

This module is designed to help you to:

- distinguish between vibration and waves;
- distinguish between longitudinal and transverse waves;
- identify the geometrical shape of a wave front;
- visualize a progressive wave as propagation of phase;
- derive the equation of a plane progressive wave.

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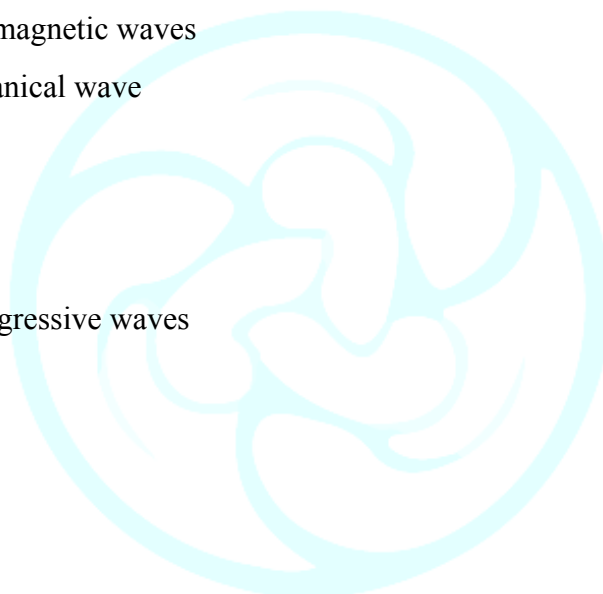
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15.1.1 Introduction

In this module we discuss the basic features of WAVES. You might have seen waves in the sea or in water created in a pond by throwing a pebble. Here we shall try to understand the propagation of waves by answering the question: what actually propagates physically to create a wave? In a wave motion, transfer of energy, or some kind of disturbance, occurs. The same thing happens in case of vibrations.

At the very beginning, let us try to understand the difference between 'vibrations' and 'waves'. Then we shall talk about propagation of mechanical waves. In the process we shall get to know about another kind of wave found in nature, that is, an electromagnetic wave. We shall relate mechanical and electromagnetic waves to what are known as longitudinal and transverse waves.

Then we shall proceed to seek the answer to the question: what actually propagates? Thereby we shall revisit the concept of phase and introduce the term 'wave front'. Thereafter we shall see that a progressive wave is the propagation of a wave front.

15.1.2 Difference between vibrations and waves

Let us distinguish between the terms: 'vibrations' and 'waves'.

In the case of a vibration, the energy remains localized within the system; whereas in the case of a wave, the energy is transmitted, from one point to another, in a 'medium'.

For example, let us consider the oscillations of a simple pendulum (Fig. 15.1.1). At an extremity, its energy is fully potential. When it oscillates back towards its mean position its potential energy decreases and its kinetic energy keeps on increasing. Its kinetic energy becomes maximum at the mean position. Due to the inertia of motion, the bob of the pendulum overshoots the mean position and goes toward the other extreme, whereby kinetic energy diminishes, and at its expense, there is a gain in potential energy. Thus, its energy keeps alternating between potential and kinetic forms and in the ideal case (of no dissipation of energy taking place), the oscillations are supposed to go on eternally.

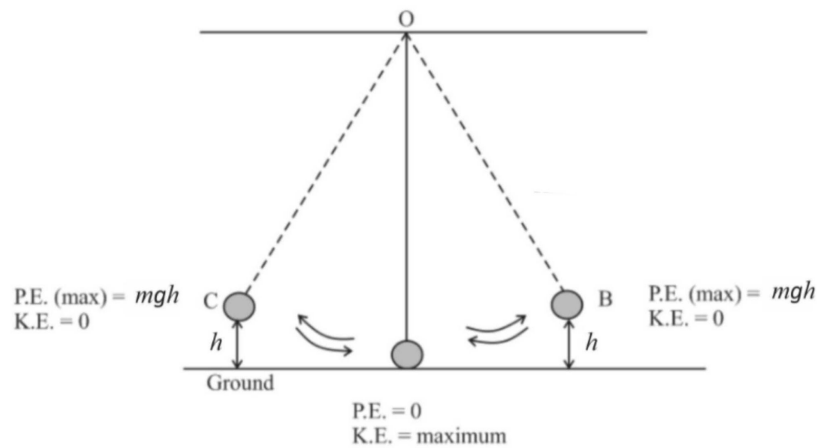
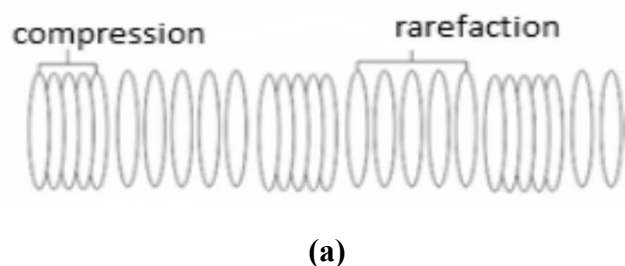


