28 Color

Roses are red and violets are blue; colors intrigue artists and physics types too. To the physicist, the colors of things are not in the substances of the things themselves. Color is in the eye of the beholder and is provoked by the frequencies of light emitted or reflected by things. We see red in a rose when light of certain frequencies reaches our eyes. Other frequencies will provoke the sensation of other colors. Whether or not these frequencies of light are actually perceived as colors depends on the eye-brain system. Many organisms, including people with defective color vision, see no red in a rose.

28.1 The Color Spectrum

Isaac Newton was the first to make a systematic study of color. By passing sunlight through a triangular-shaped glass prism, he was the first to show that sunlight is composed of a mixture of all the colors of the rainbow. The prism cast the sunlight into an elongated patch of colors on the wall (Figure 28–1). Newton called this spread of colors a **spectrum**, and noted that the colors were formed in the order red, orange, yellow, green, blue, and violet.

Sunlight is an example of what is called **white light**. Under white light, white objects appear white and colored objects appear in their individual colors. Newton showed that the colors in the spectrum were a property not of the prism but of white light itself. He demonstrated this when he recombined the colors with a second prism to produce white light again (Figure 28–2). In other words, all the colors, one atop the other, combine to produce white light. Strictly speaking, white is not a color but a combination of all the colors.

Fig. 28–1 Newton passed sunlight through a glass prism to form the color spectrum.

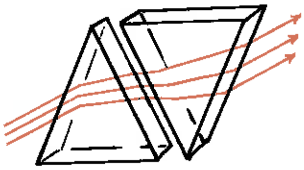

Fig. 28–2 Recombination of colors to produce white light.

Black is similarly not a color itself, but is the absence of light. Objects appear black when they absorb all visible frequencies of light. Carbon soot is an excellent absorber of light and looks very black. The dull finish of black velvet is an excellent absorber also. But even a polished surface may look black under some conditions. For example, highly polished razor blades are not black, but when stacked together and viewed end on, they appear quite black (Figure 28–3). Most of the light that gets between the closely spaced edges of the blades gets trapped and is absorbed after being reflected many times.

Fig. 28–3 When a stack of razor blades bolted together is viewed end on, the edges appear black. Light that enters the wedge-shaped spaces between the blades is reflected so many times that most of it is absorbed.

Black objects that you can see do not absorb all light that falls on them, for there is always some reflection at the surface. If not, you wouldn't be able to see them.

28.2 Color by Reflection

The colors of most objects around you are due to the way the objects reflect light. Light is reflected from objects in a manner similar to the way sound is "reflected" from a tuning fork when another that is nearby sets it into vibration. A tuning fork can be made to vibrate even when the frequencies are not matched, although at significantly reduced amplitudes. The same is true of atoms and molecules. We can think of atoms and molecules as three-dimensional tuning forks with electrons that behave as tiny oscillators that can vibrate as if attached by invisible springs (Figure 28–4).* Electrons can be forced into vibration by the vibrations of electromagnetic waves (such as light). Like acoustical tuning forks, once vibrating, they send out their own energy waves in all directions.

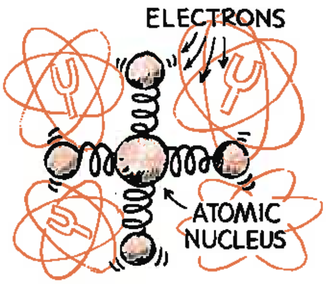

Fig. 28–4 The outer electrons in an atom vibrate as if they were attached to the nucleus by springs. As a result, atoms and molecules behave like tuning forks for light.

Different kinds of atoms and molecules have different natural vibration frequencies. The electrons of one kind of atom can be set into vibration over a range of frequencies different from the range for other kinds of atoms. At the resonant frequencies where the amplitudes of oscillation are large, light is absorbed. But at frequencies below and above the resonant frequencies, light is re-emitted. If the material is transparent, the re-emitted light passes through it. If the material is opaque, the light passes back into the medium from which it came. This is reflection.

Most materials absorb some frequencies and reflect the rest. If a material absorbs most visible frequencies and reflects red, for example, the material appears red. If it reflects all the visible frequencies, like the white part of this page, it will be the same color as the light that shines on it. If a material absorbs all the light that shines on it, it reflects none and is black.

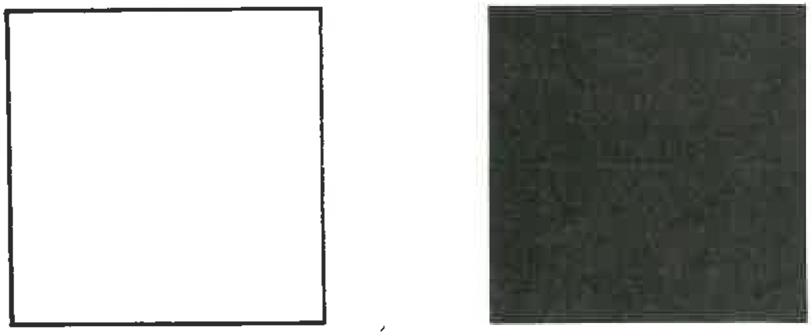

Fig. 28–5 The square on the left *reflects* all the colors illuminating it. In sunlight it is white. When illuminated with blue light, it is blue. The square on the right *absorbs* all the colors illuminating it. In sunlight it is warmer than the white square.

When white light falls on a flower, some of the frequencies are absorbed by the cells in the flower and some are reflected. Cells that contain chlorophyll absorb most of the frequencies and reflect the green part of the light that falls on them, so they appear green. The petals of a red rose, on the other hand, reflect

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* The words *oscillate* and *vibrate*, or *oscillator* and *vibrator*, can be used interchangeably; their meanings are the same.

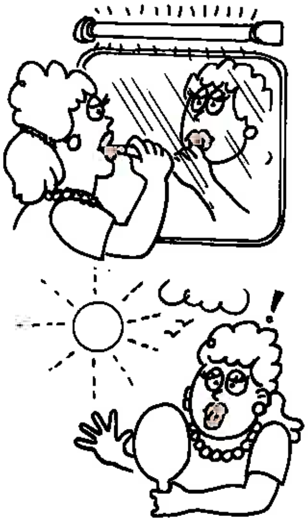


Fig. 28–6 Color depends on the light source.

primarily red light, with a lesser amount of blue. Interestingly enough, it is found that the petals of most yellow flowers, such as daffodils, reflect red and green as well as yellow. Yellow daffodils reflect a broad band of frequencies. The reflected colors of most objects are not pure single-frequency colors, but are composed of a spread of frequencies.

It is important to note that an object can reflect only frequencies that are present in the illuminating light. The appearance of a colored object therefore depends on the kind of light used. A candle flame emits light that is deficient in blue; it emits a yellowish light. Things look yellowish in candlelight. An incandescent lamp emits light that is richer toward the lower frequencies, enhancing the reds. A fluorescent lamp is richer in the higher frequencies, so blues are enhanced when illuminated with fluorescent lamps. In a fabric with a little bit of red, for example, the red will be more apparent when illuminated with an incandescent lamp than with a fluorescent lamp. Colors appear different in daylight than when illuminated with either of these lamps (Figure 28–6). The "true" color of an object is subjective and depends on the light source, although color differences between two objects are most easily detected in bright sunlight.

