Chapter 2
Representation

Abstract A real material's surface reflectance function is a very complex function of 16 variables. It is currently unfeasible to measure or to mathematically model such a function. Practical applications thus require its simplification, namely, using additional assumptions. The general reflectance functions can primarily be categorized within the frameworks of textured models and homogeneous models. This chapter describes taxonomy of both of these representation subgroups, their mutual relationships, advantages, and drawbacks.

2.1 General Reflectance Function

A real material's surface reflectance (Fig. 2.1) is a very complex physical phenomenon, which, among other considerations, intricately depends on incident and reflected spherical angles, time, and light spectrum. The reflectance thus provides a rich source of information regarding any material's surface. If we know the general reflectance function, we cannot only precisely predict how any material will appear under any possible illumination intensity, direction or spectrum, but we can also accurately recognize any such material on the basis of the visual scene's lighting conditions.

The general reflectance function (GRF) has 16 dimensions (16D):

$$Y_r^{GRF} = GRF(\lambda_i, x_i, y_i, z_i, t_i, \theta_i, \varphi_i, \lambda_v, x_v, y_v, z_v, t_v, \theta_v, \varphi_v, \theta_t, \varphi_t), \qquad (2.1)$$

where $r = [r_1, \ldots, r_{16}]$ is the multi-index with corresponding partial indices. All possible values of the index will be denoted by $\bullet$, e.g., a color input spectrum in the RGB space $Y_{\bullet,r_2,\ldots,r_{16}} = [Y_{R,r_2,\ldots,r_{16}}, Y_{G,r_2,\ldots,r_{16}}, Y_{B,r_2,\ldots,r_{16}}]$ and the missing index by $\emptyset$, e.g., a monospectral input $Y_{\emptyset,r_2,\ldots,r_{16}}$. The GRF domain (for a pixel) is the d-vector space ($Y_r^{GRF} \in \mathscr{R}^d$) where the dimensionality d depends on the GRF type, i.e., Y_r^{SVBRDF}, Y_r^{BTF} are three-dimensional ($d = 3$) in the RGB representation, while Y_r^{BRTTF} is six-dimensional in the same representation.

GRF describes the incident light with spectral value λ_i; illuminating surface location x_i, y_i, z_i in time t_i; under spherical incidence angles $\omega_i = [\theta_i, \varphi_i]$ and observed at time t_v from surface location x_v, y_v, z_v under spherical reflectance angles $\omega_v = [\theta_v, \varphi_v]$ and spectrum λ_v; here $\omega_t = [\theta_t, \varphi_t]$ are the corresponding transmittance angles where $\omega = [\theta, \varphi]$ are the elevation and azimuthal angles, respectively.

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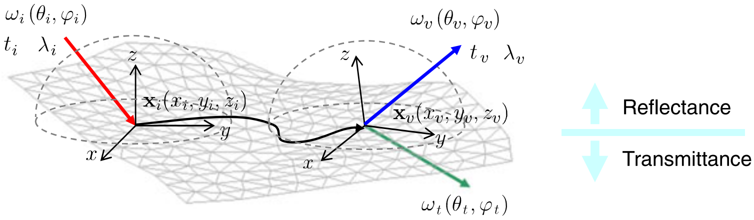

Fig. 2.1 General reflectance model

The model height parameters z_i, z_v indicate that radiance along light rays is not constant but depends on the height. The GRF function (2.1) is too complex to be accurately measured or modeled, hence some simplifying assumptions are inevitable in any practical application. The taxonomy of simplifying assumptions can be divided into two subgroups based on the possibility of neglecting a surface texture.

A visual texture is a resolution-based relative notion. Any natural surface material is textured and our perception of surfaces as textured or smoothly homogeneous (i.e., non-textured) only depends on the corresponding surface resolution. The same surface observed from a distance can be categorized as smooth, while its close observation may reveal rough-textured surface.

The smallest addressable image element indexed on a 2D lattice is referenced as a *pixel* (picture element), while the analogous image element indexed on a 3D lattice is called a *voxel* volumetric pixel or volumetric picture element. The corresponding visual texture element is referenced as *texel* (texture pixel). A similar term for a visual texture element for a pre-attentive human texture perception studies—*texton* was introduced by Bela Julesz [3].

