 VIBRATIONS

AND WAVES

Objectives

• Describe the period of a

 pendulum. (25.1)

• Describe the characteristics and

 properties of waves. (25.2)

• Describe wave motion. (25.3)

• Describe how to calculate the

 speed of a wave. (25.4)

• Give examples of transverse

 waves. (25.5)

• Give an example of a

 longitudinal wave. (25.6)

• Explain what causes

 interference patterns. (25.7)

• Describe how a standing wave

 occurs. (25.8)

• Describe how the apparent

 frequency of waves change as a

 wave source moves. (25.9)

• Describe bow waves. (25.10)

• Describe sonic booms. (25.11)

5

THE BIG

VIBRATIONS

AND WAVES

........

Waves transmit energy through

space and time.

IDEA

discover!

MATERIALS

foam cup, water

 Regions of

still water, nodes, and regions

of choppy water, antinodes,

should be observable. This

pattern is the result of the

interference of traveling

waves reflecting from the

vibrating walls of the cup.

EXPECTED OUTCOME

ANALYZE AND CONCLUDE

 ll around us we see things that wiggle and jiggle. Even

 things too small to see, such as atoms, are constantly

 wiggling and jiggling. A repeating, back-and-forth

motion about an equilibrium position is a vibration.

A vibration cannot exist in one instant. It needs

time to move back and forth. Strike a bell and

the vibrations will continue for some time

before they die down.

 A disturbance that is transmitted pro-

gressively from one place to the next

with no actual transport of matter is

a wave. A wave cannot exist in one

place but must extend from one place

to another. Light and sound are both

forms of energy that move through

space as waves. This chapter is about

vibrations and waves, and the follow-

ing chapters continue with the study of

sound and light.

A

discover!

What Are Standing Waves?

1. Fill a foam cup nearly to the top with water.

 Place the cup on a smooth, dry surface.

2. While applying a moderate downward pres-

 sure, drag the cup across the surface.

3. Adjust the downward pressure on the cup

 until a pattern of waves, called standing

 waves, appears on the surface of the water.

4. Now try to change the pattern by altering

 both the speed of the cup and the downward

 pressure.

Analyze and Conclude

1. Observing Describe the patterns that you

 produced on the surface of the water.

2. Predicting What do you think might happen if

 you were to drag the cup on a different kind

 of surface?

3. Making Generalizations Do you think stand-

 ing waves can be produced in other media?

 Explain.

1. Students should observe

 regions of still water and

 regions of choppy water.

2. The pattern changes

 because the cup vibrates

 differently on different

 surfaces.

3. Yes, because waves travel in

 all media and interference

 is a characteristic of waves.

490

490

25.1 Vibration of a

25.1 Vibration of a Pendulum

Suspend a stone at the end of a string and you have a simple pen-

dulum. Pendulums like the one in Figure 25.1 swing back and forth

with such regularity that they have long been used to control the

motion of clocks. Galileo discovered that the time a pendulum takes

to swing back and forth through small angles depends only on the

length of the pendulum—the mass has no effect. The time of a

back-and-forth swing of the pendulum is called the period.

 The period of the pendulum depends only on the length of a

pendulum and the acceleration of gravity. 25.1

 A long pendulum has a longer period than a shorter pendulum;

that is, it swings back and forth more slowly—less frequently—than a

short pendulum. When walking, we allow our legs to swing with the

help of gravity, like a pendulum. In the same way that a long pendu-

lum has a greater period, a person with long legs tends to walk with

a slower stride than a person with short legs. This is most noticeable

in long-legged animals such as giraffes and horses, which run with a

slower gait than do short-legged animals such as hamsters and mice.

CONCEPT

Pendulum

Key Terms

period, vibration, waves

 Teaching Tip Distinguish

between a simple pendulum (the

bob is very small compared to the

length of string) and a physical

pendulum (the stick makes up

a significant part of the mass).

Explain that their rotational

inertias are different.

 Ask What principle of

mechanics accounts for the

different periods of pendulums

of different lengths? Rotational

inertia

FIGURE 25.1

Two pendulums of the same

length have the same period

regardless of mass.

Demonstration

Attach a small heavy weight

to the end of a piece of string

about 1 m long. Swing it

to and fro: this is a simple

pendulum. Identify frequency

and period. Time how long

the pendulum takes to make

10 complete cycles. Repeat

to show that the result does

not change from trial to trial.

Divide the time by 10 to get

the period. Add more mass to

the end of the string without

changing the overall length of

the pendulum. Time 10 more

cycles to show that weight

does not affect the period.

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CHECK

What determines the period of a pendulum?

25.2 Wave Description

The back-and-forth vibratory motion (often called oscillatory

motion) of a swinging pendulum is called simple harmonic

motion. 25.2 The pendulum bob filled with sand in Figure 25.2

exhibits simple harmonic motion above a conveyor belt. When the

conveyor belt is stationary, the sand traces out a straight line. More

interestingly, when the conveyor belt is moving at constant speed, the

sand traces out a special curve known as a sine curve. A sine curve

is a pictorial representation of a wave. The source of all waves is

something that vibrates.

think!

What is the frequency in

vibrations per second of a

100-Hz wave?

