# Waves

**Content**



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# What is wave?

- Waves are everywhere. Whether we recognize it or not, we encounter waves on a daily basis.
- Sound waves, visible light waves, radio waves, microwaves, water waves, sine waves, cosine waves, stadium waves, earthquake waves, waves on a string, and slinky spring waves are the examples of our daily encounters with waves.
- In addition to waves, there are a variety of phenomena in our physical world that resemble waves so closely that we can describe such phenomenon as being wavelike. The motion of a pendulum, the motion of a mass suspended by a spring, and the motion of a child on a swing, can be thought of as wavelike phenomena.
- Waves (and wavelike phenomena) are everywhere!

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# Example: Water wave

- Waves are created by some form of a disturbance, such as a rock thrown into the water, a duck shaking its tail in the water or a boat moving through the water.
- The water wave travels from one location to another.
- A duck at rest on the surface of the water is observed to bob up-and-down at rather regular time intervals as the wave passes by. The waves may appear to be plane waves that travel in a straight-line direction, perhaps towards a sandy shore.
- The waves may be circular waves that originate from the point where the disturbances occur; such circular waves travel across the surface of the water in all directions.
- These mental pictures of water waves are useful for understanding the nature of a wave.



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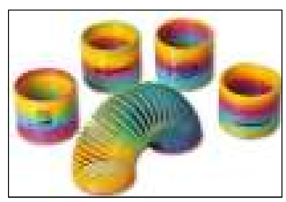
# Example: Slinky Spring

- Another picture of waves involves the movement of a slinky spring/coil. If a slinky spring is stretched out from end to end, a wave can be introduced into the slinky by either vibrating the first coil up and down vertically or back and forth horizontally.
- A wave will subsequently be seen traveling from one end of the slinky to the other.
- 
- As the wave moves along the slinky, each individual coil is seen to move out of place and then return to its original position.
- A slinky wave provides an excellent mental picture of a wave.

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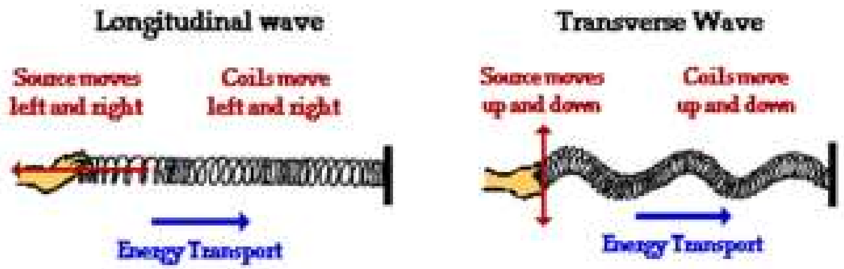
# Example: Slinky Spring




- Slinky spring is pushed forwards and backwards at a constant rate.
- A series of **rarefactions** and **compressions** occurs.

- A spring is tied at one end and the other end is moved continuously up and down.
- A waveform is exhibited on the spring.

# Example: A rope

- Holding a long jump rope with a friend and vibrating one end up and down. The up and down vibration of the end of the rope created a disturbance of the rope that subsequently moved towards the other end.
- A single disturbance could be created by the single vibration of one end of the rope.
- On the other hand, a repeated disturbance would result in a repeated and regular vibration of the rope. The shape of the pattern formed in the rope was influenced by the frequency at which we vibrated it.
- If we vibrated the rope rapidly, then a short wave was created. And if we vibrated the rope less frequently (not as often), a long wave was created.
- While we were likely unaware of it as children, we were entering the world of the physics of waves as we contentedly played with the rope.

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# Waves

- A wave is **a disturbance that transfers energy between 2 points through vibrations in a medium, without transferring matter between the 2 points.**
- No particle of the medium travels between the two points.
- Particles just oscillate in the medium about their mean position.
- The act of moving the first particle in a given direction and then returning it to its equilibrium position creates a **disturbance**. We can then observe this disturbance moving through from one end to the other. If the first particle is given a single back-and-forth vibration, then we call the observed motion of the disturbance a pulse. A **pulse** is a single disturbance moving through a medium from one location to another location.
- However, if the first particle is continuously and periodically vibrated in a back-and-forth manner, we would observe a repeating disturbance that endures over some prolonged period of time. The repeating and periodic disturbance that moves through a medium from one location to another is referred to as a **wave**.

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# Categories of Waves

- Waves whose wave profiles move and energy is transmitted from one point to another is called progressive waves.
- Waves come in many shapes and forms.
- One way to categorize waves is on the basis of the direction of movement of the individual particles of the medium relative to the direction in which the waves travel.
- Categorizing waves on this basis leads to two notable categories:

  a.) Transverse waves

  b.) Longitudinal waves

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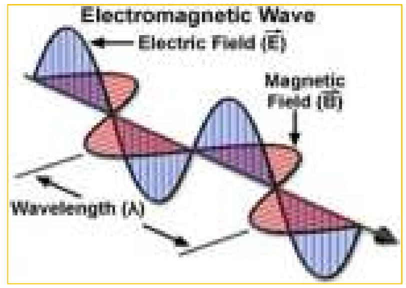
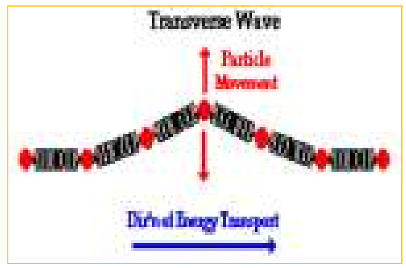
## Transverse waves

