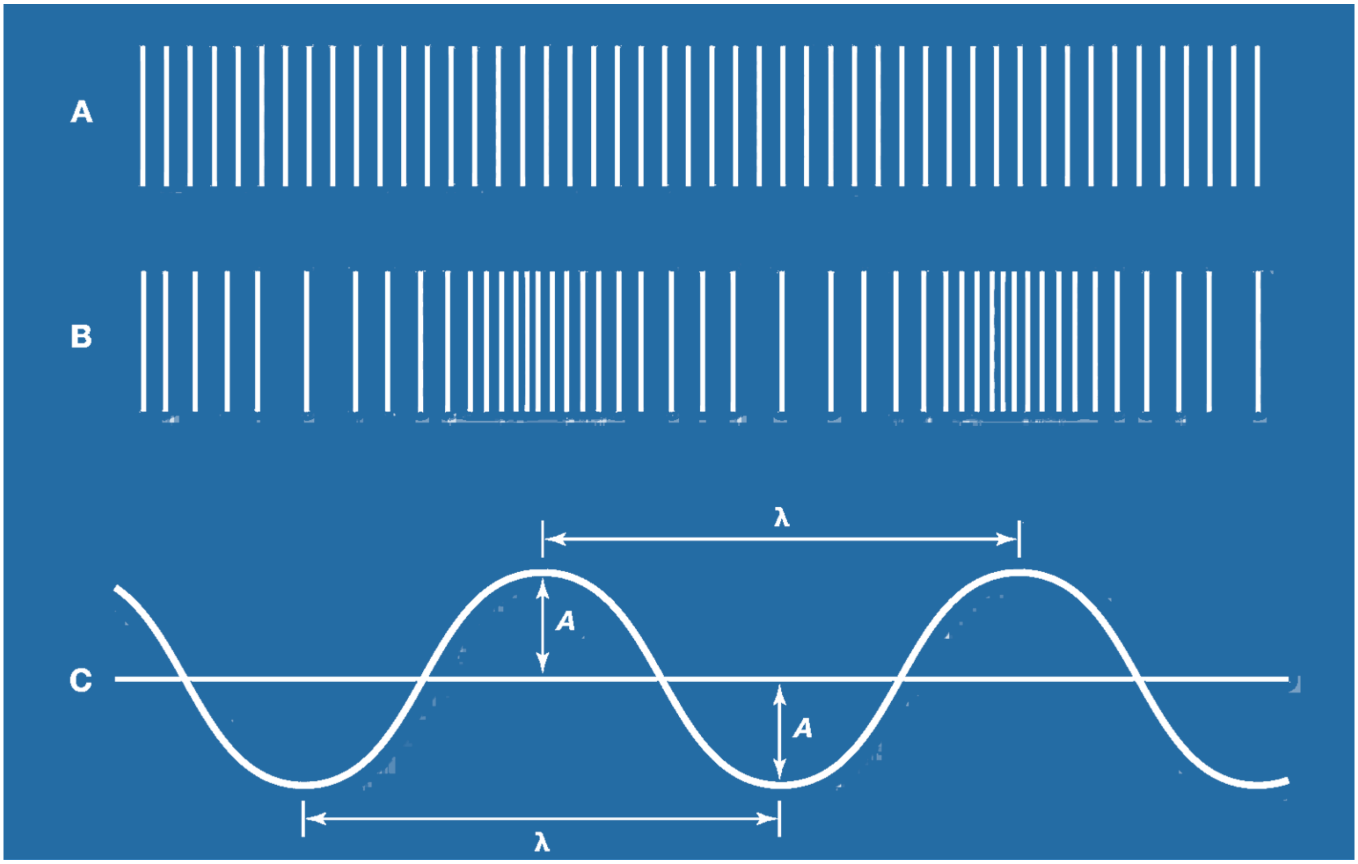
Waves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Waves

Progressive (Mechanical) wave

When a source produces a disturbance in a medium, the particles in the adjacent layers pick up the disturbance and start vibrating. These in turn transfer the disturbance to the next layers and so on. This leads to propagation of disturbance away from the source. Such ***a continuous propagating disturbance is called a progressive wave***.

