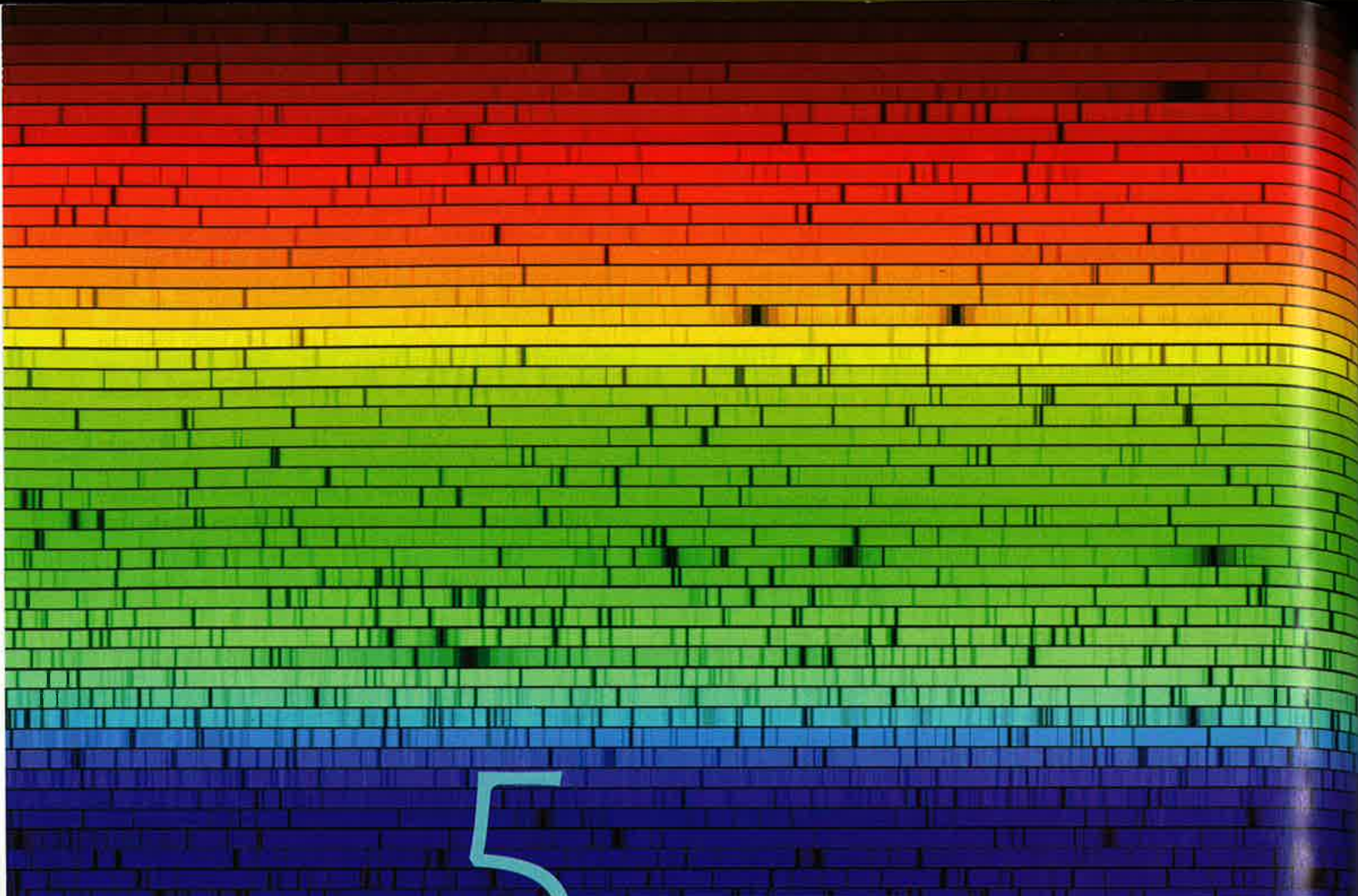


5

LIGHT AND MATTER

READING MESSAGES FROM THE COSMOS

LEARNING GOALS

5.1 LIGHT IN EVERYDAY LIFE
- How do we experience light?
- How do light and matter interact?

5.2 PROPERTIES OF LIGHT
- What is light?
- What is the electromagnetic spectrum?

5.3 PROPERTIES OF MATTER
- What is the structure of matter?
- What are the phases of matter?
- How is energy stored in atoms?

5.4 LEARNING FROM LIGHT
- What are the three basic types of spectra?
- How does light tell us what things are made of?
- How does light tell us the temperatures of planets and stars?
- How do we interpret an actual spectrum?

5.5 THE DOPPLER EFFECT
- How does light tell us the speed of a distant object?
- How does light tell us the rotation rate of a distant object?

May the warp be the white light of morning,
May the weft be the red light of evening,
May the fringes be the falling rain,
May the border be the standing rainbow.
Thus weave for us a garment of brightness.
—Song of the Sky Loom (Native American)

Ancient observers could discern only the most basic features of the light that they saw—features such as color and brightness. Over the past several hundred years, we have discovered that light carries far more information. Today, we can analyze the light of distant objects to learn what they are made of, how hot they are, how fast they are moving, and much more.

We are lucky that light carries so much information. Our present spacecraft can reach only objects within our own solar system, and except for an occasional meteorite falling from the sky, the cosmos does not come to us. In contrast, light travels throughout the universe, carrying its treasury of information wherever it goes. Light is truly the cosmic messenger, bringing the stories of distant objects to Earth.

In this chapter, we will focus our attention on learning how to read the messages carried to us by light from the cosmos. We'll begin with a brief look at the basic interactions of light and matter that create those messages, and then study the properties of light and matter individually and in some detail. With that background, we'll be ready to explore the formation of light spectra, so that we can understand how light can encode so much information about distant objects.