The GRF simplifying taxonomy in Fig. 2.2 is obviously not exhaustive—there are also other conceivable simplifying assumptions or possible combinations of them—but it contains all sub-representations that are recently studied. This taxonomy of approximating the general reflectance function stems from the following simplifying assumptions:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$)

$$Y_r^{GRF} = GRF_{A1}(\lambda_i, x_i, y_i, z_i, t_i, \theta_i, \varphi_i, \lambda_v, x_v, y_v, z_v, \theta_v, \varphi_v, \theta_t, \varphi_t);$$

A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$)

$$Y_r^{GRF} = GRF_{A2}(\lambda_i, x_i, y_i, z_i, \theta_i, \varphi_i, \lambda_v, x_v, y_v, z_v, \theta_v, \varphi_v, \theta_t, \varphi_t);$$

A3 interaction does not change wavelength ($\lambda_i = \lambda_v$, i.e., $\lambda_v = \emptyset$)

$$Y_r^{GRF} = GRF_{A3}(\lambda_i, x_i, y_i, z_i, t_i, \theta_i, \varphi_i, x_v, y_v, z_v, t_v, \theta_v, \varphi_v, \theta_t, \varphi_t);$$

A4 constant radiance along light rays ($z_i = z_v = \emptyset$)

$$Y_r^{GRF} = GRF_{A4}(\lambda_i, x_i, y_i, t_i, \theta_i, \varphi_i, \lambda_v, x_v, y_v, t_v, \theta_v, \varphi_v, \theta_t, \varphi_t);$$

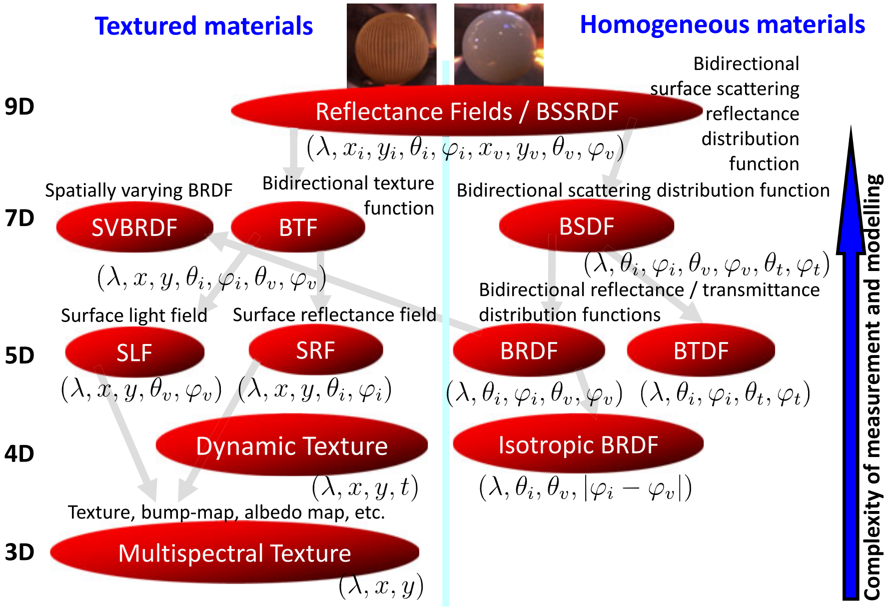

Fig. 2.2 A taxonomy of selected reflectance models

A5 no transmittance ($\theta_t = \varphi_t = \emptyset$) (no simultaneous reflectance and transmittance)

$$Y_r^{GRF} = GRF_{A5}(\lambda_i, x_i, y_i, z_i, t_i, \theta_i, \varphi_i, \lambda_v, x_v, y_v, z_v, t_v, \theta_v, \varphi_v);$$

A6 incident light leaves at the same point $x_i = x_v$, $y_i = y_v$ ($x_v = y_v = \emptyset$)

$$Y_r^{GRF} = GRF_{A6}(\lambda_i, x_i, y_i, z_i, t_i, \theta_i, \varphi_i, \lambda_v, z_v, t_v, \theta_v, \varphi_v, \theta_t, \varphi_t);$$

