8.2 Wave Behaviour

SECTION OUTCOMES

- Describe the production, characteristics, and behaviours of longitudinal and transverse mechanical waves.
- Apply the universal wave equation to explain and predict the behaviour of waves.
- Compare the relationships between frequency and wavelength to the speed of a wave in various media.
- Use scientific models to explain the behaviour of waves at barriers and interfaces between media.

KEY TERMS

- wave
- medium
- mechanical wave
- crests
- troughs
- wavelength
- frequency of a wave
- transverse wave
- longitudinal wave
- wave equation

What is a wave? When you first read the word, you probably imagine an ocean wave or a crowd in the stands at an athletic event doing "the wave." Soon you will know why the first image is a true wave in the scientific sense and the second image is not.

Figure 8.5 **(A)** The water ski does work on the water, giving it energy. The wave transmits the energy across the surface of the water. **(B)** "The wave", in which sports fans wave their arms in unison, is not a wave at all. No energy is transmitted from one person to another. Each person is using his or her own energy to make "the wave."

A **wave** is a disturbance that transfers energy through a **medium**. While the disturbance, and the energy that it carries, moves through the medium, the matter does not experience net movement. Instead, each particle in the medium vibrates about some mean (or rest) position as the wave passes. The behaviour of many physical phenomena can be described as waves. Disturbances in ropes, springs, and water are easily recognized as waves in which energy moves through the medium. Although you cannot see sound waves, they also are true waves. You usually think of sound waves travelling through air. However, they can also travel through water, steel, or a variety of other materials.

All of these waves travel through matter and are known as **mechanical waves**. Their speed does not depend on their size or the amount of energy they carry. Neither does it decrease as they move through a medium. Rather, the speed of any wave in a particular medium is the same as the speed of any other wave in that same medium. The speed of a wave in a medium is a characteristic property of that medium, in much the same way that its density or boiling point is a property of the medium.

The forces between the particles of the medium and the mass of those particles determine the speed of a mechanical wave. The greater the force between those particles, the more rapidly each particle will return to its rest position; hence, the faster the wave will move along. However, the greater the mass (inertia) of a particle in the medium, the slower it will return to its rest position and the slower the wave will move along. Generally, there is friction in the medium. This friction acts to dampen or reduce the size or height of the wave. Unlike the friction acting on a material object that is moving, the friction does not affect the speed of the wave. Similarly, when a wave is given more energy, the shape of the wave is affected, but the speed with which it moves through the medium is unaffected.

Describing Waves

All waves have several common characteristics that you can use to describe them. Figure 8.6 shows a periodic wave that looks as though it is frozen in time. The horizontal line through the centre is the rest or equilibrium position. The highest points on the wave are the **crests** and the lowest points are the **troughs**. The amplitude (A) is the distance between the rest position and a crest or trough. The **wavelength** (λ, the Greek letter lambda) is the shortest distance between two points in the medium that are in phase. Therefore, two adjacent crests are one wavelength apart. Similarly, two adjacent troughs are one wavelength apart.

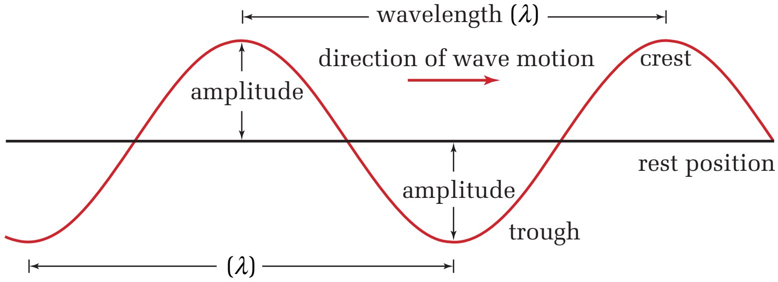


Figure 8.6 This idealized wave illustrates the features that are common to all waves.

Now imagine that the wave is no longer frozen in time but is moving. The **frequency of a wave** (f) is the number of complete wavelengths that pass a point in a given amount of time. Similar to vibrating objects, the frequency of a wave is usually described in units of hertz. The frequency of a wave is the same as the frequency of the source producing it, so it does not depend on the medium. Also, similar to vibrating objects, the period of a wave is the time it takes for one full wavelength to pass a given point.

