HUMBER ENGINEERING

ENGI 1000 - Physics 1

WEEK 13 - MODULE 10

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Module 10
Wave Motion

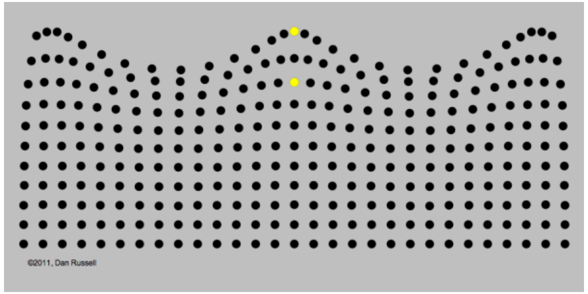
- Propagation of a Disturbance
- Classification of Waves
- Traveling Sinusoidal Waves
- The Speed of Waves on Strings
- Sound Wave and Speed of Sound Waves

Propagation of Disturbance

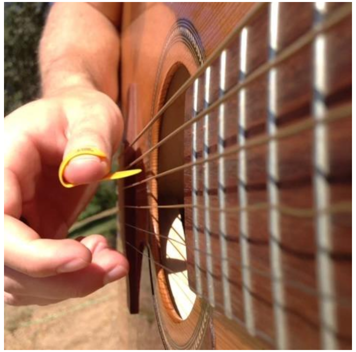
- From the previous lecture we know a vibration/oscillation is a periodic linear motion of a particle about an equilibrium position.
- When many particles vibrate and carry energy through space, they cause a wave, which can extend from one place to another place.
- When an object vibrates, it also disturbs the medium surrounding it.
- For example, when a cat's tongue touches the surface of the water, the vibrating tongue (the source) sends ripples (waves) across the bowl. Here water is the medium.

Propagation of Disturbance

- **Wave** is a form of disturbance which travels through a material medium due to the repeated periodic motion of the particles of the medium about their equilibrium positions <u>without actual transportation of matter.</u>
- The essence of wave motion is that the <u>transfer of energy</u> through space occurs without the accompanying transfer of matter.



Can you bring examples of waves?



Classification of Waves

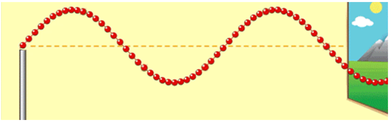
- Waves can be classified based on different aspects:
  - Based on medium through which waves travel:
    - Mechanical waves
    - Electromagnetic waves
  - Based on propagation of energy along with a wave motion
    - Progressive waves
    - Stationary waves
  - Based on dimension in which a wave is travelling:
    - One-dimensional waves
    - Two-dimensional waves
    - Three-dimensional waves
  - Based on the direction of vibration of the particles of a wave:
    - Transverse waves
    - Longitudinal waves

Classification of Waves Based on Medium

- **Mechanical Waves**
  - Mechanical waves can be produced or propagated only in a material medium.
  - These waves are governed by Newton's laws of motion.
  - Examples of mechanical waves:
    - Sound waves, Seismic waves, Waves on strings and Waves on water surface
- **Electromagnetic Waves**
  - These are the waves which require no material medium for their production and propagation.
  - They can pass through vacuum and any other material medium.
  - Examples of electromagnetic waves:
    - Light waves, Radio waves and Microwaves

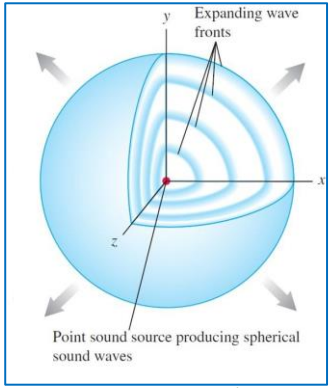
Classification of Waves Based on the Dimension

- **Waves in One-Dimension**
  - These waves travel along a line in one-dimensional space.
  - Example: A wave on a string



- **Waves in Two-Dimension**
  - These waves travel on a surface that is two-dimensional space.
  - Example: A wave on the surface of water

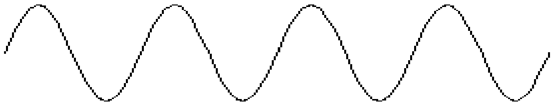
- **Waves in Three-Dimension**
  - These waves travel in the xyz space.
  - Example: Sound waves, radio waves, light waves and other electromagnetic waves



Classification of Waves Based on the Propagation of Energy

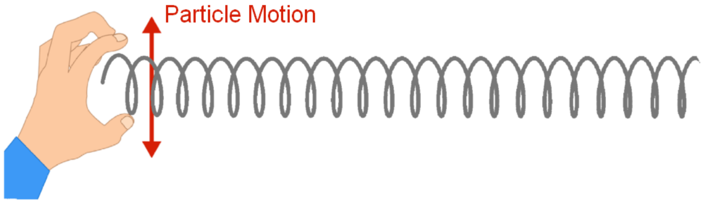
- **Stationary Waves or Standing Waves**
  - These are the waves that possess vertical oscillating movement but do **not** undergo forward motion in a horizontal direction.
  - Stationary waves generates vibration pattern within the medium.
  - Energy is **not** transferred from one point to another.

