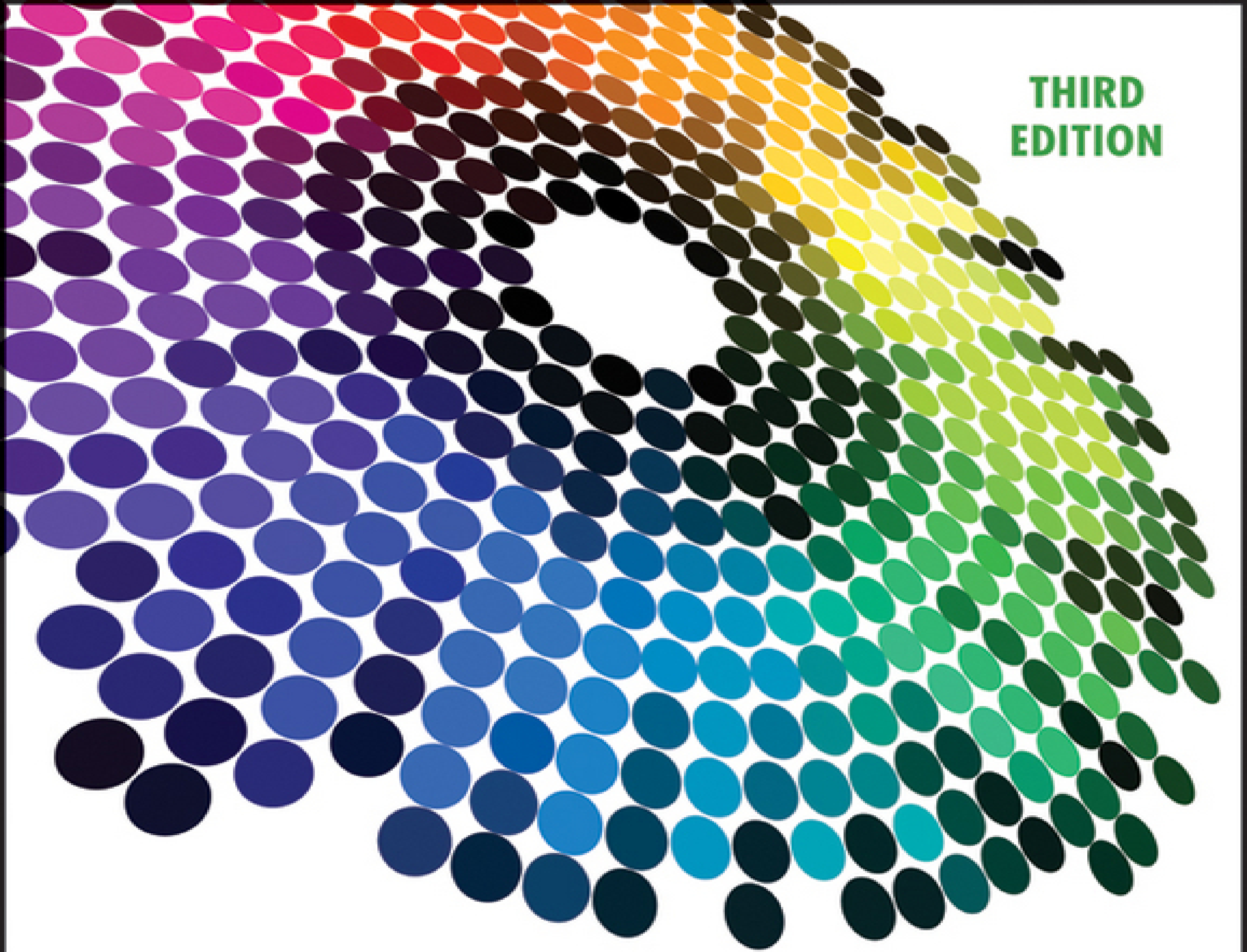

THIRD EDITION

COLOR

An Introduction to Practice and Principles

ROLF G. KUEHNI

WILEY

Preface

This third edition follows the outline of the previous editions, but approximately half of the text has been edited or rewritten and new text has been added to bring it, in a general manner, up to date. It has also been possible to include many more color figures, now integrated into the text. Additional 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 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. It 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. The book can be a stepping stone to more in-depth studies based on the references.

