



**FIGURE 16.26** In 1940, the Tacoma Narrows Bridge in Washington state collapsed. Heavy cross winds drove the bridge into oscillations at its resonant frequency. Damping decreased when support cables broke loose and started to slip over the towers, allowing increasingly greater amplitudes until the structure failed (credit: PRI's *Studio 360*, via Flickr)

### ✓ CHECK YOUR UNDERSTANDING

A famous magic trick involves a performer singing a note toward a crystal glass until the glass shatters. Explain why the trick works in terms of resonance and natural frequency.

#### Solution

The performer must be singing a note that corresponds to the natural frequency of the glass. As the sound wave is directed at the glass, the glass responds by resonating at the same frequency as the sound wave. With enough energy introduced into the system, the glass begins to vibrate and eventually shatters.

## 16.9 Waves

### LEARNING OBJECTIVES

By the end of this section, you will be able to:

- State the characteristics of a wave.
- Calculate the velocity of wave propagation.



**FIGURE 16.27** Waves in the ocean behave similarly to all other types of waves. (credit: Steve Jurveston, Flickr)

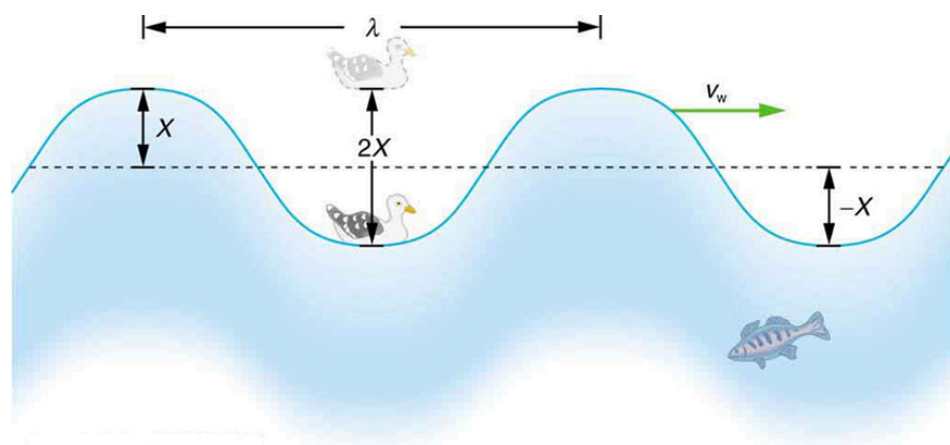
What do we mean when we say something is a wave? The most intuitive and easiest wave to imagine is the familiar water wave. More precisely, a **wave** is a disturbance that propagates, or moves from the place it was created. For water waves, the disturbance is in the surface of the water, perhaps created by a rock thrown into a pond or by a swimmer splashing the surface repeatedly. For sound waves, the disturbance is a change in air pressure, perhaps created by the oscillating cone inside a speaker. For earthquakes, there are several types of disturbances, including disturbance of Earth's surface and pressure disturbances under the surface. Even radio waves are most easily understood using an analogy with water waves. Visualizing water waves is useful because there is more to it than just a mental image. Water waves exhibit characteristics common to all waves, such as amplitude, period, frequency and energy. All wave characteristics can be described by a small set of underlying principles.

A wave is a disturbance that propagates, or moves from the place it was created. The simplest waves repeat

themselves for several cycles and are associated with simple harmonic motion. Let us start by considering the simplified water wave in [Figure 16.28](#). The wave is an up and down disturbance of the water surface. It causes a sea gull to move up and down in simple harmonic motion as the wave crests and troughs (peaks and valleys) pass under the bird. The time for one complete up and down motion is the wave's period  $T$ . The wave's frequency is  $f = 1/T$ , as usual. The wave itself moves to the right in the figure. This movement of the wave is actually the disturbance moving to the right, not the water itself (or the bird would move to the right). We define **wave velocity**  $v_w$  to be the speed at which the disturbance moves. Wave velocity is sometimes also called the *propagation velocity* or *propagation speed*, because the disturbance propagates from one location to another.

### Misconception Alert

Many people think that water waves push water from one direction to another. In fact, the particles of water tend to stay in one location, save for moving up and down due to the energy in the wave. The energy moves forward through the water, but the water stays in one place. If you feel yourself pushed in an ocean, what you feel is the energy of the wave, not a rush of water.



**FIGURE 16.28** An idealized ocean wave passes under a sea gull that bobs up and down in simple harmonic motion. The wave has a wavelength  $\lambda$ , which is the distance between adjacent identical parts of the wave. The up and down disturbance of the surface propagates parallel to the surface at a speed  $v_w$ .

The water wave in the figure also has a length associated with it, called its **wavelength**  $\lambda$ , the distance between adjacent identical parts of a wave. ( $\lambda$  is the distance parallel to the direction of propagation.) The speed of propagation  $v_w$  is the distance the wave travels in a given time, which is one wavelength in the time of one period. In equation form, that is

$$v_w = \frac{\lambda}{T} \quad 16.66$$

or

$$v_w = f\lambda. \quad 16.67$$

This fundamental relationship holds for all types of waves. For water waves,  $v_w$  is the speed of a surface wave; for sound,  $v_w$  is the speed of sound; and for visible light,  $v_w$  is the speed of light, for example.

### Take-Home Experiment: Waves in a Bowl

Fill a large bowl or basin with water and wait for the water to settle so there are no ripples. Gently drop a cork into the middle of the bowl. Estimate the wavelength and period of oscillation of the water wave that propagates away from the cork. Remove the cork from the bowl and wait for the water to settle again. Gently drop the cork at a height that is different from the first drop. Does the wavelength depend upon how high above the water the cork is dropped?

