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27 COLOR

Lab manual author Paul Robinson displays a variety of colors when he is illuminated by only a red, green, and blue lamp.

Roses are red and violets are blue; colors intrigue artists and physics types too. To the physicist, the colors of objects are not in the substances of the objects themselves or even in the light they emit or reflect. Color is a physiological experience and is in the eye of the beholder. So when we say that light from a rose is red, in a stricter sense we mean that it *appears* red. Many organisms, including people with defective color vision, do not see the rose as red at all.

The colors we see depend on the frequency of the light we see. Lights of different frequencies are perceived as different colors; the lowest-frequency light we detect appears to most people as the color red, and the highest frequency as violet. Between them range the infinite number of hues that make up the color spectrum of the rainbow. By convention these hues are grouped into the seven colors of red, orange, yellow, green, blue, indigo, and violet. These colors together appear white. The white light from the sun is a composite of all the visible frequencies.

Selective Reflection

Except for light sources such as lamps, lasers, and gas discharge tubes (which we will treat in Chapter 30), most of the objects around us reflect rather than emit light. They reflect only part of the light that is incident upon them, the part that gives them their color. A rose, for example, doesn't emit light; it reflects light (Figure 27.1). If we pass sunlight through a prism and then place a deep-red rose in various parts of the spectrum, the petals appear brown or black in all parts of the spectrum except in the red. In the red part of the spectrum, the petals appear red, but the green stem and leaves appear black. This shows that the red petals have the ability to reflect red light but not light of other colors; likewise the green leaves have the ability to reflect green light but not other colors. When the rose is held in white light, the petals appear red and the leaves green because the petals reflect the red part of the white light and the leaves reflect the green part. To understand why objects reflect specific colors of light, we must turn our attention to the atom.

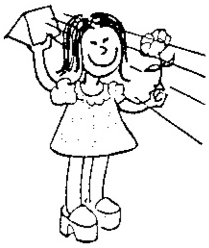

FIGURE 27.1 The colors of things depend on the colors of light that illuminate them.

Light is reflected from objects in a manner similar to the way sound is "reflected" from a tuning fork when a nearby tuning fork sets it into vibration. One tuning fork can make another vibrate even when the frequencies are not matched, although at significantly reduced amplitudes. The same is true of atoms and molecules. The outer electrons that buzz about the atomic nucleus can be forced into vibration by the vibrating electric fields of electromagnetic waves.[*] Once vibrating, these electrons send out their own electromagnetic waves just as vibrating acoustical tuning forks send out sound waves.

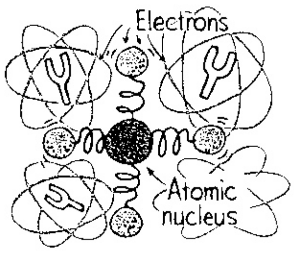

FIGURE 27.2 The outer electrons in an atom vibrate and resonate just as weights on springs would do. As a result, atoms and molecules behave somewhat like optical tuning forks.

Different materials have different natural frequencies for absorbing and emitting radiation. In one material, electrons oscillate readily at certain frequencies; in another material, they oscillate readily at different frequencies.

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.

Usually a material absorbs light of some frequencies and reflects the rest. If a material absorbs most of the visible light that is incident upon it but reflects red, for example, it appears red. That's why the petals of a red rose are red and the stem green. The atoms of the petals absorb all visible light except red, which they reflect; the stem

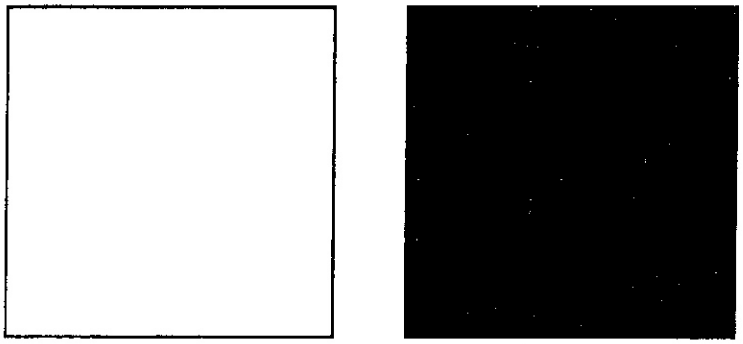

FIGURE 27.3 The square on the left *reflects* all the colors illuminating it. In sunlight it is white. When illuminated with blue light, it is blue. The square on the right *absorbs* all the colors illuminating it. In sunlight it is warmer than the white square.

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[*] The words *oscillation* and *vibration* both refer to periodic motion—motion that regularly repeats.

FIGURE 27.4 The bunny's dark fur absorbs all the radiant energy in incident sunlight and therefore is black. Light fur on other parts of the body reflects light of all frequencies and therefore is white.

absorbs all except green, which it reflects. An object that reflects light of all the visible frequencies, as the white part of this page does, is 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.

Interestingly, the petals of most yellow flowers, like 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.

An object can reflect only those frequencies present in the illuminating light. The appearance of a colored object therefore depends on the kind of light that illuminates it. An incandescent lamp, for instance, emits more light in the lower than in the higher frequencies, enhancing any reds viewed in this light. In a fabric having only a little bit of red in it, the red is more apparent under an incandescent lamp than under a fluorescent lamp. Fluorescent lamps are richer in the higher frequencies, and so blues are enhanced under them. Usually we define an object's "true" color as the color it has in daylight. So when you're shopping, the color of a garment you see in artificial light is not quite its true color (Figure 27.5).