- A transverse wave is a wave in which the vibrations of the particles of the wave are at right angles to the direction in which the energy of the wave is travelling

- Examples:
  - water waves
  - electromagnetic waves
  - rope/string vibration up & down

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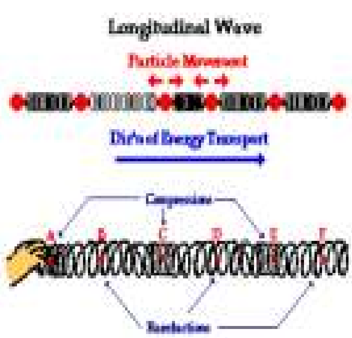
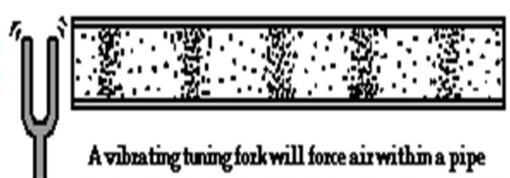
## Longitudinal waves

- A longitudinal wave is one in which the direction of the vibrations of the particles of the wave are along the direction in which the energy of the wave is travelling.
- Example:
  - sound wave which vibrates forwards and backwards
  - seismic waves (earthquakes)
  - slinky spring vibrating forth and back



A vibrating tuning fork will force air within a pipe to begin vibrating back and forth in a direction parallel to the energy transport; sound is a longitudinal wave.

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# Distinguish between

| Transverse waves | Longitudinal waves |
|---|---|
| • Wave in which the direction of the vibrations of the particles of the wave are at right angles to the direction in which the energy of the wave is travelling<br><br>➢Electromagnetic wave<br>➢Water wave<br><br>➢**Can be polarized** | • Wave in which the direction of the vibrations of the particles of the wave are along to the direction in which the energy of the wave is travelling.<br><br>➢Sound wave<br>➢Seismic wave<br><br>➢**Cannot be polarized** |

# Check your understanding

1. In order for John to hear Jill, air molecules must move from the lips of Jill to the ears of John. True or False.

2. Jack and Jill are experimenting with pulses on a rope. They vibrate an end up and down to create the pulse and observe it moving from end to end. How does the position of a point on the rope, before the pulse comes, compare to the position after the pulse has passed?

3. Minute after minute, hour after hour, day after day, ocean waves continue to splash onto the shore. Explain why the beach is not completely submerged and why the middle of the ocean has not yet been depleted of its water supply.

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# Check your understanding

1. A medium is able to transport a wave from one location to another because the particles of the medium are ____.
   a. frictionless
   c. able to interact
   b. isolated from one another
   d. very light

2. A transverse wave is transporting energy from east to west. The particles of the medium will move_____.
   a. east to west only
   b. both eastward and westward
   c. north to south only
   d. both northward and southward

3. A wave is transporting energy from left to right. The particles of the medium are moving back and forth in a leftward and rightward direction. This type of wave is known as a
   a. mechanical
   b. electromagnetic
   c. transverse
   d. longitudinal

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# Check your understanding

4. A science fiction film depicts inhabitants of one spaceship (in outer space) hearing the sound of a nearby spaceship as it zooms past at high speeds. Critique the physics of this film.

5. Describe how the fans (supporters) in a stadium must move in order to produce a longitudinal stadium wave. How about transverse wave?

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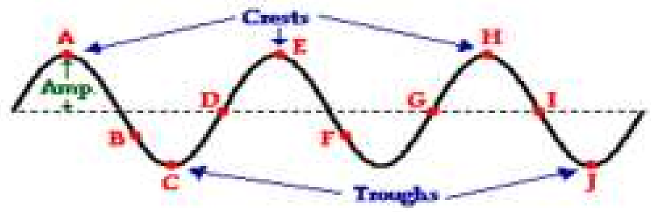
## Anatomy of a wave




- The **peak or crest** of a wave is the point on the medium which exhibits the maximum amount of positive or upwards displacement from the rest position (i.e. points A, E and H)
- The **trough** of a wave is the point on the medium which exhibits the maximum amount of negative or downwards displacement from the rest position (i.e. points C and J)
- **Wavelength, λ,** is the distance between 2 successive crests or troughs, (i.e. A-E or E-H or ½ C-J)
- The wavelength of a wave is simply the length of one complete wave cycle.
- **Amplitude** of a wave refers to the maximum amount of displacement of a particle from its rest position,

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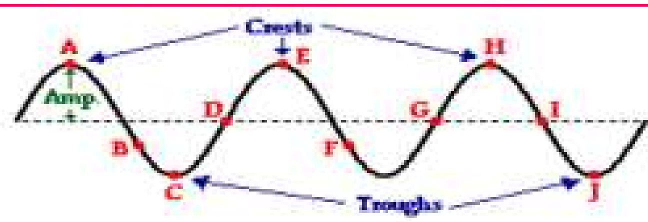
## Anatomy of a wave




