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Appearance of Interfaced Lambertian Microfacets, using STD Distribution

M. Ribardière[1], D. Meneveaux[1], B. Bringier[1], L. Simonot[2]

[1]XLIM (CNRS-UMR7252), University of Poitiers
[2]PPRIME (CNRS-UPR3346), University of Poitiers

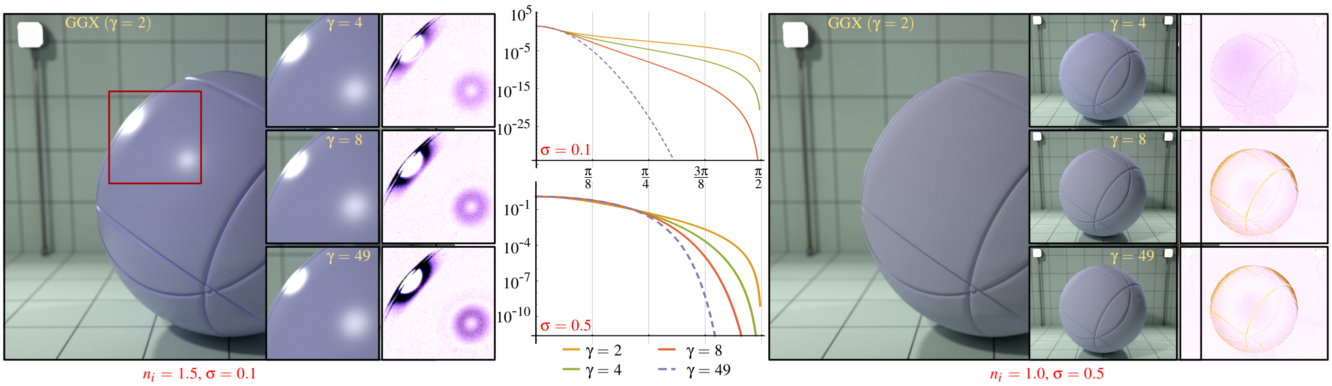

Figure 1: *Interfaced Lambertian microfacets (IL) using STD distribution, illustrating the changes of appearance. Left: Rough specular microfacets; Right: Rough Lambertian microfacets; Middle: STD plots (Log) in slopes space, for various values of γ. STD distribution includes GGX ($\gamma = 2$) and Beckmann's ($\gamma \to \infty$) distributions, while the interfaced Lambertian model covers a range from Lambertian and rough Lambertian materials to pure Fresnel mirrors.*

Abstract

This paper presents the use of Student's T-Distribution (STD) with interfaced Lambertian (IL) microfacets. The resulting model increases the range of materials while providing a very accurate adjustment of appearance. STD has been recently proposed as a generalized distribution of microfacets which includes Beckmann and GGX widely used in computer graphics; IL corresponds to a physical representation of a Lambertian substrate covered with a flat Fresnel interface. We illustrate the appearance variations that can be observed, and discuss the advantages of using such a combination.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture

1. Introduction

Microfacets theory has been widely employed for representing rough materials. The corresponding models have many advantages, such as physcal plausibility, simplicity of representation, simplicity of use, to cite only a few examples. The model is defined thanks to three important factors [TS67, CT82, ON94, APS00, WMLT07]: f^μ, D, G, each of them having being deeply discussed in the literature. f^μ defines the microfacet BRDF; D describes the *distribution* of normals; G expresses the *Geometric Attenuation Factor* (or GAF, from now on). Many recent studies have discussed the physical realism/plausibility of these materials [APS00, WMLT07, Hei14, MBT*17], with generalizations for broadening the range of appearances [BSH12, Hof16]. This paper focuses on the appearance variations based on the representation of *interfaced Lambertian microfacets* described by Meneveaux et al. [MBT*17], coupled with the generalized Student's T-Distribution recently proposed by Ribardière et al. [RBMS17]. The advantage of this combination concerns its generality, since it includes with the same set of parameters many well-known models such as Lambert, Cook-Torrance [CT82], Oren-Nayar [ON94]; It generalizes at the same time the widely used distributions of GGX [WMLT07] and Beckmann's [BS63], with many intermediate variations. This paper illustrates the range of variations that can be handled as well as the

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thin adjustments that are made possible thanks to a single additional parameter γ.

