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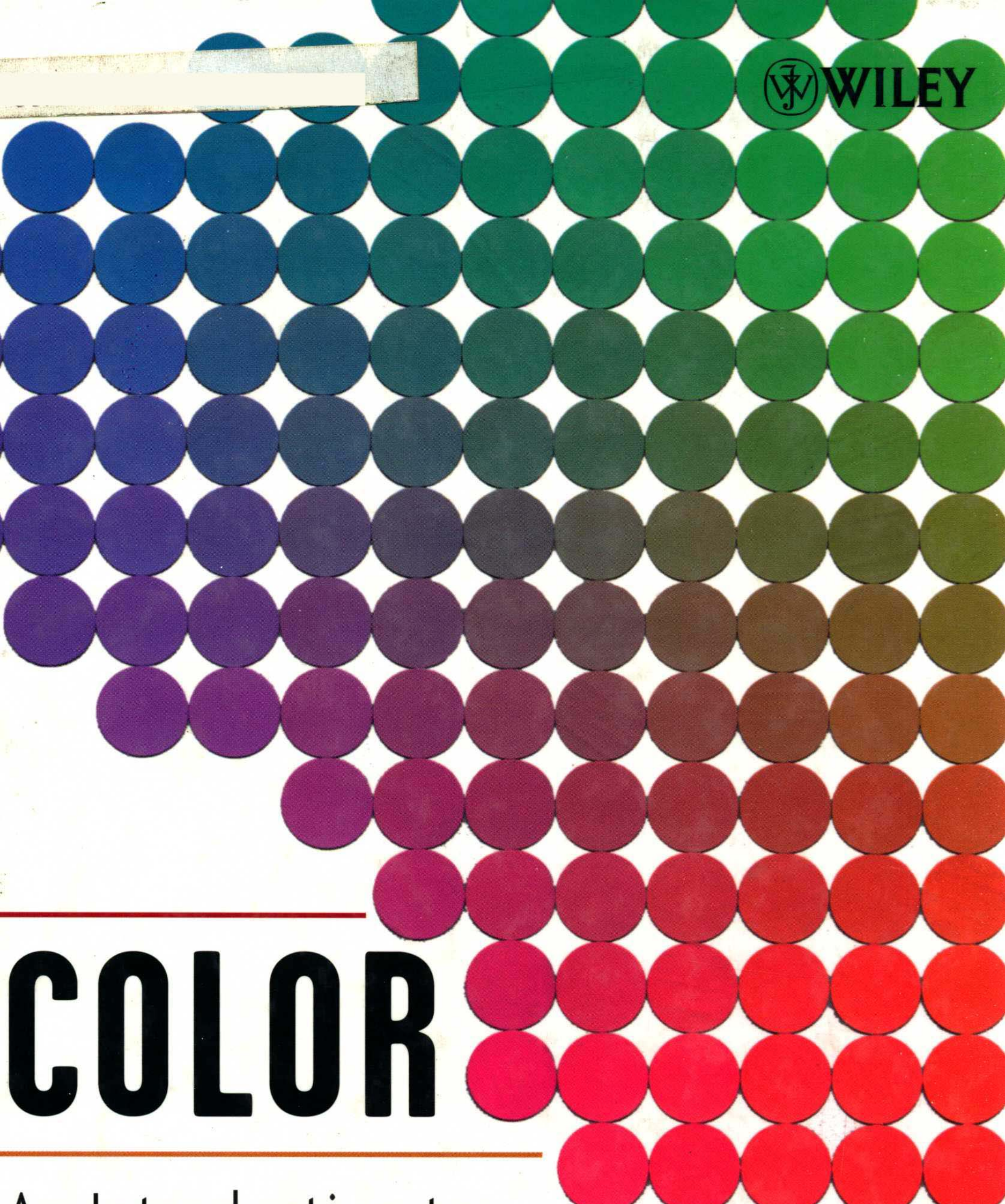

COLOR

An Introduction to Practice and Principles

SECOND EDITION

ROLF G. KUEHNI

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By convention there is color, by convention sweetness and bitterness, but in reality there are atoms and space.

