Wolves are social animals, and they howl to communicate over distances of several miles with other members of their pack. How are such sounds made? How do they travel through the air? And how are other wolves able to hear these sounds from such a great distance?

Motion That Repeats Again and Again

Up to this point in the book, we have generally considered processes that have a clear starting and ending point, such as a car accelerating from rest to a final speed, or a solid being heated from an initial to a final temperature. In Part IV, we begin to consider processes that are *periodic*—they repeat. A child on a swing, a boat bobbing on the water, and even the repetitive bass beat of a rock song are *oscillatory motions* that happen over and over without a starting or ending point. The *period*, the time for one cycle of the motion, will be a key parameter for us to consider as we look at oscillatory motion.

Our first goal will be to develop the language and tools needed to describe oscillations, ranging from the swinging of the bob of a pendulum clock to the bouncing of a car on its springs. Once we understand oscillations, we will extend our analysis to consider oscillations that travel—*waves*.

The Wave Model

We've had great success modeling the motion of complex objects as the motion of one or more particles. We were even able to explain the macroscopic properties of matter, such as pressure and temperature, in terms of the motion of the atomic particles that comprise all matter.

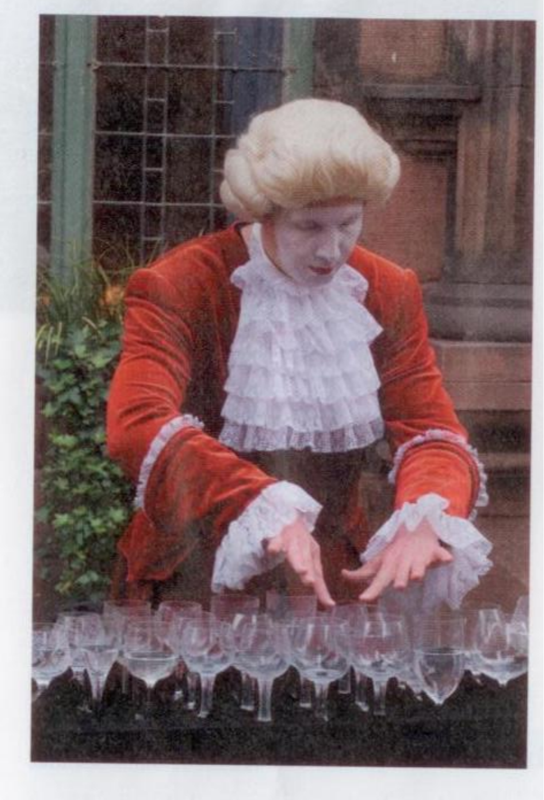
Now it's time to explore another way of looking at nature, the *wave model*. Familiar examples of waves include

- Ripples on a pond.
- The sound of thunder.
- The swaying ground of an earthquake.
- A vibrating guitar string.
- The colors of a rainbow.