While a wave travels through a medium such as a spring, the particles do not need to vibrate in the same direction in which the wave is moving (see Figure 8.7). When the particles of a medium vibrate at right angles to the direction of the motion, the wave is called a **transverse wave**. Water waves and waves on a rope are examples of transverse waves.

PHYSICS FILE

Electromagnetic waves transmit energy just as mechanical waves do. However, electromagnetic waves do not require a medium but can travel through a vacuum. All forms of electromagnetic waves, from long radio waves, through visible light, up to gamma rays with very short wavelengths, travel at the same speed through a vacuum, 3×10^8 m/s. You could say that the speed of any electromagnetic wave is the same in the absence of a medium. However, when travelling through a medium, different wavelengths do, in fact, travel at different speeds. How fast is 3×10^8 m/s? Light can travel around the world 7.5 times in 1 s!

COURSE CHALLENGE: SPACE-BASED POWER

Interference: Communication versus Energy Transmission

Research current allocations of microwave bandwidths. How closely are these bandwidth slices packed? What kind of current research dealing with microwave interference is being done?

ELECTRONIC LEARNING PARTNER

Learn more about wave terminology in your Electronic Learning Partner.

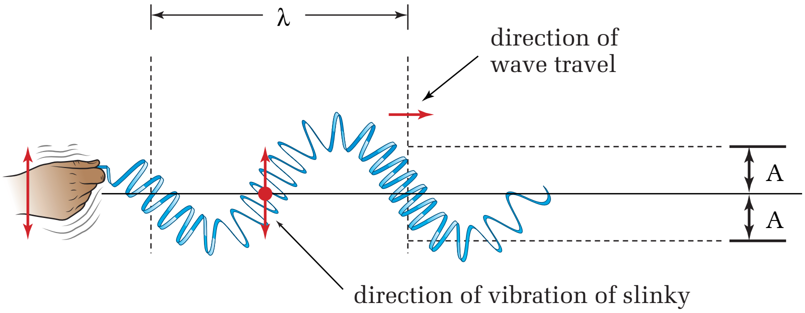


Figure 8.7 When a transverse wave travels along a spring, the segments of the spring vibrate from side to side, perpendicular to the direction of the wave motion.

ELECTRONIC LEARNING PARTNER

Visual examples of transverse and longitudinal waves are available on your Electronic Learning Partner.

When the particles of a medium vibrate parallel to the direction of the motion of the wave, it is called a **longitudinal wave** (see Figure 8.8). Once again, the speed of the wave is determined only by the medium. Sound waves, which you will study in more detail in Chapter 9, are examples of longitudinal waves.

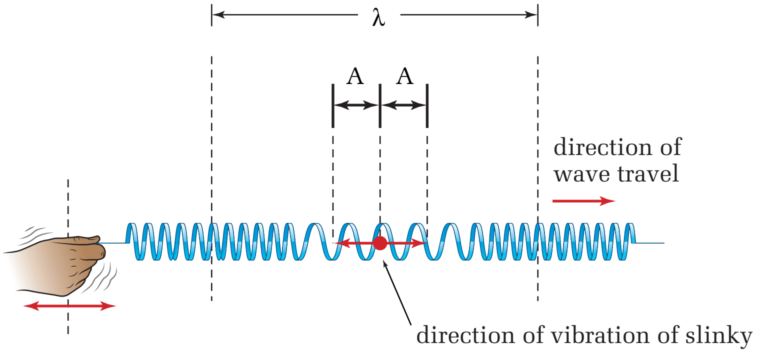


Figure 8.8 When a longitudinal wave travels along a spring, the segments of the spring vibrate parallel to the direction of the wave motion.

Earth Link

Earthquakes generate both transverse and longitudinal waves. Since the longitudinal waves travel faster through Earth and reach seismographs (earthquake detectors) first, they are called primary or P-waves. Transverse waves travel much slower and are called secondary or S-waves. From the difference in the time of arrival of the two waves, seismologists can estimate the distance from the detector to the quake. Do research for recent earthquake information. Especially focus on the recorded waves and time intervals. Attempt your own mathematical calculations for the distance between detectors and the earthquake's epicentre.