Classification of waves

1. Mechanical waves and electromagnetic waves

Based on the nature of disturbance which propagates, waves are classified as

- **Mechanical waves: waves which are elastic disturbances and *require a material medium* for their propagation, are called mechanical waves**.

  In the case of mechanical waves, particles in the medium oscillate without drifting along the direction of wave propagation.

Example: Sound waves, seismic waves and shock waves.

- **Electromagnetic waves: waves which are the disturbances in electric and magnetic fields and *do not require a material medium* for their propagation, are called electromagnetic waves.**

  In the case of electromagnetic waves, there are oscillating electric and magnetic fields mutually at right angles and at right angles to the direction of wave propagation.

Example: Light waves, radio waves, infra red waves, x-rays, γ-rays etc.

☞	Electromagnetic waves can travel through matter and also through vacuum but mechanical waves cannot travel through vacuum.

2. One dimensional, two dimensional and three dimensional waves

Based on the way the waves spread, waves are classified as

- **One-dimensional waves:** Waves which travel along a straight line.

  Example: waves along a stretched string.
- **Two-dimensional waves:** Waves which travel in a plane.

  Example: waves on the still surface of a pond.
- **Three-dimensional waves:** Waves which travel in space and spread in all directions around the source.

  Example: sound waves in air.

3. Longitudinal and transverse waves

Based on the direction of vibration of the particles of a medium with respect to the direction of propagation, waves are classified as

- **Longitudinal waves**

  Waves in which the oscillations of the particles of a medium are along the direction of wave propagation are **called longitudinal waves.**

  Longitudinal waves are formed by a sequence of alternate compressions and rarefactions.

Example: sound waves.

- **Transverse waves**

  Waves in which the oscillations of the particles of a medium are perpendicular to the direction of wave propagation are called **transverse waves.**

  A transverse wave consists of a sequence of crests and troughs.

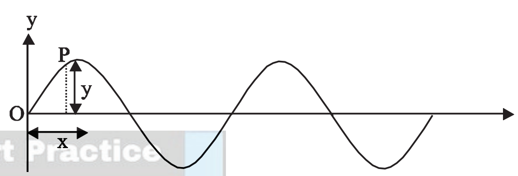
  Example: waves on the surface of water, waves on a string.

Characteristics of mechanical progressive waves

1. Waves are produced by continuous periodic vibrations generated at a point in a medium.
2. The elastic and inertial property of a medium is responsible for wave propagation.
3. Waves transport energy (and momentum) from the source of vibration (disturbance) away from it.
   However, the particles of matter themselves do not move away. They only perform simple harmonic vibrations about their mean positions.
4. Waves in a homogeneous medium travel with constant velocity at a given temperature.
5. All the vibrating particles along a wave vibrate with the same frequency. For a three dimensional wave, the amplitude decreases as the distance from the source increases.
6. Waves undergo reflection, refraction, diffraction etc.
7. Only transverse waves undergo polarisation.
8. Wave propagation is longitudinal inside solids, liquids and gases. Wave propagation can be transverse on a liquid surface, inside solids and on strings.

Wave equation

Consider a stretched string, which is in equilibrium along x-axis.



Let the free end of the string be subjected to periodic up-down motion. A wave is setup in the string. During the wave motion, the maximum displacement of each particle in the string is the same along a direction perpendicular to the string.

- The displacement y of a particle on the string at an instant of time depends on its x - coordinate.
- The displacement y of a particle at a given value of x depends on time.

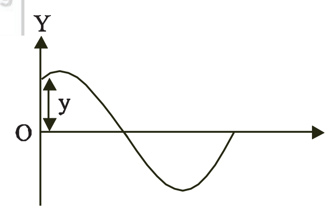
Thus, in general, the displacement is, $y = f(x, t)$

An equation that gives the displacement of a particle in a medium at any point at any instant of time is called a wave equation.