The remainder of this article is organized as follows. Section 2 recalls the general microfacet theory, the application to interfaced Lambertian microfacets, as well as STD distribution. Section 3 explains how such a combination can be implemented within a Monte-Carlo lighting simulation system. Section 4 illustrates our results. Section 5 presents our conclusions and future work.

2. Previous Work and Notations

Let us consider a surface sample of normal $\mathbf{n}$ lit by a collimated light source from direction $\mathbf{i}$. The radiance reflected toward a direction $\mathbf{o}$ is given by the BRDF $f(\mathbf{i},\mathbf{o},\mathbf{n})$. The representation $f(\mathbf{i},\mathbf{o},\mathbf{n})$ is defined by a statistical description of a microfacet distribution. Given the BRDF $f^{\mu}(\mathbf{i},\mathbf{o},\mathbf{m})$ of an individual microfacet associated with a normal $\mathbf{m}$, its contribution is weighted by the distribution $D(\mathbf{m})$ and a geometric attenuation factor $G(\mathbf{i},\mathbf{o},\mathbf{m})$. $D(\mathbf{m})$ is related to the surface roughness, while the attenuation factor $G(\mathbf{i},\mathbf{o},\mathbf{m})$ determines the visible portion of a microfacet of normal $\mathbf{m}$ from both the light source and the observer [TS67, BBS02, Hei14]; G has a major influence at grazing angles. Many authors have studied the use of various distributions and geometric attenuation factors [CT82, WMLT07, BSH12]. The equation for the general case of microfacet based BRDFs is [ON94, WMLT07]:

$$f(\mathbf{i},\mathbf{o},\mathbf{n}) = \int_{\Omega_+} \frac{|\mathbf{im}|}{|\mathbf{in}|} f^{\mu}(\mathbf{i},\mathbf{o},\mathbf{m}) \frac{|\mathbf{om}|}{|\mathbf{on}|} D(\mathbf{m}) G(\mathbf{i},\mathbf{o},\mathbf{m}) d\omega_m. \quad (1)$$

With purely specular microfacets, Equation 1 simplifies to [WMLT07]:

$$f(\mathbf{i},\mathbf{o},\mathbf{n}) = \frac{F(\mathbf{i},\mathbf{h})D(\mathbf{h})G(\mathbf{i},\mathbf{o},\mathbf{h})}{4|\mathbf{in}||\mathbf{on}|}, \quad (2)$$

where $\mathbf{h} = \frac{\mathbf{i}+\mathbf{o}}{||\mathbf{i}+\mathbf{o}||}$ is the half angle vector between $\mathbf{i}$ and $\mathbf{o}$, and $F(\mathbf{i},\mathbf{h})$ corresponds to Fresnel's reflectance, depending on the refractive index of the material, n_i. This equation defines the *glossy* aspect of the surface.

The colored aspect of the surface (or *body reflection*) is often modeled with a Lambertian term, though this combination makes the general representation not physically realistic, due to the increasing specular lobe for grazing angles, not compensed by a diminution of the Lambert constant term [KSK01, MBT*17].

2.1. Rough Interfaced Lambertian BRDF

Interfaced Lambertian surfaces [MBT*17] correspond to a Lambertian substrate of intrinsic reflectance K_d (dependent on wavelength λ), covered with a flat interface corresponding to a refractive index discontinuity n_i (a real index for dielectrics), as illustrated in Figure 2.