—Democritus (c. 460 B.C.–c. 370 B.C.) Fragment 125

In his younger years the sixth Ch'an patriarch Hui-neng visited the Fa-hsing temple. He overheard a group of visitors arguing about a banner flapping in the wind. One declared: "The banner is moving." Another insisted: "No, it is the wind that is moving." Hui-neng could not contain himself and interrupted them: "You are both wrong. It is your mind that moves."

—Tun-huang manuscript, Tenth century

Preface to the Second Edition

This is the third version of an introductory text on the subject of color and color technology. It follows the outline of the first edition of the current book closely, but approximately three quarters of the text has been rewritten for two main reasons: to bring it, in a general manner, up-to-date and to broaden its nontechnical aspects. More stress has been placed on the widening chasm of views about the nature of color: Is it located in nature and physically easily definable or a complex construct of the brain/mind?

Color is a much more encompassing subject than is usually conveyed in standard textbooks on color science and technology. It is part of the very complex vision process whose functioning, despite many advances, remains unknown in detail. There is also the continuing discrepancy between what is known about the physiological processes of color vision and the final results in our conscious experiences. At the same time technological treatment of color is becoming more and more mathematical model driven in a time of economic world competition and of the need to speed up all processes.

The intent remains to provide a relatively simple but technically correct and up-to-date introduction to many aspects of color. The book is intended to be a largely nontechnical text that is reasonably comprehensive, short, and nonmathematical.

Artists, designers, craftsmen, philosophers, psychologists, color technologists, students in many fields with interests in color, or any other person interested in this subject will find first-level answers to many questions related to color as well as insight into the historical development of our knowledge and thinking on the subject. Using the notes, the book can be a stepping stone to more in-depth studies.

Over the years I have become indebted to many people who helped to widen my horizons of this deeply fascinating subject, for which I am grateful. In turn, I hope this book helps open the horizons of many of its readers.

Contents

1

Sources of Color

For the normally sighted color is everywhere. In the interior of a dwelling are natural and stained woods, wallpapers, upholstery fabrics, pottery, paintings, plants and flowers, a color television set, and many more things. Out of doors, and depending on the time of the year, there is a riot of colors such as those on an alpine summer meadow, or a sparseness, with olives, browns, garnets, and grays. Colors can be pleasantly subdued, enhancing relaxation, or loud and calling to us from advertising billboards or magazines. Color entices us to eat, consume, or at least to buy.

Color likely has helped us to survive as a species. Our (known) contacts with the world and the universe are by way of our five senses. Persons with a normally functioning visual system obtain what is probably the largest amount of information about the world surrounding them from vision, and color is an important outcome of this flow of information. In the past several thousand years color has blossomed into much more than just a survival and communications tool. We have learned to derive esthetic pleasure from it by way of crafts, design, and art.

The question of the nature of color experiences has puzzled humans since antiquity and has resulted in many and varied answers. The number of different color phenomena in the natural world, from colored sunsets and rainbows and the color of a rose to those of an opal and the glow of phosphors, has made understanding the phenomenon of color rather difficult. The popular view is shaped strongly by our everyday experiences. Bananas are yellow, a ruby-throated hummingbird has a dazzling red patch below his beak, clear water and the sky are blue, and so on. A fabric is dyed with red dye; when painting we use variously colored pigments or we draw with variously colored crayons or ink pens. The rainbow has four colors, or is it

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six or seven? In a mirror we see colors of objects appearing slightly duller and deeper than in the original. On a winter day, toward evening, shadows look deeply blue. We are told that color illustrations in an art book are printed just with four pigments and that all colors on a TV screen are "made" from a red, a blue, and a green phosphor.

