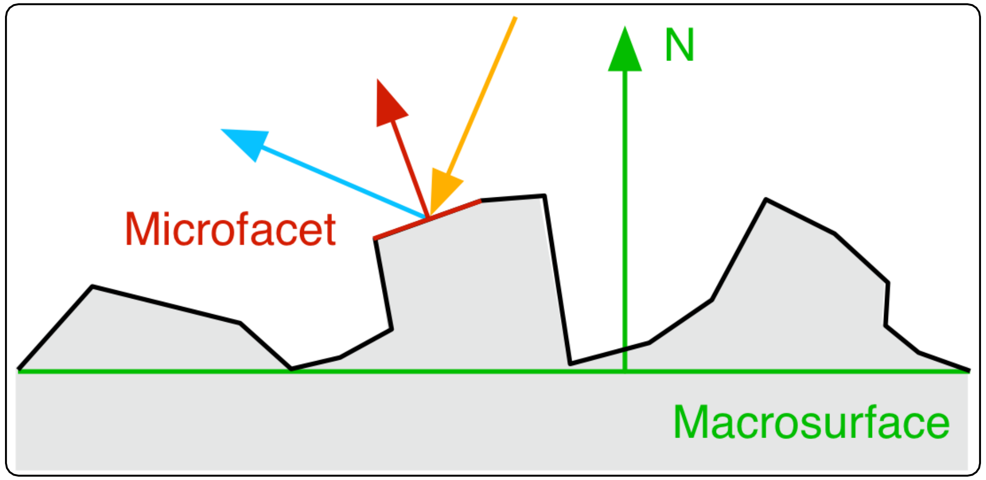
- PBR resolves around two fundamental concepts: Bidirectional Reflectance Distribution Function (BRDF). and energy conservation.

Bidirectional Reflectance Distribution Function (BRDF)

- The BRDF is a mathematical function that defines how a surface reflects light.
- Physically accurate BRDF uses microfacet model which describes the interactions between light and materials.

Energy Conservation

- In the real world, the amount of light reflected by a surface never exceeds the amount of light it receives.
- PBR adheres to this principle, ensuring that the energy of incoming light is conserved when calculating the reflected light.
  → This results in more accurate and believable shading.

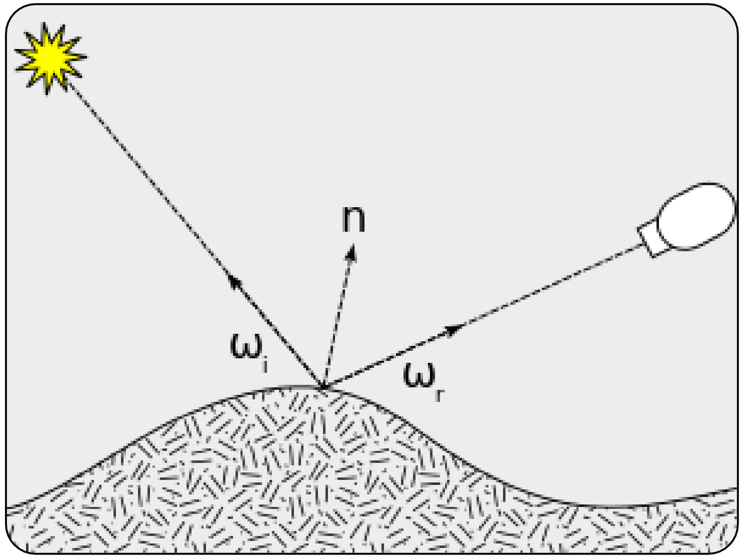


BRDF

BRDF?

- This is a mathematical function that describes how light is reflected at an opaque surface.
  - Opaque surface refers to a common surface that are neither metallic nor transparent.
  - It includes plastic, wood, and stone.

- In other words, BRDF describes a relationship between followings:
  - Incoming light direction (ω_i),
  - Outgoing light direction (ω_r),
  - Surface normal (n).



BRDF

Conceptually, BRDF is made up of three different type of photon-surface interaction[brdf]:

- Uniform diffuse contribution ($f_{r,ud}$)
  - This accounts for the light dispersed uniformly throughout the entire hemisphere.
  - When photons coming from a given direction interact with the surface, they change their direction in a different and uncorrelated way.
- Specular contribution ($f_{r,sp}$)
  - This is responsible for producing mirror-like reflections from the mean plane of the reflective surface which can be computed based on Fresnel reflectivity.
  - This is observed when the surface's roughness is small compared to the wavelength - Upon interacting with the surface, photons from a specific direction are all reflected in the same specular direction.
- Directional diffuse contribution ($f_{r,dd}$)
  - This represents the light scattered across the hemisphere while maintaining a distinct directional characteristic.
  - When photons coming from a given direction interact with the surface, they change their direction in a different but correlated way.