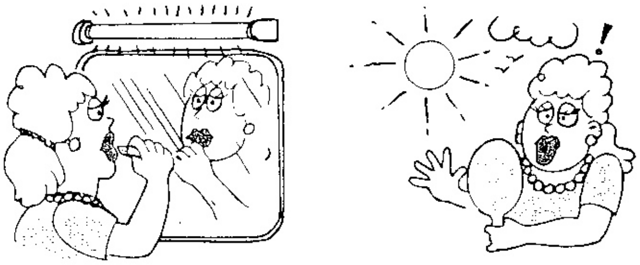

FIGURE 27.5 Color depends on the light source.

Selective 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 light and absorbs light of the other colors that illuminate it. The piece of glass contains dyes or *pigments*—fine particles that selectively absorb light of certain frequencies and selectively transmit others. From an atomic point of view, electrons in the pigment atoms selectively absorb illuminating light of certain frequencies. Light of other frequencies is re-emitted from molecule to molecule in the glass. The energy of the absorbed light increases the kinetic energy of the molecules and the glass is warmed. Ordinary window glass is colorless because it transmits light of all visible frequencies equally well.

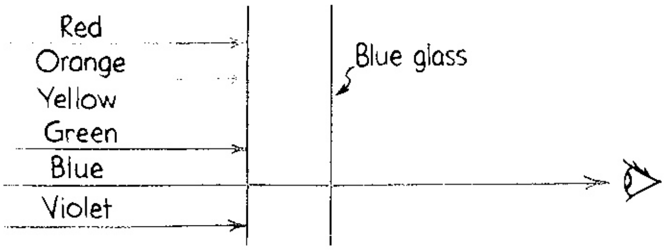

FIGURE 27.6 Only energy having the frequency of blue light is transmitted; energy of the other frequencies is absorbed and warms the glass.

CHECK YOURSELF

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 rose, why do the petals look black?
3. If you hold a small source of white light between you and a piece of red glass, you'll see two reflections from the glass: one from the front surface and one from the back surface. What color is each reflection?

Mixing Colored Light

The fact that white light from the sun is a composite of all the visible frequencies is easily demonstrated by passing sunlight through a prism and observing the rainbow-colored spectrum. The intensity of light from the sun varies with frequency, being most intense in the yellow-green part of the spectrum. It is interesting to note that our eyes have evolved to have maximum sensitivity in this range. That's why more new fire engines are painted yellow-green, particularly at airports where visibility is vital. Our sensitivity to yellow-green light is also why at night we see better under the illumination of yellow sodium-vapor lamps than under common tungsten-filament lamps of the same brightness.

The graphical distribution of brightness versus frequency is called the *radiation curve* of sunlight (Figure 27.7). Most whites produced from reflected sunlight share this frequency distribution.

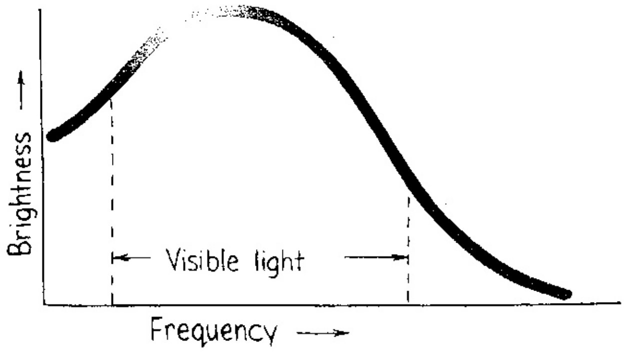

FIGURE 27.7 The radiation curve of sunlight is a graph of brightness versus frequency. Sunlight is brightest in the yellow-green region, in the middle of the visible range.

All the colors combined make white. Interestingly, the perception of white also results from the combination of only red, green, and blue light. We can understand this by dividing the solar radiation curve into three regions, as in Figure 27.8. Three types

CHECK YOUR ANSWERS

1. The leaves absorb rather than reflect the red light, and so become warmer.
2. The petals absorb rather than reflect the green light. Because green is the only color illuminating the rose and because green contains no red to be reflected, the rose reflects no color and appears black.
3. The reflection from the front surface is white because the light doesn't go far enough into the colored glass to allow absorption of nonred light. Only red light reaches the back surface because the pigments in the glass absorb all the other colors, and so the back reflection is red.

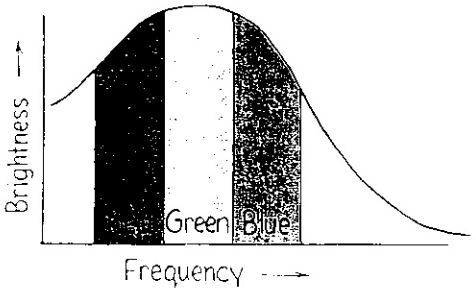

FIGURE 27.8 Radiation curve of sunlight divided into three regions: red, green, and blue. These are the additive primary colors.

of cone-shaped receptors in our eyes perceive color. Light in the lowest third of the spectral distribution stimulates the cones sensitive to low frequencies and appears red; light in the middle third stimulates the mid-frequency-sensitive cones and appears green; light in the high-frequency third stimulates the higher-frequency-sensitive cones and appears blue. When all three types of cones are stimulated equally, we see white.

Project red, green, and blue lights on a screen. Where they all overlap, white is produced. Where two of the three colors overlap, another color is produced (Figure 27.9). In the language of physicists, colored lights that overlap are said to *add* to each other. So we say that red, green, and blue light *add to produce white light,* and that any two of these colors of light add to produce another color. Various amounts of red, green, and blue, the colors to which each of our three types of cones are sensitive, produce any color in the spectrum. For this reason, red, green, and blue are called the **additive primary colors.** A close examination of the picture on most color television tubes will reveal that the picture is an assemblage of tiny spots, each less than a millimeter across. When the screen is lit, some of the spots are red, some green, some blue; the mixtures of these primary colors at a distance provide a complete range of colors, plus white.[*]