I am indebted to many people for helping to open 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.

Rolf G. Kuehni

1

Sources of Color

For the normally sighted person, 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 seen as colored. Outdoors, and depending on the time of the year, there is a riot of colors such as those on an alpine summer meadow, or they are spare in a desert, 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 experiences are 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 aesthetic 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 rubythroated 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 draw with variously colored crayons or ink pens. The rainbow has four colors, or is it 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 display screen are "made" from red, blue, and green light-emitting phosphor compounds.

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 a tablet display is red, and 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 much 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 somehow triggered by an overflying aircraft rather than by a burglar.

There are two sets of facts that complicate understanding of the phenomenon of color: (1) many different stimuli can result in an essentially identical color experience and (2) a particular stimulus can result in many different color experiences, usually as the result of changes in illumination and/or surrounding stimuli. The same situation applies to vision in general. These facts can be seen as indicating that colors are subjective phenomena rather than components of objects. On the other hand, the facts that blood is red, that bananas when ripe are yellow, and that we can make some object look blue by painting it with blue pigments, and countless other results of observation, have produced the common point of view that colors are located in objects. In support of the former position, Newton already said with respect to color perceived in light: “For the rays, to speak properly, are not coloured. In them there is nothing else than a certain power and disposition to stir up a sensation of this or that Colour” (Newton 1704). The “objective” position is represented by a comment in a recent book: “The pessimistic notion that colors are ‘mere mental paint’ and have no relation to the physical and chemical constitution of things at all is popular in science and (especially) in philosophy, but it has no basis in fact” (Koenderink 2010). This matter is a subject of argumentation ranging back to the early Greek philosophers and has as yet not found a factually supported convincing answer, as will be discussed in slightly more detail in Chapter 2.

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**: a phenomenon of light (as red, brown, pink, or gray) [?] or visual perception that enables one to differentiate otherwise identical objects; b (1): the aspect of the appearance of objects and light sources that may be described in terms of hue, lightness, and saturation for objects and hue, brightness, and saturation for light sources <the changing *color* of the sky>; *also:* a specific combination of hue, saturation, and lightness or brightness <comes in six *colors>;* (2): a color other than and as contrasted with black, white, or gray. (Merriam-Webster 2011)

Scientists have not been able to do better and have resorted to a circular definition: "Color: Attribute of visual perception consisting of any combination of chromatic and achromatic content. This attribute can be described by chromatic color names such as yellow or brown, red, pink, green, blue, purple, etc., or by achromatic color names such as white, gray, black, etc., and qualified by bright, dim, light, dark, etc., or by combinations of such names." (CIE 1987). 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 beam of sunlight passes through a glass prism, as described by Newton (Fig. 1.1). What leaves the prism is the same light entering it. But on leaving the prism, the beam has been transformed into a band of light that, when viewed as reflected from a white surface, produces in the observer's vision system a multitude of color experiences: the colors known as those of the spectrum. A less elaborate method for viewing these colors is by looking at a compact disk at different angles in daylight or the light of a lamp.

A considerable number of processes and materials can result in color experiences. Many have been discovered by artisans and craftsmen 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 physical phenomena. Nassau has identified and described a total of 15 causes of color, with four dealing with geometrical and physical optics, and those remaining dealing with various effects involving electrons in atoms or molecules of materials and causing absorption or emission of light at selected wavebands (Nassau 2003). 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. German poet and natural scientist 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.