A general form of the wave equation is $y = f(x \pm v t)$.

Displacement relation in a wave (Equation for a progressive wave)

Consider a sinusoidal wave. As the wave travels along the positive x-direction, particles of the medium perform simple harmonic vibrations. Different particles along the wave are in different states of vibration.



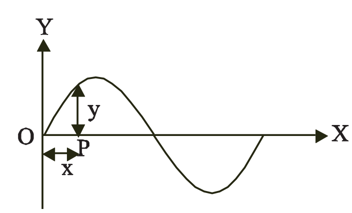
Let the displacement of the particle at the origin (x = 0) at an instant be represented by

$y = A\sin\omega t$ ... (1)

where A is the amplitude and ω is the angular frequency.

This equation can represent the displacement of the particle at the origin. This equation can be converted into a general equation as follows.

A particle at P exhibits the same state of vibration as that of a particle at the origin after a time lag. The time taken by the disturbance to reach the point P at a distance x from the origin is $\frac{x}{v}$ where, v is the velocity of the wave. The state of motion of the particle at P is same as that of the particle at the origin at a slightly earlier time $= \left(t - \frac{x}{v}\right)$.



i.e., displacement of particle P at a distance x at time t = displacement of a particle at O at time $\left(t - \frac{x}{v}\right)$.

RHS is given by equation (1) on replacing t by $\left(t-\frac{x}{v}\right)$.

We get the equation for the motion of the particle at P as

$$y = A\sin\omega\left(t-\frac{x}{v}\right) \quad \text{... (2)}$$

Therefore, $y = A\sin(\omega t - kx)$ ... (3)

where $k = \frac{\omega}{v} = \frac{2\pi}{\lambda}$ is called **angular wave number** or **propagation constant.**

Equations (2) and (3) represent a wave travelling along the **positive X-direction**.

In equation (3), $(\omega t - kx)$ represents the phase of a particle at distance x from the origin at time t.

Other forms of wave equation

Substituting $\omega = 2\pi f$ and $f = \frac{v}{\lambda}$ in equation (2), we get $y = A\sin\frac{2\pi}{\lambda}(vt - x)$ ... (4)

Substituting $v = \frac{\lambda}{T}$ in equation (4) we get $y = A\sin 2\pi\left[\frac{t}{T}-\frac{x}{\lambda}\right]$ ... (5)

The equations for a wave travelling in the **negative X-direction** are

- $y = A\sin\omega\left(t+\frac{x}{v}\right)$
- $y = A\sin(\omega t + kx)$
- $y = A\sin\frac{2\pi}{\lambda}(vt + x)$
- $y = A\sin 2\pi\left[\frac{t}{T}+\frac{x}{\lambda}\right]$

Intensity of a wave

Intensity of a wave is defined as the average energy transported by the wave per unit time across unit area perpendicular to the direction of wave propagation.

Expression for Intensity of a wave

In the case of a sinusoidal mechanical wave of amplitude *A*, frequency *f*, propagating with a velocity *v* in a medium of density ρ, the intensity *I* is given by,

$$I = 2\pi^2 A^2 f^2 \rho v$$

The SI unit of intensity is J s^{-1} m^{-2} or watt per meter square W m^{-2}

- $I \propto A^2$, $I \propto f^2$, $I \propto \rho$, $I \propto v$
- $I \propto \frac{1}{d^2}$ for a point source in an isotropic medium, when the absorption by the medium is negligible.
- $v \propto \sqrt{T}$ and $\rho \propto \frac{1}{T} \Rightarrow I \propto \frac{1}{\sqrt{T}}$ (where T = temperature)
- $I \propto p$ (because $\rho \propto p$ and v is independent of p, p = pressure)

Principle of superposition

When two or more waves of the same nature travel past a point simultaneously, the net disturbance at the point is the vector sum of the disturbances due to the individual waves.