To cope with these confusingly varied sources of color we just disregard them in our everyday languages. An apple is red, the traffic light is red, the rose as seen reflected in a mirror is red, the bar in the bar graph on the computer video display is red, the paint on the brush is red. All of these varied experiences have something in common: redness. We simply attach the perceived phenomenon to the object without bothering about the source or thinking about the nature of color.

We normally experience color as a result of the interaction between light, materials, and our visual apparatus, eye and brain. However, there are also means of having color experiences in the dark, with eyes closed:

Under the influence of migraine headaches
Under the influence of certain drugs
By direct electrical stimulation of certain cells in the brain
By pressing against the eyeballs or hitting the temples moderately hard
By dreaming

In some manner these situations or actions trigger responses in our visual system that have the same result as conventional color stimuli. Such phenomena are not unlike an electronic burglar alarm triggered by on overflying aircraft rather than by a burglar.

The fact that a variety of color stimuli may result in identical experiences for human observers points to color being a subjective phenomenon. Not all philosophers agree; some claim color resides in objects. A convincing theory of what it is in objects such as those mentioned earlier and many others that results in a specific experience of reddishness has not been forthcoming, however. To the author it seems more sensible to assume that colors are not real and the world in front of us is not colored. Newton already made the point about prismatic light by saying "the rays to speak properly are not coloured." On the other hand, this fact seems to fly in the face of our apparent everyday experiences with colorants, materials expressly used to impart color on other materials. But colorants are simply materials that modify reflectance properties.

Color is the result of the activity of one of our five senses, vision. So far, we have not succeeded in defining the essence of the results of sensory activities, emotions, or feelings: what is sweet, what is happy, or blue? Dictionary definitions of color are, therefore, of necessity vague: "a phenomenon of light (as red, brown, pink, or gray) or visual perception that enables one to differentiate otherwise identical objects" (1).

Scientists are equally helpless and have resorted to a circular definition: "perceived color is the attribute of visual perception that can be described by color names: white, gray, black, yellow, orange, brown, red, green, blue, purple, and so on or by combinations of such names" (2). Before considering the difficult subject of the nature of color further it is useful to gain a fuller understanding of the causes of color.

One of the most impressive displays of color occurs when in an otherwise dark room a narrow circular beam of sunlight passes through a glass prism. What leaves the prism is the same light entering it, but on leaving the prism the circular beam has been transformed into a band of light that, when reflected from a white surface, produces in the observer's vision system a multitude of color experiences: the colors known as those of the rainbow. A less elaborate method for viewing these colors is by looking at a compact disk at different angles in the light of a lamp.

A considerable number of processes and materials can result in color experiences. Many have been discovered by artists and craftspersons over the course of millennia, but until recently the underlying causes remained mostly hidden. Colored materials (many used as colorants) are commonly thought to interact in similar ways with light, but their apparent color is in fact caused by a variety of specific phenomena. Nassau has identified and described a total of fifteen causes of color, four dealing with geometrical and physical optics, those remaining with various effects involving electrons in atoms or molecules of materials and causing absorption or emission of light at selected wavebands (3). With the exceptions listed earlier, color phenomena have one common factor: light. Aristotle wrote that the potential of color in materials is activated by light. Goethe called colors "the actions and sufferings of light." The most common source of light is the process of incandescence. Our first step is to gain understanding of the nature of light and incandescence.

LIGHT

Light is a certain kind of electromagnetic radiation, which is a convenient name for the as yet not fully explained phenomenon of energy transport through space. Electromagnetic radiation, depending on its energy content, has different names: X rays capable of passing through our bodies and on prolonged exposure causing serious harm, ultraviolet radiation that can tan or burn our skin, light that we employ to gain visual information about the world around us, infrared radiation that we experience on our skin as warmth or heat, information transmission waves for radio and television, or electricity transmitted and used as a convenient source of energy (Fig. 1.1). Electromagnetic radiation travels at high speed (the speed of light, about 300,000 kilometers per second [km/s]). The eye, our visual sensory organ, is sensitive to a narrow band of electromagnetic radiation, the visible spectrum.