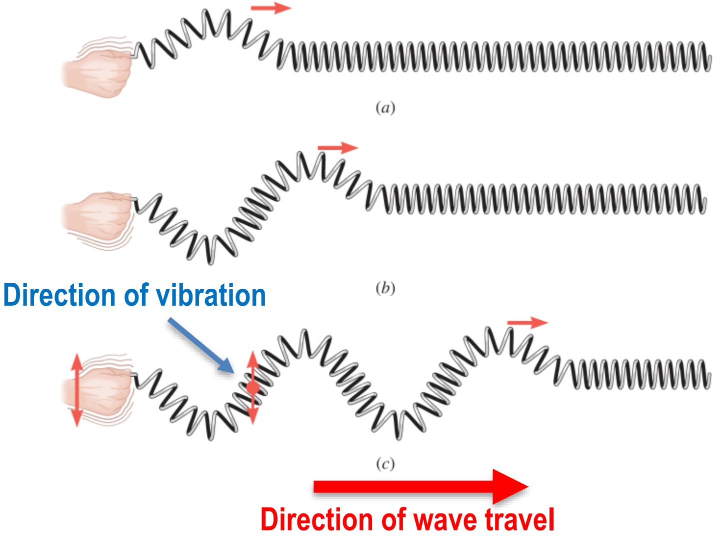
- **Progressive Waves**
  - These waves continuously travel in one direction where the amplitude is kept constant.
  - Progressive waves allow the propagation of energy from one point to another point through the medium.



Classification of Waves Based on Vibration of Particles

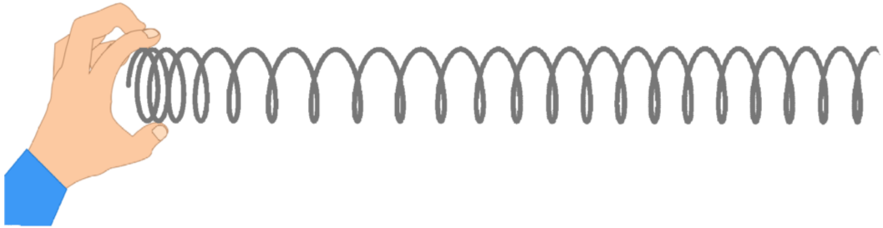
- **Transverse Waves**
  - The disturbance occurs perpendicular to the direction of travel of the wave or the energy transport.
  - The medium vibrates perpendicular to the direction of energy transport.
  - Example of transverse waves:
    - Vibrations in stretched strings of musical instruments such as guitars and banjos
    - Radio waves, light waves and microwaves

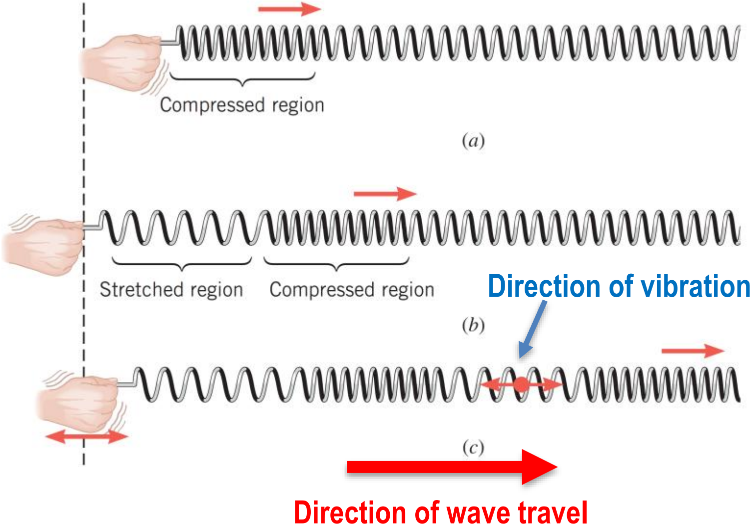




Classification of Waves Based on Vibration of Particles

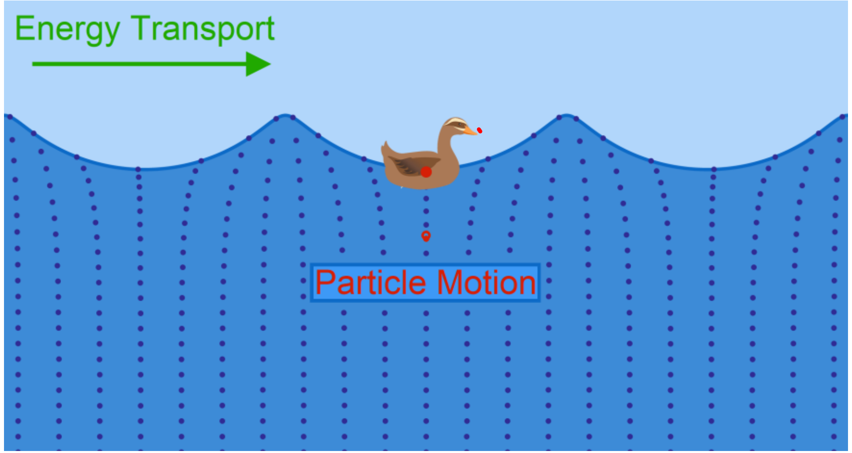
- **Longitudinal Waves**
  - The disturbance occurs parallel to the direction of travel of the wave or the energy transport.
  - The medium vibrates parallel to the direction of energy transport.
  - Example of longitudinal waves:
    - A sound wave is a longitudinal wave.

