A REFLECTANCE MODEL FOR COMPUTER GRAPHICS

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Abstract

This paper presents a new reflectance model for rendering computer synthesized images. The model accounts for the relative brightness of different materials and light sources in the same scene. It describes the directional distribution of the reflected light and a color shift that occurs as the reflectance changes with incidence angle. The paper presents a method for obtaining the spectral energy distribution of the light reflected from an object made of a specific real material and discusses a procedure for accurately reproducing the color associated with the spectral energy distribution. The model is applied to the simulation of a metal and a plastic.

Key words: computer graphics, image synthesis, reflectance, shading

Computing Reviews category: 8.2

Introduction

The rendering of realistic images in computer graphics requires a model of how objects reflect light. The reflectance model must describe both the color and the spatial distribution of the reflected light. The model is independent of the other aspects of image synthesis, such as the surface geometry representation and the hidden surface algorithm.

Most real surfaces are neither ideal specular (mirror-like) reflectors nor ideal diffuse (Lambertian) reflectors. Phong [13,14] proposed a reflectance model for computer graphics that was a linear combination of specular and diffuse reflection. The specular component was spread out around the specular direction by using a cosine function raised to a power. Subsequently, Blinn [5,6] used similar ideas together with a specular reflection model from [22] which accounts for the off-specular peaks that occur when the incident light is at a grazing angle relative to the surface normal. Whitted [23] extended these models by adding a term for ideal specular reflection from perfectly smooth surfaces. All of these models are based on geometrical optics (ray theory).

The foregoing models treat reflection as consisting of three components: ambient, diffuse and specular. The ambient component represents light that is assumed to be uniformly incident from the environment and that is reflected equally in all directions by the surface. The diffuse and specular components are associated with light from specific light sources. The diffuse component represents light that is scattered equally in all directions. The specular component represents highlights, light that is concentrated around the mirror direction. The specular component was assumed to be the color of the light source and the Fresnel equation was used to obtain the angular variation of the intensity, but not the color, of the specular component. The ambient and diffuse components were assumed to be the color of the material. The resulting models produce images that look realistic for certain types of materials.

This paper presents a reflectance model for rough surfaces that is more general than previous models. It is based on geometrical optics and is applicable to a broad range of materials, surface conditions, and lighting situations. The basis of this model is a reflectance definition that relates the brightness of an object to the intensity and size of each light source that illuminates it. The model predicts the directional distribution and spectral composition of the reflected light. A procedure is described for calculating RGB values from the spectral energy distribution. The new reflectance model is then applied to the simulation of a metal and a plastic, with an explanation of why images rendered with previous models often look plastic and how this plastic appearance can be avoided.

The Reflectance Model

Given a light source, a surface, and an observer, a reflectance model describes the intensity and spectral composition of the reflected light reaching the observer. The intensity of the reflected light is determined by the intensity and size of the light source and by the reflecting ability and surface properties of the material. The spectral composition of the reflected light is determined by the spectral composition of the light source and the wavelength-selective reflection of the surface. In this section, the appropriate reflectance definitions are introduced and are combined into a general reflectance model. Figure 1 contains a summary of the symbols used in this model.

The geometry of reflection is shown in Figure 2. An observer is looking at a point P on a surface. V is the unit vector in the direction of the viewer, N is the unit normal to the surface, and L is the unit vector in the direction of a specific light source. H is a normalized vector in the direction of the angular bisector of V and L, and is defined by

$$H = \frac{V+L}{\mathrm{len}(V+L)} \quad .$$

It is the unit normal to a hypothetical surface that would specularly reflect light from the light source to the viewer. α is the angle between H and N, and θ is the angle between H and V, so that $\cos(\theta) = V \cdot H = L \cdot H$.

The energy of the incident light is expressed as energy per unit time and per unit area of the reflecting surface. The intensity of the incident light is similar, but is expressed per unit projected area and, in addition, per unit solid angle [19]. The energy in an incoming beam of light is

$$E_i = I_i (N \cdot L) d\omega_i \quad .$$

Except for mirrors or near-mirrors, the incoming beam is reflected over a wide range of angles. For this reason, the reflected intensity in any given direction depends on the incident energy, not just on the incident intensity. The ratio of the reflected intensity in a given direction to the incident energy from another direction (within a small solid angle) is called the bidirectional reflectance. This reflectance is fundamental for the study of reflection (for additional discussion, see [19]). For each light source, the bidirectional reflectance R is thus

$$R = \frac{I_r}{E_i} \quad .$$

The reflected intensity reaching the viewer from each light source is then

$$I_r = RE_i$$
$$= RI_i (N \cdot L) d\omega_i \quad .$$

The bidirectional reflectance may be split into two components, specular and diffuse. The specular component represents light that is reflected from the surface of the material. The diffuse component originates from internal scattering (in which the incident light penetrates beneath the surface of the material) or from multiple surface reflections (which occur if the surface is sufficiently rough). The specular and diffuse components can have different colors if the material is not homogeneous. The bidirectional reflectance is thus

$$R = sR_s + dR_d \;, \quad \text{where } s+d=1.$$

In addition to direct illumination by individual light sources, an object may be illuminated by background or ambient illumination. All light that is not direct illumination from a specific light source is lumped together into ambient illumination. The amount of light reflected toward the viewer from any particular direction of ambient illumination is small, but the effect is significant when integrated over the entire hemisphere of illuminating angles. Consequently, it is convenient to introduce an ambient (or