The basic nature of electromagnetic radiation and its mode of transport are not yet fully known. Some experiments show that it travels in the form of waves (comparable to those created when throwing a pebble into a calm pond) or in the form of individual packets of energy, called quanta (singular quantum) or photons. When regarded as waves, the energy content of radiation is usually expressed in terms of wavelength: the shorter the distance between neighboring peaks of waves, the higher the energy content. Wavelength is commonly measured in metric units and the wavelength of visible light ranges from approximately 400 nanometers (nm, billionth of a meter) to 700 nm. When considered as quanta, the energy content is usually expressed as electron volts (eV). Visible electromagnetic radiation can exist

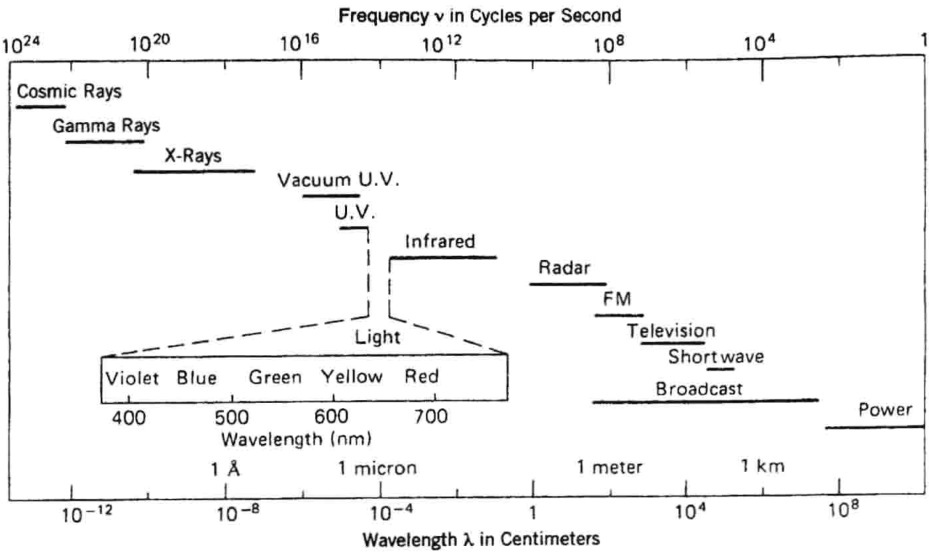

FIGURE 1.1 *Schematic representation of the electromagnetic spectrum.* IES Lighting Handbook, *New York: Illuminating Engineering Society, 1972. Used with permission.*

at a single wavelength (monochromatic) or be a mixture of many wavelengths (polychromatic).

Electromagnetic radiation can interact with matter in different ways:

- *Absorption:* Quanta are absorbed by matter, interact with it in certain ways, and after loss of some energy are reemitted
- *Transmission:* Quanta pass through matter unchanged; certain forms of matter impede the speed of the quanta, which at interfaces of two different kinds of transmitting matter, can result in a change of direction (refraction)
- *Scattering:* Certain matter is impenetrable to quanta and they are scattered or reflected by it, changing direction in the process .
- *Interference:* Quanta can interact with neighboring quanta in certain conditions.

Light is normally produced by a glowing body in a process called incandescence: the sun, for example, a burning wax candle, or an electrically heated tungsten metal coil in a light bulb.

INCANDESCENCE

Incandescence is the shedding of electromagnetic radiation by a very hot material, resulting in light that can give rise to color experiences. Our dominant example of an incandescent body is the sun. The nature of incandescence is most easily observed in the work of a blacksmith (alas, with fewer and fewer opportunities to do so). An iron rod or a horseshoe, placed in an intense coal fire, will as it heats up begin to give off a dull reddish glow. When viewing it in the dark, we recognize it as the source of reddish light. As the temperature of the metal increases so does the intensity of the emitted light. Simultaneously, reddishness diminishes and the object becomes "white-hot." With a further increase in temperature, it eventually assumes a bluish white appearance. Energy is absorbed by the horseshoe from the fire and emitted in visible form by the glowing metal. The imparted energy can have many sources: thermonuclear in the case of the sun; electrical in the case of a light bulb, chemical in the case of burning coal. All elements can, in proper conditions, be made to show incandescence, as can many inorganic molecules. Organic molecules (those containing carbon), are usually destroyed before they show incandescence, with incandescence produced by their decomposition products (say, in the case of candle wax). The nature of the emitted energy depends on the form of the incandescent material: gaseous substances emit energy in one or more distinct bands; incandescent liquids and solids emit energy across broad spectrum bands.

