



ROY S. BERNIS

Billmeyer and Saltzman's

**PRINCIPLES OF
COLOR
TECHNOLOGY**

FOURTH EDITION

WILEY

Billmeyer and Saltzman's

Principles of Color Technology

Billmeyer and Saltzman's

PRINCIPLES OF COLOR TECHNOLOGY

Fourth Edition

Roy S. Berns

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Program of Color Science

Munsell Color Science Laboratory

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This edition is dedicated to the most important person in my life—Susan Stanger.

Susan, you bring out the best in me and I love you for it.

Contents

Preface, xi

Chapter 1 Physical Properties of Colors 1

- A. WHAT THIS BOOK IS ABOUT?, 1
- B. THE SPECTRUM AND WAVE THEORY, 2
- C. LIGHT SOURCES, 3
- D. CONVENTIONAL MATERIALS, 5
 - Transmission, 5
 - Absorption, 6
 - Surface Scattering, 7
 - Internal Scattering, 7
 - Terminology – Dyes Versus Pigments, 10
 - Spectral Characteristics of Conventional Materials, 12
- E. FLUORESCENT MATERIALS, 12
- F. GONIOAPPARENT MATERIALS, 14
 - Metallic Materials, 14
 - Pearlescent Materials, 14
 - Interference Materials, 15
 - Diffraction Materials, 16
- G. PHOTOCROMIC AND THERMOCHROMIC COLORANTS, 16
- H. SUMMARY. 16

Chapter 2 Color and Spatial Vision 17

- A. TRICHROMACY, 17

- B. LIGHT AND CHROMATIC ADAPTATION, 21
- C. COMPRESSION, 23
- D. OPPONENCY, 23
- E. SPATIAL VISION, 26
- F. OBSERVER VARIABILITY, 29
- G. SUMMARY. 34

Chapter 3 Visual Color Specification 37

- A. ONE-DIMENSIONAL SCALES, 37
 - Hue, 37
 - Lightness, 38
 - Chromatic Intensity, 39
- B. THREE-DIMENSIONAL SYSTEMS, 39
 - Geometries, 39
 - Natural Color System, 40
 - Munsell Color System, 42
 - Other Color-Order Systems, 46
- C. COLOR APPEARANCE: MULTIDIMENSIONAL SYSTEMS, 46
- D. COLOR-MIXING SYSTEMS, 47
 - RGB and HSB, 47
 - The Pantone Matching System, 48
 - Limitations of Color-Mixing Systems for Color Specification, 49
- E. SUMMARY. 49

Chapter 4 Numerical Color Specification: Colorimetry 51

- A. COLOR MATCHING, 51
- B. DERIVATION OF THE STANDARD OBSERVERS, 53
 - Theoretical Considerations, 53
 - The Color-Matching Experiment, 54
 - The 1924 CIE Standard Photopic Observer, 57
 - The 1931 CIE Standard Colorimetric Observer, 58
 - The 1964 CIE Standard Colorimetric Observer, 61
 - Cone-Fundamental-Based Colorimetric Observers, 62
- C. CALCULATING TRISTIMULUS VALUES FOR MATERIALS, 62
- D. CHROMATICITY COORDINATES AND THE CHROMATICITY DIAGRAM, 63
- E. CALCULATING TRISTIMULUS VALUES AND CHROMATICITY COORDINATES FOR SOURCES, 67
- F. TRANSFORMATION OF PRIMARIES, 68
 - Displays, 68
 - Cone Fundamentals, 71
- G. APPROXIMATELY UNIFORMLY SPACED SYSTEMS, 71
 - L^* Lightness, 72
 - $u'v'$ Uniform-Chromaticity Scale Diagram, 72
 - CIELUV, 73
 - CIELAB, 74
 - Rotation of CIELAB Coordinates, 75
- H. COLOR-APPEARANCE MODELS, 78
- I. WHITENESS AND YELLOWNESS, 83
 - Whiteness, 83
 - Yellowness, 84
- J. SUMMARY. 84

Chapter 5 Color-Quality Specification 85

- A. PERCEPTIBILITY AND ACCEPTABILITY VISUAL JUDGMENTS, 85
- B. COLOR-DIFFERENCE GEOMETRY, 86

- C. ELLIPSES AND ELLIPSOIDS, 89
- D. THE COLOR-DIFFERENCE PROBLEM, 92
- E. WEIGHTED COLOR-DIFFERENCE FORMULAS, 96
- F. CMC(L:C) COLOR-DIFFERENCE FORMULA, 99
- G. CIEDE2000 COLOR-DIFFERENCE FORMULA, 100
- H. UNIFORM COLOR-DIFFERENCE SPACES, 105
- I. DETERMINING COLOR-TOLERANCE MAGNITUDE, 106
- J. SUMMARY. 110

Chapter 6 Color and Material-Appearance Measurement 111

- A. BASIC PRINCIPLES OF MEASURING COLOR AND MATERIAL APPEARANCE, 111
- B. THE SAMPLE, 112
- C. VISUAL COLOR MEASUREMENT, 113
- D. MEASUREMENT GEOMETRIES, 114
 - Bidirectional Reflectance Distribution Function, 115
 - CIE Recommended Geometries for Measuring Spectral Reflectance Factor, 115
 - CIE Recommended Geometries for Measuring Spectral Transmittance Factor, 118
 - Multiangle Geometries, 118
- E. SPECTROPHOTOMETRY, 119
- F. SPECTRORADIOMETRY, 121
- G. FLUORESCENCE MEASUREMENTS, 122
- H. PRECISION AND ACCURACY MEASUREMENTS, 124
 - Repeatability, 125
 - Intramodel Reproducibility, 127
 - Accuracy, 128
- I. SPECTRAL IMAGING, 134
- J. MATERIAL-APPEARANCE MEASUREMENTS, 137

- Gloss, 137
- Microstructure – Bidirectional Reflectance Distribution Function, 137
- Macrostructure, 142
- Sparkle and Graininess, 143
- K. SUMMARY. 144

Chapter 7 **Lighting** **145**

- A. STANDARD ILLUMINANTS, 145
- B. LUMINANCE, ILLUMINANCE, AND LUMINOUS EFFICACY, 148
- C. CORRELATED COLOR TEMPERATURE, 149
- D. COLOR RENDITION, 150
- E. SUMMARY. 155

Chapter 8 **Metamerism and Color Inconstancy** **157**

- A. METAMERISM TERMINOLOGY, 157
- B. PRODUCING METAMERS, 158
- C. INDICES OF METAMERISM, 160
 - Special Index of Metamerism, 160
 - General Index of Metamerism, 162
 - Using Indices of Metamerism, 163
- D. COLOR INCONSTANCY AND INDICES OF COLOR INCONSTANCY, 164
- E. SUMMARY. 168

Chapter 9 **Optical Modeling of Colored Materials** **169**

- A. GENERIC APPROACH TO COLOR MODELING, 169
- B. MODELING TRANSPARENT MATERIALS, 171

- C. MODELING OPAQUE MATERIALS, 174
 - Opaque Paints, 176
 - Opaque Textiles, 181
- D. MODELING GONIOAPPARENT MATERIALS, 184
- E. COLOR-FORMULATION SOFTWARE, 184
- F. SUMMARY. 188

Chapter 10 **Color Imaging** **189**

- A. ANALYSIS AND SYNTHESIS, 190
- B. COLOR MANAGEMENT, 191
- C. ADDITIVE VERSUS SUBTRACTIVE MIXING, 195
- D. DISPLAYS AND ENCODING, 198
- E. PRINTING, 204
- F. DIGITAL CAMERAS, 212
 - Colorimetric Accuracy, 213
 - Spectral Accuracy, 217
- G. SPECTRAL COLOR REPRODUCTION, 219
- H. SUMMARY. 219

Bibliography **221**

Annotated Bibliography **237**

Recommended Books **243**

Index **247**

Preface

This is the second time I have revised and updated *Billmeyer and Saltzman's Principles of Color Technology*. The four editions span 50 years, beginning in 1966. The first edition focused on *how* to measure color and correctly interpreting the data. Billmeyer and Saltzman encouraged readers to use common sense, to measure enough samples for a good mean estimate, to always be on the lookout for metamerism, and to *think and look*.

In their preface to the second edition, they wrote, “We have been gratified to see the unexpectedly wide use of *Principles of Color Technology* as a textbook. We found, however, very little need to change the text to accommodate this use: a few numerical examples have been added to assist both the instructor and the student.” They did add a chapter *Problems and Future Directions in Color Technology*, where material that was research oriented and not introductory was included.

When I began to revise the book for a third edition in 1998, the text was 30 years old. The field had matured considerably. An understanding of colorimetry was necessary for the new application—digital imaging. The majority of the text was rewritten and color imaging was added to the chapter *Producing Colors*. I added an appendix, *Mathematics of Color Technology*, principally to support color imaging and for use in graduate courses in color science. I retained the style of the first edition to the best of my abilities.

Two years ago, I began the fourth edition. The third edition was 20 years old. I sent out a questionnaire to colleagues to ask about content and the appropriate mathematical level. I included both industrial scientists and educators. The respondents split into two groups. One group wanted the book to be simpler, having less historical background and returning the book to the first edition. The argument was that instrument manufacturers were not providing adequate industrial education and this book should fill the gap. The mathematical level of the book should remain at an algebra level. The other group wanted the book expanded to include color-appearance models, multivariate analyses of colorimetric data, and measurements of visual texture. This group also wanted less historical background and assumed that any scientist or engineer with a college degree would have

some experience with matrix algebra. My experiences, both industrial and academic, were more aligned with the second group.

This edition, as was the third, is another rewrite. The content has been reorganized from 6 to 10 chapters. Color imaging has its own chapter. Metamerism, still of utmost importance, has its own chapter along with color inconsistency. Color measurement has been expanded to include measuring color and material appearance using conventional spectrophotometers and spectroradiometers and imaging devices that characterize surface topography and visual texture. I used the simplest mathematics I could, which in many cases, is matrix algebra. At its first introduction, I provide both algebra and matrix algebra. I have removed a lot of history and formulas no longer in use. I have increased the number of numerical examples. The mathematics appendix was removed. The annotated bibliography has returned from the first and second editions and I added a section of recommended books for those who want a color science library. I have endeavored to keep the voice of Billmeyer and Saltzman and their informal writing style. Although I am the sole author, “we” is used liberally. In each case, I imagined the three of us discussing the particular point. If we were not unanimous, the point was removed.

I learned very early in my career to ask for help. I still do and I sincerely thank the following for their help: Paula Alessi, David Alman, Yuta Asano, Paul Beymore, Janet Bridgland, Ellen Carter, Robert Chung, Guihua Cui, Maxim Derhak, Christopher Edwards, Patrick Emmel, Mark Fairchild, Susan Farnand, James Ferwerda, Edmond and Susan Gilbert, Nick Harkness, Luke Hellwig, Sean Herman, Robert Hirschler, Kurt Huemiller, Emmett Ientilucci, Fu Jiang, Eric Kirschner, Andeas Kraushaar, Rolf Kuehni, Hideyasu Kuniba, Jennifer Kruschwitz, Ann Laidlow, M. Ronnier Luo, Manuel Melgosa, Michael Murdoch, Francis O'Donnell, Yongmin Park, Jonathan Phillips, Daniella Pinna, Michael Pointer, Mark Rea, Danny Rich, Javier Romero, Renzo Shamey, M. James Shyu, Susan Stanger, Philipp Urban, Stephen Viggiano, Joseph Voelkel, Stephen Westland, David Wyble, Hao Xie, and Joanne Zwinkels.

Finally, I would like to acknowledge the generosity of the late Richard and Elizabeth Hunter for establishing the Hunter Professorship in Color Science, Appearance, and Technology at Rochester Institute of Technology. As the Hunter Professor, I have the freedom to engage in intellectual

pursuits of my choosing. This book is tangible evidence of this freedom.

*Rochester, New York
August 2018*

ROY S. BERNS

Chapter 1

Physical Properties of Colors

A. WHAT THIS BOOK IS ABOUT?

This is a book about *color*, *colorants*, the *coloring* of materials including measurement and control, and *reproducing the color* of materials through imaging.

Color can mean many things. In this book, color may mean a certain kind of light, its effect on the human eye, or — most important of all — the result of this effect in the mind of the viewer. We describe each of these aspects of color, and relate them to one another.

Colorants, on the other hand, are purely physical things. They are the dyes and pigments used in the process of coloring materials.

Coloring is a physical process: that of applying dyes to textiles or incorporating, by dispersion, pigments into paints, inks, and plastics. A part of this book is devoted to describing these physical substances and processes.

But color is much more than something physical. Color is what we see—and we repeat this many times—it is the result of the physical modification of light by colorants as detected by the human eye (called a response process) and interpreted in the brain (called a perceptual process, which introduces psychology). This is an enormously complicated train of events. To describe color and coloring, we must understand something of each aspect of it. A large portion of the book deals with this problem.