A7 no subsurface scattering;
A8 no self-shadowing;
A9 no self-occlusion;
A10 no inter-reflections;
A11 the energy conservation condition states that all incident light can be either reflected or absorbed

$$\int_{\Omega} Y_r^{BRDF} \cos\theta_v \, d\varphi_v \, d\theta_v \leq 1; \tag{2.2}$$

A12 Helmholtz reciprocity [6] states that BRDF does not change if the incidence and exitance angles are swapped:

$$BRDF(\lambda, \theta_i, \varphi_i, \theta_v, \varphi_v) = BRDF(\lambda, \theta_v, \varphi_v, \theta_i, \varphi_i); \tag{2.3}$$

A13 fixed illumination ($\theta_i = const.$, $\varphi_i = const.$);
A14 fixed viewing angle ($\theta_v = const.$, $\varphi_v = const.$);

A15 no spatial dependence

$$Y_r^{GRF} = GRF_{A15}(\lambda_i, z_i, t_i, \theta_i, \varphi_i, \lambda_v, z_v, t_v, \theta_v, \varphi_v, \theta_t, \varphi_t);$$

A16 no reflectance ($\theta_v = \varphi_v = \emptyset$)

$$Y_r^{GRF} = GRF_{A16}(\lambda_i, x_i, y_i, z_i, t_i, \theta_i, \varphi_i, \lambda_v, x_v, y_v, z_v, t_v, \theta_t, \varphi_t); \quad \text{and}$$

A17 reflectance depending on azimuthal difference (isotropy), i.e., $(\varphi_i - \varphi_v)$ and $(\varphi_i - \varphi_t)$

$$Y_r^{GRF} = GRF_{A17}\big(\lambda_i, x_i, y_i, z_i, t_i, \theta_i, (\varphi_i - \varphi_v), \lambda_v, x_v, y_v, z_v, t_v, \theta_v, (\varphi_i - \varphi_t)\big).$$

Assumption A4 means no reflectance changes along the incident or reflected light ray path. Assumption A6 allows the existence of a subsurface scattering but represents each pixel's integrated reflection (direct as well as scattered reflection). Assumption A7 excludes any subsurface scattering at all. Assumption A17 is the texture isotropy condition, i.e., GRF is independent on simultaneous rotation of illumination and viewing azimuthal angles around the surface normal. Textures not obeying A17 are anisotropic.

2.2 Textured Model Representation Taxonomy

Textured models consider spatial textural information to be too important for surface reflectance representation to be neglected. Thus they all respect and model spatially dependent reflectance within simplifications of the applied GRF model.

2.2.1 Bidirectional Surface Scattering Reflectance Distribution Function

The model based on the bidirectional surface scattering reflectance distribution function (BSSRDF—Fig. 2.3) was proposed by Nicodemus et al. [4] and later studied by several other researchers [2, 7]. The BSSRDF is defined on the measured object's geometry. At a larger scale we call this *reflectance fields*, which share the same parametrization but are defined on a convex surface surrounding the measured object.

The BSSRDF model is based on the first five of our above-specified simplifying assumptions:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$);
A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$);
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$; i.e., $\lambda_v = \emptyset$);
A4 constant radiance along light rays ($z_i = z_v = \emptyset$);
A5 no transmittance ($\theta_t = \varphi_t = \emptyset$).

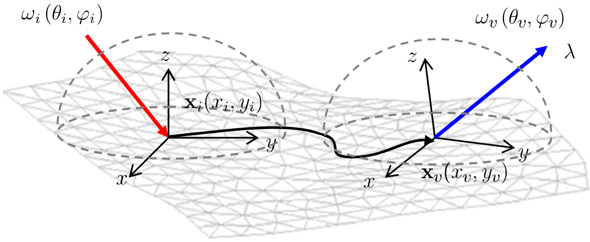

Fig. 2.3 BSSRDF reflectance model

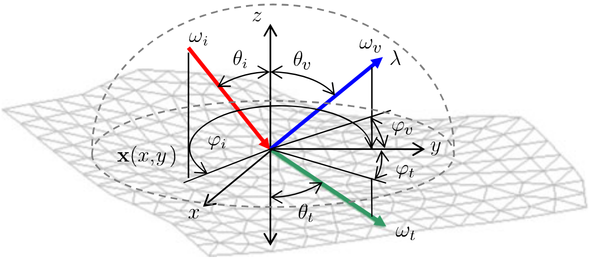

Fig. 2.4 BRTTF reflectance model

The BSSRDF reflectance model is thus nine-dimensional:

$$Y_r^{BSSRDF} = BSSRDF(\lambda, x_i, y_i, \theta_i, \varphi_i, x_v, y_v, \theta_v, \varphi_v). \tag{2.4}$$