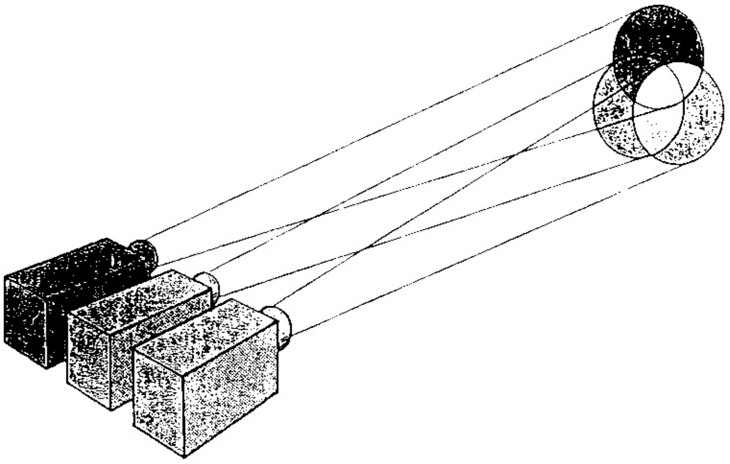

FIGURE 27.9 Color addition by the mixing of colored lights. When three projectors shine red, green, and blue light on a white screen, the overlapping parts produce different colors. White is produced where all three overlap.

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[*] It's interesting to note that the "black" you see on the darkest scenes on a black-and-white TV tube is simply the color of the tube face itself, which for many tubes is more a light gray than black. Because our eyes are sensitive to the contrast with the illuminated parts of the screen, we see this gray as black.

Complementary Colors

Here's what happens when two of the three additive primary colors are combined:

Red + Blue = Magenta
Red + Green = Yellow
Blue + Green = Cyan.

We say that magenta is the opposite of green; cyan is the opposite of red; and yellow is the opposite of blue. Now, when we add in the opposite color, we get white.

Magenta + Green = White (=Red + Blue + Green)
Yellow + Blue = White (=Red + Green + Blue)
Cyan + Red = White (=Blue + Green + Red)

When two colors are added together to produce white, they are called **complementary colors.** Every hue has some complementary color that when added to it will produce white.

The fact that a color and its complement combine to produce white light is nicely used in lighting stage performances. Blue and yellow lights shining on performers, for example, produce the effect of white light—except where one of the two colors is absent, as in the shadows. The shadow of one lamp, say the blue, is illuminated by the yellow lamp and appear yellow. Similarly, the shadow cast by the yellow lamp appears blue. This is a most interesting effect.

We see this effect in Figure 27.10, where red, green, and blue light shine on the golf ball. Note the shadows cast by the ball. The middle shadow is cast by the green spotlight and is not dark because it is illuminated by the red and blue lights, which make magenta. The shadow cast by the blue light appears yellow because it is illuminated by red and green light. Can you see why the shadow cast by the red light appears cyan?

CHECK YOURSELF

1. From Figure 27.9, find the complements of cyan, of yellow, and of red.
2. Red + blue = ____.
3. White − red = ______.
4. White − blue = ______.

CHECK YOUR ANSWERS

1. Red, blue, cyan.
2. Magenta.
3. Cyan.
4. Yellow.

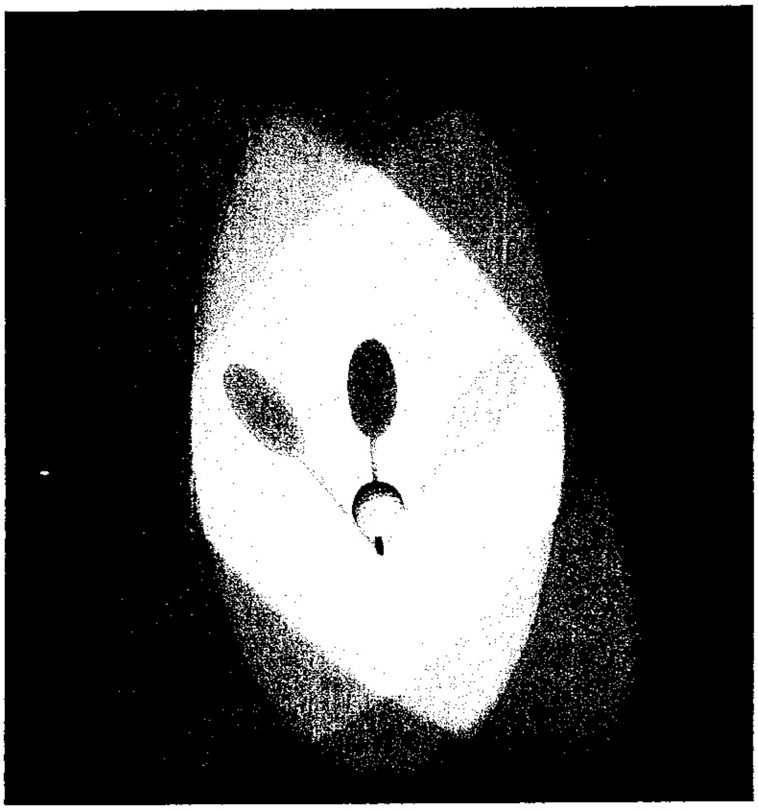

FIGURE 27.10 The white golf ball appears white when illuminated with red, green, and blue lights of equal intensities. Why are the shadows of the ball cyan, magenta, and yellow?

Mixing Colored Pigments

Every artist knows that if you mix red, green, and blue paint, the result will not be white, but a muddy dark brown. Red and green paint certainly do not combine to form yellow, as is the rule for mixing colored lights. Mixing pigments in paints and dyes is entirely different than mixing lights. Pigments are tiny particles that absorb specific colors. For example, pigments that produce the color red absorb the complementary color cyan. So something painted red absorbs mostly cyan, which is why it reflects red. In effect, cyan has been *subtracted* from white light. Something painted blue absorbs yellow, and so reflects all the colors except yellow. Take yellow away from white and you've got blue. The colors magenta, cyan, and yellow are the **subtractive primaries.** The variety of colors you see in the colored photographs in this or any other book are the result of magenta, cyan, and yellow dots. Light illuminates the book, and light of some frequencies is subtracted from the light reflected. The rules of color subtraction differ from the rules of light addition.

