# Principles of Appearance Acquisition and Representation

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# Principles of Appearance Acquisition and Representation

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## Abstract

Algorithms for scene understanding and realistic image synthesis require accurate models of the way real-world materials scatter light. This study describes recent work in the graphics community to measure the spatially- and directionally-varying reflectance and subsurface scattering of complex materials, and to develop efficient representations and analysis tools for these datasets. We describe the design of acquisition devices and capture strategies for reflectance functions such as BRDFs and BSSRDFs, efficient factored representations, and a case study of capturing the appearance of human faces.

# Contents

# 1

# Radiometry and Appearance Models

Comprehending the visual world around us requires understanding the role of *materials*. In essence, we think of the appearance of a material as being a function of how that material interacts with light. The material may reflect light or may exhibit more complex phenomena such as subsurface scattering.

Reflectance is itself a complex phenomenon. In general, a surface may reflect a different amount of light at each position, and for each possible direction of incident and exitant light (Figure 1.1, left). So, to completely characterize a surface's reflection we need a six-dimensional function giving the amount of light reflected for each combination of these variables (position and incident and exitant directions are two dimensions each). Note that this does not even consider such effects as time or wavelength dependence. We will consider those later, but for now let us simply ignore all time dependence and assume that any wavelength dependence is aggregated into three color channels: red, green, and blue.

These reflectance functions embody a significant amount of information. They can tell us whether a surface is shiny or matte, metallic or dielectric, smooth or rough. Knowing the reflectance function for

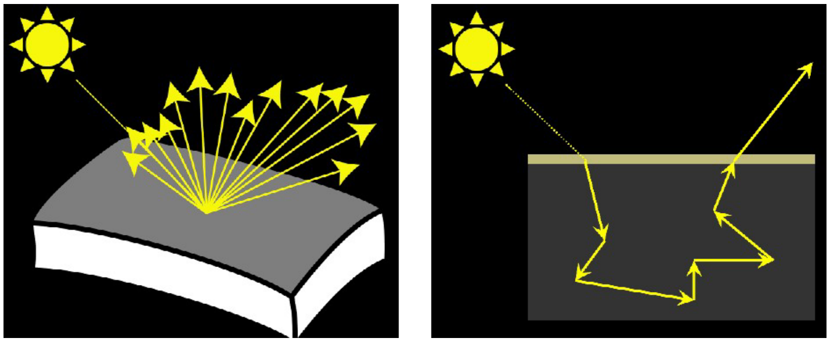

Fig. 1.1 Materials can exhibit reflectance (left), subsurface scattering (right), or more complex scattering phenomena.

a surface allows us to make complete predictions of how that surface appears under any possible lighting.

For translucent surfaces, the interaction with light can no longer be described as simple reflection. This is because light leaves the surface at a different point than where it entered (Figure 1.1, right). So, in order to characterize such surfaces we need a function that gives the amount of light that is scattered from each possible position (2D) to each other position (another 2D). To be even more correct, of course, it would be necessary to account for the directional dependency as well.

This study covers the basic principles of how materials are described, how the appearance of real-world objects may be measured, and how a knowledge of appearance aids in a variety of applications. In addition to the obvious application domain of image synthesis, having a complete knowledge of a material's appearance can help in interpreting images. It will aid in 3D reconstruction, view interpolation, and object recognition. Furthermore, knowing how to characterize materials can help in understanding how humans perceive surfaces.

This section covers foundational topics. It will survey the domain of *radiometry* and introduce the definition of the Bidirectional Reflectance-Distribution Function (BRDF): a function describing surface reflectance at a point. It will then cover generalizations of the BRDF, including spatial variation and subsurface scattering. Finally, it will consider the many different types of data that can be captured that characterizes "appearance," and how they relate to each other.

## 1.1 Radiometry

The field of radiometry is concerned with the characterization of the "amount" of electromagnetic radiation, including light, flowing in space. Though this chapter presents some fundamental concepts, the reader is referred to classic works such as those of Ishimaru [80] for more details.

To begin, it is necessary to consider the different quantities related to light flow, and the *radiometric units* in which they are expressed. Light is a form of electromagnetic energy, and so can be measured using the SI units of Joules. Because in graphics and vision we usually consider steady-state flows, instead of individual pulses or quanta, we will most often be interested in the amount of energy flowing per unit time. This is known as "radiant flux" ($\Phi$) or just "power," and hence may be measured using the SI units of Watts.

Although having a way of characterizing the total flow of light is useful, we will need to consider more complex quantities in order to talk about concepts such as light sources and surface reflectance.

**Point Light in a Direction:** Consider an ideal light source (idealized as a point in space). If the light were being emitted uniformly in all directions, describing its power (in Watts) would characterize it completely. However, it is possible that light is not being emitted equally in all directions. In this case, characterizing the power being emitted in a *particular* direction requires a different unit. In such cases, we can talk about the amount of power being emitted per unit *solid angle*.

So what exactly is a solid angle, and how is it measured? A useful analogy is to the way an angle is defined in the plane. One radian is defined as the angle subtended by an arc of a circle, with the arc length being equal to the circle's radius. Equivalently, an angle in radians may be calculated by dividing the length of a circular arc by the radius.