- A high energy wave is characterized by a high amplitude; a low energy wave is characterized by a low amplitude.
- Putting a lot of energy into a transverse pulse will not affect the wavelength, the frequency or the speed of the pulse.
- **The energy imparted to a pulse will only effect the amplitude of that pulse**.
- The **period, T** of wave motion is the time in which a particle of the medium completes one oscillation.
- **In short, period is time taken for 1 oscillation.**

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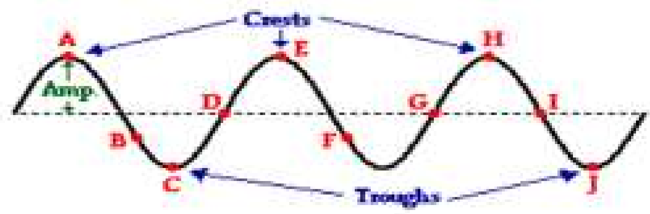
## Anatomy of a wave




- **Frequency, f** is the number of waves, which pass through a given point in one second. It is denoted by the term Hz (hertz) and 1Hz = $1s^{-1}$ = 1cycle per second (f = 1 / period, T)
- **In short, frequency is number of oscillations in 1 second.**
- **Wave speed, v** is the distance moved by a wave in one second.
- **Formula** $v = f\lambda$
- Keep note that the wave speed does not depend on the amplitude, frequency, wavelength of the wave.
- The wave speed depends upon the medium through which the wave is moving.
- Only an alteration in the properties of the medium will cause a change in the speed !

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## Check your understanding

- A wave of frequency 120Hz has a wavelength of 5.0m. What is the speed of the wave?
- A radar wave is an electromagnetic wave whose speed is $3.0 \times 10^8$ $ms^{-1}$. If its frequency is 1.64 GHz, find its wavelength.
- What is the range of frequencies for visible light? One end of spectrum the wavelength of red light is 700nm and the other end of spectrum the wavelength of violet light is 400nm. Light travels with a speed of $3.0 \times 10^8$ $ms^{-1}$ in a vacuum.

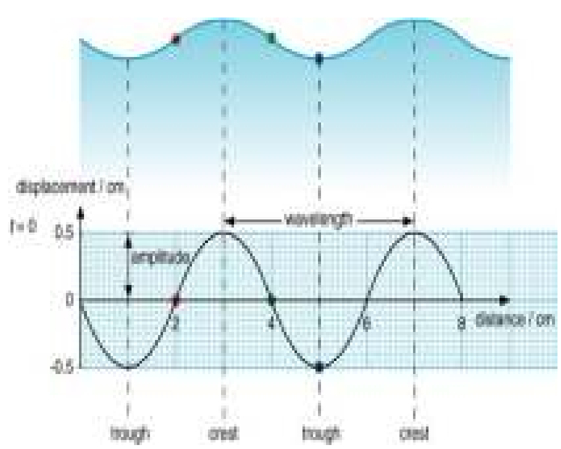
# Displacement - Distance Graph

- The graph is used to show the **displacement of MANY particles** at **different positions** at a **particular time.**
- Can be used to describe both transverse and longitudinal waves.
- From a displacement-distance graph, we can directly read the following information:
  i.) Amplitude of the wave
  ii.) Wavelength of the wave
  iii.) Location of the particles
  (transverse: up or down) / (longitudinal: left or right)

# Displacement - Distance Graph (Transverse wave)

**Displacement-distance graph of a *transverse wave* when *t=0***

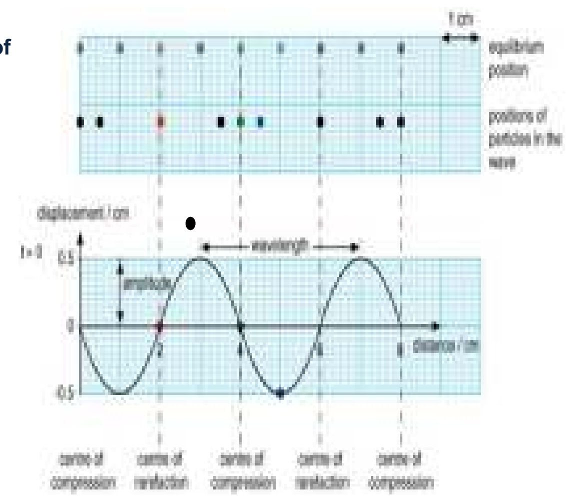
The displacement tells us how far **(up or down)** the particles are displaced form original point.



# Displacement - Distance Graph (Longitudinal wave)

**Displacement-distance graph of a *longitudinal wave* when *t=0***

The displacement tells us how far **(right or left)** the particles are displaced form original point.