Fig.15.1.1: *simple pendulum*

The point to be noted, in the above example, is that the energy of the system, be it kinetic or potential, or a combination of both, is owned by the system, i.e. the simple pendulum. In other words, the energy remains localized within the system. In the case of a wave, on the other hand, the energy spreads out into the medium. We shall understand this by way of studying the propagation of a mechanical wave. Before that we shall briefly talk about two kinds of waves – mechanical and electromagnetic.

15.1.3 Mechanical and electromagnetic waves

Mechanical waves are caused by vibrations (i.e. to and fro motions) of medium particles. Water waves, sound waves, waves produced by earthquakes, are examples of mechanical waves. Light waves, radio waves, are some of the examples of electromagnetic waves which are vibrations of electric and magnetic fields. Waves carry energy from one place to another. As mentioned earlier, waves are of two types – mechanical waves and electromagnetic waves. Mechanical waves require material a medium having inertia and elasticity for their propagation. Light waves and radio waves, on the other hand, do not require any material medium for their propagation.



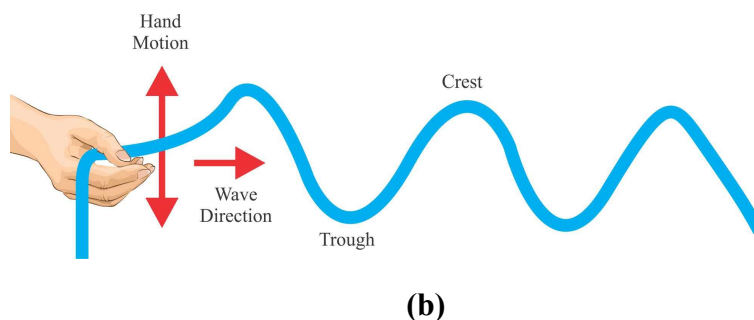


Fig. 15.1.2(a, b): Longitudinal wave and transverse wave

Depending upon the relative direction of vibrations of ‘particles’ with respect to the direction of propagation, waves can be classified as longitudinal waves and transverse waves. In a longitudinal wave, the particles of the medium vibrate to and fro about their mean positions, along the direction of propagation of the wave. Sound waves are longitudinal waves. Longitudinal waves propagate in the form of compressions and extensions, or condensations and rarefactions [Fig. 15.1.2(a)].

If particles of the medium vibrate up and down, about their mean positions at right angles to the direction of propagation of waves, transverse waves are produced. Transverse waves propagate in the form of crests and troughs. Light waves, radio waves and all other forms of electromagnetic waves, are transverse waves. However, for the electromagnetic waves, electric and magnetic fields, not the particles, vibrate in the directions perpendicular to the direction of the propagation of the wave [Fig. 15.1.2(b)].

Now we shall study the propagation of a mechanical wave.

15.1.4 Propagation of a mechanical wave

In the case of a mechanical wave, the energy of a particle, which is vibrating, gets transmitted to its contiguous particle, and so on, and thus to the entire medium. For example, if we drop a pebble in a pond, the energy (imparted) spreads on the whole surface of water in the form of ripples. In the case of an electromagnetic wave, the transmission of energy, from one point to another, takes place through the propagation of its oscillating electric and magnetic fields.

Now, when the energy gets transmitted, via the propagation of a wave, what is it that actually propagates? Is it right to say that it is energy that propagates? Indeed, energy does propagate. Sometimes, however, we say that the pulse propagates or the disturbance propagates. What do we mean by a disturbance?