Answer: 25.2.1

FIGURE 25.2

Frank Oppenheimer, founder

of the Exploratorium® science

museum in San Francisco, demon-

strates that a pendulum swinging

back and forth traces out a straight

line over a stationary surface and a

sine curve when the surface moves

at constant speed.

 The period of the

CHECK pendulum depends

only on the length of a pendulum

and the acceleration of gravity.

CONCEPT

Teaching Resources

• Problem-Solving Exercises in

 Physics 12-1, 12-2

• Laboratory Manual 68, 69

• Probeware Lab Manual 13

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CHAPTER 25

VIBRATIONS AND WAVES

491

491

25.2 Wave

Description

Key Terms

simple harmonic motion, sine

curve, crest, trough, amplitude,

wavelength, frequency, hertz

 Teaching Tip Begin by

tapping your lecture table or the

chalkboard. Call attention to how

frequently you tap and relate

this to the term frequency. Call

attention to the time interval

between taps and relate this

to the period. Establish the

reciprocal relationship between

frequency and period.

 Teaching Tip Move a piece of

chalk up and down on the board,

tracing and retracing a vertical

straight line. Call attention to

how “frequently” you oscillate

the chalk, again tying this to

the definition of frequency.

Discuss the idea of displacement

and amplitude (maximum

displacement). With appropriate

motions, show different

frequencies and different

amplitudes. Then do the same

while walking across the front

of the board tracing out a sine

wave. Repeat showing waves of

different wavelengths.

 Teaching Tip Point out that

since a vibration is also called a

cycle, one hertz is also one cycle

per second.

(1 kHz 5 103 cycles/s;

1 MHz 5 106 cycles/s)

FIGURE 25.3

A sine curve is a pictorial

representation of a wave.

Be clear about the

distinction between

frequency and speed.

How frequently a wave

vibrates is altogether

different from how fast

it moves from one loca-

tion to another.

The Parts of a Wave A weight attached to a spring undergoes

vertical simple harmonic motion as shown in Figure 25.3. A marking

pen attached to the bob traces a sine curve on a sheet of paper that

is moving horizontally at constant speed. Like a water wave, the high

points on a wave are called crests. The low points on a wave are

called troughs. The straight dashed line represents the “home” posi-

tion, or midpoint of the vibration. The term amplitude refers to the

distance from the midpoint to the crest (or trough) of the wave. So

the amplitude equals the maximum displacement from equilibrium.

 The wavelength of a wave is the distance from the top of one

crest to the top of the next one. Or equivalently, the wavelength is the

distance between successive identical parts of the wave. The wave-

lengths of waves at the beach are measured in meters, the wavelengths

of ripples in a pond in centimeters, and the wavelengths of light in

billionths of a meter (nanometers).

Frequency The number of vibrations an object makes in a unit of

time is an object’s frequency. The frequency of a vibrating pendu-

lum, or object on a spring, specifies the number of back-and-forth

vibrations it makes in a given time (usually one second). A complete

back-and-forth vibration is one cycle. If it occurs in one second, the

frequency is one vibration per second or one cycle per second. If two

vibrations occur in one second, the frequency is two vibrations or

two cycles per second. The frequency of the vibrating source and the

frequency of the wave it produces are the same.

 The unit of frequency is called the hertz (Hz). A frequency of

one cycle per second is 1 hertz, two cycles per second is 2 hertz, and

so on. Higher frequencies are measured in kilohertz (kHz—thou-

sands of hertz), and still higher frequencies in megahertz (MHz—

millions of hertz) or gigahertz (GHz—billions of hertz). AM radio

waves are broadcast in kilohertz, while FM radio waves are broadcast

in megahertz; radar and microwave ovens operate at gigahertz. A

station at 960 kHz broadcasts radio waves that have a frequency of

960,000 hertz. A station at 101 MHz broadcasts radio waves with a

frequency of 101,000,000 hertz. As Figure 25.4 shows, these radio-

wave frequencies are the frequencies at which electrons vibrate in the

transmitting antenna of a radio station.

FIGURE 25.4

Electrons in the transmitting

antenna of a radio station at

960 kHz on the AM dial

vibrate 960,000 times each

second and produce

960-kHz radio waves.

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 If the frequency of a vibrating object is known, its period can be

calculated, and vice versa. Suppose, for example, that a pendulum

makes two vibrations in one second. Its frequency is 2 Hz. The time

needed to complete one vibration—that is, the period of vibration—

is 1/2 second. Or if the vibration period is 3 Hz, then the period is 1/3

second. As you can see below, frequency and period are inverses of

each other:

 11

 frequencyor period

 periodfrequency

CONCEPT

think!

The Sears Tower in

Chicago sways back and

forth at a frequency of

about 0.1 Hz. What is

its period of vibration?

Answer: 25.2.2

 The source of all

CHECK waves is something

that vibrates.

CONCEPT

Teaching Resources

• Reading and Study

 Workbook

• Transparency 50

• PresentationEXPRESS

• Interactive Textbook

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CHECK

What is the source of all waves?

25.3 Wave Motion

 Common Misconception

When a wave travels in a medium,

the medium moves with the wave.

 As a wave travels through

a medium, there is no transfer of

matter.

FACT

25.3 Wave Motion

Most of the information around us gets to us in some form of wave.