Although this model is the best reflectance representation we currently have at our disposal, its complexity makes measurement in this model very difficult (Sect. 3.8). No satisfactory BSSRDF data have been collected yet. Similarly, only approximate local BSSRDF visualization methods (not capable of a sufficient enlargement of a texture) have been developed so far.

2.2.2 Bidirectional Reflectance and Transmittance Texture Function

The bidirectional reflectance transmittance texture function (BRTTF) (Fig. 2.4) is a vector function which returns transmittance and reflectance values simultaneously.

BRTTF is a nine-dimensional model:

$$Y_r^{BRTTF} = BRTTF(\lambda, x, y, \theta_i, \varphi_i, \theta_v, \varphi_v, \theta_t, \varphi_t) \tag{2.5}$$

which simplifies the BSSRDF model by accepting the validity of Assumptions A1 through A4, and A6:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$);
A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$);
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$, i.e., $\lambda_v = \emptyset$);
A4 constant radiance along light rays ($z_i = z_v = \emptyset$);
A6 incident light leaves at the same point.

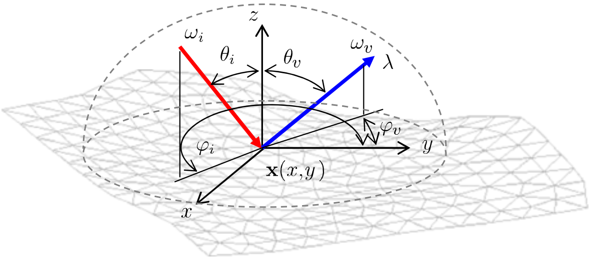

Fig. 2.5 BTF reflectance model

This model thus simultaneously represents both reflectance and transmittance properties of the GRF under the assumption that the incident light is partly reflected and partly transmitted from the incident location.

2.2.3 Bidirectional Texture Function

The seven-dimensional bidirectional texture function (BTF) reflectance model (Fig. 2.5) is currently the state-of-the-art GRF model which can be simultaneously measured and modeled. Nevertheless, BTF requires the most advanced modeling as well as high-end hardware support.

The BTF reflectance model

$$Y_r^{BTF} = BTF(\lambda, x, y, \theta_i, \varphi_i, \theta_v, \varphi_v) \tag{2.6}$$

accepts Assumption A6 in addition to the five BSSRDF assumptions (thus A1 through A6 are accepted in it):

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$),
A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$),
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$, i.e., $\lambda_v = \emptyset$),
A4 constant radiance along light rays ($z_i = z_v = \emptyset$),
A5 no transmittance ($\theta_t = \varphi_t = \emptyset$),
A6 incident light leaves at the same point

but not A7 through A10.

2.2.4 Spatially Varying BRDF

Another seven-dimensional spatially varying BRDF (SVBRDF) reflectance model

$$Y_r^{SVBRDF} = SVBRDF(\lambda, x, y, \theta_i, \varphi_i, \theta_v, \varphi_v) \tag{2.7}$$

is similar to BTF, except for the local effects which are missing (A7 through A10) and the BRDF restrictions (A11, A12). This additional assumption allows us to simplify SVBRDF measurement but increases its compression rate, thereby worsening

