

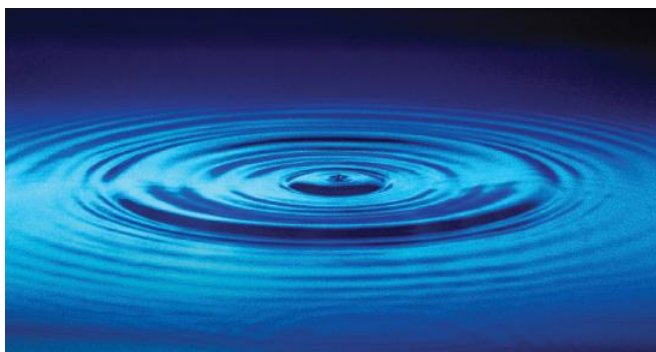
## 6.1: Waves and Electromagnetic Radiation

### Learning Objectives

- To learn about the characteristics of electromagnetic waves.
- Types include light, X-Rays, infrared and microwaves

Scientists discovered much of what we know about the structure of the atom by observing the interaction of atoms with various forms of radiant, or transmitted, energy, such as the energy associated with the visible light we detect with our eyes, the infrared radiation we feel as heat, the ultraviolet light that causes sunburn, and the x-rays that produce images of our teeth or bones. All these forms of radiant energy should be familiar to you. We begin our discussion of the development of our current atomic model by describing the properties of waves and the various forms of electromagnetic radiation.

**Figure 2.1.1 A Wave in Water**

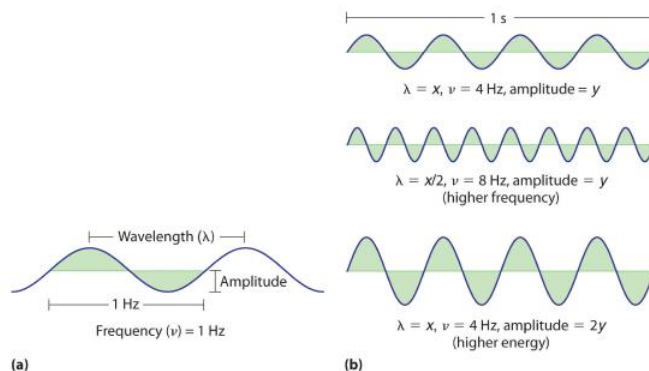


*When a drop of water falls onto a smooth water surface, it generates a set of waves that travel outward in a circular direction.*

### Properties of Waves

A wave is a periodic oscillation that transmits energy through space. Anyone who has visited a beach or dropped a stone into a puddle has observed waves traveling through water (Figure 2.1.1). These waves are produced when wind, a stone, or some other disturbance, such as a passing boat, transfers energy to the water, causing the surface to oscillate up and down as the energy travels outward from its point of origin. As a wave passes a particular point on the surface of the water, anything floating there moves up and down.

**Figure 2.1.2 Important Properties of Waves**



(a) Wavelength ( $\lambda$  in meters), frequency ( $\nu$ , in Hz), and amplitude are indicated on this drawing of a wave. (b) The wave with the shortest wavelength has the greatest number of wavelengths per unit time (i.e., the highest frequency). If two waves have the same frequency and speed, the one with the greater amplitude has the higher energy.

Waves have characteristic properties (Figure 2.1.2). As you may have noticed in Figure 2.1.1, waves are periodic phenomena, such as waves, that repeat regularly in both space and time; that is, they repeat regularly in both space and time. The distance between two corresponding points in a wave—between the midpoints of two peaks, for example, or two troughs—is the wavelength ( $\lambda$ ). The

distance between two corresponding points in a wave—between the midpoints of two peaks or two troughs..  $\lambda$  is the lowercase Greek lambda, and  $\nu$  is the lowercase Greek nu. Wavelengths are described by a unit of distance, typically meters. The frequency ( $\nu$ )The number of oscillations (i.e., of a wave) that pass a particular point in a given period of time. of a wave is the number of oscillations that pass a particular point in a given period of time. The usual units are oscillations per second ( $1/s = s^{-1}$ ), which in the SI system is called the hertz (Hz). It is named after German physicist Heinrich Hertz (1857–1894), a pioneer in the field of electromagnetic radiation. The amplitudeThe vertical height of a wave, which is defined as half the peak-to-trough height., or vertical height, of a wave is defined as half the peak-to-trough height; as the amplitude of a wave with a given frequency increases, so does its energy. As you can see in [Figure 2.1.2](#) , two waves can have the same amplitude but different wavelengths and vice versa. The distance traveled by a wave per unit time is its speed ( $v$ )The distance traveled by a wave per unit time., which is typically measured in meters per second (m/s). The speed of a wave is equal to the product of its wavelength and frequency:

$$(\text{wavelength})(\text{frequency}) = \text{speed} \quad (2.1.1)$$

$$\lambda \nu = v$$

$$\left( \frac{\text{meters}}{\text{wave}} \right) \left( \frac{\text{wave}}{\text{second}} \right) = \frac{\text{meters}}{\text{second}}$$

Be careful not to confuse the symbols for the speed,  $v$ , with the frequency,  $\nu$ .

Water waves are slow compared to sound waves, which can travel through solids, liquids, and gases. Whereas water waves may travel a few meters per second, the speed of sound in dry air at 20°C is 343.5 m/s. Ultrasonic waves, which travel at an even higher speed (>1500 m/s) and have a greater frequency, are used in such diverse applications as locating underwater objects and the medical imaging of internal organs.

#### Videos



Light Speed, Wavelength, and Frequency | Dimensional Analysis by Doc Schuster



Waves in General by JaHu Productions - a bit faster. Also discusses sound waves

## Electromagnetic Radiation

**Figure 2.1.3 The Nature of Electromagnetic Radiation**

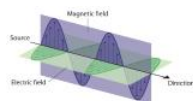


Figure 2.1.3 The Nature of Electromagnetic **Radiation** All forms of electromagnetic radiation consist of perpendicular oscillating electric and magnetic fields.

Water waves transmit energy through space by the periodic oscillation of matter (the water). In contrast, energy that is transmitted, or radiated, through space in the form of periodic oscillations of electric and magnetic fields is known as electromagnetic radiation. Energy that is transmitted, or radiated, through space in the form of periodic oscillations of electric and magnetic fields. (Figure 2.1.3). Some forms of electromagnetic radiation are shown in Figure 2.1.4. In a vacuum, all forms of electromagnetic radiation—whether microwaves, visible light, or gamma rays—travel at the speed of light ( $c$ ) The speed with which all forms of electromagnetic radiation travel in a vacuum., a fundamental physical constant with a value of  $2.99792458 \times 10^8$  m/s (which is about  $3.00 \times 10^8$  m/s or  $1.86 \times 10^5$  mi/s). This is about a million times faster than the speed of sound.

Because the various kinds of electromagnetic radiation all have the same speed ( $c$ ), they differ in only wavelength and frequency. As shown in Figure 2.1.4 and Table 2.1.1, the wavelengths of familiar electromagnetic radiation range from  $10^1$  m for radio waves to  $10^{-12}$  m for gamma rays, which are emitted by nuclear reactions. By replacing  $v$  with  $c$  in Equation 2.1.1, we can show that the frequency of electromagnetic radiation is inversely proportional to its wavelength:

$$c = \lambda \nu$$

$$\nu = \frac{c}{\lambda} \quad (2.1.2)$$

For example, the frequency of radio waves is about  $10^8$  Hz, whereas the frequency of gamma rays is about  $10^{20}$  Hz. Visible light, which is electromagnetic radiation that can be detected by the human eye, has wavelengths between about  $7 \times 10^{-7}$  m (700 nm, or  $4.3 \times 10^{14}$  Hz) and  $4 \times 10^{-7}$  m (400 nm, or  $7.5 \times 10^{14}$  Hz). Note that when frequency increases, wavelength decreases;  $c$  being a constant stays the same. Similarly when frequency decreases, wavelength increases,

Here is a [video from Oxford University Press](#) which goes through the calculation



### Videos

- [Calculating Frequency Given Wavelength](#) - Johnny Cantrell
- [Wavelength Frequency Problems](#) - Cayer Chem

### Examples

- [Quantum Chemistry](#) - Ohio State
- [Quantum Chemistry Quizzes](#) - mhe education
- [AP Chemistry Chapter 7 Review](#) - Science Geek
- [Quantum Theory of the Atom Practice Quiz](#) - Northrup

Answers for these quizzes are included. There are also questions covering more topics in Chapter 2.