28.3 Color by Transmission

The color of a transparent object depends on the color of the light it transmits. A red piece of glass appears red because it absorbs all the colors that compose white light, except red, which it transmits. Similarly, a blue piece of glass appears blue because it transmits primarily blue and absorbs the other colors that illuminate it.

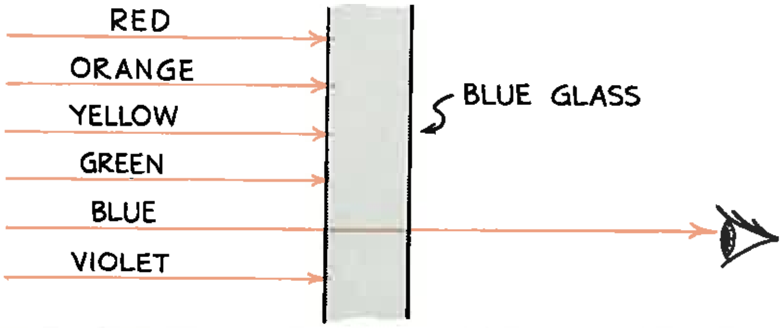


Fig. 28–7 Blue glass transmits only energy of the frequency of blue light; energy of the other frequencies is absorbed and warms the glass.

The material in the glass that selectively absorbs colored light is known as a **pigment**. From an atomic point of view, electrons in the pigment atoms are set into vibration by the illuminating light. Some of the frequencies are absorbed by the pigment, and others are re-emitted from atom to atom in the glass. The energy of the absorbed light increases the kinetic energy of the atoms, and the glass is warmed. Ordinary window glass is colorless because it transmits all visible frequencies equally well.

▶ **Questions**

1. When red light shines on a red rose, why do the leaves become warmer than the petals?
2. When green light shines on a red rose, why do the petals look black?
3. What color does a daffodil appear when illuminated with red light? With yellow light? With green light? With blue light?

28.4 Sunlight

White light from the sun is a composite of all the visible frequencies. The brightness of solar frequencies is uneven, as indicated in the graph of brightness versus frequency (Figure 28–8). The graph indicates that the lowest frequencies of sunlight, in the red region, are not as bright as those in the middle-range yellow and green region. Yellow-green is the brightest part of sunlight. (Since humans evolved in the presence of sunlight, it is not surprising that we are most sensitive to yellow-green. That is why it is more and more common for new fire engines to be painted yellow-green, particularly at airports where visibility is vital.

▶ **Answers**

1. The petals appear red because they reflect red light. The leaves absorb rather than reflect red light, so the leaves become warmer.
2. The petals absorb rather than reflect the green light. Since green is the only color illuminating the rose, and green contains no red to be reflected, the rose looks no color at all—black.
3. A daffodil reflects red, yellow, and green light, so when illuminated with any of these colors it reflects that color and appears that color. A daffodil does not reflect blue, so when illuminated with blue light it looks black.

This also explains why at night we see better under the illumination of yellow sodium-vapor lamps than under tungsten lamps of the same brightness.) The blue part of sunlight is not as bright, and the violet is even less bright.

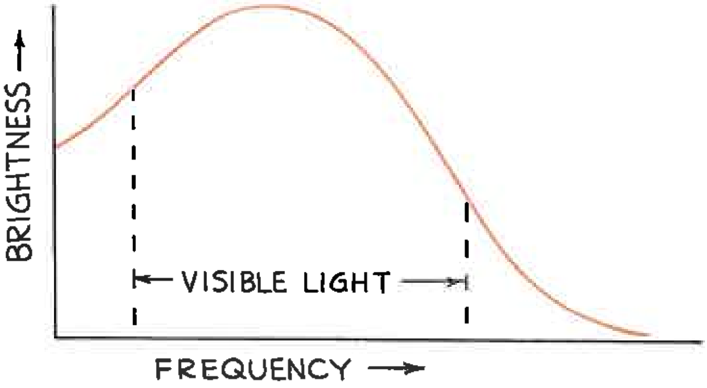


Fig. 28–8 The radiation curve of sunlight is a graph of brightness versus frequency. Sunlight is brightest in the yellow-green region, in the middle of the visible range.

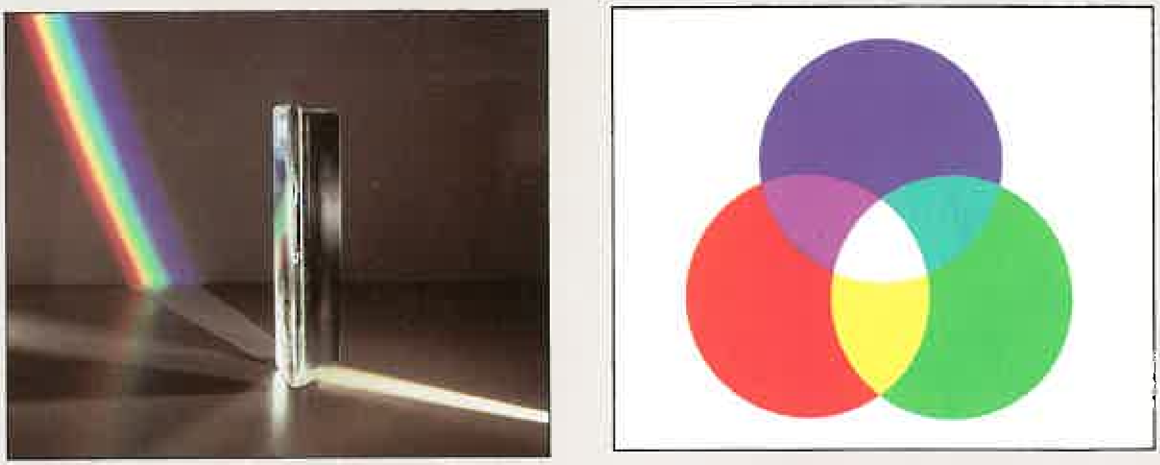
This graphical distribution of brightness versus frequency is called the *radiation curve* of sunlight. Most whites produced from reflected sunlight share this frequency distribution.

28.5 Mixing Colored Light

All the visible frequencies mixed together produce white. Interestingly enough, white also results from the combination of only red, green, and blue light. Look at Figure 28–9 and Plate 1 of the colored illustrations. (All the colored illustrations are in the four-page color section in this chapter. Many of the effects caused by the physics of color are shown there.) When a combination of only red, green, and blue light of equal brightness is overlapped on a screen, it appears white. Where red and green light alone overlap, the screen appears yellow. Red and blue light alone produce the bluish-red color called *magenta*. Green and blue light alone produce the greenish-blue color called *cyan*.