Color printing is an interesting application of color mixing. Three photographs (color separations) are taken of the illustration to be printed: one through a magenta filter, one through a yellow filter, and one through a cyan filter. Each of the three negatives has a different pattern of exposed areas that corresponds to the filter used and the color distribution in the original illustration. Light is shone through these negatives onto metal plates specially treated to hold printer's ink only in areas that have

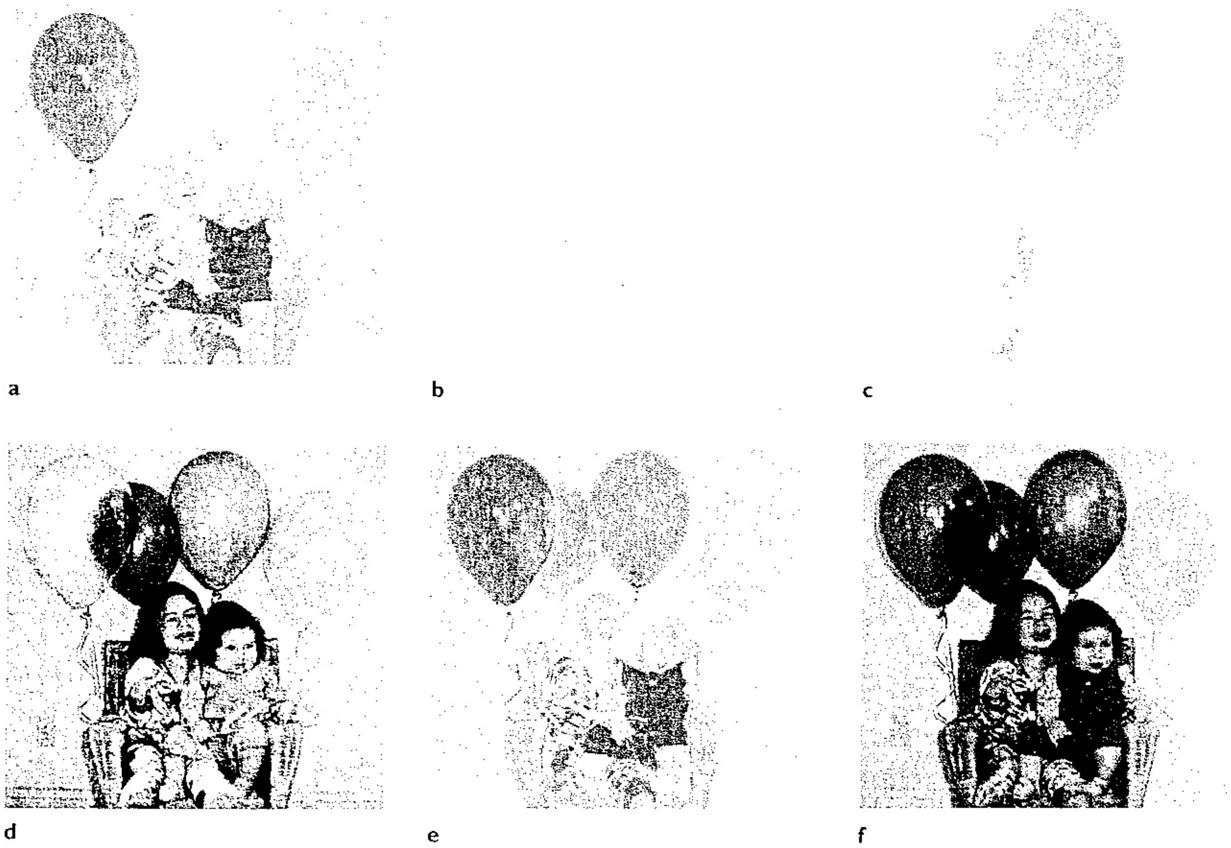

FIGURE 27.11 Only four colors of ink are used to print color illustrations and photographs—(*a*) magenta, (*b*) yellow, (*c*) cyan, and (*d*) black. When magenta, yellow, and cyan are combined, they produce (e). Addition of black produces the finished result, (*f*).

been exposed to light. The ink deposits are regulated on different parts of the plate by tiny dots. Inkjet printers deposit various combinations of magenta, cyan, yellow, and black inks. Examine the color in any of the figures in this or any book with a magnifying glass and see how the overlapping dots of these colors give the appearance of many colors. Or look at a billboard up close.

We see that all the rules of color addition and subtraction can be deduced from Figures 27.9, 27.10, and 27.12.

When we look at the colors on a soap bubble or soap film, we see cyan, magenta and yellow predominantly. What does this tell us? It tells us that some primary colors have been subtracted from the original white light! (How this happens will be discussed in Chapter 29.)

Why the Sky Is Blue

Not all colors are the result of the addition or subtraction of light. Some colors, like the blue of the sky, are the result of selective scattering. Consider the analogous case of sound: If a beam of a particular frequency of sound is directed to a tuning fork of similar frequency, the tuning fork is set into vibration and redirects the beam in mul-

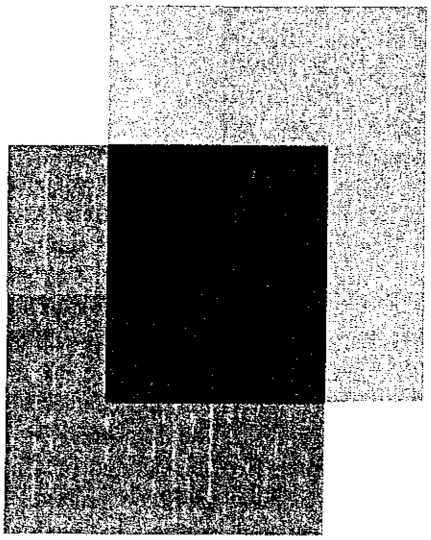

FIGURE 27.12 Dyes or pigments, as in the three transparencies shown, absorb and effectively subtract light of some frequencies and transmit only part of the spectrum. The subtractive primary colors are yellow, magenta, and cyan. When white light passes through overlapping sheets of these colors, light of all frequencies is blocked (subtracted) and we have black. Where only yellow and cyan overlap, light of all frequencies except green is subtracted. Various proportions of yellow, cyan, and magenta dyes will produce nearly any color in the spectrum.