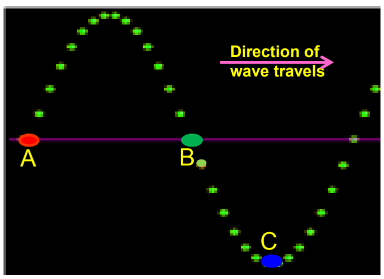


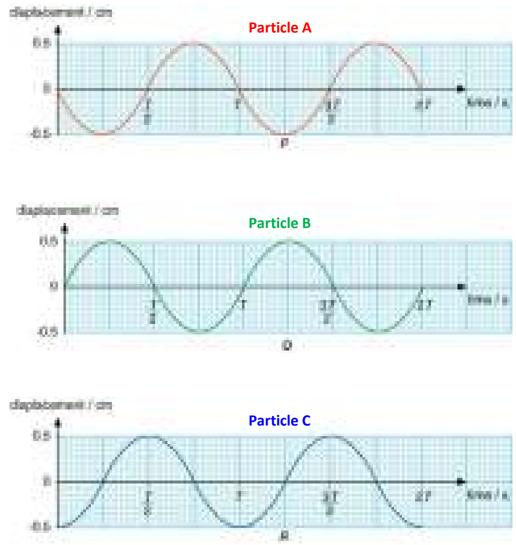

# Displacement - Time Graph

- The graph is used to show the **displacement of ONE particle** at **different time** at a **particular position.**
- Can be used to describe both transverse and longitudinal waves.
- From a displacement-time graph, we can directly read the following information:
  i.) Amplitude of the wave
  ii.) Period of the wave (as well as frequency, f = 1 / T)
  iii.) Location of the particles
  (transverse: up or down) / (longitudinal: left or right)

# Displacement - Time Graph

- Graphs beside show 3 individual graph for 3 different particles
- Each particles has its own displacement-time graph
- Each graph is different because each particle is at a different position



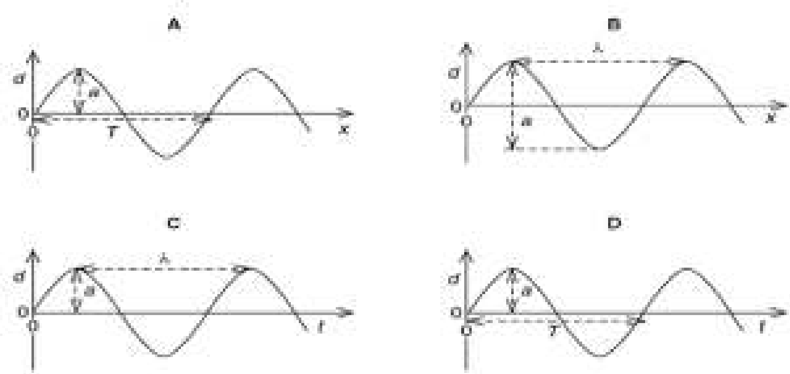




# Example 1

The four graphs represent a progressive wave on a stretched string. Graphs **A** and **B** show how the displacement *d* varies with distance *x* along the string at one instant. Graphs **C** and **D** show how the displacement *d* varies with time *t* at a particular value of *x*.

The labels on the graphs are intended to show the wavelength $\lambda$, the period *T*, and the amplitude *a* of the wave, but only one graph is correctly labelled.

Which graph is correctly labelled?

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# Example 2

Which of the following is true for all transverse waves?

**A** They are all electromagnetic.

**B** They can all be polarised.

**C** They can all travel through a vacuum.

**D** They all involve the oscillation of atoms.

Electromagnetic waves of wavelength $\lambda$ and frequency $f$ travel at speed $c$ in a vacuum.

Which of the following describes the wavelength and speed of electromagnetic waves of frequency $f/2$?

| | wavelength | speed in a vacuum |
|---|---|---|
| **A** | $\lambda/2$ | $c/2$ |
| **B** | $\lambda/2$ | $c$ |
| **C** | $2\lambda$ | $c$ |
| **D** | $2\lambda$ | $2c$ |

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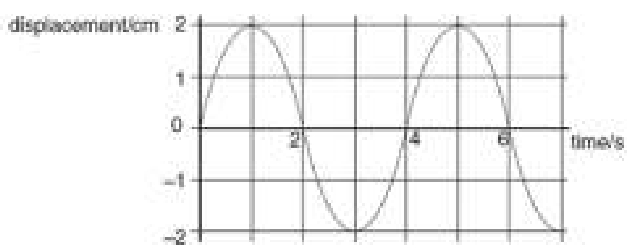
# Example 3

The graph shows how the displacement of a particle in a wave varies with time.




Which of the following is correct?

**A** The wave has an amplitude of 2 cm and could be either transverse or longitudinal.

**B** The wave has an amplitude of 2 cm and must be transverse.

**C** The wave has an amplitude of 4 cm and could be either transverse or longitudinal.

**D** The wave has an amplitude of 4 cm and must be transverse.

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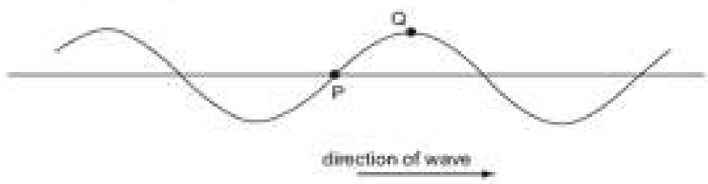
# Example 4

The diagram shows a transverse wave on a rope. The wave is travelling from left to right.

