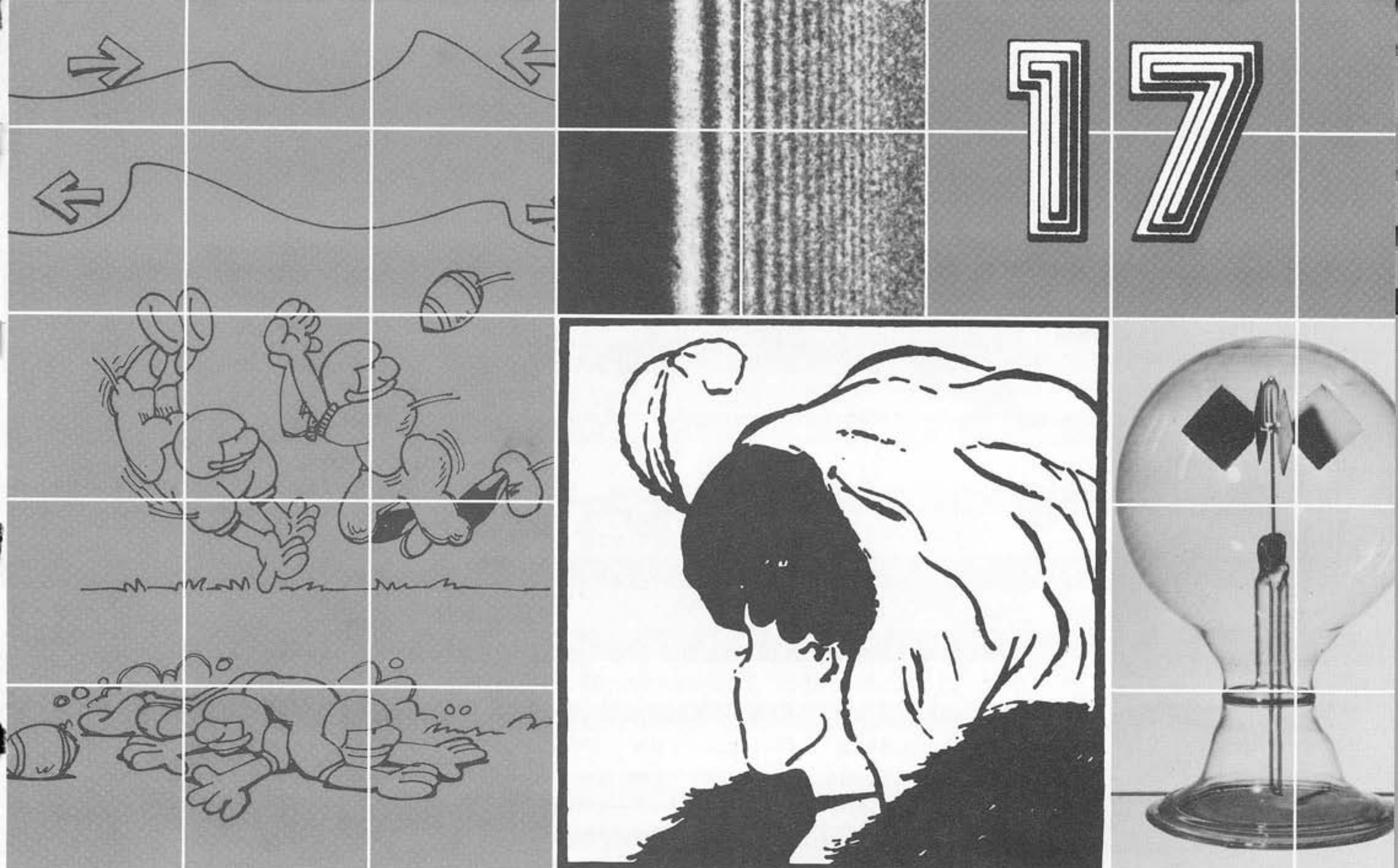


Figure 17-1 R. L. Gregory, The Intelligent Eye, 1970, McGraw Hill.

Wave-Particle Duality

Which do you see—the young lady or the old woman? Designed by an American psychologist, E. G. Boring, the sketch that opens this chapter illustrates a phenomenon called object ambiguity. We can perceive the same sketch to be two very different objects. The black band at her neck, the rear profile of her chin, the dainty eyelashes—all combine to produce an image of a beautiful young woman. Then, before our eyes, the image dissolves. The black band becomes a cruel mouth; the dainty chin turns into a hideous nose. We now see an ugly old woman. These two very different perceptions can emerge as we shift our gaze from one part of the sketch to another. They also emerge spontaneously as we keep our gaze fixed. Perceptions arise from the way we think about what we see as well as from what we actually see.

This chapter deals with an ambiguity in science—what we might call *model ambiguity.* Like the young woman and old hag in Boring's sketch, the wave model and the particle model provide us two very different perceptions of nature. Both models emerge from our attempts to explain how energy gets from one place to another. The particle model associates energy with mass. Energy is transferred from a source to a receiver during collisions—relatively

Figure 17-2
Wave disturbances pass through one another undisturbed; particles cannot!

abrupt events. By contrast, the wave model associates energy with the amplitude of a disturbance. The transfer of energy from source to receiver is more gradual and continuous. Phenomena can be categorized as behaving like particles or waves. When ambiguities arise, superposition phenomena such as interference and diffraction offer the critical test. Wave disturbances pass through one another undisturbed—particles cannot!

Early in this century, physicists began to realize the extent to which both models describe the same phenomena. Waves can be described as particles; particles, as waves. Diffraction and interference phenomena reveal a wavelike character in light, but the *photoelectric effect* shows light to have a particlelike character as well. Electrons have mass but can be diffracted like waves. All particles turn out to have a wavelike character described by *de Broglie wavelengths*. Nature reveals a *wave-particle duality*—an ambiguity uncharacteristic of science. While the meaning of this wave-particle duality remains a subject of intense debate, many physicists now accept the *Bohr complementarity principle*. The two models exclude one another, yet both are necessary for a complete description of nature.

THE PARTICLE NATURE OF WAVES

Early in the nineteenth century, Thomas Young and his contemporaries *appeared* to resolve the intense debate over whether light was a particle or a wave. The diffraction and interference effects were so striking and Young's mathematical explanation of the phenomena in terms of waves so compelling that few scientists challenged the conclusion that light is composed of waves. Ironically, just as the controversy was being resolved by diffraction and interference experiments, investigations into the photoelectric effect revealed a completely new facet of light. These experiments not only reopened the wave-particle controversy surrounding the nature of light; they eventually shook the very foundations of physics.

