8.1 Vibrations

SECTION OUTCOMES

- Describe and explain amplitude, frequency, and phase of vibration.
- Analyze and experiment with the components of, and conditions required for, resonance to occur in a vibrating object.

KEY TERMS

- periodic motion
- cycle
- period
- rest position
- amplitude
- frequency
- hertz
- phase difference
- in phase
- out of phase
- natural frequency
- resonance

The motion of particles in a mechanical wave and the energy transmitted by a wave are quite different from the motion and energy that you studied in Units 1, 2, and 3. After you sent a wave pulse down the spring in the investigation, all parts of the spring returned to their original positions. As the wave pulse passed through each section of the spring, that section moved from side to side or back and forth, but then returned to its initial position. Only the *energy* travelled down the spring. To initiate the wave, you had to move your hand back and forth. Similarly, most waves are started by vibrating objects such as the student's hand in Figure 8.1. Learning how to describe vibrations is an important first step in understanding and describing waves and their motion.

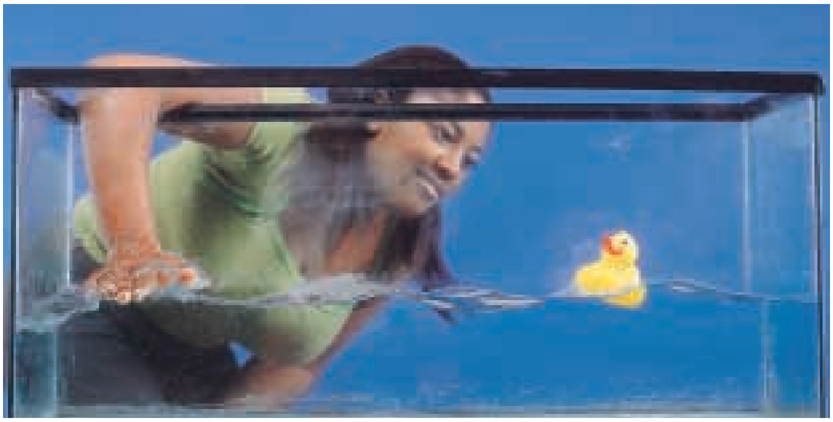


Figure 8.1 You can transmit energy to the duck, making it bounce up and down, by creating water waves. Your hand, the water, and the duck vibrate only up and down, but the wave has transmitted energy from your hand to the duck.

Amplitude, Period, Frequency, and Phase of Vibrations

When an object moves in a repeated pattern over regular time intervals, it is undergoing **periodic motion**. One complete repeat of the pattern is called a **cycle** or vibration. The time required to complete one cycle is the **period** (T). Figure 8.2 shows two types of periodic motion. A simple pendulum moves from side to side, perpendicular to its length, while a mass on a spring oscillates up and down, parallel to its length. When a pendulum or a mass on a spring is not in motion but is allowed to hang freely, the position it assumes is called its **rest position**. When in motion, the distance from the rest position to the maximum displacement is the **amplitude** (A) of the vibration.