MA™ **Light and Spectroscopy Tutorial, Lesson 1**

5.1 LIGHT IN EVERYDAY LIFE

Look around you right now. What do you see? You may be tempted to list nearby objects, but all you're really seeing is *light* that has interacted with those objects. Through intuition and experience, you're able to interpret the colors and patterns of the light and turn them into information about the objects and substances that surround you.

Astronomers do much the same thing when studying the universe with telescopes. Telescopes collect the light of distant objects, and astronomers then extract information from the light. Knowing how to extract the maximum amount of information from light requires a deeper understanding of what light is and how it interacts with matter. We'll start developing that understanding by taking a closer look at our everyday experience with light.

How do we experience light?

You can tell that light is a form of energy even without opening your eyes. Outside on a hot, sunny day you can feel your skin warm as it absorbs sunlight. If you remember that greater warmth means more molecular motion, you'll realize that sunlight must be transferring its energy to the molecules in your skin. The energy that light carries is called *radiative energy*; recall that it is one of the three basic categories of energy, along with kinetic and potential energy (see Figure 4.10).

Energy and Power We measure energy in units of joules [Section 4.3], so we can use these energy units to measure the total amount of energy that light transfers to your skin. In astronomy, however, we are usually more interested in the *rate* at which light carries energy toward or away from us than in the total amount of energy it carries. After all, because light always travels through space at the speed of light, we cannot hold light in our hands in the same way that we can hold a hot potato, which has thermal energy, or a rock, which has gravitational potential energy. In science, the rate of energy flow is called **power**, which we measure in units called **watts**. A power of 1 watt means an energy flow of 1 joule per second:

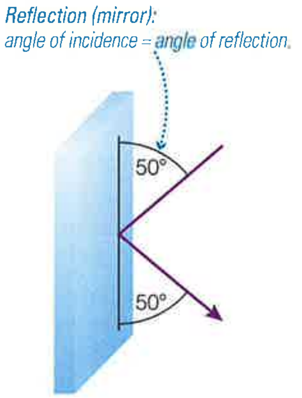
$$1 \text{ watt} = 1 \text{ joule/s}$$

For example, a 100-watt light bulb requires 100 joules of energy (which you buy from the electric company) for each second it is turned on. Interestingly, the power requirement of an average human—about 10 million joules per day—is about the same as that of a 100-watt light bulb.

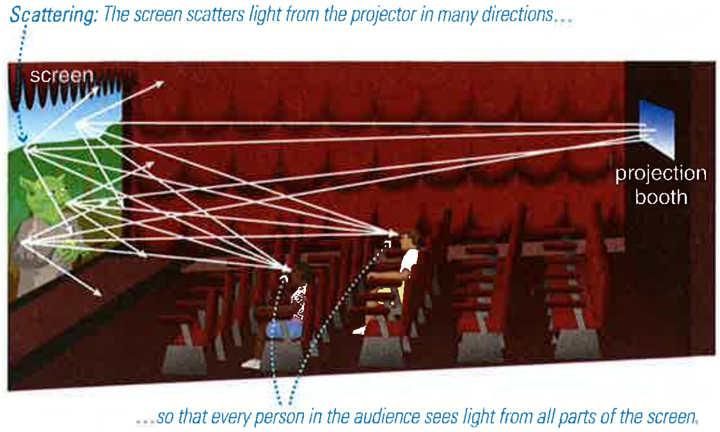
Light and Color Everyday experience tells us that light comes in different forms that we call *colors*. You've probably seen a prism split light into the rainbow of light called a **spectrum** (Figure 5.1). The basic colors in a rainbowlike spectrum are red, orange, yellow, green, blue, and violet. We see *white* when the basic colors are mixed in roughly equal proportions. Light from the Sun or a light bulb is often called *white light*, because it contains all the colors of the rainbow. *Black* is what we perceive when there is no light and hence no color.

The wide variety of all possible colors comes from mixtures of just a few colors in varying proportions. Your television takes advantage of this fact to simulate a huge range

FIGURE 5.1 When we pass white light through a prism, it disperses into a rainbow of color that we call a *spectrum*.



a A mirror reflects light along a simple path: The angle at which the light strikes the mirror is the same angle at which it is reflected.



b A movie screen scatters light in many different directions, so that each member of the audience can watch the movie. The pages in a book do the same thing, which is why you can read them from different angles and distances.

FIGURE 5.2 Reflection and scattering.

of colors by combining only red, green, and blue light; these three colors are often called the *primary colors of vision,* because they are the colors directly detected by cells in your eyes. Colors tend to look different on paper, so artists generally work with an alternate set of primary colors: red, yellow, and blue. If you do any graphic design work, you may be familiar with the CMYK process that mixes the four colors cyan, magenta, yellow, and black to produce a great variety of colors; the CMYK process was used to print this book.

SEE IT FOR YOURSELF

If you have a magnifying glass handy, hold it close to your TV set to see the individual red, blue, and green dots. If you don't have a magnifying glass, try splashing a few droplets of water onto your TV screen (carefully!). What do you see? What are the drops of water doing?

You can produce a spectrum with either a prism or a **diffraction grating**, which is a piece of plastic or glass etched with many closely spaced lines. If you have a compact disc or DVD handy, you can make a spectrum for yourself. The bottom of a CD or DVD is etched with many closely spaced circles and therefore acts like a diffraction grating. That's why you see rainbows of color on the bottom of the disc when you hold it up to the light.

How do light and matter interact?

If you think about the interactions between light and matter that you see in everyday life, you'll realize that light can interact with matter in four basic ways:

- **Emission:** A light bulb *emits* visible light; the energy of the light comes from electrical potential energy supplied to the light bulb.
- **Absorption:** When you place your hand near an incandescent light bulb, your hand *absorbs* some of the light, and this absorbed energy warms your hand.
- **Transmission:** Some forms of matter, such as glass or air, *transmit* light, which means allowing it to pass through.
- **Reflection/scattering:** Light can bounce off matter (Figure 5.2), leading to what we call *reflection* (when the bouncing is all in the same general direction) or *scattering* (when the bouncing is more random).