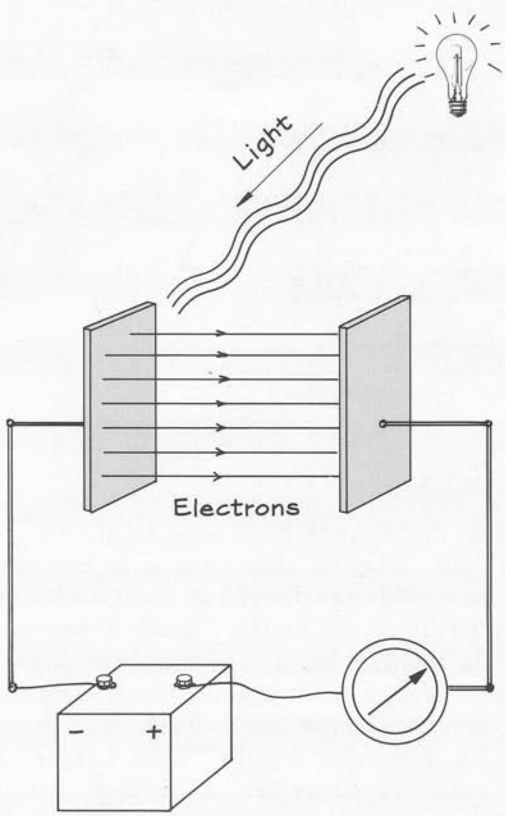


Figure 17-3
Two oppositely charged metal plates are placed inside an evacuated glass tube. When illuminated with visible light, the negative plate ejects electrons, which are then drawn across to the positively charged plate.

The Photoelectric Effect

During the latter part of the nineteenth century, a series of accidental discoveries showed that light could knock electrons loose from metal surfaces, a phenomenon called the **photoelectric effect.** These observations led to a series of controlled experiments similar to that illustrated in Figure 17-3. Two metal plates, one positively charged and the second negatively charged, were placed inside a glass tube. Light was directed toward the negative plate. Electrons ejected from the negative plate were attracted to the positive plate. A meter detected the motion of these electrons.

We can think about the photoelectric effect in terms of our two models, the particle model and the wave model. Light, the energy source, transfers the energy stored in its electromagnetic waves to electrons, the energy receivers. In turn, the electrons transform this wave energy into the electrical potential energy required to release them from the metal plate and the kinetic energy needed to move across to the positive plate. Light delivers wave energy; electrons transform it into particle energy. This hardly seems startling—wave energy is transformed into particle energy daily as the earth absorbs the thermal radiation transmitted to us from the sun. What is startling, however, is that the energy delivered by the light cannot be explained in terms of the wave model. To see why, let's examine what we expect to happen when we vary the intensity and frequency of the light source used to illuminate the metal plates.

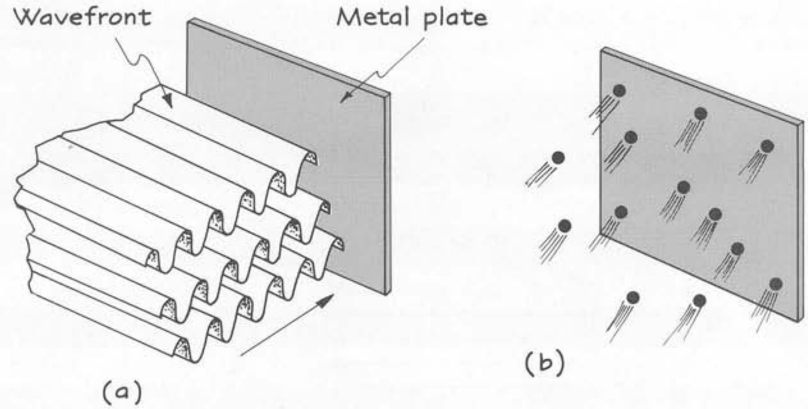


Figure 17-4

(a) When we think of light as an electromagnetic wave, its changing electric fields cause the electrons to vibrate. Some vibrate far enough to break free from the metal surface. **(b)** When we think of light as a particle, photons collide with individual electrons, knocking them free from the metal surface.

Light Waves Can't Do It

As you might expect, the interaction between a light wave and an electron is complex. Figure 17-4(a), however, shows one way of imagining what happens when light waves reach the metal surface. Light waves consist of vibrating electric and magnetic fields. As the light wave enters the metal, electrons (which are negatively charged) begin to vibrate in response to these changing electric and magnetic fields. The electrical bonds holding the electrons to their atoms are a little like rubber bands. Small vibrations do not enable the electron to escape—the rubber band always pulls it back. Larger vibrations, however, could eventually stretch the rubber band far enough that it breaks. The electron escapes from the atom with whatever energy is left over after the bond has been broken. This extra energy becomes the kinetic energy of the ejected electron.

We can use this model to predict what might happen if we vary the intensity (brightness) or frequency (color) of the light source. The intensity of the light source describes the amplitude of the individual waves. Dim light consists of waves with small amplitudes; bright light consists of waves with large amplitudes. We could imagine metal surfaces for which the amplitude of the waves in dim light is too small to break the electrical bonds holding the electrons. Increasing the intensity of this light should increase the vibration of the electrons, eventually to the point that the electrons break free. Increasing the intensity even further should increase the kinetic energy of the ejected electrons. On the other hand, the frequency of the light should have little effect on either the ejection of electrons or their kinetic energy. Changing the frequency of the light source simply changes the rate at which wave disturbances reach the metal surface. If the amplitudes of the waves are not sufficient to help the electrons break the bonds, changing the rate at which these waves reach the metal surface should not make much difference. Similarly, changing the frequency of the incident light should not affect the kinetic energy the ejected electrons have.

Much to the bewilderment of early experimenters, the ejection of electrons and the kinetic energy they had once ejected turned out to depend on the *frequency* of the incident light, not the intensity. The intensity of the light affected the number of electrons ejected but little else. Table 17-1 summarizes the results typical of experiments performed with cesium, sodium, and tungsten plates. At some frequencies of incident light, no electrons are ejected regardless of the intensity of light used. Tungsten, for example, will not eject electrons when illuminated with visible light. Only ultraviolet frequencies (10×10^{14} hertz (Hz)) work. Exposing cesium plates to red light (4.5×10^{14} Hz) has no effect, no matter how long or with what intensity of light you illuminate them. Orange light (5×10^{14} Hz) causes the immediate ejection of electrons. Each metal surface seems to require some minimum frequency of light before it ejects electrons. Once ejected, the electrons have kinetic energies that depend on the frequency, not the intensity, of the light used. At frequencies above the minimum frequency needed to eject the electrons, increasing the frequency of light increases the kinetic energy of the ejected electrons.

