Waves

Unit: Mechanical Waves

NGSS Standards/MA Curriculum Frameworks (2016): HS-PS4-1

AP® Physics 2 Learning Objectives/Essential Knowledge (2024): 14.1.A, 14.1.A.1, 14.1.A.1.i, 14.1.A.1.ii, 14.1.A.2, 14.1.A.3, 14.1.A.3.i, 14.1.A.3.iii, 14.1.A.4, 14.1.A.5, 14.1.A.5.i, 14.1.A.5ii, 14.1.A.6, 14.1.A.6.i, 14.2.A, 14.2.A.1, 14.2.A.1.i, 14.2.A.1.ii, 14.2.A.1.iii, 14.2.A.1.iv, 14.2.A.1.vi, 14.2.A.3

Mastery Objective(s): (Students will be able to…)

- Describe and explain properties of waves (frequency, wavelength, etc.)
- Differentiate between transverse, longitudinal and transverse waves.
- Calculate wavelength, frequency, period, and velocity of a wave.

Success Criteria:

- Parts of a wave are identified correctly.
- Descriptions & explanations account for observed behavior.

Language Objectives:

- Describe how waves propagate.

Tier 2 Vocabulary: wave, crest, trough, frequency, wavelength

Labs, Activities & Demonstrations:

- Show & tell: transverse waves in a string tied at one end, longitudinal waves in a spring, torsional waves.
- Buzzer in a vacuum.
- Tacoma Narrows Bridge collapse movie.
- Japan tsunami TV footage.

Notes:

wave pulse: a single disturbance that travels from one place to another* and transfers energy without transferring matter between two locations.

wave: a continuous, periodic disturbance with well-defined wavelength and frequency.

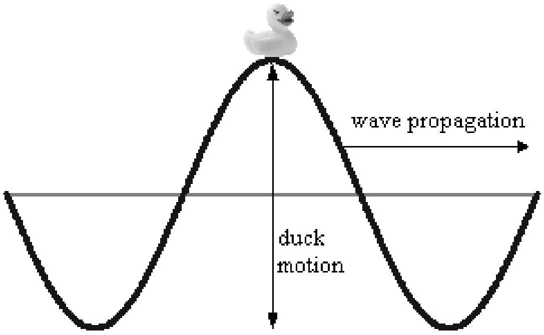
medium: a substance that a wave travels through.

propagation: the process of a wave traveling through space.

* This is my favorite definition in these notes. I jokingly suggest that I nickname some of my students "wave" based on this definition.

<u>mechanical wave</u>: a wave that propagates through a medium via contact between particles of the medium. Some examples of mechanical waves include ocean waves and sound waves.

1. The energy of the wave is transmitted via the particles of the medium as the wave passes through it.
2. The wave travels through the medium. The particles of the medium are moved by the wave passing through and then return to their original position. (The duck sitting on top of the wave below is an example.)



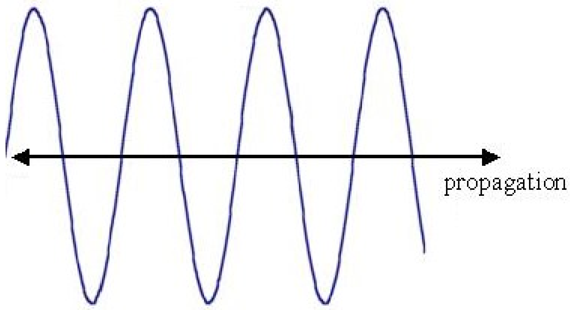
3. Waves generally move fastest in solids and slowest in liquids. The velocity of a mechanical wave is dependent on characteristics of the medium:

state	relevant factors	example: medium	example: velocity of sound
gas	density, pressure	air (20 °C and 1 atm)	$343\frac{m}{s}$ $(768\frac{mi}{hr})$
liquid	density, compressibility	water (20 °C)	$1\,481\frac{m}{s}$ $(3\,317\frac{mi}{hr})$
solid	stiffness	steel (longitudinal wave)	$6\,000\frac{m}{s}$ $(13\,000\frac{mi}{hr})$