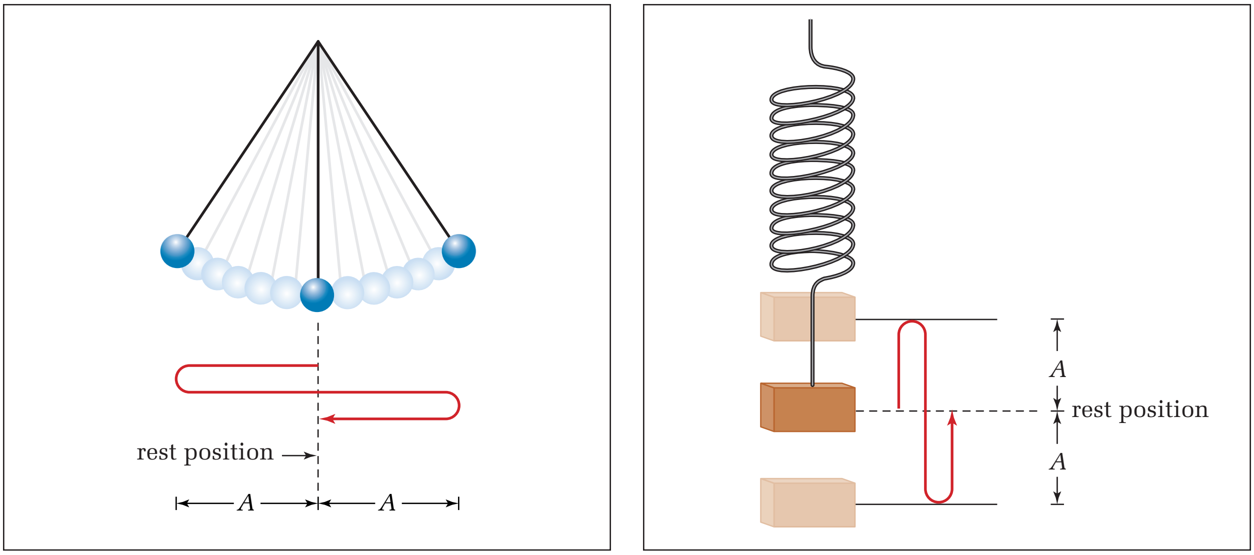


Figure 8.2 **(A)** When a simple pendulum completes one full cycle of its motion, it is in its original position. **(B)** One full cycle of the motion of the mass on a spring brings the mass back to the rest position.

One of the most common terms used to describe periodic motion is **frequency** (f), which is the number of cycles completed in a specific time interval. The frequency is the reciprocal, or inverse, of the period. The SI unit of frequency is s^{-1} or $\frac{1}{s}$ (reciprocal seconds). This unit has been named the **hertz** (Hz) in honour of German scientist Heinrich Hertz (1857–1894), who discovered radio waves.

PERIOD AND FREQUENCY

The period is the quotient of the time interval and the number of cycles.

$$T = \frac{\Delta t}{N}$$

The frequency is the quotient of the number of cycles and the time interval.

$$f = \frac{N}{\Delta t}$$

The frequency is the reciprocal, or inverse, of the period.

$$f = \frac{1}{T}$$

Quantity	**Symbol**	**SI unit**
period	T	s (seconds)
frequency	f	Hz (hertz)
time interval	Δt	s (seconds)
number of cycles	N	none (pure number)

Note: $1\ \text{Hz} = \frac{1}{\text{s}} = 1\ \text{s}^{-1}$

Even when vibrating objects have the same amplitude and frequency, they may not be at the same point in their cycles at the same time. When this occurs, we say that there is a **phase difference** between them. Two vibrating objects are **in phase** when they are always moving in the same direction at the same time. If, during any part of their cycles, the two objects are moving in opposite directions, they are vibrating **out of phase**. Figure 8.3 illustrates this.

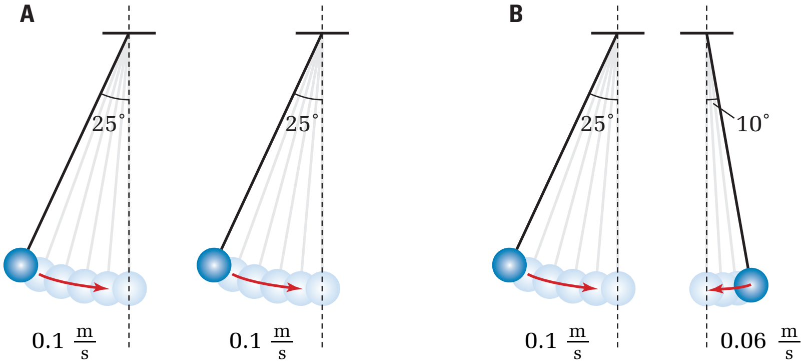


Figure 8.3 **(A)** When two pendulums are moving in unison, they are said to be "in phase." **(B)** Since these two pendulums are moving in opposite directions, they are moving "out of phase."

PHYSICS FILE

The pendulum in the photograph is called a Foucault pendulum. It is named after French scientist Jean-Bernard-Leon Foucault (1819–1868), who built the first one in Paris. A Foucault pendulum has a very large mass suspended by a very long wire that does not constrain the pendulum to swing in a specific plane. Earth's rotation causes the plane of the swing of a Foucault pendulum to rotate very gradually. For example, the plane of Foucault's first pendulum in Paris made one complete rotation in about 32 h. This rotation was the first "laboratory" evidence that Earth rotates on its axis.