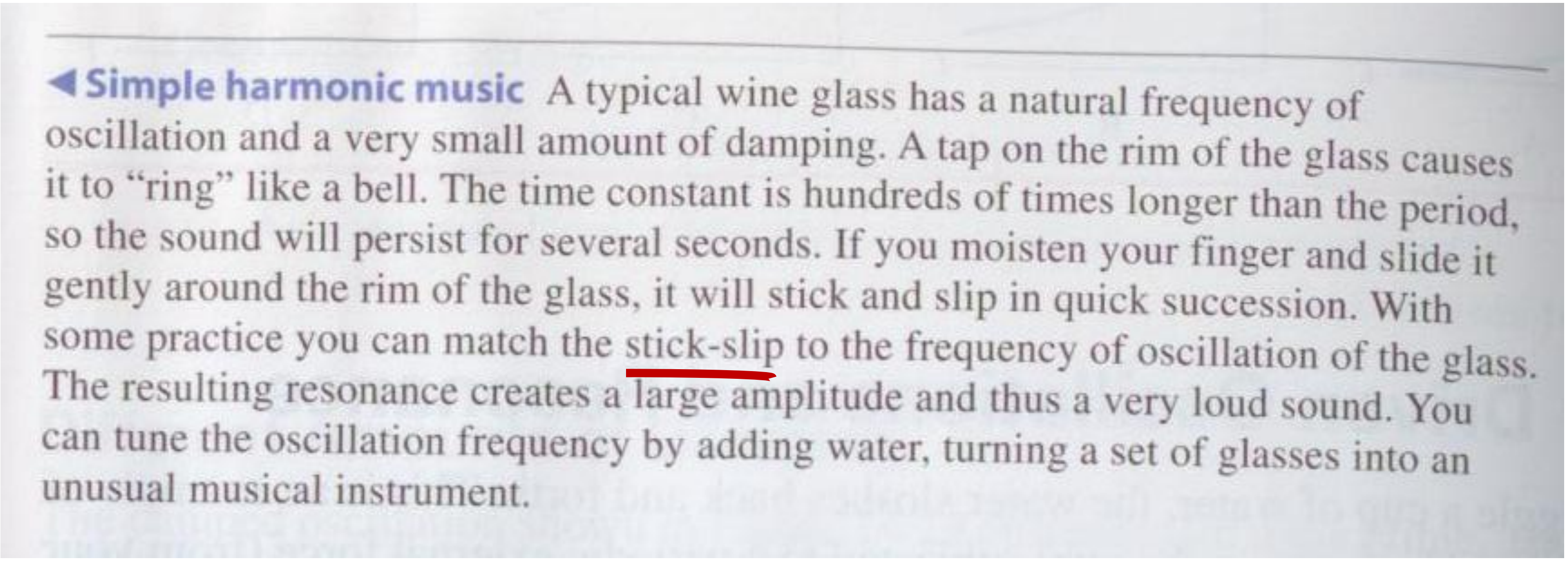
Despite the great diversity of types and sources of waves, there is a single, elegant physical theory that is capable of describing them all. Our exploration of wave phenomena will call upon water waves, sound waves, and light waves for examples, but our goal will be to emphasize the unity and coherence of the ideas that are common to *all* types of waves. As was the case with the particle model, we will use the wave model to explain a wide range of phenomena.

When Waves Collide

The collision of two particles is a dramatic event. Energy and momentum are transferred as the two particles head off in different directions. Something much gentler happens when two waves come together—the two waves pass through each other unchanged. Where they overlap, we get a *superposition* of the two waves. We will finish our discussion of waves by analyzing the standing waves that result from the superposition of two waves traveling in opposite directions. The physics of standing waves will allow us to understand how your vocal tract can produce such a wide range of sounds, and how your ears are able to analyze them.