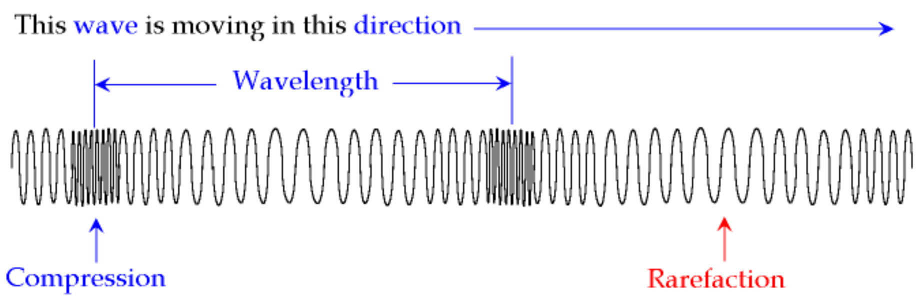
<u>electromagnetic wave</u>: a wave of electricity and magnetism interacting with each other. Electromagnetic waves can propagate through empty space and are slowed down by interactions with a medium. Electromagnetic waves are discussed in more detail in the *Electromagnetic Waves* section starting on page 358.

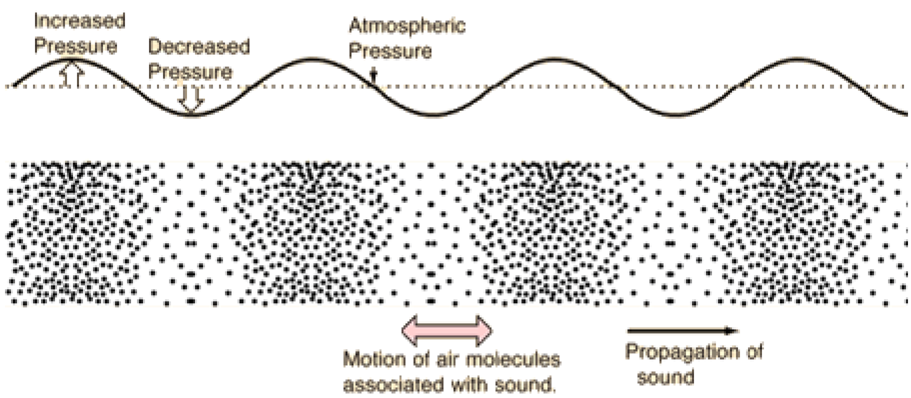
Types of Waves

transverse wave: moves its medium up & down (or back & forth) as it travels through. Examples: light, ocean waves



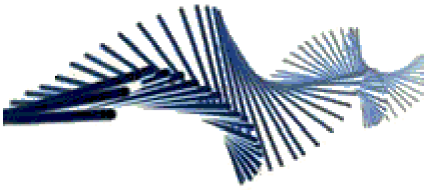
longitudinal wave (or compressional wave): compresses and decompresses the medium as it travels through. Examples: compression of a spring, sound.





honors (not AP®)

torsional wave: a type of transverse wave that propagates by twisting about its direction of propagation.



The most famous example of the destructive power of a torsional wave was the Tacoma Narrows Bridge, which collapsed on November 7, 1940. On that day, strong winds caused the bridge to vibrate torsionally. At first, the edges of the bridge swayed about eighteen inches. (This behavior had been observed previously, earning the bridge the nickname “Galloping Gertie”.) However, after a support cable snapped, the vibration increased significantly, with the edges of the bridge being displaced up to 28 feet! Eventually, the bridge started twisting in two halves, one half twisting clockwise and the other half twisting counterclockwise, and then back again. This opposing torsional motion eventually caused the bridge to twist apart and collapse.