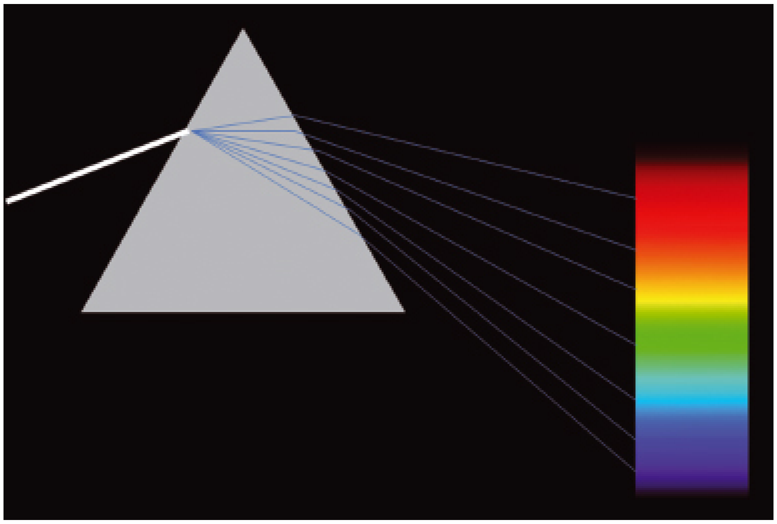

FIGURE 1.1 *Schematic representation of a narrow beam of daylight light passing through a prism and being separated according to wavelength by refraction. The individual wavelength rays do not appear colored unless directly viewed front-on or after reflection from a white surface.*

LIGHT

Light consists of a certain range 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 (UV) 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. 1.2). Electromagnetic radiation travels at high speed (the speed of light, about 300,000 km/s). The human eye, our visual sensory organ, is sensitive to a narrow band of electromagnetic radiation, the visible spectrum.

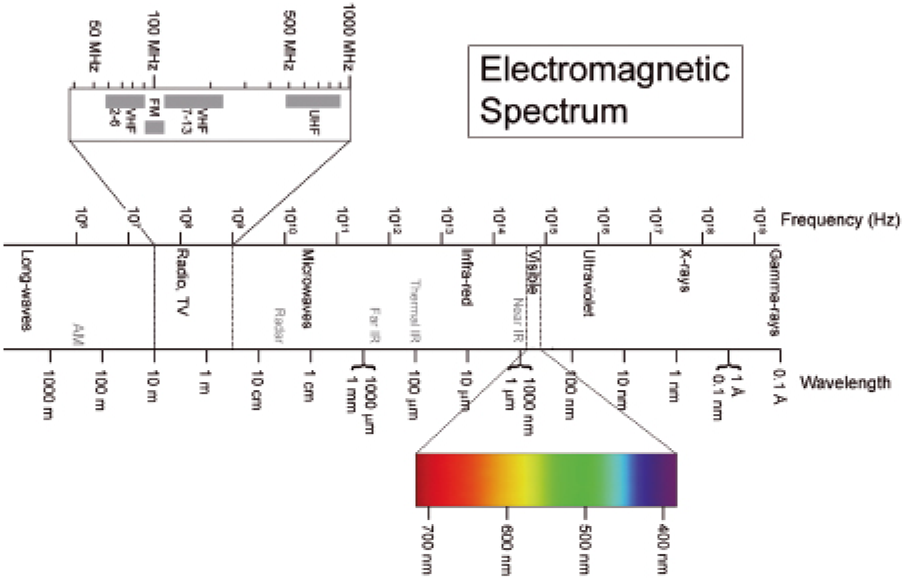

FIGURE 1.2 Schematic representation of the electromagnetic spectrum (Wikimedia Commons).

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 in round figures from 400 to 700 nm (nanometers, a billionth of a meter). When considered as quanta, the energy content is usually expressed as electronvolts (eV) (see definition in the Glossary). Visible electromagnetic radiation can exist 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, in the process changing direction.
- *Interference.* Quanta can interact with neighboring quanta in certain conditions.

Light is normally produced by a glowing body in a process called incandescence; for example, the sun, a burning wax candle, or an electrically heated tungsten metal coil in a light bulb, but there are other modes of generation.

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, where the energy is produced by what is known as nuclear fusion. The nature of incandescence as produced on Earth 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, as it heats up—when it reaches about 900°F (525°C)—will 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 and its energy content. Simultaneously, reddishness diminishes and the object becomes “white hot.” With 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 case of the sun; electrical in case of a light bulb; and chemical in 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 case of candle wax). The nature of the emitted energy depends on the form of the incandescent material: gaseous substances and many chemical elements emit energy in one or more distinct bands; incandescent liquids and solids tend to 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 of the atom, 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 UV or infrared. As mentioned, the temperature of an object has to be at least about 900°F before significant amounts of radiation are emitted (for more details, see Turner 2007).