What is the explanation for energy absorption and incandescence? The accepted theory is based on an atomic model of matter, with protons and neutrons in the central nucleus, and electrons located in shells around the nucleus. Each of the shells has limited spaces for electrons. Shells that are filled to their limit or where electrons are in pairs are in a relatively stable state. As the atom or molecule absorbs energy, it passes through various stages of excitation. Each stage involves the electron(s) of the outermost shell. Absorption of energy will raise the excitable outer electron(s) to the next rung on an excitation ladder. At any given time the assembly of atoms or molecules in matter is not only absorbing energy but also shedding it: while in some atoms or molecules the outer electrons are being raised to the next level of excitation, in others they fall back one or more rungs to bring the atom into equilibrium with the average energy content of the surrounding matter. As mentioned, the shed energy is in the form of quanta or waves. If the shed energy is such that its wavelength falls between 400 and 700 nm, we sense it as light. At other levels they fall into other areas in the electromagnetic spectrum, such as ultraviolet or infrared.

The energy rungs possible derive from strict physical laws, and there are many rungs on the energy ladder of an atom or molecule. Electrons can cascade back in a variety of the ways, but there are statistically preferred paths, that is, the average electron will, on a statistical basis, descend on the energy ladder by a specific path. In the case of gases, this results in narrow bands of emitted energy. Following are examples of elements that in gaseous form emit most energy in a few narrow bands:

Element	Wavelength of Most Significant Emission (nm)	Apparent Color
Sodium	589,590	Yellow
Lithium	610,670	Orange-red
Lead	406	Blue-violet
Barium	553, 614	Yellow-green

The resulting color appearances have been used in analytical chemistry to help identify materials. In the case of incandescent solid materials, quanta of individual atoms or molecules have more widely varying energy levels, resulting in continuous energy distributions.

The amount and energy distribution of emitted light are functions of the temperature of the emitting matter. The higher the temperature, the higher the amount and average energy level of the emitted quanta. Emission ceases completely only in the vicinity of the lowest possible temperature, that is, 0 kelvin (4). To be seen as light, the temperature of the emitting material must be above 1000 K.

BLACKBODY RADIATION

A blackbody is an idealized nonexistent material that is a perfect absorber and emitter of energy. It absorbs and emits energy indiscriminately at all wavelengths. At a given temperature the emission of such matter can be calculated on a theoretical basis. Examples of black body emission at different temperatures are illustrated in Figure 1.2. Many real materials produce an emission spectrum quite similar to that of a blackbody. Blackbody temperature, expressed on the absolute Kelvin scale, is in turn routinely used to qualitatively express the emission behavior of a light source even if its emission spectrum is unlike that of a blackbody. Thus, light sources are classified by their correlated color temperature, that is, the temperature of a radiating blackbody that has the same apparent color. Figure 1.2 also indicates that the emission spectrum of the sun as measured on earth quite closely resembles that of a blackbody at approximately 6000 K. It also shows that brightness sensitivity of the human visual system is tuned to the emission of the solar spectrum.