Sound is energy that travels to our ears in the form of a wave. Light is

energy that comes to our eyes in the form of a different kind of wave

(an electromagnetic wave). The signals that reach our radio and tele-

vision sets also travel in the form of electromagnetic waves.

 When energy is transferred by a wave from a vibrating source to a

distant receiver, there is no transfer of matter between the two points.

To see this, think about the very simple wave produced when one end

of a horizontally stretched string is shaken up and down as shown

in Figure 25.5. After the end of the string is shaken, a rhythmic dis-

turbance travels along the string. Each part of the string moves up

and down while the disturbance moves horizontally along the length

of the string. It is the disturbance that moves along the length of the

string, not parts of the string itself.

Link to ENTOMOLOGY

 Noisy Bugs Big bumblebees flap

 their wings at about 130 flaps per

 second, and produce sound of 130 Hz.

 A honeybee flaps its wings at 225 flaps

 per second and produces a higher-

 pitched sound of 225 Hz. The annoying

 high-pitched whine of a mosquito

results from its wings flapping at 600 Hz. These sounds are produced

by pressure variations in the air caused by vibrating wings.

FIGURE 25.5

When the string is shaken

up and down, a disturbance

moves along the string.

 Teaching Tip Point out that

if a leaf is floating in a pond as

a wave passes, the leaf will move

up and down with the water

but will not move along with

the wave.

Demonstration

Have a student hold one

end of a stretched spring or

a Slinky while you hold the

other. Send transverse pulses

along it, stressing the idea

that the disturbance rather

than the medium moves along

the spring. Shake the spring

and produce a sine wave. Then

send a stretch and squeeze

(elongation and compression)

down the spring, showing

a longitudinal pulse. Send a

sequence of pulses and you

have a wave. After some

discussion, produce standing

waves.

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CHAPTER 25

VIBRATIONS AND WAVES

493

493

discover!

MATERIALS

pen, paper, wide

pan, water

 In Part 1,

students will create a pictorial

representation of a wave.

They will observe the same

pattern as in Figure 25.2. In

Part 2, students will actually

make waves.

EXPECTED OUTCOME

THINK, PART 1

FIGURE 25.6

A circular water wave in a still

pond moves out from the center

in an expanding circle.

The wavelength

The wavelength

increases.

THINK, PART 2

decreases.

For: Links on wave motion

Visit: www.SciLinks.org

Web Code: csn – 2503

 Drop a stone in a quiet pond and you’ll produce a wave that

moves out from the center in an expanding circle as shown in Figure

25.6. It is the disturbance that moves, not the water, for after the dis-

turbance passes, the water is where it was before the wave passed.

 When someone speaks to you from across the room, the sound wave

is a disturbance in the air that travels across the room. The air molecules

themselves do not move along, as they would in a wind. The air, like the

rope and the water in the previous examples, is the medium through

which wave energy travels. The energy transferred by a wave from

a vibrating source to a receiver is carried by a disturbance in a

medium. Energy is not transferred by matter moving from one place to

another within the medium.

CONCEPT

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CHECK

How does a wave transfer energy?

discover!

Making Waves

Part 1

 The energy

CHECK transferred by a

wave from a vibrating source

to a receiver is carried by a

disturbance in a medium.

CONCEPT

1. Oscillate a marking pen back and forth across a piece of paper

 as you slowly pull the paper in a direction perpendicular to your

 oscillation.

2. Repeat Step 1, but pull the paper faster this time.

3. Think What happens to the wavelength of the curves when you

 pull the paper faster?

Teaching Resources

• Reading and Study

 Workbook

• Problem-Solving Exercises

 in Physics 13-1

• PresentationEXPRESS

• Interactive Textbook

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Part 2

1. Repeatedly dip your finger into a wide pan of water to make

 circular waves on the surface.

2. Repeat Step 1, but dip your finger more frequently.

3. Think What happens to the wavelength of the waves when you dip

 your finger more frequently?

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25.4 Wave Speed

think!

If a water wave vibrates up and down two times each second and the

distance between wave crests is 1.5 m, what is the frequency of the wave?

What is its wavelength? What is its speed? Answer: 25.4.1

 Teaching Tip Explain that the

frequency of a vibrating source is

the same as the frequency of the

wave it produces.

 Teaching Tip Explain or

derive wave speed: Speed 5

wavelength 3 frequency.

Support this with the freight

car example.

 Teaching Tip Have students

calculate the wavelengths of

their favorite local radio stations.

Wavelength 5 speed/frequency.

For example, 1000-kHz waves

have wavelengths 5 (3 3 108 m/s)/

(106 Hz) 5 300 m. Surprisingly

long!

25.4 Wave Speed

The speed of a wave depends on the medium through which the wave

moves. Sound waves, for example, move at speeds of about

330 m/s to 350 m/s in air (depending on temperature), and about four

times faster in water. Whatever the medium, the speed, wavelength,

and frequency of the wave are related. Consider the simple case of

water waves, as shown in Figure 25.7. Imagine that you fix your eyes

at a stationary point on the surface of water and observe the waves

passing by this point. If you observe the distance between crests (the

wavelength) and also count the number of crests that pass each

second (the frequency), then you can calculate the horizontal

distance a particular crest moves each second. For example, in

Figure 25.7, one crest passes by the bird every second. The waves

therefore move at 1 meter per second.