With an understanding of color in this broad sense, we can approach some commercial problems involving color. These problems are concerned with answering such

questions as, Does this sample have the same color as the one I made yesterday, or last week, or last year? Does this batch of material have the same color as a standard? Does this reproduced image match the original? How much of what colorants do I use to produce a color just like this one? How can I choose colorants that will perform satisfactorily in a certain application?

Historically, most of these questions have had only subjective answers, based on the skill and memory of the trained color matcher or press operator. Fortunately, through the application of the principles of color technology and the use of color measurement, we can provide objective answers. We consider the industrial application of color technology largely in this objective vein.

In summary, we provide a brief résumé of the present state of the art of color, color control, coloring, color reproduction, and colorants—a very complex field. To simplify, we have omitted much. Among our omissions are conflicting points of view: we tend to present our best current opinion rather than a studied evaluation of all sides of any question. Some topics that are important to include are still evolving; for these cases, we will present the general concepts rather than focus on a particular solution. We hope our readers will be stimulated to seek more detailed and more varied information on many of the subjects we touch upon only briefly.

To this end we provide—and consider of major importance—an annotated bibliography in which we identify those citations among all of our references that we consider key to the body of knowledge comprising color technology. We also provide an annotated list of recom-

mended books to establish a color-science library. We hope that our readers will recognize with us that this book can be no more than a beginning and that they will make use of its bibliography and book recommendations as a guide to the extensive and often complex literature on color.

This book is *not* a “how to” manual for any process or industry. It does not tell you the best way to make a beige shade in vinyl plastic at the lowest cost. Nor does it provide a detailed study of what ink amounts in a multi-ink printer are necessary to reproduce the beige plastic. It *does* tell you in principle how to avoid having that beige go off-shade in tungsten light; it *does* tell why different combinations of inks can match the beige.

This book is *not* an instrument manual or a catalog of instruments; it does not tell you how to operate any specific color-measuring instrument—designed for a single color or many colors simultaneously—to measure samples of a given material. It *does* tell you what types of instruments are available and for what purposes they can or cannot be used. It *does* tell you how to make the best use of these instruments.

This book does *not* attempt to give the “best” ways to use color, the “best” ways to use colorants, or the “best” colorants to use for any application. These are important practical questions, but to answer them would require much more detail than can be put into this book. For these subjects, as for others we do not discuss, there are references to the literature.

B. THE SPECTRUM AND WAVE THEORY

To describe *color*, we must talk about physical actions, such as producing a stimulus in the form of light, both directly and indirectly by interacting with a material, and subjective results, such as receiving and interpreting this stimulus in the eye and the brain or *visual system*. (Throughout the book, important terms will be set in italics the first time they are introduced.) This is depicted in Figure 1.1, a figure we will show throughout this book. Since color exists only in the mind of the viewer, these latter effects are the more important to us. To aid in understanding them, we first consider the *visible spectrum*.

Visible radiation is a form of energy, part of the family that includes radio waves and X-rays, as well as ultraviolet and infrared radiation. Radiation we can see is called *light*. Light can be described by its *wavelength*, for which the *nanometer* (nm) is a convenient unit of length, shown in Figure 1.2. One nanometer is 1/1 000 000 000 m.

The relation of light to the other members of its family is shown in Figure 1.3. The relative insensitivity of the eye limits the visible part of the spectrum to a narrow band of wavelengths between about 380 and 780 nm. The hue we recognize as blue lies below about 480 nm; green, roughly between 480 and 560 nm; yellow, between 560 and 590 nm; orange, between 590 and 630 nm; and red at wavelengths

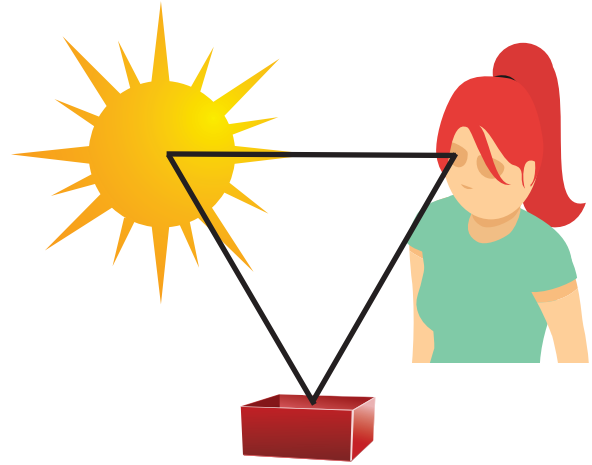


Figure 1.1 Color results from the interaction of a light source, an object, and the eye and brain, or visual system.

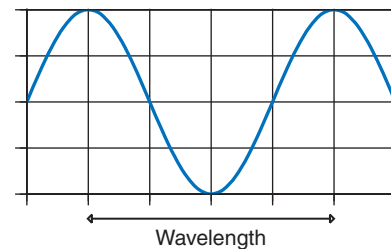


Figure 1.2 Radiation can be described as a wave. The distance from peak to peak is called its *wavelength*.

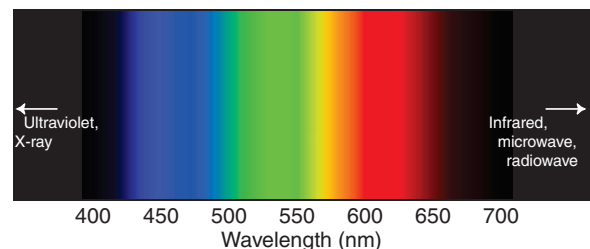


Figure 1.3 A rendition of the visible spectrum and its relationship to other kinds of radiation (not to scale).

longer than 630 nm. Magenta, which is produced by mixing red and blue light from the extremes of the spectrum, is one common hue not found in the spectrum.

The vast majority of colored stimuli are composed of many wavelengths, shown as graphs where radiation, in the case of lighting, or reflection, in the case of an opaque material, is plotted as a function of wavelength. Such graphs are shown in Figures 1.4 and 1.5. Newton (1730) and others (see Hunt 2000) showed many years ago, by using a prism to disperse light into a spectrum, that white light is normally made up of all the visible wavelengths, shown in Figure 1.6.

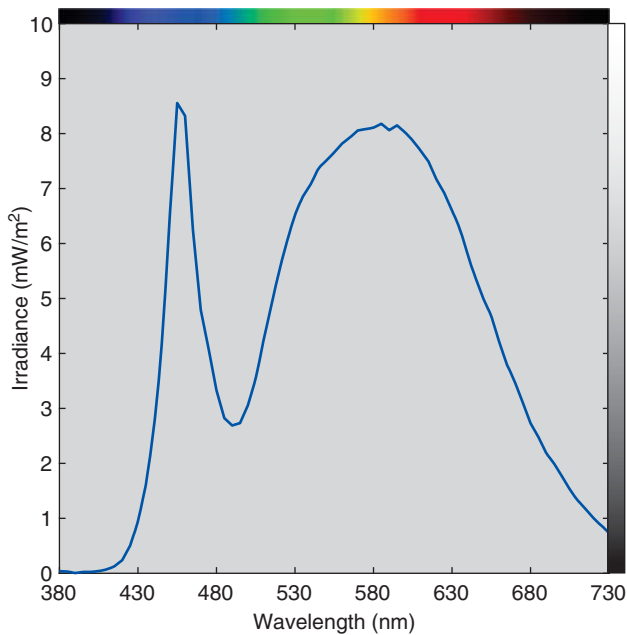


Figure 1.4 The *spectral irradiance* (defined in Chapter 6) of a solid-state white light.

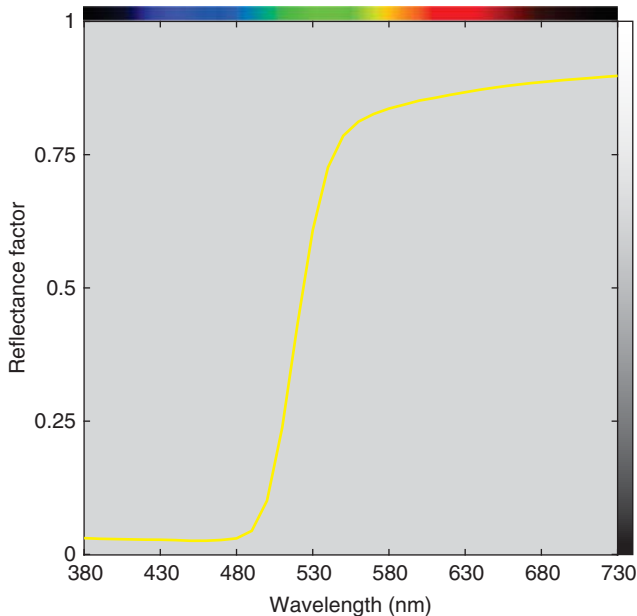


Figure 1.5 The *spectral reflectance factor* (defined in Chapter 6) of a yellow paint.

C. LIGHT SOURCES

Many of the objects we think of as sources of light emit light that is white or nearly white—the sun, hot metals like the filaments of light bulbs, and solid-state lamps, among others. The light from any source can be described in four ways.

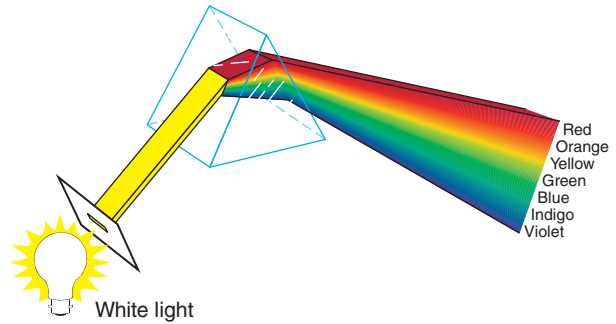


Figure 1.6 Dispersing white light into a spectrum. The color names are somewhat arbitrary; these were used by Newton (1730).

The first is *irradiance*, the amount of light received on a surface per unit area, often defined by watts per unit area expressed in meters squared (W/m^2) and the letter “E.”

The second is *radiance*, the amount of light emanating from or falling on a surface per unit projected area, often defined by watts per unit area per *solid angle* expressed in meters squared steradians ($\text{W}/\text{m}^2 \text{Sr}$) and the letter “L.” We can think of solid angle as a measure of the size of an object relative to a fixed position. An object that is close to us subtends a larger solid angle than the same object viewed from a distance. Instruments that measure irradiance have diffusers while instruments that measure radiance have lenses, described in more detail in Chapter 6.

The third is to normalize the spectrum relative to a specific wavelength, and the fourth is to normalize to the same intensity (“brightness”). Daylight and a solid-state light are plotted the last three ways in Figure 1.7. Because solid-state lights can be narrow-band, such as shown in Figure 1.7, plotting multiple sources normalized to the same intensity is the most descriptive way to compare spectra.

Definitions

Throughout the book, we will be defining various terms. Unless otherwise noted, definitions are based on the CIE International Lighting Vocabulary (CIE 2011) or the ASTM Standard Terminology of Appearance (2013a).

- **Radiant flux:** The time rate of flow of radiant energy. “Power” and “flux” are synonymous.
- **Irradiance:** The radiant flux incident per unit area.
- **Radiance:** Radiant flux in a beam, emanating from a surface, or falling on a surface, in a given direction, per unit of projected area of the surface as viewed from that direction, per unit of solid angle.