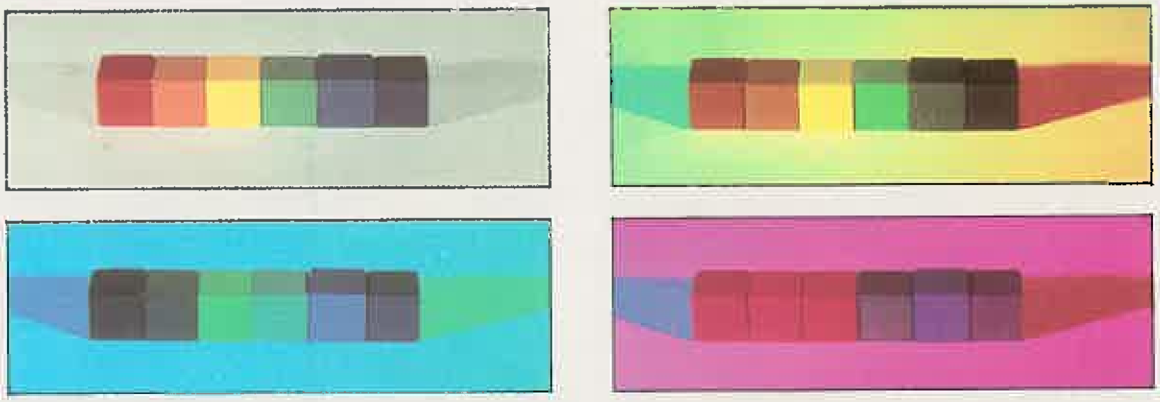
This is understood if the frequencies of white light are divided into three regions: the lower-frequency red end, the middle-frequency green part, and the higher-frequency blue end (Figure 28–10). The low and middle frequencies combined appear yellow to the human eye. The middle and high frequencies com-

Plate 1



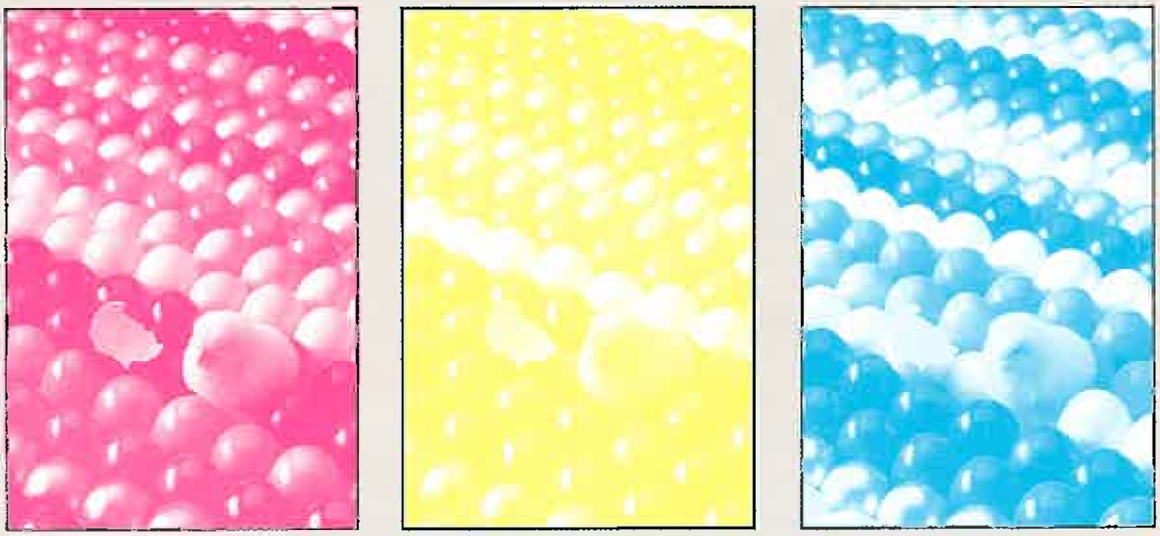
(Left) When sunlight passes through a prism, it separates into a spectrum of all the colors of the rainbow. (Right) When red light, green light, and blue light from three separate projectors overlap on a screen, they add to produce white light. The overlap of red and green light alone produces yellow; the overlap of green and blue light alone produces cyan (greenish blue); the overlap of red and blue light alone produces magenta (bluish red).

Plate 2



(Top left) Under white light, the colored blocks appear red, orange, yellow, green, blue, and purple, and the shadows are gray. (Top right) When the blocks are lit by red light from the right and green light from the left, the blocks themselves reflect no blue light; the shadow on the left, where red light is absent, appears green; similarly the shadow on the right appears red; the background reflects both red and green light and appears yellow. (Bottom left) The blocks are lit by green light and blue light. (Bottom right) The blocks are lit by red light and blue light. For the last two photos, identify which color of light comes from which direction, and explain the apparent colors of the blocks and the background.

Plate 3



In the printing of all these colored illustrations, only four colors of ink are used: magenta, yellow, cyan, and black. The first three images of the chicken and the colored eggs show how the photo appears when printed separately in magenta, yellow, and cyan ink. The fourth image shows the combination of those three images. The fifth image includes black ink as well.