Returning to our example of a blacksmith and stating that, at least at higher temperatures, the emission spectrum of iron is close to that of a blackbody, the apparent change in color at increasing temperatures can now be explained in terms of the emission spectrum, as illustrated in Figure 1.2. The burning coal surrounding the metal radiates like a blackbody at a temperature of about 1800 K. At this temperature the emission in the visible range is low at low wavelength and high at high wavelength. Such a spectral power distribution is commensurate with light having an orange-reddish appearance. The common incandescent light bulb (in which a tungsten wire is made to glow by its resistance to the flow of electrical current) also has an emission spectrum close to that of a blackbody. Incandescent lamps are typically operated at 2500 K, with an approximate emission spectrum as illustrated in Figure 1.2. It is evident that an incandescent lamp does not make efficient use of energy, since most of the emitted radiation is not visible. Incandescent lamps become very hot during operation because most of the emitted energy is in the infrared region, and we sense that energy as heat. Fluorescent lamps, on the other hand, emit most of their energy in the visible spectrum and thereby operate cooler and are more energy efficient. The most energy-efficient fluorescent lamps are the so-called triband lamps emitting light in three relatively distinct bands around 440 nm, 540 nm, and 610 nm. Because in the other regions of the visible spectrum their emissions are low, they are more energy efficient than other fluorescent lamps that emit light throughout the whole visible

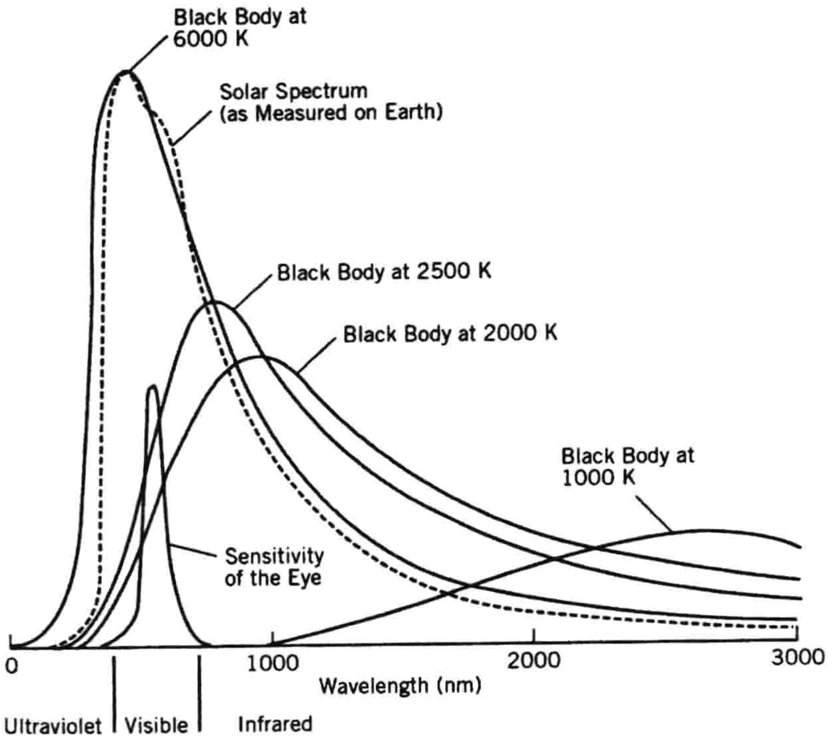

FIGURE 1.2 Blackbody emission spectra at various temperatures (in degrees kelvin), the solar spectrum as measured on the surface of the earth (dashed line), and the spectral brightness sensitivity of the human visual system.

range. The appearance of certain reflecting materials can change significantly as a function of the spectral power distribution of the light under which they are viewed (see color constancy, Chapter 4).

Blackbodies at temperatures beginning at 2500 K and higher emit light that, especially after adaptation (see Chapter 3), is seen as colorless. When objects with a high flat reflectance function are seen in this light they appear white. As a result such light is commonly termed *white.* This neutral experience is our response to the pervasive presence of daylight in our life. There are many other spectral power distributions that result in the corresponding light appearing colorless, or "white." One thing they all have in common is that, despite their variation in spectral power, they have an effect on our visual apparatus very similar to that of daylight.