Materials that transmit light are said to be *transparent,* and materials that absorb light are called *opaque.* Many materials are neither perfectly transparent nor perfectly opaque. For example, dark sunglasses and clear eyeglasses are both partially transparent, but the dark glasses absorb more and transmit less light. Materials can also affect different colors of light differently. For example, red glass transmits red light but absorbs other colors, while a green lawn reflects (scatters) green light but absorbs all other colors.

Let's put these ideas together to understand what happens when you walk into a room and turn on the light switch (Figure 5.3). The light bulb begins to emit white light, which is a mix of all the colors in the spectrum. Some of this light exits the room, transmitted through the windows. The rest of the light strikes the surfaces of objects inside the room, and the material properties of each object determine the colors it absorbs or reflects. The light coming from each object therefore carries an enormous amount of information about the object's location, shape and structure, and composition. You acquire this information when light enters your eyes, where special cells in your retina absorb it and send signals to your brain. Your brain interprets the messages that light carries, recognizing materials and objects in the process we call vision.

All the information that light brings to Earth from the universe was encoded by one of the four basic interactions between light and matter common to our everyday experience. However, our eyes perceive only a tiny fraction of all the information contained in light. Modern instruments can break light into a much wider variety of colors and can analyze those colors in far greater detail. In order to understand how to decode that information, we need to examine the nature of light and matter more closely.

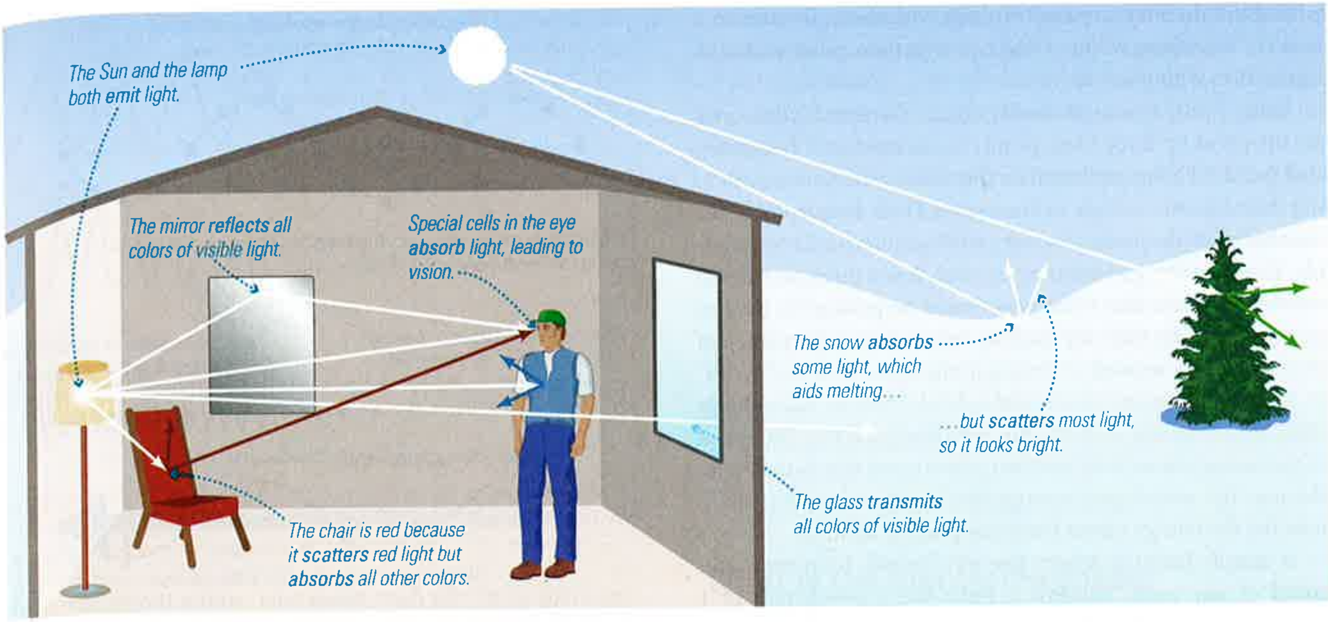


FIGURE 5.3 Interactive Figure This diagram shows examples of the four basic interactions between light and matter: emission, absorption, transmission, and reflection (or scattering).

5.2 PROPERTIES OF LIGHT

Light is familiar to all of us, but its nature remained a mystery for most of human history. Experiments performed by Isaac Newton in the 1660s provided the first real insights into the nature of light. It was already well known that passing light through a prism produced a rainbow of colors, but most people thought that the colors came from the prism rather than from the light itself. Newton proved that the colors came from the light by placing a second prism in front of the light of just one color, such as red, from the first prism. If the rainbow of color came from the prism itself, the second prism would have produced a rainbow just like the first. But it did not: When only red light entered the second prism, only red light emerged, proving that the color was a property of the light and not of the prism.

Newton's work tells us something about the nature of color, but it still does not tell us exactly what light *is*. In this section, we'll investigate modern understanding of the nature of light.

What is light?

Newton himself guessed that light is made up of countless tiny particles. However, other scientists soon conducted experiments that demonstrated that light behaves like waves. Thus began one of the most important debates in scientific history: Is light a wave or a particle? To understand this question, and our modern answer to it, we must first understand the differences between particles and waves.

Particles and Waves in Everyday Life Marbles, baseballs, and individual atoms and molecules are all examples of *particles*. A particle of matter can sit still or it can move from one place to another. If you throw a baseball at a wall, it moves from your hand to the wall.