MODEL PROBLEM

Period and Frequency

A mass suspended from the end of a spring vibrates up and down 24 times in 36 s. What are the frequency and period of the vibration?

Frame the Problem

- The *mass* is undergoing *periodic motion*.
- The *period* is the time for one complete cycle.
- The *frequency* is the reciprocal of the *period*.

Identify the Goal

(a) The period, T, of the motion

(b) The frequency, f, of the motion

Variables and Constants

Known	Unknown
$N = 24$	T
$\Delta t = 36\ \text{s}$	f

Strategy

Calculations

You can find the period because you know the total time interval and the number of cycles. Substitute these values into the equation.

$$T = \frac{\Delta t}{N}$$

Divide.

$$T = \frac{36\ \text{s}}{24}$$

(a) The period of the vibrating mass is 1.5 s.

$$T = 1.5\ \text{s}$$

You can also find the frequency from the number of cycles and the total time interval.

$$f = \frac{N}{\Delta t}$$

Substitute.

$$f = \frac{24}{36\ \text{s}}$$

Divide.

$$f = 0.67\ \text{s}^{-1}$$
$$f = 0.67\ \text{Hz}$$

(b) The frequency of the vibrating mass is 0.67 Hz.

Validate

The unit of the period was seconds, which is correct.

The unit for the frequency was seconds to the negative one, or reciprocal seconds, which is equivalent to hertz. That is the correct unit of frequency.

The period and frequency were calculated individually, but they should be the reciprocal of each other. Check to see if they are.

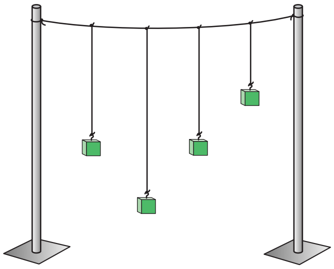
$$f = \frac{1}{T}$$
$$f = \frac{1}{1.5\ \text{s}}$$
$$f = 0.67\ \text{s}^{-1}$$
$$f = 0.67\ \text{Hz}$$

The frequency is the reciprocal of the period.

PRACTICE PROBLEMS

1. A metronome beats 54 times over a 55 s time interval. Determine the frequency and period of its motion.
2. Most butterflies beat their wings between 450 and 650 times per minute. Calculate in hertz the range of typical wing-beating frequencies for butterflies.
3. A watch spring oscillates with a frequency of 3.58 Hz. How long does it take to make 100 vibrations?
4. A child swings back and forth on a swing 12 times in 30.0 s. Determine the frequency and period of the swinging.

TRY THIS...



Assemble the apparatus shown here, using strings and masses tied to retort stands or other solid supports. Make two pendulums the same length, one longer than the pair, and one shorter. One at a time, pull each pendulum to the side and let it swing. Observe any response of the other pendulums.

Natural Frequencies and Resonance

When an object, like a simple pendulum or a mass on a spring, is allowed to vibrate freely, it vibrates at a specific frequency called its **natural frequency**. The natural frequency of a simple pendulum depends on its length — shorter pendulums have higher natural frequencies than longer ones. What determines the frequency with which a mass vibrates on the end of a spring?

When you push a child on a swing, you need not push very hard to make the child swing higher and higher. What you do have to do is to push at the right times, that is, with a frequency equal to the natural frequency of the swing and the child. As well, the cycle of pushing must be *in phase* with the motion of the child and the swing. This condition is true for all vibrating objects. If energy, no matter how small the amount, is added to a system during each cycle and none is removed, the amplitudes of the vibration will become very large. This phenomenon is called **resonance**.

QUICK LAB

Natural Frequency of a Mass on a Spring

TARGET SKILLS

- Identifying variables
- Performing and recording

What factors affect the frequency of vibration of a mass on a spring? Does the frequency change with time? Does the amplitude affect the frequency? Does the amount of mass influence the frequency? Answer these questions by carrying out the following experiment. You will need two different-sized springs, three different masses, a stopwatch, a metre stick, a retort stand, and a clamp.