α	angle between N and H
θ	angle between L and H or V and H
D	facet slope distribution function
d	fraction of reflectance that is diffuse
$d\omega_i$	solid angle of a beam of incident light
E_i	energy of the incident light
F	reflectance of a perfectly smooth surface
f	unblocked fraction of the hemisphere
G	geometrical attenuation factor
H	unit angular bisector of V and L
I_i	average intensity of the incident light
I_{ia}	intensity of the incident ambient light
I_r	intensity of the reflected light
I_{ra}	intensity of the reflected ambient light
L	unit vector in the direction of a light
k	extinction coefficient
m	root mean square slope of facets
N	unit surface normal
n	index of refraction
R_a	ambient reflectance
R	total bidirectional reflectance
R_d	diffuse bidirectional reflectance
R_s	specular bidirectional reflectance
s	fraction of reflectance that is specular
V	unit vector in direction of the viewer
wm	relative weight of a facet slope

Figure 1. Summary of symbols.

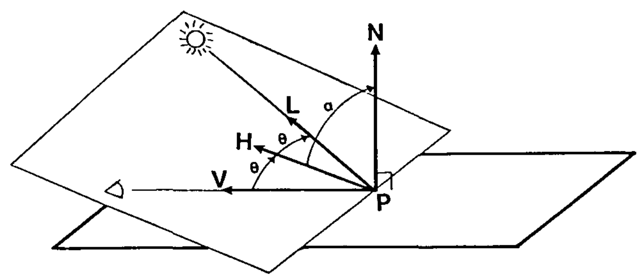


Figure 2. The geometry of reflection.

hemispherical-directional) reflectance, R_a. This reflectance is an integral of the bidirectional reflectance R and is thus a linear combination of R_s and R_d. For simplicity, we assume that R_a is independent of viewing direction. In addition we assume that the ambient illumination is uniformly incident. The reflected intensity due to ambient illumination is defined by

$$I_{ra} = R_a I_{ia} f \quad .$$

The term f is the fraction of the illuminating hemisphere that is not blocked by nearby objects (such as a corner) [24]. It is given by

$$f = \frac{1}{\pi} \int (N \cdot L) d\omega_i \quad ,$$

where the integration is done over the unblocked part of the illuminating hemisphere.

The total intensity of the light reaching the observer is the sum of the reflected intensities from all light sources plus the reflected intensity from any ambient illumination. Assuming that f=1, the basic reflectance model used in this paper becomes:

$$I_r = I_{ia} R_a + \sum_{\ell} I_{i\ell} (N \cdot L_\ell) d\omega_{i\ell} (sR_s + dR_d) \quad .$$

This formulation accounts for the effect of light sources with different intensities and different projected areas which may illuminate a scene. For example, an illuminating beam with the same intensity (I_i) and angle of illumination (N·L) as another beam, but with twice the solid angle ($d\omega_i$) of that beam, will make a surface appear twice as bright. An illuminating beam with twice the intensity of another beam, but with the same angle of illumination and solid angle, will also make a surface appear twice as bright.

This paper does not consider the reflection of light from other objects in the environment. This reflection can be calculated as in [23] or [6] if the surface is perfectly smooth, but even this pure specular reflection should be wavelength dependent.

The above reflectance model implicitly depends on several variables. For example, the intensities depend on wavelength, s and d depend on the material, and the reflectances depend on these variables plus the reflection geometry and the surface roughness. The next two sections consider the directional and wavelength dependence of the reflectance model.

Directional Distribution of the Reflected Light

The ambient and diffuse components reflect light equally in all directions. Thus, R_a and R_d do not depend on the location of the observer. On the other hand, the specular component reflects more light in some directions than in others, so that R_s does depend on the location of the observer.

The angular spread of the specular component can be described by assuming that the surface consists of microfacets, each of which reflects specularly [22]. Only facets whose normal is in the direction H contribute to the specular component of reflection from L to V. The specular component is

$$R_s = \frac{F}{\pi} \frac{D}{(N \cdot L)} \frac{G}{(N \cdot V)} \quad .$$

The Fresnel term F describes how light is reflected from each smooth microfacet. It is a function of incidence angle and wavelength and is discussed in the next section. G, the geometrical attenuation factor, accounts for the shadowing and masking of one facet by another and is discussed elsewhere in detail [5,6,22]. Briefly it is

$$G = \min \left\{ 1, \frac{2(N \cdot H)(N \cdot V)}{(V \cdot H)}, \frac{2(N \cdot H)(N \cdot L)}{(V \cdot H)} \right\} \quad .$$

The facet slope distribution function D represents the fraction of the facets that are oriented in the direction H. Various facet slope distribution functions have been considered by Blinn [5,6]. One of the formulations he described is the Gaussian model [22]:

$$D = ce^{-(\alpha/m)^2} \quad ,$$

where c is an arbitrary constant.