We cannot explain these results in terms of the wave model of light. The energy supplied to each electron depends on the frequency of the light, not the intensity. A wave picture like that in Figure 17-4(a) no longer gives us any way of picturing the transfer of energy from light to the electrons. Changing the intensity of the light and thus the amplitude of the waves does not have any effect until the right frequency of light is used. The electrons just seem to wait for the right frequency to come along. Once we have the minimum frequency for a given metal surface, increasing the intensity of the light still does not affect the energy of the ejected electrons. Individual electrons absorb energy associated only with the frequency of the light. The wave model, so beautifully demonstrated by interference and diffraction, so well accepted at the end of the last century, seems inadequate after all.

Packets of Energy

The results of the photoelectric experiments led Albert Einstein to propose that in its interaction with electrons, light could be best described as a stream of small particles, or "energy packets." Each packet, called a **photon,** acts as

Table 17-1 Results of Photoelectric Experiments*

Frequency of Incident Light (Hz)	Kinetic Energy of Released Electrons (J)		
	Cesium	Sodium	Tungsten
(Red) 4.5×10^{14}	None emitted	None emitted	None emitted
(Orange) 5.0×10^{14}	0.109×10^{-19}	None emitted	None emitted
(Green) 5.5×10^{14}	0.440×10^{-19}	0.120×10^{-19}	None emitted
(Blue) 6.0×10^{14}	0.772×10^{-19}	0.451×10^{-19}	None emitted

*These results are the same for all intensities of light illuminating the metal surface.

Energy of photon
Planck's constant
$E = hf$
Frequency

a unit when it interacts with an electron. Using an idea introduced originally by Max Planck, Einstein suggested that the energy carried by each photon is defined by:

$$\text{Energy} = (\text{Planck's constant}) \times (\text{frequency})$$

where Planck's constant is defined to be 6.63×10^{-34} joule · seconds (J · s). Planck's constant is a proportionality constant that converts frequencies in hertz to energies in joules. For example, the energy carried by a photon of orange light (frequency = 5.0×10^{14} Hz) is $(6.63 \times 10^{-34}\ \text{J} \cdot \text{s}) \times (5.0 \times 10^{14}\ \text{Hz})$, or 3.32×10^{-19} J. Higher frequencies of light have photons with larger energies.

SELF-CHECK 17A

Compared to a photon of orange light, how much energy is carried by 1 photon of green light? (The frequency of green light is 5.5×10^{14} Hz.)

Einstein's concept of the photon provides a solution to the problems posed by the photoelectric effect. Each photon acts as a unit when it interacts with matter. When a photon encounters an electron, it transfers all its energy to the electron and ceases to exist. By associating energy with frequency, the photon explains why electrons are ejected by light of one frequency but not of another. It also explains why the kinetic energy of the released electrons depends only on the frequency of the incident light. For example, the energy needed to remove an electron from a sodium atom is 3.52×10^{-19} J. As shown in an earlier example, a photon of orange light carries 3.32×10^{-19}J —not enough to free the electron. A photon of blue light, however, carries 3.97×10^{-19} J—more than enough to free the electron. The electron absorbs all the energy carried by the photon, uses 3.52×10^{-19} J to escape from the atom and has 0.45×10^{-19} J left over as kinetic energy. This matches the observations listed in Table 17-1.

The concept of the photon also explains how the intensity of the incident light is related to the number of electrons ejected by the metal surface. Einstein's picture of light is that it consists of a stream of photons. The greater the number of photons emitted by a light source is, the more intense the light appears. If we illuminate a metal surface with a frequency of light large enough to cause the emission of electrons, the number of electrons ejected depends on the number of photons striking the surface. More intense light means more photons strike the metal surface and thus more electrons are ejected. The total energy carried by light in a given time interval depends on the light intensity (number of photons per second) and the light frequency (energy carried per photon).

Einstein's solution to the problems posed by the photoelectric effect was based upon the concept of **quantization of energy,** which had been introduced a few years earlier by Max Planck. After studying the energy radiated by solids, Planck proposed that energy is not continuous. The energy emitted cannot be any value; it appears in chunks, or discrete quantities, called quanta. The photon is a light **quantum.** The energy carried by orange light, for example, appears in chunks of 3.32×10^{-19} J. When orange light with a frequency of 5.0×10^{14} Hz is absorbed by matter, the energy transferred is never some fraction of 3.32×10^{-19} J. It is always equal to some whole number times 3.32×10^{-19} J. Admittedly tiny, these quanta play an enormously important role in explaining phenomena like the photoelectric effect.

The idea that a quantity can be quantized is not new. We are familiar with many materials that appear continuous from a distance but are, in fact, built up of identical chunks. From a hundred yards or so, a brick wall looks rather continuous. But as you walk closer it becomes apparent that the wall is, in fact, made up of lots of discrete "quanta," called bricks. A piece of gold looks solid and continuous, but chemists will hasten to point out that it is built up from billions of identical "quanta" called atoms. The mass of the chunk of gold will be some whole number times the mass of an individual gold atom. Other quantities, like electrical charge, are also quantized. The concept that energy might be quantized is a little surprising but hardly impossible to accept. What is startling, however, is that something thought to be a wave, like light, transfers energy like particles.

Does it Really Work?

Step into the beam of light traveling across a closing elevator door; the door reopens. Hold the product code on a box of corn flakes in front of a small beam of light; the cash register adds the cost to your grocery bill. As the sun rises, the electric eye on a street lamp senses the coming daylight; the street lamp turns off. These and a variety of other devices take advantage of the photoelectric effect and, in so doing, assure us that photons are real.

Figure 17-5
Photoelectric cells, often called *electric eyes,* can be found in a variety of everyday devices.

Sometimes called an electric eye, the device used in elevator doors and street lamps is a **photoelectric cell** (Figure 17-5). Two separated metal plates are placed inside a glass tube. When light strikes the negative plate, electrons are released and attracted to the positive plate. The motion of the electrons can then act as a switch, turning the device on or off. In automatic doors, a light source is placed directly across from the photoelectric cell. As long as light strikes the photoelectric cell, the door remains closed. Once you step between the light source and the photoelectric cell, the motion of electrons in the cell stops and the door is opened. In street lamps, the photoelectric cell is used to detect sunlight. When daylight strikes the photoelectric cell, the street lights turn off. When night falls and no light strikes the cells, the street lights turn on.

Photoelectric cells have proven enormously useful in coding and decoding information. In laser-operated cash registers, for example, laser light is absorbed by the series of black lines that make up the universal product code

(UPC) found on most grocery store products (Figure 17-6). A photoelectric cell detects the pattern of absorbed and reflected light, converting it into a pattern of electrical signals, which operate the cash register and change inventory records. Many libraries use similar systems to maintain lender records and book inventories.

Figure 17-6
In laser-operated cash registers, a photoelectric cell is used to detect the pattern of light reflected from the universal product code.