Securely attach a spring to a clamp on a retort stand. Hang a mass on the end of the spring. Stretch the spring a measured distance by pulling on the mass. Release the mass and determine the length of time it takes for the mass to complete five full cycles. Calculate the frequency. Carry out the procedure for three different amplitudes.

Repeat the experiment using a different mass. To determine if the frequency changes with time, after taking one measurement, allow the mass to continue vibrating on the spring and measure the time it takes for five more cycles.

Repeat the entire procedure for a different spring.

Analyze and Conclude

1. Which factors affected the frequency of the mass on a spring?
2. Explain how you could determine that some factors did not affect the frequency.
3. What was the natural frequency of each of your combinations of spring, mass, and stretch distance?

You may have experienced another example of resonance when driving or riding in a car. If the wheels were not properly aligned and balanced, the entire car would start to vibrate severely at a certain speed. These vibrations can occur only when the vibrations produced by the spinning of the automobile's wheels are equal to a natural frequency of vibration of the automobile itself.

Mechanical resonance can cause serious problems for engineers constructing buildings, bridges, and aircraft. The Tacoma Narrows Bridge collapsed on November 7, 1940, because resonance was created in its centre span by relatively moderate winds of 60 to 70 km/h. Over a period of two hours, the vibrations of the centre span increased steadily, until they became so violent that the bridge collapsed into the river below (see Figure 8.4).

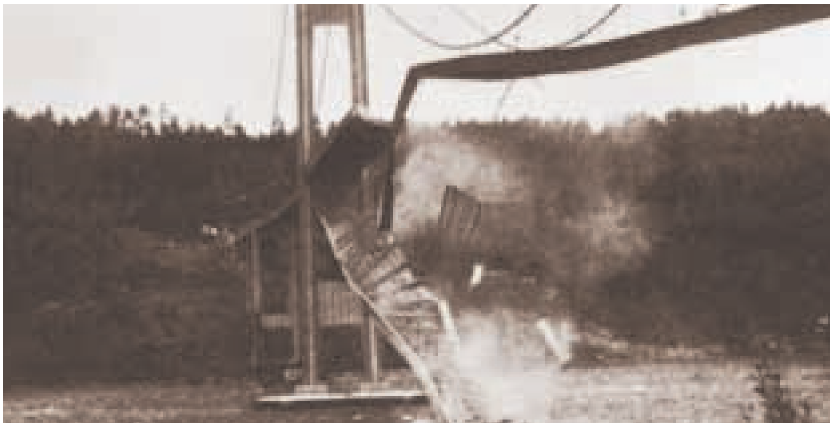


Figure 8.4 Resonance produced such violent vibrations in the original Tacoma Narrows Bridge that it collapsed.

History Link

Galileo Galilei first investigated the constant frequency of a simple pendulum around 1600. Although he never constructed it, Galileo also proposed a design for a mechanical clock regulated by such a pendulum. It was not until around 1759 that John Harrison constructed an extremely accurate clock or chronometer. Finally, seafarers could determine their longitude on long ocean voyages with the aid of this accurate chronometer. This helped the Royal Navy to control the seas and Britain to dominate world trade during the nineteenth century.

Web Link

www.mcgrawhill.ca/links/atlphysics

For more pictures and information about the Tacoma Narrows Bridge collapse, go to the above Internet site and click on **Web Links**.

8.1 Section Review

1. **K/U** Give three examples of periodic motion. What makes them periodic?
2. **C** Explain in your own words the meaning of the terms "cycle," "period," and "frequency."
3. **K/U** If a simple pendulum is lengthened, what happens to its frequency? To its period?
4. **K/U** Sketch diagrams illustrating
   - **(a)** two masses on springs vibrating in phase
   - **(b)** two pendulums vibrating out of phase
5. **K/U** Period is typically measured in units of seconds and frequency in units of hertz. How are these two units related to each other? Why are they related in this manner?
6. **C** Describe what happens when resonance occurs in an object. Explain how this is produced.
7. **MC** Provide two examples of resonance in everyday life.