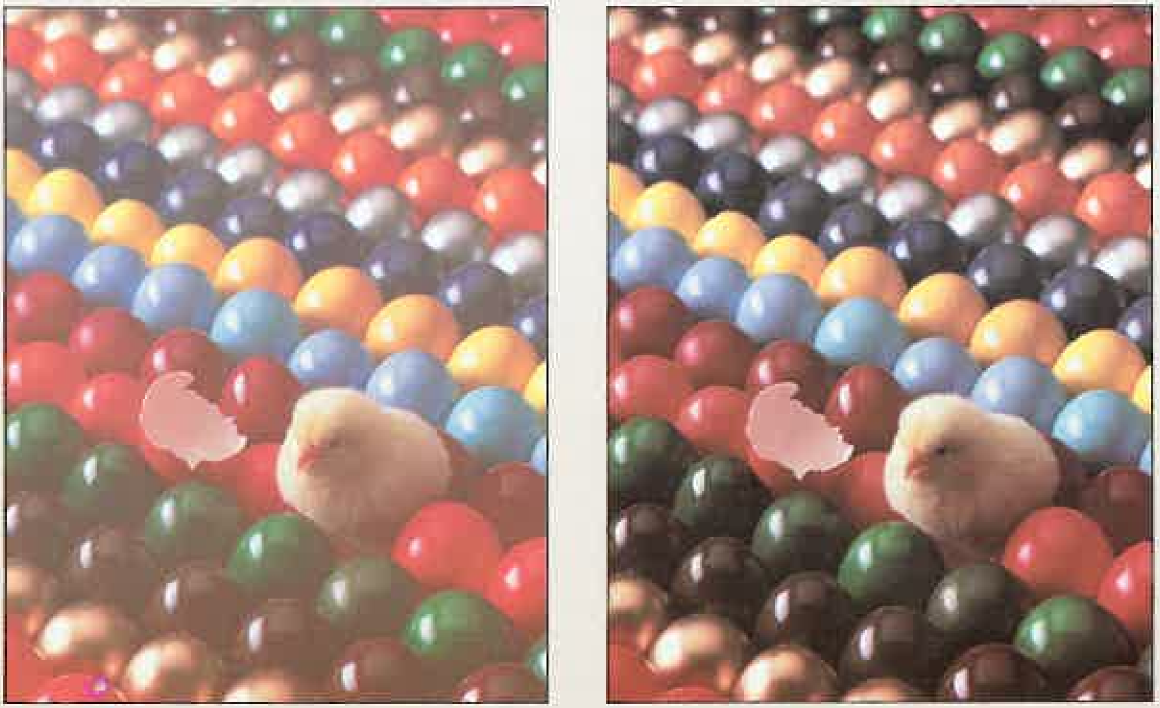
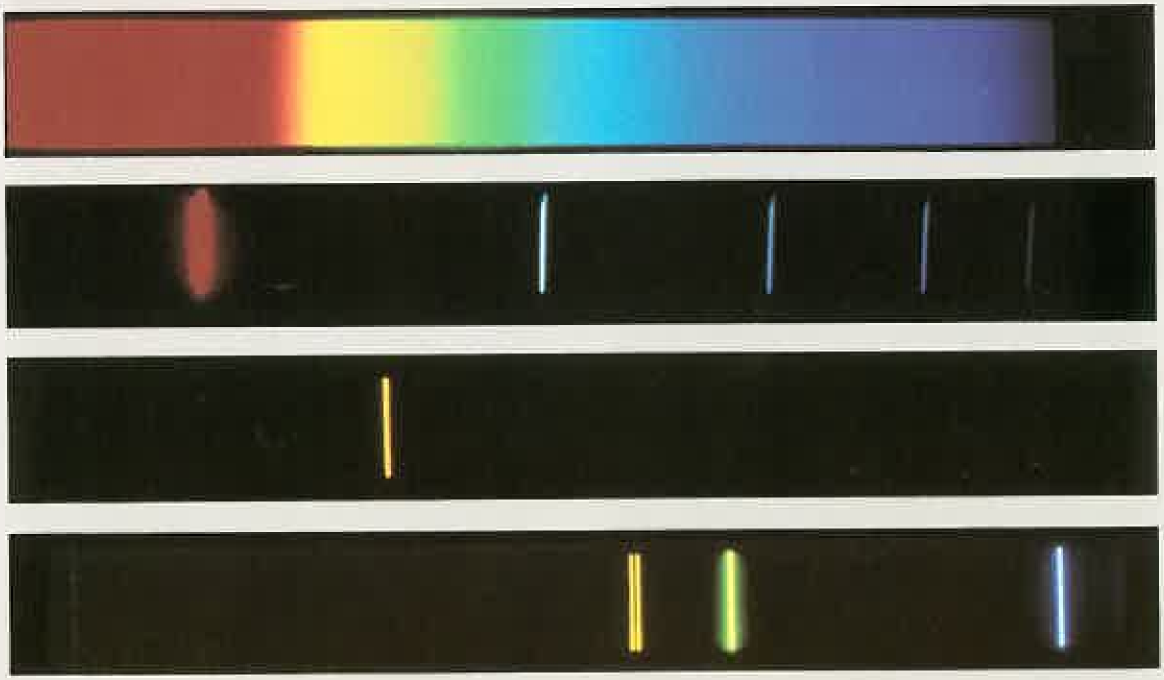


Plate 4

The blue appearance of distant foliage-covered mountains can be explained in terms of scattering (see Sections 28.8 and 28.9).

Plate 5



(From top to bottom) The continuous spectrum of an incandescent lamp and the line spectra of three elements: hydrogen, sodium, and mercury (see Section 28.11).

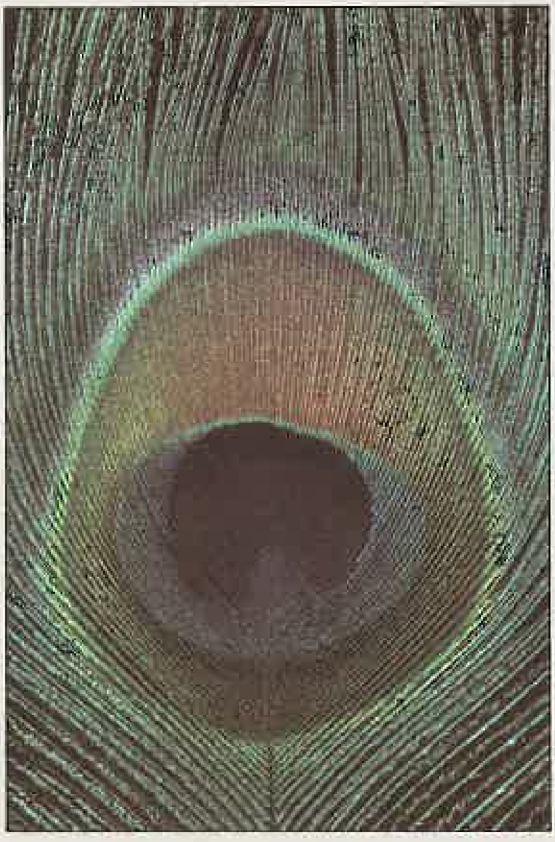
Plate 6

A double rainbow. In the inner rainbow, which is brighter, red appears at the outside edge and violet appears at the inside edge. The colors are in reverse order in the outer rainbow, which is due to an extra reflection inside each water drop (see Section 29.11).

Plate 7

The colors that flash from a compact disk (CD) are due to the interference of light waves that reflect from the tiny pits on the surface of the disk, which act like a diffraction grating (see Section 31.4).

Plate 8



The brilliant colors in a peacock feather are due to iridescence (see Section 31.6).

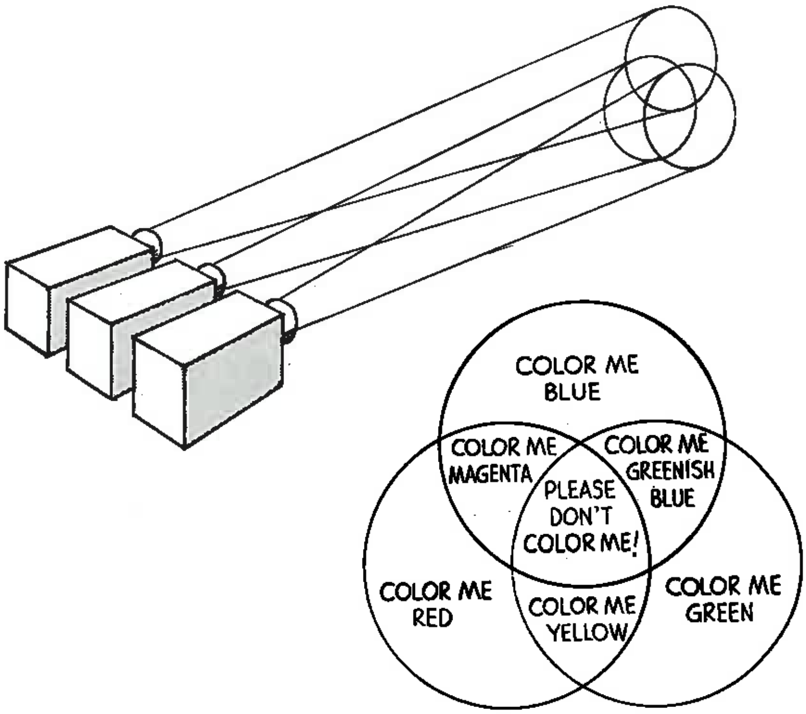


Fig. 28–9 When red light, green light, and blue light of equal brightness are projected on a white screen, the overlapping areas appear different colors. Where all three overlap, white is produced. See Plate 1 for a color version of this illustration.