Now think about what happens when you toss a pebble into a pond (Figure 5.4). The ripples moving out from the place where the pebble lands are *waves* consisting of *peaks*, where the water is higher than average, and *troughs*, where the water is lower than average. If you watch as the waves pass by a floating leaf, you'll see the leaf rise up with the peak and drop down with the trough, but the leaf itself does *not* travel across the pond's surface with the wave. This observation tells us that the particles (molecules) of water are moving up and down but are not moving outward with the waves. That is, the waves carry *energy* outward from the place where the pebble

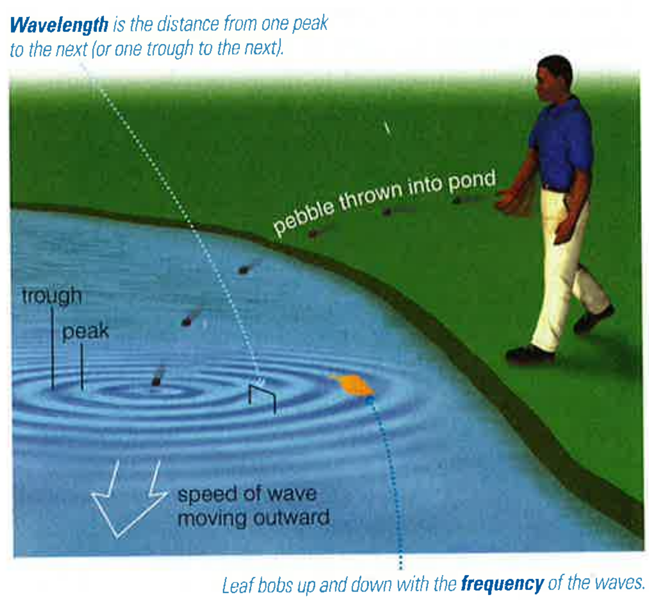


FIGURE 5.4 Interactive Figure Tossing a pebble into a pond generates waves. The waves carry energy outward, but matter does *not* travel outward. Matter, such as a floating leaf or the water itself, bobs up and down and sloshes back and forth as the waves pass by.

landed but do not carry matter along with them. In essence, a particle is a *thing*, while a wave is a *pattern* revealed by its interaction with particles.

For our purposes in this book, we can characterize the waves on the pond by three basic properties: wavelength, frequency, and speed.* Their **wavelength** is the distance from one peak to the next (or one trough to the next). Their **frequency** is the number of peaks passing by any point each second. For example, if we see the leaf bobbing up and down three times each second, we know that three peaks must be passing by the leaf each second. We then say that the waves have a frequency of three **cycles per second** (referring to the up-and-down "cycles" of the passing waves). Cycles per second often are called **hertz (Hz)**, so we can also describe this frequency as 3 Hz. The **speed** of the waves tells us how fast their peaks travel across the pond. Because the waves carry energy, the speed essentially tells us how fast the energy travels from one place to another.

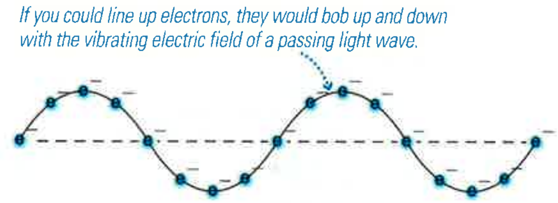
A simple formula relates the wavelength, frequency, and speed of any wave. Suppose a wave has a wavelength of 1 centimeter and a frequency of 3 hertz. The wavelength tells us that each time a peak passes by, the wave peak has traveled 1 centimeter. The frequency tells us that three peaks pass by each second. The speed of the wave must therefore be 3 centimeters per second. If you try a few more similar examples, you'll find the general rule

$$\text{wavelength} \times \text{frequency} = \text{speed}$$

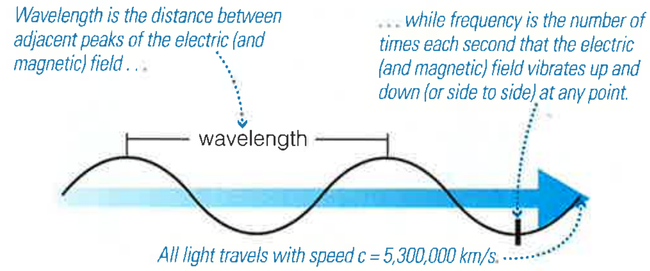
Light as an Electromagnetic Wave You've probably heard that light is a wave, but it isn't quite like the waves we see in everyday life. More familiar waves always move through some form of matter. For example, the waves on the pond move through the water, causing particles (molecules) of water to vibrate up and down and slosh back and forth, while sound waves move through air and cause air molecules to vibrate back and forth. The vibrations of matter allow the waves to transmit energy from one place to another, even though particles of matter do not travel along with the waves. In contrast to these everyday examples of waves, we do not see anything move up and down when light travels through space. So what, exactly, is "waving" when a light wave passes by?

The answer is what scientists call electric and magnetic fields. The concept of a **field** is a bit abstract. Fields associated with forces, such as electric and magnetic fields, describe the strength of the force that any particle would experience at any point in space. For example, the gravitational force that Earth exerts on an orbiting satellite depends on Earth's mass, the satellite's mass, and the distance of the satellite from Earth's center [Section 4.4]. We can therefore characterize the force that *any* object would experience at the satellite's distance by saying that Earth creates a *gravitational field* equal to the force on the satellite divided by the satellite's mass. In other words, Earth's gravitational field at any point

*A fourth characteristic of a wave is its *amplitude*, defined as half the height from trough to peak. Amplitude is related to the brightness of light, but we will not discuss it in this book.



a Electrons move when light passes by, showing that light carries a vibrating electric field.



b The vibrations of the electric field determine the wavelength and frequency of a light wave. Light also has a magnetic field (not shown) that vibrates perpendicular to the direction of the electric field vibrations.