## EXAMPLE 16.8

### Calculate the Velocity of Wave Propagation: Gull in the Ocean

Calculate the wave velocity of the ocean wave in [Figure 16.28](#) if the distance between wave crests is 10.0 m and the time for a sea gull to bob up and down is 5.00 s.

#### Strategy

We are asked to find  $v_w$ . The given information tells us that  $\lambda = 10.0$  m and  $T = 5.00$  s. Therefore, we can use  $v_w = \frac{\lambda}{T}$  to find the wave velocity.

#### Solution

1. Enter the known values into  $v_w = \frac{\lambda}{T}$ :

$$v_w = \frac{10.0 \text{ m}}{5.00 \text{ s}}. \quad 16.68$$

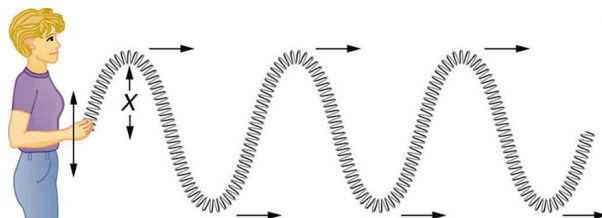
2. Solve for  $v_w$  to find  $v_w = 2.00$  m/s.

#### Discussion

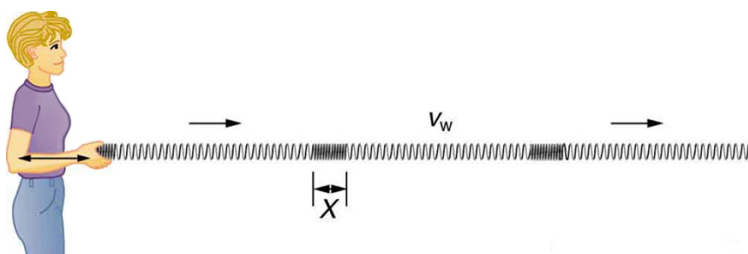
This slow speed seems reasonable for an ocean wave. Note that the wave moves to the right in the figure at this speed, not the varying speed at which the sea gull moves up and down.

### Transverse and Longitudinal Waves

A simple wave consists of a periodic disturbance that propagates from one place to another. The wave in [Figure 16.29](#) propagates in the horizontal direction while the surface is disturbed in the vertical direction. Such a wave is called a **transverse wave** or shear wave; in such a wave, the disturbance is perpendicular to the direction of propagation. In contrast, in a **longitudinal wave** or compressional wave, the disturbance is parallel to the direction of propagation. [Figure 16.30](#) shows an example of a longitudinal wave. The size of the disturbance is its amplitude  $X$  and is completely independent of the speed of propagation  $v_w$ .



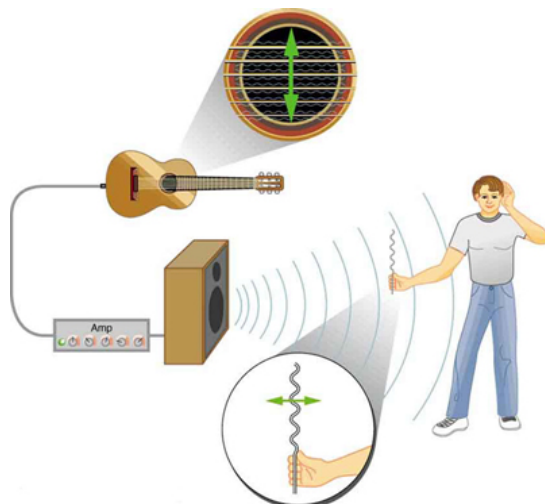
**FIGURE 16.29** In this example of a transverse wave, the wave propagates horizontally, and the disturbance in the cord is in the vertical direction.



**FIGURE 16.30** In this example of a longitudinal wave, the wave propagates horizontally, and the disturbance in the cord is also in the horizontal direction.

Waves may be transverse, longitudinal, or a *combination of the two*. (Water waves are actually a combination of transverse and longitudinal. The simplified water wave illustrated in [Figure 16.28](#) shows no longitudinal motion of the bird.) The waves on the strings of musical instruments are transverse—so are electromagnetic waves, such as visible light.

Sound waves in air and water are longitudinal. Their disturbances are periodic variations in pressure that are transmitted in fluids. Fluids do not have appreciable shear strength, and thus the sound waves in them must be longitudinal or compressional. Sound in solids can be both longitudinal and transverse.



**FIGURE 16.31** The wave on a guitar string is transverse. The sound wave rattles a sheet of paper in a direction that shows the sound wave is longitudinal.

Earthquake waves under Earth's surface also have both longitudinal and transverse components (called compressional or P-waves and shear or S-waves, respectively). These components have important individual characteristics—they propagate at different speeds, for example. Earthquakes also have surface waves that are similar to surface waves on water.

### ✓ CHECK YOUR UNDERSTANDING

Why is it important to differentiate between longitudinal and transverse waves?

#### **Solution**

In the different types of waves, energy can propagate in a different direction relative to the motion of the wave. This is important to understand how different types of waves affect the materials around them.



### PHET EXPLORATIONS

#### **Wave on a String**

Watch a string vibrate in slow motion. Wiggle the end of the string and make waves, or adjust the frequency and amplitude of an oscillator. Adjust the damping and tension. The end can be fixed, loose, or open.

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## 16.10 Superposition and Interference

### LEARNING OBJECTIVES

By the end of this section, you will be able to:

- Explain standing waves.
- Describe the mathematical representation of overtones and beat frequency.