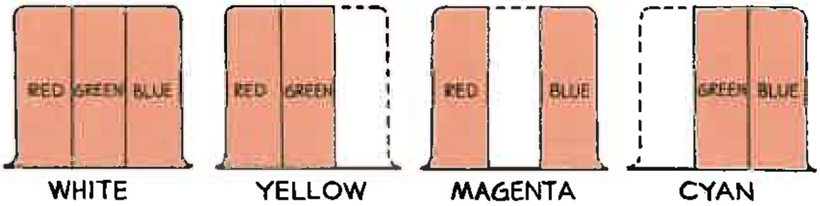


Fig. 28–10 (Left) The lower-frequency, middle-frequency, and high-frequency parts of white light appear *red*, *green*, and *blue*. (Right) To the human eye, red + green = yellow; red + blue = magenta; green + blue = cyan.

bined appear greenish-blue (cyan). The low and high frequencies combined appear bluish-red (magenta).

In fact, almost any color at all can be made by overlapping light of three colors and adjusting the brightness of each color of light. The three colors do not have to be red, green, and blue, although those three produce the highest number of different colors. This amazing phenomenon is due to the way the human eye works.

Color television is based on the ability of the human eye to see combinations of three colors as a variety of different colors. A close examination of the picture on most color television tubes will reveal that the picture is made up of an assemblage of tiny spots, each less than a millimeter across. When the screen is lit, some of the spots are red, some green, and some blue. At a distance the mixtures of these colors provide a complete range of colors, plus white.*

28.6 Complementary Colors

Two colors of light which when added appear white are called **complementary colors**. For example, red and cyan are complementary colors, since cyan is made from green and blue light (no red), and red, green, and blue light together appear white. Notice in Figure 28–9 that with only two colors of light, the following colors are produced:

red + green = yellow
red + blue = magenta
blue + green = cyan

A little thought will show that:

blue + yellow = white
green + magenta = white
red + cyan = white

Every hue has some complementary color that when added will produce white.

Now, if you begin with white light and *subtract* some color from it, the resulting color will appear as the complement of the one subtracted. Not all the light incident upon an object is reflected. Some is absorbed. The part that is absorbed is in effect subtracted from the incident light. If white light falls on a pigment that absorbs red light, for example, the light reflected appears cyan. A pigment that absorbs blue light will appear yellow; similarly, a pigment that absorbs yellow light will appear blue. Whenever you subtract a color from white light, you end up with the complementary color.

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* On a black and white television set, the black you see in the darkest scenes is simply the color of the tube face itself, which is more a light gray than black. Your eyes are sensitive to the contrast with the illuminated parts of the screen and you see the light gray as black. In your mind, you make it black.

▶ **Questions**

1. What are the complementary colors of (a) magenta, (b) blue, and (c) cyan?
2. What color does red light plus blue light appear?
3. What color does white light *minus* yellow light appear?
4. What color does white light *minus* green light appear?

28.7 Mixing Colored Pigments

Every artist knows that if you mix red, green, and blue paint, the result will be not white but a muddy dark brown. Red and green paint certainly do not combine to form yellow as red and green light do. The mixing of paints and dyes is an entirely different process from the mixing of colored light.

Paints and dyes contain finely divided solid particles of pigment that produce their colors by absorbing certain frequencies and reflecting other frequencies of light. Pigments absorb a relatively wide range of frequencies and reflect a wide range as well. In this sense, pigments reflect a mixture of colors.

Blue paint, for example, reflects mostly blue light, but also violet and green; it absorbs red, orange, and yellow light. Yellow paint reflects mostly yellow light, but also red, orange, and green; it absorbs blue and violet light. When blue and yellow paints are mixed, then between them they absorb all the colors except green. The only color they both reflect is green (Figure 28–11), which is why the mixture looks green. This process is called *color mixing by subtraction*, to distinguish it from the effect of mixing colored light, which is called *color mixing by addition*.

So if you cast lights on the stage at a school play, you use the rules of color addition to produce various colors. But if you mix paint, you use the rules of color subtraction.

▶ **Answers**

1. (a) Green; (b) yellow; (c) red.
2. Magenta.
3. Blue.
4. Magenta.

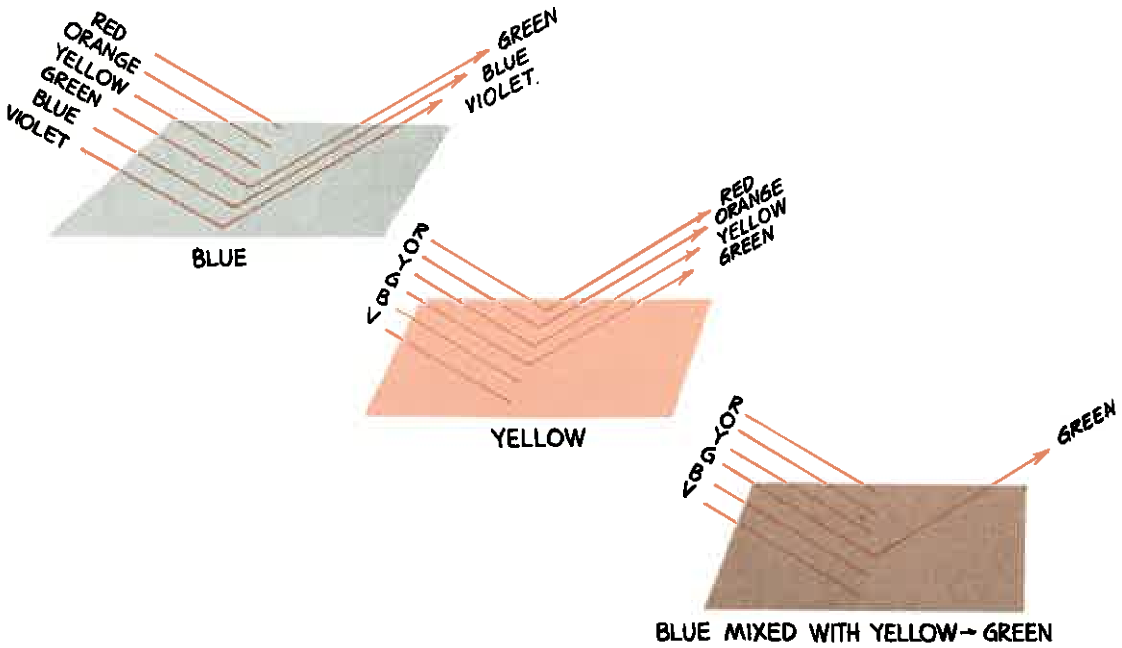

Fig. 28–11 (Left) Blue pigment reflects not only blue light, but also colors to either side of blue—namely, green and violet. It absorbs red, orange, and yellow light. (Center) Yellow pigment reflects not only yellow light, but also red, orange, and green. It absorbs blue and violet light. (Right) When blue and yellow pigments are mixed, the only common color reflected is green. The other colors have been *subtracted* from the incident white light.