FIGURE 5.5 Interactive Figure Light is an electromagnetic wave.

in space depends only on Earth's mass and the distance of that point from Earth's center. Likewise, we can describe the forces that charged particles exert on one another in terms of *electric fields* and *magnetic fields*.

Light waves are vibrations of both electric and magnetic fields caused by the motions of charged particles. We therefore say that light is an **electromagnetic wave**. Just as the ripples on a pond will cause a leaf to bob up and down, the vibrations of the electric field in an electromagnetic wave will cause an electron to bob up and down. If you could set up electrons in a row, they would wriggle like a snake as light passed by (Figure 5.5a). The distance between peaks in this row of electrons would tell us the wavelength of the light wave, while the number of times each electron bobs up and down would tell us the frequency (Figure 5.5b).

All light travels through empty space at the same speed—the **speed of light** (represented by the letter c), which is about 300,000 kilometers per second. Because the speed of any wave is its wavelength times its frequency, we find a very important relationship between wavelength and frequency for light: *The longer the wavelength, the lower the frequency, and vice versa.* For example, light waves with a wavelength of 1 centimeter must have half the frequency of light waves with a wavelength of $\frac{1}{2}$ centimeter and one-fourth the frequency of light waves with a wavelength of $\frac{1}{4}$ centimeter (Figure 5.6).

Photons: "Particles" of Light In everyday life, waves and particles appear distinctly different: No one would confuse the ripples on a pond with a baseball. However, experiments have shown that light behaves as *both* a wave and a particle. We therefore say that light comes in individual "pieces," called **photons**, that have properties of both particles and waves. Like baseballs, photons of light can be counted individually and can

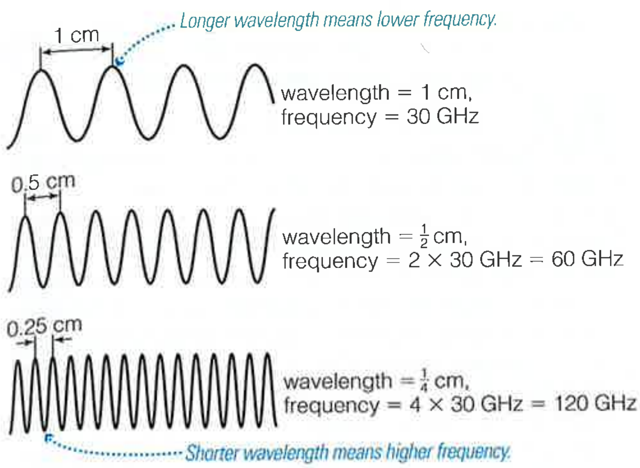


FIGURE 5.6 Because all light travels through space at the same speed, light of longer wavelength must have lower frequency, and vice versa. (GHz stands for gigahertz, or 10^9 hertz.)

hit a wall one at a time. Like waves, each photon is characterized by a wavelength and a frequency. The idea that light can be both a wave and a particle may seem quite strange, but it is fundamental to our modern understanding of physics. (We will discuss some of the implications of this wave-particle duality in Chapter S4.)

Just as a moving baseball carries a specific amount of kinetic energy, each photon of light carries a specific amount of radiative energy. The shorter the wavelength of the light (or, equivalently, the higher its frequency), the higher the energy of the photons.

To sum up, our modern understanding maintains that light is both a particle and a wave, an idea we describe by saying that light consists of individual photons characterized by wavelength, frequency, and energy. The wavelength, frequency, and energy are related in a very specific way because all photons travel through space at the same speed—the speed of light.

THINK ABOUT IT

If you assume that each of the three waves shown in Figure 5.6 represents a photon of light, which one has the most energy? Which one has the least energy? Explain.

What is the electromagnetic spectrum?

Newton's experiments proved that white light is actually a mix of all the colors in the rainbow. Later scientists found that there is light "beyond the rainbow" as well. Just as there are sounds that our ears cannot hear (such as the sound of a

SPECIAL TOPIC

What Do Polarized Sunglasses Have to Do with Astronomy?

If you go to the store to buy a pair of sunglasses, you'll face a dizzying array of choices. Sunglasses come in different styles, different tints, and with different efficiencies in blocking ultraviolet and infrared light. Most of these choices should at least make sense to you (well, perhaps not all of the styles), but one option may be less familiar: The labels on some sunglasses say that they are "polarized." What does this mean? The term comes from a property of light, called *polarization*, that has to do with the direction in which a light wave vibrates and how those vibrations change when light bounces off or passes through matter. Polarization turns out to be important not only to your sunglasses but also to astronomy.

It's easiest to understand the idea of polarization if you think about how waves move on a string when you shake one end of it. The string vibrates either up and down or back and forth while the wave itself moves along the string, perpendicular to the direction of vibration. Light waves move in a similar way, with the electric and magnetic fields vibrating either up and down or side to side compared with the direction of travel. For example, the wave shown in Figure 5.5b is moving to the right on the page while its electric field vibrates up and down on the page.

The direction of vibration affects the way light interacts with matter. As Figure 5.5a indicates, an electric field that vibrates up and down will make electrons move up and down as the wave passes by. Thus, the direction in which the electric field vibrates determines the direction in which charged particles will vibrate as the wave passes by. Because the direction of wave vibration matters, we give it a name: the *polarization* of the wave. In other words, an individual wave moving toward you can be polarized with its vibrations up and down or side to side, or some direction in between those two. (In all cases, the polarization is perpendicular to the direction of travel.)

