A TEXTBOOK OF

Physics

FOR GRADE X

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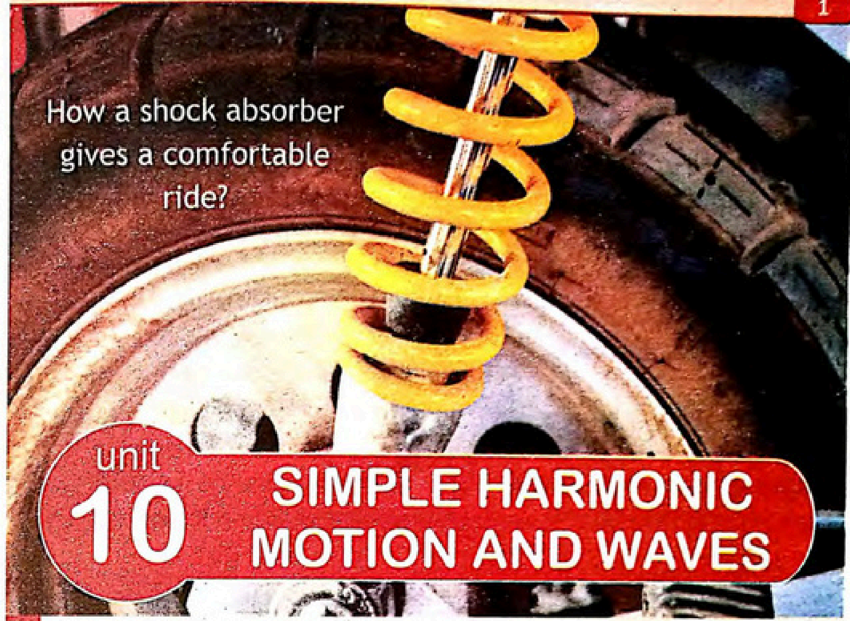
Khyber Pakhtunkhwa Textbook Board, Peshawar

Contents



unit 10 SIMPLE HARMONIC MOTION AND WAVES

STUDENT LEARNING OUTCOME

After studying this chapter you should be able to

- ✓ state the conditions necessary for an object to oscillate with SHM.
- ✓ explain SHM with simple pendulum, ball and bowl examples.
- ✓ draw forces acting on a displaced pendulum.
- ✓ solve problems by using the formula $T = 2\pi\sqrt{l/g}$ for simple pendulum
- ✓ understand that damping progressively reduces the amplitude of oscillation.
- ✓ describe wave motion as illustrated by vibrations in rope, slinky spring and by experiments with water waves.
- ✓ describe that waves are means of energy transfer without transfer of matter.
- ✓ distinguish between mechanical and electromagnetic waves.
- ✓ identify transverse and longitudinal waves in mechanical media, slinky and springs.
- ✓ define the terms speed (v), frequency (f), wavelength (λ), time period (T), amplitude, crest, trough, cycle, wave front, compression and rarefaction.
- ✓ derive equation $v=f\lambda$.
- ✓ solve problems by applying the relation $f = 1/T$ and $v = f\lambda$.
- ✓ describe properties of waves such as reflection, refraction and diffraction with the help of a ripple tank.

CONTENTS

Many objects vibrate or oscillate—an object on the end of a spring, a tuning fork, a pendulum, beating of heart, a plastic ruler held firmly over the edge of a table and gently struck, the strings of a guitar or piano, vehicles oscillate up and down when they hit a bump, buildings and bridges vibrate during an earth quake. Indeed, because most solids are elastic, they vibrate when given an impulse.

Because it is so common in everyday life and occurs in so many areas of physics, oscillatory (or vibrational) motion is of great importance. Mechanical oscillations or vibrations are fully described on the basis of Newtonian mechanics.

10.1 OSCILLATORY MOTION

The repeated back and forth motion about certain equilibrium (mean) position is termed as oscillation or oscillatory motion. The same motion repeats over and over – a particle goes back and forth over the same path in exactly the same way. Following are few terminologies associated with oscillatory motion.

A. Cycle/Vibration: One complete round trip of the vibrating body about mean position is called vibration/cycle. To complete one vibration/cycle, the particle must be at the same point and heading in the same direction as it was at the start.