BRDF - Diffuse Reflection

BRDF terms $f_{r,ud}, f_{r,sp,}$ and $f_{r,dd}$ can be derived from the two main components:

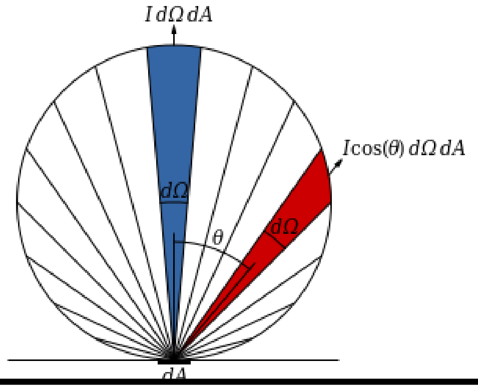
- Diffuse reflection
- Specular reflection

Lambertian diffuse model (default diffuse BRDF used in UE4):

- This models a perfect diffuse surface that scatters incident illumination equally in all directions.
- The surface's luminance is isotropic, and the luminous intensity obeys Lambert's cosine law.
- Although the model is not physically plausible, the result is a reasonable approximation to many real-world surfaces.
  - $r_d = \frac{d_r}{\pi}(N \cdot L); dr = baseColor(1 - metalness); N =$ normal; $L =$ light direction

Lambert's cosine law[coslaw]:

An ideal diffuse radiator is directly proportional to the cosine of the angle θ between the observer's line of sight and the surface normal. This abstracts the number of photons per second emitted into each wedges in the circle given the incidence of the light.



BRDF - Specular Reflection

Specular reflection is often represented by microfacet-based models:

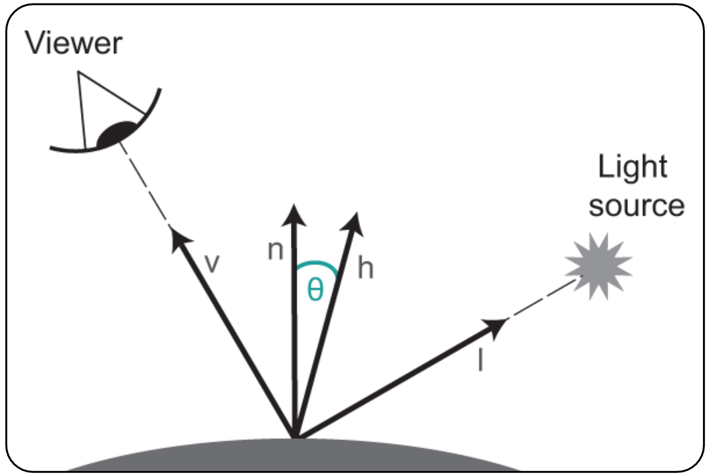
- Microfacet-based models?
  - This is a key aspect of the BRDF in PBR, as they account for the microscopic surface details of a material.
  - This helps simulate the complex light interactions that occur on a material’s surface.

- Popular Microfacet-based models:
  - Cook-Torrance model
  - GGX (Ground glass unknown, or Trowbridge-Reitz model) model

BRDF - Specular Reflection

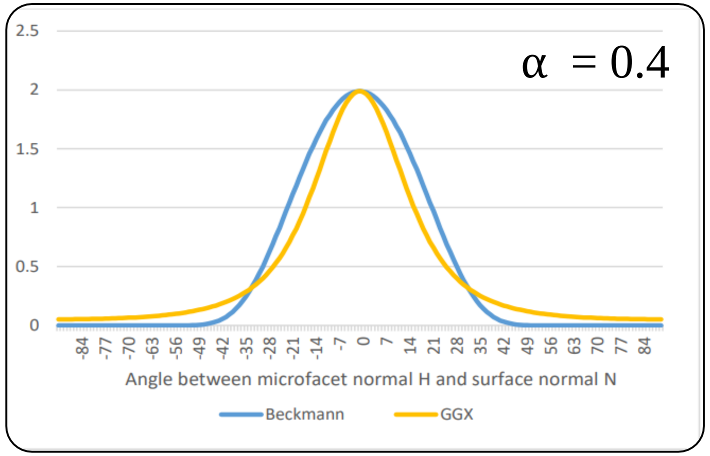
Microfacet models[ctr]:

- Typically, a microfacet model reflection term is defined as three "pluggable" components that can be replaced with equations of your choice when calculating reflectance.
  - Normal Distribution Term (*D*)
  - Geometric Attenuation Term (*G*)
  - Fresnel Term (*F*)



- $r_s = \frac{F(L,H)G(L,V,H)D(N,H)}{4(N\cdot L)(N\cdot V)}; H = half\ vector; V = view\ vector$

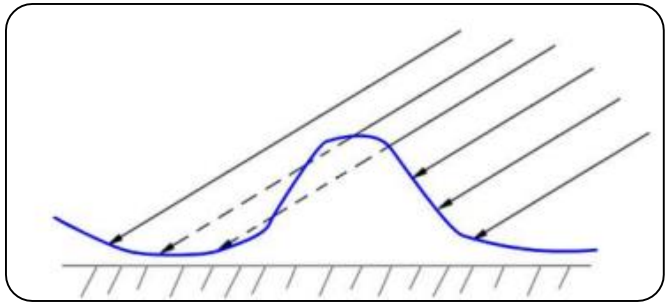
- The *D* defines the shape of the specular highlight.
  - It represents the probability distribution of microfacet normal aligning with *H*[ggx]:
    - $D(N,H) = \frac{\pi((N\cdot H)^2(\alpha^2-1)+1)^2}{\alpha^2}; \alpha = \sqrt{\frac{2}{shininess+2}}$



BRDF - Specular Reflection

Microfacet models[ctr]:

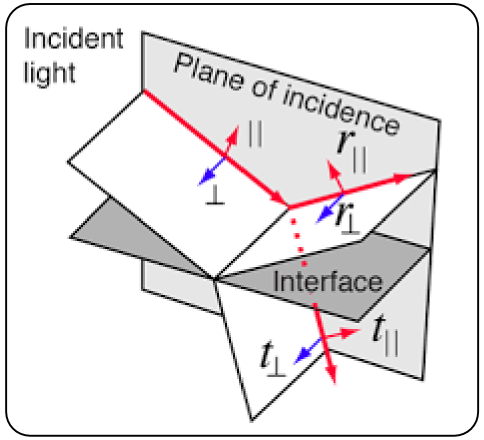
- The G describes the fraction of microfacets which are neither occluded or shadowed.
  - There are two significant micro-surface profiles: V-Cavity model & Smith model[smith].
    - In this lecture, we will discuss Smith's model[smith] (randomized distribution of slope model).
  - In the Smith's model, the micro-surface is considered as a collection of tiny facets, each with its own orientation.
  - The model takes into account two effects:
    - Shadowing effect: this occurs when one facet blocks light.
    - Masking effect: this occurs when one facet obscure the microfacets from the viewer's perspective.
  - To compute these, smith's model considers the statistical distribution of facet orientations and the overall roughness of the surface ($G_1(H,L)$ = shadowing function, $G_1(H,V)$ = masking function).
    - $G(L,V,H) = \frac{1}{1+G_1(H,L)+G_1(H,V)}$
    - $G_1(H,S) = \frac{1}{1+\lambda(\alpha)}$; $\alpha = \frac{(H\cdot S)}{\alpha\sqrt{1-(H\cdot S)^2}}$
    - $\lambda_{GGX}(\alpha) = \frac{-1+\sqrt{1+\frac{1}{\alpha^2}}}{2}$

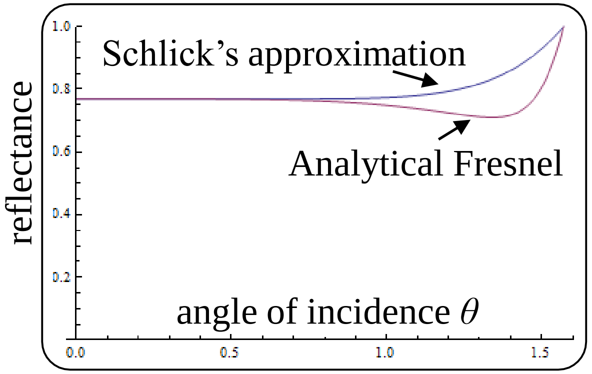


BRDF - Specular Reflection

Microfacet models[ctr]:

- The F describes how much light will be reflected off the surface, determining how much light will contribute to evaluated BRDF.
- The F is based on the Fresnel equations, which describe the reflection and transmission of light at the interface between two different media, such as air and a solid surface[fresnel].
- When light strikes a surface, part of it is reflected, and part of it is transmitted (or absorbed) depending on the material properties and the incidence angle.
  - In computer graphics field, a widely used approximation of the F is the Schlick's approximation[sch], which simplifies the Fresnel equations and provides a more computationally efficient method for calculating the Fresnel reflectance.
  - He uses the observation that when viewed under 90 degrees, all materials exhibit perfect reflectance, and we can use only one parameter $F(\theta)$ which denotes the Fresnel reflectance at angle θ (angle between the L and H).
    - $F(L, H) = F(\theta) = F(0) + \big(F(90) - F(0)\big) * (1 - \cos\theta)^5$
    - $F(0) = \frac{(n-1)^2}{(n+1)^2}$; n = material's index of refraction



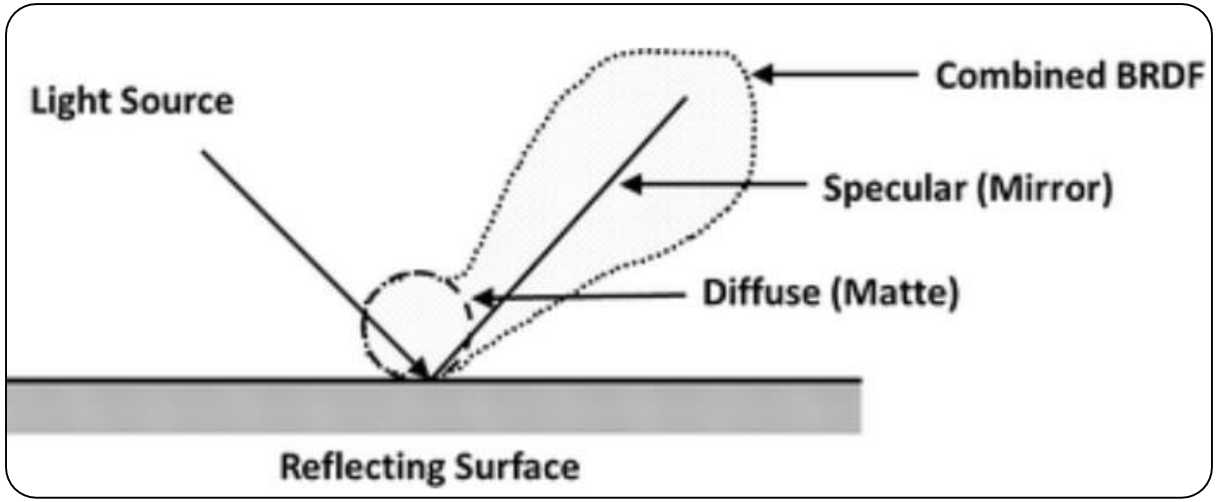


BRDF – Combining diffuse & specular

Combining BRDFs:

- To couple r_d and r_s, Fresnel term based blending is widely used.
  - BRDF = (1- $F(L,H)$) r_d + r_s; $r_s = \frac{F(L,H)G(L,V,H)D(N,H)}{4(N\cdot L)(N\cdot V)}$
- This usually results in physically plausible renderings while ensuring the law of conservation of energy over various lighting conditions and viewing angles.

[brdf_pic]



