Pearson

2.2: The Nature of Light

Key Concept Video The Nature of Light

Before we explore electrons and their behavior within the atom, we must understand some of the properties of light. As quantum-mechanical theory was developed, light was (surprisingly) found to have many characteristics in common with electrons. Chief among these characteristics is the *wave–particle duality* of light. Certain properties of light are best described by thinking of it as a wave, while other properties are best described by thinking of it as a particle. In this section, we first explore the wave behavior of light, and then its particle behavior. We then turn to electrons to see how they display the same wave–particle duality.

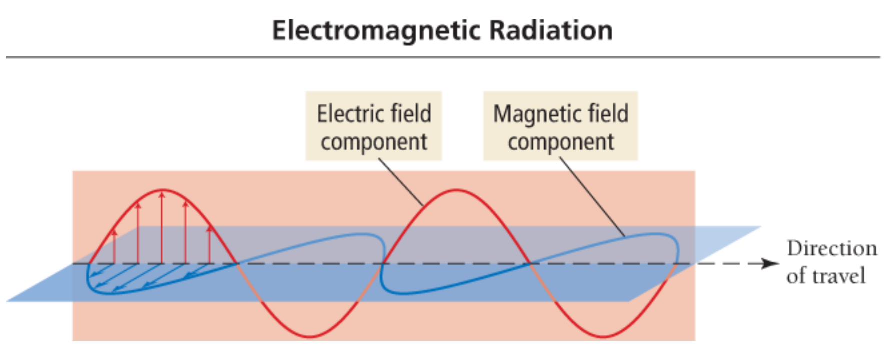
The Wave Nature of Light

Light is **electromagnetic radiation**, a type of energy embodied in oscillating electric and magnetic fields. A *magnetic field* is a region of space where a magnetic particle experiences a force (think of the space around a magnet). An *electric field* is a region of space where an electrically charged particle experiences a force. A proton, for example, has an electric field around it. If you bring another charged particle into that field, that particle experiences a force.

Electromagnetic radiation can be described as a wave composed of oscillating, mutually perpendicular electric and magnetic fields propagating through space, as shown in Figure 2.1. In a vacuum, these waves move at a constant speed of 3.00×10^8 m/s (186,000 mi/s)fast enough to circle the Earth in one-seventh of a second. This great speed is the reason for the delay between the moment when you see a firework in the sky and the moment when you hear the sound of its explosion. The light from the exploding firework reaches your eye almost instantaneously. The sound, traveling much more slowly (340 m/s), takes longer. The same thing happens in a thunderstorm—you see the flash of lightning immediately, but the sound of thunder takes a few seconds to reach you. (The sound of thunder is delayed by five seconds for each mile between you and its origin.)

Figure 2.1 Electromagnetic Radiation

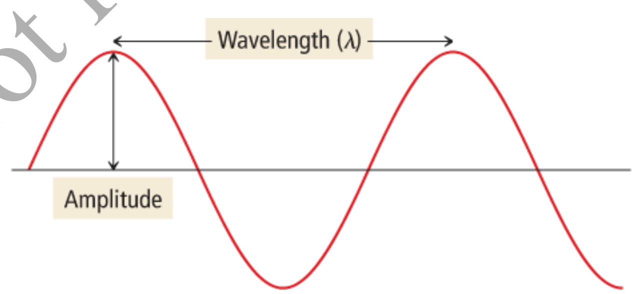
Electromagnetic radiation can be described as a wave composed of oscillating electric and magnetic fields. The fields oscillate in perpendicular planes.



Because light travels nearly a million times faster than sound, the flash of lightning reaches your eyes before the roll of thunder reaches your ears.

We can characterize a wave by its *amplitude* and its *wavelength*. In the graphical representation shown here, the **amplitude** of the wave is the vertical height of a crest (or depth of a trough). The amplitude of the electric and magnetic field waves in light determines the light's *intensity* or brightness—the greater the amplitude, the greater the intensity. The **wavelength (λ)** of the wave is the distance between adjacent crests (or any two analogous points) and is measured in units such as meters, micrometers, or nanometers.