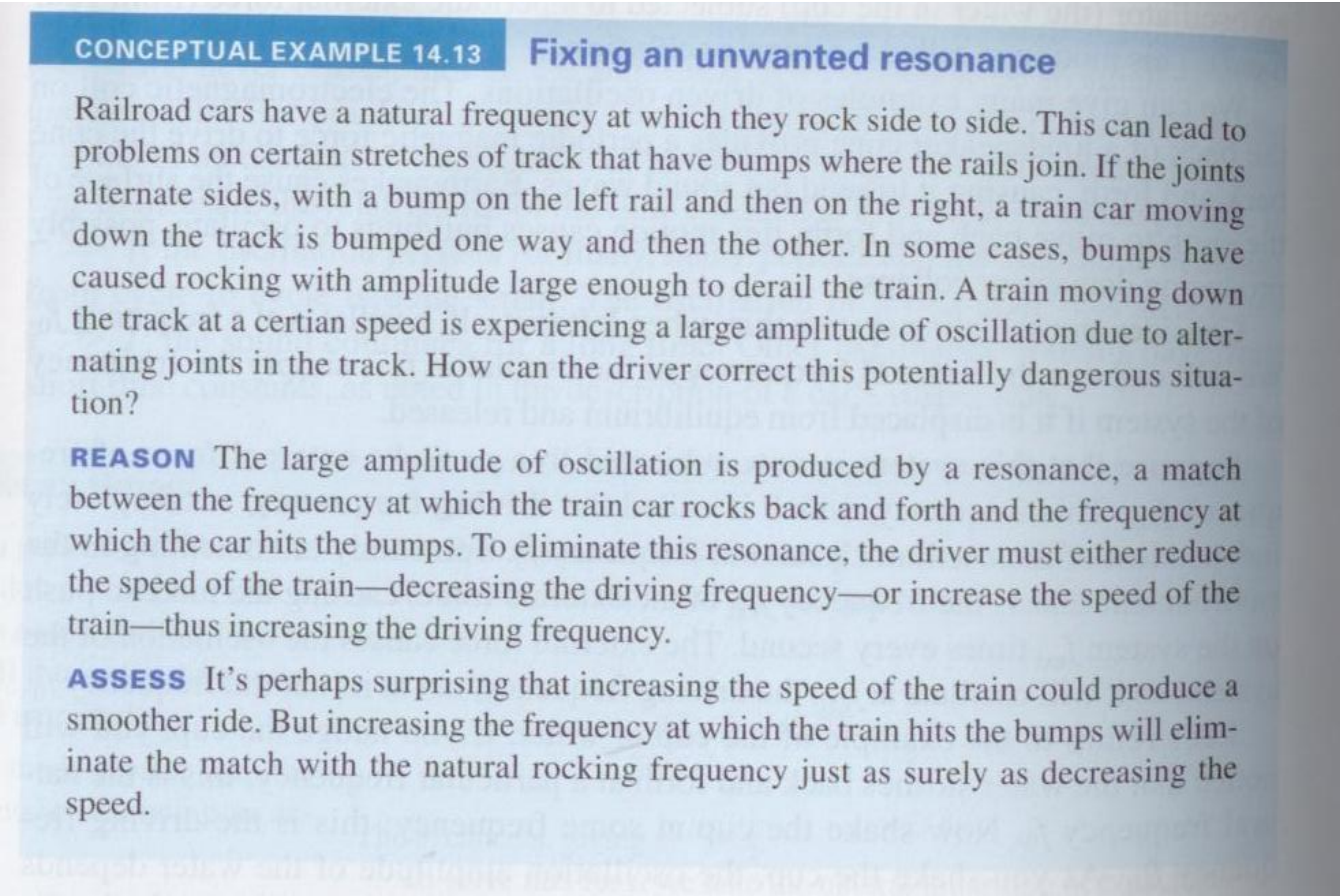


Natural Frequency – the frequency something likes to vibrate at.



◀ Simple harmonic music A typical wine glass has a natural frequency of oscillation and a very small amount of damping. A tap on the rim of the glass causes it to "ring" like a bell. The time constant is hundreds of times longer than the period, so the sound will persist for several seconds. If you moisten your finger and slide it gently around the rim of the glass, it will stick and slip in quick succession. With some practice you can match the stick-slip to the frequency of oscillation of the glass. The resulting resonance creates a large amplitude and thus a very loud sound. You can tune the oscillation frequency by adding water, turning a set of glasses into an unusual musical instrument.

Resonance – Driving frequency matches the natural frequency.



CONCEPTUAL EXAMPLE 14.13 **Fixing an unwanted resonance**

Railroad cars have a natural frequency at which they rock side to side. This can lead to problems on certain stretches of track that have bumps where the rails join. If the joints alternate sides, with a bump on the left rail and then on the right, a train car moving down the track is bumped one way and then the other. In some cases, bumps have caused rocking with amplitude large enough to derail the train. A train moving down the track at a certian speed is experiencing a large amplitude of oscillation due to alternating joints in the track. How can the driver correct this potentially dangerous situation?

REASON The large amplitude of oscillation is produced by a resonance, a match between the frequency at which the train car rocks back and forth and the frequency at which the car hits the bumps. To eliminate this resonance, the driver must either reduce the speed of the train—decreasing the driving frequency—or increase the speed of the train—thus increasing the driving frequency.

ASSESS It's perhaps surprising that increasing the speed of the train could produce a smoother ride. But increasing the frequency at which the train hits the bumps will eliminate the match with the natural rocking frequency just as surely as decreasing the speed.

FIGURE 14.26 The structures of the ear.