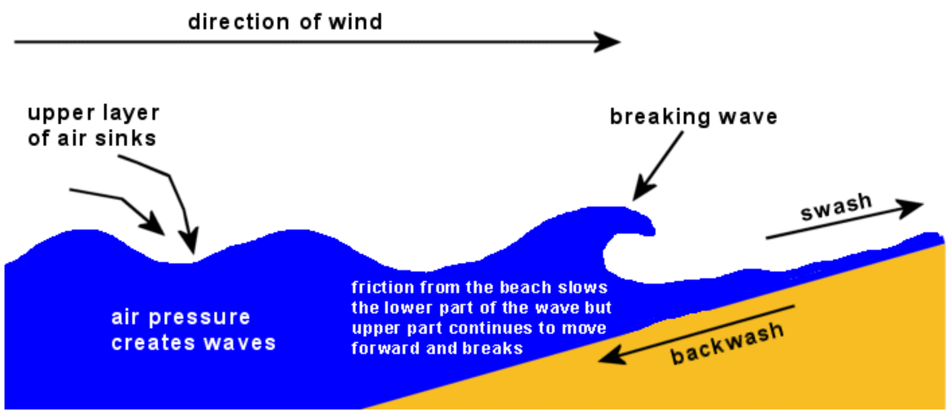
The bridge’s collapse was captured on film. Video clips of the bridge twisting and collapsing are available on the internet. There is a detailed analysis of the bridge’s collapse at http://www.vibrationdata.com/Tacoma.htm *honors (not AP®)*

Ocean Waves

Surface Waves

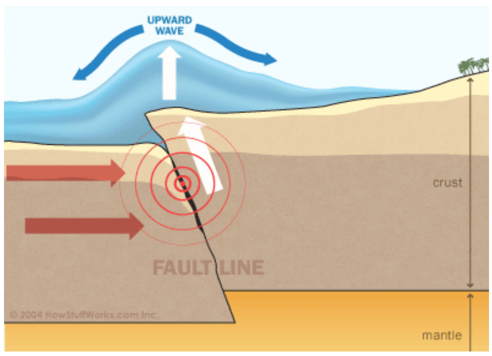
<u>surface wave</u>: a transverse wave that travels at the interface between two mediums.

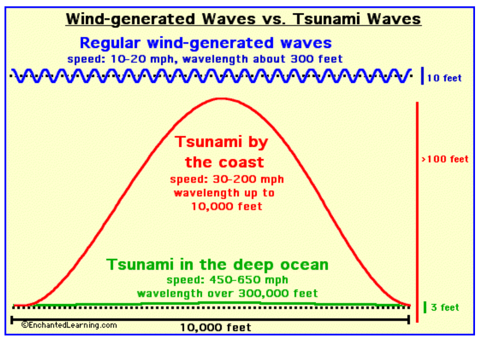
Ocean waves are an example of surface waves, because they travel at the interface between the air and the water. Surface waves on the ocean are caused by wind disturbing the surface of the water. Until the wave gets to the shore, surface waves have no effect on water molecules far below the surface.



Tsunamis

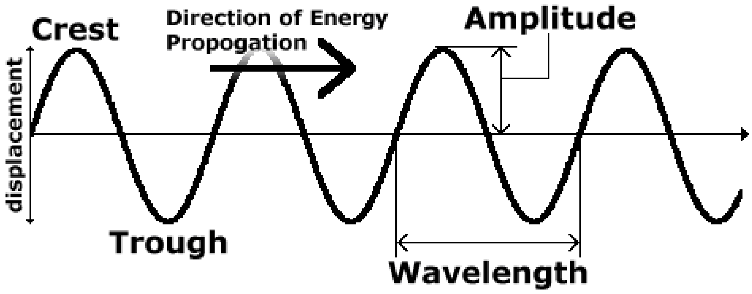
The reason tsunamis are much more dangerous than regular ocean waves is because tsunamis are created by earthquakes on the ocean floor. The tsunami wave propagates through the entire depth of the water, which means tsunamis carry many times more energy than surface waves.





This is why a 6–12 foot high surface wave breaks harmlessly on the beach; however, a tsunami that extends 6–12 feet above the surface of the water includes a significant amount of energy throughout the entire depth of the water, and can destroy an entire city.