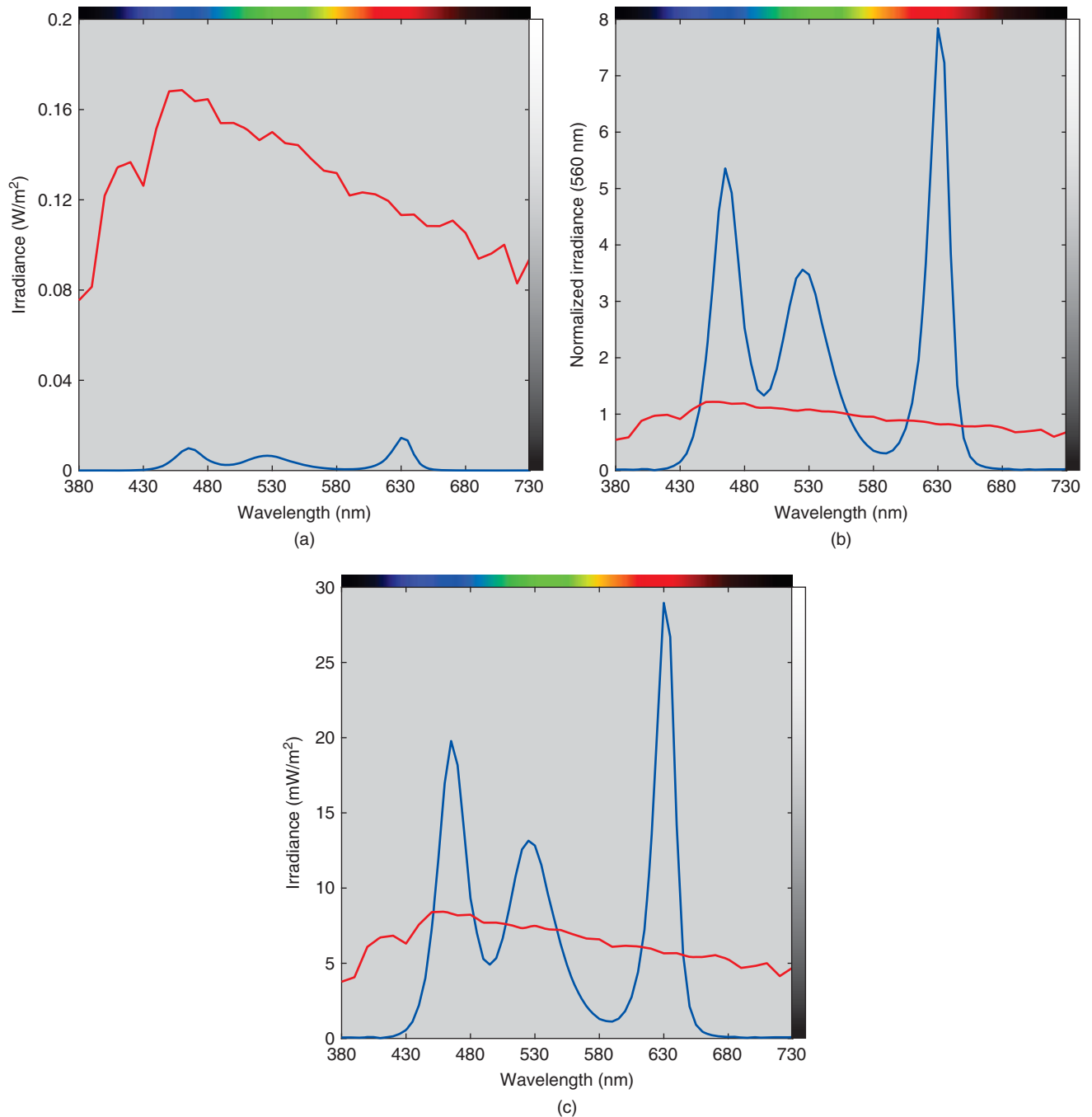


Figure 1.7 Daylight (red lines) and a solid-state light (blue lines) are plotted as (a) irradiance, (b) normalized at 560 nm, and (c) normalized to equal illuminance (“intensity”), all as a function of wavelength. Both sources have the same *correlated color temperature* (defined in Chapter 7).

A number of light sources have been defined by the *International Commission on Illumination* (Commission Internationale de l’Éclairage, or *CIE*) for use in describing color (ISO 2007a; CIE 2018). These distributions are known, in CIE terminology, as *illuminants*. They are based on physical standards or on statistical representations of measured light. There are illuminants for incandescent, fluorescent, outdoor

daylight, indoor daylight, solid state, and high-pressure (e.g. sodium and metal halide) lighting. Different industries have standardized specific illuminants for color specification. In manufacturing, two common CIE illuminants are *D65*, corresponding to indirect outdoor daylight (e.g. from a north-facing window in the northern hemisphere or under cloudy conditions), and *A*, corresponding to incandescent

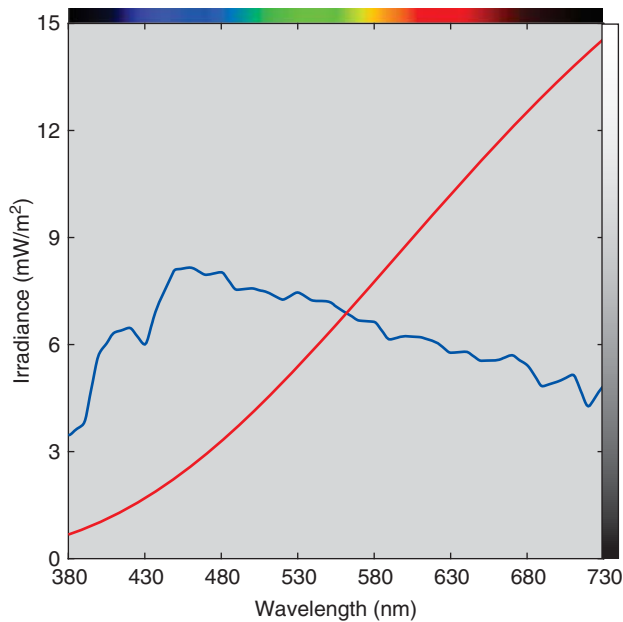


Figure 1.8 CIE illuminants D65 (blue line) and A (red line) plotted at equal illuminance as a function of wavelength.

lighting; these illuminants are plotted in Figure 1.8. We will have much more to say about lighting in Chapter 7.

D. CONVENTIONAL MATERIALS

When light strikes an object, one or more things pertinent to color can happen:

Transmission

The light can go through essentially unchanged. It is said to be *transmitted* through the material, which is described as *transparent*. If the material is colorless, all the light is transmitted except for a small amount that is *reflected* from the two surfaces of the object, shown in Figure 1.9 for a smooth surface.

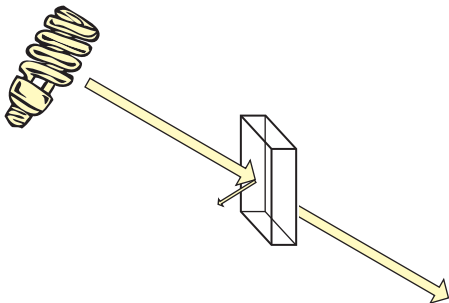


Figure 1.9 Light interacting with a smooth, transparent, colorless object. A small amount of light is reflected in the specular, or mirror-like, direction (drawn only at the front surface).

The small amount of reflected light results from light slowing down inside the material. The reduction in speed relative to a vacuum (the speed in air is almost identical) is defined by a quantity called the *refractive index*, notated by n . Water has a refractive index of 1.33. Since the speed of light in air is about 300 000 km/s, dividing by 1.33 calculates the speed of light in water, about 225 000 km/s. The term “refracted” is used because in addition to the change in speed, the light is bent or refracted. Putting a spoon halfway into a glass of water and looking from the side, the spoon appears bent.

We might perform an experiment where a ray of *monochromatic* light (one wavelength) strikes a piece of glass at various angles. In this experiment, we can measure how the light changes both its direction and intensity, depicted in Figure 1.10 when the ray of light strikes at 45° from straight on—that is, at *normal incidence*. At a refractive index change, such as the front surface of the material, the specular angle is in the direction such that equal angles are made by the incident and reflected light beams with the normal to the surface. The intensity of the specular light depends on the light’s incident angle, wavelength, and *polarization* state, calculated using the *Fresnel equations*, described in a nearby sidebar. The wavelength dependency explains how light is dispersed into a spectrum by a prism.

As light of a specific wavelength travels toward you, the wave oscillates along one or more planes. When the oscillation is restricted to a single plane, it is said to be *polarized*, otherwise unpolarized. A polarizing filter will only pass

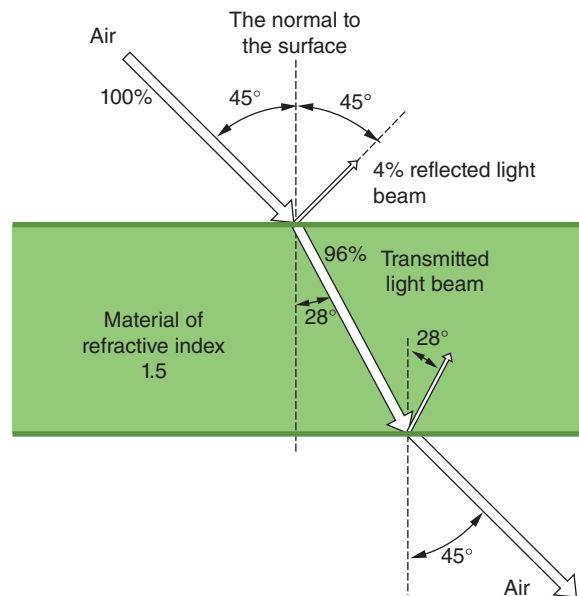


Figure 1.10 At every boundary where there is a change in *refractive index*, some of the light is reflected. The direction of the light beam is changed by an amount that depends on the change in refractive index and the original direction of the beam.

light along a single plane. First-surface reflections tend to have polarization parallel to a surface. Polarizing lenses on sunglasses block parallel polarization thereby reducing glare from streets, water, and ice.

As light is refracted through a material of dissimilar refractive index, the specific angle is calculated using *Snell's law* (Tilley 2011). The intensity of this light is the difference between the incident and reflected light. For window glass, typically with a refractive index around 1.5, only about 90% of the light passes through the glass for normal incidence.

First-Surface Reflections

The light reflected at the interface of two media with dissimilar refractive indices is often referred to as *first-surface reflection*. When the surface is smooth, this reflection occurs at the specular angle. Determining the percentage of the incident light reflected is attributed to Fresnel and for the case shown in Figure 1.10, Eqs. (1.1) and (1.2) are used (Wyszecki and Stiles 1982):

$$R_{\text{parallel}} = \left\{ \frac{\cos(\theta) - \left[\left(\frac{n_{\text{material}}}{n_{\text{air}}} \right)^2 - \sin^2(\theta) \right]^{1/2}}{\cos(\theta) + \left[\left(\frac{n_{\text{material}}}{n_{\text{air}}} \right)^2 - \sin^2(\theta) \right]^{1/2}} \right\}^2 \quad (1.1)$$

$R_{\text{perpendicular}} =$

$$\left\{ \frac{\left(\frac{n_{\text{material}}}{n_{\text{air}}} \right)^2 \cos(\theta) - \left[\left(\frac{n_{\text{material}}}{n_{\text{air}}} \right)^2 - \sin^2(\theta) \right]^{1/2}}{\left(\frac{n_{\text{material}}}{n_{\text{air}}} \right)^2 \cos(\theta) + \left[\left(\frac{n_{\text{material}}}{n_{\text{air}}} \right)^2 - \sin^2(\theta) \right]^{1/2}} \right\}^2 \quad (1.2)$$

where θ is the incident angle and n is refractive index. The amount of reflected light depends on the polarization of the incident light, either parallel or perpendicular to the plane of the material. In many cases, the light is unpolarized and the two polarization states are averaged, as in Eq. (1.3)

$$R_{\text{unpolarized}} = \frac{(R_{\text{parallel}} + R_{\text{perpendicular}})}{2} \quad (1.3)$$

For glass with a refractive index of 1.5, the first-surface reflectance varies between 4% at normal incidence and 100% at the angle perpendicular to the normal angle (90°).

The remaining light enters the material, Eq. (1.4)

$$T = 1 - R_{\text{unpolarized}} \quad (1.4)$$

Absorption

In addition to being transmitted, light may be *absorbed*, or lost as visible light. (If a very large amount of light is absorbed, we can sense that at least part of it is converted into heat.) If the material absorbs part of the light, it appears colored but is still transparent Figure 1.11; if all the light is absorbed, the material is black and is said to be *opaque* Figure 1.12.

For transparent materials, knowledge about their absorption properties as a function of wavelength can be used

The light changes direction as it refracts, the angle defined using *Snell's law*, shown in Eq. (1.5)

$$\theta_{\text{transmitted}} = \arcsin \left\{ \frac{n_{\text{air}}}{n_{\text{material}}} \sin(\theta_{\text{incident}}) \right\} \quad (1.5)$$

Quite often, the spectral transmittance of glass or plastic is measured using spectrophotometers where the angle of incidence is along the normal (0°) and the light is unpolarized. In this case, the Fresnel equations reduce to Eq. (1.6) and the reflected light is notated as K_1 (Saunderson 1942)

$$K_1 = \left(\frac{n_{\text{material}} - n_{\text{air}}}{n_{\text{material}} + n_{\text{air}}} \right) \quad (1.6)$$

The light travels through the material and again encounters a refractive-index change and the same formulas are used to calculate the amount of first-surface reflection, the amount of light entering air, and its refracted angle. The first-surface reflected light continues to inter-reflect inside the material, and as a consequence, less light transmits than when assuming just the two surfaces of the material. For normal incidence, the transmitted light depends on K_1 and the inherent transmittance properties of the material, that is, its internal transmittance, T_{internal} , shown in Eq. (1.7) (Allen 1980)

$$T_{\text{measured}} = \frac{(1 - K_1)^2 T_{\text{internal}}}{1 - K_1^2 T_{\text{internal}}^2} \quad (1.7)$$

Because the change in first-surface reflection is nearly constant for incident light angles found in spectrophotometers used for color measurement, Eq. (1.7) is used to calculate transmitted light, irrespective of the spectrophotometer geometry.