Within this visible range our eyes perceive radiation of different wavelengths (or frequencies) as light of different colors, ranging from red to violet in order of decreasing wavelength. The components of white light—a mixture of all the frequencies of visible light—can be separated by a prism, as shown in part (b) in Figure 2.1.4. A similar phenomenon creates a rainbow, where water droplets suspended in the air act as tiny prisms.

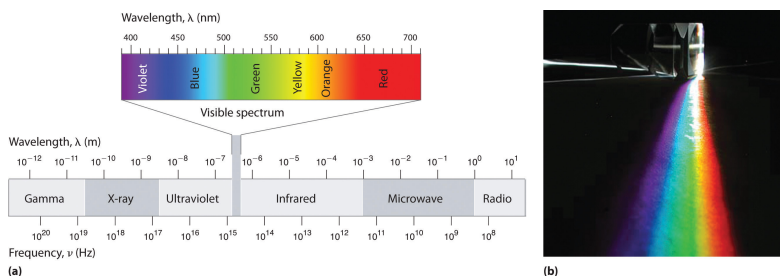


Figure 2.1.4 The Electromagnetic Spectrum (a) This diagram shows the wavelength and frequency ranges of electromagnetic radiation. The visible portion of the electromagnetic spectrum is the narrow region with wavelengths between about 400 and 700 nm. (b) When white light is passed through a prism, it is split into light of different wavelengths, whose colors correspond to the visible spectrum.

This video reviews the ideas in Figure 2.1.4



Table 2.1.1 Common Wavelength Units for Electromagnetic Radiation

Unit	Symbol	Wavelength (m)	Type of Radiation
picometer	pm	$10^{-12}$	gamma ray
angstrom	Å	$10^{-10}$	x-ray
nanometer	nm	$10^{-9}$	x-ray
micrometer	$\mu\text{m}$	$10^{-6}$	infrared
millimeter	mm	$10^{-3}$	infrared
centimeter	cm	$10^{-2}$	microwave
meter	m	$10^0$	radio

As you will soon see, the energy of electromagnetic radiation is directly proportional to its frequency and inversely proportional to its wavelength:

$$E \propto \nu \quad (2.1.3)$$

$$E \propto \frac{1}{\lambda} \quad (2.1.4)$$

Whereas visible light is essentially harmless to our skin, ultraviolet light, with wavelengths of  $\leq 400$  nm, has enough energy to cause severe damage to our skin in the form of sunburn. Because the ozone layer described in [Chapter 7.6 "Chemical Reactions in the Atmosphere"](#) absorbs sunlight with wavelengths less than 350 nm, it protects us from the damaging effects of highly energetic ultraviolet radiation.

### Note the Pattern

The energy of electromagnetic radiation increases with increasing frequency and decreasing wavelength.

### Example 2.1.1

Your favorite FM radio station, WXYZ, broadcasts at a frequency of 101.1 MHz. What is the wavelength of this radiation?

**Given:** frequency

**Asked for:** wavelength

**Strategy:**

Substitute the value for the speed of light in meters per second into [Equation 2.1.2](#) to calculate the wavelength in meters.

**Solution:**

From [Equation 2.1.2](#), we know that the product of the wavelength and the frequency is the speed of the wave, which for electromagnetic radiation is  $2.998 \times 10^8$  m/s:

$$\lambda\nu = c = 2.998 \times 10^8 \text{ m/s}$$

Thus the wavelength  $\lambda$  is given by

$$\lambda = \frac{c}{\nu} = \left( \frac{2.988 \times 10^8 \text{ m/s}}{101.1 \text{ MHz}} \right) \left( \frac{1}{10^6 \text{ s}^{-1}} \right) = 2.965 \text{ m}$$

Exercise

As the police officer was writing up your speeding ticket, she mentioned that she was using a state-of-the-art radar gun operating at 35.5 GHz. What is the wavelength of the radiation emitted by the radar gun?

**Answer:** 8.45 mm

In [Section 2.2](#) and [Section 2.3](#), we describe how scientists developed our current understanding of the structure of atoms using the scientific method described in [Chapter 1](#). You will discover why scientists had to rethink their classical understanding of the nature of electromagnetic energy, which clearly distinguished between the particulate behavior of matter and the wavelike nature of energy.