You may have learned as a child that you could make any color with crayons or paints of three so-called primary colors: red, yellow, and blue. Actually, the three paint or dye colors that are most useful in color mixing by subtraction are magenta (bluish red), yellow, and cyan (greenish blue). These are the colors used in printing illustrations in full color.*

Color printing is done on a press that prints each page with four differently colored inks (magenta, yellow, cyan, and black) in succession. Each color of ink comes from a different plate, which transfers the ink to the paper. The ink deposits are regulated on different parts of the plate by tiny dots. Examine the colored pictures in this book or in any magazine with a magnifying glass and see how the overlapping dots of three colors plus black give the appearance of many colors. The color section shows the images made by the four plates, separately and combined.

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* Note that magenta, yellow, and cyan are used to make other colors by *subtraction*, as when colored paints or dyes are mixed. When colors are mixed by *addition*, as when colored light is mixed, red, green, and blue are the most useful colors to mix.

28.8 Why the Sky Is Blue

If a sound beam of a particular frequency is directed to a tuning fork of similar frequency, the tuning fork will be set into vibration and effectively redirect the beam in multiple directions. The tuning fork **scatters** the sound. A similar process occurs with the scattering of light from atoms and particles that are far apart from one another—as in the atmosphere.

We know that atoms behave like tiny optical tuning forks and re-emit light waves that shine on them. Very tiny particles do the same. The tinier the particle, the higher the frequency of light it will scatter. This is similar to small bells that ring with higher notes than larger bells. The nitrogen and oxygen molecules and the tiny particles that make up the atmosphere are like tiny bells that "ring" with high frequencies when energized by sunlight. Like the sound from bells, the re-emitted light is sent in all directions. It is scattered.

Most of the ultraviolet light from the sun is absorbed by a protective layer of ozone gas in the upper atmosphere. The remaining ultraviolet sunlight that passes through the atmosphere is scattered by atmospheric particles and molecules. Of the visible frequencies, violet is scattered the most, followed by blue, green, yellow, orange, and red, in that order. Red is scattered only a tenth as much as violet. Although violet light is scattered more than blue, our eyes are not very sensitive to violet light. Our eyes are more sensitive to blue, so we see a blue sky.

The blue of the sky varies in different places under different conditions. Where there are a lot of particles of dust and other particles larger than oxygen and nitrogen molecules, the lower frequencies of light are scattered more. This makes the sky less blue, and it takes on a whitish appearance. After a heavy rainstorm, when the particles have been washed away, the sky becomes a deeper blue.

The higher that one goes into the atmosphere, the fewer molecules there are in the air to scatter light. The sky appears darker. When there are no molecules, as on the moon for example, the "sky" is black.

Clusters of water molecules in a variety of sizes make up clouds. The different-size clusters result in a variety of scattered frequencies: low frequencies from larger droplets and high frequencies from tinier clusters of water molecules. The overall result is a white cloud. The electrons in a cluster vibrate together and in step, which results in the scattering of a greater amount of energy than when the same number of electrons vibrate separately. Hence, clouds are bright!

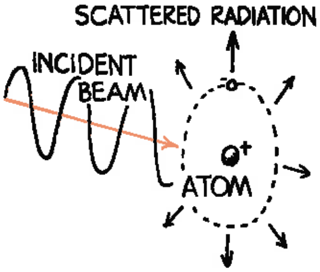

Fig. 28–12 A beam of light falls on an atom and causes the electrons in the atom to vibrate. The vibrating electrons, in turn, re-emit light in various directions. Light is scattered.

Fig. 28–13 When the air is full of particles larger than molecules, lower frequencies as well as blue are scattered. These add to give white, as seen in the haze against distant mountains (above) or in white clouds (below).

28.9 Why Sunsets Are Red

The lower frequencies of light are scattered the least by nitrogen and oxygen molecules. Therefore red, orange, and yellow light are transmitted through the atmosphere more readily than violet and blue. Red light, which is scattered the least, passes through more atmosphere without interacting with matter than light of any other color. Therefore, when light passes through a thick atmosphere, the lower frequencies are transmitted while the higher frequencies are scattered. At dawn and at sunset, sunlight reaches us through a longer path through the atmosphere than at noon.

~~At noon~~ sunlight travels through the least amount of atmosphere to reach the earth's surface (Figure 28–14). Only a small amount of high-frequency light is scattered from sunlight. As the day progresses and the sun is lower in the sky, the path through the atmosphere is longer, and more blue is scattered from the sunlight. High-frequency light is scattered, and lower-frequency light predominates in the sunlight that reaches the earth. The sun appears progressively redder, going from yellow to orange and finally to a red-orange at sunset. (The sequence is reversed between dawn and noon.)

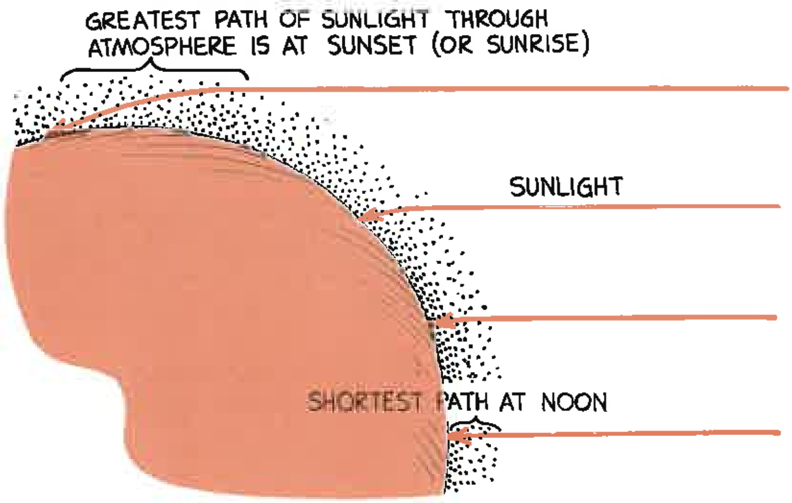

Fig. 28–14 A beam of sunlight must travel a longer path through the atmosphere at sunset than at noon. As a result, more blue is scattered from the beam at sunset than at noon. By the time a beam of white light gets to the ground at sunset, only the lower frequencies survive, producing a red sunset.