Light transmitting through a material as shown in Figure 1.10, that is, at 45° incidence relative to the normal angle of a material with a refractive index of 1.5, results in the following values: $R_{\text{parallel}} = 0.080$, $R_{\text{perpendicular}} = 0.013$, $R_{\text{unpolarized}} = 0.047$, $T_{\text{inside top surface}} = 0.953$, $\theta_{\text{transmitted}} = 28.1$, and $T_{\text{measured}} = 0.092$.

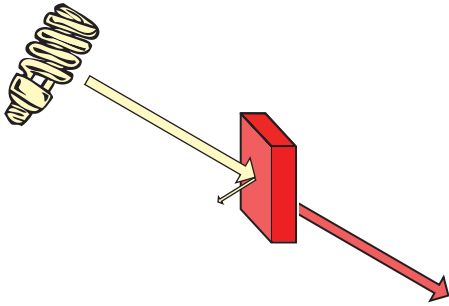


Figure 1.11 Light interacting with a smooth, *transparent* colored object.

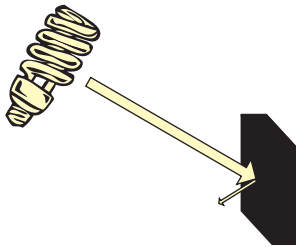


Figure 1.12 Light interacting with a smooth, *opaque* colored object.

to estimate their color. *Bouguer* or *Lambert's law* is used to predict changes in color with changes in a material's thickness (Bouguer 1729; Lambert 1760). *Beer's law* is used to predict changes in color with changes in concentration (Beer 1852, 1854). These laws and their use in predicting color mixtures are described in detail in Chapter 9.

Surface Scattering

Many materials do not produce specular reflections; rather they appear *matte*, *satin*, or *semi-glossy* to borrow terms from the paint industry. The first-surface reflections are *scattered*, caused by a rough surface, shown in Figure 1.13. Surfaces will vary between perfect mirrors and *perfect reflecting diffusers* where light is scattered in all directions equally. (The scattering of a perfect reflecting diffuser is a combination of

surface and internal scattering, described below; in addition, light is not absorbed.)

The specific light scattering about the specular angle is called *bidirectional reflectance distribution function* or *BRDF* (Nicodemus et al. 1977), and numerous models have been derived that predict the BRDF of various materials (Dorsey, Rushmeier, and Sillion 2008). Simpler models have two adjustable parameters, similar to a normal distribution where the mean and standard deviation are changed, shown in Figure 1.14 for the Ward model (Ward 1992; Pellacini, Ferwerda, and Greenberg 2000). There are changes in the distinctness of image of the checkerboard background and the shape, sharpness, and intensity of the specular highlight. Hunter (1937) identified six types of gloss: (i) specular gloss, identified by shininess; (ii) sheen, identified by surface shininess at grazing angles; (iii) contrast gloss, identified by contrasts between specularly reflecting areas of surfaces and other areas; (iv) absence-of-bloom gloss, identified by the absence of reflection haze or smear adjacent to reflected highlights; (v) distinctness-of-reflected-image gloss, identified by the distinctness of images reflected in surfaces; and (vi) absence-of-surface-texture gloss, identified by the lack of surface texture and surface blemishes. These rendered cue balls encompass the first five.

The surface roughness of a transparent coating, such as a polyurethane finish or automotive clear coat, affects the material appearance beneath, shown in Figure 1.15 where a painting becomes nearly unrecognizable when the surface is very rough.

Internal Scattering

Light may be scattered when it interacts with matter. Some light is absorbed and re-emitted at the same wavelength, but now part of the light travels in one direction, part in another, until ultimately some light travels in many different directions. The effects of light scattering are both common and important. Light scattering by the molecules of the air accounts for the blue color of the sky, and scattering from larger particles accounts for the white color of clouds, smoke, milk, and most white pigments.

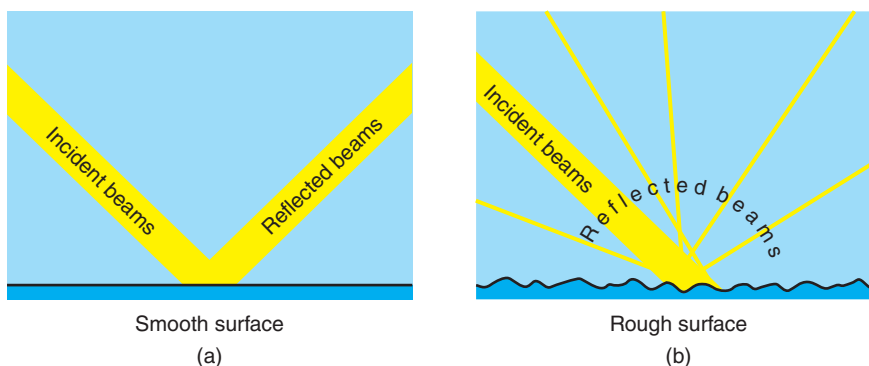


Figure 1.13 Incident light reflecting from smooth and rough surfaces. (a) Specular reflection of light from a mirror-like surface. (b) Diffuse reflection of light from a rough surface.

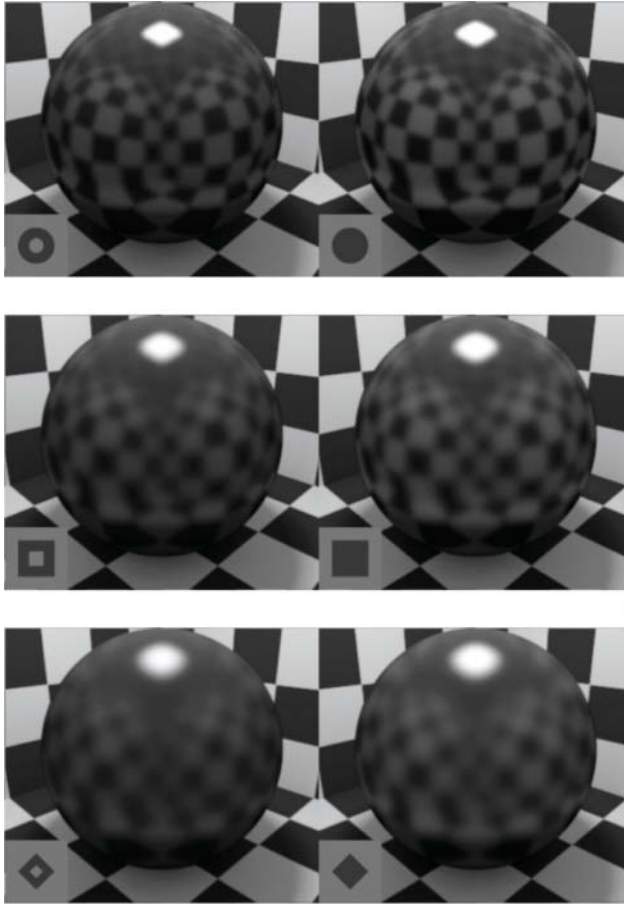


Figure 1.14 Rendered black cue ball using the Ward BRDF model where specular lobe energy is increased going from left to right and specular lobe width is increased going from top to bottom. Source: From Pellacini, Ferwerda, and Greenberg (2000).

When there is enough scattering, we say that light is *diffusely reflected* from a material. If only part of the light passing through the material is scattered, and part is transmitted, the material is said to be *translucent* or *turbid*, shown in Figure 1.16. If the scattering is so intense that no light passes through the material (some absorption is often present), it is said to be *opaque*, shown in Figure 1.17. The color of the material depends on the amount and kind of scattering and absorption present: if there is no absorption and the same amount of scattering at each wavelength, the material looks white, otherwise colored.

Scattering results when light falls on small particles with a refractive index different from that of the surrounding *medium*. The amount of light that is scattered depends strongly on the difference in refractive index between the two materials. When the two have the same refractive index, no light is scattered and the boundary between them, as every microscopist knows, cannot be seen, depicted in Figure 1.18.

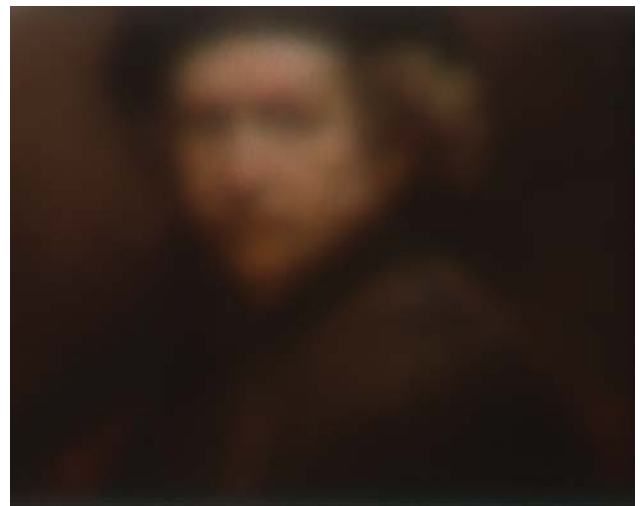


Figure 1.15 Detail of Rembrandt van Rijn (Dutch, 1606–1669), *Self-Portrait*, 1659. Oil on canvas, 83.8 cm × 66 cm (33 1/4 in. × 26 in.). Washington, National Gallery of Art, 1937.1.72. For these images, a photograph of the painting is viewed through (top) clear and (bottom) sandblasted glass. Source: Adapted from Berns and de la Rie (2003).

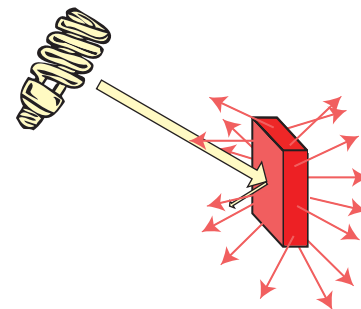


Figure 1.16 The scattering of light by a turbid or translucent material. In such a material, some light is transmitted and some is diffusely reflected by scattering.

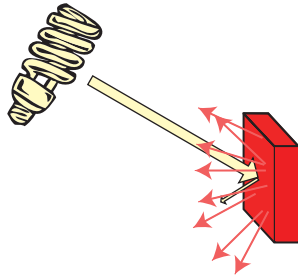


Figure 1.17 With an opaque material, no light is transmitted, but some is diffusely reflected by scattering.

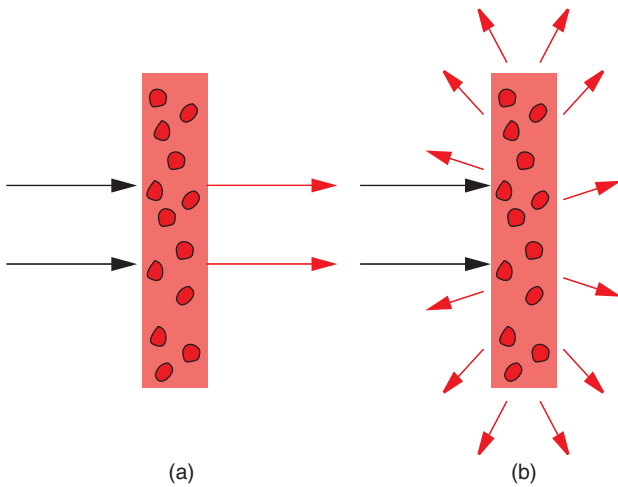


Figure 1.18 (a) If particles are placed in a medium of the same refractive index, there is no scattering, but (b) if there is a difference in refractive indices, scattering results.

As the difference increases, scattering increases, shown in Figures 1.19 and 1.20. The amount of light scattering also depends strongly on the size of the scattering particles (Gueli et al. 2017), shown in Figures 1.21 and 1.22. Very small particles scatter very little light. Scattering increases with increasing *particle size* until the particles are about the same size as the wavelength of light and then decreases for still larger particles.

For these reasons, pigments are most efficient as light scatterers when their refractive index is quite different from that of the medium, for example, resin, plastic, or linseed oil, with which they are to be used, and their particle diameter is about equal to the wavelength of light. When pigments are of very small particle size and have about the same refractive index as the medium with which they are used, they scatter so little light that they look transparent. Scattering can therefore be controlled by selection of pigments with appropriate differences in refractive index or by control of particle size. One can get transparent coatings with very small particle iron-oxide pigments in spite of the difference in refractive

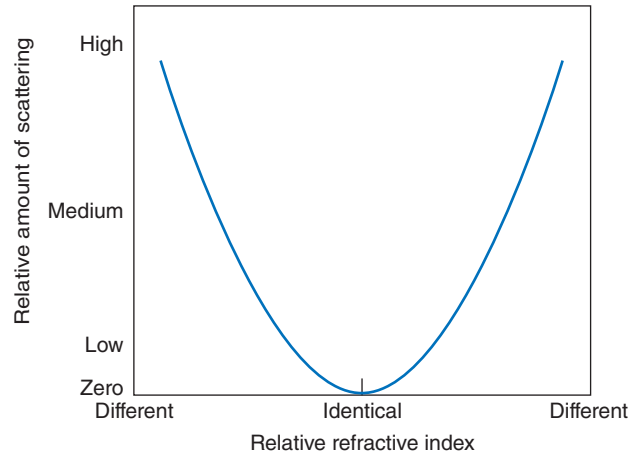


Figure 1.19 Scattering increases as the difference in refractive index between particles and their surrounding medium increases.