Moving to the concept of solid angles, we will be working in three dimensions (vs. two for angles), and will be looking at a sphere (vs. a circle). The fundamental unit of solid angle is known as the *steradian*, and is defined as the area of some region on a sphere divided by the

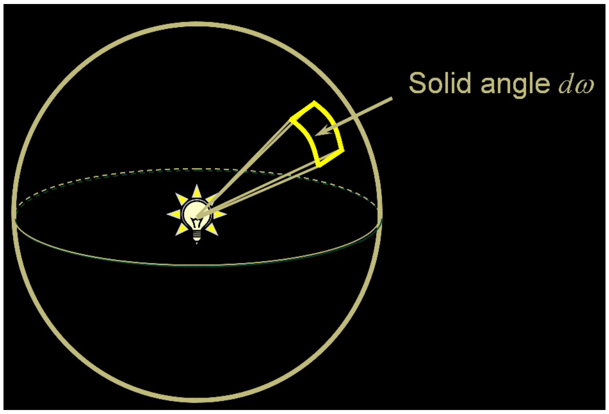

Fig. 1.2 Point light source emitting light in a direction.

square of the sphere's radius. A complete sphere thus has $4\pi$ steradians, and smaller solid angles define smaller regions of the space of directions.

So, measuring the directional power or *radiant intensity* of a point light source can be done using the units of Watts per steradian:

$$I = \frac{d\Phi}{d\omega}. \qquad [\mathrm{W \cdot sr^{-1}}] \tag{1.1}$$

The same amount of power emitted into a smaller solid angle will result in a larger measurement (e.g., consider a laser, which has relatively low power but concentrated into a small solid angle).

**Light Falling on a Surface:** Another radiometric quantity we often wish to measure is called *irradiance*. It represents the amount of light falling onto a surface. Because the same radiant flux will be "more concentrated" when falling onto a smaller area of surface than a larger surface, we define irradiance $E$ as power per unit area:

$$E = \frac{d\Phi}{dA}. \qquad [\mathrm{W \cdot m^{-2}}] \tag{1.2}$$

Note that we write this definition in differential form, to emphasize that we are concerned with the limit of incident power per unit area, as that area shrinks to zero.

Given this definition of irradiance, there are two immediate and easily-observed "laws" that emerge. The first is the inverse-square law: moving a point light source away from a surface reduces irradiance in proportion to the inverse square of the distance. Secondly, tilting a surface away from a point light results in a lower irradiance, in proportion to the cosine of the angle between the surface normal and the direction toward the light. This "cosine law" is often written as the dot product between the (unit-length) surface normal and light vectors.

**Light Emitted from a Surface in a Direction:** We now come to the final, and most complex, radiometric quantity we are going to consider, which describes the emission of light from a surface. This can be thought of as combining the two concepts we just saw: the emitted light can vary with direction (hence we must control for its directional distribution, as we did with the point-light case), and we are interested in the amount of light emitted per unit surface area. This is almost enough for a practical definition of *radiance*, but it is conventional to use a slightly different, "observer-based" definition of surface area, instead of the one used for irradiance. In particular, an observer or sensor measuring light emitted from a surface will be sensitive to *projected* surface area, perpendicular to the viewing direction (see Figure 1.3).

Hence, we arrive at the definition of radiance: power emitted per unit projected area (perpendicular to the viewing direction) per unit

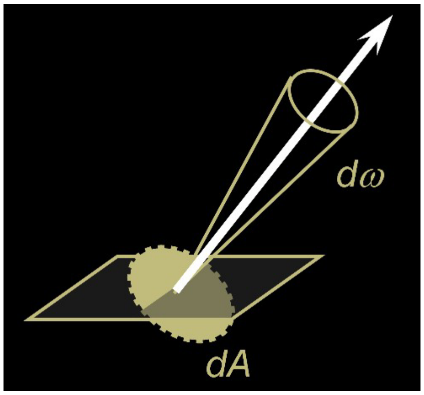

Fig. 1.3 Radiance is defined as light emitted from a surface, in a specific direction, per unit (projected) area.

solid angle:

$$L = \frac{d\Phi}{dA_{\text{proj}}\, d\omega}. \qquad [\mathrm{W \cdot m^{-2} \cdot sr^{-1}}] \tag{1.3}$$

Radiance is perhaps the most fundamental unit in computer vision and graphics. It is easy to show that the irradiance on a camera sensor is proportional to the radiance of the surfaces it is imaging, with the constant of proportionality determined by the imaging optics. (More accurately, the optical system effectively integrates the radiance over the solid angle subtended by the aperture, as seen from the surface.) The sensor irradiance at each pixel is converted to an electrical signal, then digitized, and so the pixel values we deal with in digital images are (ignoring effects such as gamma applied to the pixel values) proportional to radiance.

Integrating radiance over all exitant angles, including a cosine term to account for projected area, gives a quantity called *radiant exitance*, which is frequently encountered in graphics simulations:

$$M = \int_{\Omega} L(\theta, \varphi) \cos\theta \, d\omega. \qquad [\mathrm{W \cdot m^{-2}}] \tag{1.4}$$

When radiance is equal for all exitant directions, as is the case for some surfaces, this quantity is usually called *radiosity* and is conventionally denoted by the symbol $B$.

**The Plenoptic Function and the Light Field:** Radiance in a scene may be represented by the *plenoptic function*, which is a positive function defined on a five-dimensional domain:

$$L(x, y, z, \theta, \phi) \qquad [\mathrm{W \cdot m^{-2} \cdot sr^{-1}}]. \tag{1.5}$$

representing the radiance in every ray direction at every point in three-dimensional space [1]. Since radiance is constant along rays in free space, we can often drop one of these dimensions, and the resulting four-dimensional entity is referred to as the *lumigraph* [60] or, more commonly, the *(4D) light field* [105]. (Note that the term “light field” was originally introduced by Gershun [53] to describe a vector, rather than scalar, version of the 5D function.) The set of rays representing a light field may be parameterized in several ways, in addition to the obvious point/angle parameterization $L(x,y,\theta,\phi)$. In particular, it is common to parameterize a "light slab" by the positions of ray intersections with two planes: $L = L(u,v,s,t)$, where $(u,v)$ and $(s,t)$ are the coordinates on two specified planes.