The colors of the sun and sky are consistent with our rules for color mixing. When blue is subtracted from white light, the complementary color that is left is yellow. When green is subtracted, magenta is left. The amount of scattering of each frequency depends on atmospheric conditions, which change from day to day and give us a variety of sunsets.

The next time you find yourself admiring a crisp blue sky, or delighting in the shapes of bright clouds, or watching a beautiful sunset, think about all those ultratiny optical tuning forks vibrating; you'll appreciate these everyday wonders of nature even more!

▸ Questions

1. If molecules in the sky scattered low-frequency light instead of high-frequency light, how would the colors of the sky and sunsets appear?
2. Distant dark mountains are bluish in color. What is the source of this blueness? (*Hint:* Exactly what is between you and the mountains you see?)
3. Distant snow-covered mountains reflect a lot of light and are bright. But they sometimes look yellowish, depending on how far away they are. Why are they yellow? (*Hint:* What happens to the reflected white light as it travels from the mountain to you?)

28.10 Why Water Is Greenish Blue

The color of water is not the beautiful deep blue that you often see on the surface of a lake or the ocean. That blue is the reflected color of the sky. The color of water itself, as you can see by looking at a piece of white material under water, is a pale greenish blue.

Water is transparent to nearly all the visible frequencies of light. Water molecules absorb infrared waves. This is because

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▸ Answers

1. If low frequencies were scattered, the noontime sky would appear reddish orange. At sunset more reds would be scattered by the longer path of the sunlight, and the sunlight would be predominantly blue and violet. So sunsets would appear blue!
2. If you look at distant dark mountains, very little light from them reaches you, and the blueness of the atmosphere between you and the mountains predominates. The blueness is of the low-altitude "sky" between you and the mountains. That's why distant mountains look blue!
3. The reason that distant snow-covered mountains often appear a pale yellow is because the blue in the white light from the snowy mountains is scattered on its way to you. What happens to white when blue is scattered from it? The complementary color left is yellow.

   Why do you see the scattered blue when the background is dark, but not when the background is bright? Because the scattered blue is faint. A faint color will show itself against a dark background, but not against a bright background. For example, when you look from the earth's surface at the atmosphere against the darkness of space, the atmosphere is sky blue. But astronauts above who look below through the same atmosphere to the bright surface of the earth do not see the same blueness.

water molecules resonate to the frequencies of infrared. The energy of the infrared waves is transformed into kinetic energy of the water molecules. That is why sunlight warms water.

Water molecules resonate very weakly to the visible-red frequencies. This causes a gradual absorption of red light by water. A 15-m layer of water reduces red light to a quarter of its initial brightness. There is very little red light in the sunlight that penetrates below 30 m of water. When red is taken away from white light, what color remains? Or this question can be asked in another way: What is the complementary color of red? The complementary color of red is cyan—a greenish-blue color. In sea water, the color of everything at these depths looks greenish blue.

It is interesting to note that many crabs and other sea animals that appear black in deep water are found to be red when they are raised to the surface. At great depths, black and red look the same. So both black and red sea animals are hardly seen by predators and prey in deep water. They have survived an evolutionary history while more visible varieties have not.

In summary, the sky is blue because blue from sunlight is reemitted in all directions by molecules in the atmosphere. Water is greenish blue because red is absorbed by molecules in the water. The colors of things depend on what colors are reflected by molecules, and also by what colors are absorbed by molecules.

28.11 The Atomic Color Code—Atomic Spectra

Every element has its own characteristic color when made to emit light. If the atoms are far enough apart so that their vibrations are not interrupted by neighboring atoms, their true colors are emitted. This occurs when atoms are made to glow in the gaseous state. (In the solid state, as in a lamp filament, where atoms are crowded together, the characteristic colors of the atoms are smudged to produce a continuous spectrum.) Neon gas, for example, glows a brilliant red; mercury vapor glows a bluish violet; and helium glows a pink. The glow of each element is unlike the glow of any other element.

The light from glowing elements can be analyzed with an instrument called a **spectroscope**. This chapter began with a brief account of Newton's investigation of light passing through a prism. The spectrum formed in Newton's first experiment was impure. This was because it was formed by overlapping circular images of the circular hole in his window shutter. He later produced a better spectrum by first passing light through a thin slit and then focusing it with lenses through the prism and onto a white screen (Figure 28–15). If the slit is made narrow, overlapping is reduced and the colors in the resulting spectrum are much clearer.

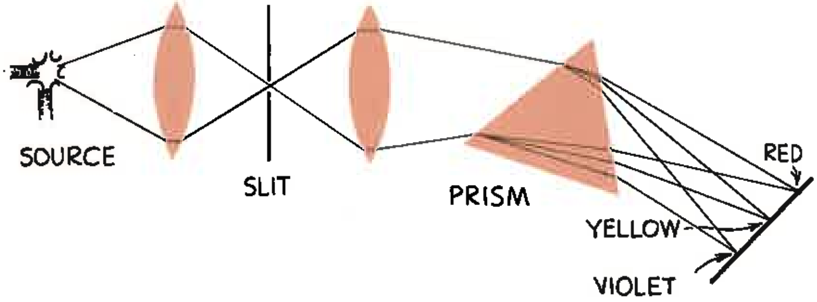

Fig. 28–15 A fairly pure spectrum is produced by passing white light through a thin slit, two lenses, and a prism.

This arrangement of thin slit, lenses, and a prism (or a diffraction grating) is the basis for the spectroscope (Figure 28–16).* A spectroscope displays the spectra of the light from hot gases and other light sources. (*Spectra* is the plural of *spectrum*.) The spectra of light sources are viewed through a magnifying eyepiece.

Fig. 28–16 A spectroscope. Light to be analyzed is placed near the thin slit at the left, where it is focused by lenses onto either a diffraction grating (shown) or a prism on the rotating table in the middle, and then viewed through the eyepiece on the right.

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* Although a *diffraction grating* works differently from a prism, it too spreads light into a spectrum. It is more commonly used than a prism in spectroscopes. A *spectrometer* is similar to a spectroscope except that it also measures the wavelengths of a spectrum and records the spectrum (on film for example).

When light from a glowing element is analyzed through a spectroscope, it is found that the colors are the composite of a variety of different frequencies of light. The spectrum of an element appears not as a continuous band of color but as a series of lines (see Figure 28–17 and the color section). Each line corresponds to a distinct frequency of light. Such a spectrum is known as a **line spectrum**. The spectral lines seen in the spectroscope are images of the slit through which the light passes. Note that each colored line appears in the same position as that color in the continuous spectrum.