Microfacets are associated with a BRDF $f^{\mu}(\mathbf{i},\mathbf{o},\mathbf{m})$ defined by a pure specular interface reflection $f_s^{\mu}(\mathbf{i},\mathbf{o},\mathbf{m})$, combined with the material body diffuse reflection $f_b^{\mu}(\mathbf{i},\mathbf{o},\mathbf{m})$:

$$f^{\mu}(\mathbf{i},\mathbf{o},\mathbf{m}) = f_s^{\mu}(\mathbf{i},\mathbf{o},\mathbf{m}) + f_b^{\mu}(\mathbf{i},\mathbf{o},\mathbf{m}). \quad (3)$$

Body scattering f_b^{μ} accounts for the first interface transmission

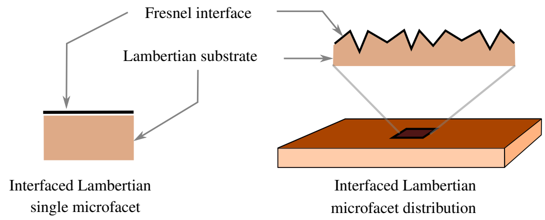

Figure 2: *Surface built up with interfaced Lambertian microfacets. The substrate scatters light while the interface provides brightness.*

of light $T(\mathbf{i},\mathbf{m})$, followed by a Lambertian reflection due to the substrate, inner multiple interactions between interface and substrate, and the final transmission $T(\mathbf{o},\mathbf{m})$ toward the outgoing direction [MBT*17]:

$$f_b^{\mu}(\mathbf{i},\mathbf{o},\mathbf{m}) = \frac{1}{\pi n_i^2} T(\mathbf{i},\mathbf{m}) T(\mathbf{o},\mathbf{m}) \frac{K_d}{(1 - K_d r_i)}, \quad (4)$$

where r_i is the internal reflectance on the flat interface lit by a Lambertian source coming from the medium of refractive index n_i (an analytic formulation is given in [MBT*17]). Figure 3 shows the curves and a rendered 3D object with materials corresponding to a flat interfaced Lambertian surface, with varying values of n_i.

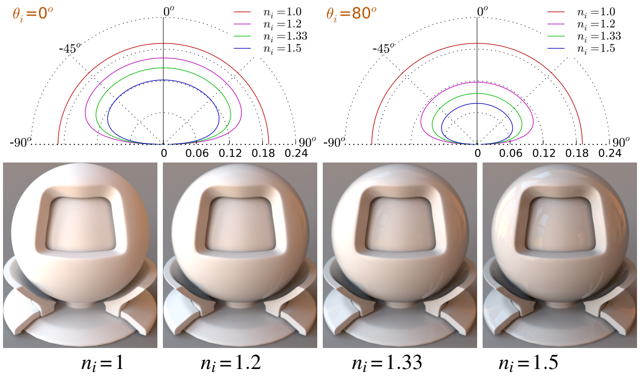

Figure 3: *(top) Plot of the* body *BRDF of a flat interfaced Lambertian surface with $K_d = 0.6$ and $n_i = \{1.0, 1.2, 1.33, 1.5\}$; (bottom) Rendered images of the complete associated BRDFs applied on a 3D object.*

For a given distribution of IL microfacets, Equation 3 should be replaced in Equation 1. The resulting macroscopic BRDF is then composed of a direct reflection term f_s equivalent to Equation 2 and a body reflection term f_b (Equation 4 in the integral of Equation 1).

This representation has the advantage of handling several models widely used in computer graphics: (i) When $K_d = 0$, this formulation corresponds to purely specular microfacets [TS67, CT82]; (ii) When $n_i = 1$, then $T = 1$ and $r_i = 0$, and it corresponds to purely Lambertian microfacets [ON94]; (iii) When $\sigma = 0$, the BRDF is a flat interfaced Lambertian surface; (iv) When $n_i = 1$ and $\sigma = 0$, the model is equivalent to a flat Lambertian material.