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 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 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 Emissions (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. Other materials emit light of continuous energy distributions. An important example is the metal tungsten that has a high melting point and, when electrically heated to a certain temperature, emits broadband light but with the highest output of energy in the near infrared region. It has been used for a century as an incandescent emitter in light bulbs, now being replaced with more energy-efficient fluorescent lamps.

Amount and energy distribution of emitted light are functions of the temperature of the emitting matter. The higher the temperature, the higher the average energy level of the emitted quanta. Emission ceases completely only in the vicinity of the lowest possible temperature, that is, 0 K (approximately –460°F).

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 blackbody emission at different temperatures are illustrated in Figure 1.3. Many real materials produce an emission spectrum quite similar to that of a black body. Black body temperature, expressed on the absolute Kelvin temperature 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 1.3 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.

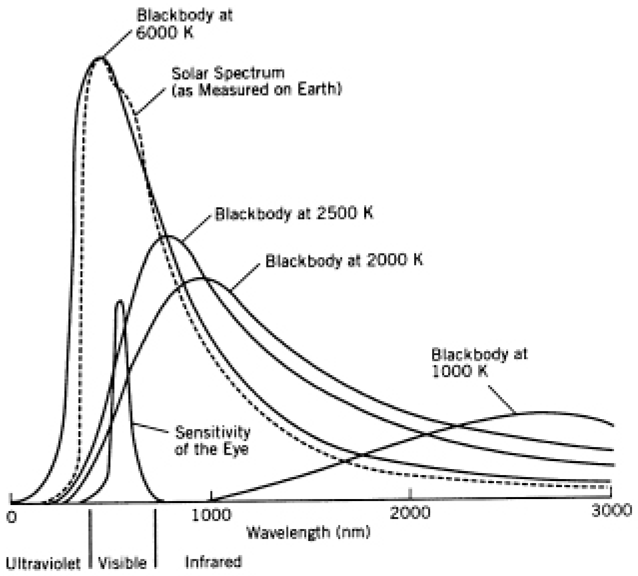

FIGURE 1.3 *Blackbody emission spectra at various temperatures (in degrees Kelvin), the solar spectrum as measured on the surface of the earth (dashed line), and the spectral brightness sensitivity of the human visual system.*

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 1.3. Low burning coal radiates like a blackbody at a temperature of about 1800 K. At this temperature, the emission in the visible region is low at low wavelengths and high at high wavelengths. Such a spectral power distribution is commensurate with light having an orange-reddish appearance. The common incandescent light bulb also has an emission spectrum close to that of a black body. Incandescent lamps are typically operated at 2500 K, with an approximate emission spectrum as illustrated in Figure 1.3. It is evident that, as mentioned, 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, 540, and 610 nm regions, respectively, in which the sensors of the human visual system have greatest sensitivity. 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 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 the section on color constancy in 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.” They all have in common that despite their variation in spectral power, they have an effect on our visual apparatus very similar to that of daylight.

LUMINESCENCE

Light can also 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 as light. Chemiluminescence is produced at low temperatures by certain chemical reactions, mainly oxidations. Natural chemiluminescence, also called bioluminescence, can be observed in glowworms, 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 objects displaying chemiluminescence.

Photoluminescence appears in two forms: fluorescence and phosphorescence. Fluorescence is due to the properties of certain molecules to absorb near-UV or visible light and to 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 (i.e., lower energy content). Fluorescent whitening agents, present in many detergents, absorb UV radiation between 300 and 380 nm and emit visible radiation from 400 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 to 550 nm and emits light at 600–700 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 (Fig. 1.4). 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 incandescent state with the application of an electric field. The energy emitted by the mercury is in the near-UV range. 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.*