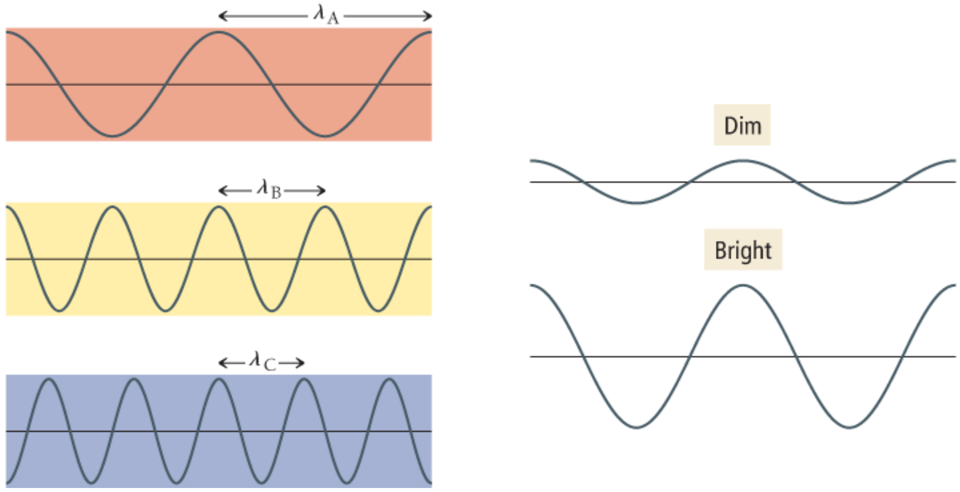
> The symbol λ is the Greek letter lambda, pronounced "lamb-duh."



The wavelength of a light wave determines its color (Figure 2.2).

Figure 2.2 Wavelength and Amplitude

Wavelength and amplitude are independent properties. The wavelength of light determines its color. The amplitude, or intensity, determines its brightness.



Like all waves, light is also characterized by its **frequency (ν)**, the number of cycles (or wave crests) that pass through a stationary point in a given period of time. The units of frequency are cycles per second (cycle/s) or simply s^{-1}. An equivalent unit of frequency is the hertz (Hz), defined as 1 cycle/s. The frequency of a wave is directly proportional to the speed at which the wave is traveling—the faster the wave, the more crests will pass a fixed location per unit time. Frequency is also *inversely* proportional to the wavelength (λ)—the farther apart the crests, the fewer will pass a fixed location per unit time. For light, therefore, we can write:

[2.1]

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

where the speed of light, c, and the wavelength, λ, are both expressed in terms of the same unit of distance. Wavelength and frequency represent different ways of specifying the same information—if we know one, we can calculate the other.

> The symbol ν is the Greek letter nu, pronounced “noo.”

The different colors in *visible light*—light that can be seen by the human eye—correspond to different wavelengths (or frequencies). White light, produced by the sun or by a light bulb, contains a spectrum of wavelengths and therefore a spectrum of colors. We see these colors—red, orange, yellow, green, blue, indigo, and violet—in a rainbow or when white light is passed through a prism (Figure 2.3). Red light, with a wavelength of about 750 nanometers (nm), has the longest wavelength of visible light; violet light, with a wavelength of about 400 nm, has the shortest. (Recall that nano means 10^{-9}.) The presence of a variety of wavelengths in white light is responsible for the way we perceive colors in objects. When a substance absorbs some colors while reflecting others, it appears colored. For example, a red shirt appears red because it reflects predominantly red light while absorbing most other colors (Figure 2.4). Our eyes see only the reflected light, making the shirt appear red.

Figure 2.3 Components of White Light

We can pass white light through a prism and decompose it into its constituent colors, each with a different wavelength. The array of colors makes up the spectrum of visible light.

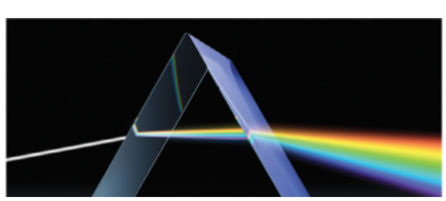


Figure 2.4 The Color of an Object

Example 2.1 Wavelength and Frequency

Calculate the wavelength (in nm) of the red light emitted by a barcode scanner that has a frequency of $4.62 \times 10^{14}\ \mathrm{s}^{-1}$.

SOLUTION

You are given the frequency of the light and asked to find its wavelength. Use Equation 2.1, which relates frequency to wavelength. You can convert the wavelength from meters to nanometers by using the conversion factor between the two $(1\ \mathrm{nm} = 10^{-9}\ \mathrm{m})$.

$$
\begin{aligned}
\nu &= \frac{c}{\lambda} \\
\lambda &= \frac{c}{\nu} = \frac{3.00 \times 10^{8}\ \mathrm{m}/\cancel{\mathrm{s}}}{4.62 \times 10^{14}\ /\cancel{\mathrm{s}}} \\
&= 6.49 \times 10^{-7}\ \mathrm{m} \\
&= 6.49 \times 10^{-7}\ \cancel{\mathrm{m}} \times \frac{1\ \mathrm{nm}}{10^{-9}\ \cancel{\mathrm{m}}} = 649\ \mathrm{mm}
\end{aligned}
$$

FOR PRACTICE 2.1 A laser dazzles the audience at a rock concert by emitting green light with a wavelength of 515 nm. Calculate the frequency of the light.