We need to coin the term, from the jargon of mechanics, to understand what it is that propagates in a wave. If we look at the mathematical form of the displacement-time or the velocity-time equation, for a simple harmonic oscillation, we find its form as

Displacement or velocity or any other relevant parameter = Amplitude $\times$ {(sine or cosine) of (phase)}

Thus, the basic features of a vibration are its amplitude and phase. For a wave, the amplitude of the wave becomes equal to the amplitude of the vibration. What propagates is the phase of the vibration. For the vibration, phase is not a time varying quantity; for a wave it becomes a time varying quantity which propagates from point to point and hence also keeps on varying with position.

When the phase of a vibration propagates, we call such a wave a 'progressive' wave. We shall come across situations where the phase ceases to propagate with 'position'. Such a wave is called a 'stationary' or a 'standing' wave.

We shall now seek the answer to the question: What actually propagates in a progressive wave?

15.1.5 Wavefront

If a wave propagates from a point source in all directions in (a uniform isotropic) space, the particles equidistant from the source, at any point of time, will be in the same phase of motion. Such points will lie on a sphere. In other words, the locus of all points in the same phase of motion will be a sphere. The propagation of the wave, in such a case, can be visualized in the form of expanding spheres (each having a 'constant' phase), as shown in Fig. 15.1.3.

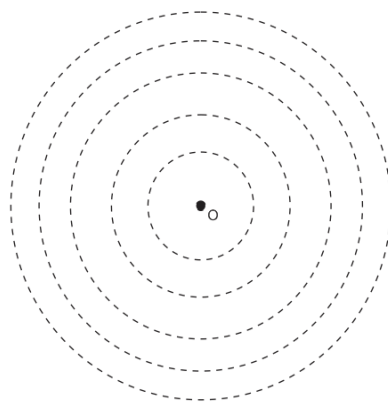


Fig. 15.1.3: From the point source 'O', waves propagate in the form of expanding spheres

We get to see some kind of a resemblance of such a situation when we observe waves, emanating from a point in a pond, where a pebble is dropped. Since the motion occurs on a plane, we get to see expanding circles in place of expanding spheres. The locus of all points, in the same phase, at any (given) point of time, are circles. We assign a name to this geometrical aspect of propagation. We call the locus of all points, in the same phase of motion, at any (given) point of time, as a 'wave front'.

In the case of a wave propagating in all directions, (from a point source in a uniform isotropic medium) in space (three dimensions), the wave front is spherical. From a point source, in a uniform isotropic medium on a plane (two dimensions), the wave front is circular (as mentioned above in the case of a pond). In these cases, we call the waves spherical waves and circular waves, respectively.

For a linear source, if the wave is propagating in all directions, (in a uniform isotropic medium in planes perpendicular to the linear source), the wave front is cylindrical and the wave is called a cylindrical wave.

You may also imagine a linear source as consisting of a chain of particles, each particle producing circular wavefronts in planes perpendicular to the axis of the cylinder. Combination of these circular wavefronts at any instant of time gives rise to the cylindrical wavefront at that instant of time.

The simplest of the waves, (that is also the most illustrative one), is the case of wave propagation in a uniform isotropic medium in a fixed direction (one dimensional propagation, like in case of a wave on a string). In this case the locus of all points, in the same phase of motion, at a particular time, is a plane. Such a wave is called a plane progressive wave, its associated wave front is planar.

With the introduction of the idea of a wave front, we get to have something (less abstract than phase), which can be visualized as 'propagating in a wave'. We can now say that the propagation of a wave is actually the propagation of its associated wave fronts.

15.1.6 Progressive wave

Progressive waves are waves that propagate in a given direction with a finite velocity. Energy and momentum get transmitted along the direction of propagation of waves. However, there is no transmission of ‘matter’, (as shown in Fig. 15.1.4). Progressive waves can be transverse or longitudinal.

Activity 15.1.1

Help students in groups of three to four students, to bend two metallic wires in the form of ‘waves’, as shown in Fig. 15.1.4 (a), 15.1.4 (b).