At the instant shown, the points P and Q on the rope have zero displacement and maximum displacement respectively.




Which of the following describes the direction of motion, if any, of the points P and Q at this instant?

| | point P | point Q |
|---|---|---|
| A | downwards | stationary |
| B | stationary | downwards |
| C | stationary | upwards |
| D | upwards | stationary |

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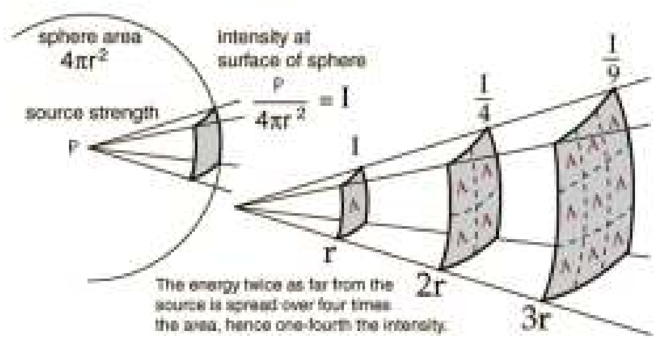
# Intensity

- Intensity of a wave is defined as the amount energy passing through per unit area per unit time.

$$I = \frac{Energy}{area\ x\ time} = \frac{Power}{area} = \frac{P}{4\pi r^2} \text{ (unit Wm}^{-2}\text{)}$$

- This equation holds true when we consider a point source, emitting power, P which is distributed over a spherical surface or radius, r from the source.

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# Intensity

- We see that the **intensity of a wave I is inversely proportional to the square of its distance.**

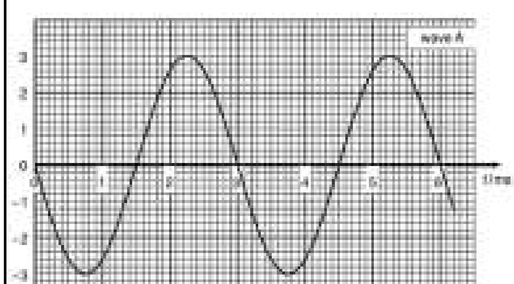
$$I \propto (1/r)^2 \quad ; \quad I = k(1/r)^2$$

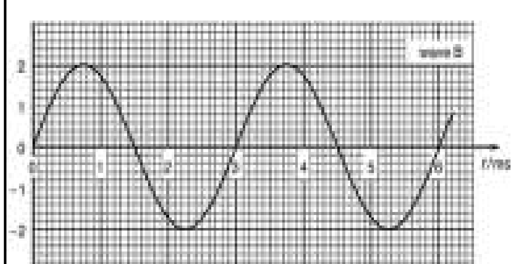
- Besides that, the **intensity of a wave is directly proportional to the square of the amplitude of the wave**.

$$I \propto A^2 \quad ; \quad I = kA^2$$



# Example 5





- Using data from the graph, deduce for this wave

(a) ratio $\dfrac{\text{amplitude at A}}{\text{amplitude at B}}$

(b) ratio $\dfrac{\text{intensity at A}}{\text{intensity at B}}$

# Example 6

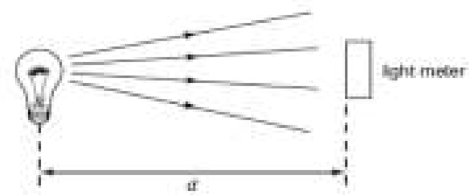
- When a plane wave of amplitude, *A* is incident on a surface area, *S* that is placed perpendicular to the direction of travel of the wave, the energy per unit time intercepted by the surface is *P*. If the amplitude of the wave is increased to *2A* and the area of the surface is reduced to *S/2*, what is the new energy per unit time intercepted by this smaller surface?

# Example 7

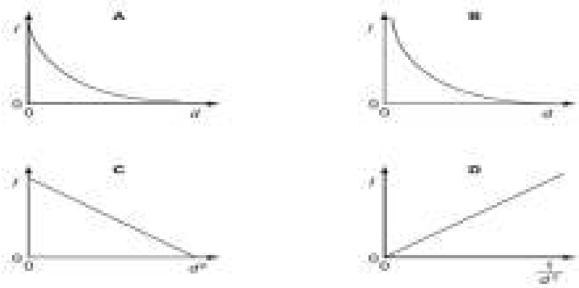
- At a distance of 20 m from a point source of waves the amplitude of a wave is 1.6 mm and it has an intensity of 4.4 x $10^{-3}$ $Wm^{-2}$. Find the intensity and amplitude of this wave at distances of 40m and 100 m from the source.

# Example 8

A light meter measures the intensity $I$ of the light falling on it. Theory suggests that this varies as the inverse square of the distance $d$.




Which graph of the results supports this theory?