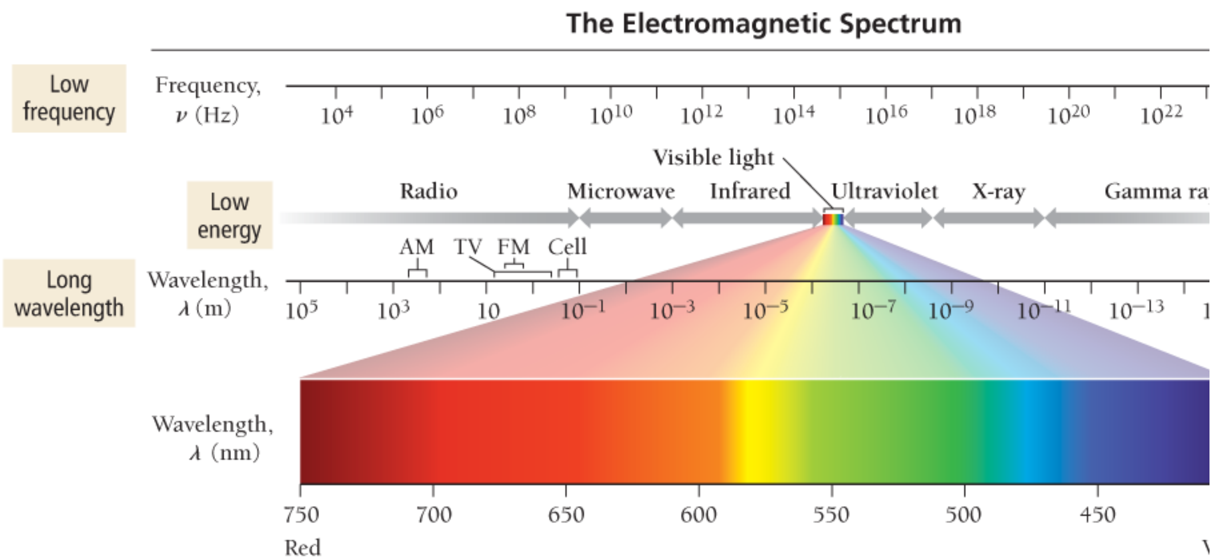
Answers to For Practice and For More Practice problems are found in Appendix IV.

The Electromagnetic Spectrum

Visible light makes up only a tiny portion of the entire **electromagnetic spectrum**, which includes all wavelengths of electromagnetic radiation. Figure 2.5 shows the main regions of the electromagnetic spectrum, ranging in wavelength from 10^{-15} m(gamma rays) to 10^{5} m(radio waves). Short-wavelength, high-frequency radiation is on the right, and long-wavelength, low-frequency radiation on the left. As you can see, visible light constitutes only a small region in the middle.

Figure 2.5 The Electromagnetic Spectrum

The right side of the spectrum consists of high-energy, high-frequency, short-wavelength radiation. The left side consists of low-energy, low-frequency, long-wavelength radiation.



We will discuss gamma rays in more detail in Chapter 20.

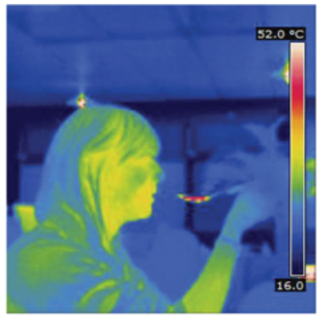
We will see later in this section that short-wavelength light inherently has greater energy than long-wavelength light. The most energetic forms of electromagnetic radiation have the shortest wavelengths. The form of electromagnetic radiation with the shortest wavelength is the **gamma (γ) ray**. Gamma rays are produced by the sun, other stars, and certain unstable atomic nuclei on Earth. Excessive exposure to gamma rays is dangerous to humans because the high energy of gamma rays can damage biological molecules.

The wavelengths of gamma rays and X-rays overlap a bit. Radiation produced by radioactive nuclei are often called gamma rays regardless of their wavelength.

Next on the electromagnetic spectrum, with longer wavelengths than gamma rays, are **X-rays**, familiar to us from their medical use. X-rays pass through many substances that block visible light and are therefore used to image bones and internal organs. Like gamma rays, X-rays are energetic enough to damage biological molecules. While several annual exposures to X-rays are relatively harmless, too much exposure to X-rays increases cancer risk.

Sandwiched between X-rays and visible light in the electromagnetic spectrum is **ultraviolet (UV) radiation**, most familiar to us as the component of sunlight that produces a sunburn or suntan. While not as energetic as gamma rays or X-rays, ultraviolet light still carries enough energy to damage biological molecules. Excessive exposure to ultraviolet light increases the risk of skin cancer and cataracts and causes premature wrinkling of the skin.