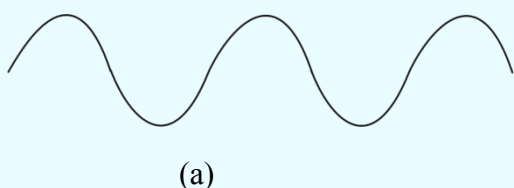


Fig. 15.1.4 (a): Wave Pattern 1

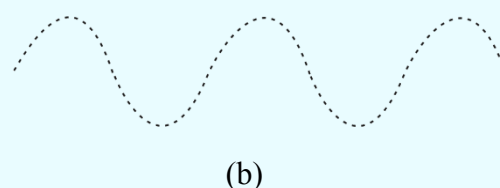


Fig. 15.1.4 (b): Wave Pattern 2

Take care that the two wave patterns are as similar as possible, i.e. their wavelengths are the same. Keep the two wave patterns over one another (Fig. 15.1.5)

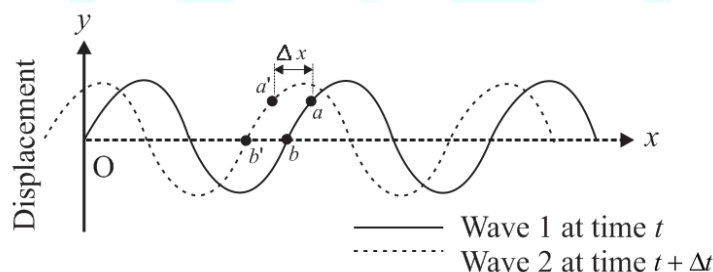


Fig. 15.1.5: Two identical waves not in phase

Now, place the wave models as shown in Fig. 15.1.5. This shows the model of a wave at two instants of time which differ by a small time interval. Engage students in discussion by the following questions: Do you think Fig.15.1.5 represents a shift of wave pattern to the right (i.e. positive direction of x - axis) by a distance ‘ $b'b$ ’? Can we consider that this shift has taken place in a small time interval Δt ? What is the speed of the wave? Can we take the speed of the wave equal to $\frac{\text{Distance}}{\text{Time}}$, or speed = $\frac{\Delta x}{\Delta t}$?

15.1.7 Propagation of phase

To understand this concept, let us perform an activity.

Activity 15.2.2

Set up two identical pendulums. By suspending from their respective supports they are kept one behind the other.

Display the bob of the first pendulum, about 5 to 10 cm from its mean position, and let it go. keep a close watch on its oscillations, now display the bob of the second pendulum, through the same distance, in the same sense, as the first one. release it exactly when the bob of the first pendulum passes through its mean position and is moving the same direction as the second pendulum would now do.

Observe carefully .Do the two pendulums have the same time period?

Do they oscillate in phase with one another? Which one of the two, if any, leads the other in phase by $\pi/2$?

Waves differing by phase are shown schematically in the following figures (Figs. 15.1.6 & 15.1.7(a), 15.1.7(b), 15.1.7(c)).