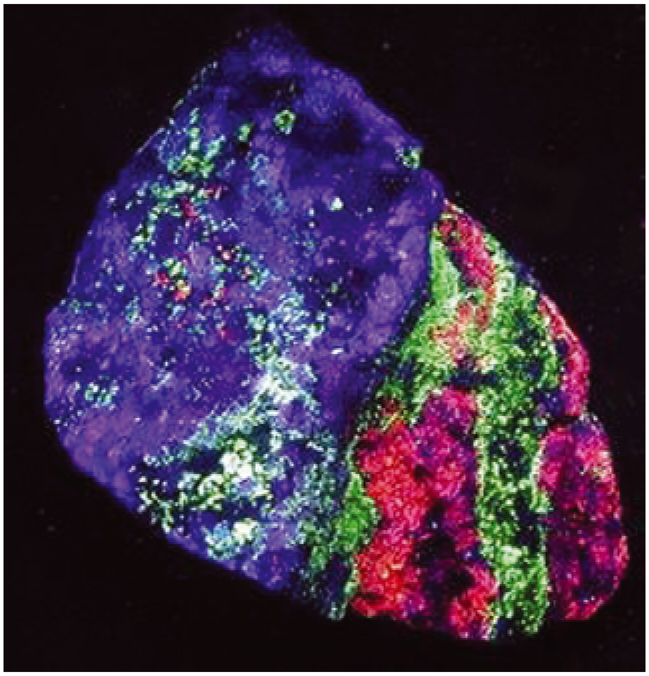

FIGURE 1.4 *Fluorescent mineral as seen in UV illumination.*

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.

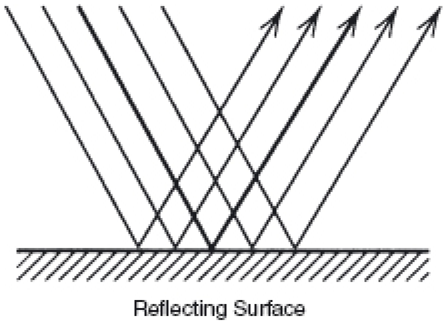

FIGURE 1.5 *Reflection of light from a plane surface.*

By definition, the most efficient absorber is the blackbody absorbing and emitting 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 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). In case of reflection, the angle of incidence (the angle at which the photons strike the surface) is equal to the angle of reflection (Fig. 1.5). 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 roughsurfaced 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. 1.6). Typical scattering materials are textile fibers (small diameter, comparatively smooth columns of matter), water droplets suspended in the 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 feathers, 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.

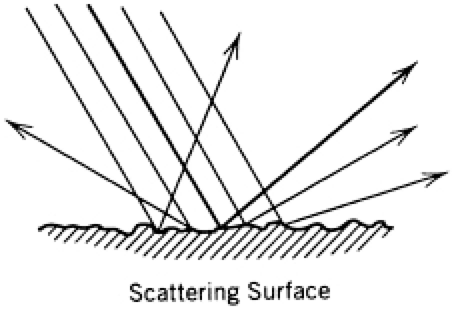

FIGURE 1.6 *Scattering of light on an uneven surface.*

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 black sky, such as what astronauts experience. 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, with the surroundings 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 without being scattered, 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 (e.g., 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 70–80% of photons arriving at their surface.

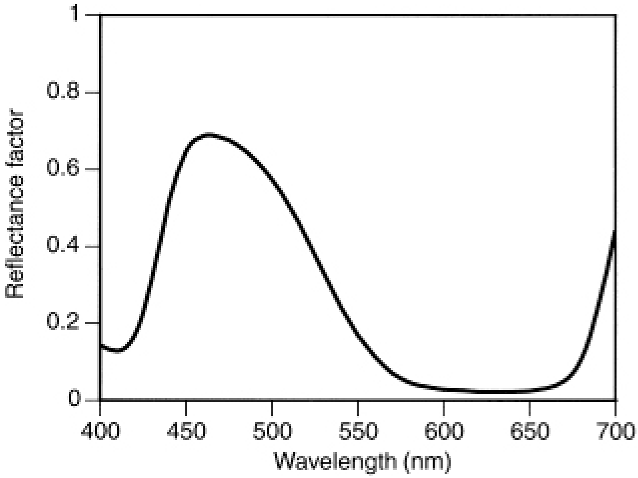

FIGURE 1.7 *Spectral reflectance function of an object causing a perception of blue when viewed in standard conditions.*

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 1.7 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 of photons leaving the surface to that arriving at the surface of the object (see Chapter 6 for further discussion).