To produce a medical X-ray, the patient is exposed to short-wavelength electromagnetic radiation that passes through the skin to create an image of bones and internal organs.



Warm objects emit infrared light, which is invisible to the eye but can be captured on film or by detectors to produce an infrared photograph.

Next on the spectrum is **visible light**, ranging from violet (shorter wavelength, higher energy) to red (longer wavelength, lower energy). Visible light—at low to moderate intensity—does not carry enough energy to damage biological molecules. It does, however, cause certain molecules in our eyes to change their shape, sending a signal to our brains that results in our ability to see.

Beyond visible light lies **infrared (IR) radiation**. The heat you feel when you place your hand near a hot object is infrared radiation. All warm objects, including human bodies, emit infrared light. Although infrared light is invisible to our eyes, infrared sensors can detect it and are often employed in night vision technology to help people "see" in the dark.

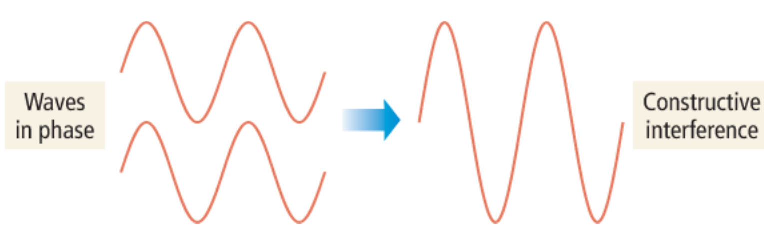
Beyond infrared light, at longer wavelengths still, are **microwaves**, used for radar and in microwave ovens. Although microwave radiation has longer wavelengths and therefore lower energies than visible or infrared light, it is efficiently absorbed by water and can therefore heat substances that contain water. The longest wavelengths are those of **radio waves**, which are used to transmit the signals responsible for AM and FM radio, cellular telephone, television, and other forms of communication.

Conceptual Connection 2.1 **Electromagnetic Radiation**

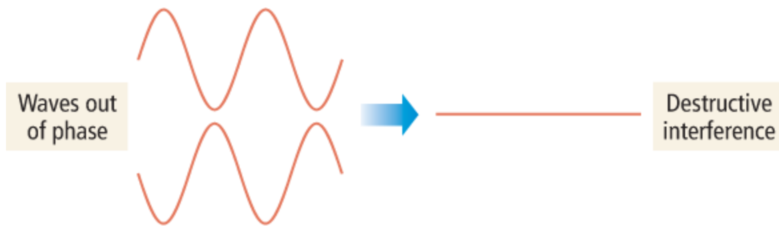
Interactive

Interference and Diffraction

Waves, including electromagnetic waves, interact with each other in a characteristic way called **interference**: they cancel each other out or build each other up, depending on their alignment. For example, if two waves of equal amplitude are *in phase* when they interact—that is, they align with overlapping crests—a wave with twice the amplitude results. This is called **constructive interference**.



If, however, two waves are completely *out of phase* when they interact—that is, they align so that the crest from one overlaps with the trough from the other—the waves cancel by **destructive interference**.



Waves also exhibit a characteristic behavior called **diffraction** (Figure 2.6). When a wave encounters an obstacle or a slit that is comparable in size to its wavelength, it bends (or *diffracts*) around it. The diffraction of light through two slits separated by a distance comparable to the wavelength of the light, coupled with interference, results in an *interference pattern* as shown in Figure 2.7. Each slit acts as a new wave source, and the two new waves interfere with each other. The resulting pattern is a series of bright and dark lines that can be viewed on a screen (or recorded on a film) placed a short distance behind the slits. At the center of the screen, the two waves travel equal distances and interfere constructively to produce a bright line. A small distance away from the center in either direction, the two waves travel slightly different distances, so that they are out of phase. At the point where the difference in distance is one-half of one wavelength, the interference is destructive and a dark line appears on the screen. Moving a bit further away from the center produces constructive interference again because the difference between the paths is one whole wavelength. The end result is the interference pattern. Notice that interference results from the ability of a wave to diffract through two slits—an inherent property of waves.

Figure 2.6 Diffraction

In this view from above, we can see how waves bend, or diffract, when they encounter an obstacle or slit with a size comparable to their wavelength. When a wave passes through a small opening, it spreads out. Particles, by contrast, do not diffract; they simply pass through the opening.