We rarely notice polarization in everyday life because our eyes are not equipped to detect this property of light. Each of the light waves entering our eyes (or, more technically, each individual photon) has a certain direction of polarization. If all the waves taken together have no preferential direction of vibration, we say that the light is *unpolarized*. However, some physical processes can produce waves with a particular direction of polarization—which is where your sunglasses and astronomy come in.

When light reflects off a flat, horizontal surface like the ground or a lake, the surface tends to reflect light in which the electric field is vibrating along (parallel to) the surface and to transmit or absorb light with electric fields vibrating in other directions. As a result, the reflected light becomes polarized, with its electric field vibrating horizontally. Polarized sunglasses are designed to block out horizontally polarized light, which means they block the light reflected from horizontal surfaces—which is otherwise known as "glare." Of course, the polarized glasses work only if you are wearing them horizontally as well; if you turn a pair of polarized sunglasses so that the two lenses are no longer horizontal to the ground, they will not block glare effectively.

In astronomy, we aren't worried about glare from distant objects, but if we learn that a light source is producing polarized light, it tells us something about the nature of the source. For example, light that passes through clouds of interstellar dust tends to be polarized, telling us that the dust grains in the cloud must be preferentially absorbing light with electric fields vibrating in a particular direction. More detailed analysis has taught us that the polarization arises because the microscopic dust grains have an elongated shape and all tend to be aligned in the same way due to magnetic fields within the clouds. Polarization arises in many other astronomical contexts as well, including the study of the leftover radiation from the Big Bang. However, while polarization has provided important insights into many astronomical processes, its analysis can be fairly technical, and we will not discuss it further in this book.

dog whistle), there is light that our eyes cannot see. In fact, the spectrum of **visible light** that splits into the rainbow of color is only a tiny part of the complete range of light's wavelengths. Visible light differs from other forms of light only in the wavelength and frequency of the photons.

Because we sometimes describe light as an electromagnetic wave, the complete spectrum of light is usually called the **electromagnetic spectrum**. Light itself is often called **electromagnetic radiation.** Figure 5.7 shows the complete electromagnetic spectrum.

Notice that we give names to various portions of the electromagnetic spectrum. Visible light has wavelengths ranging from about 400 nanometers at the blue or violet end of the rainbow to about 700 nanometers at the red end. (A nanometer [nm] is a billionth of a meter.) Light with wavelengths somewhat longer than red light is called **infrared**, because it lies beyond the red end of the rainbow. **Radio waves** are the longest-wavelength light. That is, radio waves are a form of light, *not* a

COMMON MISCONCEPTIONS

Can You Hear Radio Waves?

Most people associate the term *radio* with sound, but radio waves are a form of *light* with long wavelengths—too long for our eyes to see. Radio stations encode sounds (such as voices and music) as electrical signals and broadcast the signals as radio waves. What we call "a radio" in daily life is an electronic device that receives these radio waves and decodes them to re-create the sounds played at the radio station. Televisions, cell phones, and other wireless devices also work by encoding and decoding information in the form of light called radio waves. Note that there's nothing special about encoding sounds with radio waves—any form of light could work in principle. Indeed, fiber-optic cables transmit sounds and data by encoding them with infrared or visible light. To summarize, we cannot actually hear radio waves; we hear only the decoded signals that they carry.