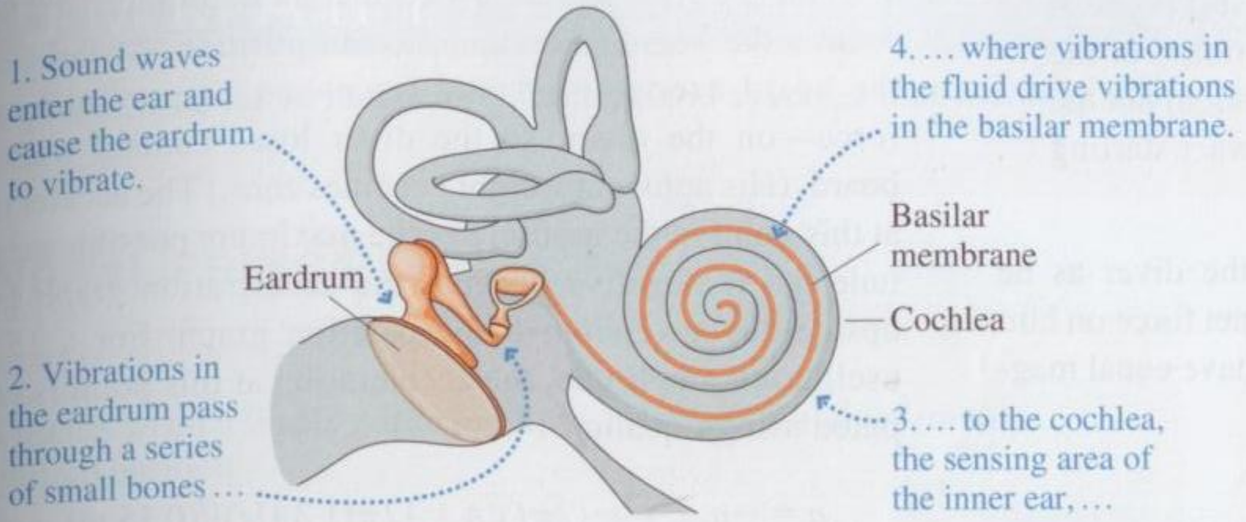
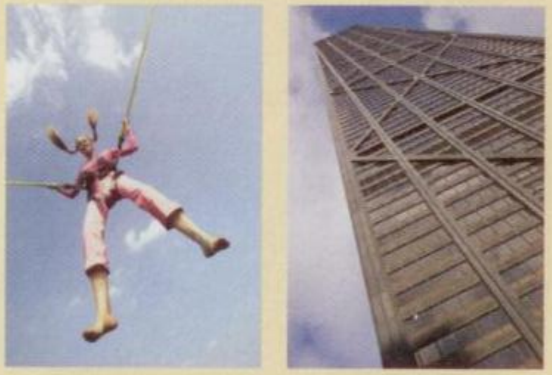


FIGURE 14.27 shows a very simplified model of the cochlea. As a sound wave travels down the cochlea, it causes a large-amplitude vibration of the basilar membrane at the point where the membrane's natural oscillation frequency matches the sound frequency—a resonance. Lower-frequency sound causes a response farther from the stapes. Sensitive hair cells on the membrane sense the vibration and send nerve signals to your brain. The fact that different frequencies produce maximal response at different positions allows your brain to very accurately determine frequency because a small shift in frequency causes a detectable change in the position of the maximal response. People with no musical training can listen to two notes and easily determine which is at a higher pitch.

We now know a bit about how your ear responds to the vibration of a sound wave—but how does this vibration get from a source to your ear? This is a topic we will consider in the next chapter, when we look at *waves,* oscillations that travel.

Spring Systems

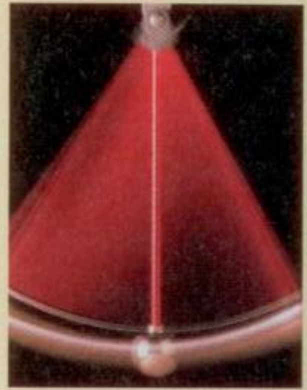
Oscillations occur in any system having a restoring force that pushes the system back toward an equilibrium position.



A person bouncing up and down on elastic cords and the swaying of a tall building in the wind are both examples of simple harmonic motion.

An oscillation is characterized by the **period** (the time for one oscillation) and the **amplitude** (the size of the oscillation).