**Radiometry vs. Photometry:** The preceding discussion has focused purely on physical (radiometric) units, which is appropriate when dealing with acquisition apparatus. However, there is a parallel set of *photometric* units, which also take into account the intensity perceived by a human observer. In particular, they account for the fact that the human eye is sensitive to a range of wavelengths from 400 (blue) to 700 (red) nanometers, but that the sensitivity is not constant within that range.

The original photometric unit was an "international standard candle," defined in terms of carbon filament lamps. Today, the *candela* is one of the seven base SI units: one candela is the luminous intensity of a light source producing 1/683 Watt per steradian, at a frequency of $540 \times 10^{12}$ Hz (corresponding to green light with a wavelength of approximately 555 nm). Beginning with this unit, it is possible to define concepts analogous to radiant flux, irradiance, and radiance, namely luminous power (measured in lumens, where one lumen is equal to one candela times one steradian), illuminance (measured in lux = lumens per square meter), and luminance (measured in nits = candelas per square meter or lux per steradian).

While it is important to be aware of the difference between radiometry and photometry, we will assume single-wavelength, radiometric measurements in the remainder of this section.

## 1.2 Surface Reflectance

Having learned about radiometry, we are now ready to define the Bidirectional Reflectance-Distribution Function (BRDF), which characterizes reflection at a point on a surface [142]. Formally, it is the ratio between the reflected radiance of a surface and the irradiance that caused that reflection. The radiance and irradiance are each measured at a particular angle of exitant and incident light, respectively, so the BRDF is usually written as a function of four variables: the polar angles of incident and exitant light.

$$f_{\mathrm{r}}(\boldsymbol{\omega}_{\mathrm{i}} \to \boldsymbol{\omega}_{\mathrm{o}}) = f_{\mathrm{r}}(\theta_{\mathrm{i}}, \varphi_{\mathrm{i}}, \theta_{\mathrm{o}}, \varphi_{\mathrm{o}}) = \frac{dL_{\mathrm{o}}(\boldsymbol{\omega}_{\mathrm{o}})}{dE_{\mathrm{i}}(\boldsymbol{\omega}_{\mathrm{i}})}. \qquad [\mathrm{sr}^{-1}] \qquad (1.6)$$

The BRDF has units of inverse steradians and is often written as a differential quantity. This is to emphasize that there is no such thing as light arriving from *exactly* one direction, and being reflected into exactly one outgoing direction. Rather, we must look at non-zero incident and exitant solid angles, and consider the limit as those approach zero.

Because BRDFs are 4D functions, they are a bit tricky to visualize directly. Instead, we often visualize two-dimensional slices of this function. Figure 1.4 shows two 2D slices of a BRDF, each corresponding to one direction of incidence (the arrow) and all possible directions of reflection. The blue surface is a hemisphere stretched such that its radius in any direction is the reflected radiance in that direction, and is known as a goniometric plot.

You will note that, for this particular BRDF, some of the incident light is reflected equally in all directions. This is the constant-radius (spherical) portion of the surface you see. However, there is also a bump in the surface, indicating that there is a concentrated reflection in one particular direction.

If we change the direction of incidence, we see that the constant portion of the function remains unchanged, but the position of the bump moves. In fact, the bump always appears near the direction of

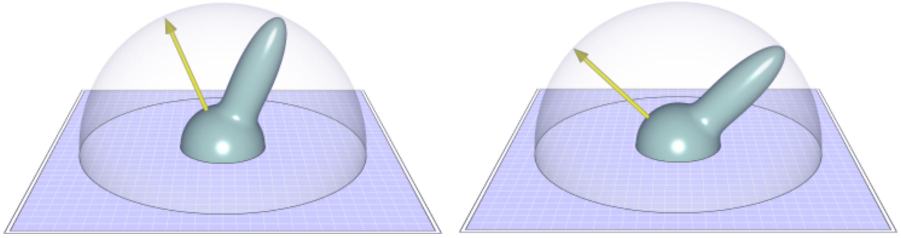

Fig. 1.4 Goniometric view of slices of a BRDF corresponding to two incident directions (denoted by the yellow arrows).

"ideal mirror reflection" of the incident direction. This is known as a specular highlight, and it gives a surface a shiny appearance.

**Properties of the BRDF:** Before we look at specific BRDF models, let us discuss a few properties shared by all BRDFs. The first is **energy conservation**. Because all incident light must be either reflected or absorbed, and no light may be created during reflection, it is impossible for a surface to reflect more light than was incident on it. Expressing this mathematically, we see that the integral of the BRDF over all outgoing directions, scaled by a cosine term to account for foreshortening, must be less than one:

$$\forall \boldsymbol{\omega}_{\mathrm{i}} : \int_{\Omega} f_{\mathrm{r}}(\boldsymbol{\omega}_{\mathrm{i}}, \boldsymbol{\omega}_{\mathrm{o}}) \cos\theta_{\mathrm{o}} \, d\boldsymbol{\omega}_{\mathrm{o}} \leq 1. \tag{1.7}$$

A second, more subtle, property of BRDFs is that they must be unchanged when the angles of incidence and exitance are swapped:

$$f_{\mathrm{r}}(\boldsymbol{\omega}_{\mathrm{i}} \rightarrow \boldsymbol{\omega}_{\mathrm{o}}) = f_{\mathrm{r}}(\boldsymbol{\omega}_{\mathrm{o}} \rightarrow \boldsymbol{\omega}_{\mathrm{i}}). \tag{1.8}$$

This is a condition known as **Helmholtz reciprocity**, and is due to the symmetry of light transport [186]. Some systems, such as the work on Helmholtz stereopsis [211], have relied on this property, which often expressed as camera/projector duality: in many imaging systems it is possible to interchange the roles of camera and projector, provided that cosine terms are properly accounted for.