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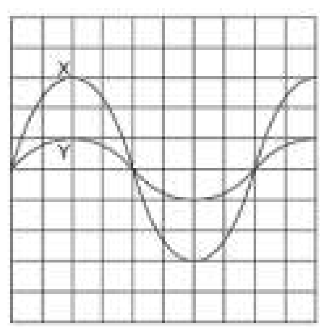
# Example 9

The diagram represents the screen of a cathode-ray oscilloscope displaying two sound waves labelled X and Y.




What is the ratio $\frac{\text{intensity of sound wave X}}{\text{intensity of sound wave Y}}$?

**A** $\frac{9}{1}$ **B** $\frac{3}{1}$ **C** $\frac{\sqrt{3}}{1}$ **D** $\frac{1}{1}$

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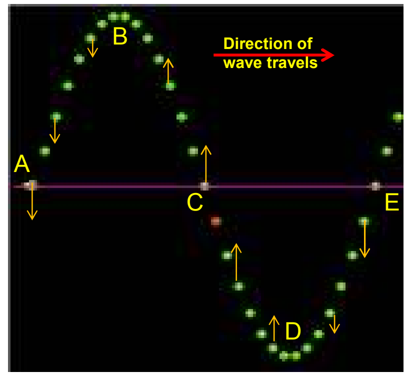
# Phase Difference (of 1 wave)

- In a waveform of **one complete cycle**, we observed that all the particles within this one cycle would be displaced differently & having different direction of motion, at a given time.
- This difference between one particle with another is called the phase difference.
- The term 'phase' is used because we speak & analyze their difference in terms of degree or radian.
- In short, phase difference is a fraction of a cycle by which 1 particle moves behind the other.
- 1 complete cycle consists of 2π radians or 360°
- Below are examples of the phase difference between two particles.




a.) A & B = 90° , π/2 rad
b.) A & C = 180° , π rad
c.) A & D = 270° , 3π/2 rad
d.) A & E = 360° / 0° , 2π rad

e.) B & D = 180° , π rad
f.) B & C = 90° , π/2 rad
g.) C & E = 180° , π rad
h.) B & E = 270° , 3π/2 rad

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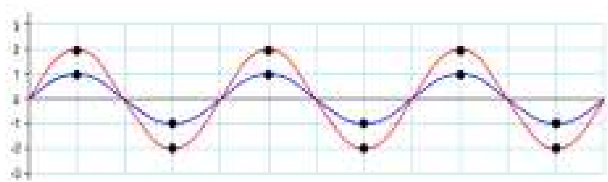
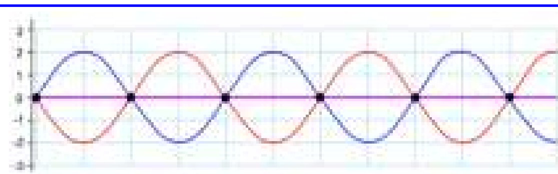
# Phase Difference (of 2 waves)

- Apart from that, we can also speak about phase difference when we analyze **2 different waves.**
- If the 2 individual waves have the **same frequency** but **different phase** then the waves will have **phase difference** & **the phase difference will be a constant value.**
- However, if the 2 individual waves **does not have the same frequency**, their **phase difference will NOT be constant** as it will change continuously with respect to time.

**2 different waves**
**1.) same frequency**
**2.) zero phase difference.**
**(in-phase)**



**2 different waves**
**1.) same frequency**
**2.) 180° phase difference.**
**(anti-phase)**



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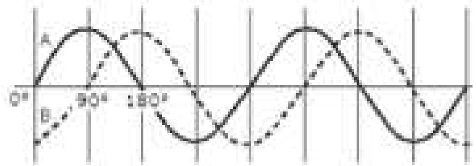
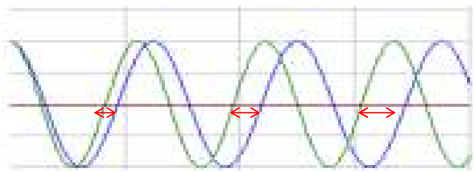
# Phase Difference (of 2 waves)

**2 different waves**
**1.) same frequency**
**2.) 90° phase difference.**
**(out-of-phase)**




**2 different waves**
**1.) different frequency**
**2.) phase difference changes.**



- Draw a diagram to illustrate 2 waves with same frequency which are (a) $\pi/2$ radians out of phase and (b) $3\pi/4$ radians out of phase.

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# Phase Difference Calculation

- If a graph of displacement-time is given, then period, T = 2π radian / 360°
- If a graph of displacement-distance is given, then wavelength, λ = 2π radian / 360°

- Thus to calculate the phase difference, these equations can be applied:

- **For displacement-distance graph**

$$phase\ difference = \frac{\Delta\, distance}{wavelength}\ x\ (2\pi \text{ or } 360°)$$

- **For displacement-time graph**

$$phase\ difference = \frac{\Delta\, time}{period}\ x\ (2\pi \text{ or } 360°)$$

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## Example 10

- A wave of frequency 400 Hz is traveling at a speed of 320 $ms^{-1}$ Calculate the phase difference between two points 0.2 m apart on the wave.

The frequency of a certain wave is 500 Hz and its speed is 340 $m\,s^{-1}$.

What is the phase difference between the motions of two points on the wave 0.17 m apart?