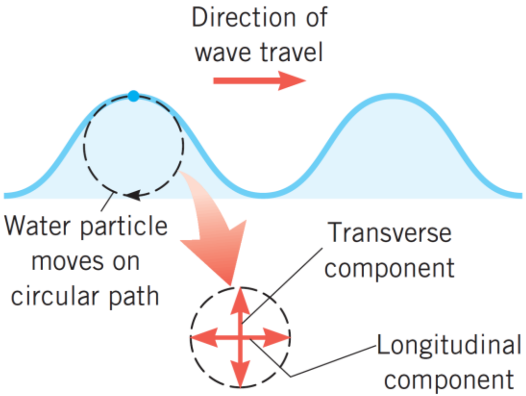




Classification of Waves Based on Vibration of Particles

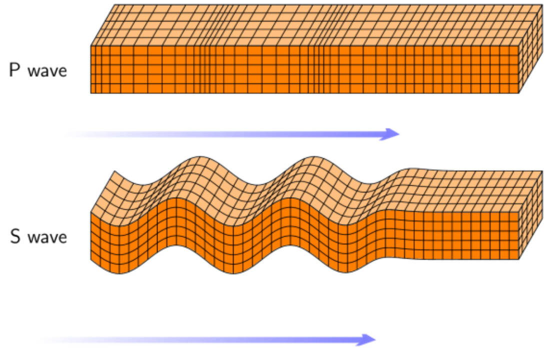
- **Combination of Transverse and Longitudinal Waves**
  - The motion of a water wave includes both transverse and longitudinal components.
  - The water particles at the surface move clockwise on nearly circular paths as the wave moves from left to right.





Classification of Waves Based on Vibration of Particles

- **Combination of Transverse and Longitudinal Waves**
  - **Earthquake:** represents disturbance that results in *seismic waves*
  - Two types of waves: transverse and longitudinal
    - Longitudinal waves:
      - Speed: 7 – 8 km/s
      - Called **P waves** (“P” for *primary,* because they travel faster than transverse waves)
    - Transverse waves:
      - Called **S waves** (“S” for *secondary*)
      - Speed: 4 – 5 km/s



- By recording time interval between arrivals of two types of waves at seismograph the distance from seismograph to point of origin of waves can be determined.

Quick Quiz 1

- In a long line of people waiting to buy tickets, the first-person leaves, and a pulse of motion occurs as people step forward to fill the gap. As each person steps forward, the gap moves through the line. The propagation of this gap is
    a) transverse
    b) longitudinal

- Consider “the wave” at a baseball game: people stand up and raise their arms as the pulse arrives at their location, and the resultant pulse moves around the stadium. This pulse is
    a) transverse
    b) longitudinal

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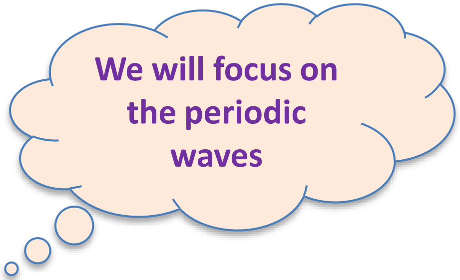
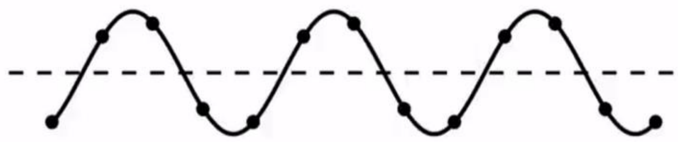
Pulse Waves and Periodic Waves

- **Pulse Wave:** is a disturbance with finite length.
- For example, if you shook the end of a rope once you would produce a pulse wave

- **Periodic Wave:** is a repetitive disturbance with infinite length.
- For example, if you hold end of a rope and jiggle it up and down.
- Periodic waves can have many different shapes, but the simplest one is sinusoidal waveform.

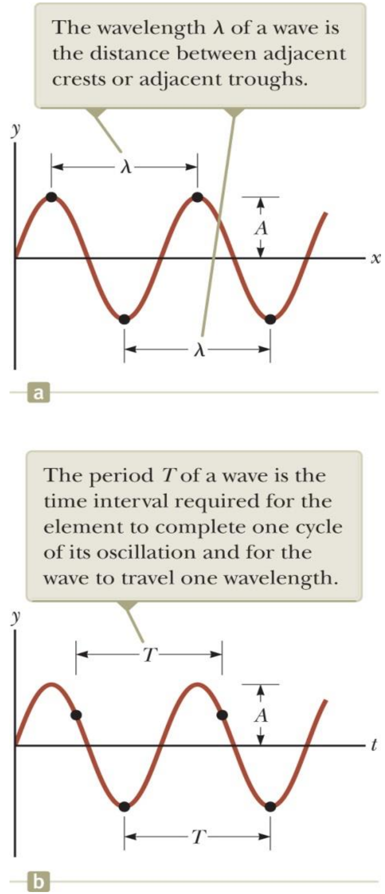




Periodic Waves

- A periodic wave repeats in both **space** and **time**.
- **Snapshot Graph:** A graph that shows the wave's displacement as a function of position at a single instant of a time.
- **Historic Graph:** A graph that shows the wave's displacement as a function of time at a single position in space.
  - **Amplitude (A):** The maximum value of a wave's disturbance. The highest amplitude is called **crest** of the wave, and the lowest is called the **trough**.
  - **Wavelength (λ):** The ***distance*** over which the wave pattern repeats.
  - **Period (T):** The ***time*** for one complete oscillation.
  - **Frequency (f):** Number of wave cycles per unit time. It is inverse of the period.