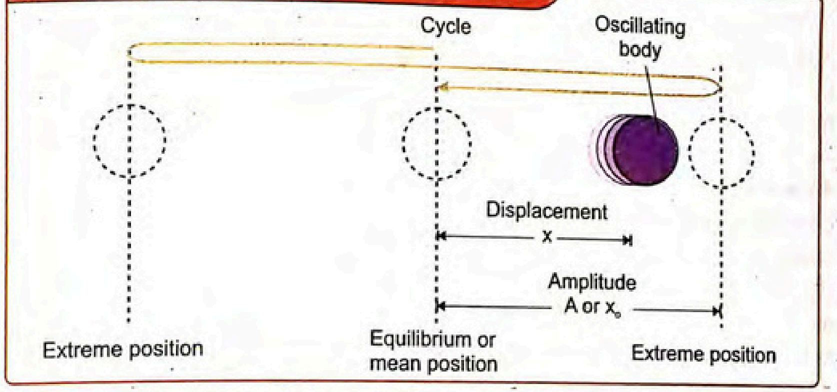
B. Time period: The time required to complete one cycle is called time period (T). The time period is measured in seconds (s).

C. Frequency: The number of cycles that the particle completes per unit time is called frequency (f). The units of frequency are cycles per second (s^{-1}), or *hertz (Hz)*.

D. Relation between time period (T) and frequency (f): Time period and frequency are reciprocal of each other.

$$T = \frac{1}{f} \qquad (10.1)$$

Figure 10.1 - Terminologies of Oscillatory Motion



E. Displacement: The distance of oscillating body from the mean position at any instant of time is called its displacement (x). Displacement is measured in metres (m).

F. Amplitude: The maximum displacement of the body from its mean position in a cycle is called amplitude (x_o). Amplitude being a length, is measured in metres (m).

EXAMPLE 10.1: FREQUENCY OF OSCILLATION

What is the frequency of oscillation if the time period is 20 ms?

GIVEN	REQUIRED
Time period 'T' = 20 ms = 0.02 s	frequency 'f' = ?

SOLUTION: Since the time period and frequency are reciprocal of each other, therefore

$$f = \frac{1}{T} \qquad \text{Putting values} \qquad f = \frac{1}{0.02\,s}$$

Therefore $f = 50\,s^{-1} = 50\,Hz$ — Answer

Hence, in one second the particle will vibrate 50 times for a time period of 20 ms.

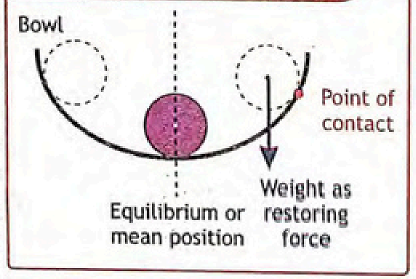
ASSIGNMENT 10.1: PERIOD OF OSCILLATION

When an object oscillates with a frequency of 0.5 Hz, what is its time period?

10.2 SIMPLE HARMONIC MOTION (SHM)

Vibration or oscillation is repeated back and forth motion along the same path. Vibrations occur in the vicinity of a point of stable equilibrium. An equilibrium point is a point at which the net force acting on the body is zero. An equilibrium point is also called stable point when at small displacements from it the net force pushes the body back to the equilibrium point. Such a force is called a restoring force since it tends to restore equilibrium.

Figure 10.2 - Harmonic Motion



Consider a bowl and ball example under stable equilibrium condition as shown in figure 10.2, when ball is displaced from its equilibrium position, it will start moving under restoring force towards equilibrium position, opposite to the displacement 'x'. After reaching equilibrium position the object will continue under inertia and will reach the other extreme position and thus it will continue to oscillate back and forth. Simple harmonic motion (SHM) is a special kind of vibratory or oscillatory motion— which occurs whenever the restoring force F_{res} is proportional to the displacement x from equilibrium. Mathematically

$$F_{res} \propto -x \qquad \text{(10.2)}$$

Where the negative sign signifies that the restoring force 'F_{res}' is directed towards the equilibrium position opposite to the displacement 'x'. We can also define simple harmonic motion in terms of acceleration as the type of motion in which the acceleration a is directly proportional to the displacement x and is directed towards the mean position. Mathematically

$$a \propto -x \qquad \text{(10.3)}$$

Equation 10.2 and equation 10.3, represent the condition for simple harmonic motion (SHM).