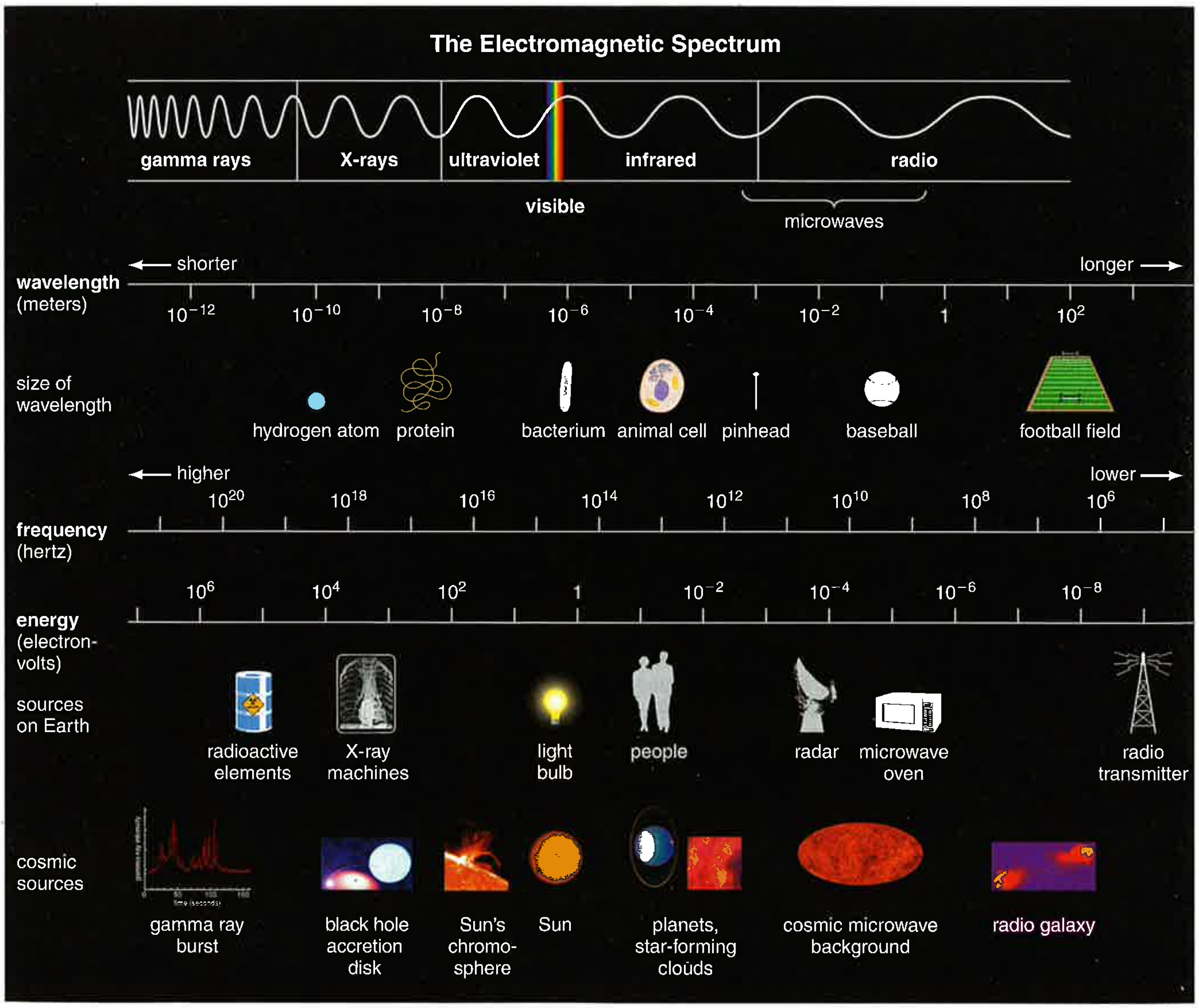


FIGURE 5.7 Interactive Figure The electromagnetic spectrum. Notice that wavelength increases as we go from gamma rays to radio waves, while frequency and energy increase in the opposite direction.

form of sound. The region near the border between infrared and radio waves, where wavelengths range from micrometers to millimeters, is sometimes given the name **microwaves.**

On the other side of the spectrum, light with wavelengths somewhat shorter than blue light is called **ultraviolet**, because it lies beyond the blue (or violet) end of the rainbow. Light with even shorter wavelengths is called **X rays**, and the shortest-wavelength light is called **gamma rays**. Notice that visible light is an extremely small part of the entire electromagnetic spectrum: The reddest red that our eyes can see has only about twice the wavelength of the bluest blue, but the radio waves from your favorite radio station are a billion times longer than the X rays used in a doctor's office.

The different energies of different forms of light explain many familiar effects in everyday life. Radio waves carry so little energy that they have no noticeable effect on our bodies. However, radio waves can make electrons move up and down in an antenna, which is how your car radio receives the radio waves coming from a radio station. Molecules moving around in a warm object emit infrared light, which is why we sometimes associate infrared light with heat. Receptors in our eyes respond to visible-light photons, making vision possible. Ultraviolet photons carry enough energy to harm cells in our skin, causing sunburn or skin cancer. X-ray photons have enough energy to penetrate through skin and muscle but can be blocked by bones or teeth. That is why doctors and dentists can see our bone structures on photographs taken with X-ray light.

Just as different colors of visible light may be absorbed or reflected differently by the objects we see (see Figure 5.3), the various portions of the electromagnetic spectrum may interact in very different ways with matter. For example, a brick wall is opaque to visible light but transmits radio waves, which is why radios and cell phones work inside buildings. Similarly, glass that is transparent to visible light may be opaque to ultraviolet light. In general, certain types of matter tend to interact more strongly with certain types of light, so each type of light carries different information about distant objects in the universe. That is why astronomers seek to observe light of all wavelengths, from radio waves to gamma rays [Section 6.4].

COMMON MISCONCEPTIONS

What Could You See with X-Ray Vision?

The idea of having "X-ray vision" that would allow you to see through walls is part of Hollywood culture and dates back to old Superman comics. But is it really possible? At first, the idea might seem reasonable; after all, you've probably seen a doctor or dentist holding up "X rays" that allow you to see your bones or teeth. However, the "X rays" that the doctor or dentist holds up are not a form of light; they are just pieces of film. The images of your bones and teeth are made with the help of a special machine that works somewhat like the flash on an ordinary camera but emits X rays instead of visible light. This machine flashes the X rays at you, and the X rays that are transmitted through your body are recorded on film or with an electronic detector. Thus, what you see is the image left by these X rays, not the X rays themselves, which have wavelengths far too short for human eyes. If you think about this process, you'll realize that X-ray vision would do you no good, even if it were possible. People, walls, and other ordinary objects do not emit any X rays of their own, so there'd be nothing to see with your X-ray vision.

COMMON MISCONCEPTIONS

Is Radiation Dangerous?

Many people associate the word *radiation* with danger. However, the word *radiate* simply means "to spread out from a center" (note the similarity between *radiation* and *radius* [of a circle]). Radiation is energy being carried through space. If energy is being carried by particles of matter, such as protons or neutrons, we call it *particle radiation*. If energy is being carried by light, we call it *electromagnetic radiation*.

High-energy forms of radiation, such as particles from radioactive materials or X rays, are dangerous because they can penetrate body tissues and cause cell damage. Low-energy forms of radiation, such as radio waves, are usually harmless. The visible-light radiation from the Sun is necessary to life on Earth. Thus, while some forms of radiation are dangerous, others are harmless or beneficial.

5.3 PROPERTIES OF MATTER

Light carries information about matter across the universe, but we are usually more interested in the matter the light is coming from than in the light itself. Planets, stars, and galaxies are made of matter, and we must understand the nature of matter if we are to decode the messages we receive in light.

What is the structure of matter?

Like the nature of light, the nature of matter remained mysterious for most of human history. Nevertheless, ancient philosophers came up with some ideas that are still with us today.

The ancient Greek philosopher Democritus (c. 470–380 B.C.) wondered what would happen if we broke a piece of matter, such as a rock, into ever smaller pieces. Democritus believed that the rock would eventually break into particles so small that nothing smaller could be possible. He called these particles *atoms*, a Greek term meaning "indivisible." Building upon the beliefs of earlier Greek philosophers, Democritus thought that all materials were composed of just four basic *elements:* fire, water, earth, and air. He proposed that the different properties of the elements could be explained by the physical characteristics of their atoms. For example, Democritus suggested that atoms of water were smooth and round, so water flowed and had no fixed shape, while burns were painful because atoms of fire were thorny. He also imagined atoms of earth to be rough and jagged, so that they could fit together like pieces of a three-dimensional jigsaw puzzle, and he used this idea to suggest that the universe began as a chaotic mix of atoms that slowly clumped together to form Earth.