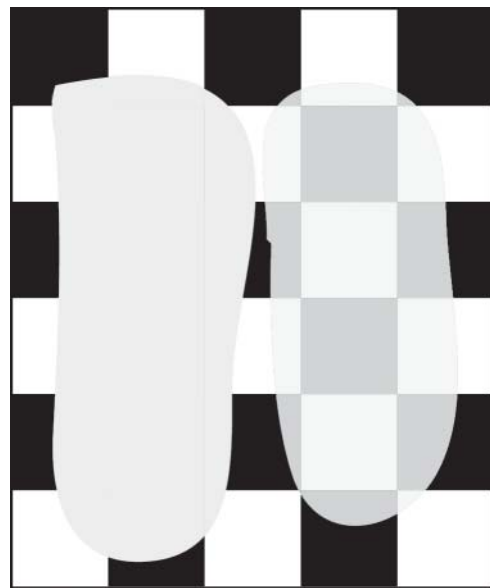


Figure 1.20 Two white paints applied at identical thickness to a checkerboard substrate. The difference in refractive index between the colorant and its medium determines opacity. The paint on the left has a larger difference than that on the right.

index between the medium and the pigment. By control of the particle size, one can get scattering with organic pigments in spite of a relatively close match for refractive index. Depending on a pigment's particle size, small changes, due to process variability, can have a large effect on scattering power and, in turn, color.

Knowledge of the absorption and scattering properties of colorants as functions of the wavelength allows us to predict their colors. This is discussed in Chapter 9.

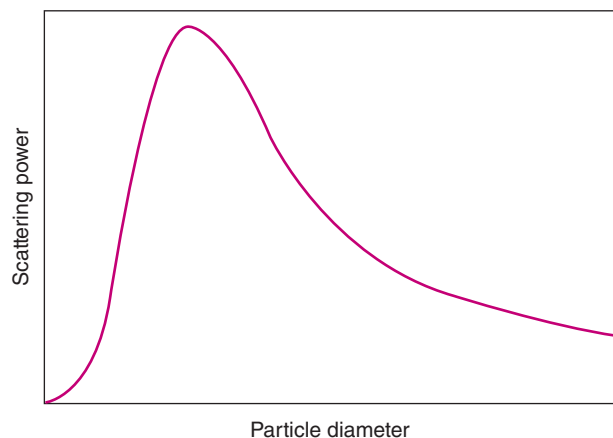


Figure 1.21 Scattering as a function of particle size for a typical pigment.

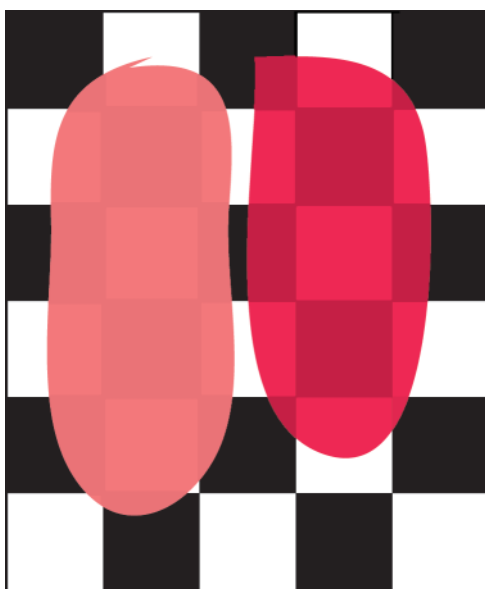


Figure 1.22 Although transparency or the lack of it is sometimes used to tell a dye from a pigment, this distinction does not always hold. Here, the same colorant is shown to have different transparency depending on its particle size and degree of dispersion. The sample on the right has smaller particle size.

Terminology – Dyes Versus Pigments

While *colorant* is the correct term for describing the materials used to impart color to objects, the word is still somewhat unfamiliar. Most people prefer to speak of dyes or pigments instead of using the more general term. But the need to use two words to include all colorants, as well the confusion existing between dyes and pigments, is a strong argument for changing to the word *colorant*. Even more confusing to those seeking precise definitions is the use of the word *color* in place of *colorant*. Sometimes, the use of the word “color”

is due to familiarity and legacy. The most notable example is the *Colour Index*TM, first printed in 1924 (<http://colour-index.com/>). Its name belies an extensive usage of the word “colorant” and, to a lesser extent, the word “substance.” As it is used in this book, color means an effect perceived by an observer and determined by the interaction of the three components of light source, object, and observer (or two components when considering colored lights or displays).

In the past, it was easy to distinguish between a dye and a pigment. A dye was a soluble substance used to color material from a solvent. A pigment was an insoluble, particulate material that was dispersed in the medium it colored and produced scattering. While this simple distinction still holds in most cases, there are many exceptions so that additional criteria must be sought to make a distinction between these two types of colorants. No single definition is completely satisfactory since a given chemical compound can be either a dye or a pigment depending on how it is used.

For many years it has been commonly stated that “dyes are soluble; pigments, insoluble.” This is generally true: most dyes are water-soluble at some stage in their application to a fiber or fabric. But there are some exceptions, or at least borderline cases. Vat dyes, for example, indigo used to color blue jeans, are normally insoluble in water but are “solubilized” chemically during the dyeing operation. In contrast to dyes, pigments are always insoluble in the medium in which they are used: any degree of solubility (called *bleed* in pigment-using industries) is considered a defect. We know of no exceptions to this. To put it another way, however, whenever a colorant normally used as the insoluble pigment is utilized in solution, it is simply called a dye!

Another traditional distinction between dyes and pigments is that dyes are organic and pigments are inorganic substances. The number of inorganic dyes is almost zero, but the number of organic pigments has grown steadily since the rise of the organic chemical industry. Today the distinction works only one way: most dyes are still organic, but it is not true that most chromatic pigments are inorganic. Until recently, all white pigments were inorganic, for example, titanium dioxide or zinc oxide, but now plastic microspheres are used as efficient lightweight scattering pigments.

A third distinction arose from the use of dyes and pigments to color materials such as paints or plastics. Colorants that dissolved in the medium and thus gave transparent mixtures were called dyes, in contrast to pigments, which did not dissolve but scattered light and gave translucent or opaque formulations. If opacity is desired, pigments are used, whereas if one wants to color a transparent medium without spoiling its transparency, dyes soluble in the medium (generally classed as solvent-soluble or oil-soluble dyes) are used. Another method to achieve transparency is to use pigments with very small particle sizes, and if possible of similar refractive index to the medium. When well

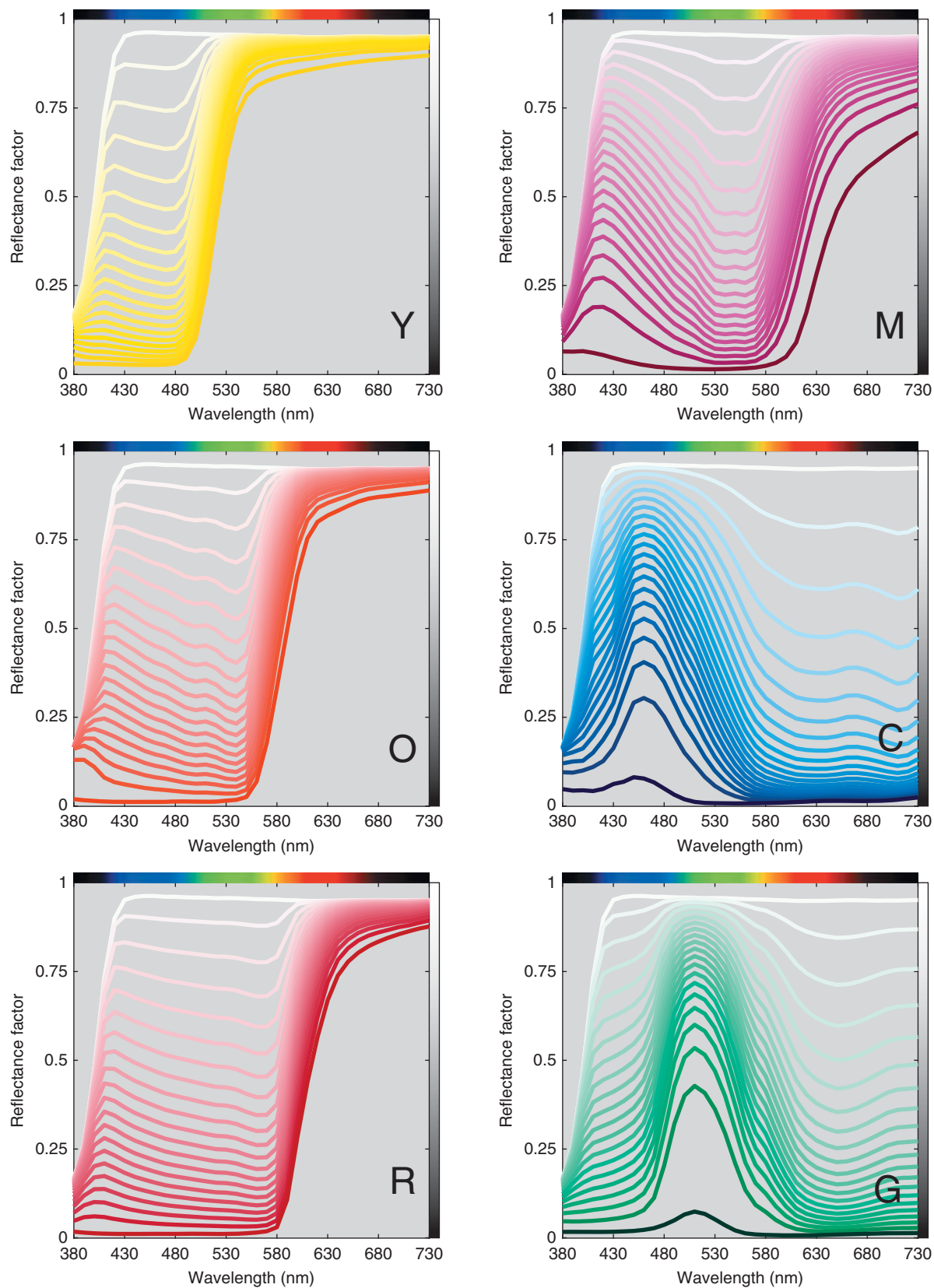


Figure 1.23 Spectral reflectance curves of the following acrylic dispersion paints, each mixed with titanium white (PW 6) at varying ratios: arylide yellow (PY 74), pyrrole orange (PO 73), pyrrole red (PR 254), quinacridone magenta (PR 122), phthalocyanine blue (PB 15), and phthalocyanine green (PG 36).

dispersed, the resulting colored materials are effectively transparent.

A final distinction, to us the one with greatest validity and fewest exceptions, is based on the mechanism by which the colorant is bound to the substrate. If the colorant has an affinity for the substrate (textile, paper, etc.) and will become a part of the colored material without the need for an intermediate binder, we consider such a colorant to be a dye. This substantivity or affinity for the substrate clearly distinguishes dyes from pigments. Pigments have no affinity to the substrate and require a binder so that the pigment is fixed to the substrate. A pigment applied to a surface without a binder will not adhere to the surface.

The Colour Index (C.I.) has become the arbiter of how a coloring material is classified. Available only online, it describes 27 000 individual products. A generic name and a five-digit number that gives the chemical constitution when disclosed (the exact chemical nature of many colorants is still a trade secret) define a colorant, for example, C.I. Pigment Yellow 74 No. 11741. We will define a colorant by its common name based on its chemical composition or historical name with the color-index generic name in parentheses, for example, arylide yellow (PY 74).

- **Radiant flux:** Power emitted, transmitted, or received in the form of radiation.
- **Incident radiant flux:** Radiant flux falling on or striking a material.
- **Transmission:** The process whereby radiant energy passes through a material or object.
- **Transmittance:** The ratio of the transmitted radiant flux to the incident radiant flux under specified geometric and spectral conditions.
- **Absorption:** The transformation of radiant energy to a different form of energy by interaction with matter.
- **Absorptance:** The ratio of the absorbed radiant flux to the incident radiant flux.
- **Reflection:** The process by which radiant energy is returned from a material or object.
- **Reflectance:** Ratio of the reflected radiant flux to the incident radiant flux in the given conditions.
- **Reflectance factor:** Ratio of the radiant flux reflected from the specimen to the radiant flux reflected from the perfect reflecting diffuser under the same geometric and spectral conditions of measurement.
- **Specular reflection:** Reflection that excludes diffuse reflection, as in a mirror.
- **Diffuse reflection:** Reflection that excludes specular (mirror) reflection.