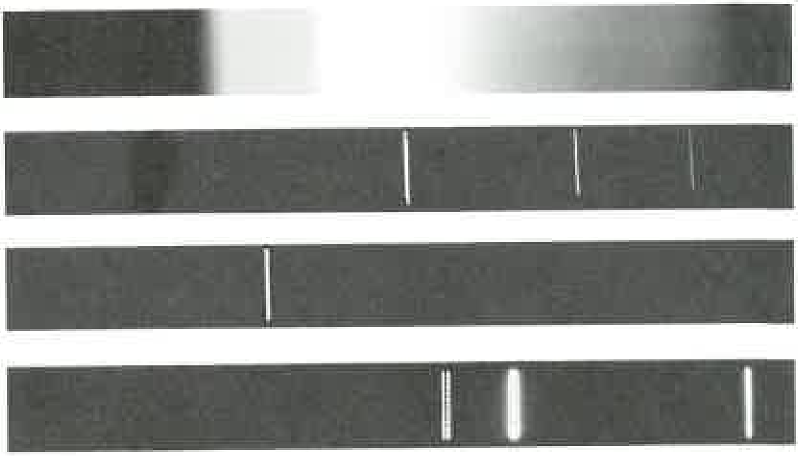

Fig. 28–17 (From top to bottom) The continuous spectrum of an incandescent lamp and the line spectra of three elements: hydrogen, sodium, and mercury. The color section shows the spectra in color.

The light from each different element produces its own characteristic pattern of lines. This is because each element has its own distinct configuration of electrons, and these emit distinct frequencies of light when electrons change from one energy state to another in the atom.* The frequencies of light emitted by atoms in the gaseous state are the "fingerprints" of the elements. Much of the information that physicists have about atomic structure is from the study of atomic spectra. The atomic composition of common materials, the sun, and distant galaxies is revealed in the spectra of these sources. The spectrometer is a very useful and powerful tool.

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* Electrons in atoms behave differently when materials glow and are sources of illumination than when materials simply reflect light that shines on them. This distinction won't be treated in detail here, except to say that when materials are made to glow, the electrons in their atoms do more than simply vibrate—they move from one orbit to another in a process called *excitation*. There is more to learn about all this in follow-up physics courses.

28 Chapter Review

Concept Summary

White light is a combination of light of all visible frequencies.

- Black is the absence of light; objects that appear black absorb all visible frequencies.

The color of an object is due to the color of the light it reflects (if opaque) or transmits (if transparent).

- Light is absorbed when its frequency matches the natural vibration frequencies of the electrons in the atoms of a material illuminated by the light.

Color mixing by addition is the mixing of light of different frequencies.

- The eye sees a combination of red, green, and blue light of equal brightness as white.

Color mixing by subtraction is the mixing of colored paints or dyes, which absorb most frequencies except for the ones that give them their characteristic color.

- When paints or dyes are mixed, the mixture absorbs all the frequencies each paint or dye absorbs.

Scattering of violet and blue frequencies of sunlight in all directions is what gives the sky its blue color.

- When sunlight travels a long path through the atmosphere, as at dawn or sunset, only the lower frequencies of light are transmitted; the higher ones are scattered out.

Atoms of each element have characteristic line spectra that can be used to identify the element.

Important Terms

complementary colors (28.6)
line spectrum (28.11)
pigment (28.3)
scatter (28.8)
spectroscope (28.11)
spectrum (28.1)
white light (28.1)

Review Questions

1. List the order of colors in the color spectrum. (28.1)
2. Are black and white real colors, in the sense that red and green are? Explain. (28.1)
3. A vibrating tuning fork emits sound. What is emitted by the vibrating electrons of atoms? (28.2)
4. What happens to light of a certain frequency that encounters atoms of the same resonant frequency? (28.2)
5. Why does the color of an object look different under a fluorescent lamp than under an incandescent lamp? (28.2)
6. a. What color(s) of light does a transparent red object *transmit*?
   b. What color(s) does it *absorb*? (28.3)
7. What is the function of a pigment? (28.3)
8. Why are more and more fire engines being painted yellow-green instead of red? (28.4)
9. How can yellow be produced on a screen if only red light and green light are available? (28.5)
10. What is the name of the color produced by a mixture of green and blue light? (28.5)

11. What colors of spots are lit on a television tube to give full color? (28.5)

12. What are complementary colors? (28.6)

13. What color is the complement of blue? (28.6)

14. The process of producing a color by mixing pigments is called *color mixing by subtraction*. Why do we say "subtraction" instead of "addition" in this case? (28.7)

15. What colors of ink are used to print full-color pictures in books and magazines? (28.7)

16. What is light scattering? (28.8)

17. a. Do the tiniest particles in the air scatter high or low frequencies of light?
    b. How about larger particles? (28.8)

18. Why is the sky blue? (28.8)

19. Why is the sky sometimes whitish? (28.8)

20. Why are clouds white? (28.8)

21. Why are sunsets red? (28.9)

22. Why is water greenish blue? (28.10)

23. What is a spectroscope, and what is its function? (28.11)

24. Does the red light from glowing neon gas have only one frequency or a mixture of frequencies? (28.11)

25. Why might atomic spectra be considered the "fingerprints" of atoms? (28.11)

Activities

1. Stare at a brightly colored object for a minute or so. The color receptors in your eyeballs become fatigued, so that when you look at a white area afterward, you see an afterimage of the complementary color. This is because the fatigued receptors send a weaker signal to the brain. All the colors produce white, but all the colors minus one produce the complementary to the missing color. Try it and see.

2. Make up a cardboard tube with closed ends of metal foil. Punch a hole in each end with a pencil, one about 3 or so millimeters and the other twice as big. Put your eye to the smaller hole and look through both holes at the colors of things against the black background of the tube. Colors will appear very different from how they appear against ordinary backgrounds.

3. Simulate your own sunset: Add a few drops of milk to a glass of water and look through it to a lit incandescent bulb. The bulb appears to be red or pale orange, while light scattered to the side appears blue. Try it and see.

Think and Explain

1. Why is space beyond the world's atmosphere black?

2. In a dress shop that has only fluorescent lighting, a customer insists on taking a garment into the daylight at the doorway. Is she being reasonable? Explain.

3. What color would a yellow cloth appear if illuminated with sunlight? With yellow light? With blue light?

4. A spotlight is coated so that it won't transmit blue from its white-hot filament. What color is the emerging beam of light?

5. How could you use the spotlights at a play to make the yellow clothes of the performers suddenly change to black?

6. A stage performer stands where beams of red and green light cross.
    a. What is the color of her white shirt under this illumination?
    b. What are the colors of the shadows she casts on the stage floor?

7. Very big particles, such as droplets of water, absorb more radiation than they scatter. How does this fact help to explain why rain clouds appear dark?

8. The only light to reach very far beneath the surface of the ocean is greenish blue. Objects at these depths either reflect greenish blue or reflect no color at all. If a ship that is painted red, green, and white sinks to the bottom of the ocean, how will these colors appear?

9. The element helium is so named because it was discovered in the sun—named "Helios" in Greek—before it was detected on earth. What instrument do you suppose enabled this discovery?

10. A lamp filament is made of tungsten. When made to glow, it emits a continuous spectrum—all the colors of the rainbow. When tungsten *gas* is made to glow, however, the light is a composite of very discrete colors. Why is there a difference in spectra?