In addition to the ones mentioned by Blinn, other facet slope distribution models are possible. In particular, models for the scattering of radar and infrared radiation from surfaces are available, and are applicable to visible wavelengths. For example, Davies [8] described the spatial distribution of electromagnetic radiation reflected from a rough surface made of a perfect electrical conductor. Bennett and Porteus [3] extended these results to real metals, and Torrance and Sparrow [21] showed that they apply to nonmetals as well. Beckmann [2] provided a comprehensive theory that encompasses all of these materials and is applicable to a wide range of surface conditions ranging from smooth to very rough. For rough surfaces, the Beckmann distribution function is

$$D = \frac{1}{m^2 \cos^4 \alpha} e^{-\left\{\frac{\tan^2 \alpha}{m^2}\right\}} \quad .$$

This distribution function is similar in shape to the three functions mentioned by Blinn. The advantage of the Beckmann function is that it gives the absolute magnitude of the reflectance without introducing arbitrary constants; the disadvantage is that it requires more computation.

In all of the facet slope distribution functions, the spread of the specular component depends on the rms slope m. Small values of m signify gentle facet slopes and give a distribution that is highly directional around the specular direction, as shown in Figure 3a for the Beckmann distribution model and in Figure 3b for the Gaussian model. Large values of m imply steep facet slopes and give a distribution that is spread out, as shown in Figures 3c and 3d for the Beckmann and Gaussian models, respectively. Note the similarity between the two models.

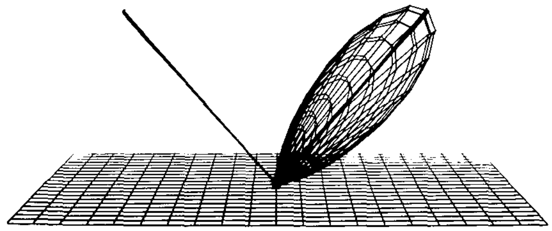


Figure 3a. Beckmann distribution for m=0.2.

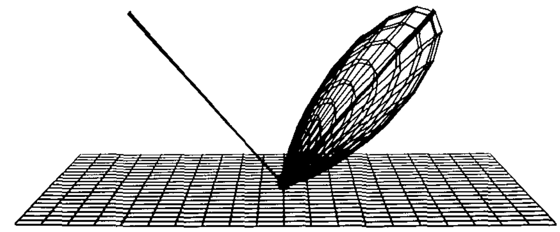


Figure 3b. Gaussian distribution for m=0.2.

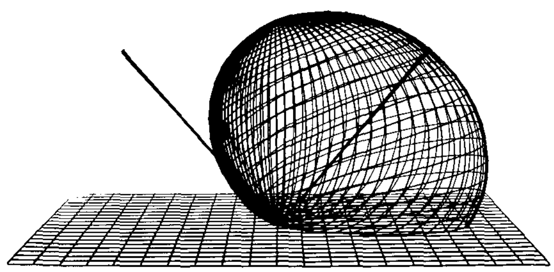


Figure 3c. Beckmann distribution for m=0.6.

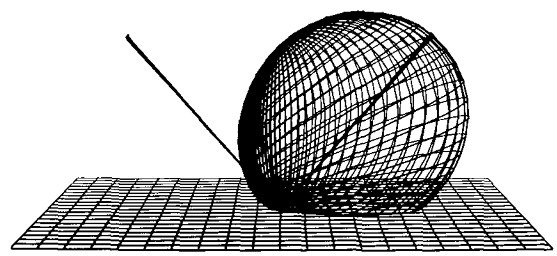


Figure 3d. Gaussian distribution for m=0.6.

The wavelength dependence of the reflectance is not affected by the surface roughness except for surfaces that are almost completely smooth, which are described by physical optics (wave theory) and which have a distribution function D that is wavelength dependent. The Beckmann distribution model accounts for this wavelength dependence and for the transition region between physical and geometrical optics, i.e., between very smooth surfaces and rough surfaces. For simplicity we will ignore the cases in which D is wavelength dependent. (For a further discussion, see [2] and [8].)

Some surfaces have two or more scales of roughness, or slope m, and can be modeled by using two or more distribution functions [15]. In such cases, D is expressed as a weighted sum of the distribution functions, each with a different value of m:

$$D = \sum_j wm_j D(m_j) \quad ,$$

where m_j = rms slope of the jth distribution.
wm_j = weight of the jth distribution. The sum of these weights is 1.

Spectral Composition of the Reflected Light

The ambient, diffuse, and specular reflectances all depend on wavelength. R_a, R_d, and the F term of R_s may be obtained from the appropriate reflectance spectra for the material. A nonhomogeneous material may have different reflectance spectra for each of the three reflectances, though R_a is restricted to being a linear combination of R_s and R_d.

Reflectance spectra have been measured for thousands of materials and have been collected in [9,16-18]. The reflectance data are usually for illumination at normal incidence. These values are normally measured for polished surfaces and must be multiplied by $1/\pi$ to obtain the bidirectional reflectance for a rough surface [19]. Most materials were measured at only a few wavelengths in the visible range (typically around 10 to 15), so that values for intermediate wavelengths must be interpolated (a simple linear interpolation seems to be sufficient). The reflectance spectrum of a copper mirror for normal incidence is shown for visible wavelengths in Figure 4a. In choosing a reflectance spectrum, careful consideration must be given to the conditions under which which the measurements were made. For example, some metals develop an oxide layer with time which can drastically alter the color [1].