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



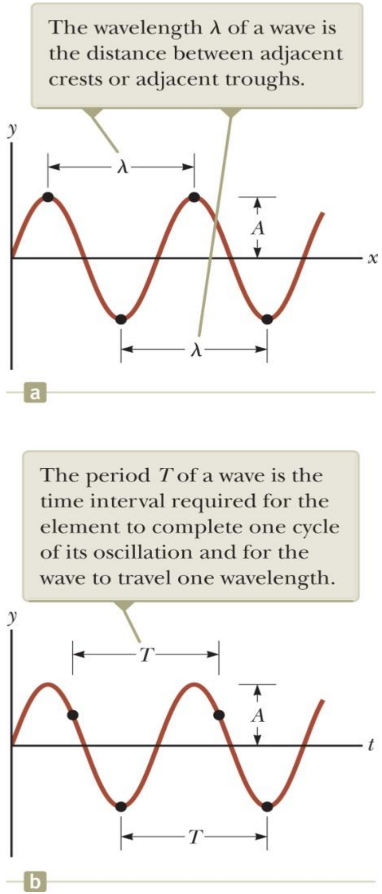
Periodic Waves

- **Wave Speed:** A periodic wave consist of identical cycles, each of which has a length λ and requires a time T to pass, so the wave speed is defined as:

$$\boxed{v = \frac{\lambda}{T}} \qquad \boxed{v = f\lambda}$$

- Note that the definition is general and is applicable to longitudinal and transverse waves.

- The wave speed depends on the physical properties of the medium.



Quick Quiz 2

- A sinusoidal wave of frequency *f* is traveling along a stretched string. The string is brought to rest, and a second traveling wave of frequency 2*f* is established on the string.
- What is the **wave speed** of the second wave?
    - a) twice that of the first wave
    - b) half that of the first wave
    - c) the same as that of the first wave
    - d) impossible to determine

Quick Quiz 3

- A sinusoidal wave of frequency *f* is traveling along a stretched string. The string is brought to rest, and a second traveling wave of frequency 2*f* is established on the string.
- What is the **wavelength** of the second wave?
    a) twice that of the first wave
    b) half that of the first wave
    c) the same as that of the first wave
    d) impossible to determine

Quick Quiz 4

- A sinusoidal wave of frequency *f* is traveling along a stretched string. The string is brought to rest, and a second traveling wave of frequency 2*f* is established on the string.
- What is the **amplitude** of the second wave?
    a) twice that of the first wave
    b) half that of the first wave
    c) the same as that of the first wave
    d) impossible to determine

Mathematic Descriptions of Waves

- Consider two snapshots of a pulse wave at time $t = 0$ and at some later time t.
- Initially the wave disturbance y is some function of position x

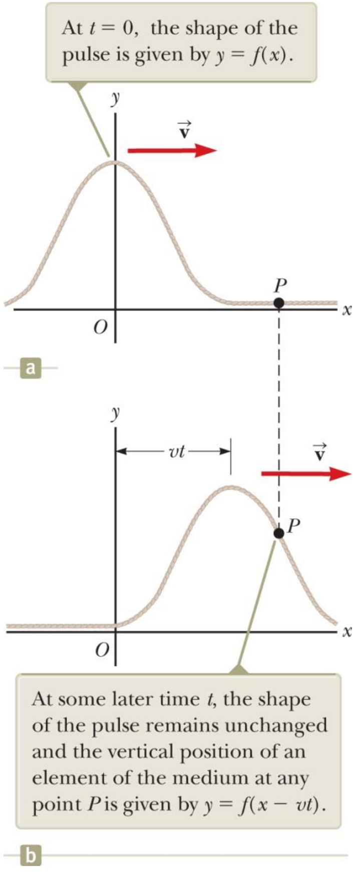
$$y = f(x)$$

- Later the pulse has moved to the **right** a distance vt, but its shape is same.
- We can represent the displaced wave as a function of time and position

$$y = f(x - vt) \quad \rightarrow \quad y(x,t) = f(x - vt)$$

- If the wave moves to the **left**, we can represent the displaced wave as

$$y(x,t) = f(x + vt)$$



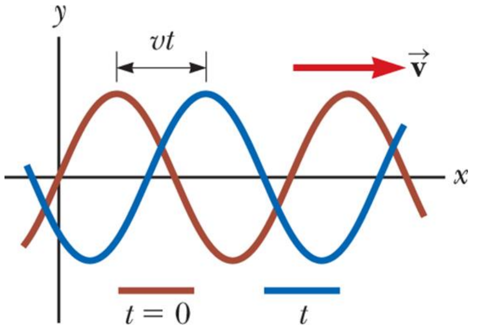
Mathematic Descriptions of Sinusoidal Waves

- Consider two snapshots of a sinusoidal wave at time $t = 0$ and at some later time t.
- The initial sinusoidal wave disturbance y as a function of position x is obtained as

$$y = A\sin(\omega t) = A\sin\left(\frac{2\pi}{T} \cdot \frac{x}{v}\right) \longrightarrow \boxed{y = A\sin\left(\frac{2\pi}{\lambda} x\right)}$$

- We can represent the displaced wave to the **right** as a function of time and position

$$\boxed{y(x,t) = A\sin\left(\frac{2\pi}{\lambda}(x - vt)\right)}$$



- We can express the wave function in convenient form by defining the $k = 2\pi/\lambda$ as the wave number,

$$\boxed{y(x,t) = A\sin(kx - \omega t + \phi)}$$

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Mathematic Descriptions of Sinusoidal Waves

Example 1 (Traveling Sinusoidal Wave): A sinusoidal wave traveling in the positive *x* direction has an amplitude of 15.0 cm, a wavelength of 40.0 cm, and a frequency of 8.00 Hz. The vertical position of an element of the medium at *t* = 0 and *x* = 0 is also 15.0 cm as shown in the figure.