TIP: Harmonic Motion

Not all periodic vibrations are examples of simple harmonic motion since all restoring forces are not proportional to the displacement. Any restoring force can cause oscillatory motion. An electrocardiogram traces the periodic pattern of a beating heart, but the motion of the recorder needle is not a simple harmonic motion. As the restoring force in this case is not always proportional to the displacement from the equilibrium position.

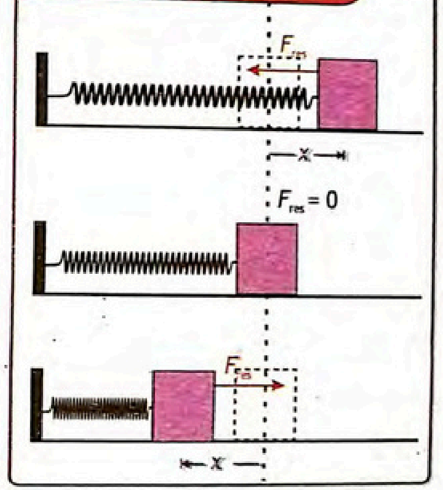
10.3 MOTION OF MASS ATTACHED TO A SPRING

Consider a block of mass m attached to one end of elastic spring, which can move freely on a frictionless horizontal surface as shown in the figure 10.3. When the block is displaced the elastic restoring force pulls the block towards equilibrium position. For an ideal spring that obeys Hook's Law the elastic restoring force F_{res} is directly proportional to the displacement x from equilibrium position.

$$F_{res} \propto -x$$

Since F and x always have opposite directions therefore we have a negative sign in equation. Each spring is different, and so is the force required to deform it.

Figure 10.3 - Mass Spring System



The stiffness of the spring, or spring constant, is represented by the letter k. The equation for Hooke's law is

$$F_{res} = -kx \qquad (1)$$

Thus motion of mass attached to spring is SHM. Restoring force produces acceleration in the body, given by newton's second law of motion as

$$F_{res} = ma \qquad (2)$$

Comparing equation 1 and equation 2, we get

$$ma = -kx$$

or

$$a = -\frac{k}{m}x \qquad \text{(10.4)}$$

As spring constant k and mass m does not change during oscillation of mass attached to spring therefore they are regarded as constants

$$a \propto -x$$

If the restoring force obeys Hooks law precisely, the oscillatory motion of mass attached to spring is simple harmonic.

EXAMPLE 10.2: SPRING RESTORING FORCE

A spring has a spring constant of 48.0 N/m. This spring is pulled to a distance of 55 cm from equilibrium. What is the restoring force?

GIVEN

Displacement 'x' = 55 cm = 0.55 m

Spring constant k = 48.0 N/m

REQUIRED

Restoring force 'F_{res}' = ?

SOLUTION: Figure 10.4 shows that displacement to the right is positive, so the restoring force is negative because it is to the left, according to Hooke's law.

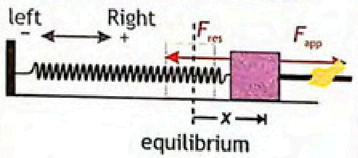
$$F_{res} = -kx$$

Putting values $F_{res} = -48\frac{N}{\cancel{m}} \times 0.55\cancel{m}$

$$F_{res} = -26.4N \text{ —— Answer}$$

The restoring force is 26.4 N [left].

Figure 10.4 - *Example 10.2*



ASSIGNMENT 10.2: SPRING RESTORING FORCE

Determine the restoring force of a spring displaced 1.5 m, with the spring constant of 30.0 N/m.

10.3.1 Time period 'T' and frequency 'f' of mass spring system: Since acceleration in SHM is

$a = -\text{constant}\,x$ Where Constant $= \frac{4\pi^2}{T^2}$

Therefore $a = -\frac{4\pi^2}{T^2}x$ —— (1)

TIP: Angular Frequency

Angular frequency is the measure of angular displacement per unit time.