Properties of Waves



crest: the point of maximum positive displacement of a transverse wave. (The highest point.)

trough: the point of maximum negative displacement of a transverse wave. (The lowest point.)

wavelength (λ): the length of the wave, measured from a specific point in the wave to the same point in the next wave. Unit = distance (m, cm, nm, *etc.*)

velocity: the velocity of a wave depends on its frequency (f) and its wavelength (λ):

$$v = \lambda f$$

The velocity of electromagnetic waves (such as light, radio waves, microwaves, X-rays, *etc.*) is called the speed of light, which is $3.00\times10^{8}\,\frac{\text{m}}{\text{s}}$ in a vacuum. The speed of light is slower in a medium that has an index of refraction* greater than 1.

The velocity of a wave traveling through a string under tension (such as a piece of string, a rubber band, a violin/guitar string, *etc.*) depends on the tension and the ratio of the mass of the string to its length:

$$v_{string} = \sqrt{\frac{F_T L}{m}}$$

where F_T is the tension in the string, L is the length, and m is the mass.

* The index of refraction is a measure of how much light bends when it moves between one medium and another. The sine of the angle of refraction is proportional to the speed of light in that medium. Index of refraction is part of the *Refraction* topic starting on page 465.

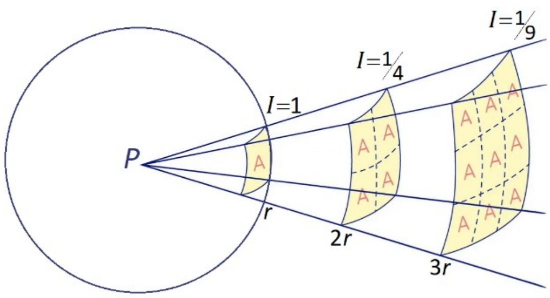
amplitude (A): the distance of maximum displacement of a point in the medium as the wave passes through it.

For a transverse wave, the amplitude is the maximum height of a crest or depth of a trough.

For a longitudinal wave, the amplitude is a particle of the medium's maximum distance from the equilibrium point. In the case of sound waves, we perceive the amplitude as loudness, which is described in more detail in the topic *Sound Level (Loudness)*, starting on page 343.

intensity: the intensity of a wave pulse is the power transferred per unit area, where the area is defined as the region where the wave pulse strikes or passes through a plane perpendicular to the direction of propagation.

For example, suppose that a wave pulse transfers a power $P = 1\,\text{W}$ through an area $A = 1\,\text{m}^2$ at a distance $r = 1\,\text{m}$. This wave pulse would have an intensity of $I = \frac{P}{A} = 1\,\frac{W}{m}$.



As the wave pulse travels farther from its source, it spreads out, which means its intensity decreases as the square of distance (this comes from the surface area of a sphere, which is $4\pi r^2$), so at a distance of 2 m, the wave pulse would have an intensity of $0.25\,\frac{\text{W}}{\text{m}}$, and at a distance of 3 m, the wave pulse would have an intensity of $0.11\,\frac{\text{W}}{\text{m}}$.

The intensity of a wave pulse is proportional to the square of its amplitude.

Periodic Waves

Periodic waves are waves that have consistent, regular repetitions.

frequency (f or ν): the number of waves that travel past a point in a given amount of time. Unit = $^1/_{\text{time}}$ (Hz = $^1/_{\text{s}}$)

Note that while high school physics courses generally use the variable f for frequency, college courses often use ν (the Greek letter "nu", which is different from but easy to confuse with the Roman letter "v").

The energy of a wave is proportional to both its amplitude and its frequency. Each pulse carries an amount of energy proportional to the amplitude. The number of pulses of energy delivered in a given amount of time is the frequency. (Think of boxing: the strength of each punch is the amplitude, and the number of punches per second is the frequency.)

period or time period (T): the amount of time between two adjacent waves. Unit = time (usually seconds)

$$T = {}^1/_f$$

sinusoidal waves: a wave whose graph of displacement *vs.* time is the trigonometry function sine or cosine.

Most of the periodic waves that we will study in this class are sinusoidal waves. Some examples include light waves, sound waves, motions of springs and pendulums, uniform circular motion, vibrations, (electrical) alternating current, vibrations (such as strings in musical instruments), and some aspects of ocean currents, climate cycles, population cycles, and economic trends.