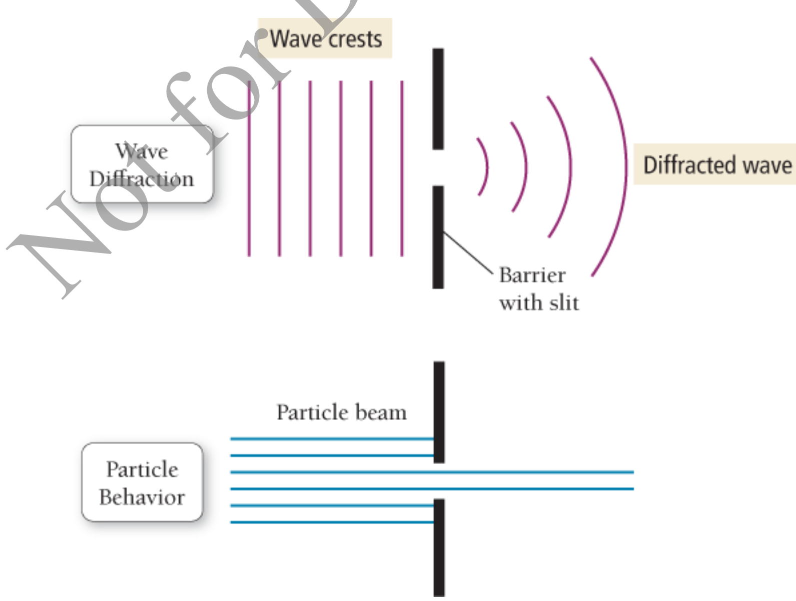
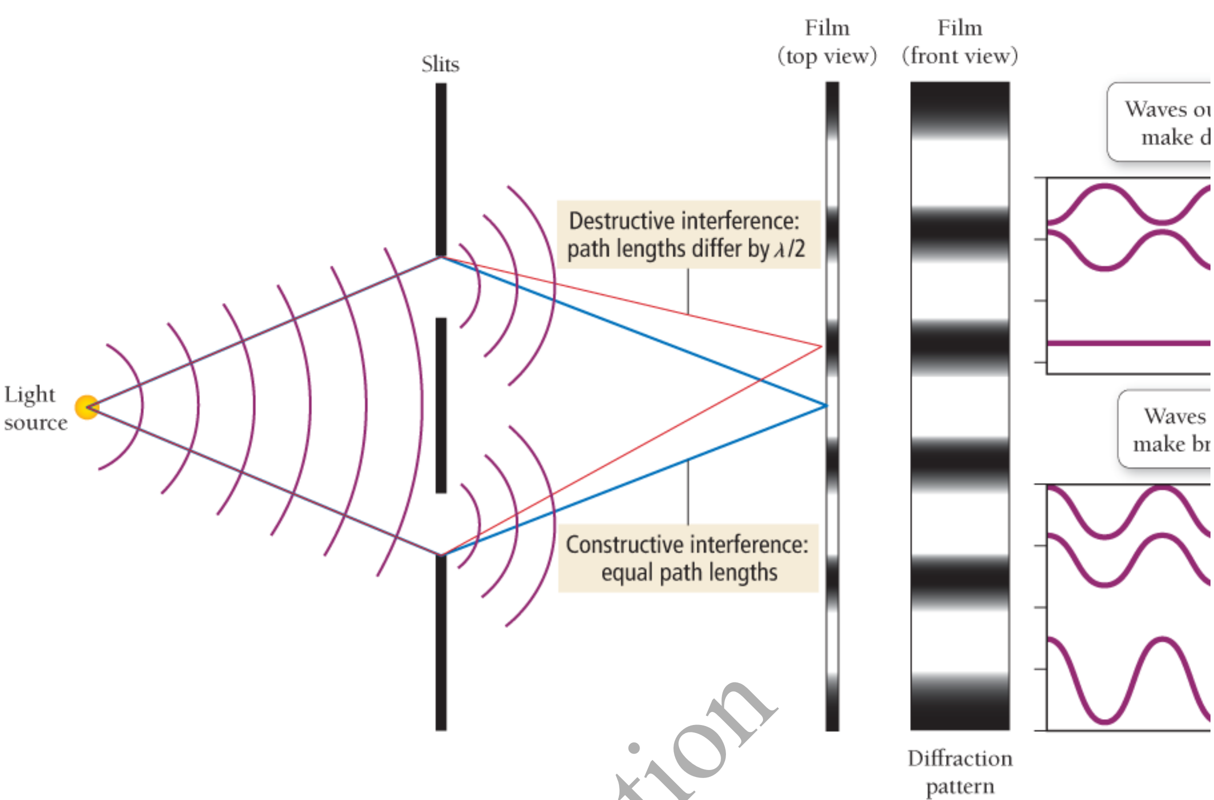


Figure 2.7 Interference from Two Slits

When a beam of light passes through two small slits, the two resulting waves interfere with each other. Whether the interference is constructive or destructive at any given point depends on the difference in the path lengths traveled by the waves. The resulting interference pattern appears as a series of bright and dark lines on a screen.

