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A Taxonomy of Bidirectional Scattering Distribution Function Lobes for Rendering Engineers

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Abstract

We propose a taxonomy and terminology for rendering engineers to use in describing the main categories of mathematical lobes that are combined to implement bidirectional scattering distribution functions (BSDFs). Bringing consistent language to this area will increase clarity in API names, textbooks, and scholarly publications. We developed this taxonomy and terminology for consistency across our own upcoming works. The taxonomy corresponds to the major BSDF implementation branches in a renderer, rather than surface appearance, and is consistent with physical considerations. The terminology aligns as closely as possible with previous work in rendering and adjacent fields, while resolving inconsistencies among them. The taxonomy is not intended for art direction, machine vision research, optics, material/lighting engineering, or other areas where the critical distinctions between materials differ from those needed by a renderer.

1. Motivation

In computer graphics, *materials* are at the core of creating and analyzing images, the definition varies across contexts. Materials abstract surface geometry and internal volumetric structure at many scales, chemical properties, and physical states. They almost always vary with position and may also vary in time. Materials are also an arbitrary indirection point in modeling, where we might say that two objects have the same shape but different materials, thus grouping all differences between the objects into whatever "material" means within that system...friction coefficient, flammability, animation, audio properties, etc.

Many communities need ways of describing materials, including illumination engineers, artists working in both natural and digital media, optical physicists, surface physicists, mechanical engineers, and rendering engineers such as ourselves. The scope of "materials" and taxonomy and terminology for them appropriately varies across those groups based on their goals.

Rendering engineers (including scientists and students) currently employ inconsistent terminology among ourselves, which creates confusion. For this group, we propose a taxonomy of a well-defined domain: *the mathematical terms in a bidirectional scattering distribution function* (BSDF, a.k.a. BxDF) at an optical surface, which is implicitly between materials that we need not taxonomize. We use **lobe** to mean "mathematical term" in this paper to avoid confusion with linguistic "terms" = "terminology."

Within rendering engineering, there are subcommunities such as visual effects for live action, computer-generated animated film, video game developers, predictive rendering, and expressive rendering. Each has evocative terminology for BSDF terms, often adapted from adjacent fields, such as the art the renderer is intended to create or the underlying physics from which it is derived. The engineers in these groups need to communicate with each other to share advances. The US National Bureau of Standards [NRH*77] established (and the Illuminating Engineering Society follows) the definition of what are now known as BSDFs for physical and virtual measurements, but have not defined the common terms used to implement BSDFs.

In focusing on the functions, can set aside the sources of their constant parameters, which may be, e.g., read from textures, evaluated from a shader-node graph, or computed in explicit code. We also intentionally do not address displacement/normal/bump mapping for larger-scale features, phase functions in the context of participating media, or emission functions for light sources. Finally, we note but do not resolve that a "layered" BSDF denotes within the academic graphics community a compositing of the *filtering effects* of a stack of thin physical surfaces, such as varnish on wood (e.g., [KSK01]); whereas in the game development community "layered" denotes compositing BSDF *parameters* to disguise texture reuse.

Many popular analytic BSDFs resemble the Disney model [Bur12], which is an "uber-shader" that sums simpler lobes with weights assigned by artists. Each of these lobes has a pedigree in BSDF research and a history of usage that influences the terminology in this paper. Examples of related BSDF models include the Autodesk Standard Surface [GPA*19], the Filament Standard Model [GA20], and the UE4 Standard Material [Tea20]. BSDFs need not be artist-weighted sums (PBRT and Mitsuba are both trending towards measured or simulated curves), nor analytic; any representation of a function, such as tabular, stochastic, or machine-learning inference may represent one, and they can still be factored into lobes.

For implementation details, the SIGGRAPH 2012-2017 courses on physically based shading [HMC*17] contain production examples of BSDFs, their implementations, and their use, and the MERL 100 database [MPBM03] is a large set of measured BSDFs.

2. Methodology

To bridge the rendering subcommunities, we considered what common need they have for distinguishing and naming BSDF terms. We observe that branches occur between distinct implementation choices within the source code or algorithm of a renderer. Those choices require names, which appear in APIs, prose, and derivations.

For example, a probability distribution function that takes on only finite values is abstracted and sampled differently in code than one which may contain Dirac delta impulses.