Spectral Characteristics of Conventional Materials

From the standpoint of color, the effect of an object on light can be described by its *spectral transmittance* or *reflectance curve* (for transparent or opaque materials, respectively; both are needed for translucent objects). These curves show the fraction of the light reflected at each wavelength from the material (compared to that reflected from a suitable white reflecting standard, usually the perfect reflecting diffuser) or transmitted through it (compared to that transmitted by a suitable standard, usually air). These curves describe the object just as the spectral power distribution curve describes a source of light. The spectral reflectance curves of several common colorants are plotted in Figure 1.23. In each plot, the colorant is in *masstone* form in which the colorant is dispersed in a medium at high concentration, for example, tube paint, and intermixed with a white colorant in masstone form, resulting in a tint series (*tint ladder*). The white determines the maximum reflectance at each wavelength. Yellow, orange, and red colorants absorb light at shorter wavelengths and reflect light at longer wavelengths. The transition wavelength region from short to long wavelengths differentiates the three colorants. Magenta and purple colorants absorb light in the middle wavelengths. Cyan colorants absorb light at longer wavelengths. Green colorants absorb light at short and long wavelengths. Each colorant has a unique spectral “signature” that sometimes can be used for identification. For example, the secondary reflectance at longer wavelengths identifies the cyan as phthalocyanine blue. However, the clarity of the signature depends on concentration, and as a consequence, reflectance is transformed nonlinearly such that spectra are invariant with changes in concentration (Derby 1952; Johnston-Feller 2001).

E. FLUORESCENT MATERIALS

Most dyes and pigments dissipate absorbed light in the form of heat. However, *luminescent* materials emit light without heat, a process known as *photoluminescence*. This occurs by absorbing light over a range of wavelengths and *emitting* them, most often, at longer wavelengths. When the emitted light continues after *excitation* ceases, it is called *phosphorescence*. When the emission ceases when excitation ceases, it is called *fluorescence*. The emitted light is always diffuse.

Fluorescent whitening agents (FWAs) absorb *ultraviolet radiation* between about 300 and 400 nm and re-emit this radiation as light between 400 and 500 nm. FWAs are used commonly to whiten paper and textiles to make materials look “whiter than white.” What happens is that such a material radiates more *visible* light than is incident on it, making it look brighter than a nonfluorescent material that, at best, can only reflect all the visible light that falls on it.

- **Luminescence:** Emission of light ascribable to non-thermal excitation.
- **Photoluminescence:** Luminescence produced by the absorption of light (excitation); distinguished from ordinary reflection by a time delay and, usually, a shift toward longer wavelengths.
- **Phosphorescence:** Photoluminescence that continues after excitation ceases.
- **Fluorescence:** Photoluminescence that ceases when excitation ceases.
- **Total radiance factor:** The sum of fluorescent and nonfluorescent reflected light from a specimen in comparison to the reflected light from a perfect reflecting diffuser under identical specified geometric conditions.

To obtain this effect, the light source must contain energy at the appropriate wavelengths in the ultraviolet range to produce the emission in the blue region of the visible spectrum. Since soiled textiles are usually yellowish, the emitted blue light replaces the amount of blue light absorbed by the yellow. In a similar fashion, FWAs are used to counteract the yellow appearance of many resins and papers. FWAs are also used to produce “bright white” paper, shown in Figure 1.24.

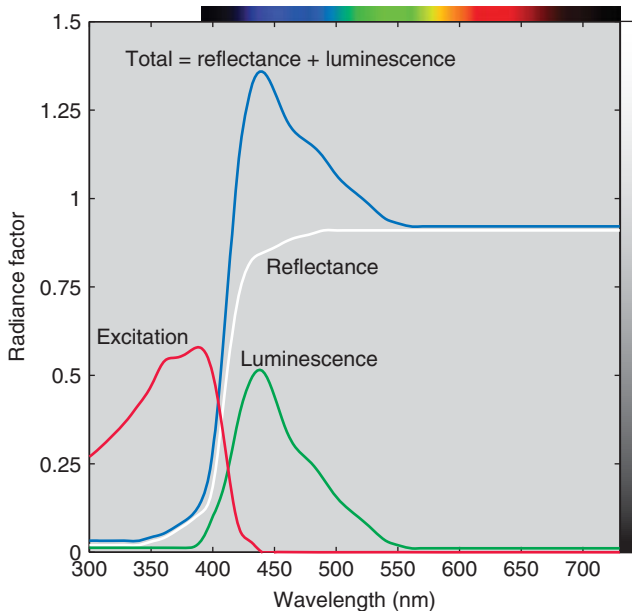


Figure 1.24 Spectral properties of “bright white” paper illuminated by skylight. (Note the wavelength scale extending from 300 to 730 nm.) Any absorbed radiation within the excitation region leads to luminescence that occurs across a range of wavelengths. The reflectance spectrum is the property of the paper without the FWA. The paper’s appearance is determined by its *total radiance factor*, the luminescent and non-luminescent components added together.

Fluorescent colorants both absorb and emit light within the visible spectrum and are used in many products. As shown in Figure 1.25, the green light causes excitation of a fluorescent colorant, which emits diffuse light that is orange in color. As with FWAs, the combined fluorescent emission and nonfluorescent reflection produce spectra that exceed the reflection of a perfect reflecting diffuser, seen in Figure 1.26. The emission of both fluorescent colorants and FWAs depends on the spectral properties of the light source, making standardized measurements that correlate with appearance difficult. Ideally, the light source in an instrument used to measure fluorescent materials should have the same spectral properties as the viewing environment used to illuminate them. Several measurement techniques are described in Chapter 6.

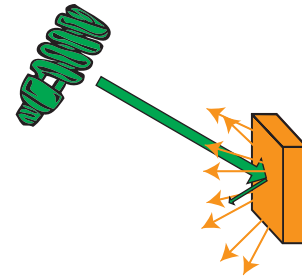


Figure 1.25 The emission of light by an opaque, fluorescent object. The green light is re-emitted diffusely at longer wavelengths, leading to an orange color.

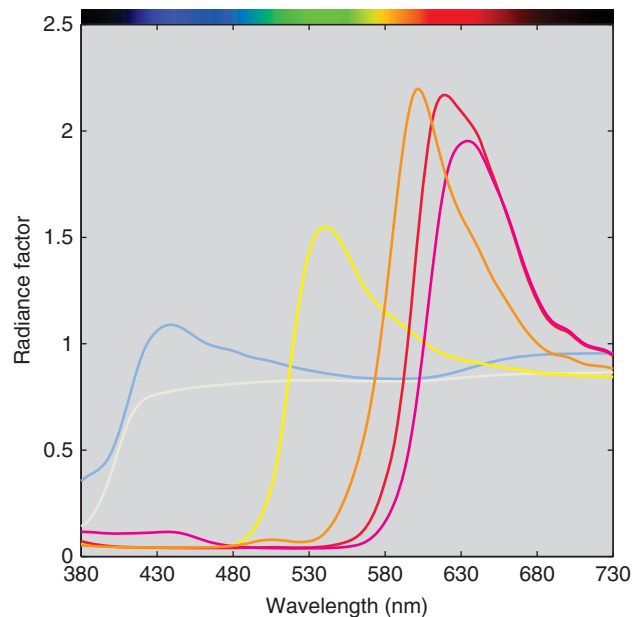


Figure 1.26 Spectral radiance factor of nonfluorescent paper (white line), paper containing FWAs (blue line), fluorescent yellow (yellow line), orange (orange line), red (red line), and magenta (magenta line) paints. The illumination is daylight.

F. GONIOAPPARENT MATERIALS

Thus far, we have described opaque materials having internal reflections (ignoring surface reflections) that are diffuse, and as a consequence, their appearance is largely independent of illuminating and viewing geometries. Such materials are often referred to as *isotropic* and *Lambertian* materials. Coatings containing *metal flakes*, *pearlescent pigments*, *interference pigments*, and *diffraction pigments* have appearances that can change with changes in illumination or viewing angle. These materials are known as *gonioapparent* materials. The terms *effect pigment* and *goniochromatic pigments* are also used. Quite often, these changes are most dramatic near the specular angle, irrespective of the incident angle. Thus, geometries are defined relative to the specular angle, known as the *aspecular angle*, shown in Figure 1.27.

Anisotropic is another common term associated with gonioapparent materials. However, not all coatings containing effect pigments are anisotropic. For example, a coating containing metal flakes can appear isotropic if the flakes have a small particle size and are dispersed with a random orientation within the coating.

Metallic Materials

Since the Egyptians' first use of gold overlays in decorative arts, metals have been used to alter the reflectance properties of man-made objects. One of the distinct characteristics of metals is that their specular reflections are the color of the metal rather than the color of the light source. Because of adhesion problems with thin beaten

- *Isotropic*: Having an appearance that is independent of illuminating and viewing geometry.
- *Anisotropic*: Having an appearance that is dependent on illuminating and viewing geometry.

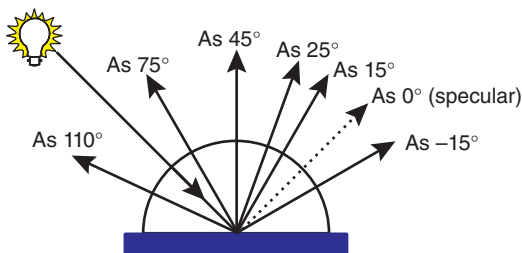


Figure 1.27 Common angles when measuring opaque gonioapparent materials. All the listed angles are *aspecular* angles. The light source is defined as 45° from the normal angle.

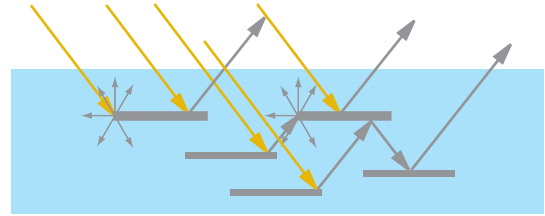


Figure 1.28 Aluminum flakes are oriented within a vehicle. Incident light is specularly reflected. At the edge of a flake, the light is reflected diffusely. Thus, smaller flake diameter increases the amount of diffuse reflection.

metal overlays, powdered metals were mixed with vehicles and applied as paints. Today, commonly used metals include gold, bronze, copper, zinc, stainless steel, nickel, graphite, and aluminum.

Aluminum flake is widely used in the automotive industry to create paint finishes with a metallic appearance. Under a microscope, the pigment particles can look like corn flakes, hence their name. It is also possible to produce metallic pigments that resemble thin disks (Maile, Pfaff, and Reyniers 2005). The aluminum flakes tend to be between 0.1 and 2 μm in thickness with diameters ranging between 0.5 and 200 μm . Flake diameter affects both the diffuse and specular properties of the coating, shown in Figure 1.28. Large diameters produce a narrower specular distribution. Decreasing diameter increases the amount of diffuse reflection, resulting in a widening of the specular distribution and a “whitening” of the finish. These can be used in combination to increase or decrease the difference between the mid-aspecular and either the near-aspecular or far-aspecular properties. (Colloquially, mid- and far-aspecular are known as face and flop colors, respectively.)

The addition of metallic flake to paint produces large changes in color with changes in viewing angle, simulated (Kirchner and Houweling 2009) in Figure 1.29. These large changes accentuate contours. The orientation of the flakes within the paint is another parameter affecting appearance. For quality control, multiangle measurements are required when aluminum or other metal flakes are added to coatings. Imaging techniques may also be required. These topics are described in Chapter 6.