The spectral energy distribution of the reflected light is found by multiplying the spectral energy distribution of the incident light by the reflectance spectrum of the surface. An example of this is shown in Figure 4b. The spectral energy distributions of the sun and a number of CIE standard illuminants are available in [7]. The spectral energy distribution of CIE standard illuminant D6500, which approximates sunlight on a cloudy day, is the top curve shown in Figure 4b. The lower curve shows the corresponding spectral energy distribution of light reflected from a copper mirror illuminated by CIE standard illuminant D6500 at normal incidence. It is obtained by multiplying the top curve by the reflectance spectrum in Figure 4a.

In general, R_d and F will vary with the geometry of reflection. For convenience, we will subsequently take R_d to be the bidirectional

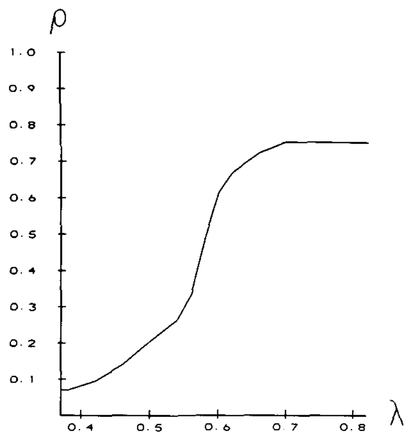


Figure 4a. Reflectance spectrum of a copper mirror for normal incidence. Wavelength is in microns.

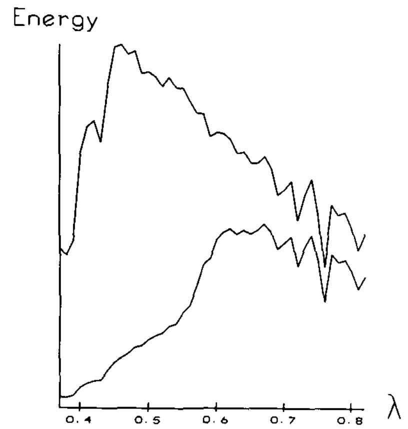


Figure 4b. Top curve: Spectral energy distribution of CIE standard illuminant D6500. Bottom curve: Spectral energy distribution of light reflected from a copper mirror illuminated by D6500.

reflectance for illumination in a direction normal to the reflecting surface. This is reasonable because the reflectance varies only slightly for incidence angles within about 70 degrees of the surface normal [20]. We will specifically allow for the directional dependence of F, however, as this leads to a color shift when the directions of incidence and reflection are near grazing.

The reflectance F may be obtained theoretically from the Fresnel equation [20]. This equation expresses the reflectance of a perfectly smooth, mirror-like surface in terms of the index of refraction (n) and the extinction coefficient (k) of the surface and the angle of illumination (θ). In general, both n and k vary with wavelength but their values are frequently not known. On the other hand, experimentally measured values of the reflectance at normal incidence are frequently known.

To obtain the spectral and angular variation of F, we have adopted a practical compromise. If n and k are known, we use the Fresnel equation. If not,

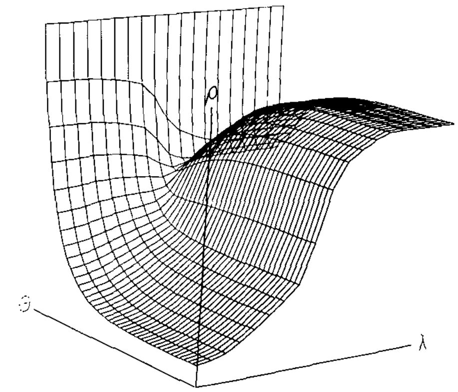
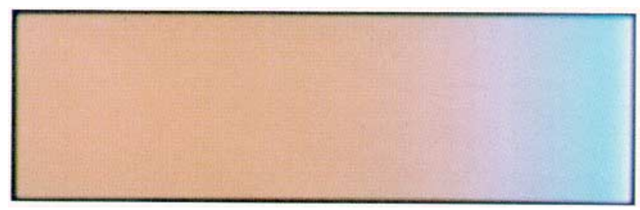
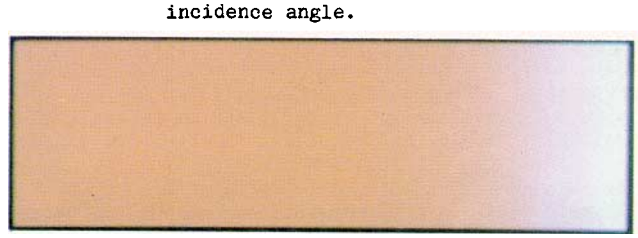


Figure 5a. Reflectance (ρ) of a copper mirror as a function of wavelength (λ) and incidence angle (θ).



$\theta=0$ $\theta=\pi/2$

Figure 5b. The color of copper as a function of incidence angle.



$\theta=0$ $\theta=\pi/2$

Figure 5c. The color of copper as approximated by the method discussed in this paper.

but the normal reflectance is known, we fit the Fresnel equation to the measured normal reflectance for a polished surface. For nonmetals, for which k=0, this immediately gives us an estimate of the index of refraction n. For metals, for which k is generally not 0, we set k=0 and get an effective value for n from the normal reflectance. The angular dependence of F is then available from the Fresnel equation. The foregoing procedure yields the correct value of F for normal incidence and a good estimate of its angular dependence, which is only weakly dependent on the extinction coefficient k.