Whether two materials have BSDFs that cause them to *appear* different is not the primary distinction for a rendering engineer. Whether the BSDFs can be implemented using the same algorithm is what matters.

Considering the implementation of physically based (or inspired) renderers, we found a hierarchy comprising three levels of implementation branches for BSDFs that was common across textbooks [DRS07, AMHH*18, PJH16, HvDM*13, MS16, McG19, Shi20] and libraries (e.g., [PJH16, KWR*17, NDVZJ19, GA20]). Each of the branches corresponds to a mathematical distinction and is loosely correlated with different physical phenomenon. We researched the names applied to these within the rendering and adjacent communities, and then selected what we felt to be the least ambiguous for each as a proposed canonical term.

3. BSDFs

A bidirectional scattering distribution function [BDW81] represents the distribution of scattered light over outgoing directions at a point on a surface, due to incoming light from a specific direction at the same point. It is radiometrically defined as the ratio of the change in outgoing radiance [$\mathrm{W\,m^{-2}\,sr^{-1}}$] at a point a direction to the change in incident irradiance [$\mathrm{W\,m^{-2}}$] at the same point.

For a given surface position, time, and wavelength of light (neglecting polarization), the BSDF is scalar-valued with units of per-steradian [$\mathrm{sr^{-1}}$]. It is often denoted $f_s(\hat{\omega}_i, \hat{\omega}_o)$ with unit vector arguments, or with angles, $f_s(\theta_i, \phi_i, \theta_o, \phi_o)$.

Analytic BSDF models have **parameters** that vary spatially, temporally, or spectrally but which are constant with respect to the angle arguments. Albedo and the microfacet roughness are examples.

The BSDF is a superset of special cases of the bidirectional reflectance distribution function (BRDF) and bidirectional transmission distribution function (BTDF). BSDFs commonly incorporate small-scale subsurface effects in which the incident and outgoing points for light on the surface may be slightly different but are within the precision limitations of the application at hand.

There are several related concepts of reflectance. The bidirectional scattering surface reflectance distribution function (BSSRDF) [JMLH01] has independent incident and outgoing positions. The directional-hemispherical reflectance function (DHRF) [NRH*77] is the integral of the BRDF over the outgoing hemisphere; the hemispherical-directional reflectance function (HDRF) [NRH*77] is the integral of the BRDF over the incident hemisphere. The bi-hemispherical reflectance function (BHRF) [NRH*77] measures reflectance under uniform diffuse illumination.

BSDFs are typically employed in a renderer both for evaluation when shading (i.e., direct illumination) and for sampling one direction proportional to the BSDF (and other factors), given the other direction. E.g., path tracing [Kaj86] samples the incoming direction given the outgoing one, photon scattering [Jen96] samples the outgoing direction given the incoming one, and bidirectional path tracing [LW98] uses both. There are other, less common cases such as in a Metropolis Light Transport [VG97] path mutation where where the structure of the renderer follows the BSDF.

4. Taxonomy

Figure 4 is our taxonomy of composable BSDF lobes. Bold words in this section and the diagram define our terminology. In the figure, the italic text describes how to recognize each lobe and gives an informal description of the physical phenomenon it models. The blue text explains why the distinction between terms at the same level is needed when implementing and modeling BSDF algorithms. We note some well-known analytic BSDFs and real-world surfaces that are dominated by each term. Choosing the most specific category to exploit its properties for quality or performance is the goal in BSDF and renderer implementation.

Each of the terms in the diagram except for retroreflection has a **reflection** (incoming and outgoing light on the same side of the surface) and a **transmission** (incoming and outgoing on opposite sides of the surface) variant. **Refractive** lobes are oriented away from the straight-through transmission direction, typically due to a change in refractive index. **Isotropic** BSDFs have rotational symmetry about the normal vector that *anisotropic* ones lack. Some BSDFs shift