Pendulum Systems



A mass swinging on the end of a rod or a cord is a **pendulum**—and another example of simple harmonic motion. Its motion is mathematically the same as that of a mass on a spring.

The period of a pendulum is determined by the pendulum length and the strength of gravity; the amplitude doesn't affect the period. This makes a pendulum the ideal basis for a clock.

The tuning fork oscillates at a particular frequency. There is one particular spot on a membrane in the inner ear that also oscillates at this exact frequency.

We'll see that the concept of **resonance** explains how your ear can distinguish different frequencies.

Related real-world example

Vibrations in the ear

Sound waves entering the ear cause the oscillation of a membrane in the cochlea. The vibration can be modeled as a mass on a spring. The period of oscillation of a segment of the membrane depends on mass (the thickness of the membrane) and stiffness (the rigidity of the membrane).

Motion of legs while walking

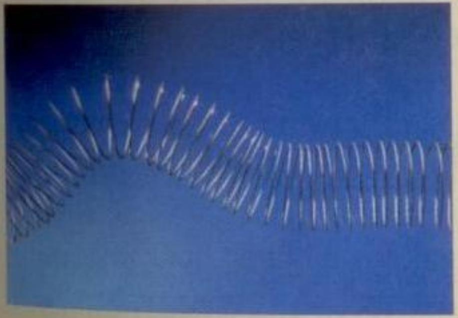
The motion of a walking animal's legs can be modeled as pendulum motion. The rate at which the legs swing depends on the length of the legs and the free-fall acceleration *g*.

This bat's ears are much more prominent than its eyes. It would appear that hearing is a much more important sense than sight for bats. How does a bat use sound waves to locate prey?

Fun Fact: **Bats are not blind!**

The Wave Model

A **wave** is a disturbance traveling through a medium.



The wave propagates, but the particles of the medium don't. Here the coils of a stretched spring simply move up and back down as the wave passes.

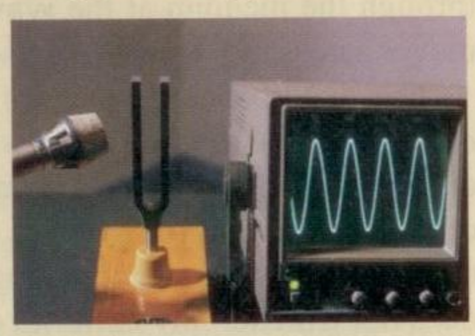
Wave Properties

A few basic quantities can describe any type of wave.

This train of ocean waves is periodic. How fast do the waves move? That's the wave **speed.** What is the distance between successive wave crests? That's the **wavelength.** How many waves strike the beach each minute? That's the **frequency.**

Types of Waves

Our model can describe any type of wave, from ocean waves to vibrating strings, but two types of waves are especially important: **sound** and **light.**



Displaying the sound waves from a tuning fork clearly shows their periodic nature.

Visible light comes in a range of wavelengths corresponding to the colors of the rainbow.

Energy and Intensity

All waves carry energy. How much? That's a question of **intensity.** Your ears are sensitive to sounds over a remarkable range of intensities, so we use the logarithmic **decibel** scale for sound intensity level.

A lens focuses sunlight onto a small area, increasing the intensity.

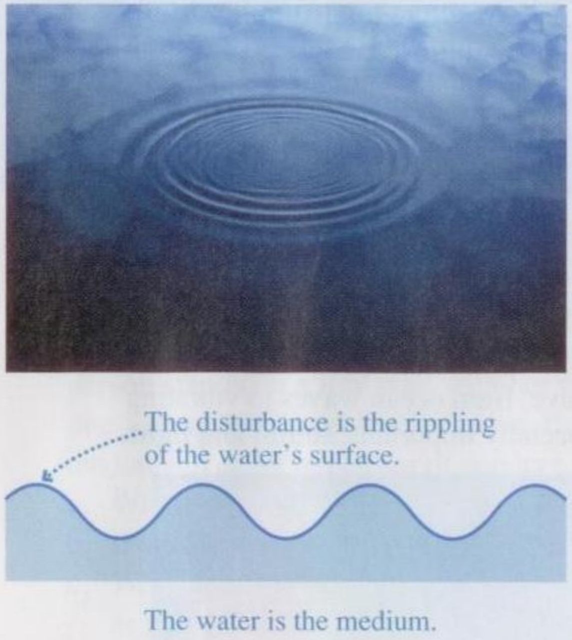


FIGURE 15.1 Ripples on a pond are a traveling wave.