To illustrate this procedure, the Fresnel equation for unpolarized incident light and k=0 is

$$F = \frac{1}{2}\frac{(g-c)^2}{(g+c)^2}\left\{1 + \frac{(c(g+c)-1)^2}{(c(g-c)+1)^2}\right\},$$

where

$$c = \cos(\theta) = V \cdot H$$
$$g^2 = n^2 + c^2 - 1.$$

(Note that a similar expression in [5] is missing the 1/2 factor.) At normal incidence, $\theta = 0$, so c=1, g=n and

$$F_0 = \left\{\frac{n-1}{n+1}\right\}^2 .$$

Solving for n gives the equation

$$n = \frac{1 + \sqrt{F_0}}{1 - \sqrt{F_0}} .$$

Values of n determined in this way are then substituted into the original Fresnel equation to obtain the reflectance F at other angles of incidence. The procedure may repeated at other wavelengths to obtain the spectral and directional dependence of the reflectance.

The dependence of the reflectance on wavelength and the angle of incidence implies that the color of the reflected light changes with the incidence angle. Reflectance spectra for copper are shown in Figure 5a. As the incidence angle (θ) approaches $\pi/2$, the color of the reflected light approaches the color of the light source (since the reflectance F approaches unity). The colors corresponding to the reflection of white light (CIE standard illuminant D6500) from copper are shown as a function of θ in Figure 5b. It is evident that the color shift from the Fresnel equations only becomes important as θ approaches $\pi/2$ (i.e., as the angle between V and L approaches π).

Calculation of the color shift is computationally expensive. It can be simplified in one of two ways: by creating lookup tables or by using the following approximation. Values of F are first calculated for a value of n corresponding to the average normal reflectance. These values are then used to interpolate between the color of the material at $\theta=0$ and the color at $\theta=\pi/2$, which is the color of the light source because $F_{\pi/2}$ is 1.0 at every wavelength. For example, let the red component of the color at normal incidence be Red_0 and let the red component of the color of the incident light be $Red_{\pi/2}$. Then the red component of the color at other angles is

$$Red_\theta = Red_0 + (Red_{\pi/2} - Red_0)\,\frac{\max(0, F_\theta - F_0)}{F_{\pi/2} - F_0} .$$

The green and blue components are interpolated similarly. Figure 5c shows the effect of using the approximate procedure to estimate the color of copper as a function of incidence angle. The approximate procedure yields results that are similar to those from the complete (but more expensive) procedure (Figure 5b). The foregoing approximation must always be used if the spectral energy distribution of the reflected light is not known, in which case all of the RGB values are estimates.

Determining the RGB Values

For a computer synthesized scene to be realistic, the color sensation of an observer watching the synthesized scene on a color television monitor must be approximately equivalent to the color sensation of an observer watching a corresponding scene in the real world. To produce this equivalent color sensation, the laws of trichromatic color reproduction are used to convert the spectral energy distribution of the reflected light to the appropriate RGB values for the particular monitor being used.

Every color sensation can be uniquely described by its location in a three dimensional color space. One such color space is called the XYZ space. A point in this space is specified with three coordinates, the color's XYZ tristimulus values. Each spectral energy distribution is associated with a point in the XYZ color space and thus with tristimulus values. If two spectral energy distributions are associated with the same tristimulus values, they produce the same color sensation and are called metamers. The red, green, and blue phosphors of a monitor can be illuminated in proportions to produce a set of spectral energy distributions which define a region of XYZ space called the gamut of the monitor. The goal, then, is to find the proportions of phosphor illumination that produce a spectral energy distribution that is a metamer of the spectral energy distribution of the reflected light.

These proportions are determined by calculating the XYZ tristimulus values that are associated with the spectral energy distribution of the reflected light and then calculating the RGB values that produce a spectral energy distribution with these tristimulus values. To do this, the spectral energy distribution of the reflected light is multiplied by the XYZ matching functions (obtained from [7]) at every wavelength. The resulting spectra are then integrated to obtain the XYZ tristimulus values. These XYZ values are converted by a matrix multiplication to RGB linear luminance values for a particular set of phosphors and monitor white point. The linear luminances are then converted to RGB voltages, taking into account the nonlinearities of the monitor and the effects of viewing conditions. For a more complete description of this procedure, see [12].

The monitor has a maximum luminance at which it can reproduce a given chromaticity. Any XYZ values that represent luminances greater than this maximum are outside the gamut of the monitor. To avoid this problem, all XYZ values in the scene are scaled equally so that they all lie inside the monitor gamut and usually so that the color with the greatest luminance is reproduced on the monitor at the maximum luminance possible for its chromaticity. But even with scaling, some spectral energy distributions are associated with trimstimulus values that lie outside the gamut of the monitor. Because such a color cannot be reproduced on the monitor at any luminance, it must be approximated by a similar color that lies inside the monitor gamut. This color may be chosen in many different ways; in this case we have decided it is appropriate to maintain the same hue, desaturating the color as necessary. To do this, the tristimulus XYZ values are converted to a color space in which locations are specified by dominant wavelength and purity. The purity is then reduced while the dominant wavelength (and thus roughly the hue) is held constant until the color lies inside the monitor gamut. The resulting color is then converted back to XYZ space. (For a discussion of dominant wavelength and purity, see [11].)