2.2. Student's T-Distribution

For computer graphics, Beckmann's distribution [BS63] and GGX [TR75, WMLT07, Bur12] are the most popular functions. The corresponding Smith-Bourlier GAF can be derived analytically for these distributions, and they are also interesting for importance sampling. GGX distribution exhibits a thinner bell shape with a longer tail than that of Beckmann. It has been generalized by Burley [Bur12] and denoted as GTR, but the Smith-Bourlier GAF cannot be derived analytically and the generalization does not include Beckmann's distribution. Student's T-Distribution (STD) generalization handles both cases [RBMS17]. It is defined as:

$$D^{STD}(m) = \frac{(\gamma-1)^{\gamma}\sigma^{2\gamma-2}}{\pi\cos^4\theta_m\left((\gamma-1)\sigma^2+\tan^2\theta_m\right)^{\gamma}}, \tag{5}$$

where σ is the *roughness* parameter; $\gamma > 1.5$ controls the shape of the distribution bell, for a given roughness parameter σ. Statistically speaking, γ represents the number of samples modeled by a bivariate Student's T-Distribution. When γ=2, STD remains equal to GGX, and when $\gamma \to \infty$, STD tends to Beckmann's distribution (values of γ higher than 40 correspond very closely to Beckmann). The slope distributions for σ=0.1 and $\sigma = 0.5$ with γ={2,4,8,49} are provided in Figure 1. The next section explains how STD and IL can be coupled and straightforwardly integrated in a physically-based rendering system.

3. Monte-Carlo Integration

The two terms f_s and f_b (Section 2.1) can be processed independently during the rendering process. Let us consider the rendering equation, associated with a non-emissive material:

$$L_o(x,\mathbf{o},\mathbf{n}) = \int_{\Omega_+} L_i(x,\mathbf{i},\mathbf{n}) f(\mathbf{i},\mathbf{o},\mathbf{n}) |\mathbf{in}| d\omega_i, \tag{6}$$

where x is the considered surface element location, $L_o(x,\mathbf{o},\mathbf{n})$ corresponds to the outgoing radiance, $L_i(x,\mathbf{o},\mathbf{n})$ is the incident radiance coming from direction ω_i, and $f(\mathbf{i},\mathbf{o},\mathbf{n}) = f_s(\mathbf{i},\mathbf{o},\mathbf{n}) + f_b(\mathbf{i},\mathbf{o},\mathbf{n})$. With IL, the model requires a specific integration since both the glossy and body terms rely on a microfacet distribution.

The first step consists in choosing between surface and body sampling. Ideally, f_s and f_b should be integrated to determine weighting. This process is performed as described by Meneveaux et al. [MBT*17], using the the total specular reflectance R_s and the total body reflectance R_b. The proportion between R_s or R_b is used for choosing between the specular and the body direction.

The second step concerns the sampling of the selected term. The glossy component f_s (Equation 2) corresponds to the usual Cook-Torrance formulation (with potentially different distributions and/or attenuation factors). It is thus managed with the existing importance sampling strategies [WMLT07], that can be applied identically with STD [RBMS17]. The body component f_b can also be estimated using stochastic sampling, with importance sampling, based on $D(\mathbf{m})|\mathbf{mn}|$. All microfacets contribute to the body term, but the Monte Carlo integration process only requires sampling one of them for each estimation during path tracing [MBT*17].

Light inter-reflections between microfacets can also be handled, using either V-cavities with Torrance-Sparrow's GAF [MBT*17], or Heitz's process with Smith-Bourler GAF [HHdD15].

4. Appearance Variations

The use of STD with IL microfacets provides a wide range of dielectric materials. This section illustrates some results obtained with different sets of parameters, and discusses the effects of masking, shadowing and inter-reflection.

Glossy dielectric materials

Figure 4 illustrates the comparison for the same roughness parameter σ, and two values of γ of STD, with Smith-Bourlier GAF (without the effects due to microfacet multiple reflections in this case).