Interference from Two Slits



When a reflected wave meets an incoming wave near the shore, the two waves interfere constructively for an instant, producing a large-amplitude spike.

> Understanding interference in waves is critical to understanding the wave nature of the electron, as you will soon see.

The Particle Nature of Light

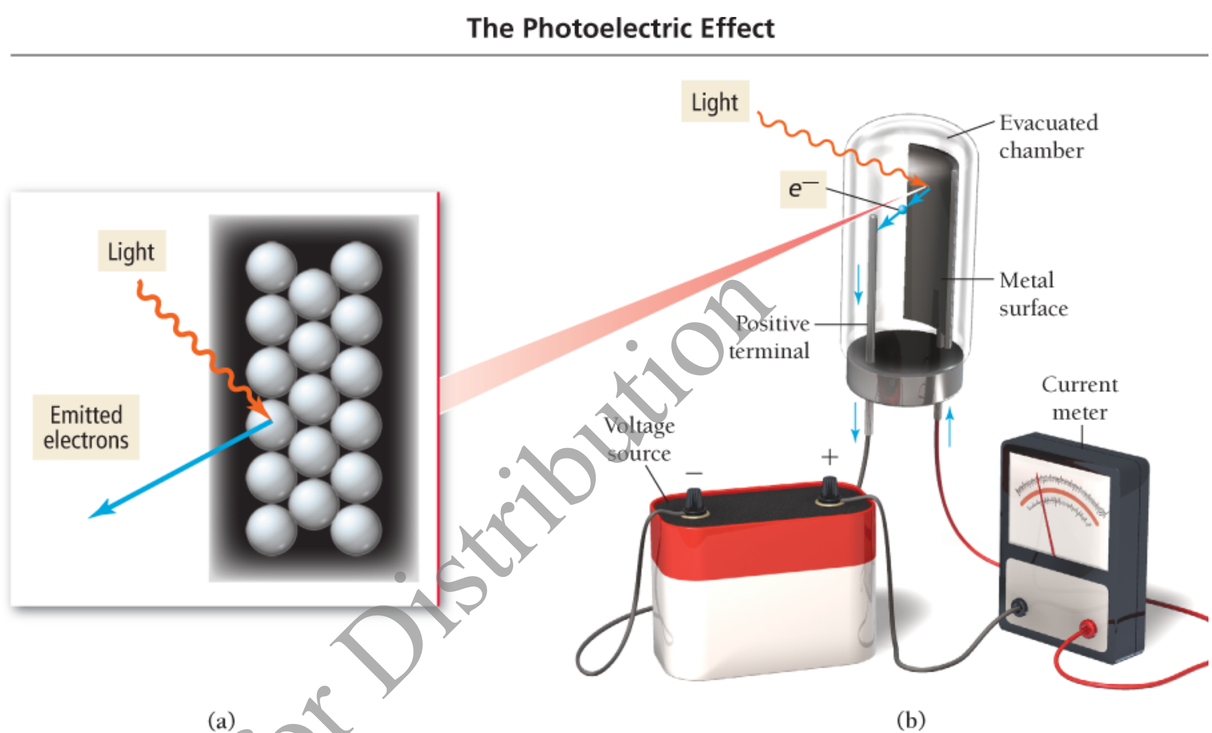
Prior to the early 1900s, and especially after the discovery of the diffraction of light, light was thought to be purely a wave phenomenon. Its behavior was described adequately by classical electromagnetic theory, which treated the electric and magnetic fields that constitute light as waves propagating through space. However, a number of discoveries brought the classical view into question. Chief among these was the *photoelectric effect*.

> The term *classical*, as in classical electromagnetic theory or classical mechanics, refers to descriptions of matter and energy before the advent of quantum mechanics.

The **photoelectric effect** is the observation that many metals emit electrons when light shines upon them, as shown in Figure 2.8. Classical electromagnetic theory attributed this effect to the transfer of energy from the light to an electron in the metal, which resulted in the dislodgment of the electron. If this explanation were correct, the amount of energy transferred from the light to the electron would have to exceed the electron's **binding energy**, the energy with which the electron is bound to the metal. Since the energy of a classical electromagnetic wave depends only on its amplitude (or intensity), the rate at which electrons would leave the metal due to the photoelectric effect would depend only on the intensity of the light shining upon the surface (not on the wavelength). If the intensity of the light was low, there should be a *lag time* (or a delay) between the initial shining of the light and the subsequent emission of an electron. The lag time would be the minimum amount of time required for the dim light to transfer sufficient energy to the electron to dislodge it.