Though all real BRDFs satisfy the above two properties, measured data (which can include non-local effects) and the adhoc shading models used in graphics and vision frequently do not. The term *physically-plausible BRDF* is sometimes used for reflectance functions that satisfy energy conservation and reciprocity.

Some, but not all, BRDFs have a property called **isotropy**: they are unchanged if the incoming and outgoing vectors are rotated by the same amount about the surface normal. With isotropy, a useful simplification may be made: the BRDF is really a three-dimensional function in this case, and depends only on the *difference* between the azimuthal angles of incidence and exitance.

The inverse of isotropy is **anisotropy**. An anisotropic BRDF does not remain constant when the incoming and outgoing angles are

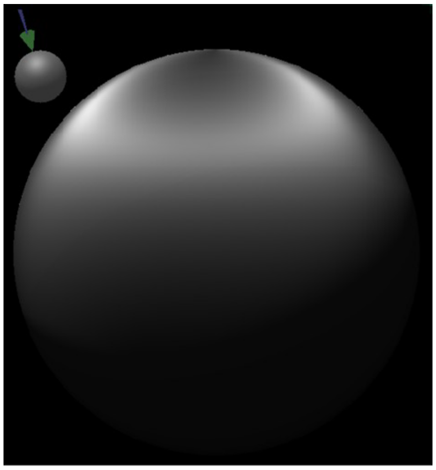

Fig. 1.5 Anisotropic reflection.

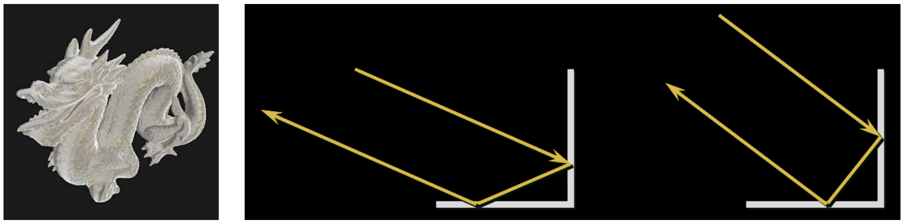

Fig. 1.6 Left: dusty surfaces exhibit an increase in reflection toward grazing angles [152]. Right: corner-reflectors are one example of a configuration that may produce retroreflection.

rotated. In this case, a full four-dimensional function is necessary to characterize the behavior of the surface. Anisotropic materials are frequently encountered when the surface has a strongly directional structure at the small scale: brushed metals are one example (Figure 1.5).

Another commonly observed characteristic of some BRDFs is **asperity scattering**: an increase in light reflected into all grazing angles, as is typical for "dusty" surfaces (Figure 1.6, left). Finally, some BRDFs exhibit **retro-reflection**. That is, they scatter light most strongly back into the direction from which it arrived. Street signs and the paint found on roads are common examples of this phenomenon, which is created through "corner reflector" configurations (Figure 1.6, right) or particles of high-index material embedded in paint.

**Parameterization:** Thus far, we have assumed that the 4D BRDF domain is parameterized by the spherical coordinates of the incident and reflected directions. We are free to choose any parameterization, of course, and there are others with significant advantages. We may require a parameterization without singularities, for example, or we may want one that allows a more compact or intuitive representation.

One useful parameterization of the BRDF [159] uses the "halfway" vector $\boldsymbol{h}$ (i.e., the vector halfway between the incoming and reflected rays) and a "difference" vector $\boldsymbol{d}$, which is just the incident ray in a frame of reference in which the halfway vector is at the north pole (see Figure 1.7). Using the spherical angles of $\boldsymbol{h}$ and $\boldsymbol{d}$, a point in the BRDF domain is written:

$$(\theta_{\mathrm{h}}, \varphi_{\mathrm{h}}, \theta_{\mathrm{d}}, \varphi_{\mathrm{d}}) \subset [0, 2\pi) \times [0, \pi/2) \times [0, \pi) \times [0, \pi/2). \tag{1.9}$$

A typical BRDF varies slowly over much of its domain, and the halfway/difference parameterization exploits this by moving the coordinate axes away from these regions. The axes are aligned with directions of common BRDF phenomena (specular and retro-reflective peaks) and this enables representations that are both intuitive and efficient.

Isotropy and Helmholtz reciprocity are conveniently described using the halfway/difference parameterization. Helmholtz reciprocity implies that the BRDF is unchanged under $\varphi_{\mathrm{d}} \longrightarrow \varphi_{\mathrm{d}} + \pi$, so that $\varphi_{\mathrm{d}}$ can be restricted to $[0, \pi)$. Isotropy implies that the BRDF is a constant