Transmission refers to the mostly unimpeded passage of light through a transparent object, such as a layer of pure water. The spectral distribution of a light beam, after passing through such a layer, is unchanged. If the layer contains absorbing materials, for example, dyes, a portion of the light is absorbed and the remainder transmitted. The amount of absorbed light in this case depends on the absorbing material and the thickness of the layer. If the dye is completely dissolved (at the molecular level, i.e., free of agglomerates causing scattering) the Beer-Lambert-Bouguer law allows the determination of the amount of light absorbed and transmitted (see Glossary). The size of single molecules relative to the wavelengths of light defines if a material, completely dissolved, results in scattering.

REFRACTION

The term refraction is used to denote a change in the direction of a stream of photons when passing from one medium into another (Fig. 1.8). When light that is passing through air obliquely strikes the surface of a transparent object, such as water or glass, it changes direction according to the laws of refraction (see Glossary). This phenomenon is the basis of the rainbow or the image formation in a camera or in the eye. In both camera and eye, refraction is controlled by lens design. Photons striking the surface of a photographic lens or the lens of an eye at a given position (except for the center) change direction as they pass through the lens and exit it. In this manner, they are narrowly focused on the film, light sensor, or the light-sensitive layer of the eye, forming an image, inverted and reduced in size of the world in front of the lens. The change in direction is a function of the optical densities of the two transparent media involved (lens material and air) and of the energy level of the photons (i.e., inversely, their wavelength). Photons of higher energy change direction more strongly than those of lower energy. Refraction, therefore, is an effective technique for separating the components of a mixture of wavelengths, such as sunlight. A glass prism is a useful practical tool to accomplish this: when a narrow beam of polychromatic light passes through a prism, its components are separated as they leave the prism (see Figs. 1.1 and 1.9). The individual components, when seen reflected from a white screen or a mirror, are perceived to be colored. If the light used is daylight, the perceived colors are those of the complete visible spectrum. Light from (always approximately) 400 to 490 nm causes a bluish experience; from 490 to 570 nm a greenish experience; from 570 to 590 nm a yellowish experience; from 590 to 630 nm an orangish experience; and from 630 to 700 nm a reddish experience. When the direction of the flow of photons is reversed, the resulting stimulus, when viewed under standard conditions, is seen as white again.

FIGURE 1.8 *The apparent bending of the pencil and the double image is due to refraction effects.*

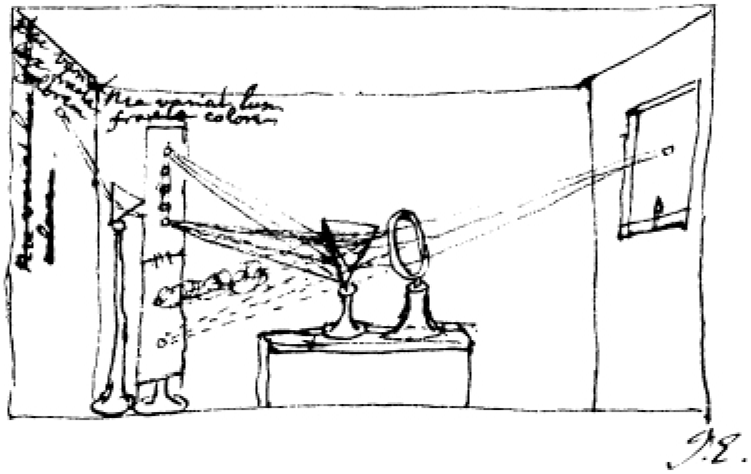

FIGURE 1.9 *Newton’s sketch of his experiment of refracting sunlight with a prism into its spectral components. The light passing through a small hole on the right is collected by a lens and passes through the prism, where it is refracted into its spectral components in an elongated band on the upper left. Openings in the screen allow light of certain wavelengths to pass through. A second prism behind one of the openings shows that the refracted narrow band light coming from the first prism does not change further in passage through a second one. In a separate experiment, he also showed that this process is reversible.*

The most spectacular natural display of refraction is the rainbow. Refraction effects can also be seen in cut crystal, diamonds, or other gemstones having “fire.” A difficulty resulting from refraction in lenses is known as chromatic aberration. Because of the specific effect of refraction on light of different wavelengths, its photons emanating from a given point and passing through the lens can only be focused on a common point on the other side of the lens if the lens has been corrected for chromatic aberration.