 You can calculate the speed of a wave by multiplying the

wavelength by the frequency. For example, if the wavelength is

3 meters and if two crests pass a stationary point each second, then

3 meters 2 waves pass by in 1 second. The waves therefore move at

6 meters per second. In equation form, this relationship is written as

v

f

where v is wave speed, l (Greek letter lambda) is wavelength, and

f is wave frequency. This relationship holds for all kinds of waves,

whether they are water waves, sound waves, radio waves, or light waves.

 fThe equation v

makes sense: During

each vibration, a wave

travels a distance of one

wavelength.

FIGURE 25.7

If the wavelength is 1 meter, and one

wavelength per second passes the pole,

then the speed of the wave is 1 m/s.

CHAPTER 25

VIBRATIONS AND WAVES

495

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Be sure to distinguish

electromagnetic waves from

longitudinal sound waves.

Consider discussing Chapter 27

and Chapter 37 material here

to lead into the family of

electromagnetic waves. Show

how electromagnetic waves

are grouped according to their

wavelengths and frequencies.

Table 25.1

Wavelength (m)

Sound Waves

Frequency (Hz)

Wave Speed (m/s)

2.13

1.29

0.86

0.64

160

264

396

528

340

340

340

340

think!

What is the wavelength

of a 340-Hz sound wave

when the speed of sound

in air is 340 m/s?

Answer: 25.4.2

 Table 25.1 shows some wavelengths and corresponding frequen-

cies of sound in air at the same temperature. Notice that the product of

wavelength and frequency is the same for each example—340 m/s in this

case. During a concert, you do not hear the high notes in a chord before

you hear the low notes. The sounds of all instruments reach you at the

same time. Notice that long wavelengths have low frequencies, and short

wavelengths have high frequencies. Wavelength and frequency vary

inversely to produce the same wave speed for all sounds.

CONCEPT

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CHECK

How do you calculate the speed of a wave?

do the math!

If a train of freight cars, each 10 m long, rolls by you at the rate

of 2 cars each second, what is the speed of the train?

You can look at this problem in two ways, the Chapter 4 way and the

Chapter 25 way.

 From Chapter 4 recall:

v

d

t

2

 10 m

1s

20 m/s

Note that d is the length of that part of the train that passes you in

time t.

 Here in Chapter 25 we compare the train to wave motion,

where the wavelength corresponds to 10 m, and the frequency is

2 Hz. Then

wave speed

wavelength frequency

(10 m) (2 Hz)20 m/s

 You can calculate the

CHECK speed of a wave by

multiplying the wavelength by

the frequency.

CONCEPT

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Teaching Resources

• Reading and Study

 Workbook

• PresentationEXPRESS

• Interactive Textbook

 One of the nice things about physics is that different ways of

looking at things produce the same answer. When this doesn’t hap-

pen, and there is no error in computation, then the validity of one (or

both!) of those ways is suspect.

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25.5 Transverse

FIGURE 25.8

A person creates a trans-

verse wave by shaking

the free end of a rope up

and down. The arrows

represent the motion of

the rope.

Waves

Key Term

transverse wave

 Waves in the

CHECK stretched strings

of musical instruments and the

electromagnetic waves that

make up radio waves and light

are transverse.

CONCEPT

25.5 Transverse Waves

Suppose you create a wave along a rope by shaking the free end up

and down, as shown in Figure 25.8. The motion of the rope is at right

angles to the direction in which the wave is moving. Whenever the

motion of the medium is at right angles to the direction in which

 Waves in thea wave travels, the wave is a transverse wave.

stretched strings of musical instruments and the electromagnetic

waves that make up radio waves and light are transverse.

CONCEPT

25.6 Longitudinal

Waves

Key Term

longitudinal wave

 Teaching Tip Allow

students to play with large

springs or Slinkys until they can

demonstrate and explain the

difference between transverse

and longitudinal waves.

 Ask With respect to the

direction of the wave’s motion,

how do the directions of

vibrations differ for transverse

and longitudinal waves?

Perpendicular for transverse;

parallel for longitudinal

......

CHECK

What are some examples of transverse waves?

25.6 Longitudinal Waves

Not all waves are transverse. Sometimes the particles of the

medium move back and forth in the same direction in which the

wave travels. When the particles oscillate parallel to or along the

direction of the wave rather than at right angles to it, the wave is

 Sound waves are longitudinal waves.a longitudinal wave.

 Both transverse and longitudinal waves can be demonstrated with

a loosely-coiled spring, as shown in Figure 25.9. A transverse wave is

demonstrated by shaking the end of a coiled spring up and down. A

longitudinal wave is demonstrated by shaking the end of the coiled

spring in and out. In this case we see that the medium vibrates paral-

lel to the direction of energy transfer.

CONCEPT

......

CHECK

What is an example of a longitudinal wave?

CONCEPT

Transverse and longitudi-

nal waves transfer energy

from left to right.

a. When the end of a

coiled spring is shaken up

and down, a transverse

wave is produced.

b. When it is shaken in

and out, a longitudinal

wave is produced.

CHAPTER 25

VIBRATIONS AND WAVES

CHECK

Teaching Resources

• Reading and Study

 Workbook

• Transparency 51

• PresentationEXPRESS

• Interactive Textbook

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FIGURE 25.9

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Sound waves are

longitudinal waves.