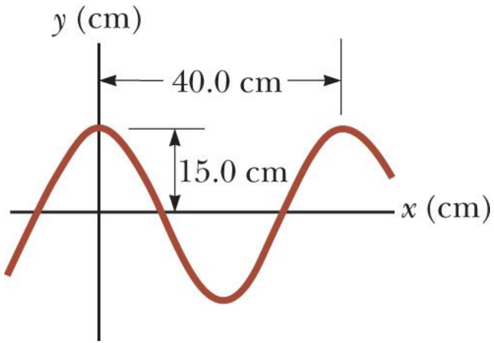
(a) Find the wave number *k*, period *T*, angular frequency ω, and speed *v* of the wave.

$$k = \frac{2\pi}{\lambda} \quad \rightarrow \quad k = \frac{2\pi \text{ rad}}{40.0 \text{ cm}} = \boxed{15.7 \text{ rad/m}}$$

$$T = \frac{1}{f} \quad \rightarrow \quad T = \frac{1}{8.00 \text{ s}^{-1}} = \boxed{0.125 \text{ s}}$$

$$\omega = 2\pi f \quad \rightarrow \quad \omega = 2\pi(8.00 \text{ s}^{-1}) = \boxed{50.3 \text{ rad/s}}$$

$$v = \lambda f \quad \rightarrow \quad v = (40.0 \text{ cm})(8.00 \text{ s}^{-1}) = \boxed{3.20 \text{ m/s}}$$



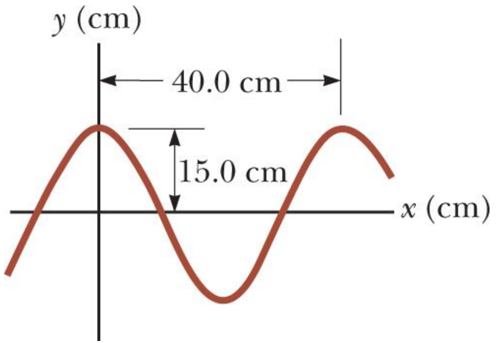
Mathematic Descriptions of Sinusoidal Waves

Example 1 (Traveling Sinusoidal Wave): A sinusoidal wave traveling in the positive *x* direction has an amplitude of 15.0 cm, a wavelength of 40.0 cm, and a frequency of 8.00 Hz. The vertical position of an element of the medium at *t* = 0 and *x* = 0 is also 15.0 cm as shown in the figure.

(b) Determine the phase constant ϕ and write a general expression for the wave function.

$$y(x,t) = A\sin(kx - \omega t + \phi)$$

At *t* = 0 and *x* = 0 $\rightarrow$ $15.0 = (15.0)\sin\phi \;\rightarrow\; \sin\phi = 1 \;\rightarrow\; \phi = \dfrac{\pi}{2}\text{ rad}$



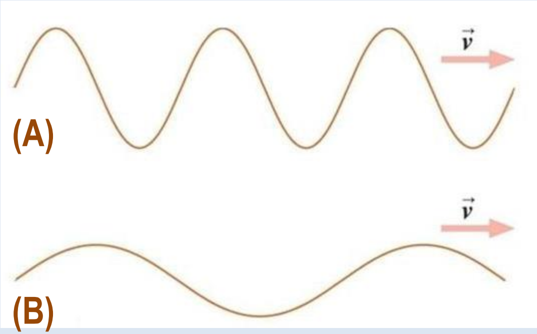
$$y(x,t) = A\sin\left(kx - \omega t + \frac{\pi}{2}\right) = A\cos(kx - \omega t)$$

$$y(x,t) = 0.150\cos(15.7x - 50.3t)$$

Quick Quiz 5

- The figure shows two waves propagating with the same speed. Which has the greater

  a) Amplitude
  b) Wavelength
  c) Period
  d) Wave number
  e) Frequency



Speed of Waves on Strings

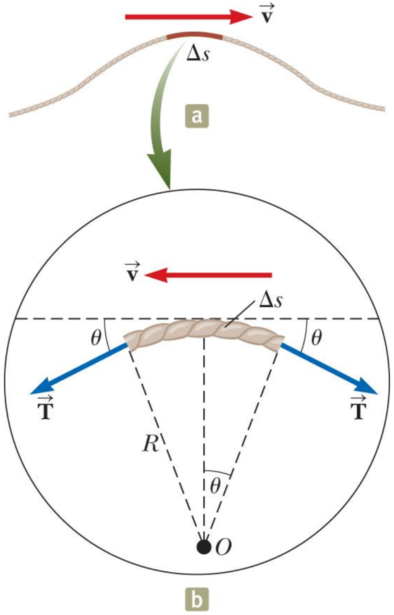
- The speed of wave is determined by the properties of the material or the medium through which the wave travels
- Consider a small-amplitude pulse wave moving to the right with uniform speed of v on a stretched string under tension force of T.
- The speed of the small-amplitude on the string is:

$$\boxed{v = \sqrt{\frac{T}{\mu}}}$$

Tension force (N)

Speed of wave (m/s)

Linear density of string (kg/m)



- The linear density μ is defined as the mass per unit length of the string.