INTERFERENCE

Puddles of water with bright multicolored bands on the surface are a common occurrence near a car repair shop or a gas station after a rain shower. Similarly, and aesthetically more appealing, bright shimmering colors can be seen on the wings of some butterflies when viewed from a certain angle, or on the feathers of some birds, such as the peacock or some kinds of hummingbirds (Fig. 1.10). Such colors are called iridescent and differ from the scatter-effect colors of the blue jay. Hue and intensity of color appearance change with the angle at which the surface is viewed. These colors are due to a physical effect called interference, a term used to denote the temporary splitting of light waves into parts that are later recombined. Depending on the path the beam components follow after splitting, the light waves may be in or out of phase when recombined, that is, the wave peaks and valleys may or may not match. If they do, the intensity of the resulting beam is the sum of those of its components; if they don't match, the two components cancel each other. A typical source of interference is a thin transparent film, such as an oil film on water, or a soap bubble. Whether or not the reflected light will be in or out of phase depends on the thickness of the film. If in phase, light of varying wavelengths will emerge at corresponding angles, giving rise to pure, strong color stimuli, the color of which depends on the angle of viewing. Several colors (as in a thin oil film on the surface of water) can be seen if the film causing interference varies in thickness.

FIGURE 1.10 *Image of a hummingbird (*Colibri thalassinus*). The iridescent blue and green coloration is due to interference effects (Mdf, Wikimedia Commons).*

DIFFRACTION

Diffraction is a special case of the combined effect of scattering and interference. The behavior of a light wave arriving at the edge of a solid material (think of the edge of a razor blade) is influenced by the sharpness of the edge. Depending on its wavelength in relation to the dimensional properties of the edge, the wave passes unimpeded by the edge, is scattered at the edge, or is absorbed, reflected, or refracted by the edge-forming material. If several properly dimensioned edges exist, such as when fine lines are inscribed or etched into a glass or metal plate, the resulting scatter at the edges is subject to interference effects: waves in phase will reinforce, those out of phase will cancel each other out. When daylight strikes such an assembly of edges (called a grating), waves in phase are enhanced in different directions: a display of spectral colors results when viewed from different angles. A typical example is the surface of a compact disk, although because of the irregularity of the embedded digital patterns and their curvature, the effect is less than perfect. Gratings made by an inscribing process called ruling or other techniques are used widely today in optical equipment for separating polychromatic (broadband) light into its components (Fig. 1.11).

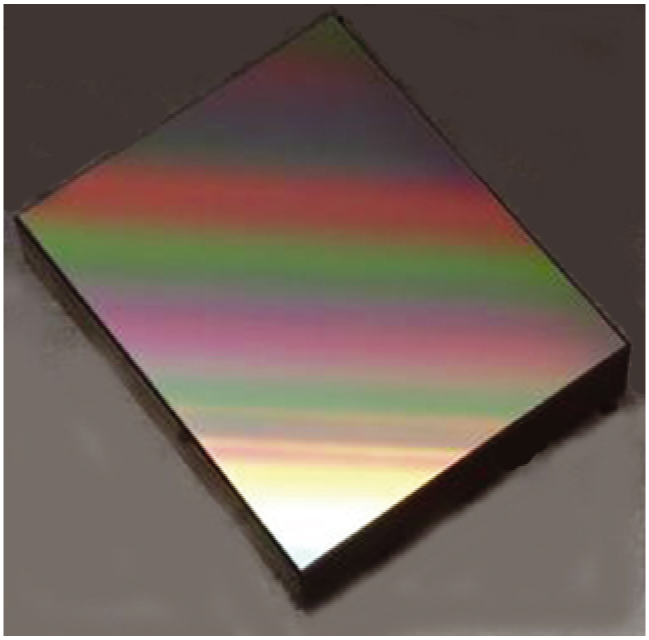

FIGURE 1.11 *Image of a grating used to separate mixed lights into their spectral components using the diffraction effect.*