**A** $\frac{\pi}{4}$ rad **B** $\frac{\pi}{2}$ rad **C** $\frac{3\pi}{4}$ rad **D** $\pi$ rad

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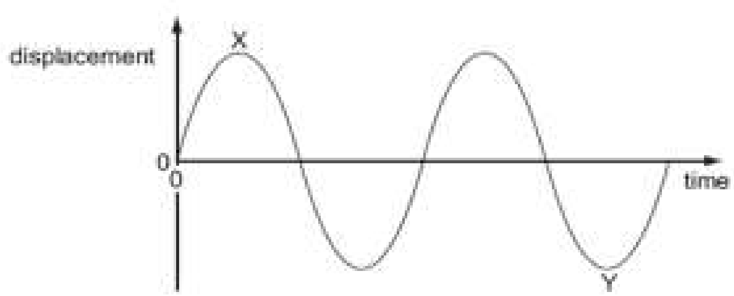
## Example 11

A displacement-time graph for a transverse wave is shown in the diagram.




The phase difference between X and Y can be expressed as $n\pi$.

What is the value of $n$?

**A** 1.5 **B** 2.5 **C** 3.0 **D** 6.0

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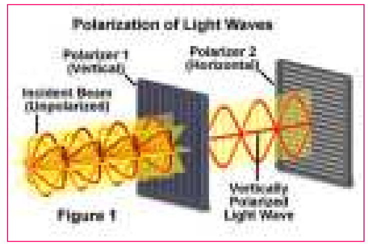
# Polarization

- Process by which a *waves' oscillations are made to occur in one plane only*
- Associated with transverse waves only !
- Longitudinal waves cannot be polarized !
- Application such as in sunglasses.
  - minimize light transmission.




- If the polarized light from 1st polarizer is then directed to 2nd polarizer, the light will **not be allowed** through the 2nd polarizer if its preferred direction is at right angles to that of the 1st filter.
- http://micro.magnet.fsu.edu/primer/java/polarizedlight/3dpolarized/index.html

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# Example 12

- . Which of the following is true for all transverse waves?

  **A** They are all electromagnetic.
  **B** They can all be polarised.
  **C** They can all travel through a vacuum.
  **D** They all involve the oscillation of atoms.

- . Which observation indicates that sound waves are longitudinal?

  **A** Sound can be reflected from a solid surface.
  **B** Sound cannot be polarised.
  **C** Sound is diffracted around corners.
  **D** Sound is refracted as it passes from hot air to cold air.

- . Which of the following applies to a progressive transverse wave?

| | transfers energy | can be polarised |
|---|---|---|
| **A** | no | no |
| **B** | no | yes |
| **C** | yes | no |
| **D** | yes | yes |

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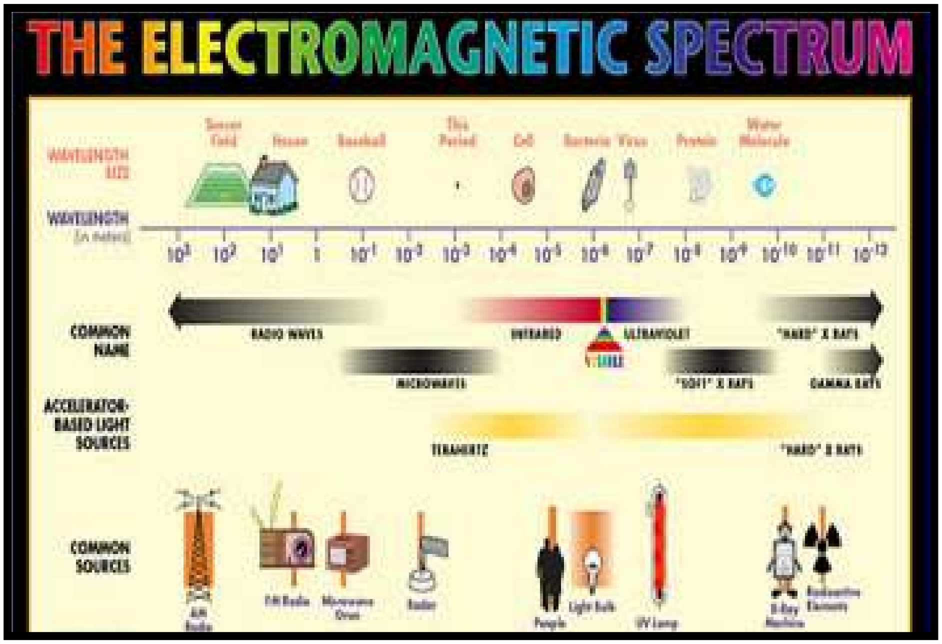


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## Properties of electromagnetic waves

- In general, all electromagnetic waves travel at the same speed which is the speed of light $3.0 \times 10^8$ m/s
- They are all **transverse waves**, with the oscillations being electric and magnetic fields.
- There is no sharp division in term of wavelength or frequency to group these 7 categories of EM waves. The division shown in the table below are somewhat arbitrary.
- In fact, they are categorized according to how they are produced.