In a sinusoidal wave, the general equation for displacement vs. time is:

$$x(t) = A\cos(2\pi ft) = A\cos(\omega t)$$

where:

- $x(t)$ = position as a function of time
- x = displacement from equilibrium position
- t = time
- f = frequency
- ω = angular velocity

The equation for displacement as a function of position is:

$$y(x) = A\cos\left(2\pi \frac{x}{\lambda}\right)$$

where:

- *y(x)* = displacement (*y*-position) as a function of position in the direction of propagation (*x*-position)
- *x* = position in the direction of propagation (*x*-position)
- *λ* = wavelength

Sample Problem:

Q: The Boston radio station WZLX broadcasts waves with a frequency of 100.7 MHz. If the waves travel at the speed of light, what is the wavelength?

A: $f = 100.7\,\text{MHz} = 100\,700\,000\,\text{Hz} = 1.007\times10^8\ \text{Hz}$

$v = c = 3.00\times10^8\ \frac{\text{m}}{\text{s}}$

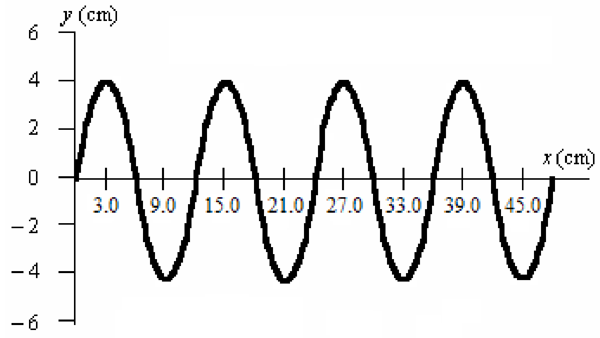
$v = \lambda f$

$3.00\times10^8 = \lambda\,(1.007\times10^8)$

$\lambda = \dfrac{3.00\times10^8}{1.007\times10^8} = 2.98\,\text{m}$

Homework Problems

1. **(M)** Consider the following wave:



   a. What is the amplitude of this wave?

   b. What is its wavelength?

   c. If the velocity of this wave is $30\,\frac{m}{s}$, what is its period?

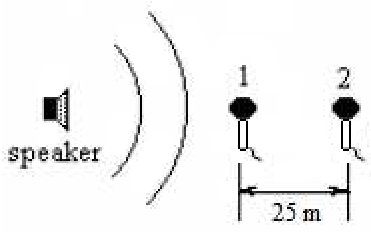
2. **(M)** What is the speed of wave with a wavelength of 0.25 m and a frequency of 5.5 Hz?

   Answer: $1.375\,\frac{m}{s}$

3. **(S)** A sound wave traveling in water at 10 °C has a wavelength of 0.65 m. What is the frequency of the wave.
   (*Note: you will need to look up the speed of sound in water at 10 °C in* Table W. Properties of Water and Air *on page 509 of your Physics Reference Tables*.)

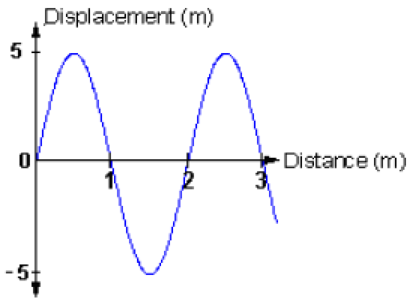
   Answer: 2 226Hz

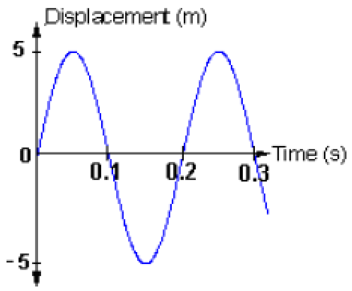
4. **(S)** Two microphones are placed in front of a speaker as shown in the diagram to the right. If the air temperature is 30 °C, what is the time delay between the two microphones?



Answer: 0.0716 s

5. **(M)** The following are two graphs of the same wave. The first graph shows the displacement *vs.* distance, and the second shows displacement *vs.* time.





a. What is the wavelength of this wave?

b. What is its amplitude?

c. What is its frequency?

d. What is its velocity?