Mechanical Waves

Mechanical waves are waves that involve the motion of a substance through which they move, the **medium.** For example, the medium of a water wave is the water, the medium of a sound wave is the air, and the medium of a wave on a stretched string is the string.

As a wave passes through a medium, the atoms that make up the medium are displaced from equilibrium, much like pulling a spring away from its equilibrium position. This is a **disturbance** of the medium. The water ripples of **FIGURE 15.1** are a disturbance of the water's surface.

A wave disturbance is created by a *source*. The source of a wave might be a rock thrown into water, your hand plucking a stretched string, or an oscillating loudspeaker cone pushing on the air. Once created, the disturbance travels outward through the medium at the **wave speed** v. This is the speed with which a ripple moves across the water or a pulse travels down a string.

The disturbance propagates through the medium, and a wave does transfer *energy*, but **the medium as a whole does not travel!** The ripples on the pond (the disturbance) move outward from the splash of the rock, but there is no outward flow of water. Likewise, the particles of a string oscillate up and down but do not move in the direction of a pulse traveling along the string. **A wave transfers energy, but it does not transfer any material or substance outward from the source.**

You may have been at a sporting event in which spectators do "The Wave." The wave moves around the stadium, but the spectators (the medium, in this case) stay right where they are. This is a clear example of the principle that a wave does not transfer any material.

Electromagnetic and Matter Waves

Mechanical waves require a medium, but there are waves that do not. Two important types of such waves are electromagnetic waves and matter waves.

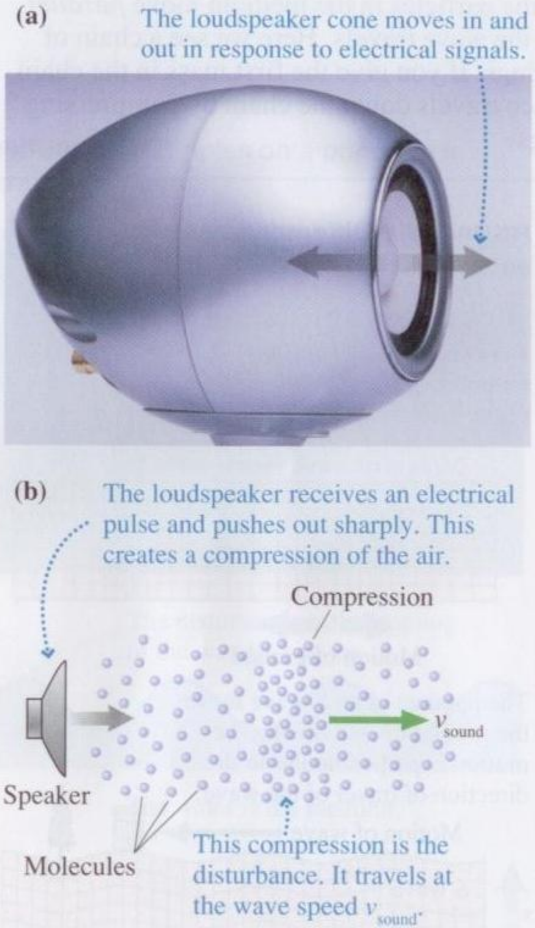
Electromagnetic waves are waves of an *electromagnetic field.* Electromagnetic waves are very diverse, including visible light, radio waves, microwaves, and x rays. Electromagnetic waves require no material medium and can travel through a vacuum; light can travel through space, though sound cannot. At this point, we have not defined what an "electromagnetic field" is, so we won't worry about the precise nature of what is "waving" in electromagnetic waves. The wave model can describe many of the important aspects of these waves without a detailed description of their exact nature. We'll look more closely at electromagnetic

Sound Waves

Next, let's see how a sound wave in air is created using a loudspeaker. When the loudspeaker cone in **FIGURE 15.4a** moves forward, it compresses the air in front of it, as shown in **FIGURE 15.4b**. The *compression* is the disturbance that travels forward through the air. This is much like the sharp push on the end of the chain of springs on the preceding page, so **a sound wave is a longitudinal wave.** We usually think of sound waves as traveling in air, but sound can travel through any gas, through liquids, and even through solids. A wave similar to that in Figure 15.4b is produced if you hit the end of a metal rod with a hammer.