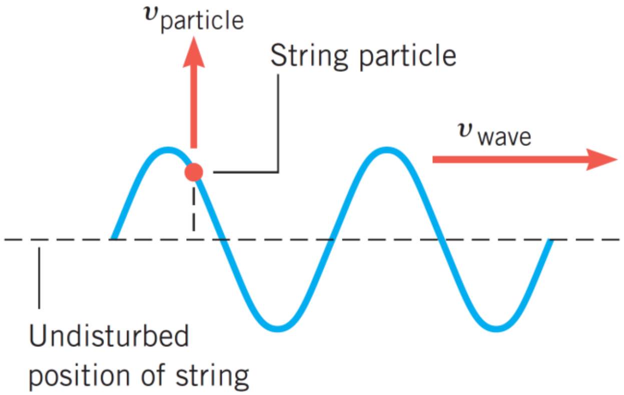
Speed of Waves on Strings

- Note that the speed of the wave on a string is different from the speed at which a string particle moves.
- The speed of the wave on the string is determine by the tension T and linear density μ of the string:

$$v_{wave} = \sqrt{\frac{T}{\mu}}$$

- The speed of the of the string particles is characteristics of the simple harmonic motion

$$v_{particle} = -\omega A sin(\omega t + \phi)$$



Speed of Waves on Strings

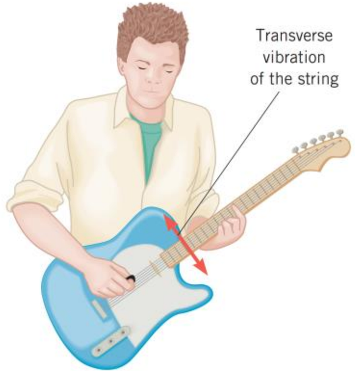
Example 2 (Waves on Guitar Strings): Transverse waves travel on each string of an electric guitar after the string is plucked. The length of each string between its two fixed ends is 0.628 m, and the mass is 0.208 g for the highest pitched E string and 3.32 g for the lowest pitched E string. Each string is under a tension of 226 N. Find the speeds of the waves on the two strings.

The speed of the wave for the high-pitched E

$$v = \sqrt{\frac{T}{\mu}} \quad \rightarrow \quad v = \sqrt{\frac{226\ N}{(0.208 \times 10^{-3}\ kg)/(0.628\ m)}} = 826\ m/s$$

The speed of the wave for the low-pitched E

$$v = \sqrt{\frac{T}{\mu}} \quad \rightarrow \quad v = \sqrt{\frac{226\ N}{(3.32 \times 10^{-3}\ kg)/(0.628\ m)}} = 207\ m/s$$



Quick Quiz 6

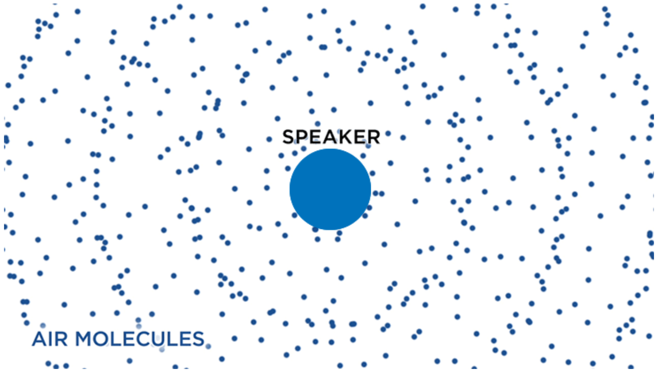
- For a wave pulse on a string to travel twice as fast, the string tension must be

  a) Increased by a factor of 4.
  b) Increased by a factor of 2.
  c) Decreased to one half its initial value.
  d) Decreased to one fourth its initial value
  e) Not possible. The pulse speed is always the same.

Sound Wave

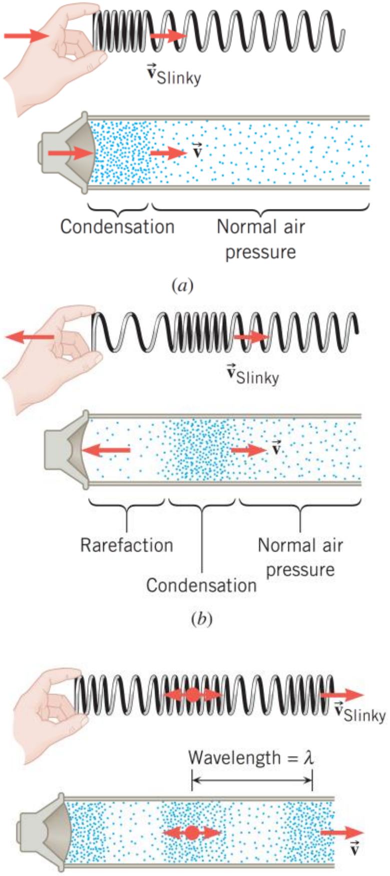
- **Sound** is a longitudinal mechanical wave that is created by a vibrating object, such as guitar string, the human vocal cords, or the diaphragm of a loudspeaker.
- Sound can be created or transmitted **only** in a medium, such as gas, liquid or solid.
- Sound **cannot** exist in a vacuum.