FIGURE 27.13 The rich colors of Sneezlee represent many frequencies of light. The photo, however, is a mixture of only yellow, magenta, cyan, and black.

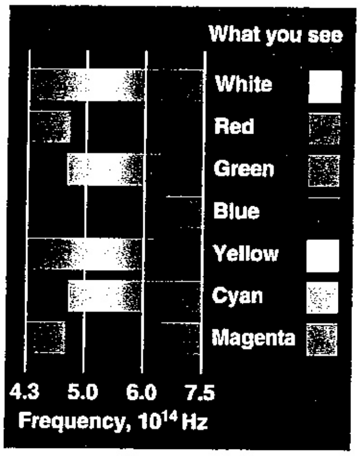

FIGURE 27.14 Approximate ranges of frequencies we sense as the additive primary colors and the subtractive primary colors.

tiple 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 they are in the atmosphere.[*]

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[*] This type of scattering is called *Rayleigh scattering* and occurs whenever the scattering particles are much smaller than the wavelength of incident light and have resonances at frequencies higher than those of the scattered light. Scattering is much more complex than our simplified treatment here.

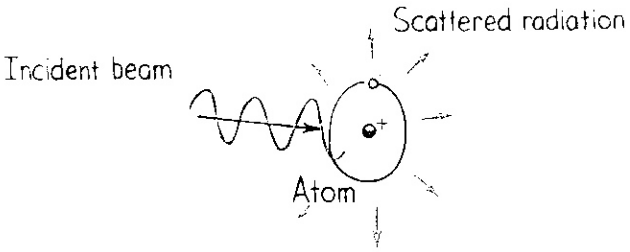

FIGURE 27.15 A beam of light falls on an atom and increases the vibrational motion of electrons in the atom. The vibrating electrons re-emit the light in various directions. Light is scattered.

Recall Figure 27.2, where we learned that atoms behave like tiny optical tuning forks and re-emit light waves that shine on them. Molecules and larger collections of atoms do the same. The tinier the particle, the greater amount of higher-frequency light it will re-emit. This is similar to the way small bells ring with higher notes than larger bells. The nitrogen and oxygen molecules that make up most of the atmosphere are like tiny bells that "ring" with high frequencies when energized by sunlight. Like sound from the bells, the re-emitted light is sent in all directions. When light is re-emitted in all directions, we say the light is *scattered*.

Of the visible frequencies of sunlight, violet is scattered the most by nitrogen and oxygen in the atmosphere, 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. Therefore the blue scattered light is what predominates in our vision, and we see a blue sky!

The blue of the sky varies in different places under different conditions. A principal factor is the water-vapor content of the atmosphere. On clear, dry days the sky is a much deeper blue than on clear days with high humidity. Places where the upper air is exceptionally dry, such as Italy and Greece, have beautifully blue skies that have

FIGURE 27.16 In clean air the scattering of high-frequency light gives us a blue sky. When the air is full of particles larger than molecules, lower-frequency light is also scattered, which add to give a whitish sky.

inspired painters for centuries. Where the atmosphere contains a lot of particles of dust and other particles larger than oxygen and nitrogen molecules, light of the lower frequencies is also scattered strongly. 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 grayish haze in the skies over large cities is the result of particles emitted by car and truck engines and by factories. Even when idling, a typical automobile engine emits more than 100 billion particles per second. Most are invisible but act as tiny centers to which other particles adhere. These are the primary scatterers of lower-frequency light. The largest of these particles absorb rather than scatter light, and a brownish haze is produced. Yuk!

Why Sunsets Are Red

Light that isn't scattered is light that is transmitted. Because red, orange, and yellow light are the least scattered by the atmosphere, light of these lower frequencies is better transmitted through the air. Red, which is scattered the least, and therefore, transmitted the most, passes through more atmosphere than any other color. So the thicker the atmosphere through which a beam of sunlight travels, the more time there is to scatter all the higher-frequency components of the light. This means the light that best makes it through is red. As Figure 27.17 shows, sunlight travels through more atmosphere at sunset, and that is why sunsets (and sunrises) are red.

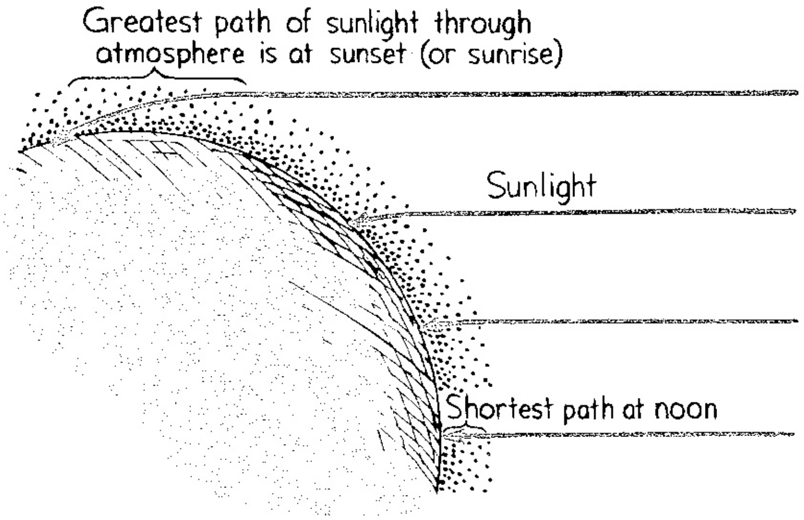

FIGURE 27.17 A sunbeam must travel through more atmosphere at sunset than at noon. As a result, more blue is scattered from the beam at sunset than at noon. By the time a beam of initially white light gets to the ground, only light of the lower frequencies survives to produce a red sunset.