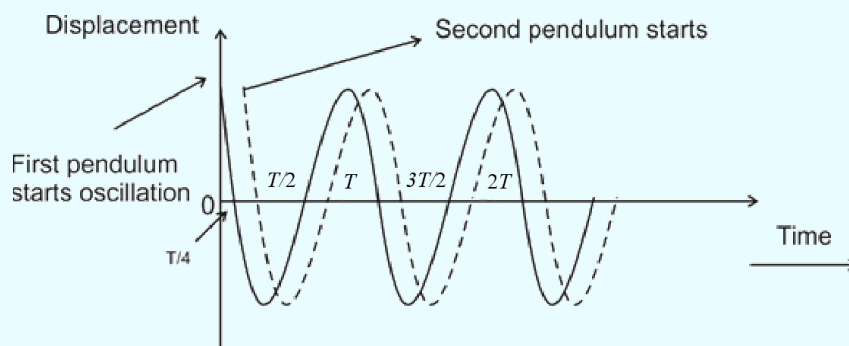


Fig. 15.1.6: Two pendulums differing in phase by $\frac{\pi}{2}$

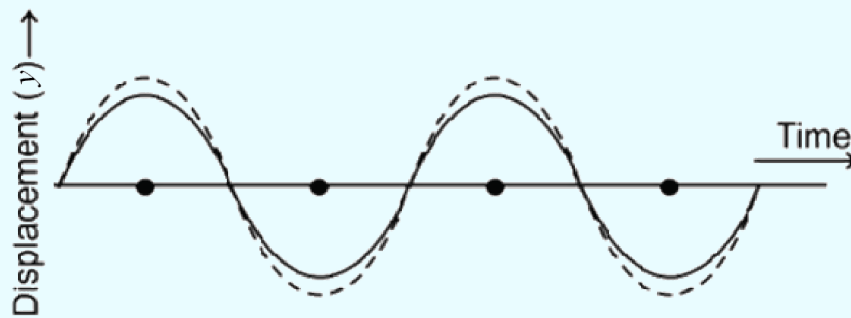


Fig. 15.1.7(a): Waves are in same phase

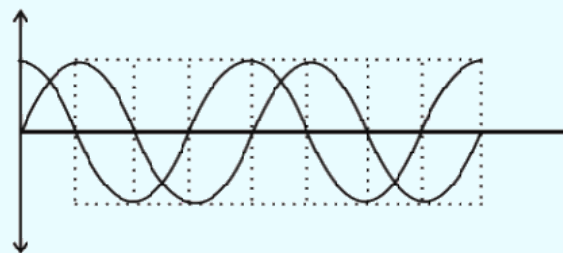


Fig. 15.1.7(b): Two waves having phase difference $\frac{\pi}{2}$

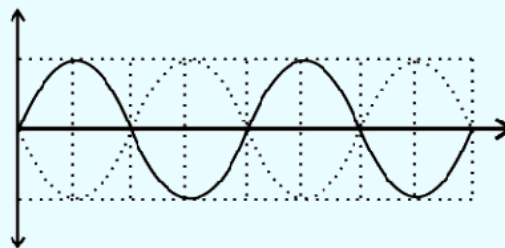


Fig. 15.1.7(c): Two waves are in opposite phase or have phase difference π

Thus, in a progressive wave the phase propagates which can otherwise be visualized as propagation of the wave front. Hence, in the case of a progressive wave the phase is not only a time varying quantity, it also varies with position.

We will study further about these in the next module.

15.1.8 Equation of a plane progressive wave

Now, Let us discuss the framing of the equation of a progressive wave.

The displacement vs. time equation of a simple harmonic vibration is

$$x = a \sin \omega t$$

The displacement is a function of time only. But we have learnt that propagation of a wave is actually the propagation of phase. So, phase is a function of the position (x) of the particle in the medium and time (t). Thus the equation can be expressed as

$$y = f(x, t) \quad (15.1.1)$$

Where y is the displacement of the particle at a distance x from the source of the wave at time t . Our first task is to combine x, t judiciously so that we get a suitable argument of the function f . The simplest way to connect x and t is through a velocity and so we choose the form of (x, t) as $(vt - x)$. It has the dimension of length and the natural choice for meaning of v is that it is the velocity of the wave.

$$\text{Thus } y = f(vt - x) \quad (15.1.2)$$

The chief characteristic of a wave can be described by the situation that the phase at a position x_1 , at time t_1 , gets repeated at time t_2 at the position x_2 .

$$\text{So, we claim that } y(x_1, t_1) = y(x_2, t_2) \quad (15.1.3)$$

In other words, we would like to verify whether or not

$$f(vt_1 - x_1) = f(vt_2 - x_2), \text{ where } v = \frac{x_2 - x_1}{t_2 - t_1}.$$

Considering propagation in two directions of the x -axis,

$$\text{Now, } vt_1 - x_1 = \frac{x_2 - x_1}{t_2 - t_1} t_1 - x_1 = \frac{x_2 t_1 - x_1 t_2}{t_2 - t_1}$$

$$\text{and } vt_2 - x_2 = \frac{x_2 - x_1}{t_2 - t_1} t_2 - x_2 = \frac{x_2 t_1 - x_1 t_2}{t_2 - t_1}$$

$$\therefore vt_1 - x_1 = vt_2 - x_2$$

$$\text{or } y(x_1, t_1) = y(x_2, t_2)$$

Thus, $(vt - x)$ can be accepted as the argument of the function f , so the equation of a progressive wave can be expressed as.

$$y = f(vt - x) \quad (15.1.4)$$

In order that f is a plane progressive harmonic wave, the form of f must be sinusoidal, that is either sine or cosine. So we rewrote Eq(15.1.4) as,

$$y = a \sin k(vt - x) \quad (15.1.5)$$

We introduce k and a from dimensional considerations; k has the dimensions of reciprocal length, since $v(t - x)$ has the dimension of length, and the argument of the sine function must be dimensionless. Clearly, a has the same dimensions as y . Since a is the maximum value of y , it is the amplitude of the wave, while kv is the coefficient of t .