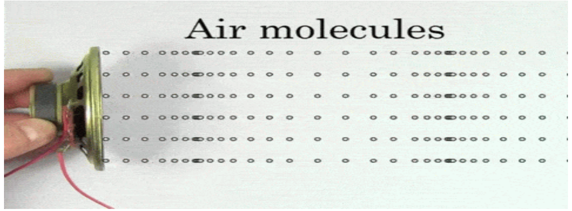
How sound waves are produced and why they are longitudinal?

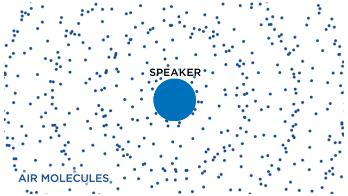


Sound Wave

- Consider the vibrating diaphragm of a loudspeaker.
  - When the diaphragm moves outward, it compresses the air directly in front of it.
  - This compression causes the air pressure to rise slightly. The region is called a **condensation**, and it travels away from the speaker at the speed of sound.
  - After producing a condensation, the diaphragm reverses its motion and moves inward.
  - The inward motion produces a region known as a **rarefaction**, where the air pressure is slightly less than normal.
  - The rarefaction also travels away from the speaker at the speed of sound.
  - The air molecule vibrate back and forth **parallel** to the line of the wave.







Speed of Sound

- Sound travels through gases, liquids, and solids. Its speed depends on the properties of the medium.
- Near room temperature, the speed of sound in air is 343 m/s.
- In general, sound travels slowest in gases, faster in liquids, and fastest in solids.
- For example, sound travels more than four times faster in water (1493 m/s) and more than seventeen times faster in steel (5960 m/s) than it does in air.

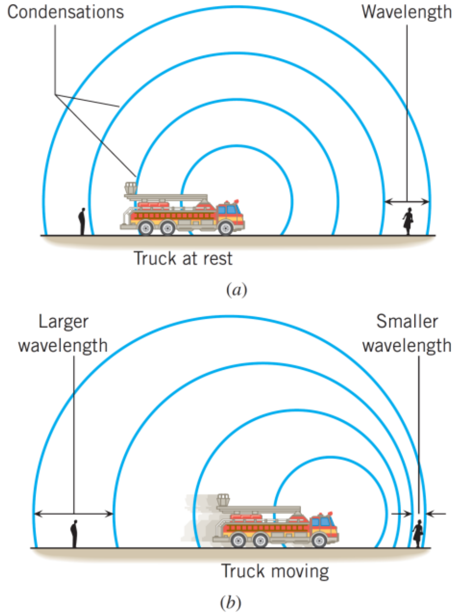
TABLE 16.1 Speed of Sound in Various Media

Medium	v (m/s)	Medium	v (m/s)	Medium	v (m/s)
Gases		**Liquids at 25°C**		**Solids**[a]	
Hydrogen (0°C)	1 286	Glycerol	1 904	Pyrex glass	5 640
Helium (0°C)	972	Seawater	1 533	Iron	5 950
Air (20°C)	343	Water	1 493	Aluminum	6 420
Air (0°C)	331	Mercury	1 450	Brass	4 700
Oxygen (0°C)	317	Kerosene	1 324	Copper	5 010
		Methyl alcohol	1 143	Gold	3 240
		Carbon tetrachloride	926	Lucite	2 680
				Lead	1 960
				Rubber	1 600

[a]Values given are for propagation of longitudinal waves in bulk media. Speeds for longitudinal waves in thin rods are smaller, and speeds of transverse waves in bulk are smaller yet.

The Doppler Effect – Moving Source

- **Doppler effect** is the change in frequency or pitch of the sound detected by an observer because the sound source and the observer have different velocities with respect to the medium of sound propagation.



  - Consider the sound emitted by a siren on the stationary fire truck, and the air is assumed be stationary.
  - Since the sound pattern is symmetrical, observer standing in front of or behind the truck detect the same number of condensations per second and hear the same frequency.
  - Once the truck begins to move, the observer in front of the truck hears a higher pitch, but the observer behind the truck hear lower pitch sound.

The Doppler Effect – Moving Source

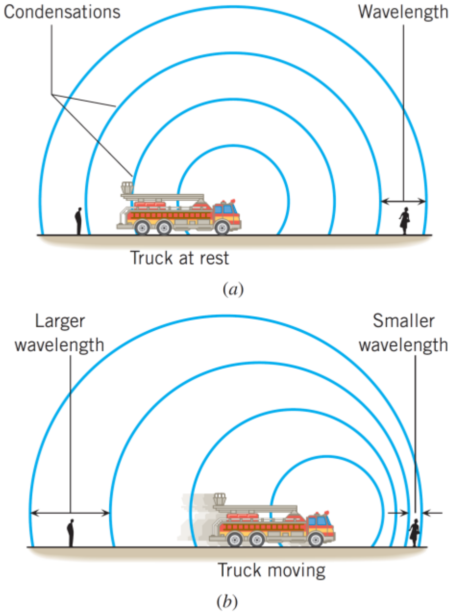
- **Doppler effect** is the change in frequency or pitch of the sound detected by an observer because the sound source and the observer have different velocities with respect to the medium of sound propagation.
  - The frequency perceived by the stationary observer f_o is

$$\boxed{f_o = f_s\left(\frac{v}{v - v_s}\right)}$$

Source moving toward stationary observer

$$\boxed{f_o = f_s\left(\frac{v}{v + v_s}\right)}$$

Source moving away from stationary observer



- f_o: The frequency perceived by the stationary observer
- f_s: The frequency of the sound emitted by the source
- v_s: The speed of the source of sound
- v: The speed of sound