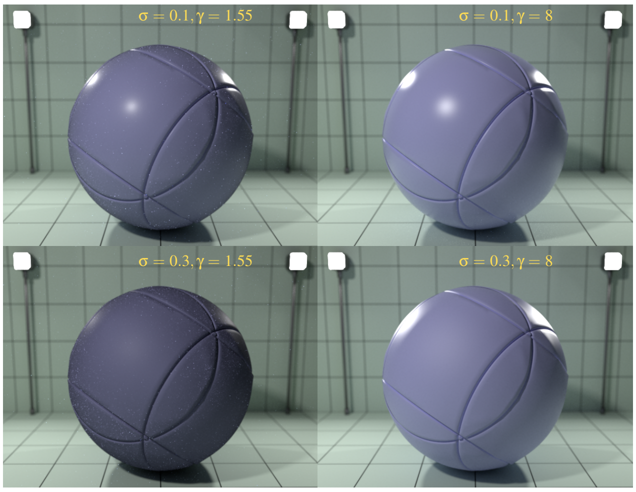

Figure 4: *Comparisons of the appearance change according to* γ*, for two roughness values (with direct reflection only in this case) and* $n_i = 1.5$*. (top) With* $\sigma = 0.1$ *and* $\gamma = \{1.55, 8\}$*; (bottom) With* $\sigma = 0.3$ *and* $\gamma = \{1.55, 8\}$.

The specular spots are sharper when γ increases, and the object becomes brighter (the surface appears darker when γ is lower due to roughness, and light multiple reflections between microfacets should be handled as illustrated below). The surface brightness is closer when handling multiple bounces. Differences are also clearly visible when changing the GAF, as illustrated in Figure 5. The appearance importantly changes at grazing angles; Smith-Bourlier GAF is often preferred. Torrance-Sparrow representation is now considered as unrealistic by several authors, though mathematically correct in terms of energy conservation. Visually, using Torrance-Sparrow GAF tends to increase the glossy aspect at grazing angles.

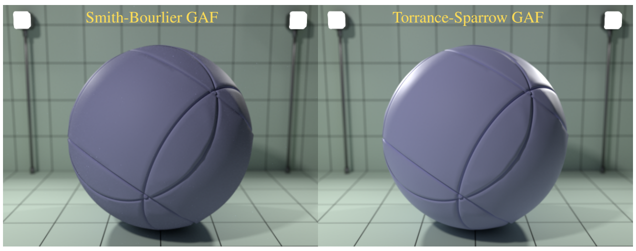

Figure 5: *Illustration of the influence of the GAF function between Smith-Bourlier and Torrance-Sparrow, for* $\gamma = 1.75$*,* $\sigma = 0.5$ *and* $n_i = 1.5$.

Rough Lambertian materials

The STD distribution also brings noticeable changes of appearance with rough diffuse materials. The right part of Figure 1 shows the differences for the same roughness, with γ={2,4,8,49}. Figure 6 also shows that light multiple reflections between microfacets have an actual effect visually, especially when roughness increases.

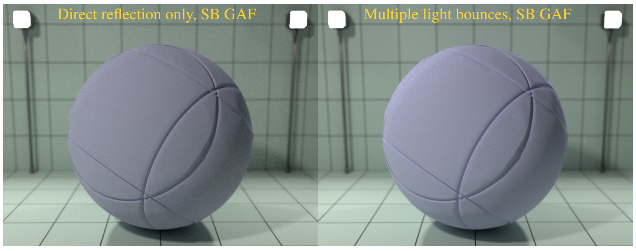

Figure 6: *Appearance of rough Lambertian materials* ($n_i = 1.0$) *with and without handling multiple light bounces between microfacets, with* $\gamma = 8, \sigma = 0.7$ *and Smith-Bourlier GAF.*

5. Conclusions and Future Work

Combining interfaced Lambertian microfacets with STD provides a physically plausible model for handling colored glossy and Lambertian or rough Lambertian objects, with the same representation. Only few parameters are necessary to provide an accurate control of the appearance. Another advantage is that it includes by construction several existing BRDF models, with distributions that are often used in academic research or in the industry. In the future, we aim at defining an approximate version of this combination, in order to reduce computation time. This would provide a possible use for interactive applications and measured data fitting for comparisons with real world materials. Our presentation brings some more details and more results on these aspects.

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