Figure 2.8 The Photoelectric Effect

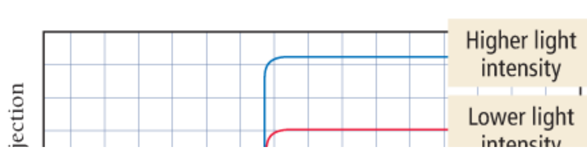
(**a**) When sufficiently energetic light shines on a metal surface, the surface emits electrons. (**b**) The emitted electrons can be measured as an electrical current.

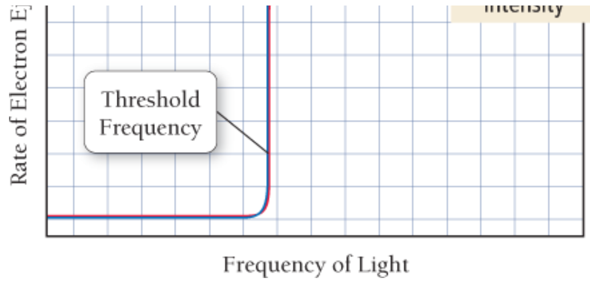


The experimental results, however, do not support the classical prediction. High-frequency, low-intensity light produces electrons *without* the predicted lag time. Furthermore, the light used to dislodge electrons in the photoelectric effect exhibits a *threshold frequency*, below which no electrons are emitted from the metal, no matter how long the light shines on the metal. Figure 2.9 is a graph of the rate of electron ejection from the metal versus the frequency of light used. Notice that increasing the intensity of the light does not change the threshold frequency. In other words, low-frequency (long-wavelength) light *does not* eject electrons from a metal regardless of its intensity or its duration. But high-frequency (short-wavelength) light *does* eject electrons, even if its intensity is low. What could explain this unexpected behavior?

Figure 2.9 Threshold Frequency

A plot of the electron ejection rate versus frequency of light for the photoelectric effect. Electrons are only ejected when the energy of a photon exceeds the energy with which an electron is held to the metal. The frequency at which this occurs is the *threshold frequency*.





In 1905, Albert Einstein (1879–1950) proposed a bold explanation for the photoelectric effect: *Light energy must come in packets*. According to Einstein, the amount of energy (E) in a light packet depends on its frequency (v) according to the following equation:

> Einstein was not the first to suggest that energy was quantized. Max Planck used the idea in 1900 to account for certain characteristics of radiation from hot bodies. However, Planck did not suggest that light actually traveled in discrete packets.

[2.2]

$$E = hv$$

where h, called *Planck's constant*, has the value $h = 6.626 \times 10^{-34}$ J $\cdot$s A *packet* of light is called a **photon** or a **quantum** of light. Since $\nu = c/\lambda$ the energy of a photon can also be expressed in terms of wavelength:

> The energy of a photon is directly proportional to its frequency and inversely proportional to its wavelength.

[2.3]

$$E = \frac{hc}{\lambda}$$

Unlike classical electromagnetic theory, in which light was viewed purely as a wave whose intensity was *continuously variable*, Einstein suggested that light was *lumpy*. From this perspective, a beam of light is *not* a wave propagating through space, but a shower of particles (photons), each with energy hv.

Example 2.2 Photon Energy

A nitrogen gas laser pulse with a wavelength of 337 nm contains 3.83 mJ of energy. How many photons does it contain?

SORT You are given the wavelength and total energy of a light pulse and asked to find the number of photons it contains.

GIVEN: $E_{\text{pulse}} = 3.83$ mJ
$\lambda = 337$ nm

FIND: number of photons

STRATEGIZE In the first part of the conceptual plan, calculate the energy of an individual photon from its wavelength.

In the second part, divide the total energy of the pulse by the energy of a photon to get the number

In the second part, divide the total energy of the pulse by the energy of a photon to get the number of photons in the pulse.

CONCEPTUAL PLAN

$$\lambda \xrightarrow{E = \frac{hc}{\lambda}} E_{\text{photon}}$$

$$\frac{E_{\text{pulse}}}{E_{\text{photon}}} = \text{number of photons}$$

RELATIONSHIPS USED

$E = hc/\lambda$(Equation 2.3)

SOLVE To execute the first part of the conceptual plan, convert the wavelength to meters and substitute it into Equation 2.3 to calculate the energy of a 337-nm photon.

To execute the second part of the conceptual plan, convert the energy of the pulse from mJ to J. Then divide the energy of the pulse by the energy of a photon to obtain the number of photons.