The motion of a wave on a string is determined by the internal dynamics of the string. Similarly, the motion of a sound wave in air is determined by the physics of gases that we explored in Chapter 12. Once created, the wave in Figure 15.4b will propagate forward; its motion is entirely determined by the properties of the air.

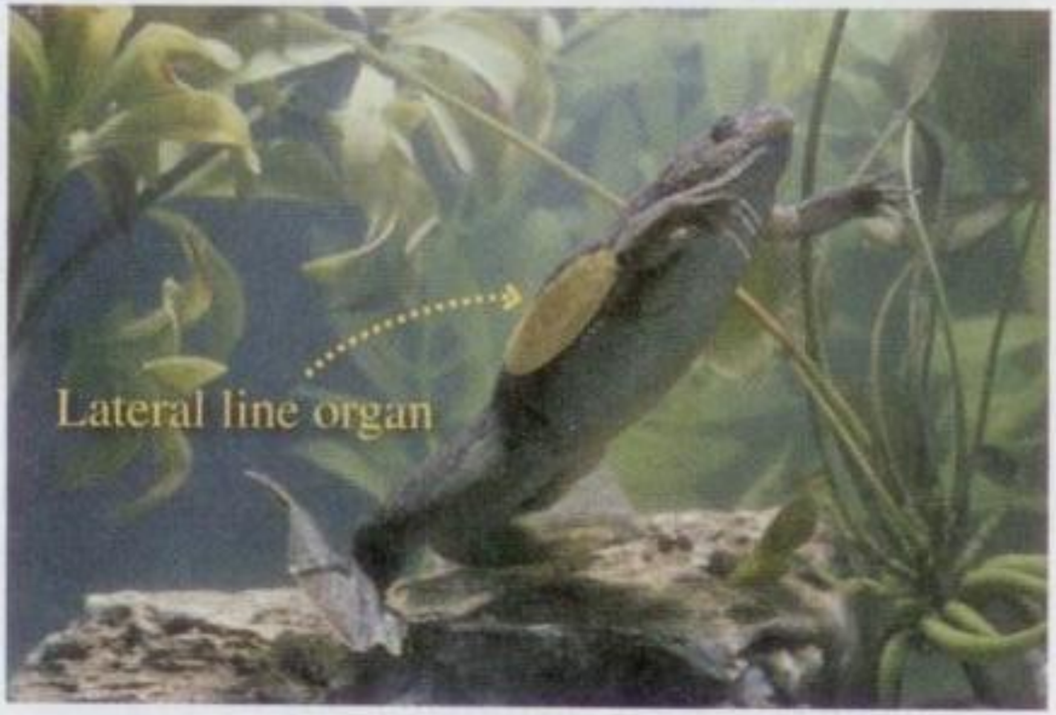
FIGURE 15.4 A sound wave produced by a loudspeaker.