Energy Conservation

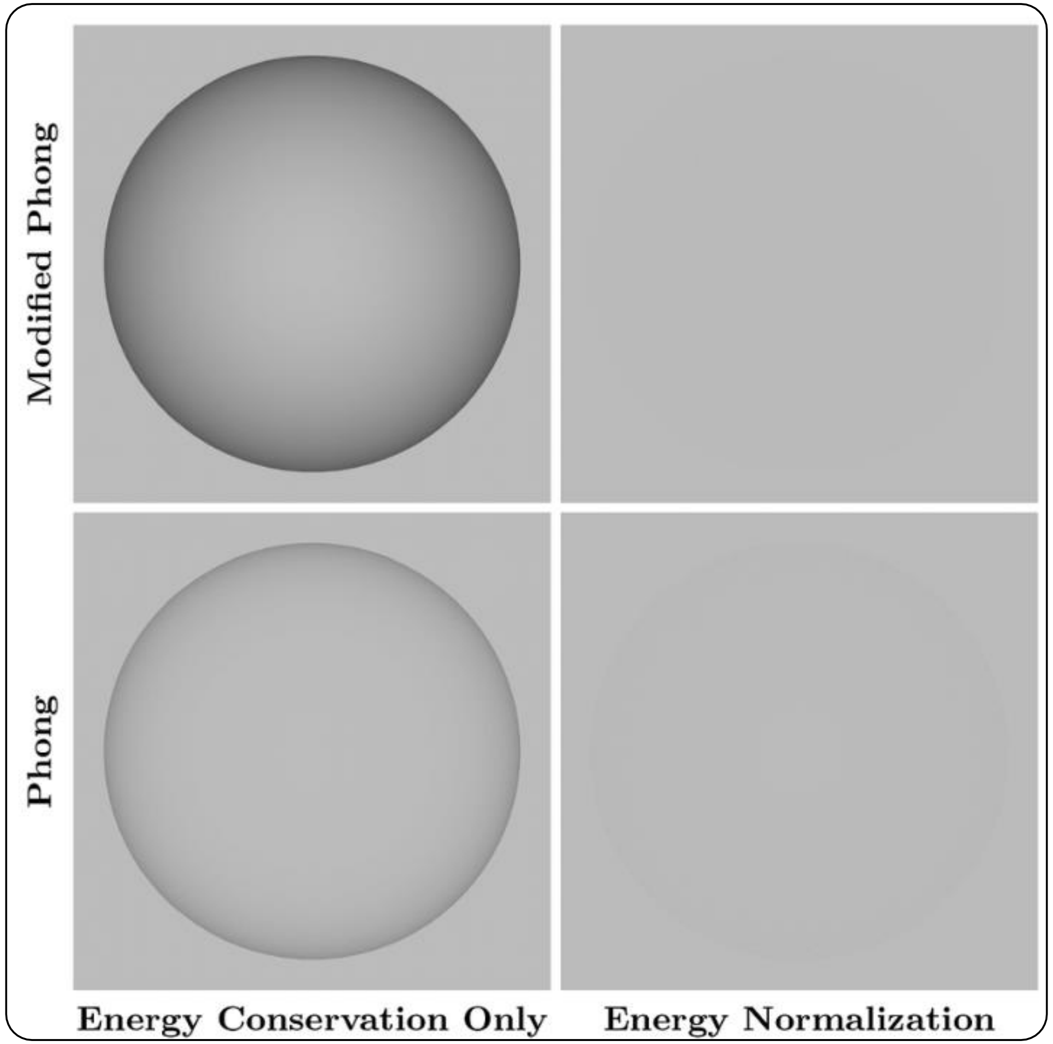
Energy Conservation Principles

- This principle is derived from the first law of thermodynamics.
  - In the context of rendering, this means that a surface can only reflect, transmit, or absorb the incoming light.
  - Then, the light reflected from the surface will never be more intense than it was before it hit the surface.
- In practice, some energy loss occurs even for physically-based BRDFs.
  - It is often caused by the lack of multiple reflections between microfacets.
- There are several algorithms that can check the energy conservation properties of BRDFs.
  - **White furnace test**: A surface is surrounded by a perfectly white environment, and the reflected radiance is measured. If the surface is energy conserving, the surface will disappear against the white background (standard test).
  - **Hemisphere balance test**: This is similar to the white furnace test but focuses on the balance between incoming and outgoing radiance. In this test, we integrate the BRDF for a given incident light over the hemisphere and check that the result does not exceed unity.
  - **Non-negative radiance test**: This test verifies that the BRDF's outgoing radiance is non-negative for all possible combinations of incident and outgoing light directions. This test can be performed by evaluating the BRDF for a wide range of incident and outgoing light directions.

Energy Conservation

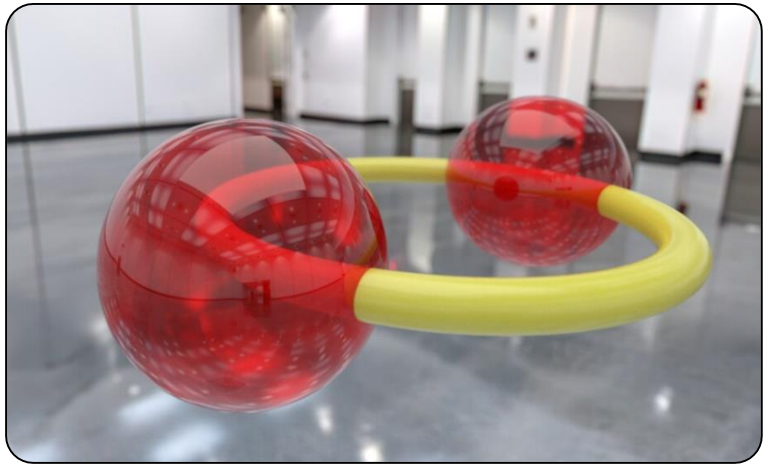
White furnace test example

[wht_pic]