LUMINESCENCE

Light also can be created by processes not based on the absorption of energy. This phenomenon is called *luminescence*. There are three basic processes: electroluminescence, chemiluminescence, and photoluminescence.

Sparks, arcs of light, lightning, some types of laser light, and gas discharges are examples of electroluminescence. Here, under the influence of an electric field, electrons collide with particles of matter, resulting in the emission of the appropriate energy level to be seen by us as light. Chemiluminescence is produced at low temperatures by certain chemical reactions, mainly oxidations. Natural chemiluminescence, also called *bioluminenscence*, can be observed in glowworm, fireflies, and certain deep-sea fish, as well as on decaying wood or putrefying meat. Glowing liquid-filled plastic tubes are a commercial form of chemiluminescence.

Photoluminescence appears in two forms: fluorescence and phosphorescence. Fluorescence is due to the properties that certain molecules have to absorb near-ultraviolet or visible light and shed it not in the form of infrared energy, as most absorbers of visible energy do, but in the form of visible radiation of a somewhat higher wavelength (that is, lower energy content). Fluorescent whitening agents, present in many detergents, absorb ultraviolet radiation between 300 and 380 nm and emit visible radiation from 400 nm to 480 nm. This light has a bluish appearance, and materials treated with such products appear very white in color. Fluorescent dyes or pigments (see also Chapter 8) absorb and emit visible energy, for example, a fluorescent "red" dye absorbs light from about 450 nm to 550 nm and emits light at 600 to 700 nm. Fluorescent colorants appear to glow faintly because of the emission of light, but they are weak emitters. There are also inorganic materials that fluoresce, for example, certain minerals. Fluorescent light tubes are another example of the process of fluorescence. The tubes are coated on their interior with fluorescing phosphor compounds. They contain a small amount of mercury that is brought to the incandescent state with the application of an electric field. The energy emitted by the mercury is in the near-ultraviolet. It is absorbed by the phosphor compounds that in turn emit broadband visible light. The term *fluorescence* is applied in cases where the emission of light stops at the same time the flow of absorbed energy is interrupted. Some substances, for example elementary phosphor, are capable of storing absorbed energy for a time. They continue to emit light for some time after the exciting energy is interrupted. This process is named *phosphorescence*.

ABSORPTION, REFLECTION, SCATTERING, AND TRANSMISSION

From creation to oblivion the fate of light can pass through many stations. If it consists of a broad band of energy, selective action at different energy levels results in changes in the spectral power distribution, and when viewed may result in color experiences. When light quanta are absorbed by matter, that is, if the photons of the light beam interact with atoms or molecules that can respond to their energy level, the result is loss of energy by the quanta and later reemission at a lower energy level, typically in the infrared. The radiation is lost as a visible stimulus and has become a stimulus sensed as heat.

By definition, the most efficient absorber is the blackbody, which absorbs and emits energy indiscriminately (if by strict rules) over a wide energy band. Real objects are often selective absorbers. Of particular interest in this discussion is their absorption

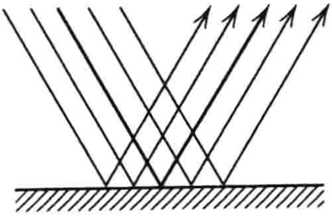

FIGURE 1.3 *Reflection of light from a plane surface.*

of visible light. Some absorb very little, say, a layer of "white" paint, a lot, such as a layer of "black" paint, or at any level between. Real objects do not absorb all light energy falling on them, and some of the photons are scattered or reflected. Reflection is a special form of scattering. It is the process by which photons arriving at a smooth-surfaced material change their direction of travel on impact and are returned (like a ball thrown against a wall) (5). In the case of reflection, the angle of incidence (the angle at which the photons strike the surface) is equal to the angle of reflection (Fig. 1.3). Reflection is unequivocally predictable, while scattering is only predictable in a statistical sense. Scattering refers to the change in direction suffered by radiation on impact with a rough-surfaced material or with fine particles of uniform or varying shape. In this case, reflection is in many directions. The surface involved may appear smooth to our senses, as does the surface of a dried layer of paint. However, the pigment particles in the paint form a microscopically rough surface, scattering light in many directions (Fig. 1.4). Typical scattering materials are textile fibers (small diameter, comparatively smooth columns of matter); water droplets suspended in air in the form of clouds or fog; smog and dust particles; milk (fine oily droplets in a water-based emulsion); and some types of bird feather, for example, those of blue jays. Many colorants, particularly pigments, are scattering materials. Many artificial materials display a complex interplay of external reflection, transmission, and internal scattering of light, for example, glossy paint.