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25.7 Interference

Key Terms

interference pattern,

constructive interference,

destructive interference, out of

phase, in phase

 Teaching Tip Describe

interference by drawing

Figure 25.10 on the board. If

you have a ripple tank, show

the overlapping of water waves

and interference.

Physics on the Job

Seismologist

When an earthquake occurs, the sudden release of energy produces

waves. Seismologists study and interpret those waves in order to

determine the strength and location of the earthquake. They compare

the speed, amplitude, and reception of primary longitudinal waves

with secondary transverse waves. Because they understand how waves

travel and the materials through which they pass, seismologists are

able to describe earthquakes, learn about the composition of Earth,

and possibly predict future earthquakes. Seismologists conduct

research from university and government facilities, such as the National

Earthquake Information Service (NEIS) in Colorado.

25.7 Interference

A material object such as a rock will not share its space with another

rock. But more than one vibration or wave can exist at the same

time in the same space. If you drop two rocks in water, the waves

produced by each can overlap and form an interference pattern.

An interference pattern is a regular arrangement of places where

wave effects are increased, decreased, or neutralized. Interference

patterns occur when waves from different sources arrive at the

same point—at the same time.

 In constructive interference, the crest of one wave overlaps the

crest of another and their individual effects add together. The result

is a wave of increased amplitude. As Figure 25.10a shows, this is

called reinforcement. In destructive interference, the crest of one

wave overlaps the trough of another and their individual effects are

reduced. The high part of one wave simply fills in the low part of

another. As Figure 25.10b shows, this is called cancellation.

Sound, a longitudinal

wave, requires a medium.

It can’t travel in a vacuum

because there’s nothing

to compress and stretch.

FIGURE 25.10

There are two types of wave

interference. a. In construc-

tive interference, the waves

reinforce each other to pro-

duce a wave of increased

amplitude. b. In destructive

interference, the waves can-

cel each other and no wave

is produced.

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FIGURE 25.11

a. Two overlapping water

waves produce an interfer-

ence pattern.

b. Overlapping concentric

circles produce a pictorial

representation of an interfer-

ence pattern.

 Teaching Tip Make a pair

of transparencies of concentric

circles. Superimpose them on

your overhead projector and

show the variety of interference

patterns that result when their

centers are displaced. One

example is shown in Figure 25.12.

 Ask Can waves overlap

in such a way as to produce

a zero amplitude? Yes, that is

the destructive interference

characteristic of all waves.

a

b

 Wave interference is easiest to see in water. Figure 25.11a shows

the interference pattern made when two vibrating objects touch the

surface of water. The gray “spokes” are regions where waves cancel

each other out. At points along these regions, the waves from the two

objects arrive “out of step,” or out of phase, with one another. When

waves are out of phase, the crests of one wave overlap the troughs

of another to produce regions of zero amplitude. The dark and light-

striped regions are where the waves are “in step,” or in phase, with

each other. When waves are in phase, the crests of one wave overlap

the crests of the other, and the troughs overlap as well.

 Interference patterns are nicely illustrated by

the overlapping of concentric circles printed on a

pair of clear sheets, as shown in Figures 25.11b and

25.12. When the sheets overlap with their centers

slightly apart, a so-called moiré pattern is formed

that is very similar to the interference pattern of

water waves (or any kind of waves). A slight shift

in either of the sheets produces noticeably differ-

ent patterns. If a pair of such sheets is available,

be sure to try this and see the variety of patterns

for yourself.

 Interference is characteristic of all wave

motion, whether the waves are water waves, sound

waves, or light waves. The interference of sound is

discussed in the next chapter, and the interference

of light in Chapter 31.

CONCEPT

FIGURE 25.12

A moiré pattern is very similar

to an interference pattern.

 Interference patterns

CHECK occur when waves

from different sources arrive at

the same point—at the same

time.

CONCEPT

Teaching Resources

• Reading and Study

 Workbook

• Laboratory Manual 71

• PresentationEXPRESS

• Interactive Textbook

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CHECK

What causes interference patterns?

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CHAPTER 25

VIBRATIONS AND WAVES

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25.8 Standing

Waves

Key Terms

standing wave, node, antinode

 Teaching Tip Emphasize that

a standing wave is the result of

interference.

 Teaching Tip Use a long thin

spring or a rope to demonstrate

standing waves. Have students

identify the nodes and come up

close to inspect them. Change

the frequency and show that only

specific frequencies allow the

creation of standing waves.

 Teaching Tidbit Figure

25.14a shows the lowest

frequency of vibration of a

standing wave—the fundamental

frequency.

 Teaching Tip Point out that

for a string free at one end and a

tube open at one end and closed

at the other end, standing waves

form when odd integer multiples

of quarter wavelengths fit into

the vibrating medium. A soda-

pop bottle is an example of a

tube open at one end and closed

at the other end.

think!

Is it possible for one wave

to cancel another wave so

that the combined ampli-

tude is zero? Explain your

answer.

Answer: 25.8

25.8 Standing Waves

If you tie a rope to a wall and shake the free end up and down, you

will produce a wave in the rope. The wall is too rigid to shake, so

the wave is reflected back along the rope to you. By shaking the rope

just right, you can cause the incident (original) and reflected waves

to form a standing wave. A standing wave is a wave that appears to

stay in one place—it does not seem to move through the medium.