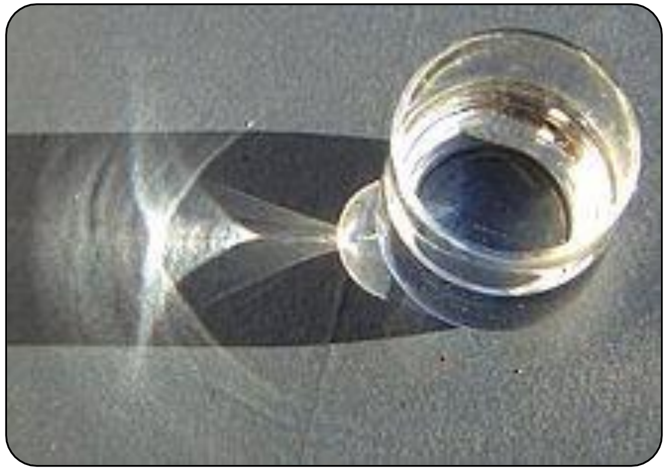


PBR Challenges

1. Handling complex materials
   - Accurately representing complex materials such as translucent objects, fabrics, or anisotropic materials remains challenging.
     - Translucent objects (glass or wax) allow some light to pass through while scattering and reflecting the rest.
       - Accurate rendering of such objects requires modeling subsurface scattering: the phenomenon of light penetrating the surface, interacting with the material, and scattering before exiting the objects.
       - This involves solving the complex volumetric light transport equations and dynamic capturing of refractions, reflections, and caustics caused by the interaction of light with translucent materials.