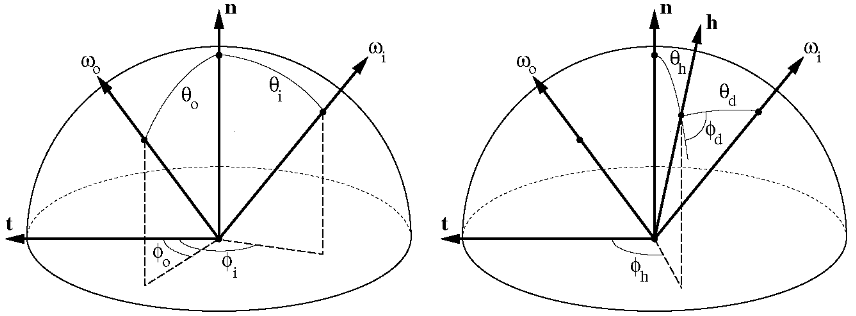

Fig. 1.7 Halfway/difference angle parameterization of BRDFs. Instead of treating the BRDF as a function of $(\theta_{\mathrm{i}}, \varphi_i)$ and $(\theta_{\mathrm{o}}, \varphi_o)$, as shown at left, the BRDF is considered a function of the half-angle $(\theta_{\mathrm{h}}, \varphi_h)$ and a difference angle $(\theta_{\mathrm{d}}, \varphi_d)$, as shown at right. The vectors marked $\boldsymbol{n}$ and $\boldsymbol{t}$ are the surface normal and tangent, respectively.

function of $\varphi_{\mathrm{h}}$, meaning that this dimension can simply be ignored in the isotropic case.

For glossy surfaces, specular peaks occur at small half-angles (i.e., $\theta_{\mathrm{h}} \approx 0$), but variation with respect to the difference angle ($\theta_{\mathrm{d}}$) is governed primarily by Fresnel reflection and tends to be limited for small and moderate values of $\theta_{\mathrm{d}}$.

**Lambertian BRDF:** We now turn to looking at specific examples of BRDFs. We will look at simple examples, such that the reflectance may be written as a mathematical formula. Real surfaces, of course, are more complex than this, and mathematical models frequently do not predict the reflectance with great accuracy.

The simplest possible BRDF is just a constant:

$$f_{\mathrm{r}} = \mathit{const.} = \rho/\pi. \tag{1.10}$$

(Keep in mind that the BRDF is defined in terms of irradiance, which has the "incident cosine law" implicitly included.) This results in a matte or diffuse appearance, and is known as ideal Lambertian reflectance. This BRDF is frequently written as a constant $\rho$ divided by $\pi$. In this case, $\rho$ is interpreted as the diffuse albedo: it is the fraction of light that is reflected (vs. absorbed) by the surface. Plugging this BRDF into the energy conservation integral verifies that the surface conserves energy precisely when the albedo is less than or equal to one.

**Phong and Blinn–Phong BRDFs:** Another simple analytic BRDF is the Phong model [153], designed to qualitatively mimic the the appearance of glossy materials:

$$f_{\mathrm{r}} = k_{\mathrm{s}}\,(\boldsymbol{r} \cdot \boldsymbol{v})^{n}, \tag{1.11}$$

where $\boldsymbol{v}$ is the view direction and $\boldsymbol{r}$ is the mirror reflection of the light direction from the tangent plane. Note that the Phong "BRDF" used in computer graphics often includes an additional $1/\cos\theta_{\mathrm{o}}$ factor, which is canceled by the irradiance "cosine law." This is not a physically-plausible BRDF: it does not exhibit reciprocity, and does not conserve energy.

A common variant of this model is sometimes known as the Blinn-Phong model [9]:

$$f_{\mathrm{r}} = k_{\mathrm{s}} \, (\boldsymbol{n} \cdot \boldsymbol{h})^{n}, \tag{1.12}$$

though again it is often stated as a physically-implausible shading model rather than a BRDF. Lewis [106] introduced a physically-plausible BRDF based on this model that is appropriately scaled to conserve energy.

In contrast to the Lambertian BRDF, the distribution of reflected light in these models is not constant. In fact, there is a lobe centered around the direction of ideal mirror reflection for each incident angle, containing significantly more energy than the rest of the domain. This is known as the specular lobe, and its size and width (fall-off) are controlled by the parameters $k_{\mathrm{s}}$ and $n$, respectively.

There are a few things to remember when working with the above models. First, they are not physically-based and only qualitatively reproduce the rough appearance of a specular lobe. Second, in computer graphics these models are frequently not presented as BRDFs, but rather operate on incident illumination quantities that have not had the "cosine law" applied. In this case, the models that are actually used are equivalent to "BRDFs" with the incident cosine divided out, and hence do not satisfy Helmholtz reciprocity. Finally, the specular exponents $n$ in the original Phong and Blinn-Phong formulations are not equivalent in the widths of highlights they produce. To obtain roughly-equivalent highlights from the Blinn-Phong model, it is necessary to use an $n$ that is four times as large as in the Phong model.

**Lafortune BRDF:** A popular model used for fitting analytic functions to measured BRDF data is the Lafortune model [93]:

$$f_{\mathrm{r}} = \left(C_{\mathrm{x}} l_{\mathrm{x}} v_{\mathrm{x}} + C_{\mathrm{y}} l_{\mathrm{y}} v_{\mathrm{y}} + C_{\mathrm{z}} l_{\mathrm{z}} v_{\mathrm{z}}\right)^{n}, \tag{1.13}$$

in which $l_{\mathrm{x}}$, $v_{\mathrm{x}}$, etc. represent the components of the light vector $\boldsymbol{l}$ and view vector $\boldsymbol{v}$, in a coordinate system in which the surface normal is oriented along the $z$ axis. This model reduces to Phong by choosing $-C_x = -C_y = C_z = \sqrt[n]{k_s}$, but through suitable choice of parameters can also represent non-Lambertian diffuse reflection, off-specular reflection, anisotropy, and retro-reflection. It is also common to fit a sum of multiple lobes of (1.13) to measured datasets.