Certain parts of a standing wave remain stationary. Nodes are the

stationary points on a standing wave.

 Interestingly enough, you could hold your fingers on either side

of the rope at a node, and the rope would not touch them. Other

parts of the rope would make contact with your fingers. The posi-

tions on a standing wave with the largest amplitudes are known

as antinodes. Antinodes occur halfway between nodes.

 Standing waves are the result of interference. When two waves of

equal amplitude and wavelength pass through each other in opposite

directions, the waves are always out of phase at the nodes. As Figure

25.13 shows, the nodes are stable regions of destructive interference.

 A standing wave

CHECK forms only if half a

wavelength or a multiple of half

a wavelength fits exactly into the

length of the vibrating medium.

CONCEPT

Teaching Resources

• Reading and Study

 Workbook

• Problem-Solving Exercises in

 Physics 13-3

• Transparency 52

• PresentationEXPRESS

• Interactive Textbook

• Next-Time Question 25-1

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FIGURE 25.13

The incident and reflected waves interfere

to produce a standing wave. The nodes

are places that remain stationary.

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25.9 The Doppler

 You can produce a variety of standing waves by shaking the rope

at different frequencies. Once you find a frequency that produces a

standing wave, doubling or tripling the frequency will also produce a

standing wave. A standing wave forms only if half a wavelength

or a multiple of half a wavelength fits exactly into the length of the

vibrating medium. In Figure 25.14a, the rope length equals half a

wavelength. In Figure 25.14b, the rope length equals one wavelength.

In Figure 25.14c, the rope length equals one and one-half wave-

lengths. If you keep increasing the frequency, you’ll produce more

interesting waves.

FIGURE 25.14

You can produce a variety of

standing waves.

a. Shake the rope until you set up

a standing wave of 1 wavelength.2

b. Shake with twice the frequency

and produce a standing wave of

1 wavelength.

c. Shake with three times the fre-

quency and produce a standing

wave of 1 1 wavelengths.2

Effect

Key Terms

Doppler effect, blue shift,

red shift

 Common Misconception

Changes in wave speed cause the

Doppler effect.

 The Doppler effect is an

apparent change in frequency

due to the motion of the source.

FACT

 Teaching Tip Place an

electronic whistle that emits a

sound of about 3000 Hz into a

sponge, rubber, or foam ball.

Introduce the Doppler effect by

throwing the ball around the

room. Ask students to describe

what they hear as the ball moves

through the air. Then ask if the

frequency of the sound that the

whistle emits actually changes.

 Standing waves are set up in the strings of musical instruments that

are struck. They are set up in the air in an organ pipe and the air of a

soda-pop bottle when air is blown over the top. Standing waves can be

produced in either transverse or longitudinal waves.

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CONCEPT At what wavelengths can a standing

wave form in a vibrating medium?

25.9 The Doppler Effect

Imagine a bug jiggling its legs and bobbing up and down in the

middle of a quiet puddle, as shown in Figure 25.15. Suppose the bug

is not going anywhere but is merely treading water in a fixed posi-

tion. The crests of the wave it makes are concentric circles, because

the wave speed is the same in all directions. If the bug bobs in the

water at a constant frequency, the distance between wave crests (the

wavelength) will be the same for all successive waves. Waves encounter

point A as frequently as they encounter point B. This means that the

frequency of wave motion is the same at points A and B, or anywhere

in the vicinity of the bug. This wave frequency is the same as the bob-

bing frequency of the bug.

CHAPTER 25

For: Doppler Effect activity

Visit: www.PHSchool.com

Web Code: csp – 4259

VIBRATIONS AND WAVES

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 Teaching Tip Describe the

pattern that a stationary bug

jiggling in still water makes as

shown in Figure 25.15. Draw

circles to show the top view of

circular ripples made by a bug

bobbing in the water. Stress

that wave speed, wavelength,

and frequency are the same in

all directions, as shown by the

circular shape.

 Teaching Tip Now consider

a moving bug and the pattern

it makes (Figure 25.16). Explain

how the frequency of waves is

increased in front of the bug;

waves would be encountered

more often (more frequently) by

your hand placed in the water in

front of the bug. (The observer

would also encounter a shorter

wavelength; since v is a constant

for a given medium, then as f

increases, l decreases.) Similarly

waves would be encountered less

often (less frequently) behind

the bug.

FIGURE 25.15

A stationary bug jiggling

in still water produces a

circular water wave.

FIGURE 25.16

A bug swimming in still

water produces a wave

pattern that is no longer

concentric.

 Suppose the jiggling bug moves across the water at a speed less

than the wave speed. In effect, the bug chases part of the crests it has

produced. The wave pattern is distorted and is no longer concentric,

as shown in Figure 25.16. The center of the outer crest was made

when the bug was at the center of that circle. The center of the next

smaller crest was made when the bug was at the center of that circle,

and so forth. The centers of the circular crests move in the direction

of the swimming bug. Although the bug maintains the same bob-

bing frequency as before, an observer at B would encounter the crests

more often. The observer would encounter a higher frequency. This is

because each successive crest has a shorter distance to travel so they

arrive at B more frequently than if the bug were not moving toward B.