Speed, Wavelength, and Frequency: A Universal Wave Equation

Knowing the speed of a wave provides critical information in many situations. For example, knowing the speed of waves in the deep ocean makes it possible to predict when a tsunami will hit a particular shore. Knowing the speeds of the different types of seismic waves from earthquakes enables geologists to locate the epicentre of an earthquake. As you have probably discovered, it is not easy to determine the speed of a wave pulse accurately. Fortunately, it is possible to determine this value from observable properties of waves travelling through a medium. Use the following problem-solving model to find the relationship.

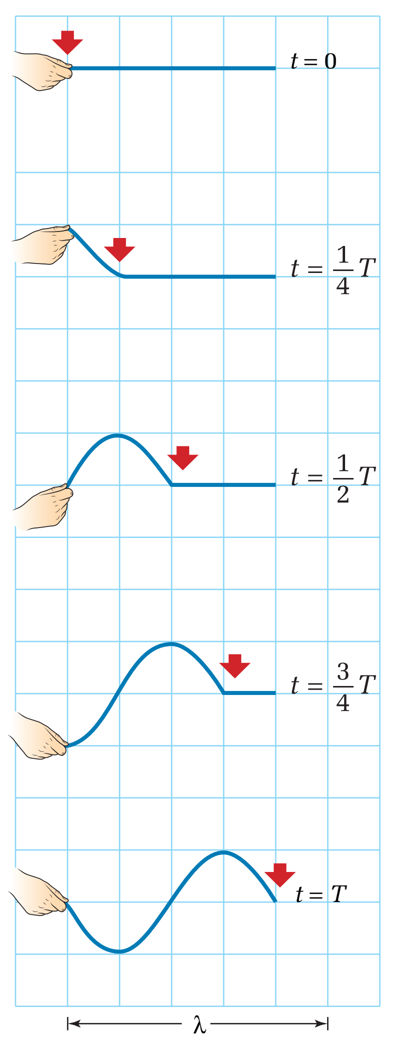
MODEL PROBLEMS

The Wave Equation

1. A wave has an amplitude, A, frequency, f, and wavelength, λ. How can you find the speed of the wave using these variables?

Frame the Problem

- A source *vibrating* with a *frequency*, f, takes a time interval, $\Delta t = T$, to complete one cycle.
- During that *time*, the *wave* that it produced *moves* a *distance*, λ, along the medium.
- The average speed of any entity is the quotient of the distance it travelled and the time interval that it was travelling. This is true for waves as well as for moving objects.



While the hand moves through one cycle, the wave moves one wavelength.

Identify the Goal

The speed, v, of a wave

Variables and Constants

Known	Unknown
$\Delta t = T = \frac{1}{f}$	v
$\Delta d = \lambda$	
A	

Strategy	Calculations
Use the formula for the velocity (or speed) of any entity.	$v = \frac{\Delta d}{\Delta t}$
Substitute in known values.	$v = \frac{\lambda}{T}$
Substitute $\frac{1}{f}$ for T.	$v = \frac{\lambda}{\frac{1}{f}}$
Simplify.	$v = \lambda f$

The speed of a wave is the product of its wavelength and its frequency: $v = \lambda f$.

Validate

The equation $v = f\lambda$ is called the **wave equation**. The wave equation can be seen simply as the form of the equation $v = \frac{\Delta d}{\Delta t}$ for waves, because we know that waves travel one wavelength in one period.

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2. A physics student vibrates the end of a spring at 2.8 Hz. This produces a wave with a wavelength of 0.36 m. Calculate the speed of the wave.

Frame the Problem

- *Vibrating* the end of a spring creates a *wave* in the spring.
- The *frequency* of the wave is the same as the *frequency* of the vibrating source.
- The *wave equation* applies to this situation.

Identify the Goal

The speed, v, of the wave

Variables and Constants

Known	**Unknown**
$f = 2.8$ Hz	v
$\lambda = 0.36$ m	

Strategy

Use the wave equation.

All needed variables are known, so substitute.