SOLUTION

$$\lambda = 337\ \cancel{\text{nm}} \times \frac{10^{-9}\ \text{m}}{1\ \cancel{\text{nm}}} = 3.37 \times 10^{-7}\ \text{m}$$

$$E_{\text{photon}} = \frac{hc}{\lambda} = \frac{\left(6.626 \times 10^{-34}\ \text{J} \cdot \cancel{\text{s}}\right)\left(3.00 \times 10^{8}\ \frac{\cancel{\text{m}}}{\cancel{\text{s}}}\right)}{3.37 \times 10^{-7}\ \cancel{\text{m}}}$$

$$= 5.8\underline{9}85 \times 10^{-19}\ \text{J}$$

$$3.83\ \cancel{\text{mJ}} \times \frac{10^{-3}\ \text{J}}{1\ \cancel{\text{mJ}}} = 3.83 \times 10^{-3}\ \cancel{\text{J}}$$

$$\text{number of photons} = \frac{E_{\text{pulse}}}{E_{\text{photon}}} = \frac{3.83 \times 10^{-3}\ \cancel{\text{J}}}{5.8\underline{9}85 \times 10^{-19}\ \cancel{\text{J}}}$$

$$= 6.49 \times 10^{15}\ \text{photons}$$

CHECK The units of the answer, photons, are correct. The magnitude of the answer (10^{15}) is reasonable. Photons are small particles and any macroscopic collection should contain a large number of them.

FOR PRACTICE 2.2 A 100-watt light bulb radiates energy at a rate of 100 J/s. (The watt, a unit of power, or energy over time, is defined as 1 J/s.) If all of the light emitted has a wavelength of 525 nm, how many photons are emitted per second? (Assume three significant figures in this calculation.)

FOR MORE PRACTICE 2.2 The energy required to dislodge electrons from sodium metal via the photoelectric effect is 275 kJ/mol. What wavelength in nm of light has sufficient energy per photon to dislodge an electron from the surface of sodium?

Interactive Worked Example 2.2 **Photon Energy**

Example 2.3 Wavelength, Energy, and Frequency

Arrange these three types of electromagnetic radiation—visible light, X-rays, and microwaves—in order of increasing:

a. wavelength
b. frequency
c. energy per photon

SOLUTION

Examine Figure 2.5 and note that X-rays have the shortest wavelength, followed by visible light and then microwaves.

a. wavelength
X-rays < visible < microwaves

Since frequency and wavelength are inversely proportional—the longer the wavelength, the shorter the frequency—the ordering with respect to frequency is the reverse of the order with respect to wavelength.

b. frequency
microwaves < visible < X-rays

Energy per photon decreases with increasing wavelength, but increases with increasing frequency; therefore the ordering with respect to energy per photon is the same as for frequency.

c. energy per photon
microwaves < visible < X-rays

FOR PRACTICE 2.3 Arrange these three colors of visible light—green, red, and blue—in order of increasing:

a. wavelength
b. frequency
c. energy per photon

Interactive Worked Example 2.3 **Wavelength, Energy, and Frequency**

Einstein's idea that light is *quantized* elegantly explains the photoelectric effect. The emission of electrons from the metal depends on whether or not a single photon has sufficient energy (as given by $h\nu$) to dislodge a single electron. For an electron bound to the metal with binding energy ϕ, the threshold frequency is reached when the energy of the photon is equal to ϕ.

> The symbol ϕ is the Greek letter phi, pronounced "fi."

Low-frequency light does not eject electrons because no single photon has the minimum energy necessary to dislodge the electron. We can draw an analogy between a photon ejecting an electron from a metal surface and a ball breaking a glass window. In this analogy, low-frequency photons are like ping-pong balls—a ping-pong ball thrown at a glass window does not break it (just as a low-frequency photon does not eject an electron). Increasing the *intensity* of low-frequency light is like increasing the number of ping-pong balls thrown at the window—doing so simply increases the number of low-energy photons but does not produce any single photon with sufficient energy. In contrast, increasing the *frequency* of the light, even at low intensity, *increases the energy of each photon*. In our analogy, a high-frequency photon is like a baseball—one baseball thrown at a glass window breaks it (just as a high-frequency photon dislodges an electron with no lag time).

Threshold frequency condition

$$\underbrace{h\nu}_{\text{energy of photon}} = \underbrace{\boldsymbol{\phi}}_{\text{binding energy of emitted electron}}$$

As the frequency of the light increases over the threshold frequency, the excess energy of the photon (beyond what is needed to dislodge the electron) transfers to the electron in the form of kinetic energy. The kinetic energy (KE) of the ejected electron, therefore, is the difference between the energy of the photon ($h\nu$) and the binding energy of the electron, as given by the equation:

$$\mathrm{KE} = h\nu - \phi$$

Although the quantization of light explains the photoelectric effect, the wave explanation of light continues to have explanatory power as well, depending on the circumstances of the particular observation. So the principle that slowly emerged (albeit with some measure of resistance) is what we now call the *wave–particle duality of light*. Sometimes light appears to behave like a wave, at other times like a particle. The behavior we observe depends on the particular experiment.

Conceptual Connection 2.2 The Photoelectric Effect

Interactive