Certain organic substances, such as the wings of some insects, have structures with the dimensions necessary for diffraction effects. Liquid crystal molecules represent another example. They are arranged in crystalline configuration such that they act as diffraction gratings. The dimension of the edges is a function of the surrounding temperature and such devices can be used as temperature indicators, among other applications. The colors of the gem opal are also a result of diffraction.

MOLECULAR ORBITALS

So far, the subject has been physical sources of color stimuli (refraction, interference, etc.) and the behavior of excited electrons in atoms and molecules. In atoms as well as in molecules, electrons are arranged in orbits around the nucleus. When electrons in the outermost orbit—called orbital electrons—from two atoms form a stable pair, the result is a chemical bond and formation of a molecule. In some molecules, orbital electrons are not confined to a particular location but can range across larger areas. Such behavior can give rise to color stimuli. A typical example is the gem sapphire, the basic material of which is aluminum oxide, capable of forming crystalline structures. In its pure form, called corundum, aluminum oxide is not a source of a color stimulus. Sapphire contains a degree of impurity in the form of iron and titanium atoms replacing aluminum in some of the molecules. Ionized aluminum has three electric charges, while iron has two and titanium four. One of the electrons from titanium tends to transfer to a neighboring molecule containing iron. As a result, both atoms end up with three electrons. This charge transfer, resulting in an excited state of the electrons, occurs only under the influence of absorbed energy. The needed energy can be supplied by absorbed photons, falling in the visible range in a broad band from approximately 550 to above 700 nm. The energy released by the excited electrons is in the infrared band and therefore not visible. As a result, only light from 400 to 550 nm is reflected, resulting in a deep blue color sensation.

A somewhat similar process takes place in most dyes and organic pigments. They consist of organic molecules made up mostly of carbon, oxygen, hydrogen, and nitrogen. Carbon atoms (as well as, under certain circumstances, those of nitrogen) can bond with other carbon atoms and form chains with alternating single and double bonds. The best known example is the closed chain, or ring, of the benzene molecule, the carbon chain of which consists of six carbon atoms with nine electron bonds. Such bonds are said to be conjugated. Benzene absorbs light in the UV region. In other, more complex molecules containing benzene rings, the absorbed energy is often of the visible range and the substances appear colored (Fig. 1.12). Molecules containing this kind of conjugated bonds are called chromophores (color bearers).

It is possible to attach to these molecules side groups capable of accepting or donating an electron. Such groups are called auxochromes (color increasers) and they affect the absorption characteristics of the chromophore to which they are attached. Two well-known natural substances derive their color from conjugated bond systems: blood and chlorophyll, the life-supporting substances of animals and plants, respectively. Today, most organic colorants are synthetic. It is likely that in the last 200 years hundreds of thousands of different molecules with conjugated bond systems have been synthesized in laboratories around the world in a never-ending search for better colorants. Some 8000 of these have found commercial significance in the past or have it today and are listed in the *Color Index International* accessible on the Internet (http://www.colour-index.org). For a more detailed discussion of colorants, see Chapter 8.

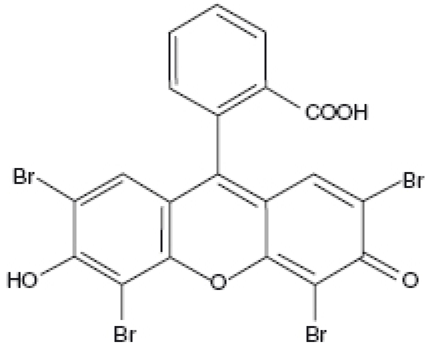

FIGURE 1.12 *Chemical structure of Color Index Acid Red 87, a strongly fluorescent red dye known as eosin.*