SELF-CHECK 17B

Most photoelectric cells in street lamps and automatic doors respond to ordinary sunlight, which has an average frequency of 5.5×10^{14} Hz. Of the three metals listed in Table 17-1, which would be the most convenient to use? Why? Which metal could not be used for these applications? Why?

Seeing with Photons

Visual information, what we see and how we interpret it, reaches us in the form of light. Many aspects of vision, such as the need for corrective lenses, can be described best in terms of the wave model of light. Others are best treated with the particle nature of light. Two of the more interesting questions posed by those investigating the quantum nature of vision are:

> What is the minimum number of photons needed before we see any light?
>
> How many photons must be reflected from an object in order for us to recognize it?

These two questions have been the subject of extensive research.

To learn about the minimum number of photons required before a person sees any light, researchers asked subjects to sit in totally dark rooms until their eyes were completely adapted to the dark. (In one experiment the subjects sat in a totally dark room with their heads held in a fixed position for 45 minutes before the experiment began.) Then, flashes of light were emitted at very low intensities. The intensity was gradually increased until the subjects first reported that they saw the light. The energy and frequency of the light emitted was then recorded. As you might expect, the results of the experiment varied from one person to the next. At a frequency of 5.9×10^{14} Hz, people reported seeing light at energies that ranged from 3×10^{-17} J to 6×10^{-17} J.

In order to determine the number of photons emitted with each flash of light, experimenters used the relationship between energy and frequency, $E = hf$. To illustrate the process they used, we assume that the light used in the experiment had a frequency of 5.9×10^{14} Hz. At this frequency, each photon has an energy of:

$$\begin{aligned} \text{Energy} &= (\text{Planck's constant}) \times \text{frequency} \\ &= (6.63 \times 10^{-34}\ \text{J} \cdot \text{s})(5.9 \times 10^{14}\ \text{Hz}) \\ &= 3.9 \times 10^{-19}\ \text{J} \end{aligned}$$

If the average person reported seeing light at an energy of 4×10^{-17} J, we can determine the number of photons present by dividing the total amount of energy by the energy/photon:

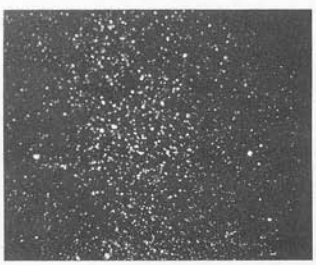
$$\text{Number of photons} = \frac{4 \times 10^{-17}\text{ J}}{3.9 \times 10^{-19}\text{ J/photon}}$$

$$= 102$$

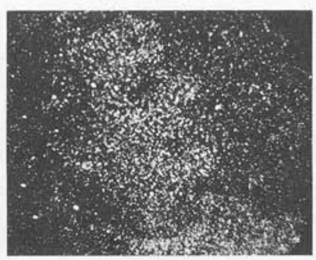
We can conclude that, on the average, about 102 photons are emitted by the lamp when the average person first reports seeing the flash. While the experimenters were careful to be sure that all these photons struck the eye, not all of them actually reached the retina. Some photons were reflected by the front of the eye; others were absorbed by the liquid in the eye. When these and other effects were taken into account, researchers concluded that some people can see light when as few as 2-5 photons strike the retina.

While 2-5 photons enable us to see light, they are not sufficient for us to identify the object emitting or reflecting them. To determine the number of photons needed to convey visual information about an object, Albert Rose, a researcher in vision, prepared the photographs shown. Each represents a photograph of the same object but with different numbers of photons present. As you would expect, the amount of information conveyed increases as more photons are used. How many photons do you need to see that the image is a face? That it is a woman's face?

Vision seems a remarkable gift—regardless of the model of light with which you investigate it. The incredibly small number of photons needed to initiate vision and the enormously large number of photons we process with each meaningful image speak eloquently of the sensitivity and intricacy of the human eye.



(a) 3,000



(b) 12,000

(c) 93,000

(d) 760,000

(e) 3,600,000

(f) 28,000,000

Albert Rose, Vision: Human and Electronic. Plenum Press (1973).

WAVE NATURE OF MATTER

Einstein's quantum picture of light is compelling, yet paradoxical. It presents a solution to the problems posed by the photoelectric effect, yet it simultaneously contradicts the wave model of light. The photoelectric effect tells us that in interactions with electrons, light energy is carried in discrete bundles called photons. Interference and diffraction phenomena tell us that in interactions with itself, light energy is spread continuously across space in the form of waves. Light seems to have a dual nature—particlelike in some situations, wavelike in others.

De Broglie Wavelengths

The discovery of the particlelike character of light waves led some physicists to wonder if particles might, under certain circumstances, display a wavelike character. Based strictly on an intuitive belief in the symmetry of nature, Louis de Broglie proposed that particles have a wavelength associated with their momentum. Called the **de Broglie wavelength,** this wavelength is defined as:

de Broglie wavelength

Planck's constant

$$\lambda = \frac{h}{mv}$$

Velocity of particle

Mass of particle

$$\text{de Broglie wavelength} = \frac{\text{Planck's constant}}{\text{momentum of particle}}$$

Using Planck's constant (h) as 6.63×10^{-34} J · s, mass in kilograms (kg), and speed in meters per second (m/s), the de Broglie wavelength is given in meters (m).

The size of the de Broglie wavelength associated with a particle depends on its momentum. An automobile traveling down the highway has a momentum of about 25,000 kg · m/s and a de Broglie wavelength of 10^{-38} m. A person sitting in the automobile has a larger wavelength—10^{-37} m—but not much larger! A bullet traveling at a speed of 500 m/s has a smaller momentum, 5 kg · m/s, but its de Broglie wavelength is still too small to detect. Smoke particles drifting about have a de Broglie wavelength of about 10^{-23} m, still too small to notice. Only when we enter the world of the atom, do we begin to notice de Broglie wavelengths. A nitrogen molecule drifting about in space has a de Broglie wavelength of about 10^{-11} m. Electrons have longer wavelengths—10^{-10} m. The smaller the momentum of the particle is, the larger its de Broglie wavelength will be.

The size of Planck's constant reflects the fact that we do not notice the wavelike character of ordinary objects. Ordinary masses moving at ordinary speeds have de Broglie wavelengths of about 10^{-30} m, extraordinarily tiny. When we move into the submicroscopic world of the atom, however, the tiny masses associated with particles like electrons result in de Broglie wavelengths that we can detect. We notice the wavelike character of electrons, but not the wavelike character of automobiles. George Gamow's delightful stories (Activity D1) transport you to an imaginary world in which Planck's constant is a much larger number. The wavelike character of objects becomes part of the ordinary world, enabling us to imagine the reality found within the atom.