Applications

This section discusses the application of the reflectance model to two particular classes of materials, metals and plastics. The main consideration is the homogeneity of the material. Substances that are composed of different materials, such that there is one material at the surface and another beneath the surface, are nonhomogeneous and may have specular and diffuse components that differ in color.

A typical plastic has a substrate that is transparent or white, with embedded pigment particles [10]. Thus, the light reflected directly from the surface is only slightly altered in color from the light source. Any color alterations are a result of the reflectance of the surface material. Light that penetrates into the material interacts with the pigments. Internal reflections thus give rise to a colored, uniformly distributed diffuse reflection.

A plastic may thus be simulated by using a colored diffuse component and a white specular component. This is just the model used by Phong and Blinn and is why so many computer graphics images that have a significant specular component look like plastic. Figure 6a shows a simulated copper-colored plastic vase. This figure was generated with the following parameters:

2 lights: I_i = CIE standard illuminant D6500
$d\omega_i$ = 0.0001 and 0.0002
Specular: s = 0.1
F = the reflectance of a vinyl mirror
D = Beckmann function with m = 0.15
Diffuse: d = 0.9
R_d = the bidirectional reflectance of copper for normal incidence
Ambient: I_{ia} = 0.01 I_i
R_a = πR_d

Metals conduct electricity. An impinging electromagnetic wave can stimulate the motion of electrons near the surface, which in turn lead to re-emission (reflection) of a wave. There is little depth penetration, and the depth penetration decreases with increasing values of the extinction coefficient k. As a result, reflection from a metal occurs essentially at the surface [16]. Thus internal reflections are not present to contribute to a diffuse component, which can be important for a nonmetal. When the rms roughness slope m is small, multiple surface reflections may also be neglected and the entire diffuse component disappears. Figure 6b shows a simulated copper vase. This figure was generated with the following parameters:

2 lights: I_i = CIE standard illuminant D6500
$d\omega_i$ = 0.0001 and 0.0002
Specular: s = 1.0
F = the reflectance of a copper

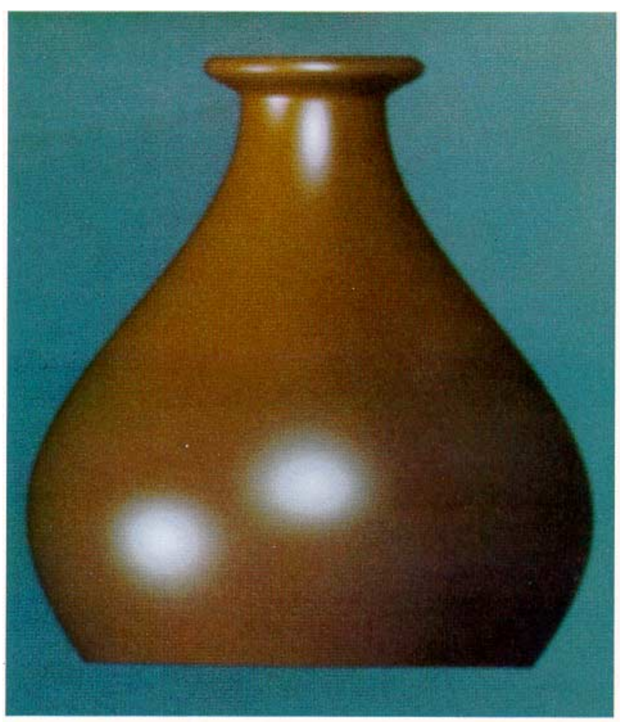


Figure 6a. A copper-colored plastic vase.

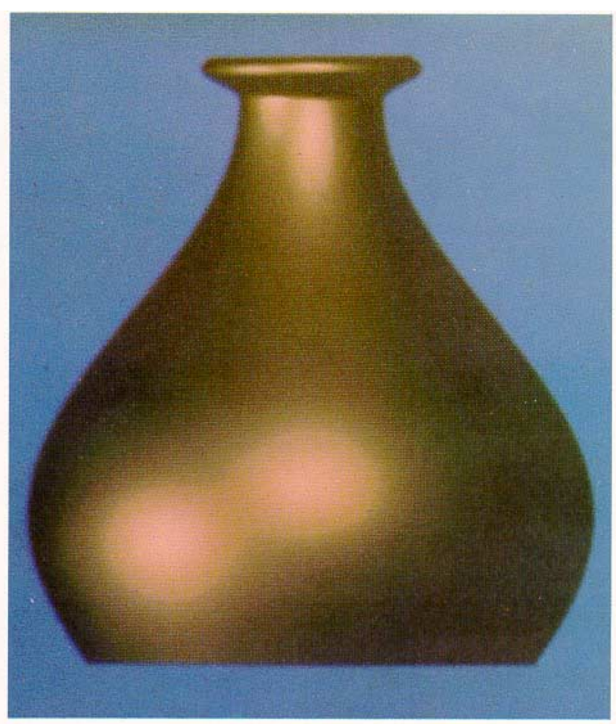


Figure 6b. A copper vase.

mirror
D = Beckmann function with
m_1 = 0.4
wm_1 = 0.4
m_2 = 0.2
wm_2 = 0.6
Diffuse: d = 0.0
R_d = the bidirectional reflectance of copper for normal incidence
Ambient: $I_{ia} = 0.01\ I_i$
$R_a = \pi R_d$

Note that two values for the rms slope are employed to generate a realistic rough surface finish. The specular reflectance component has a copper color. The copper vase in Figure 6b does not display the plastic appearance of the vase in Figure 6a, showing that a correct treatment of the color of the specular component is needed to obtain a realistic nonplastic appearance.