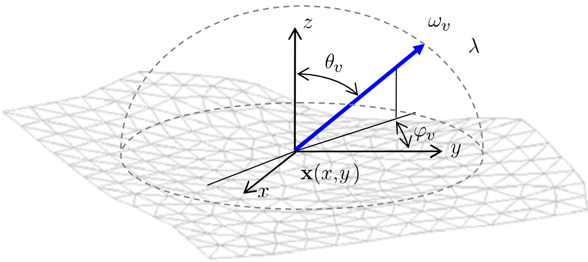

Fig. 2.6 SLF reflectance model

its visual quality. This representation is mainly due to BRDF reciprocity property restriction (A12) appropriate for measurement of nearly flat surfaces, while the missing transmittance (A5) restricts its application to opaque surfaces. This model can be formally illustrated using the same Fig. 2.5 as the BTF model. SVBRDF assumes the following 12 conditions:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$);
A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$);
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$, i.e., $\lambda_v = \emptyset$);
A4 constant radiance along light rays ($z_i = z_v = \emptyset$);
A5 no transmittance ($\theta_t = \varphi_t = \emptyset$);
A6 incident light leaves at the same point $x_i = x_v$, $y_i = y_v$ ($x_v = y_v = \emptyset$);
A7 no subsurface scattering;
A8 no self-shadowing;
A9 no self-occlusion;
A10 no inter-reflections;
A11 energy conservation;
A12 Helmholtz reciprocity [6].

The isotropic SVBRDF additionally accepts Assumption A17; it has six dimensions:

$$Y_r^{ISVBRDF} = ISVBRDF(\lambda, x, y, \theta_i, \varphi_i - \varphi_v, \theta_v).$$

2.2.5 Surface Light Field

If we fix the illumination spatial angle (Fig. 2.6) $\omega_i = [\theta_i = const., \varphi_i = const.]$ we get the 5D surface light field model [1] (SLF),

$$Y_r^{SLF} = SLF(\lambda, x, y, \theta_v, \varphi_v), \tag{2.8}$$

which accepts Assumptions A1 through A6, and A13:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$);
A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$);
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$; i.e., $\lambda_v = \emptyset$),

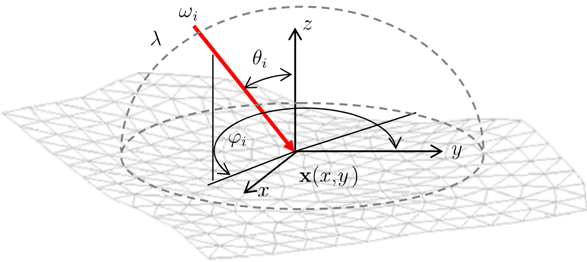

Fig. 2.7 SRF reflectance model

A4 constant radiance along light rays ($z_i = z_v = \emptyset$);
A5 no transmittance ($\theta_t = \varphi_t = \emptyset$);
A6 incident light leaves at the same point $x_i = x_v$, $y_i = y_v$ ($x_v = y_v = \emptyset$);
A13 fixed illumination ($\theta_i = const.$, $\varphi_i = const.$).

2.2.6 Surface Reflectance Field

A similar surface reflectance field (SRF) model (Fig. 2.7) fixes the viewing angle $\omega_v = [\theta_v = const., \varphi_v = const.]$.

The surface reflectance field model

$$Y_r^{SRF} = SRF(\lambda, x, y, \theta_i, \varphi_i) \tag{2.9}$$

accepts Assumptions A1 through A6, and A14:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$);
A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$);
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$; i.e., $\lambda_v = \emptyset$),
A4 constant radiance along light rays ($z_i = z_v = \emptyset$);
A5 no transmittance ($\theta_t = \varphi_t = \emptyset$);
A6 incident light leaves at the same point $x_i = x_v$, $y_i = y_v$ ($x_v = y_v = \emptyset$);
A14 fixed viewing angle ($\theta_v = const.$, $\varphi_v = const.$).

2.2.7 Multispectral Texture

The most widely used and simplest textural GRF representation, the multispectral texture, fixes both illumination $\omega_i = [\theta_i = const., \varphi_i = const.]$ and viewing $\omega_v = [\theta_v = const., \varphi_v = const.]$ angles (see Fig. 2.8). It can be either 3D for the static model (2.10) (ST) or 4D for the dynamic texture (2.11) (DT) model,

$$Y_r^{ST} = ST(\lambda, x, y), \tag{2.10}$$

$$Y_r^{DT} = DT(\lambda, x, y, t), \tag{2.11}$$

respectively. This simple model (2.11) or its monospectral variant $Y_r^{DT} = DT(x, y, t)$ is still the only DT representation used.