Calculations

$v = f\lambda$

$v = (2.8 \text{ Hz})(0.36 \text{ m})$

$v = 1.0 \text{ ms}^{-1}$

$v = 1.0 \dfrac{\text{m}}{\text{s}}$

The speed of the wave is 1.0 m/s.

Validate

The units reduced to m/s which is correct for speed.
A reasonable speed for a wave in a spring is 1.0 m/s.

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3. Water waves with wavelength 2.8 m, produced in a wave tank, travel with a speed of 3.80 m/s. What is the frequency of the straight vibrator that produced them?

Frame the Problem

- A vibrator in a water tank is producing waves.
- The *frequency* of a wave is the same as the *frequency* of the vibrating source.
- The *wave equation* applies to this situation.

Identify the Goal

The frequency, *f*, of the vibrator

Variables and Constants

Known	**Unknown**
$\lambda = 2.8 \text{ m}$	f
$v = \dfrac{3.80 \text{ m}}{\text{s}}$	

Strategy

Use the wave equation to find the frequency of the wave.

All needed values are known, so substitute into the equation.

Divide by the coefficient of *f*.

Simplify.

Calculations

$$v = f\lambda$$

Substitute first

$$\frac{3.80 \text{ m}}{\text{s}} = f(2.8 \text{ m})$$

$$\frac{3.80 \cancel{\text{m}}/\text{s}}{2.8 \cancel{\text{m}}} = f$$

$$f = 1.4 \text{ s}^{-1}$$

$$f = 1.4 \text{ Hz}$$

Solve for *f* first

$$v = f\lambda$$

$$\frac{v}{\lambda} = \frac{f\cancel{\lambda}}{\cancel{\lambda}}$$

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

$$f = \frac{\frac{3.80 \cancel{\text{m}}}{\text{s}}}{2.8 \cancel{\text{m}}}$$

$$f = 1.4 \text{ s}^{-1}$$

$$f = 1.4 \text{ Hz}$$

The frequency of the wave and, therefore, the frequency of the vibrator is 1.4 Hz.

Validate

Since the wavelength (~3 m) is shorter than the distance the wave travels in 1 s (~4 m/s), you would expect that the period would be less than 1 s. If the period is less than 1 s, then the frequency should be more than 1 s, which it is.

PRACTICE PROBLEMS

5. A longitudinal wave in a 6.0 m long spring has a frequency of 10.0 Hz and a wavelength of 0.75 m. Calculate the speed of the wave and the time that it would take to travel the length of the spring.

6. Interstellar hydrogen gas emits radio waves with a wavelength of 21 cm. Given that radio waves travel at 3.00×10^8 m/s, what is the frequency of this interstellar source of radiation?

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7. Tsunamis are fast-moving ocean waves typically caused by underwater earthquakes. One particular tsunami travelled a distance of 3250 km in 4.6 h and its wavelength was determined to be 640 km. What was the frequency of this tsunami?

8. An earthquake wave has a wavelength of 523 m and travels with a speed of 4.60 km/s through a portion of Earth's crust.

- **(a)** What is its frequency?
- **(b)** If it travels into a different portion of Earth's crust, where its speed is 7.50 km/s, what is its new wavelength?
- **(c)** What assumption(s) did you make to answer part (b)?

9. The speed of sound in air at room temperature is 343 m/s. The sound wave produced by striking middle C on a piano has a frequency of 256 Hz.

- **(a)** Calculate the wavelength of this sound.
- **(b)** Calculate the wavelength for the sound produced by high C, one octave higher than middle C, with a frequency of 512 Hz.

Web Link

www.mcgrawhill.ca/links/atlphysics

To learn more about tsunamis, go to the Internet site above and click on **Web Links**.