Figure 7 shows vases made of a variety of materials. In every case, the specular and diffuse components have the same color (i.e., $R_d=F_0/\pi$). The lighting conditions for all of the vases are identical to the lighting conditions for Figures 6a and 6b. The six metals were generated with the same parameters used for Figure 6b, except for the reflectance spectra. The six nonmetals were generated with the the following parameters:

Material	s	d	m
Carbon	0.3	0.7	0.40
Rubber	0.4	0.6	0.30
Obsidian	0.8	0.2	0.15
Lunardust	0.0	1.0	not used
ArmyOlive	0.3	0.7	0.50
Ironox	0.2	0.8	0.35

Figure 8 shows a watch made with a variety of materials and surface conditions. It is illuminated by a single light source. The outer band of the watch is made of gold, and the inner band is made of stainless steel. The pattern on the links of the outer band was made by using a rougher surface for the interior than for the border. The LEDs are standard red 640 nanometer LEDs, and their color was approximated by using a color with the same dominant wavelength.

Conclusions

1. The specular component is usually the color of the material, not the color of the light source. The ambient, diffuse, and specular components may have different colors if the material is not homogeneous.
2. The concept of bidirectional reflectance is necessary to simulate different light sources and materials in the same scene.
3. The facet slope distribution models used by Blinn are easy to calculate and are very similar to others in the optics literature. More than one facet slope distribution function can be combined to represent a surface.
4. The Fresnel equation predicts a color shift of the specular component at grazing angles. Calculating this color shift is computationally expensive unless an approximate procedure or a lookup table is used.
5. The spectral energy distribution of light reflected from a specific material can be obtained by using the reflectance model together with the spectral energy distribution of the light source and the reflectance

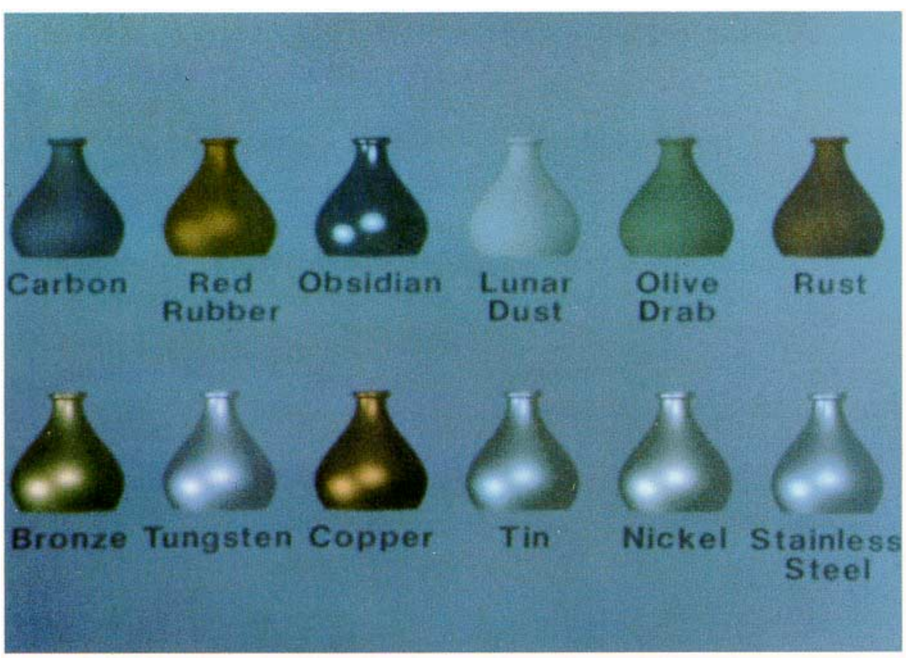


Figure 7. A variety of vases.