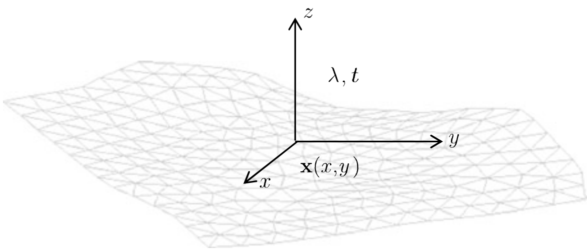

Fig. 2.8 Static-/-dynamic texture

The dynamic textures obey Assumptions A1, A3 through A5, A13, and A14:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$);
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$, i.e., $\lambda_v = \emptyset$);
A4 constant radiance along light rays ($z_i = z_v = \emptyset$);
A5 no transmittance ($\theta_t = \varphi_t = \emptyset$);
A13 fixed illumination ($\theta_i = const.$, $\varphi_i = const.$);
A14 fixed viewing angle ($\theta_v = const.$, $\varphi_v = const.$);

and static textures additionally also Assumption A2:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$);
A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$);
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$, i.e., $\lambda_v = \emptyset$);
A4 constant radiance along light rays ($z_i = z_v = \emptyset$);
A5 no transmittance ($\theta_t = \varphi_t = \emptyset$);
A13 fixed illumination ($\theta_i = const.$, $\varphi_i = const.$);
A14 fixed viewing angle ($\theta_v = const.$, $\varphi_v = const.$).

2.3 Representation Taxonomy of Homogeneous Models

If the surface resolution has low dot-per-inch resolution (DPI), its resolution is such that we can reliably approximate its appearance by a homogeneous (non-textured) model, e.g., surface observed from a large distance. By disregarding the spatial dependency, we significantly diminish both measurement and modeling problems because a reliable representation of the complicated spatially variable reflectance is very difficult. The general spatially independent reflectance function is then simplified to just 12 dimensions (12D):

$$Y_r^{GRF} = GRF(\lambda_i, z_i, t_i, \theta_i, \varphi_i, \lambda_v, z_v, t_v, \theta_v, \varphi_v, \varphi_t, \theta_t),$$

where $r = [r_1, \ldots, t_{12}]$ is again the corresponding multi-index.

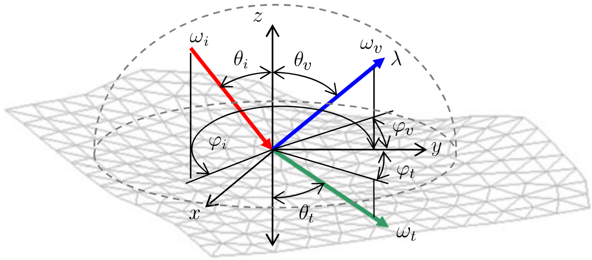

Fig. 2.9 BSDF reflectance model

2.3.1 Bidirectional Scattering Distribution Function

Bidirectional scattering distribution function (BSDF—Fig. 2.9) is a generalization of both BRDF and BTDF, also comprising scattering effects for both transmission and reflection [5] and it returns both values simultaneously.

Although BSDF is sometimes used in a slightly different context, here we understand BSDF as a union of two BRDFs (one for each side of the surface) and two BTDFs (one for light transmitted in each direction):

$$Y_r^{BSDF} = BSDF(\lambda, \theta_i, \varphi_i, \theta_v, \varphi_v, \theta_t, \varphi_t).$$

Assumptions A1 through A4, A6 through A12, A15:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$);
A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$);
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$; i.e., $\lambda_v = \emptyset$),
A4 constant radiance along light rays ($z_i = z_v = \emptyset$);
A6 incident light leaves at the same point $x_i = x_v$, $y_i = y_v$ ($x_v = y_v = \emptyset$);
A7 no subsurface scattering;
A8 no self-shadowing;
A9 no self-occlusion;
A10 no inter-reflections;
A11 energy conservation;
A12 Helmholtz reciprocity [6];
A15 no spatial dependence.

2.3.2 Bidirectional Reflectance Distribution Function

The bidirectional reflectance distribution function (BRDF) model (Fig. 2.10) is a widely used simplified version of the BSDF model.