From equation 10.4, we have $a = -\frac{k}{m}x$ —— (2)

Comparing equation 1 and 2, we get $\cancel{-}\frac{k}{m}\cancel{x} = \cancel{-}\frac{4\pi^2}{T^2}\cancel{x}$

or $\frac{k}{m} = \frac{4\pi^2}{T^2}$ re-arranging $T^2 = 4\pi^2\frac{m}{k}$

Taking square root on both sides we have $\sqrt{T^{\cancel{2}}} = \sqrt{4\pi^{\cancel{2}}}\sqrt{\frac{m}{k}}$

Time-period 'T' is the time it takes for the mass spring system to complete one vibration, and is given by the following equation:

hence $T = 2\pi\sqrt{\frac{m}{k}}$ —— 10.5

Where 'm' is the mass in kg and 'k' is the spring constant in N/m of mass spring system. It is worth noting that time period does not depend upon amplitude of oscillation. Since frequency is the reciprocal of time period therefore the frequency of mass spring system is given as

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \text{ —— 10.6}$$

EXAMPLE 10.3: MASS OF OSCILLATING MASS SPRING SYSTEM

What is the mass of a vertical mass-spring system if it oscillates with a period of 2.0 s and has a spring constant of 20.0 N/m?

GIVEN

Spring constant 'k' = 20 N/m

Time Period 'T' = 2.0 s

REQUIRED

Mass 'm' = ?

SOLUTION: The time period for mass spring system is

$T = 2\pi\sqrt{\frac{m}{k}}$ squaring $T^2 = \left[2\pi\sqrt{\frac{m}{k}}\right]^2$

or $T^2 = 4\pi^2 \times \frac{m}{k}$ isolating m $m = \frac{T^2 \times K}{4\pi^2}$

Putting values $m = \frac{(2.0\,s)^2 \times 20.0\,N/m}{4 \times (3.14)^2}$ as $N = kg\,m/s^2$

so $m = \frac{4.0\cancel{s^2} \times 20.0\frac{kg\cancel{m}}{\cancel{s^2}\cancel{m}}}{4 \times 9.86}$

Therefore $m - 2.02\,kg - 2\,kg$ —— Answer

The mass of the mass-spring oscillator is 2.0 kg.

ASSIGNMENT 10.3: TIME PERIOD OF MASS SPRING SYSTEM

A body of mass 0.2 kg is attached to a spring placed on a frictionless horizontal surface. The spring constant of spring is 4 N/m. Find the time period of oscillating mass spring system.

10.4 SIMPLE PENDULUM

A simple pendulum is an idealized model consisting of a point mass suspended by a weightless, in-extendable string supported from a fixed frictionless support.

A simple pendulum is driven by the force of gravity due to the weight of suspended mass 'm' ($W = mg$). A real pendulum approximates a simple pendulum if

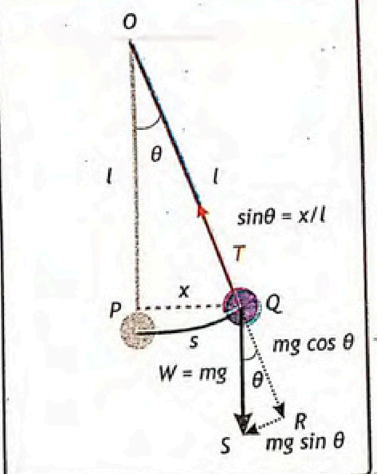
- the bob is small compared with the length l,
- mass of the string is much less than the bob's mass, and
- the cord or string remains straight and doesn't stretch.

Pull the pendulum bob aside and let it go; the pendulum then swings back and forth. Neglecting air drag and friction at the pendulum's pivot, these oscillations are periodic. We shall show that, provided the angle is small, the motion is that of a simple harmonic oscillator. As shown in figure 10.5, for ΔQRS we resolve the weight ($W = mg$) in to two components '$mg\sin\theta$' and '$mg\cos\theta$'. The component '$mg\cos\theta$' is balanced by the Tension 'T' in the string. The restoring force is only provided by component '$mg\sin\theta$'. Therefore

$$F_{rest} = -mg\sin\theta \quad (1)$$

Also note in the figure that only for small angles the arc length 's' is nearly the same length as *displacement* 'x'.