Pearlescent Materials

Pearlescent colorants are commonly used to impart the appearance resembling that of natural pearls and mother-of-pearl. Pearlescent flakes are thin, transparent platelets of high refractive index, which partially reflect and partially transmit light (Greenstein 1988; Pfaff and Reyniers 1999). Their interaction with incident light is shown in Figure 1.30. Unlike metallic flakes that only reflect light, pearlescent colorants both reflect and transmit. The specular reflection resulting from many layers of similarly oriented

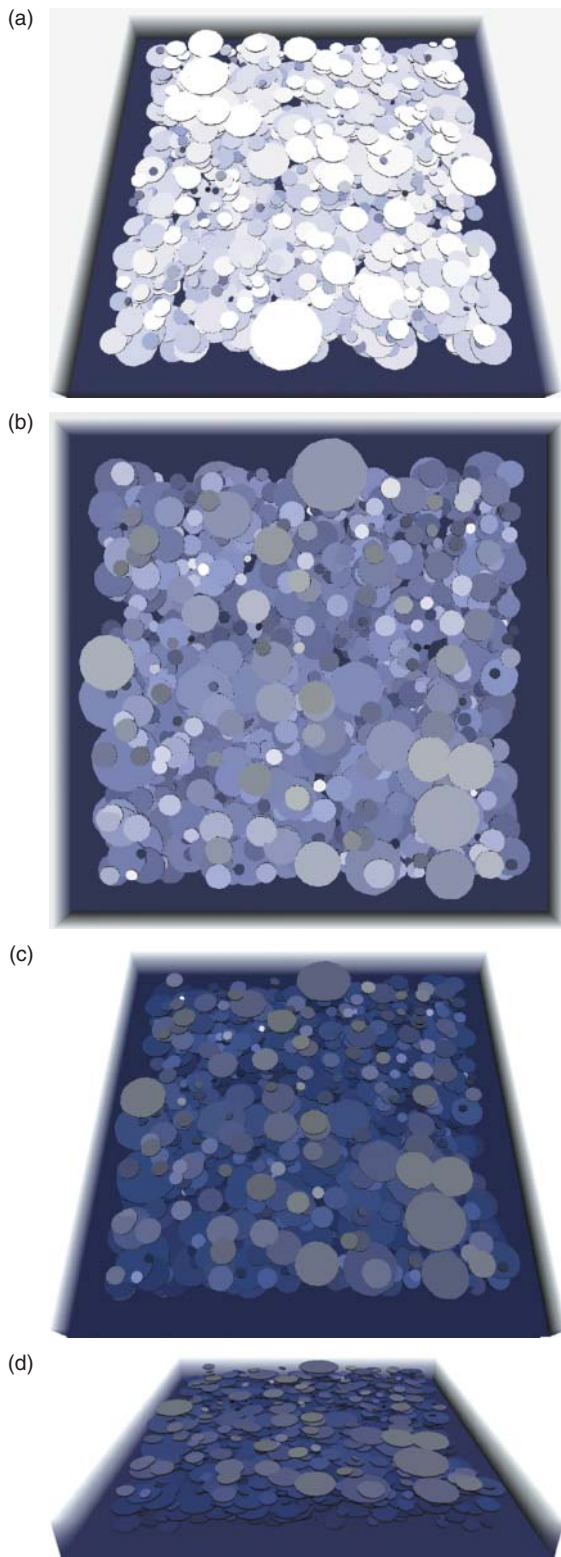


Figure 1.29 Simulating the change in appearance of a metallic coating at different viewing angles: (a) 15° aspecular, (b) 45° aspecular (“face”), (c) 75° aspecular, and (d) 110° aspecular (“flop”). Source: Courtesy of AkzoNobel.

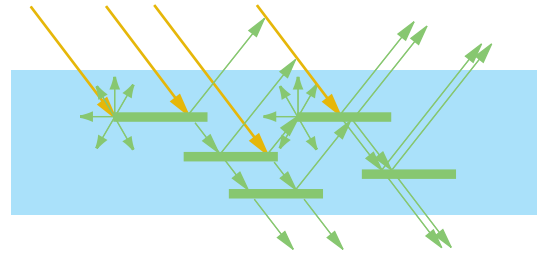


Figure 1.30 Pearlescent flakes are also oriented within a vehicle. Unlike metallic flakes, pearlescent flakes both reflect and transmit light.

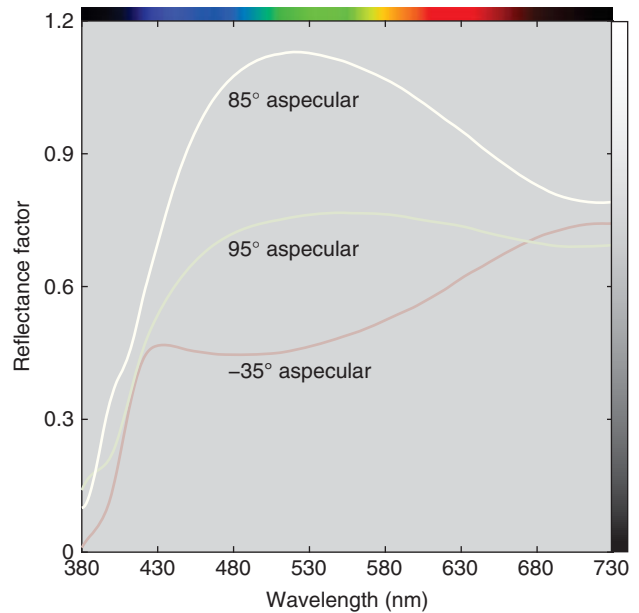


Figure 1.31 Spectral reflectance factor of a green pearlescent mica and white artist paint at each listed aspecular angle.

flakes creates a pearlescent luster. The term *nacreous* is sometimes used in place of pearlescent. During the 1950s and 1960s, basic lead carbonate was used in various plastics to create pearlescent luster (e.g. in buttons). Similar to metallic colorants, their color also varies appreciably with changes in viewing angle. The reflectance factor of a green pearlescent mica and white artist paint at three angles is shown in Figure 1.31. For large aspecular angles, the color is black.

Interference Materials

Certain platelet thicknesses of pearlescent flakes produce color due to light interference. They are known as *interference flakes* or *interference pigments*. Interference occurs through the interaction of light rays of the upper and lower surfaces of the transparent platelet (see Bolomey and Greenstein 1972; Greenstein 1988; Pfaff and Reynders 1999; Nassau 2001; Tilley 2011). Changes in the



Figure 1.32 Simulation of an interference pigment coating. Source: From Musbach (2016).

platelet thickness change the interference color. The transmission and reflection interference colors are different. Fish scales are an organic example of an interference pigment. Titanium-dioxide-coated mica is the most common pearlescent and interference flake pigment. Normal pigments can also be coated onto the mica along with titanium dioxide, resulting in combination pigments.

Recently, thin-film vapor-deposition technology has been used to create interference pigments with high-chromatic-intensity and metallic characteristics. A multilayer structure is produced that consists of a central opaque aluminum layer surrounded by a glass-like layer that is finally surrounded by a semitransparent absorber layer. Controlling the thicknesses of each layer results in a wide range of colors. Because the color results from interference alone, the change in color with change in geometry is dramatic, shown in Figure 1.32. The central aluminum layer creates a colored metallic appearance rather than a colored pearlescent appearance.

Depending on the properties of the pearlescent flake and the color of conventional pigments, very dramatic gonioapparent effects can be achieved in coatings. Modern automotive finishes and nail polishes have very interesting changes in hue and chroma with changes in illumination and viewing geometry. In order to maximize the pearlescent effects, the pearlescent flakes should have a high refractive index (often close to 3.0), optimal platelet thickness and diameter, transparency, and a smooth surface. As with metallics, varying the diameter affects the goniophotometric characteristics of the coatings. Unlike metallics (because they do not produce light interference), varying thickness changes the color of the specular reflection.

Diffraction Materials

Diffraction materials have a metal substrate embossed with parallel grooves that is coated with an inorganic substance (Ferrero et al. 2016). They are essentially tiny diffraction gratings and their colors change at all angles. When added to a coating, a rainbow effect is achieved. The particle size and its orientation within a coating affect the strength of the spectrum.

G. PHOTOCROMIC AND THERMOCHROMIC COLORANTS

In the past, photochromism and thermochromism were viewed as engineering “defects,” limiting the usage of certain colorants (van Beek 1983). Today, these properties have been exploited. Thermochromic colorants are used in textiles in which changes in body temperature change the color of the fabric (Aitken et al. 1996). Photochromic colorants are used to darken eyeglasses and change the color of nail polishes; ultraviolet radiation activates the chemical change (Viková and Vik 2006; Exelby 2008; Corns, Partington, and Towns 2009).

- *Photochromism*: A reversible change in color of a specimen due to exposure to light (or other radiation) without appreciable heating of the specimen.
- *Thermochromism*: A change in color with temperature change.

H. SUMMARY

Light is radiant flux (power) that we sense. The first step in defining color is understanding the interaction between incident light and a material. Incident light can only be reflected, transmitted, or absorbed. Materials that only reflect or absorb light are opaque. When the light transmits through the material without changing its direction, it is transparent. Translucent materials both reflect and transmit incident light. The geometric distribution of reflected and transmitted light depends on both surface and internal scattering. The surface roughness affects appearance parameters such as gloss and distinctness of image, quantified by a bidirectional reflection distribution function. Internal scattering depends on the size, orientation, and refractive index of the colorants compared with their surrounding medium. Traditional colorants produce colors that do not change with changes in illumination and viewing geometry (viewed away from specular angles). Gonioapparent colorants produce colors that do change with changes in illumination and viewing geometry. Metal, pearlescent, interference, and diffraction colorants are examples. Fluorescent colorants absorb light in one wavelength region and emit the light at longer wavelengths. Thermochromic colorants change color with changes in their temperature. Photochromic colorants change color with changes in the amount of UV radiation. The next step in understanding color is how we respond to this light, the subject of Chapter 2.

Chapter 2

Color and Spatial Vision

So far, we have limited our discussion about *color* to the physical stimulus, producing light which, when detected and interpreted through our visual system, results in the stimulus having a particular *color*. The conversion from light energy to color names such as red, green, and brown is exceedingly complex. It requires an understanding of physiology, optics, detectors, neural processing, and cognition. Every year, vision scientists fill in more pieces of the puzzle. The comprehensive textbooks of Backhaus, Kliegl, and Werner (1998), Gegenfurtner and Sharpe (1999), Palmer (1999), Valberg (2005), Daw (2012), and Livingstone (2014) are suggested for more in-depth study. Fortunately, it is not essential for our purposes in this book to know in detail how the visual system works; knowledge of a few basic principles will suffice.

A. TRICHROMACY

A cross section of the eye is shown in Figure 2.1. Light entering our eyes is imaged onto the back of the eyeball, the *retina*. The *cornea* and *lens* focus the image by changing their shape. The *iris* modulates how much light enters the eye. The retina contains *photoreceptors* that absorb a portion of the incident light and generate a signal that is eventually interpreted by the brain. In many respects, the image formation is similar to that in a camera. The quality of the retinal image depends on the absorption, scattering, and focusing properties of the *cornea*, *lens*, and fluids filling the eyeball (*aqueous* and *vitreous humor*). These optical elements influence the spectral and spatial properties of the photoreceptors, or simply, receptors.

There are two classes of receptors, *rods* and *cones*, named according to their shape. They reside within the retina, forming a *retinal mosaic*. Their placement varies throughout the retina and from person to person. In the center of the eye, there is a depression in the retina called the *fovea* or the *foveal pit*. This region contains only cones. Foveal vision is used for distinguishing very fine detail, such as for reading and seeing objects at a distance. A yellowish pigment, *macular pigment*, is also present in the fovea. The macular pigment helps protect the foveal receptors from damage from the sun. Outside the fovea, the number of cones is greatly reduced and they are situated quite far apart from one another. The remainder of the mosaic consists of rods. Since the retina is spherical, the total number of rods far exceeds the total number of cones.

A schematic of the retina in the foveal region is shown in Figure 2.2. Each individual cone does not have a separate connection to the brain; rather, there are interconnections between the horizontal, bipolar, amacrine, and ganglion cells, forming *receptive fields* (Wiesel and Hubel 1966). Thus *resolution*, the ability to resolve fine detail, depends ultimately on both the spatial mosaic of the photoreceptors and how they interconnect.

Rods detect very small amounts of light, such as starlight. A single photon of light can produce a signal. The light-sensitive material in a receptor is called a *photopigment*. Because rods have only a single photopigment, the signal results in an achromatic response where we only see objects as shades of gray. As the amount of light increases, the rods cease sending signals to the brain. During the day or in a well-lit room, the rod signals are inactive.

Cones, the second class of receptors, have much lower sensitivity to incident light. As the amount of light increases,

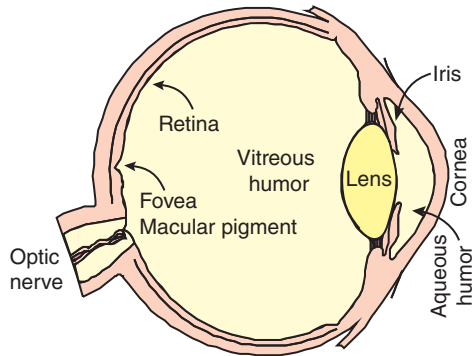


Figure 2.1 The cross section of the human eye.

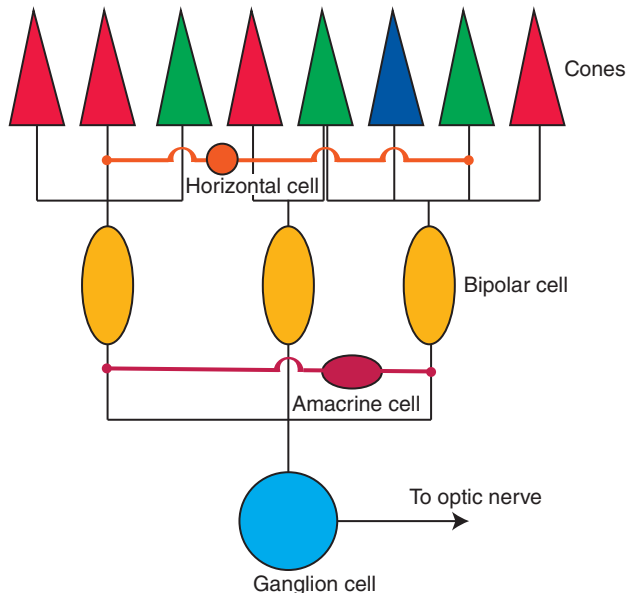


Figure 2.2 Simplified model of the retina (excluding rods).

the cones start sending neural signals. The cones are our color receptors. As the sun begins to rise in the morning, the gray world becomes colored. Our sensations of color are a result of having three types of photopigments that respond differently to light of various wavelengths. Different colored stimuli result from different cone signals. The letters L, M, and S are used to represent the three cone types with their peak sensitivities in the long, middle, and short wavelength regions, respectively. As shown in Figure 2.3, their *spectral sensitivities* overlap quite a bit, particularly those of the L and M cones. This improves color discrimination. Notice also the gap between the S and M cones. Because the spectrum is not sampled uniformly, spectral differences are only rarely used to predict visual differences.