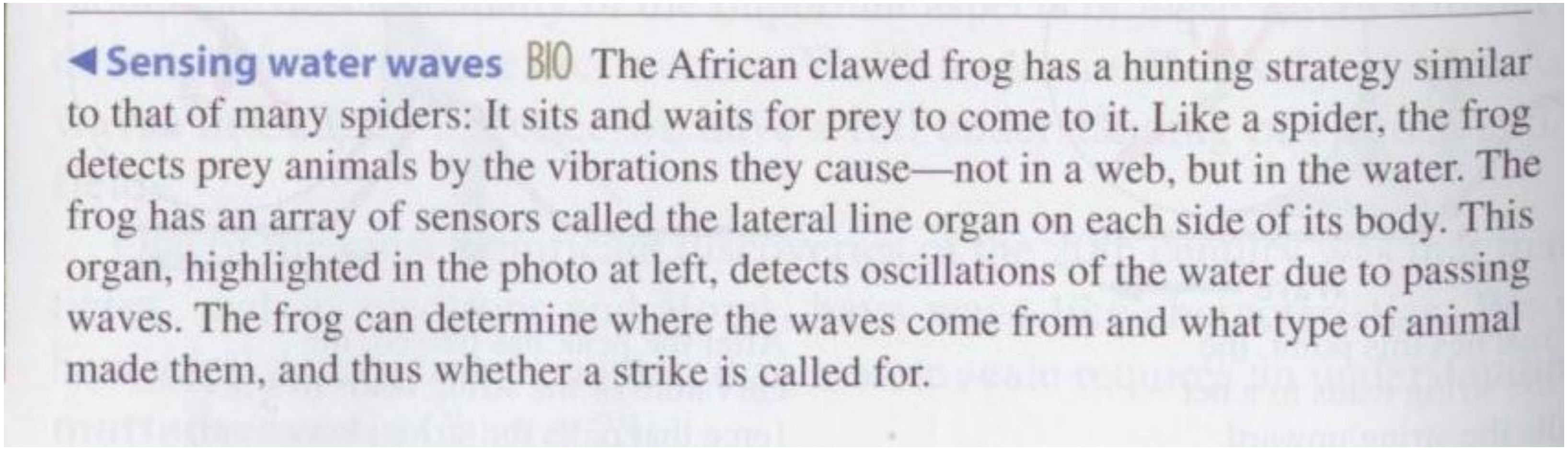


The loudspeaker cone moves in and out in response to electrical signals.

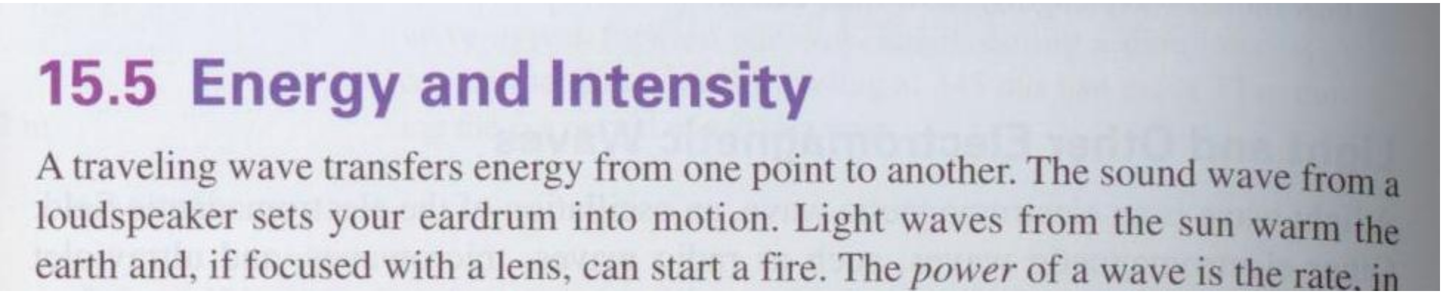
The loudspeaker receives an electrical pulse and pushes out sharply. This creates a compression of the air.

This compression is the disturbance. It travels at the wave speed v_{sound}.





◀ **Sensing water waves** BIO The African clawed frog has a hunting strategy similar to that of many spiders: It sits and waits for prey to come to it. Like a spider, the frog detects prey animals by the vibrations they cause—not in a web, but in the water. The frog has an array of sensors called the lateral line organ on each side of its body. This organ, highlighted in the photo at left, detects oscillations of the water due to passing waves. The frog can determine where the waves come from and what type of animal made them, and thus whether a strike is called for.



15.5 Energy and Intensity

A traveling wave transfers energy from one point to another. The sound wave from a loudspeaker sets your eardrum into motion. Light waves from the sun warm the earth and, if focused with a lens, can start a fire. The *power* of a wave is the rate, in

The better to hear you with BIO The great grey owl has its ears on the front of its face, hidden behind its facial feathers. Its round face works like a radar dish, collecting the energy of sound waves and "funneling" it into the ears. Collecting sound over a large area in this manner allows owls to sense very quiet sounds. Having ears on the front of the face allows them to precisely determine the source of sounds as well, an asset for a bird of prey. These owls can hear—and locate—mice moving underneath a thick blanket of snow.