At noon sunlight travels through the least amount of atmosphere to reach the Earth's surface. Only a small amount of high-frequency light is scattered from the sunlight, enough to make the sun look yellowish. As the day progresses and the sun drops lower in the sky, the path through the atmosphere is longer, and more violet and blue are scattered from the sunlight. The removal of violet and blue leaves the transmitted light redder. The sun becomes progressively redder, going from yellow to orange and finally to a red-orange at sunset. Sunsets and sunrises are unusually colorful following volcanic eruptions, because particles larger than atmospheric molecules are then more abundant in the air.[*]

The colors of the sunset are consistent with our rules for color mixing. When blue is subtracted from white light, the complementary color that is left is yellow. When higher-frequency violet is subtracted, the resulting complementary color is orange. When medium-frequency green is subtracted, magenta is left. The combinations of resulting colors vary with atmospheric conditions, which change from day to day and give us a variety of sunsets to enjoy.

CHECK YOURSELF

1. If molecules in the sky scattered low-frequency light more than high-frequency light, what color would the sky be? What color would sunsets be?
2. Distant dark mountains are bluish. What is the source of this blueness? (*Hint:* What is between us and the mountains we see?)
3. Distant snow-covered mountains reflect a lot of light and are bright. Very distant ones look yellowish. Why? (*Hint:* What happens to the reflected white light as it travels from the mountains to us?)

CHECK YOUR ANSWERS

1. If low-frequency light 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 we look at distant dark mountains, very little light from them reaches us, and the blueness of the atmosphere between us and them predominates. The blueness we attribute to the mountains is actually the blueness of the low-altitude "sky" between us and the mountains!
3. Bright snow-covered mountains appear yellow because the blue in the white light they reflect is scattered on its way to us. By the time the light gets to us, it is weak in the high frequencies and strong in the low frequencies—hence it is yellowish. For greater distances, farther away than mountains are usually seen, they would appear orange for the same reason a sunset appears orange.

   Why do we 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 we look from the Earth's surface at the atmosphere against the darkness of space, the atmosphere is sky blue. But astronauts above who look down through the same atmosphere to the bright surface of the Earth do not see the same blueness.

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[*] Sunsets and sunrises would be unusually colorful if particles larger than atmospheric molecules were more abundant in the air. This was the case all over the world for three years following the eruption of the volcano Krakatoa in 1883, when micrometer sized particles were spewed out in abundance and spread throughout the world's atmosphere. This occurred to a lesser extent following the 1991 eruption of Mount Pinatubo in the Philippines.

Practicing Physics

You can simulate a sunset with a fish tank full of water in which you've dropped a tiny bit of milk. A few drops will do. Then shine a flashlight beam through the water and you'll see that it looks bluish from the side. Milk particles are scattering the higher frequencies of light in the beam. Light emerging from the far end of the tank will have a reddish tinge. That's the light that wasn't scattered.

Why Clouds Are White

Water droplets in a variety of sizes make up clouds. The different-size droplets produce a variety of scattered frequencies: The tiniest scatter more blue than other colors; slightly larger droplets scatter slightly more higher frequencies, say, green; and still larger droplets scatter more red. The overall result is a white cloud. Electrons close to one another in a droplet vibrate together and in step, which results in a greater intensity of scattered light than from the same number of electrons vibrating separately. Hence, clouds are bright!

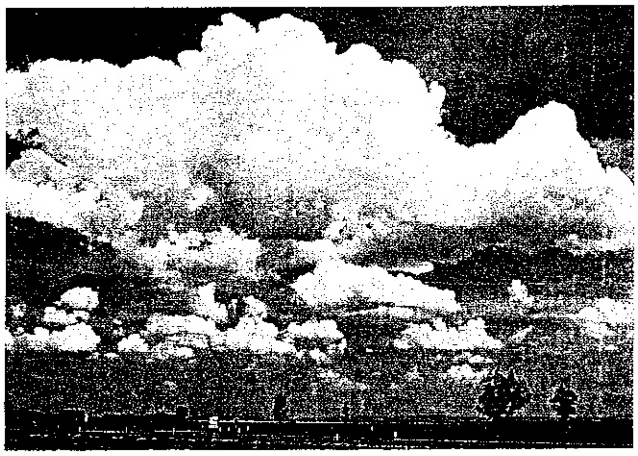

FIGURE 27.18 A cloud is composed of various sizes of water-droplets. The tiniest scatter blue light, slightly larger ones scatter green light, and still larger ones scatter red light. The result is a white cloud.

Larger assortments of droplets absorb much of the light incident upon them, and so the scattered intensity is less. This contributes to the darkness of clouds composed of larger droplets. Further increase in the size of the droplets causes them to fall as raindrops, and we have rain.

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 ultra-tiny optical tuning forks vibrating away—you'll appreciate these everyday wonders of nature even more!

Why Water Is Greenish Blue

We often see a beautiful deep blue when we look at the surface of a lake or the ocean. But that isn't the color of water; it's 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.