A STEP FURTHER—MATH

DE BROGLIE WAVELENGTHS

An automobile with a mass of 1000 kilograms moves at a speed of about 25 m/s. Its de Broglie wavelength is:

$$\lambda = \frac{h}{mv}$$
$$= \frac{6.63 \times 10^{-34}\ \text{J} \cdot \text{s}}{(1000\ \text{kg})(25\ \text{m/s})}$$
$$= 2.65 \times 10^{-38}\ \text{m}$$

This wavelength is shorter than any we are capable of detecting.

An electron with a mass of 10^{-30} kg moves at a speed of about 6×10^{6} m/s. Its de Broglie wavelength is:

$$\lambda = \frac{h}{mv}$$
$$= \frac{6.63 \times 10^{-34}\ \text{J} \cdot \text{s}}{(10^{-30}\ \text{kg})(6 \times 10^{6}\ \text{m/s})}$$
$$= 1.10 \times 10^{-10}\ \text{m}$$

This wavelength is about 0.001 that of visible light. We commonly detect wavelengths of this size.

The size of Planck's constant makes the de Broglie wavelengths associated with ordinary objects too small to notice. Only on the atomic scale do we begin to see the wave nature of matter.

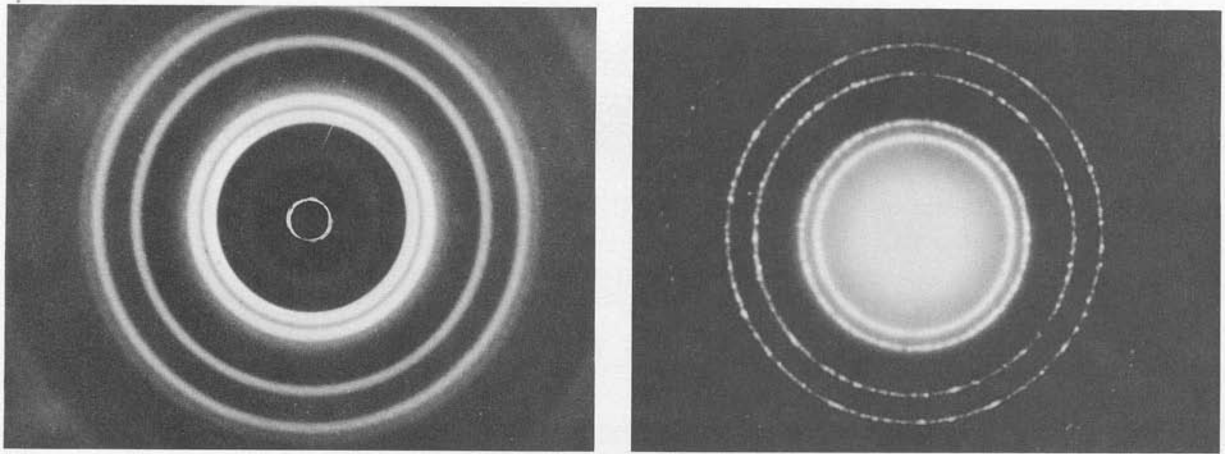
SELF-CHECK 17C

How does your de Broglie wavelength while walking at a speed of 2 m/s compare to the de Broglie wavelength of the automobile? Of the electron?

Electron Diffraction

De Broglie's concept that wavelengths can be associated with particles was originally based on a hunch. Before they could be accepted by the scientific community, these waves had to be detected. Electrons, for example, needed to demonstrate a wavelike behavior that could be explained only in terms of their de Broglie wavelengths. As you might expect, diffraction and interference phenomena provided the critical test.

As you saw in Chapter 16, interference and diffraction phenomena become noticeable only when waves pass through openings or around obstacles that are about the same size as the wavelength of the waves. Openings that are considerably larger than the wavelength of the waves simply cast ordinary



(a) (b)

Figure 17-7
(a) X rays produce a diffraction pattern after passing through a thin layer of aluminum foil. **(b)** Electrons produce a remarkably similar pattern when they pass through this same thin layer of foil.

shadows. The de Broglie wavelength associated with electrons is about 10^{-10} m, about the same size as X rays. Physicists expected that experimental arrangements that revealed diffraction and interference of X rays should reveal a similar behavior if moving electrons were used instead of X rays.

X rays are typically diffracted when they pass through thin layers of metal. The spacing between atoms in a solid metal is about the same distance as the wavelength of X rays. These spacings act like an array of slits that diffract the incident X rays, producing the pattern shown in Figure 17-7(a). If we repeat these experiments using electrons instead of X rays (Figure 17-7(b)), we see a pattern almost identical to that produced by the diffraction of X rays. Later experiments showed a resemblance between the patterns produced by electrons and those created by other wave phenomena. Electrons directed at the edge of a thin piece of magnesium oxide (Figure 17-8) produce a diffraction pattern similar to that created by visible light striking the edge of a barrier. The similarities are striking!

Once the de Broglie wavelengths associated with electrons had been detected, physicists eagerly turned to designing experiments that would enable them to observe diffraction and interference phenomena with other particles. In each case, de Broglie's relationship could be used to predict the wavelengths associated with particles of a certain size and speed. When barriers or obstacles could be created with these exceedingly small sizes, diffraction and interference effects were always observed. Protons and neutrons displayed exactly the same behavior. The de Broglie waves associated with particles are now commonly referred to as **matter waves.**

Electron Microscopes

Less than a decade after de Broglie proposed that particles have wavelengths associated with them, technology put electrons to work in building more powerful microscopes. In Chapter 16 we discussed the role that wave diffraction plays in limiting the resolution of the microscope. When the object being observed is about the same size as the wavelength of light, diffraction patterns blur the image. No matter how much you magnify an object, it will still be

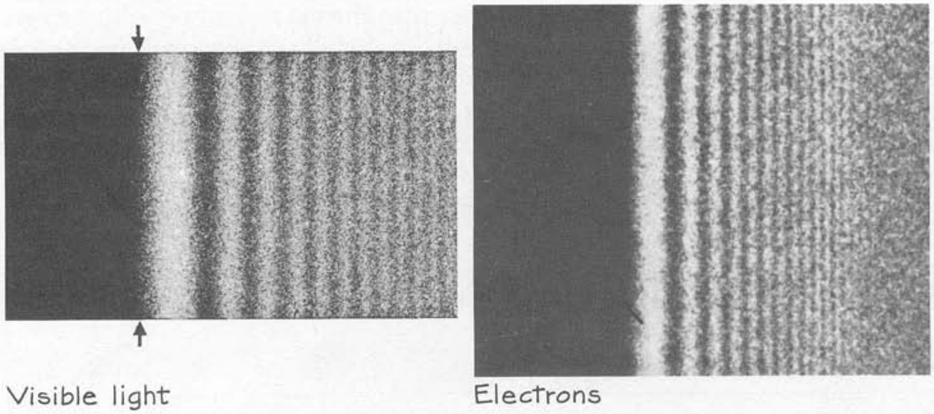


Figure 17-8
When they strike the edge of a barrier, electrons produce diffraction patterns similar to those observed with visible light.