| Radiation | Wavelength range / m |
|---|---|
| Radio waves | $10^{3} – 10^{-1}$ |
| Microwaves | $10^{-1} – 10^{-3}$ |
| Infrared | $10^{-3} – 7 \times 10^{-7}$ |
| Visible | $7 \times 10^{-7}$ (red) – $4 \times 10^{-7}$ (violet) |
| Ultraviolet | $4 \times 10^{-7} – 10^{-8}$ |
| X-rays | $10^{-8} – 7 \times 10^{-13}$ |
| γ-rays | $10^{-10} – 7 \times 10^{-15}$ |

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## Gamma Rays

- These are the ***most dangerous and penetrating*** form of electro-magnetic waves. They have the ***shortest wavelengths, and highest frequency***.
- ***Gamma rays are emitted by some radioactive nuclei, and are also produced during supernova explosions***. They do not need an electrical power source to be generated like X-rays.

## X-rays

- X-rays are produced from electrons stopped rapidly in a X-ray tube which needs an electrical power source.
- X-Rays have high energy and such short wavelength that they can go right through us. However, they cannot get through bone as easily as they can get through muscle.
- Medical practitioners use them to look at our bones and our dentists to look at our teeth.
- ***Produced when high velocity electrons strike a metal target.***

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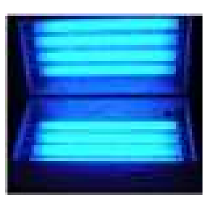
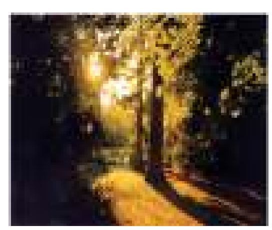
## Ultraviolet Radiation

- A dangerous type of radiation.
- Produced from very hot objects ***when electrons jump from relatively high excited states to low excited states or ground state*** within atoms and molecules.
- Also can be emitted from the sun.
- UV is ***partly absorbed*** by the ozone layer.



## Visible light

- Made up of monochromatic light with different wavelengths.
- ***Longest wavelength*** light we can see is ***red about 650 nm - 700 nm***
- ***Shortest wavelength*** light we can see is ***violet about 350 nm - 400 nm***
- ***Middle wavelength*** light we can see is ***green about 550 nm - 555 nm***



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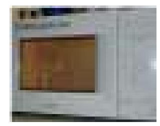
## Infrared Radiation

- Produced from hot objects and generated by vibration and rotation of atoms & molecules.
- Detectable by our skin as heat radiation.
- Keeps the earth warm.


## Microwaves

- Are produced from electrons oscillating in magnetrons.
- Very short wavelength.
- Used in radar, communications, broadcasting and preparation of food.



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## Radio waves

- Produced from electrons oscillating in aerials.
- Longest of all the electromagnetic waves.
- Used in telecommunications (radio and TV broadcasts, as well as mobile phones and walkie talkies).
- 2 common ways to transmit radio waves
- a) Amplitude modulation (AM)
- b) Frequency modulation (FM)
- Some radio waves come through the earth's atmosphere from space.


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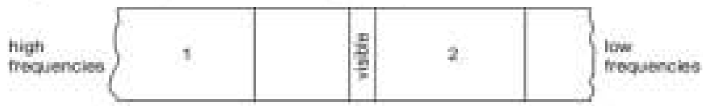
# Example 13

- The diagram illustrates part of the electromagnetic spectrum.




Which labels are correct for the regions marked 1 and 2?

| | 1 | 2 |
|---|---|---|
| A | infrared | X-rays |
| B | microwaves | X-rays |
| C | ultraviolet | microwaves |
| D | X-rays | infrared |

- An electromagnetic wave has a frequency of $10^{8}$ Hz.

In which region of the electromagnetic spectrum does the wave occur?

**A** infra-red

**B** radio

**C** ultraviolet

**D** visible

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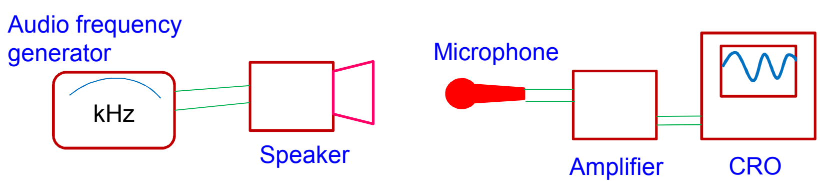
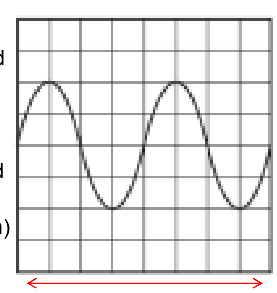
# Determination of Frequency & Wavelength of a given sound




- A microphone converts sound energy into electrical energy.
- It responds to small pressure variations in sound waves and converts them to small voltage variations having the same frequency as of the frequency generator.
- This voltage variation is amplified and fed to a CRO.
- A wave form of sound reaching the microphone is displayed on the CRO screen.
- Set the time base to appropriate scale. (Eg: $1 \times 10^{-3}$ s per cm)
- Frequency can be calculated as well as wavelength, since speed of sound in air is about 330 $ms^{-1}$

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