THE WAVE EQUATION

The speed of a wave is the product of the wavelength and the frequency.

$$v = f\lambda$$

Quantity	**Symbol**	**SI unit**
speed	v	$\frac{\text{m}}{\text{s}}$ (metres per second)
frequency	f	Hz (or s^{-1})(hertz)
wavelength	λ	m (metres)

Unit Analysis

$$(\text{frequency})(\text{wavelength}) = \text{Hz m} = \text{s}^{-1}\text{ m} = \frac{\text{m}}{\text{s}}$$

Conceptual Problem

A student is holding one end of two different ropes, A and B. The other end of each rope is tied to a wall. Rope A is heavier than rope B, causing the speed of a wave in B to be twice as fast as the speed of a wave in A ($v_B = 2v_A$). The student initiates a wave pulse in both ropes by shaking the two ends at the same time. This gives the wave pulses identical amplitudes and time intervals. The diagram shows the shape and position of the wave pulse in rope A moments after the student initiated the pulses. Copy this figure into your notebook and, below it, sketch the appearance of rope B. Carefully consider the size, shape, and position of the wave pulse in rope B compared to rope A.

Waves at Boundaries: Reflection and Transmission

When a wave moves from one medium into another, its *frequency remains the same* but its *speed changes*. As you have learned, the speed of a wave depends on the properties of the medium through which it is travelling.

Figure 8.9 shows what happens when a wave crosses the boundary between two springs joined end to end. The spring on the left is heavy and larger; thus, the wave pulse travels slowly. Once the wave pulse moves into the lighter, smaller spring on the right, it travels faster. You could call the heavy spring the "slow medium" and the light spring the "fast medium." Notice in the figure that, in addition to a transmitted wave pulse, there is also a reflected pulse. Notice, also, that the reflected pulse is on the same side of the spring as the incident and transmitted pulse. When a wave travels from a slow medium to a fast medium, the reflected wave is always on the same side of the rest position as the incoming wave.

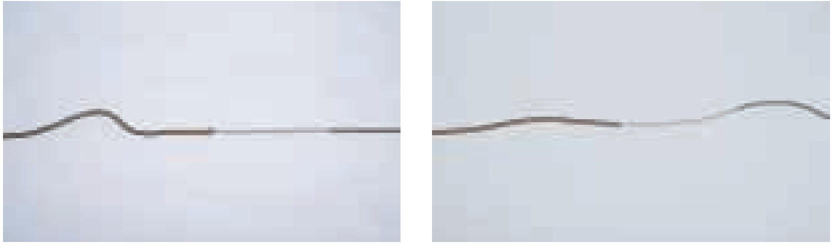


Figure 8.9 At a slow-to-fast interface between two media, the transmitted and reflected pulses are on the same side of the spring.

When a wave pulse travels from a fast medium, such as a light spring, to a slow medium, such as a heavy spring, both transmitted and reflected wave pulses result. However, the reflected pulse is inverted, that is, on the opposite side of the spring, as shown in Figure 8.10.

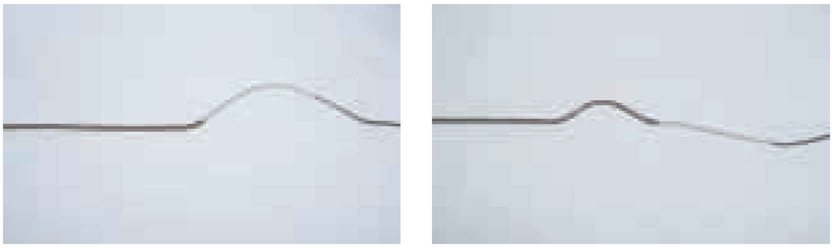


Figure 8.10 At a fast-to-slow interface, the transmitted pulse is on the same side of the spring as the original pulse, but the reflected pulse is inverted.

TRY THIS...

Attach two ropes of different thicknesses together at one end. You and your lab partner should hold the free ends of the combined ropes. First, let one partner initiate one wave pulse. Observe what happens to the pulse as it reaches and passes through the point of attachment. Then, let the other partner initiate a pulse in the opposite end. Observe the behaviour of this second pulse. Discuss any differences you observed between the behaviour of a wave pulse going from a heavy rope to a light rope in relation to a pulse travelling in the opposite direction.

When one end of a spring is attached firmly to a wall, for example, the reflected pulse is inverted as well (see Figure 8.11). You can consider reflection from an end attached to something solid to be a special case of transmission at a fast/slow boundary. The speed of the wave in the massive wall is much slower than in the spring.