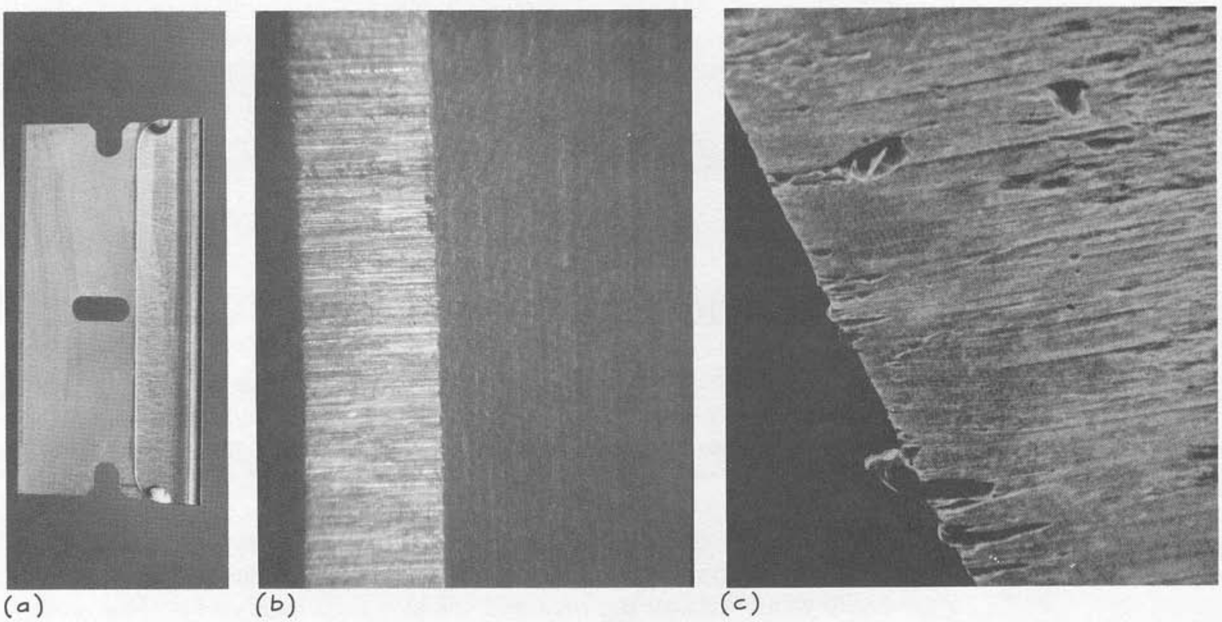


Figure 17-9
A razor blade viewed **(a)** through an ordinary eye, **(b)** through a light microscope, and **(c)** through an electron microscope. How straight is straight?

blurred. Structures smaller than the wavelength of visible light—10^{-7} m—cannot be resolved with conventional microscopes.

Electrons have much shorter wavelengths associated with them, typically about 10^{-10} m. Based strictly on a comparison of wavelengths, electron waves should be able to resolve structures that are a thousand times smaller than structures resolved with visible light. In practice, this turns out to be the case. A transmission electron microscope directs a beam of electrons toward a very thin specimen. The waves transmitted through the specimen are focused to form an image. Using electron waves, structures can be magnified more than 10,000 times their actual sizes. The major drawback seems to be the damage done to the specimen by the electrons. Live specimens often cannot be observed.

Figure 17-9 contrasts the images of a razor blade produced by a camera, a light microscope, and an electron microscope. Your eye is capable of resolving objects within 0.1 millimeter (mm) at a distance of 10 centimeters (cm).

While the image on film is slightly smaller than the actual razor blade, we can still resolve detail within about 0.1 mm. The width of the small line in (a) shows the region magnified by a light microscope and displayed in (b). A light microscope can often extend our abilities to resolve structures by a factor of 1000. Light microscopes can resolve structures separated by 10^{-7} m. Finally, the thick block in (b) shows the region magnified by a electron microscope and displayed in (c). An electron microscope, capable of resolving structures separated by 10^{-10} m, allows us an even closer glimpse of the razor blade. Our ability to resolve objects has been extended by yet another factor of 1000. If that's a new razor blade, think what an old one must look like!

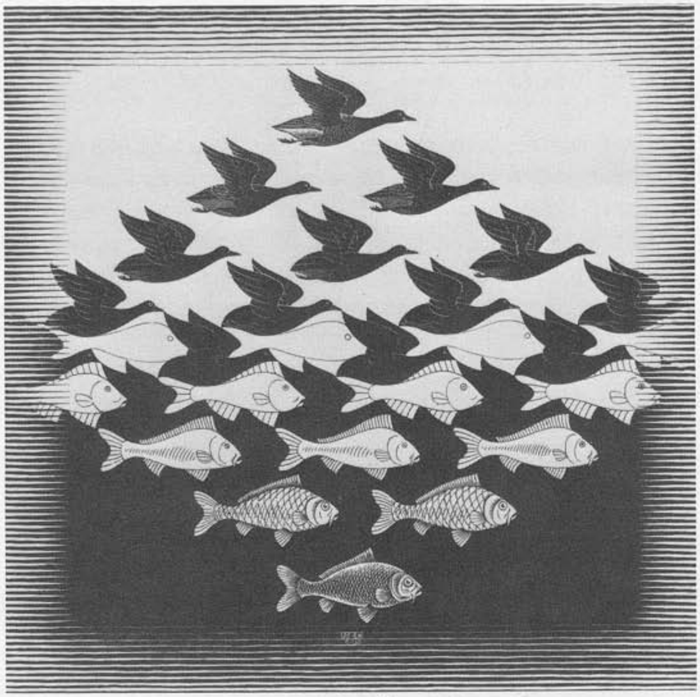
SELF-CHECK 17D

Neutrons are about 2000 times more massive than electrons. If neutrons moved at the same speed as electrons, would their de Broglie wavelengths enable us to resolve structures smaller than those resolved with the electron microscope? Why or why not?

WAVE-PARTICLE DUALITY

The particlelike character of light waves and the wavelike character of particles present a curious ambiguity. Prior to this century, physicists had come to classify energy transfer processes into two categories: particle and wave. Energy is transferred between particles when a discrete event—one particle colliding with another—occurs. Billiard balls transfer energy when they collide; bats transfer energy when they hit a baseball. Energy is transferred by waves in a more continuous fashion. Water waves continuously transfer energy, gradually wearing away the rock and soil along the land's edge. The realization that light demonstrates characteristics associated with both categories was startling. The realization that electrons—real particles with measurable masses—also demonstrate both kinds of characteristics seemed almost catastrophic. **Wave-particle duality** seemed the only answer.