 An observer at A, on the other hand, encounters a lower fre-

quency because of the longer time between wave-crest arrivals. To

reach A, each crest has to travel farther than the one ahead of it due

to the bug’s motion. As a wave source approaches, an observer

encounters waves with a higher frequency. As the wave source

moves away, an observer encounters waves with a lower frequency.

This apparent change in frequency due to the motion of the source

(or receiver) is called the Doppler effect (after the Austrian scientist

Christian Doppler, 1803–1853). The greater the speed of the source,

the greater will be the Doppler effect.

 Water waves spread over the flat surface of the water. Sound and

light waves, on the other hand, travel in three-dimensional space in

all directions like an expanding balloon. Just as circular wave crests

are closer together in front of the swimming bug, spherical sound or

light wave crests ahead of a moving source are closer together than

those behind the source and encounter a receiver more frequently.

Physics on the Job

Police Ofﬁcer

Police officers are responsible for protecting people. While that

involves catching criminals and solving crimes, it also requires that

police officers prevent drivers from speeding. In this way, police

officers protect pedestrians and people in vehicles. One way that

police officers prevent speeding is by using radar equipment. Radar

equipment sends waves toward a moving vehicle and uses the

Doppler effect to determine the speed of the vehicle. By knowing

how to operate the device, police officers can determine when a

driver is not obeying the speed limit.

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FIGURE 25.17

The pitch of sound

is higher when the

source moves toward

you, and lower when

the source moves

away.

 Teaching Tip Relate the

concept of the moving bug to the

waves from the moving sources

in Figures 25.17 and 25.18.

 Ask The waves are more

crowded in front of the

swimming bug and more spread

out behind. Is the wave speed

greater in front of the bug

(and less behind the bug)? No!

Frequency, not speed, is greater

in front of the bug and less

behind.

 Teaching Tip Emphasize the

distinction between wave speed

and wave frequency.

 Teaching Tip Swing a sound

source at the end of a string in

a horizontal circle. Relate this

to the siren of a fire engine

and the radar of the highway

patrol (Figures 25.17 and 25.18).

(Mention that sound requires a

medium; radar doesn’t.)

 Teaching Tip Point out

that light, radar, TV, and radio

waves are all electromagnetic

in nature. The waves differ

only in frequency (and hence

wavelength) and energy per

photon.

 Teaching Tip Relate the pitch

of sound to the color of light.

Both depend on frequency.

Sound The Doppler effect is evident when you hear the changing

pitch of a siren as a firetruck passes you. Look at Figure 25.17. When

the firetruck approaches, the pitch sounds higher than normal. This

occurs because the sound wave crests are encountering you more fre-

quently. When the firetruck passes and moves away, you hear a drop in

pitch because the wave crests are encountering you less frequently.

 Police make use of the Doppler effect of radar waves in measur-

ing the speeds of cars on the highway. Radar waves are electromag-

netic waves, lower in frequency than light and higher in frequency

than radio waves. Police bounce them off moving cars as shown in

Figure 25.18. A computer built into the radar system calculates the

speed of the car relative to the radar unit by comparing the frequency

of the radar with the frequency of the reflected waves.

Bats hunt moths in

darkness by echo loca-

tion and the Doppler

effect. Some moths

are protected by a

thick covering of fuzzy

scales that deaden the

echoes.

FIGURE 25.18

The police calculate a

car’s speed by measur-

ing the Doppler effect

of radar waves.

Light The Doppler effect also occurs for light. When a light source

approaches, there is an increase in its measured frequency, and

when it recedes, there is a decrease in its frequency. An increase in

frequency is called a blue shift, because the increase is toward the

high-frequency, or blue, end of the color spectrum. A decrease in

frequency is called a red shift, referring to the low-frequency, or

red, end of the color spectrum. Distant galaxies, for example, show a

red shift in the light they emit. A measurement of this shift enables

astronomers to calculate their speeds of recession. A rapidly spinning

star shows a red shift on the side turning away from us and a blue

shift on the side turning toward us. This enables a calculation of the

star’s spin rate.

think!

When a source moves

toward you, do you

measure an increase or

decrease in wave speed?

Answer: 25.9

 As a wave source

CHECK approaches, an

observer encounters waves with

a higher frequency. As the wave

source moves away, an observer

encounters waves with a

lower frequency.

CONCEPT

Teaching Resources

• Concept-Development

 Practice Book 25-1

• Problem-Solving Exercises

 in Physics 13-2

• Laboratory Manual 70

CHECK

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CONCEPT How does the apparent frequency of waves change

as a wave source moves?

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CHAPTER 25

VIBRATIONS AND WAVES

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25.10 Bow Waves

Key Term

bow wave

 Teaching Tip Ask the class

to consider the waves made by

two stones thrown in the water.

Sketch the overlapping waves as

shown below.

25.10 Bow Waves

When the speed of the source in a medium is as great as the speed

of the waves it produces, something interesting happens. The waves

pile up. Consider the bug in the previous example when it swims as

fast as the wave speed. Can you see that the bug will keep up with the

wave crests it produces? Instead of the crests getting ahead of the bug,

they pile up or superimpose on one another directly in front of the

bug, as suggested in Figure 25.19. The bug moves right along with the

leading edge of the waves it is producing.