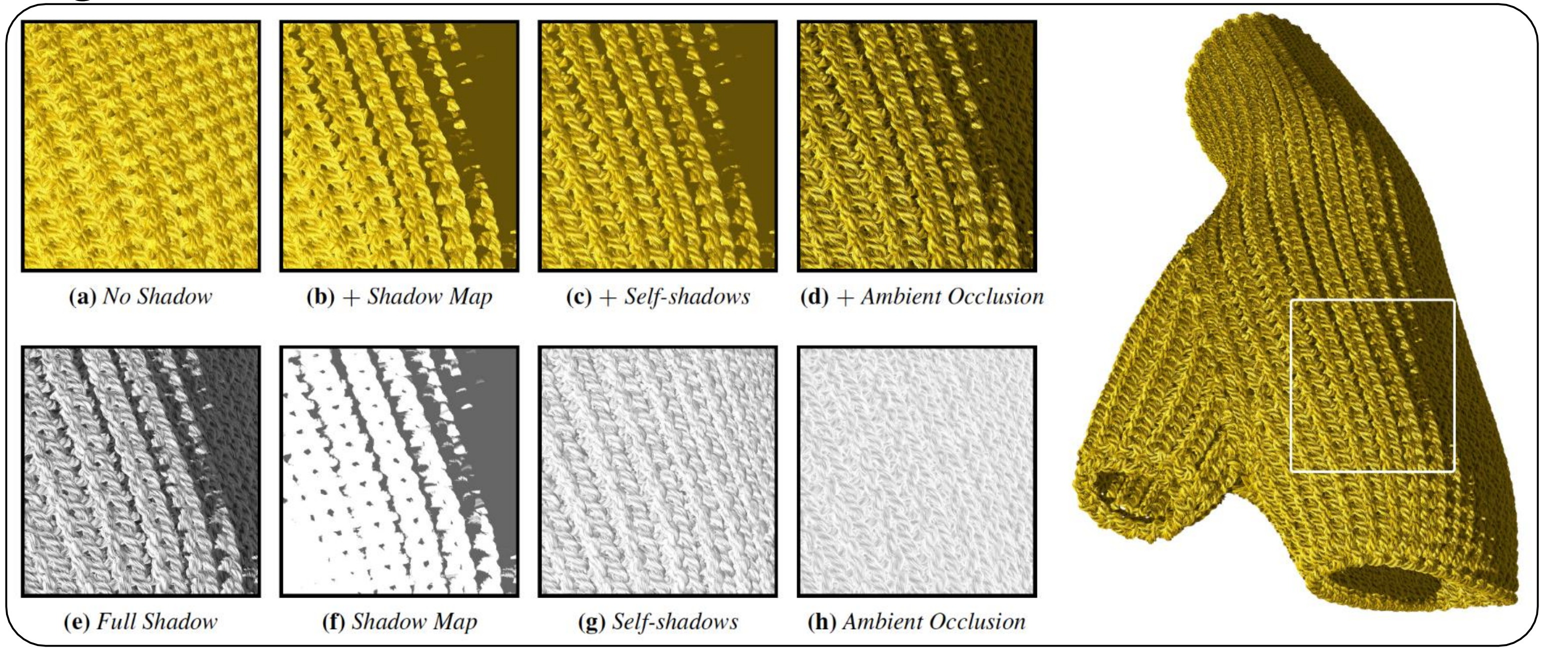
transparent example



caustic example

PBR Challenges

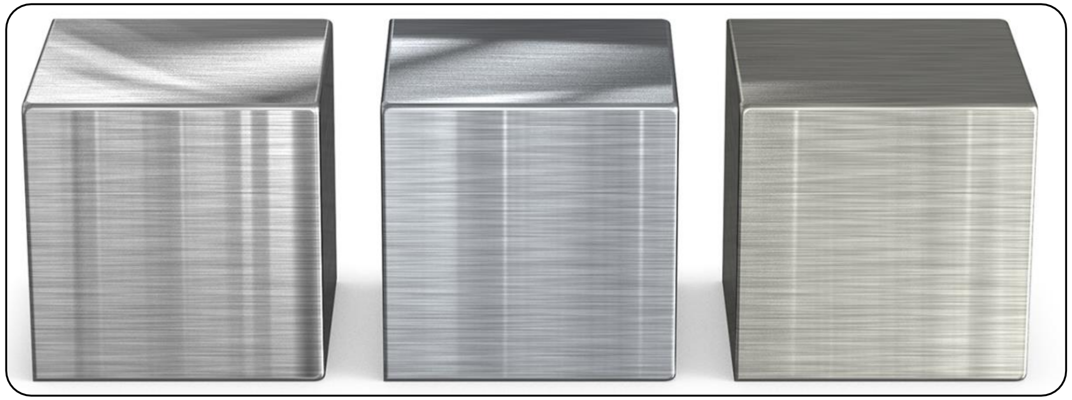
1. Handling complex materials
   - (Cont.) Accurately representing complex materials such as translucent objects, fabrics, or anisotropic materials remains challenging.
     - Fabrics exhibit complex light behavior due to woven structure and the presence of microscale fibers.
       - Accurate rendering of fabrics requires modeling the intricate interactions between light and the micro-geometry of fibers, as well as accounting for multiple scattering events, shadowing, and masking between fibers.
       - Additionally, fabrics can exhibit anisotropic reflections, further increasing the complexity of their rendering.



[fiber]

PBR Challenges

1. Handling complex materials
   - (Cont.) Accurately representing complex materials such as translucent objects, fabrics, or anisotropic materials remains challenging.
     - Anisotropic materials, such as brushed metal or hair, have direction-dependent properties that affect the way they reflect and scatter light.
       - Their unique surface microstructure causes light to behave differently depending on the incident and viewing angles.
       - PBR can be difficult to apply to these materials because accurately capturing the anisotropic behavior requires specialized models and additional computations: Standard reflection models, like the microfacet-based models, need to be adapted or extended to account for the direction-dependent behavior of anisotropic materials.