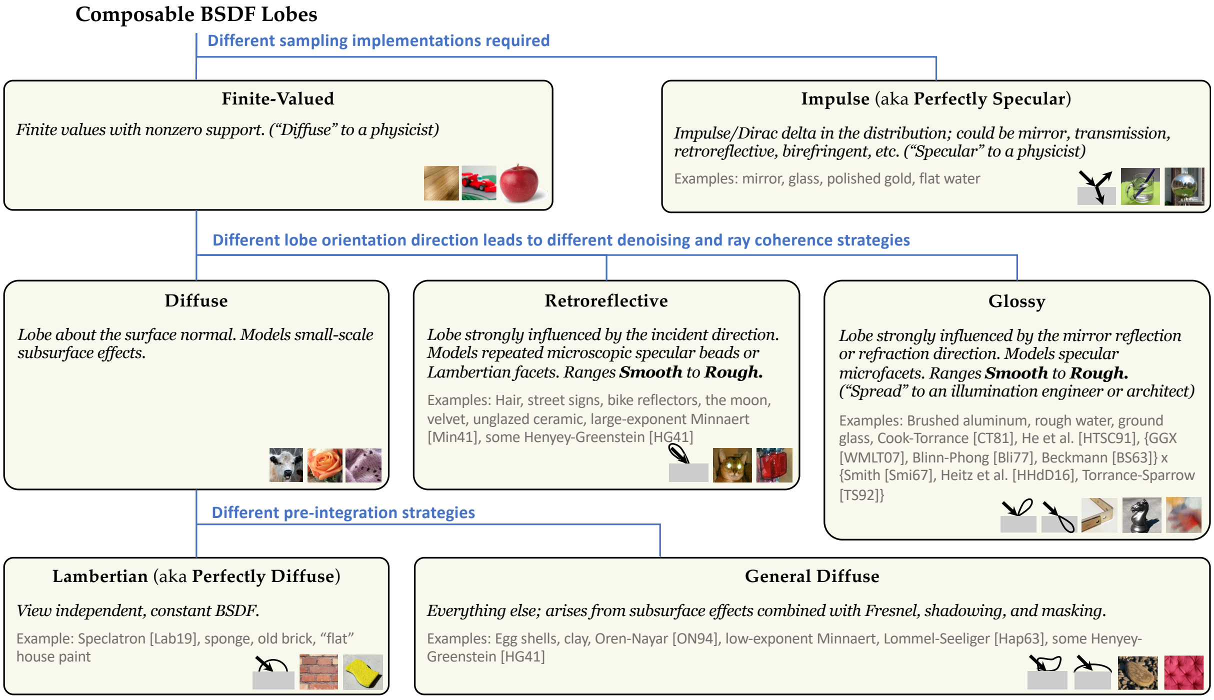

Figure 1: *The taxonomy. Icons sketch $f(45°, 0°, \theta_o, 0°)$ and show materials dominated by each lobe as an approximation.*

category based on their parameters (e.g., the same way the Henyey-Greenstein function does for phase functions).

True **Lambertian** is impossible and **impulse** is impractical, although both are useful approximations.

All real surfaces are more reflective at grazing angles. This phenomenon is modeled in physics by Fresnel's equations at the finest level. Graphics approximates [Sch94, KC17] it at many scales by interpolating between the impulse/glossy/retroreflective and diffuse lobes to simulate effects such as Fresnel, coated fibers and anisotropic sheen for cloth, clear coat rim-lighting, and peach fuzz.

4.1. Significant Previous Terminology

By design, our terminology is largely consistent with previous usage but makes it more precise.

Physics distinguishes "specular," meaning mirrorlike, from "diffuse" = finite-valued; i.e., light that is diffused.

Heckbert's path notation [Hec90] used "specular" = impulse and "diffuse" = finite-valued, because they require different sampling strategies. However, his work was on radiosity, so "diffuse" in practice always meant Lambertian. Veach's thesis [Vea98] is a foundational reference for rendering algorithms, but is inconsistent in its BSDF terminology. He mostly uses "diffuse" = Lambertian, but in other cases uses "diffuse" = finite-valued. Pharr et al. [PJH16] use "perfect specular," "retroreflective," and "Lambertian" in the same way as we define, and "glossy specular" = glossy.

Nicodemus et al. [NRH*77] use "perfectly specular" and "perfectly diffuse" in the same way we do, and "diffuse" = both retroreflective + diffuse. "Glossy" appears only once in passing; they use "rough specular" = glossy. Notably, they advise against using the unmodified phrases "specular" and "diffuse" at the time due to lack of agreement as to what those meant: "However, we feel that to do this is to make an unnecessarily artificial distinction, since the choice of what is included as specular and what as diffuse turns out to depend in many situations on the interests and objectives of the investigator or user and on the resolution capability of his instrumentation." We follow their advice in two ways: we use those terms only where modified by adjectives, and address our definitions to a specific application.

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