 The same thing happens when an aircraft travels at the speed of

sound. In the early days of jet aircraft, it was believed that this pileup

of sound waves in front of the airplane imposed a “sound barrier”

and that to go faster than the speed of sound, the plane would have

to “break the sound barrier.” What actually happens is that the

overlapping wave crests disrupt the flow of air over the wings, so that

it is harder to control the plane when it is flying close to the speed

of sound. But the barrier is not real. Just as a boat can easily travel

faster than the speed of water waves, an airplane with sufficient

power can easily travel faster than the speed of sound. Then we say

that it is supersonic—faster than sound. A supersonic airplane flies

into smooth, undisturbed air because no sound wave can propagate

out in front of it. Similarly, a bug swimming faster than the speed

of water waves finds itself always entering into water with a smooth,

unrippled surface.

FIGURE 25.19

A bug swimming at the

wave speed “keeps up”

with the wave crests it

produces.

Ask where the water is highest

above the normal water level,

and then indicate the two

places where the waves overlap

with X’s. This is constructive

interference. Extend the

swimming bug concept to speeds

greater than wave speeds and

show the regions of overlap that

produce the bow wave (sketching

Figures 25.15, 25.16, and 25.19).

Show how a series of overlaps

makes up the V-shaped envelope

shown in Figure 25.21.

 Teaching Tip Explain that

the formation of the bow

wave in Figure 25.20 is another

example of constructive

interference, with an appreciable

resulting amplitude.

FIGURE 25.20

A bug swimming faster

than the wave speed

produces a wave pattern

in which the wave crests

overlap at the edges.

 A bow wave occurs

CHECK when a wave source

moves faster than the waves

it produces.

CONCEPT

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Teaching Resources

• Reading and Study

 Workbook

• Transparency 53

• PresentationEXPRESS

• Interactive Textbook

 When the bug swims faster than wave speed, ideally it produces

a wave pattern as shown in Figure 25.20. It outruns the wave crests

it produces. The crests overlap at the edges, and the pattern made

by these overlapping crests is a V shape, called a bow wave, which

appears to be dragging behind the bug. A bow wave occurs when

a wave source moves faster than the waves it produces. The familiar

bow wave generated by a speedboat knifing through the water is pro-

duced by the overlapping of many circular wave crests.

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25.11 Shock Waves

Key Terms

shock wave, sonic boom

 Common Misconception

A sonic boom is a momentary burst

of high pressure produced when

something exceeds the speed

of sound.

 A sonic boom is actually a

continuous front of high pressure

generated by faster-than-sound

sources.

FACT

 Figure 25.21 shows some wave patterns made by sources mov-

ing at various speeds. After the speed of the source exceeds the wave

speed, increased speed produces a bow wave with a narrower V shape.

CONCEPT

FIGURE 25.21

The wave patterns made

by a bug swimming at suc-

cessively greater speeds

change. Overlapping at

the edges occurs only

when the source travels

faster than wave speed.

The analogy between bow waves

in water and shock waves in

air is useful when discussing

the shock waves produced by

supersonic aircraft.

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What causes a bow wave?

25.11 Shock Waves

A speedboat knifing through the water generates a two-dimensional

bow wave. A supersonic aircraft similarly generates a shock wave.

A shock wave is a three-dimensional wave that consists of overlap-

ping spheres that form a cone. A shock wave occurs when an

object moves faster than the speed of sound. Just as the bow wave

of a speedboat spreads until it reaches the shore of a lake, the conical

shock wave generated by a supersonic craft spreads until it reaches

the ground, as shown in Figure 25.22.

 The bow wave of a speedboat that passes by can splash and douse

you if you are at the water’s edge. In a sense, you can say that you are

hit by a “water boom.” In the same way, a conical shell of compressed

air sweeps behind a supersonic aircraft. The sharp crack heard when

the shock wave that sweeps behind a supersonic aircraft reaches the

listeners is called a sonic boom.

 We don’t hear a sonic boom from a slower-than-sound, or sub-

sonic, aircraft, because the sound wave crests reach our ears one at

a time and are perceived as a continuous tone. Only when the craft

moves faster than sound do the crests overlap and encounter the lis-

tener in a single burst. The sudden increase in pressure has much the

same effect as the sudden expansion of air produced by an explosion.

Both processes direct a burst of high-pressure air to the listener. The

ear cannot distinguish between the high pressure from an explosion

and the high pressure from many overlapping wave crests.

 Teaching Tip Questions

raised by students about shock

waves and the sonic boom can

be effectively answered by

substituting the example of an

aircraft in the air for the example

of a speedboat knifing through

the water. If you’re enjoying

a picnic lunch at the edge of a

river when a speedboat comes

by and drenches you, you won’t

attribute this to the idea that

the speedboat just exceeded the

speed of the water waves. You

know the boat is generating a

continuous bow wave so long

as it travels faster than waves in

water. Likewise for aircraft.

 Ask Why can’t a subsonic

aircraft, no matter how loud it

may be, produce a shock wave

or sonic boom? There will be no

overlapping of spherical waves

to form a cone unless the aircraft

moves faster than the waves

it generates.

Don’t confuse super-

sonic with ultrasonic.

Supersonic has to do

with speed—faster

than sound. Ultrasonic

involves frequency—

higher than we can hear.

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VIBRATIONS AND WAVES

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