**Ward BRDF:** Another popular BRDF used in fits to measurements is the Ward model [191]:

$$f_r = k_s \, \frac{\mathrm{e}^{-\tan^2\theta_\mathrm{h}\left((\cos^2\phi_\mathrm{h})/\alpha_\mathrm{x}^2 + (\sin^2\phi_\mathrm{h})/\alpha_\mathrm{y}^2\right)}}{4\pi\,\alpha_\mathrm{x}\alpha_\mathrm{y}\sqrt{\cos\theta_\mathrm{i}\cos\theta_\mathrm{o}}}. \tag{1.14}$$

Compared to the Blinn–Phong BRDF, the Ward model includes a specular peak shaped by a Gaussian function (as opposed to a power-of-cosine model), but also can model anisotropic reflection by using separate Gaussian widths $\alpha_x$ and $\alpha_y$ in two perpendicular directions.

**Torrance-Sparrow BRDF:** Numerous BRDFs have been derived from first principles that predict the aggregate reflectance for surfaces that at a small scale consists of tiny, mirror-reflective "microfacets" oriented in random directions. An early microfacet BRDF was originally developed in the physics community by Torrance and Sparrow [181], introduced to the graphics community by Blinn [9], and later refined by Cook and Torrance [18]:

$$f_\mathrm{r} = \frac{D\ G\ F}{\pi\ \cos\theta_\mathrm{i}\ \cos\theta_\mathrm{o}}. \tag{1.15}$$

There are three major terms in the model that describe the angular distribution of microfacets, how many are visible from each angle, and how light reflects from each facet.

The first term $D$ in the Torrance–Sparrow model describes the density of facets facing in any possible direction:

$$D = \frac{\mathrm{e}^{-(\tan^2\theta_\mathrm{h})/m^2}}{4m^2\ \cos^4\theta_\mathrm{h}}, \tag{1.16}$$

where $\theta_\mathrm{h}$ is the angle between the halfway vector $\boldsymbol{h}$ and the surface normal $\boldsymbol{n}$. Notice that part of this term resembles a Gaussian, and this is not a coincidence: the Torrance–Sparrow model makes the assumption that the microfacet normals have a Gaussian distribution controlled by a "roughness" parameter $m$. The $\cos^4\theta_{\mathrm{h}}$ term occurring here is a change-of-basis term: it is included to properly normalize a probability distribution expressed in terms of the halfway vector.

The next term $G$ in the Torrance–Sparrow model accounts for the fact that not all facets are visible from all directions, because they are hidden by the facets in front of them. It includes both "shadowing" and "masking" effects, representing occlusion from the point of view of the light and viewer, respectively:

$$G = \min\left\{1,\ \frac{2\cos\theta_{\mathrm{h}}\cos\theta_{\mathrm{i}}}{\cos\theta_{\mathrm{d}}},\ \frac{2\cos\theta_{\mathrm{h}}\cos\theta_{\mathrm{o}}}{\cos\theta_{\mathrm{d}}}\right\}. \tag{1.17}$$

This formula is derived by considering a particular microgeometry: the microfacets are assumed to form V-shaped grooves in the surface, which are symmetric about the (macroscopic) surface normal.

Finally, the reflection from each facet is described by the Fresnel term $F$, which predicts that reflection increases toward grazing angles. This term arises from a solution to Maxwell's equations on a surface:

$$F = \frac{1}{2}\Big(F_{\perp} + F_{\parallel}\Big) = \frac{1}{2}\left[\left(\frac{\sin(\theta_t - \theta_{\mathrm{d}})}{\sin(\theta_{\mathrm{t}} + \theta_{\mathrm{d}})}\right)^2 + \left(\frac{\tan(\theta_{\mathrm{d}} - \theta_{\mathrm{t}})}{\tan(\theta_{\mathrm{d}} + \theta_{\mathrm{t}})}\right)^2\right], \tag{1.18}$$

where $\theta_{\mathrm{t}} = \sin^{-1}\big((\sin\theta_{\mathrm{d}})/\eta\big)$, $\eta$ is the index of refraction of the surface, and the two terms represent the portion of reflected light polarized perpendicular and parallel to the plane of incidence. Note that this term involves the "difference angle" $\theta_{\mathrm{d}}$, as defined in Figure 1.7, which is the angle of incidence (and exitance) on a microfacet oriented to produce mirror reflection between the desired angles of incidence and reflection.

More recently, Ashikhmin et al. [3] generalized these types of microfacet BRDFs to allow expressing arbitrary half-angle distributions. They demonstrate how to modify these BRDFs to replace the analytic distribution in (1.16) with alternative analytic forms or tabulated (sampled) functions that can express arbitrary patterns.

**More complex analytic BRDFs:** In addition to models for primarily-specular surfaces, physically-based BRDFs have been derived for rough diffuse surfaces (the Oren–Nayar model [146]), and for dusty surfaces (the Hapke/Lommel–Seeliger model, developed to model lunar reflectance [66]). They range in complexity from simple formulas that ignore many real-world effects to complex models that attempt to account for most actually observed surface phenomena (e.g., the He–Torrance–Sillion–Greenberg model [71]). While a detailed description of these models is beyond the scope of this study, they are frequently used in photo-realistic rendering systems. One drawback of these models, however, is that their additional complexity and many parameters can make it difficult or unstable to fit them to measured data.

**Beyond Analytic BRDFs:** Although we could continue to develop mathematical BRDF formulas of increasing sophistication that explains a greater variety of optical phenomena, over the past decade it has become increasingly practical to simply measure the BRDFs of real material samples [122]. In fact, this is one of the main theses of the avenue of research surveyed in this study: that measured data can capture a greater variety of real-world optical phenomena with greater accuracy than is possible with analytic models.