$$\therefore kv = \omega$$

$$k = \frac{\omega}{v} = \frac{2\pi\nu}{v} = \frac{2\pi}{\lambda}$$

so we finally write the equation of a plane progressive harmonic wave as

$$y = a \sin \frac{2\pi}{\lambda}(vt - x) \quad (15.1.6)$$

The two other equivalent forms of Eq(15.1.6) are

$$y = a \sin (\omega t - kx) \quad (15.1.7)$$

$$\text{and } y = a \sin 2\pi \left(\frac{t}{T} - \frac{x}{\lambda} \right) \quad (15.1.8)$$

Where, $k = \frac{2\pi}{\lambda}$ wave number, T is the time period of the wave. The equation of the corresponding wave travelling along the $-ve$ x – direction is

$$y = a \sin \frac{2\pi}{\lambda}(vt + x) \quad (15.1.9)$$



Let Us Reflect

Q.15.1.1 Starting with the form of wave equation

$$y = a \sin (\omega t - kx)$$

derive the two other equivalent forms:

$$(i) \quad y = a \sin 2\pi \left(\frac{t}{T} - \frac{x}{\lambda} \right)$$

$$(ii) \quad y = a \sin \frac{2\pi}{\lambda}(vt - x)$$

Q.15.1.2 Sketch two waves having a phase difference of π .

Q.15.1.3 Distinguish between transverse and longitudinal waves. How are electromagnetic waves different from mechanical waves?



Answers

A.15.1.1. Remember the relations $\omega=2\pi/T$, $k=2\pi/\lambda$ and $v=\omega/k$. Using these relations you can show that all three forms are equivalent and any two can be obtained from the third.

A.15.1.2

Fig. 15.1.8 shows two waves with phase difference of $\pi/2$. Note that the first wave (red) has already

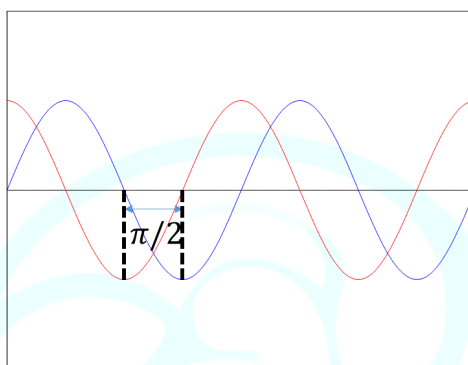


Fig. 15.1.8

achieved its first crest, while the second (blue) is just starting. The phase difference is $T/4$, or $\pi/2$

A.15.1.3 If the particles of the medium vibrate in a direction perpendicular to the direction of propagation of the wave, the wave is said to be transverse. If the particles vibrate in the direction of wave propagation, the wave is called a longitudinal wave. Electromagnetic waves are special in the sense that they propagate without a medium. In this case, instead of the particles, electric and magnetic fields vibrate in mutually perpendicular directions, which are themselves perpendicular to the direction of propagation of the wave, as shown in the figure below. (Fig 15.1.9)

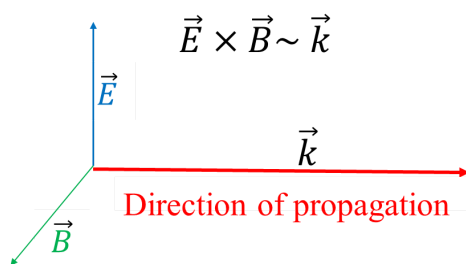


Fig 15.1.9

15.1.9 Summary

- In the case of vibrations, energy remains localized within the system; whereas in the case of wave motion, the energy gets spread into the surrounding medium.
- We encounter two kinds of waves – mechanical and electromagnetic.
- Mechanical waves require a medium for their propagation. They can be longitudinal or transverse. In the former case, the particles of the medium vibrate in the direction of the propagation of the wave. In the case of the transverse wave the particles vibrate in a direction perpendicular to the direction of propagation of the wave.
- Phase varies with both time and space in a progressive wave.
- The locus of all points in the same phase of motion in a wave at a certain point of time is called a wave front.
- For a wave travelling in a particular direction, the wave front is a plane perpendicular to the direction of motion of the wave and so it is called a plane progressive wave.

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