Duality is unusual in science. While controversy is a common occurrence, physicists expect to be able to design experiments that can differentiate one model from another—to decide whether light is a wave or a particle. Conflicts are resolved so that one model replaces another. For the first time, conflicting models could not be resolved. When physicists performed diffraction and interference experiments, light behaved like a wave. When they performed experiments on the photoelectric effect, light behaved like a particle. What was worse was that electrons behaved in much the same way. In recounting the events of the 1920s, Jacob Bronowski reports that the physicists in Göttingen, a center for research on wave-particle duality, took to saying that on Mondays, Wednesdays, and Fridays electrons behaved like particles and on Tues-



M. C. Escher—Sky and Water II, 1938. Collection Haags Gemeentemuseum—The Hague, 1981. © BEELDRECHT, Amsterdam/V.A.G.A., New York.

Figure 17-10

One picture merges into the next. Wave and particle models offer complementary views of the microscopic world. Neither by itself is sufficient.

days, Thursdays, and Saturdays they behaved like waves (*The Ascent of Man.* 1973. Boston: Little, Brown and Company, p. 364).

In one sense, wave-particle duality arises from the way we think. The sketch that opened the chapter demonstrates the extent to which we impose our own order on the things we observe. Boring drew a series of lines on a piece of paper. When we look at the lines one way, we form an image of a beautiful young lady. When we look at the lines yet another way, we see an ugly old hag. Both images arise from the same set of lines. What we see is the order that we impose on those lines. A person from an alien culture might not see either the young lady or the old hag. In science, the images we see are the models we build to describe phenomena. Our everyday world of billiard balls, baseball bats, and water waves seems best ordered by two models—waves and particles. When we look into the microscopic world, we impose these models on entirely new phenomena. To our question of whether you are a particle or a wave, the microscopic world replies both!

Niels Bohr proposed a resolution to wave-particle duality called the **complementarity principle.** He suggested that the wave model and the particle model provide complementary pictures of reality. Neither provides a complete view of reality; each is needed to explain some of our experiences in the microscopic world. Asking whether microscopic objects are particles or waves is no longer a meaningful question. We use whichever model is required to explain a particular experiment. Like Escher's *Sky and Water* (Figure 17-10), reality reveals clear models for some phenomena and ambiguous models for others. We see fish in the sea and birds in the air. Where they meet, however, we see whichever we wish to see.

CHAPTER SUMMARY

Light incident on a metal surface causes the emission of electrons. This process, called the *photoelectric effect,* converts light energy into electron energy and is used extensively in photoelectric cells. In looking at the way in which energy was exchanged in this transfer process, physicists found some surprising results. Contrary to results predicted by the wave model of light, the amount of energy transferred to the electrons depends on the frequency as well as on the intensity of the light used. These observations led Albert Einstein to propose that the energy carried by light is transferred to electrons in discrete packets, called light quanta, or *photons.* The energy carried by each photon is defined by:

$$\text{Energy} = \text{Planck's constant} \times (\text{frequency})$$

Einstein's concept of the photon explained the results of the photoelectric effect but seemed to contradict the wave model of light established by diffraction and interference effects.

Since light waves behave like particles, physicists speculated that particles might also behave like waves. Experiments revealed that electrons transmitted through thin metallic foils produce diffraction patterns analogous to those produced by light passing through narrow slits. Particles appear to have wavelike characteristics. Their wavelength, called the *de Broglie wavelength,* is defined as:

$$\text{de Broglie wavelength} = \frac{\text{Planck's constant}}{\text{momentum of particle}}$$

The short wavelengths associated with electrons have proven useful in the design of electron microscopes capable of resolving structures as small as 10^{-10} m in size.

Wave-particle duality has led to fundamental questions regarding the models we build to explain our observations. In his *complementarity principle,* Niels Bohr suggested that the wave and particle models of reality provide complementary pictures of nature. Both are needed; neither can describe the microscopic world without the other.

ANSWERS TO SELF-CHECKS

17A. Green light has a higher frequency than orange light. One photon of green light will carry more energy than one photon of orange light: $E = hf = (6.63 \times 10^{-34}\ \text{J} \cdot \text{s})(5.5 \times 10^{14}\ \text{Hz}) = 3.65 \times 10^{-19}\ \text{J}$.

17B. Cesium would be the most convenient metal to use because it emits photoelectrons over the broadest range of visible frequencies. Tungsten does not emit any photoelectrons when illuminated with visible light. It would be useless in these applications.

17C. The mass of an average person is about 80 kg. At an average walking speed of 2 m/s, a person's momentum would be 160 kg · m/s. $E = h/mv = (6.63 \times 10^{-34}\ \text{J} \cdot \text{s})/(80\ \text{kg})(2\ \text{m/s}) = 4.1 \times 10^{-36}\ \text{m}$. The de Broglie wavelength associated with a person walking is longer than that associated with an automobile but much shorter than that associated with an electron.

17D. With a mass 2000 times greater, neutrons will have a momentum 2000 times larger than the electrons. The larger the momentum of a particle is, the smaller is its de Broglie wavelength. Neutrons should enable us to resolve still smaller structures.

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Define each of the following terms:

Photoelectric effect
Photon
Quantum
Matter waves
Photoelectric cell
de Broglie wavelength
Bohr complementarity principle

A2. If light energy is transferred by waves, what variables should we expect to increase the energy supplied to the electrons in the photoelectric effect?

A3. In measurements conducted with the photoelectric effect what variable(s) affected: (a) the number of electrons ejected, (b) the kinetic energy of the electrons once released, and (c) whether the metal surface would or would not release electrons?

A4. How did Einstein's concept of the quantum explain the measurements described in Problem A3?

A5. How does the energy of an individual photon change when the frequency of light increases?

A6. Describe how a photoelectric cell is used in a street lamp.

A7. What led Louis de Broglie to propose that particles had wavelike characteristics associated with them?

A8. How does the de Broglie wavelength associated with a particle change as the particle's momentum increases?

A9. Why do we not notice the wavelike character of baseballs and automobiles?

A10. What experiments did physicists conduct to detect the wavelike character of particles proposed by de Broglie? Why were those experiments selected?

A11. How is wave-particle duality analogous to the object ambiguity described at the beginning of the chapter?

B. Using the Chapter Material

B1. Light with a frequency of 5.8×10^{14} Hz strikes metal surfaces made from each of the three metals listed in Table 17-1. Which surface(s) will emit electrons?