Scattering of photons occurs in the atmosphere as a result of water droplets, ice crystals, or dust particles. Without it the sun's light would be very harsh in an otherwise

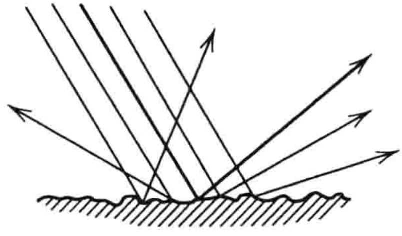

FIGURE 1.4 *Scattering of light on an uneven surface.*

black sky, such as astronauts on the moon have experienced. Scattering causes the diffused daylight we experience on the surface of the earth. Such scattering is dependent on the size of the particles in the air and wavelength of light. Larger particles or a high density (such as in a fog) scatter all light equally and are perceived as white. Heavily scattered sunlight, such as on a very cloudy day, in fog, or a snowstorm, seems to have no origin: photons meet our eyes from all angles and shadows are soft or nonexistent.

Few and small particles scatter short-wave light rays more efficiently than long-wave rays. While most rays of longer wavelength pass through the atmosphere unscattered, a higher proportion of short-wave light is scattered, resulting in a blue appearance of the clear sky. Clouds, consisting of water droplets or ice crystals, scatter light of all visible wavelengths equally and appear white. The chance of a photon being scattered also depends on the thickness of the layer it passes through. Thus, near sunset, and especially in an atmosphere with high amounts of particles (for example, in an industrial area, or after a volcanic eruption), all light except that of the longest wavelengths is scattered, causing the sun's disk to appear red. As mentioned, the blue appearance of the feathers of birds like blue jays and kingfishers are also caused by scattering at their surface.

Perfectly reflecting or scattering materials do not exist. Some come quite close, for example, a pressed surface of pure barium sulfate scatters some 98% of photons in the visible region of the spectrum. Some of the best reflecting materials are metallic mirrors. They reflect 70 to 80% of photons arriving at their surface.

Most color stimuli we encounter are the result of wavelength-specific absorption and scattering. They are known as *object colors*. They absorb or scatter all visible wavelengths to a greater or smaller degree. Figure 1.5 represents the spectral reflectance function of an object seen as having a blue color when viewed in standard conditions. Reflectance curves represent at each wavelength the ratio of the numbers

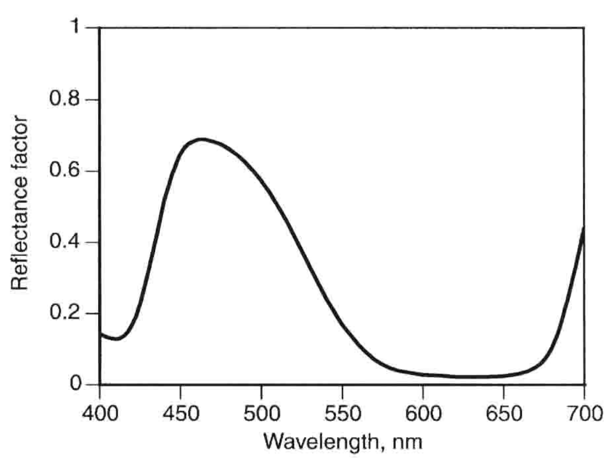

FIGURE 1.5 *Spectral reflectance function of an object causing a perception of blue when viewed in standard conditions.*