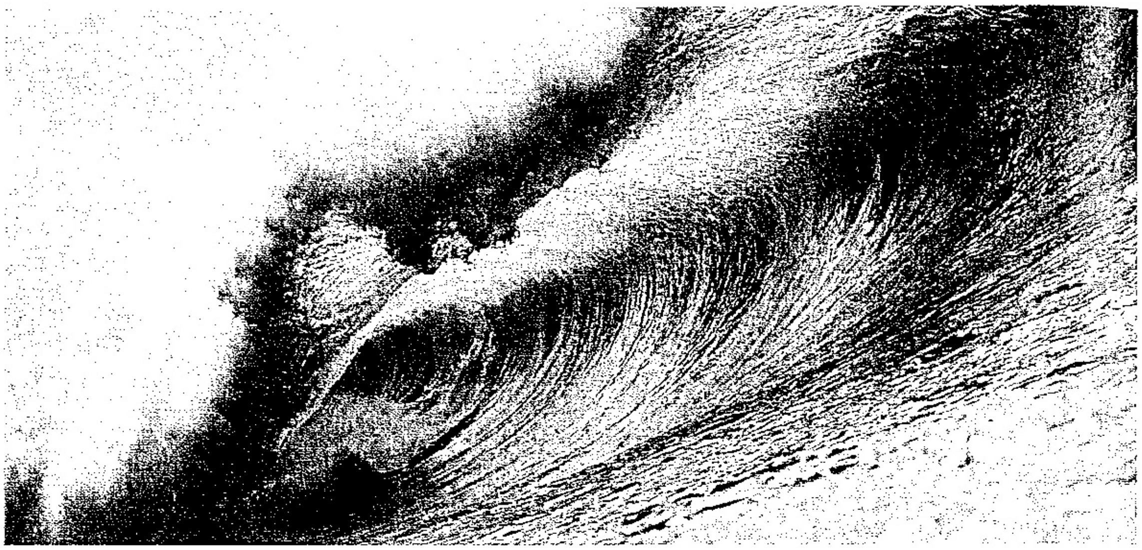

FIGURE 27.19 Water is cyan because it absorbs red light. The froth in the waves is white because, like clouds, it is composed of a variety of tiny water droplets that scatter all the visible frequencies.

FIGURE 27.20 There are no blue pigments in the feathers of a blue jay. Instead there are tiny alveolar cells in the barbs of its feathers that scatter light—mainly high-frequency light. So a blue jay is blue for the same reason the sky is blue—scattering.

Although water is transparent to light of nearly all the visible frequencies, it strongly absorbs infrared waves. This is because water molecules resonate to the frequencies of infrared. The energy of the infrared waves is transformed into internal energy in the water, which is why sunlight warms water. Water molecules resonate somewhat in the visible red, which causes red light to be a little more strongly absorbed than blue light in water. Red light is reduced to a quarter of its initial brightness by 15 meters of water. There is very little red light in the sunlight that penetrates below 30 meters of water. When red is taken away from white light, what color remains? This question can be asked in another way: What is the complementary color of red? The complementary color of red is cyan—a bluish-green color. In seawater, the color of everything at these depths looks greenish.

Many crabs and other sea creatures that appear black in deep water are found to be red when they are raised to the surface. At these depths, black and red look the same. Apparently the selection mechanism of evolution could not distinguish between black and red at such depths in the ocean.

So while the sky is blue because blue is strongly scattered by molecules in the atmosphere, water is bluish green because red is absorbed by molecules in the water. We see that the colors of things depend on which colors are scattered or reflected by molecules and also on which colors are absorbed by molecules.*

Interestingly enough, the color we see is not in the world around us—the color is in our heads. The world is filled with a montage of vibrations—electromagnetic waves that stimulate the sensation of color when the vibrations interact with the cone-shaped receiving antennae in the retinas of our eyes. How nice that eye-brain interactions produce the beautiful colors we see.

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*Scattering by small, widely spaced particles in the irises of blue eyes, rather than any pigments, accounts for their color. Absorption by pigments accounts for brown eyes.

Summary of Terms

Additive primary colors The three colors—red, blue, and green—that when added in certain proportions produce any other color in the visible-light part of the electromagnetic spectrum and can be mixed equally to produce white.

Complementary colors Any two colors that when added produce white light.

Subtractive primary colors The three colors of absorbing pigments—magenta, yellow, and cyan—that when mixed in certain proportions reflect any other color in the visible-light part of the electromagnetic spectrum.

Suggested Reading

Murphy, Pat, and Paul Doherty. *The Color of Nature.* San Francisco: Chronicle Books, 1996.

Review Questions

1. What is the relationship between the frequency of light and its color?

Selective Reflection

2. What occurs when the outer electrons that buzz about the atomic nucleus encounter electromagnetic waves?
3. When outer electrons are set into vibration, what do they emit?
4. What happens to light when it falls upon a material that has a natural frequency equal to the frequency of the light?
5. What happens to light when it falls upon a material that has a natural frequency above or below the frequency of the light?

Selective Transmission

6. What color light is transmitted through a piece of red glass?
7. What is a *pigment?*
8. Which warms more quickly in sunlight, a colorless or a colored piece of glass? Why?

Mixing Colored Light

9. What is the evidence for the statement that white light is a composite of all the colors of the spectrum?
10. What is the color of the peak frequency of solar radiation?
11. What color light are our eyes most sensitive to?
12. What is a *radiation curve?*
13. What frequency ranges of the radiation curve do red, green, and blue light occupy?
14. Why are red, green, and blue called the *additive primary colors?*

Mixing Colored Pigments

15. When something is painted red, what color is most absorbed?
16. What are the *subtractive primary colors?*
17. If you look with a magnifying glass at pictures printed full color in this or other books or magazines, you'll notice three colors of ink plus black. What are these colors?

Complementary Colors

18. What is the resulting color of equal intensities of red, blue, and green light combined? Blue light and green light?
19. What is the resulting color equal intensities of red light and cyan light combined?
20. Why are red and cyan called *complementary* colors?