Two stimuli—whether colored lights or illuminated materials—match in color when they produce the same cone signals. Color matches can be calculated by knowing the cones' spectral sensitivities and the stimuli's spectra. As

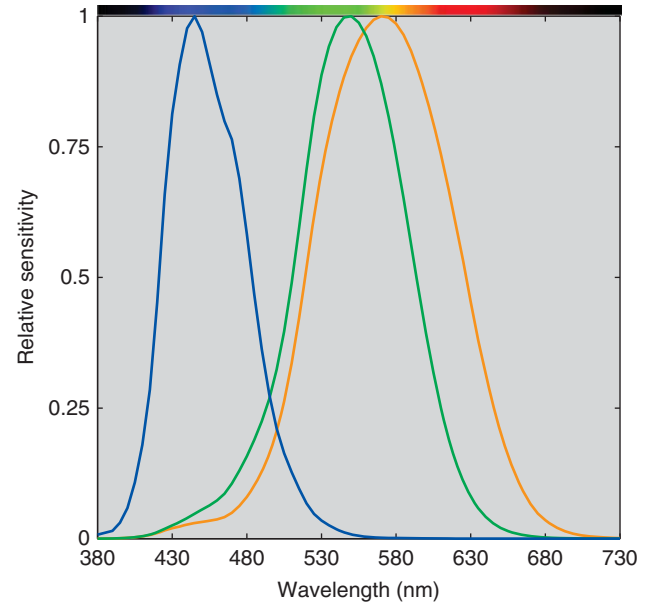


Figure 2.3 Spectral sensitivities of the human visual system cone fundamentals where the orange, green, and blue lines correspond to the L, M, and S cones, respectively. Source: Adapted from Smith and Pokorny 1975.

do any detectors of radiation, the cones integrate—that is, sum up—the light at all wavelengths incident on them. Each such integration of all the incident wavelengths reduces the entire spectrum of incident light to three signals, one for each type of cone, resulting in what is called *trichromacy*. Trichromatic theory is usually associated with Young (1802) and von Helmholtz (1866), although there is evidence that a number of scientists and technologists theorized the existence of trichromacy during the eighteenth century, notably Palmer in 1777 (Weale 1957).

The reduction from spectra to trichromatic signals is shown in Eqs. (2.1)–(2.3):

$$L = \int_{\lambda} S_{\lambda} R_{\lambda} l_{\lambda} d\lambda \quad (2.1)$$

$$M = \int_{\lambda} S_{\lambda} R_{\lambda} m_{\lambda} d\lambda \quad (2.2)$$

$$S = \int_{\lambda} S_{\lambda} R_{\lambda} s_{\lambda} d\lambda \quad (2.3)$$

where S_{λ} is an illuminant's spectral power distribution, R_{λ} is an object's spectral reflectance factor, and l_{λ} , m_{λ} , and s_{λ} are the spectral sensitivities of the human visual system. These formulas are depicted in Figure 2.4. The spectra of the illuminant and object are plotted in the top row. The light reflecting from the object is plotted in the second row. The spectral sensitivities of the object is plotted in the third row. The spectra of the product of the light entering our eyes and our cones' spectral sensitivities are shown in the fourth row.

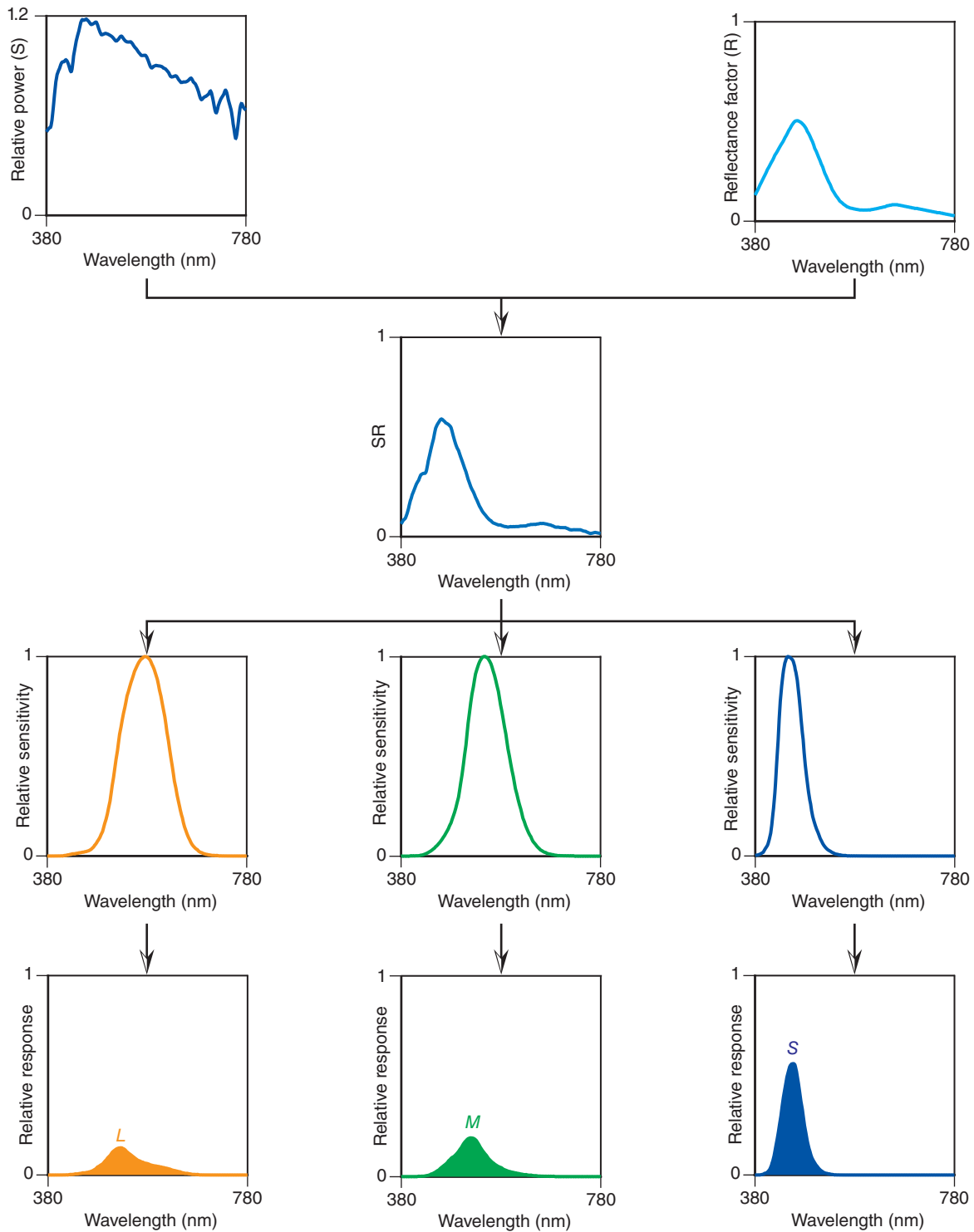


Figure 2.4 The integrated *L*, *M*, and *S* responses that result from the light entering the eye from an illuminated object. This can be calculated as the product of the spectral properties of the light source, the object, and the observer's sensitivities, followed by integration over wavelength, essentially, calculating the areas under the last row of curves.

Approximating Integration Using Summation and Matrix Algebra

Throughout this book, we will show mathematical formulas in the most straightforward way possible. In some cases, this will be in the form of matrix algebra. Integrating incident light to three trichromatic signals is commonly approximated by summation, shown in Eqs. (2.4)–(2.6)

$$L = \sum_{\lambda} S_{\lambda} R_{\lambda} l_{\lambda} \Delta \lambda \quad (2.4)$$

$$M = \sum_{\lambda} S_{\lambda} R_{\lambda} m_{\lambda} \Delta \lambda \quad (2.5)$$

$$S = \sum_{\lambda} S_{\lambda} R_{\lambda} s_{\lambda} \Delta \lambda \quad (2.6)$$

Matrix algebra is very useful when calculating *LMS* signals for several objects, particularly images where there are millions of “objects.” For such cases, Eqs. (2.4)–(2.6) become Eq. (2.7), shown for two objects:

$$\mathbf{t} = \mathbf{TSR} \quad (2.7)$$

where

$$\mathbf{T} = \begin{pmatrix} l_{\lambda} & \dots & l_{\lambda} \\ m_{\lambda} & \dots & m_{\lambda} \\ s_{\lambda} & \dots & s_{\lambda} \end{pmatrix} \quad (2.8)$$

$$\mathbf{S} = \begin{pmatrix} S_{\lambda} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & S_{\lambda} \end{pmatrix} \quad (2.9)$$

$$\mathbf{R} = \begin{pmatrix} R_{\lambda,1} & R_{\lambda,2} \\ \ddots & \ddots \\ R_{\lambda,1} & R_{\lambda,2} \end{pmatrix} \quad (2.10)$$

$$\mathbf{t} = \begin{pmatrix} L_1 & L_2 \\ M_1 & M_2 \\ S_1 & S_2 \end{pmatrix} \quad (2.11)$$

The areas under the curve are the cone responses. Because the light entering the visual system in this example has power mainly in the short wavelength region, the area under the curve for the S cones is greatest.

We have shown plots of the spectral sensitivities of the L, M, and S cones in Figures 2.3 and 2.4. Looking at the cross section of the eye in Figure 2.1, we see that the light entering our eyes is modified by the absorption and scattering properties of the cornea, aqueous humor, lens, vitreous humor, and in the fovea, macular pigment. How

are we accounting for these properties? The L, M, and S “cone responses” and “spectral sensitivities” are based on measurements that include *prereceptor absorption and scattering*. These are different than measuring the spectral absorption of the light-sensitive material in a cone, called a *photopigment*. The term *cone fundamental* is used to represent measurements made in front of the eye. When we refer to L, M, and S “cones,” we mean to say “cone fundamentals.”

■ **Metamerism:** Phenomenon in which spectrally different stimuli appear to match to a given observer.

The conversion from spectra to three signals, that is the process of trichromacy, is one of the most important properties of the visual system. This means that different spectra can produce the same trichromatic response. This property is called *metamerism* (Grassmann 1853) and there are many examples, notably images. Color printing reproduces much of our chromatic world with just four inks—cyan, magenta, yellow, and black. Color displays combine red, green, and blue lights. This is shown in Figure 2.5 where the light produced by a display matches the sunlight reflecting from light skin. Color imaging is ubiquitous because our vision is trichromatic.

The example of metamerism shown in Figure 2.5 is defined by Eqs. (2.12)–(2.14):

$$\int_{\lambda} S_{\lambda} R_{\lambda} l_{\lambda} d\lambda = \int_{\lambda} L_{\lambda} l_{\lambda} d\lambda \quad (2.12)$$

$$\int_{\lambda} S_{\lambda} R_{\lambda} m_{\lambda} d\lambda = \int_{\lambda} L_{\lambda} m_{\lambda} d\lambda \quad (2.13)$$

$$\int_{\lambda} S_{\lambda} R_{\lambda} s_{\lambda} d\lambda = \int_{\lambda} L_{\lambda} s_{\lambda} d\lambda \quad (2.14)$$

where S_{λ} is the spectral power distribution of sunlight, R_{λ} is the skin’s spectral reflectance factor, L_{λ} is the display’s spectral radiance, and l_{λ} , m_{λ} , and s_{λ} are the spectral sensitivities of the L, M, and S cones. Following the integration, the match can be defined by Eq. (2.15)

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix}_{\text{illuminated skin}} = \begin{pmatrix} L \\ M \\ S \end{pmatrix}_{\text{liquid crystal display}} \quad (2.15)$$

Metamerism also occurs in ways that are detrimental to our experience of color. Different materials often require different colorants. If the colorants are not carefully selected, metameric matches can be made in which the materials match only for one set of viewing and illuminating conditions. Imagine an automotive interior in which all of the colored parts match only in the showroom! We consider issues surrounding metamerism throughout this book, including a chapter devoted to this topic, Chapter 8.