## 1.3 6D Datasets: SVBRDFs, BTFs, and Distant-Light Reflectance Fields

Of course, the BRDF is merely the beginning of our study of the appearance of materials. Real-world objects will exhibit more complex behaviors, such as a BRDF that changes from point to point on the surface. Adding two spatial dimensions to the four directional dimensions of the BRDF leads us to the six-dimensional Spatially-Varying BRDF:

$$SVBRDF(x,y,\theta_{\mathrm{i}},\varphi_{\mathrm{i}},\theta_{\mathrm{o}},\varphi_{\mathrm{o}}). \qquad [\mathrm{sr}^{-1}] \tag{1.19}$$

Section 3 of this article describes the challenges of capturing, representing, editing, and analyzing these complex functions [94].

The study of the Spatially-Varying Bidirectional Reflectance-Distribution Function (SVBRDF) necessarily represents a shift from thinking of the appearance of "materials" to that of "objects," and therefore requires considering the role of object geometry. In cases in which the geometry is known (either because it is planar or because it has been scanned or modeled), the spatial dimensions of the SVBRDF are simply represented on a parameterization of that geometry. The SVBRDF is thus defined very close to the interface between a surface and the surrounding air, and it seeks to describe the scattering effects that occur at and immediately below this interface.

In many cases, however, it is impossible, difficult, or undesirable to model the scene geometry and to compensate for its effects during measurement. In this case, a 6D function may still be defined, with the spatial dimensions represented relative to some reference surface, or simply as image coordinates in a camera that was used for capture. In this case, the function is often called a *non-local reflectance field*, or simply *6D reflectance field*. It may be thought of as representing the *apparent* exitant light field $L(x,y,\theta_\mathrm{o},\phi_\mathrm{o})$ [105, 60] due to all possible directions of (non-local) incident light or, equivalently, the (4D) reflectance field $R(x,y,\theta_\mathrm{i},\phi_\mathrm{i})$ [30] for all possible viewing directions. When the reference geometry is planar, the term *Bidirectional Texture Function* (BTF) is frequently used [24].

BTFs and 6D reflectance fields, if sampled sufficiently densely, can represent non-local effects including those of foreshortening, occlusion, shadowing, refraction, subsurface and volumetric scattering, and interreflection. They are useful for objects that have significant mesostructure, or geometric structure that exists at or near the measurement scale. However, they give up the property that 4D “slices” at individual locations on the reference surface are proper physically-plausible BRDFs. Because of the non-local effects on apparent reflectance, they may fail to satisfy reciprocity or energy conservation and, even for surfaces with an underlying isotropic material, might not exhibit isotropy.

## 1.4 Subsurface Scattering

The SVBRDF and the BTF are not enough to characterize all materials. Many surfaces exhibit translucency: a phenomenon in which light enters the object, is reflected inside the material, and subsequently re-emerges from a different point on the surface. Such subsurface scattering can have a dramatic effect on appearance, as can be seen from these computer graphics simulations that differ in only one respect: the left image simulates surface reflection only, while the right image includes subsurface scattering [150].

In order to cope with subsurface scattering, we will need to examine more complex appearance functions: those that can include the phenomenon of light leaving the surface at a different point than the one at which it entered.

### 1.4.1 The BSSRDF

The relevant function is known as the Bidirectional Scattering-Surface Reflectance-Distribution Function, or BSSRDF:

$$S(x_\mathrm{i},y_\mathrm{i},\theta_\mathrm{i},\varphi_\mathrm{i},x_\mathrm{o},y_\mathrm{o},\theta_\mathrm{o},\varphi_\mathrm{o}) = \frac{dL(x_\mathrm{o},y_\mathrm{o},\theta_\mathrm{o},\varphi_\mathrm{o})}{d\Phi(x_\mathrm{i},y_\mathrm{i},\theta_\mathrm{i},\varphi_\mathrm{i})}. \qquad [\mathrm{m}^{-2}\cdot\mathrm{sr}^{-1}] \tag{1.20}$$

This takes the SVBRDF and adds two more variables, representing the surface location at which the light leaves the surface: we are now up to a function of eight variables.

Unlike the BRDF, which is defined relative to input power averaged over a differential area, the BSSRDF is defined relative to input power at a single point. For this reason, the BSSRDF is expressed as a fraction of incident flux instead of incident irradiance, and its units are inverse squared meters times inverse steradians [142].

As we will see later in this article, the high dimensionality of this function leads to great difficulty in capturing and working with the BSSRDF directly, especially if a high sampling rate in each dimension is desired [57].

### 1.4.2 The Dipole Model

Because of the enormous size of the BSSRDF, approximations to it have become quite popular. One of the most powerful relies on the fact that, in many cases, the appearance is dominated by light that has reflected many times within the material. In this case, the details of each scattering event become unimportant, and the appearance is well approximated by thinking of light "diffusing" away from the location at which it enters the surface, much as heat might spread [83].

It turns out that the pattern of diffusion is well approximated by a dipole: a combination of a point light some distance *below* the point at which light entered the surface, and a *negative* light source some (slightly larger) distance above the surface. Combining the contributions of these two light sources with transmissive Fresnel terms for light entering and leaving the surface (which are simply one minus the reflective Fresnel equation given in (1.18)) yield a simple, yet powerful, model:

$$S = \frac{1}{\pi} F_t(\theta_\mathrm{i})\, R_d\big(\|\boldsymbol{x}_\mathrm{i} - \boldsymbol{x}_\mathrm{o}\|\big)\, F_t(\theta_\mathrm{o}). \qquad [\mathrm{m}^{-2} \cdot \mathrm{sr}^{-1}] \tag{1.21}$$

Because of the symmetry of diffusion, the model is effectively a function of only one variable: the distance between the points of incidence and exitance.