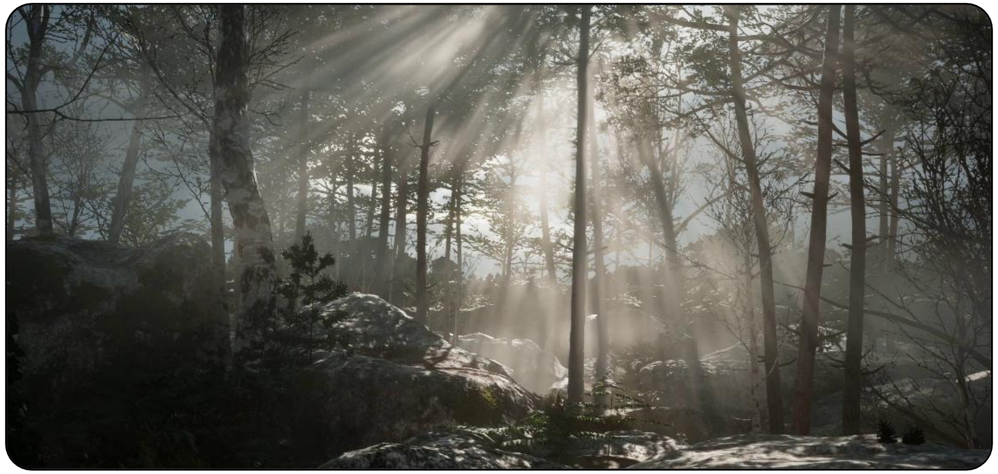
brushed metal example

brushed hair example

PBR Challenges

2. Handling homogeneous participating media

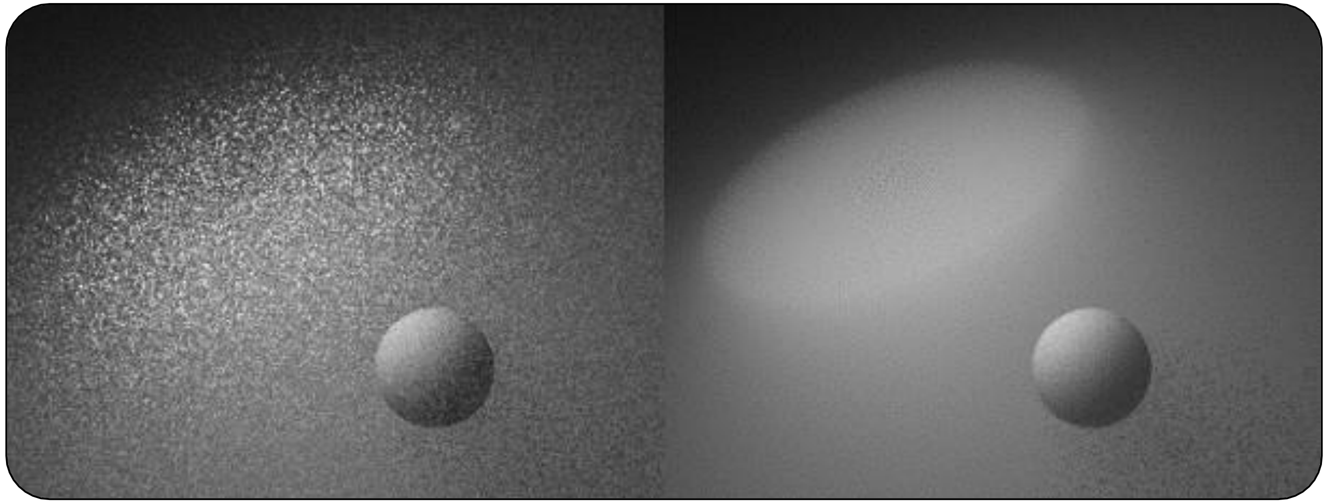
- Rendering participating media like fog, smoke, and clouds in a physically accurate manner is computationally expensive.
  - Unlike solid surfaces, fog consists of countless tiny particles suspended in the air. These particles scatter light in various directions, which makes simulating the light transport more complex compared to rendering solid surfaces.
  - Light can scatter multiple times within the fog, bouncing between particles before finally reaching the camera or leaving the volume.
  - Fog and other participating media can have varying density and composition, making the light scattering behavior more complicated.



fog rendering with PBR

PBR Challenges

3. Handling homogeneous participating media
   - Developing adaptive sampling strategies and better denoising algorithms that maintain important details and minimize artifacts is an ongoing challenge.
     - Monte Carlo methods are widely used for PBR because they can effectively approximate the complex light transport equations by randomly sampling light paths in a scene. However, this sampling process is inherently noisy, especially when the number of samples is low.
     - If 1) the number of samples is too low, 2) scenes have high-frequency features, such as small light sources, sharp reflections, or complex caustics, or 3) there exists multiple indirect lights, the result often becomes noisy.



noise examples

Reference

[brdf] Ferrero, A., Campos Acosta, J., Rabal, A. M., Pons Aglio, A., Hernanz, M. L., & Corróns, A. (2011). Principal components analysis on the spectral bidirectional reflectance distribution function of ceramic colour standards.
[bdrf2] Jakub Boksansky. Crash Course in BRDF Implementation.
[brdf_pic] Seubert, C. M., Nichols, M. E., Frey, J., Shtein, M., & Thouless, M. D. (2016). The characterization and effects of microstructure on the appearance of platelet–polymer composite coatings. Journal of materials science, 51, 2259-2273.
[cmp] Adobe (2018). THE PBR GUIDE BY ALLEGORITHMIC - PART 1.
[coslaw] WIKIPEDIA. Lambert's cosine law.
[ctr] https://graphicscompendium.com/gamedev/15-pbr
[fresnel] http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/freseq.html
[ggx] (2007). Microfacet Models for Refraction through Rough Surfaces
[sch] C. Schlick (1994). An inexpensive BRDF model for physically-based rendering. Computer graphics forum.
[smith] B. Smith (1967). Geometrical shadowing of a random rough surface. IEEE Trans. on Antennas and Propagation.
[wht_pic] Mallett, I., & Yuksel, C. (2020). Constant-time energy-normalization for the Phong specular BRDFs. The Visual Computer, 36(10-12), 2029-2038.
[fiber] Wu, K., & Yuksel, C. (2017). Real-time cloth rendering with fiber-level detail. IEEE transactions on visualization and computer graphics, 25(2), 1297-1308.