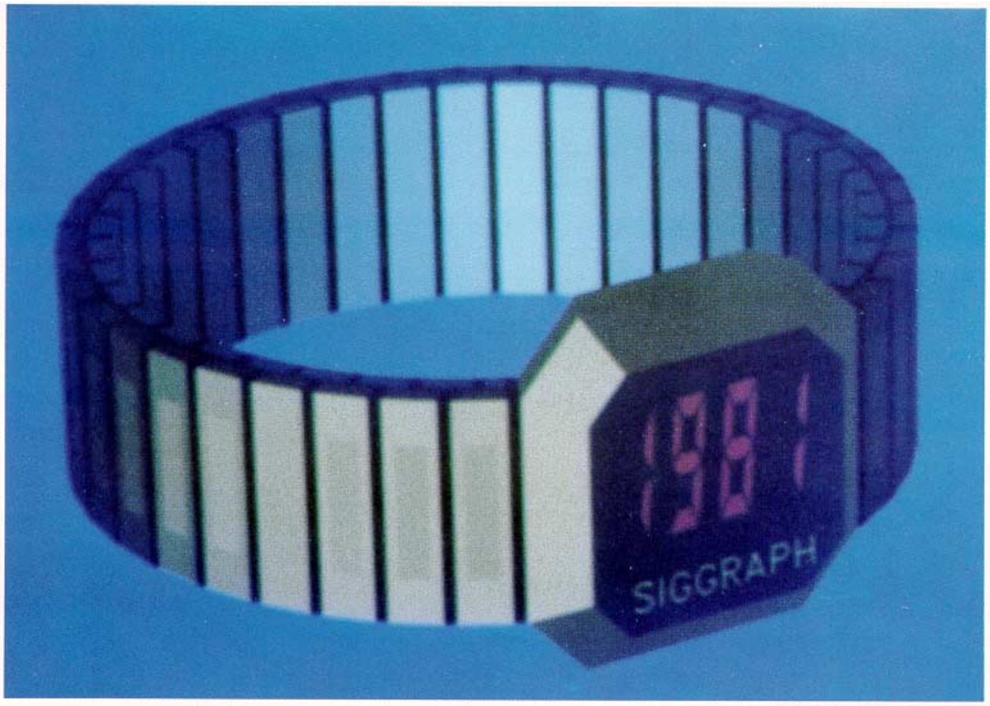


Figure 8. A watch.

spectrum of the material. The laws of trichromatic color reproduction can be used to convert this spectral energy distribution to the appropriate RGB values for the particular monitor being used.

6. Certain types of materials, notably some painted objects and plastics, have specular and diffuse components that do not have the same color. Metals have a specular component with a color determined by the light source and the reflectance of the metal. The diffuse component is often negligible for metals.

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References

1. Barkman, E. F., "Specular and Diffuse Reflectance Measurements of Aluminum Surfaces," Appearance of Metallic Surfaces, American Society for Testing and Materials Special Technical Publication 478, pp.46-58, 1970.
2. Beckmann, Petr and Spizzichino, Andre, The Scattering of Electromagnetic Waves from Rough Surfaces, MacMillan, pp.1-33, 70-98, 1963.
3. Bennett, H. E. and Porteus, J. O., "Relation Between Surface Roughness and Specular Reflectance at Normal Incidence," Journal of the Optical Society of America, v.51 pp.123-129, 1961.
4. Blinn, James F. and Newell, Martin E., "Texture and Reflection in Computer Generated Images," Communications of the ACM, v.19 pp. 542-547, 1976.
5. Blinn, James F., "Models of Light Reflection for Computer Synthesized Pictures," SIGGRAPH 1977 Proceedings, Computer Graphics, v.11 #2 pp.192-198, 1977.
6. Blinn, James F., "Computer Display of Curved Surfaces," PhD dissertation, University of Utah, Salt Lake City, 1978.
7. CIE International Commission on Illumination, "Official Recommendations of the

International Commission on Illumination," Publication CIE No. 15, Colorimetry (E-1.3.1), Bureau Central de la CIE, Paris, 1970.

8. Davies, H., "The Reflection of Electromagnetic Waves from a Rough Surface," Proceedings of the Institution of Electrical Engineers, v.101 pp.209-214, 1954.
9. Gubareff, G. G., Janssen, J. E., and Torborg, R. H., Thermal Radiation Properties Survey: A Review of the Literature, Honeywell Research Center, Minneapolis, 1960.
10. Hunter, Richard S., The Measurement of Appearance, John Wiley & Sons, New York, pp.26-30, 1975.
11. Judd, Deane B., and Wyszecki, Guenter, Color in Business, Science, and Industry, John Wiley & Sons, New York, pp.170-172, 1975.
12. Meyer, Gary W., and Greenberg, Donald P., "Perceptual Color Spaces for Computer Graphics," SIGGRAPH 1980 Proceedings, Computer Graphics, v.14 #3 pp.254-261, 1980.
13. Phong, Bui Tuong, "Illumination for Computer-Generated Images," PhD dissertation, University of Utah, Salt Lake City, 1973.
14. Phong, Bui Tuong, "Illumination for Computer Generated Pictures," Communications of the ACM, v.18 pp.311-317, 1975.
15. Porteus, J. O., "Relation between the Height Distribution of a Rough Surface and the Reflectance at Normal Incidence," Journal of the Optical Society of America, v.53 pp.1394-1402, 1963.
16. Purdue University, Thermophysical Properties of Matter, vol. 7: Thermal Radiative Properties of Metals, 1970.
17. Purdue University, Thermophysical Properties of Matter, vol. 8: Thermal Radiative Properties of Nonmetallic Solids, 1970.
18. Purdue University, Thermophysical Properties of Matter, vol. 9: Thermal Radiative Properties of Coatings, 1970.
19. Siegel, Robert and Howell, John R., Thermal Radiation Heat Transfer, McGraw-Hill, New York, pp.64-73, 1980.
20. Sparrow, Ephraim M. and Cess, R. D., Radiation Heat Transfer, McGraw-Hill, New York, pp.64-68, 1978.
21. Torrance, Kenneth E. and Sparrow, Ephraim M., "Biangular Reflectance of an Electric Nonconductor as a Function of Wavelength and Surface Roughness," Journal of Heat Transfer, v.87 pp.283-292, 1965.
22. Torrance, Kenneth E. and Sparrow, Ephraim M., "Theory for Off-Specular Reflection From Roughened Surfaces," Journal of the Optical Society of America, v.57 pp.1105-1114, September 1967.
23. Whitted, Turner, "An Improved Illumination Model for Shaded Display," Communications of the ACM, v.23 pp. 343-349, 1980.
24. Whitted, Turner, private communication.