This dipole model, originally introduced in 2001, has become popular for simulating subsurface scattering in many materials, and we will see applications of it later in this article.

### 1.4.3 Homogeneous and Heterogeneous Scattering

Of course, the dipole approximation assumes a uniform material: the same amount of scattering everywhere on the surface. For more realistic surfaces, it might be necessary to add some of the complexity of the BSSRDF back in, by considering spatial variation. For example, in Figure 1.8 it is clearly visible that internal structure affects the scattering.

## 1.5 8D Reflectance Fields

While the BSSRDF is most often associated with subsurface scattering in translucent media, measured on the material/air interface, its definition is general enough to represent light transport from incident to exitant light rays in arbitrary configurations (e.g., the two rays do not even need to intersect). When thought of in this way, it is typical to refer to this function as an *8D reflectance field*, representing the full exitant 4D light field for each possible ray of a 4D incident light field. As with the 6D reflectance field, it is common for this function to be parameterized over some arbitrary reference surface enclosing the scene. Thus, an

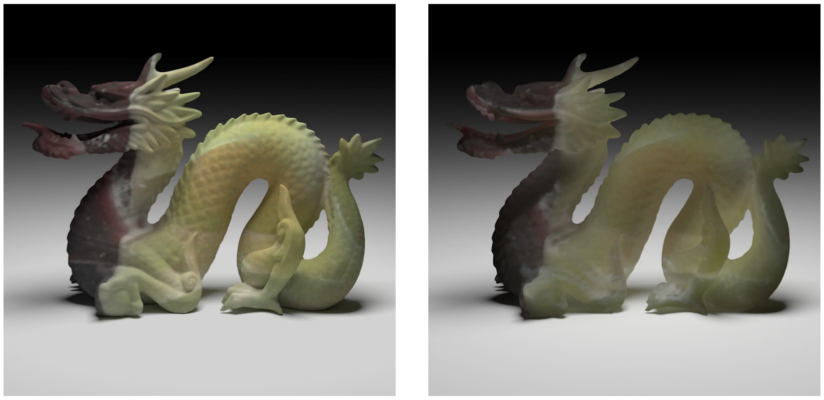

Fig. 1.8 *Left:* a synthesized image with surface reflection only. *Right:* the same model with a simulation of subsurface scattering.

8D reflectance field, if sufficiently densely sampled, can describe scattering in participating media, interreflection among multiple objects, refractions, caustics, cast shadows, etc.

A major difference between 6D and 8D reflectance fields is that the latter can include effects due to local lighting. In contrast, the 6D reflectance field carries the implicit assumption of distant (directional or environment) lighting, and thus includes the net effect of equal illumination along all incident rays having the same direction. Thus, only the 8D reflectance field can capture, for example, the effect of an individual light ray on the surface, which is often of interest for translucent materials.

## 1.6 Generalizing Reflectance and Scattering

It turns out that even BSSRDFs and 8D reflectance fields do not cover all possible aspects of surface appearance. First, one could consider all of the functions discussed above as being dependent on the wavelength of light. Moreover, some surfaces are *fluorescent*: they emit light at different wavelengths than those present in the incident light. Other surfaces may have appearance that changes over time because of chemical changes, physical processes such as drying, or weathering.

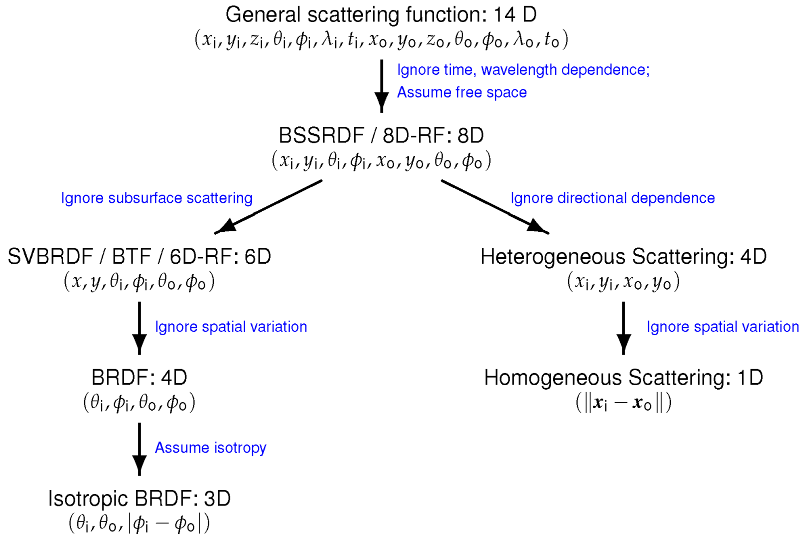

Fig. 1.9 Taxonomy of scattering and reflectance functions.

Still other surfaces might capture light and re-emit it later, leading to *phosphorescence* and other such phenomena.

Thus, a complete description of light scattering needs to add at least two wavelength and two time dimensions to the BSSRDF. Moreover, representing volumetric scattering adds two additional spatial dimensions, since this violates the assumption that radiance along light rays is constant.

So, we can think of all of the functions we have seen as specializations of a 14-dimensional scattering function, representing the distribution of light at arbitrary time, wavelength, position, and angle that is due to an incident light ray at some time, wavelength, position, and angle. While nobody has really tried to capture this full function, many efforts exist to capture one or more of its low-dimensional subsets (Figure 1.9). In fact, it can be argued that over the past decade, researchers have explored most of the subsets that "make sense," up to the limits of acquisition devices.

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