The Doppler Effect – Moving Source

Example 3 (Sound of a Passing Train): A high-speed train is traveling at a speed of 44.7 m/s when the engineer sounds the 415-Hz warning horn. The speed of sound is 343 m/s. What are the frequency and wavelength of the sound, as perceived by a person standing at a crossing,

(a) When the train is approaching

The observer frequency is

$$f_o = f_s\left(\frac{v}{v - v_s}\right) = (415\ Hz)\left(\frac{343\ m/s}{343\ m/s - 44.7m/s}\right) = 477\ Hz$$

The observer wavelength is

$$\lambda_o = \frac{v}{f_o} = \frac{343\ m/s}{477\ Hz} = 0.719\ m$$

The Doppler Effect – Moving Source

Example 3 (Sound of a Passing Train): A high-speed train is traveling at a speed of 44.7 m/s when the engineer sounds the 415-Hz warning horn. The speed of sound is 343 m/s. What are the frequency and wavelength of the sound, as perceived by a person standing at a crossing,

(b) When the train is leaving

The observer frequency is

$$f_o = f_s\left(\frac{v}{v + v_s}\right) = (415\ Hz)\left(\frac{343\ m/s}{343\ m/s + 44.7\ m/s}\right) = 367\ Hz$$

The observer wavelength is

$$\lambda_o = \frac{v}{f_o} = \frac{343\ m/s}{367\ Hz} = 0.935\ m$$

The Doppler Effect – Moving Observer

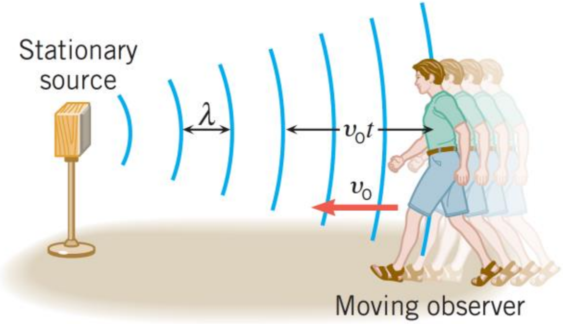
- **Doppler effect** is the change in frequency or pitch of the sound detected by an observer because the sound source and the observer have different velocities with respect to the medium of sound propagation.
  - Consider the sound emitted by a stationary source, and the air is assumed be stationary.
  - Assume the observer moves with speed v_o toward the stationary source. The moving observer encounters more condensations than a stationary observer, thus hears a greater frequency

$$f_o = f_s\left(\frac{v + v_o}{v}\right)$$

Observer moving toward stationary source

$$f_o = f_s\left(\frac{v - v_o}{v}\right)$$

Observer moving away from stationary source



The Doppler Effect – General Case

- **Doppler effect** is the change in frequency or pitch of the sound detected by an observer because the sound source and the observer have different velocities with respect to the medium of sound propagation.
  - It is possible for both the sound source and the observer to move with respect to the medium of sound.
  - If the medium is stationary, the observer frequency is

Source and observer both moving

$$f_o = f_s\left(\frac{v \pm v_o}{v \mp v_s}\right)$$

What happens when speed v_s exceeds the sound speed v.

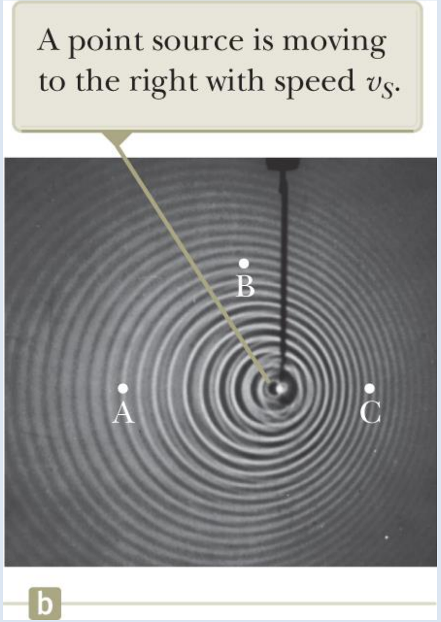
- In the numerator:
  - The plus sign applies when the observer moves toward the source
  - The minus sign applies when the observer moves away from the source
- In the denominator,
  - The minus sign is used when the source moves toward the observer
  - The plus sign is used when the source moves away from the observer

SAULT COLLEGE HUMBER Faculty of Applied Sciences & Technology

Quick Quiz 7

- Consider detectors of water waves at three locations A, B, and C in the figure. Which of the following statements is true?

    a) The wave speed is highest at location A.
    b) The wave speed is highest at location C.
    c) The detected wavelength is largest at location B.
    d) The detected wavelength is largest at location C.
    e) The detected frequency is highest at location C.
    f) The detected frequency is highest at location A.



Quick Quiz 8

- You stand on a platform at a train station and listen to a train approaching the station at a constant velocity. While the train approaches, but before it arrives, what do you hear?
  a) the intensity and the frequency of the sound both increasing
  b) the intensity and the frequency of the sound both decreasing
  c) the intensity increasing and the frequency decreasing
  d) the intensity decreasing and the frequency increasing
  e) the intensity increasing and the frequency remaining the same
  f) the intensity decreasing and the frequency remaining the same

THANK YOU

HUMBER

WE ARE HUMBER