This 5D BRDF model [4] obeys Assumptions A1 through A12, and A15:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$);
A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$);
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$; i.e., $\lambda_v = \emptyset$);

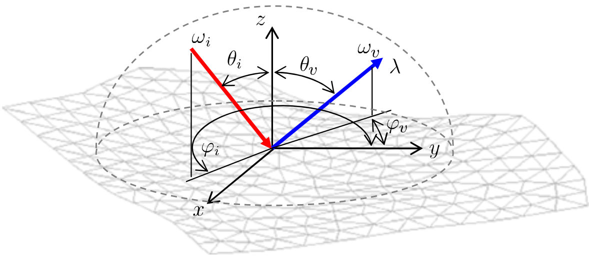

Fig. 2.10 BRDF reflectance model

A4 constant radiance along light rays ($z_i = z_v = \emptyset$);
A5 no transmittance ($\theta_t = \varphi_t = \emptyset$);
A6 incident light leaves at the same point $x_i = x_v$, $y_i = y_v$ ($x_v = y_v = \emptyset$);
A7 no subsurface scattering;
A8 no self-shadowing;
A9 no self-occlusion;
A10 no inter-reflections;
A11 energy conservation;
A12 Helmholtz reciprocity [6];
A15 no spatial dependence.

The BRDF model depends on five variables:

$$Y_r^{BRDF} = BRDF(\lambda, \theta_i, \varphi_i, \theta_v, \varphi_v).$$

If the spectral dependency is disregarded, the BRDF is a four-dimensional function depending on illumination and viewing directions, each usually specified by azimuth and elevation. The variable $Y_r^{BRDF} = BRDF(\lambda)$ (constant for all illumination and viewing angles) is called the Lambertian BRDF.

2.3.3 Bidirectional Transmittance Distribution Function

Another BSDF simplification is the bidirectional transmittance distribution function (BTDF) model (Fig. 2.11).

Bidirectional transmittance distribution function

$$Y_r^{BTDF} = BTDF(\lambda, \theta_i, \varphi_i, \theta_t, \varphi_t)$$

describes how the light passes through a transparent or partially transparent surface. This 5D model obeys Assumptions A1 through A4, A6 through A11, A15, and A16:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$);
A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$);
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$, i.e., $\lambda_v = \emptyset$);
A4 constant radiance along light rays ($z_i = z_v = \emptyset$);
A6 incident light leaves at the same point $x_i = x_v$, $y_i = y_v$ ($x_v = y_v = \emptyset$);
A7 no subsurface scattering;

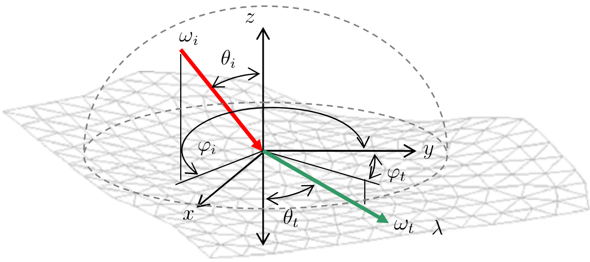

Fig. 2.11 BTDF reflectance model

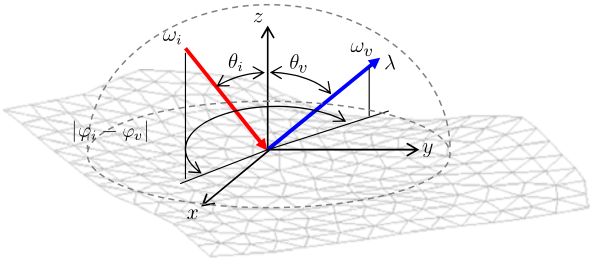

Fig. 2.12 IBRDF reflectance model

A8 no self-shadowing;
A9 no self-occlusion;
A10 no inter-reflections;
A11 energy conservation;
A15 no spatial dependence;
A16 no reflectance ($\theta_v = \varphi_v = \emptyset$).

2.3.4 Isotropic Bidirectional Reflectance Distribution Function

The isotropic bidirectional reflectance distribution function (IBRDF—Fig.2.12) model is a BRDF which depends on the azimuthal difference only.