### Key Equations

**relationship between wavelength, frequency, and speed of a wave**

[Equation 2.1.1:](#)  $v = \lambda\nu$

**relationship between wavelength, frequency, and speed of electromagnetic radiation**

[Equation 2.1.2:](#)  $c = \lambda\nu$

### Summary

A basic knowledge of the electronic structure of atoms requires an understanding of the properties of waves and electromagnetic radiation. A **wave** is a periodic oscillation by which energy is transmitted through space. All waves are **periodic**, repeating regularly in both space and time. Waves are characterized by several interrelated properties: **wavelength ( $\lambda$ )**, the distance between successive waves; **frequency ( $\nu$ )**, the number of waves that pass a fixed point per unit time; **speed ( $v$ )**, the rate at which the wave propagates through space; and **amplitude**, the magnitude of the oscillation about the mean position. The speed of a wave is equal to the product of its wavelength and frequency. **Electromagnetic radiation** consists of two perpendicular waves, one electric and one magnetic, propagating at the **speed of light ( $c$ )**. Electromagnetic radiation is radiant energy that includes radio waves, microwaves, visible light, x-rays, and gamma rays, which differ only in their frequencies and wavelengths.

### Key Takeaway

- Understanding the electronic structure of atoms requires an understanding of the properties of waves and electromagnetic radiation.

### Conceptual Problems

1. What are the characteristics of a wave? What is the relationship between electromagnetic radiation and wave energy?
2. At constant wavelength, what effect does increasing the frequency of a wave have on its speed? its amplitude?
3. List the following forms of electromagnetic radiation in order of increasing wavelength: x-rays, radio waves, infrared waves, microwaves, ultraviolet waves, visible waves, and gamma rays. List them in order of increasing frequency. Which has the highest energy?
4. A large industry is centered on developing skin-care products, such as suntan lotions and cosmetics, that cannot be penetrated by ultraviolet radiation. How does the wavelength of visible light compare with the wavelength of ultraviolet light? How does the energy of visible light compare with the energy of ultraviolet light? Why is this industry focused on blocking ultraviolet light rather than visible light?

### Numerical Problems

1. The human eye is sensitive to what fraction of the electromagnetic spectrum, assuming a typical spectral range of  $10^4$  to  $10^{20}$  Hz? If we came from the planet Krypton and had x-ray vision (i.e., if our eyes were sensitive to x-rays in addition to visible light), how would this fraction be changed?
2. What is the frequency in megahertz corresponding to each wavelength?
  1. 755 m
  2. 6.73 nm
  3.  $1.77 \times 10^3$  km
  4. 9.88 Å
  5.  $3.7 \times 10^{-10}$  m
3. What is the frequency in megahertz corresponding to each wavelength?
  1.  $5.8 \times 10^{-7}$  m
  2. 2.3 Å
  3.  $8.6 \times 10^7$  m
  4. 6.2 mm
  5. 3.7 nm
4. Line spectra are also observed for molecular species. Given the following characteristic wavelengths for each species, identify the spectral region (ultraviolet, visible, etc.) in which the following line spectra will occur. Given 1.00 mol of each compound and the wavelength of absorbed or emitted light, how much energy does this correspond to?
  1.  $\text{NH}_3$ ,  $1.0 \times 10^{-2}$  m
  2.  $\text{CH}_3\text{CH}_2\text{OH}$ , 9.0  $\mu\text{m}$
  3. Mo atom, 7.1 Å
5. What is the speed of a wave in meters per second that has a wavelength of 1250 m and a frequency of  $2.36 \times 10^5 \text{ s}^{-1}$ ?
6. A wave travels at 3.70 m/s with a frequency of  $4.599 \times 10^7$  Hz and an amplitude of 1.0 m. What is its wavelength in nanometers?
7. An AM radio station broadcasts with a wavelength of 248.0 m. What is the broadcast frequency of the station in kilohertz? An AM station has a broadcast range of 92.6 MHz. What is the corresponding wavelength range in meters for this reception?
8. An FM radio station broadcasts with a wavelength of 3.21 m. What is the broadcast frequency of the station in megahertz? An FM radio typically has a broadcast range of 82–112 MHz. What is the corresponding wavelength range in meters for this reception?
9. A microwave oven operates at a frequency of approximately 2450 MHz. What is the corresponding wavelength? Water, with its polar molecules, absorbs electromagnetic radiation primarily in the infrared portion of the spectrum. Given this fact, why are

microwave ovens used for cooking food?

#### Contributors

- Anonymous

Modified by Joshua Halpern

[Light Speed Video](#) from Doc Schuster on YouTube

[Wave Video](#) from JaHuProductions on YouTube

[Wavelength and Frequency](#) from Oxford Academic on YouTube

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