Although Democritus was wrong about there being only four types of atoms and about their specific properties, he was on the right track. All ordinary matter is indeed composed of

atoms, and the properties of ordinary matter depend on the physical characteristics of their atoms. However, by modern definition, atoms are *not* indivisible because they are composed of even smaller particles.

Atoms come in different types, and each type corresponds to a different chemical **element.** Today, we have identified more than 100 chemical elements, and fire, water, earth, and air are *not* among them. Some of the most familiar chemical elements are hydrogen, helium, carbon, oxygen, silicon, iron, gold, silver, lead, and uranium. Appendix D gives the periodic table of all the elements.

Atomic Structure Each chemical element consists of a different type of atom, and atoms are in turn made of particles that we call **protons, neutrons,** and **electrons** (Figure 5.8). Protons and neutrons are found in the tiny **nucleus** at the

MATHEMATICAL INSIGHT 5.1

Wavelength, Frequency, and Energy

The speed of any wave is the product of its wavelength and its frequency. Because all forms of light travel at the same speed (in a vacuum) of $c = 3 \times 10^8$ m/s, we can write

$$\lambda \times f = c$$

where λ (the Greek letter *lambda*) stands for wavelength and f stands for frequency. This formula is simple but revealing: Because the speed c is constant, the formula tells us that frequency must go up when wavelength goes down, and vice versa.

The formula for the radiative energy (E) carried by a photon of light is

$$E = h \times f$$

where h is *Planck's constant* ($h = 6.626 \times 10^{-34}$ joule $\times$ s). Thus, energy increases in proportion to the frequency of the photon.

EXAMPLE 1: The numbers on a radio dial for FM radio stations are the frequencies of radio waves in megahertz (MHz), or millions of hertz. If your favorite radio station is "93.3 on your dial," it broadcasts radio waves with a frequency of 93.3 million cycles per second. What is the wavelength of these radio waves?

SOLUTION:

Step 1 Understand: Radio waves are a form of light, so we know they obey the relationship

$$\lambda \times f = c$$

The speed of light is always the same and we are given the frequency ($f = 93.3$ MHz), so we have all the information needed to solve for the wavelength (λ).

Step 2 Solve: We solve for wavelength by dividing both sides of the above equation by the frequency (f), finding

$$\lambda = \frac{c}{f}$$

Now we plug in the speed of light (3×10^8 m/s) and the frequency. Remember that 1 MHz = 10^6 Hz, so the frequency in this case is 93.3×10^6 Hz. Also remember that hertz (Hz) is an abbreviation for "cycles per second"; the "cycles" have no units, so the actual units of hertz are simply "per second," equivalent to 1/s. Thus, we find

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8 \frac{\text{m}}{\text{s}}}{93.3 \times 10^6 \frac{1}{\text{s}}} = 3.2 \text{ m}$$

Step 3 Explain: We have found that radio waves with a frequency of 93.3 MHz have a wavelength of 3.2 meters. That is why radio towers are so large—they need to be longer than the size of the waves they are transmitting.

EXAMPLE 2: The wavelength of green visible light (in the middle of the visible spectrum) is about 550 nanometers (1 nm $= 10^{-9}$ m). What is the frequency of this light?

SOLUTION:

Step 1 Understand: Again, we know that visible light obeys the relation $\lambda \times f = c$. This time we are given the wavelength ($\lambda = 550$ nm $= 550 \times 10^{-9}$ m), so we need to solve the equation for the frequency.

Step 2 Solve: We solve the equation ($\lambda \times f = c$) for frequency by dividing both sides by the wavelength (λ), which gives us

$$f = \frac{c}{\lambda}$$

Now we plug in the speed of light (3×10^8 m/s) and the wavelength ($\lambda = 550 \times 10^{-9}$ m) to find

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8 \frac{\text{m}}{\text{s}}}{550 \times 10^{-9}\text{m}} = 5.45 \times 10^{14} \frac{1}{\text{s}}$$

Step 3 Explain: Our answer is about 5.5×10^{14} 1/s; remembering that the units 1/s are called hertz, this answer is equivalent to 5.5×10^{14} Hz, or 550 trillion Hz. Thus, green visible light has a frequency of about 550 trillion Hz. Notice that this frequency is extremely high, which explains in part why it took so long for humans to realize that light behaves like a wave.

EXAMPLE 3: What is the energy of a visible-light photon with wavelength 550 nanometers?

SOLUTION:

Step 1 Understand: The energy of a photon is $E = h \times f$. We are given the photon's wavelength rather than frequency, so we use the result $f = c/\lambda$ from Example 2 to write a formula for calculating energy from wavelength:

$$E = h \times f = h \times \frac{c}{\lambda}$$

Step 2 Solve: We plug in the wavelength ($\lambda = 550 \times 10^{-9}$ m) and Planck's constant ($h = 6.626 \times 10^{-34}$ joule $\times$ s) to find

$$E = h \times \frac{c}{\lambda} = (6.626 \times 10^{-34} \text{ joule} \times \text{s}) \times \frac{3 \times 10^8 \frac{\text{m}}{\text{s}}}{550 \times 10^{-9} \text{ m}} = 3.6 \times 10^{-19} \text{ joule}$$

Step 3 Explain: The energy of a single visible-light photon is about 3.6×10^{-19} joule. Note that this energy for a single photon is extremely small compared to, say, the energy of 100 joules used each second by a 100-watt light bulb.