Isotropic BRDF is 4D model obeying Assumption A1 through A12, A15, and A17:

A1 light transport takes zero time ($t_i = t_v$ and $t_v = \emptyset$);
A2 reflectance behavior of the surface is time invariant ($t_v = t_i = const.$, $t_v = t_i = \emptyset$);
A3 interaction does not change wavelength ($\lambda_i = \lambda_v$; i.e., $\lambda_v = \emptyset$);
A4 constant radiance along light rays ($z_i = z_v = \emptyset$);
A5 no transmittance ($\theta_t = \varphi_t = \emptyset$);
A6 incident light leaves at the same point $x_i = x_v$, $y_i = y_v$ ($x_v = y_v = \emptyset$);
A7 no subsurface scattering;
A8 no self-shadowing;
A9 no self-occlusion;
A10 no inter-reflections;
A11 energy conservation;

A12 Helmholtz reciprocity [6];
A15 no spatial dependence;
A17 reflectance depending on azimuthal difference $(\varphi_i - \varphi_v)$.

Assumption A17 secures unchanged Y_r^{BRDF} if both azimuthal angles are simultaneously rotated around the surface normal. The IBRDF model is then

$$Y_r^{IBRDF} = IBRDF\big(\lambda, \theta_i, |\varphi_i - \varphi_v|, \theta_v\big).$$

2.4 Attributes of Taxonomical Classes

A more complex visual texture representation means a higher visual quality but also more demanding data measurement as well as challenging model learning and synthesis. We have not even been able to measure some of these representations (GRF) or their models cannot be reliably learned from the current state-of-the-art measurement devices, for example, due to a limited spatial-sample resolution (e.g., some complex mixture models), unknown learning methods (e.g., compound MRF models), time constraints, etc. In reality it can thus even happen that the resulting visual quality of a complex visual texture model can be worse than in a simpler representation due to the necessary compromised solutions needed to build such a model.

The appropriate representation primarily depends on the intended application. Analytical applications, such as texture classification, usually do not require the high-end textural representations but can only work with some simple discriminative models. A simple example can be a scene with few spectrally distinct visual textures, which can be separated by simple spectral thresholds. Synthesis applications, such as realistic rendering, typically require demanding textural and acquisition representations (BTF, SVBRDF). However, these advanced textural representations are extremely complex, and any practical application inevitably requires a tradeoff between visual quality (ideally the highest), measurement, data storage size, processing time, and cost (ideally the lowest). This chapter tries to present a compact guide to such tradeoff options that have been proposed and studied up to this point in time.

2.4.1 Taxonomical Class Advantages

GRF the best, most descriptive, and physically correct representation;
BSSRDF the best GRF approximation which we may be able to measure in the near future;
BRTTF a manageable BTF generalization;
BTF the best GRF approximation which can be managed with recent high-end technology and mathematical knowledge;
SVBRDF measurement, compression, and modeling are simpler than for BTF;
SLF a simple textural model (BTF subset);
SRF a simple textural model (BTF subset), with ideally registered surface points;
ST the simplest visual texture, widely used in a plethora of formats and applications;

DT	similar to ST but dynamic, allows capture of dynamic behavior;
BSDF	the best GRF representation which ignores textural (spatial) properties;
BRDF	an optimal compromised untextured representation with many developed models;
BTDF	optimal for transparent homogeneous materials;
IBRDF	has models simpler than those valid for BRDF models.

2.4.2 Taxonomical Class Drawbacks

GRF	so far unmeasurable, no models exist;
BSSRDF	difficult to be reliably measured as yet, no full BSSRDF models have been published;
BRTTF	more complex than BTF;
BTF	requires expensive measurement and computing resources as well as demanding mathematical tools, internal material effects (scattering, interreflections) are captured but not isolated;
SVBRDF	worse visual quality than BTF, no modeling of internal material effects, for nearly flat, opaque materials;
SLF	illumination dependence is missing;
SRF	viewing dependence is missing;
ST	a sketchy textural approximation which ignores the most dominant appearance-forming features;
DT	similar to ST but dynamic;
BSDF	the most complex among untextured representations;
BRDF	an untextured representation, for opaque materials only;
BTDF	an untextured representation, transmittance only;
IBRDF	an untextured representation, does not capture anisotropic properties.

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