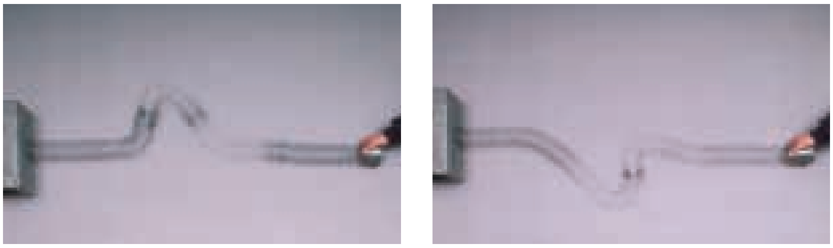


Figure 8.11 When a wave pulse is reflected from a fixed end, the reflected wave pulse is inverted.

Similarly, when a pulse travels down a spring toward an end that is not attached to anything, the free end will reflect the pulse. As shown in Figure 8.12, the reflected pulse will not be inverted. You can consider reflection from a free end as a special case of transmission at a slow-to-fast boundary.

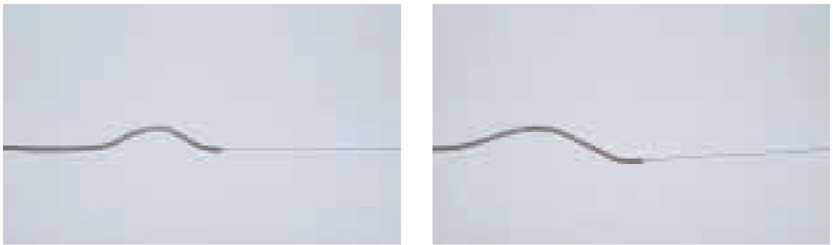


Figure 8.12 When a wave pulse is reflected from a free end, the reflected pulse is on the same side as the original pulse.

Conceptual Problem

- A good model accurately predicts observations from the widest possible set of related phenomena. Assume that the wave model presented here is a good model and also applies to water waves.

  1. If a water wave travels through water, what changes might occur that will simulate a different medium?
  2. Discuss the types of boundaries that water waves might encounter.
  3. A water wave moves from the deep ocean to the much shallower waters of the Grand Banks off the coast of Newfoundland. Use the wave model to predict how the waves will behave as they cross this boundary.

8.2 Section Review

1. **K/U** What are the essential characteristics of a wave?

2. **K/U** How do transverse and longitudinal waves differ? Give an example of each.

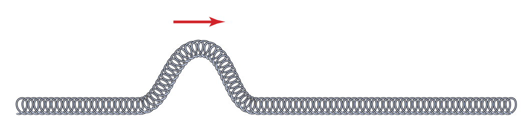
3. **C** Sketch a diagram of a transverse wave. Mark the amplitude and wavelength of the wave on your diagram. Also, mark two points, P1 and P2, that are in phase.

4. **C** Do the following:

- **(a)** State the wave equation relating the speed, frequency, and wavelength of a wave.
- **(b)** Explain how the wave equation can be derived from the fact that a wave travels a distance of one wavelength in a time of one period.

5. **K/U** A wave pulse is travelling down a spring from left to right as shown. Sketch what the spring would look like after the pulse had been reflected if

- **(a)** the opposite end of the spring was firmly held to the floor by another student.
- **(b)** the opposite end of the spring was held by a light thread so that it was free to move.



6. **K/U** After a transverse wave pulse has travelled 2.5 m through a medium, it has a speed of 0.80 m/s. How would this speed have differed if

- **(a)** the pulse had been twice the size?
- **(b)** the pulse had had twice the energy?
- **(c)** the pulse had travelled twice the distance?

7. **C** Explain the meaning of the statement, "The speed of a wave is a characteristic property of the medium through which it is travelling."

8. **K/U** A wave pulse is travelling down a spring with a speed of 2 m/s toward a second spring attached to its opposite end. Sketch what the two springs would look like after the pulse has passed into the second spring if

- **(a)** the speed of a wave in the second spring is 1 m/s.
- **(b)** the speed of a wave in the second spring is 4 m/s.
- **(c)** the speed of a wave in the second spring is 2 m/s.