Why the Sky Is Blue

21. Which interacts more with high-pitched sounds, small bells or large bells?
22. Which interacts more with high-frequency light, small particles or large particles?
23. True or false: The sky is blue because oxygen and nitrogen molecules are blue in color.
24. Why does the sky sometimes appear whitish?

Why Sunsets Are Red

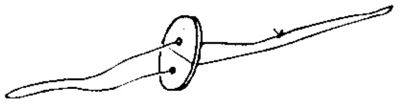
25. Why does the sun look reddish at sunrise and sunset but not at noon?
26. Why does the color of sunsets vary from day to day?

Why Clouds Are White

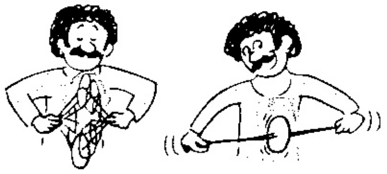
27. What is the evidence for a variety of particle sizes in a cloud?
28. What is the evidence for extra-big particles in a rain cloud?

Why Water Is Greenish Blue

29. What part of the electromagnetic spectrum is most absorbed by water?
30. What part of the visible electromagnetic spectrum is most absorbed by water?
31. What color results when red is subtracted from white light?
32. Why does water appear cyan?



Twirl the disk as shown, so the string winds up like a rubber band on a model airplane. Then tighten the string by pulling outward and the disk will spin. If half the disk is colored yellow and the other half blue, when it is spun the colors will be mixed and appear nearly white (how close to white depends on the hues of the colors). Try this for other complementary colors.



3. Fashion a cardboard tube covered at each end with metal foil. Punch a hole in each end with a pencil, one about 3 or so millimeters in diameter and the other twice as big. Put your eye to the small hole and look through the tube at the colors of things against the black background of the tube. You'll see colors that look very different from how they appear against ordinary backgrounds.

Exercises

1. In a dress shop with only fluorescent lighting, a customer insists on taking dresses into the daylight at the doorway to check their color. Is she being reasonable? Explain.
2. Why will the leaves of a red rose be heated more than the petals when illuminated with red light? What does this have to do with people in the hot desert wearing white clothes?

light, red in red light, blue in blue light, and so on for every color?

11. A spotlight is coated so that it won't transmit yellow light from its white-hot filament. What color is the emerging beam of light?
12. How could you use the spotlights at a play to make the yellow clothes of the performers suddenly change to black?
13. Suppose two flashlight beams are shone on a white screen, one beam through a pane of blue glass and the other through a pane of yellow glass. What color appears on the screen where the two beams overlap? Suppose, instead, that the two panes of glass are placed in the beam of a single flashlight. What then?
14. Does a color television work by color addition or by color subtraction? Defend your answer.
15. On a TV screen, red, green and blue spots of fluorescent materials are illuminated at a variety of relative intensities to produce a full spectrum of colors. What dots are activated to produce yellow? Magenta? White?
16. What colors of ink do color ink-jet printers use to produce a full range of colors? Do the colors form by color addition or by color subtraction?
17. What color will be transmitted through overlapping cyan and magenta filters?
18. Look at your sunburned red feet when they are under water. Why don't they look as red as when above water?
19. Why does blood of injured deep-sea divers look greenish black in underwater photographs taken with natural light, but red when flashbulbs are used?
20. By reference to Figure 27.9, complete the following equations:

Yellow light + blue light = _________ light.
Green light + _________ light = white light.
Magenta + yellow + cyan = _________ light.

21. Below is a photo of physics editor Suzanne with son Tristan wearing red and daughter Simone wearing green. Below that is the negative photo, which shows these colors differently. What is your explanation?

22. Check Figure 27.9 to see if the following three statements are accurate. Then fill in the last statement. (All colors are combined by the addition of light.)

Red + green + blue = white.

Red + green = yellow = white − blue.

Red + blue = magenta = white − green.

Green + blue = cyan = white − ________.

23. In which of these cases will a ripe banana appear black: When illuminated with red light? With yellow light? With green light? With blue light?
24. When white light is shone on red ink dried on a glass plate, the color that is transmitted is red. But the color that is reflected is not red. What is it?
25. Stare intently at an American flag. Then turn your view to a white area. What colors do you see in the image of the flag that appears on the wall?
26. Why can't we see stars in the daytime?
27. Why is the sky a darker blue when you are at high altitudes? (*Hint:* What color is the "sky" on the moon?)
28. Can stars be seen from the moon in the "daytime" when the sun is shining?
29. At the beach you can get a sunburn while under the shade of an umbrella. What is your explanation?
30. Pilots sometimes wear glasses that transmit yellow light and absorb light of most other colors. Why does this help them see more clearly?
31. Does light travel faster through the lower atmosphere or the upper atmosphere?
32. Why does smoke from a campfire look blue against trees near the ground but yellow against the sky?
33. Comment on the statement, "Oh, that beautiful red sunset is just the leftover colors that weren't scattered on their way through the atmosphere."
34. If the sky on a certain planet in the solar system were normally orange, what color would sunsets be?
35. Volcanic emissions put fine ashes in the air that scatter red light. What color does a full moon appear through these ashes?
36. Tiny particles, like tiny bells, scatter high-frequency waves more than low-frequency waves. Large particles, like large bells, mostly scatter low frequencies. Intermediate-size particles and bells mostly scatter intermediate frequencies. What does this have to do with the whiteness of clouds?
37. Very big particles, like droplets of water, absorb more radiation than they scatter. What does this have to do with the darkness of rain clouds?
38. If the atmosphere of the Earth were several times thicker, would ordinary snowfall still seem white or would it be some other color? What color?
39. The atmosphere of Jupiter is more than 1000 km thick. From the surface of this planet, would you expect to see a white sun?
40. You're explaining to a youngster at the seashore why the water is cyan colored. The youngster points to the whitecaps of overturning waves and asks why they are white. What is your answer?