B2. Orange light (5.0×10^{14} Hz) causes cesium surfaces to emit electrons with kinetic energies of 0.109×10^{-19} J. Green light (5.5×10^{14} Hz) causes the electrons to be emitted with kinetic energies of 0.440×10^{-19} J.

a. What is the change in kinetic energy that results when we use green light instead of orange light?
b. Does the same change occur if we use blue light (6.0×10^{14} Hz) instead of green light?
c. Predict the kinetic energy of electrons ejected when cesium plates are illuminated by violet light (6.4×10^{14} Hz).

B3. Calculate the energy associated with a single quantum for each of the following kinds of electromagnetic waves.

Type of Electromagnetic Wave	*Frequency (Hz)*
Radio	10^{6}
Television	10^{8}
Microwave	10^{10}
Infrared	10^{13}
Ultraviolet	10^{16}
X ray	10^{18}

B4. Blue light (6.0×10^{14} Hz) and red light (4.0×10^{14} Hz) are both incident on a sodium plate. If 3.52×10^{-19} J are required to free the electron, determine the kinetic energy of the electron after it interacts with (a) a photon of blue light, (b) a photon of red light.

B5. Two light sources, A and B, emit light of identical frequencies but different intensities. A is more intense than B.
   a. Assuming that the light has sufficient energy to release electrons from the metal plate, which will cause the release of more electrons?
   b. Which source causes the release of electrons with more kinetic energy?

B6. Calculate the de Broglie wavelength associated with each of the following objects moving at a speed of 10 m/s. How does the mass of an object affect its de Broglie wavelength?

Object	*Mass*
Electron	10^{-30} kg
Proton	10^{-27} kg
Gold atom	10^{-25} kg
Glass of water	0.5 kg
Person	100 kg
Automobile	1000 kg

B7. What is the de Broglie wavelength associated with the gold atom in Problem B6 when it moves at a speed of 1 m/s? 100 m/s? 1000 m/s? 10^6 m/s? 10^8 m/s? How does an object's speed affect its de Broglie wavelength?

B8. The de Broglie wavelength of electrons (10^{-10} m) is considerably shorter than wavelengths of visible light (10^{-7} m). How would a diffraction pattern produced by visible light compare to that shown in Figure 17-7b?

C. Extensions to New Situations

C1. Some smoke alarms use photoelectric cells with light sources placed directly across from them. As long as light strikes the cell, the alarm will not sound. When no light reaches the cell, the alarm sounds.
   a. How does this arrangement allow the alarm to detect smoke?
   b. Do you need to worry about the light source burning out and making the smoke alarm ineffective?

C2. We often hear that certain types of electromagnetic radiation cause more serious damage to human tissue than others. This damage is a result of the energy transferred to the tissue. Use the results of Problem B3 to explain why each of the following is true.
   a. X rays and gamma rays are said to be the most dangerous forms of radiation.
   b. Ultraviolet radiation causes sunburn, while visible and infrared radiation does not.

C3. Electrons in metal surfaces must receive a characteristic amount of energy, called the *work function*, before they have enough energy to leave the metal. The work function is the same for all metal plates made of the same metal. We can use the data supplied in Table 17-1 to determine the work function for cesium and sodium plates.
   a. How much energy does a single photon of orange light (5.0×10^{14} Hz) supply to a cesium plate?
   b. If an electron released from the cesium plate had a kinetic energy of 0.109×10^{-19} J, how much of the energy supplied by a photon of orange light went into releasing the electron?
   c. Repeat (a) and (b) for the data given for green and blue light. What is the work function for cesium?
   d. Determine the work function for sodium.

C4. In photochemical reactions light absorbed by a molecule initiates a chemical reaction. Two of the more common reactions occur when light strikes photographic film or a green leaf.
   a. Photographic paper and photographic film involve similar photochemical reactions. However, film must be processed in total darkness, while paper can be processed in red light. What does this tell you about the amounts of energy required to initiate the photochemical reactions in each case?
   b. Two distinct frequencies initiate the photochemical reactions involved in photosynthesis. One lies in the red portion of the visible spectrum. The second lies in

the blue portion. Which reaction requires more energy?

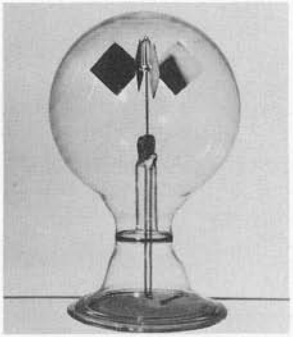
C5. Plants convert carbon dioxide to oxygen when the leaves absorb red light (4×10^{14} Hz).
 a. What is the energy associated with a single photon of this light?
 b. A total of 8×10^{-19} J are required to convert a single molecule of carbon dioxide into a molecule of oxygen. What is the minimum number of photons needed to supply this amount of energy?
 c. Measurements show that 10 photons are actually required to initiate the reaction. What is the efficiency of the reaction?

C6. The momentum associated with a photon can be calculated by rearranging de Broglie's relationship:

$$\text{Momentum of photon} = \frac{\text{(Planck's constant)}}{\text{wavelength}}$$

 a. What is the momentum of a photon of light that has a wavelength of 7×10^{-7} m?
 b. Suppose the photon in (a) is directed toward a stationary metal plate. What is the total momentum of the photon-metal plate system before the collision?
 c. What must be the total momentum of the system after the collision?
 d. Suppose the photon is absorbed by the metal plate. Describe the motion of the plate after the collision.
 e. Suppose the photon is reflected by the metal plate. Describe the motion of the plate after the collision.
 f. Will the momentum of the plate in (d) be higher or lower than that in (e)?
 g. A piece of metal with one side painted black, so light is absorbed, and the other side painted white, so light is reflected, has equal light shining on both sides. Which way will it move? (The toy shown in the next column does exist, but it moves in the opposite direction because of air currents.)

C7. Electron microscopes enable us to look more closely at matter than any visible



light microscope. Typically, electrons are directed toward the specimen at a speed of 1×10^8 m/s.
 a. What is the wavelength associated with each electron?
 b. Why does this wavelength allow us to see smaller objects than light microscopes?

C8. Planck's constant plays an important role in determining the situations in which we notice the particlelike characteristics of light and the wavelike characteristics of matter.
 a. $E = hf$ describes the size of the "chunks" of energy carried by waves. What would happen to these chunks if Planck's constant were a larger number?
 b. $\lambda = h/mv$ describes the wavelengths associated with matter. What would happen to these wavelengths if Planck's constant were a larger number?

D. Activities

D1. In *Mr. Tompkins in Paperback* (Cambridge University Press, 1969), George Gamow gives us the opportunity to imagine what life would be like if Planck's constant were a larger value. Read Chapter 7, "Quantum Billiards," and Chapter 8, "Quantum Jungle," of this delightful book.

D2. Obtain some pieces of transparent plastic that are different colors, such as red, green, and blue. Place each in front of the light source for a photoelectric cell of an elevator. How does each affect the operation of the door?