Figure 10.5 - *Simple Pendulum*



Therefore from ΔOPQ $\quad \sin\theta = \dfrac{x}{l} \quad (2)$

Putting equation 2 in equation 1 $\quad F_{rest} = -mg\dfrac{x}{l} \quad (3)$

Since mass 'm', acceleration due to gravity 'g' and length 'l' are constant for simple pendulum oscillating with small angle, therefore

$$F_{res} \propto -x$$

Which is the condition for simple harmonic motion. *Thus motion of simple pendulum can be approximated as is simple harmonic motion.*

Also by Newton's second law of motion $\quad F_{rest} = ma \quad (4)$

Comparing equation 3 and equation 4 $\quad \cancel{m}a = -\cancel{m}g\dfrac{x}{l}$

$$\text{or} \quad a = -\frac{g}{l}x \quad \boxed{10.7}$$

Since g and l are constants for oscillating simple pendulum, therefore

$$a \propto -x$$

Hence, when released the mass will move towards the equilibrium position, will cross over it due to inertia and will execute Simple Harmonic Motion (SHM).

EXAMPLE 10.4: RESTORING FORCE OF SIMPLE PENDULUM

Determine the magnitude of the restoring force for a pendulum bob of mass 100.0 g that has been pulled to an angle of 10° from the vertical.

GIVEN

mass 'm' = 100 g = 0.1000 kg

acceleration due to gravity 'g' = 9.8 m/s²

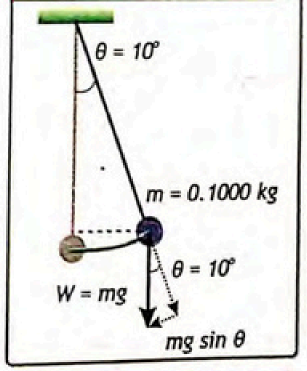
angle θ = 10°

REQUIRED

Restoring force 'F_{res}' = ?

SOLUTION: The figure 10.6 shows that the restoring force $F_{res} = mg\sin\theta$ is the component of weight that is tangential to the circular path of the pendulum.

Figure 10.6 - *Example 10.4*



$$F_{rest} = -mg\sin\theta$$

Putting values $F_{rest} = -0.1000kg \times 9.8ms^{-2} \sin 10^{\circ}$

or $F_{rest} = -0.98kgms^{-2} \times 0.17$

$F_{rest} = -0.167N$ —— Answer

The magnitude of the restoring force acting on the pendulum is 0.167 N.

ASSIGNMENT 10.4: CALCULATING ANGLE

At what angle must a pendulum be displaced to create a restoring force of 4.00 N on a bob with a mass of 500.0 g?

10.4.1 Time period 'T' and frequency 'f' of simple pendulum: It can be shown that the acceleration and displacement of a simple pendulum are related by its time-period T (the time it takes for the mass spring system to complete one cycle) by the following equation:

$$a = -\frac{4\pi^2}{T^2}x \quad \text{—— (1)}$$

From equation 10.7, we have $a = -\frac{g}{l}x$ —— (2)

Comparing equation 1 and 2, we get $\cancel{-}\frac{g}{l}\cancel{x} = \cancel{-}\frac{4\pi^2}{T^2}\cancel{x}$

or $\frac{g}{l} = \frac{4\pi^2}{T^2}$ re-arranging $T^2 = 4\pi^2\frac{l}{g}$

Taking square root on both sides, we have $\sqrt{T^2} = \sqrt{4\pi^2}\sqrt{\frac{l}{g}}$

Hence $T = 2\pi\sqrt{\frac{l}{g}}$ —— 10.8

Equation 10.8 shows that the time period 'T' of simple pendulum depends directly on the length 'l' of the pendulum and inversely on gravitational acceleration 'g'. The period of the pendulum does not depend on the mass of the pendulum bob. The period of a pendulum does not depend on its amplitude.

Since frequency is the reciprocal of time period therefore the frequency of simple pendulum is given as

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{l}} \quad \text{—— 10.9}$$

LAB WORK

To study the effect of the length of a simple pendulum on time, find the value of "g" by calculation.

EXAMPLE 10.5: DETERMINING GRAVITATIONAL FIELD STRENGTH

What is the gravitational field strength on planet Mercury, if a 0.500-m pendulum swings with a period of 2.30 s?

GIVEN

Time period 'T' = 2.3 s

Length 'l' = 0.500 m

REQUIRED

gravitational field strength 'g' = ?

SOLUTION: The time period for simple pendulum is

$T = 2\pi\sqrt{\frac{l}{g}}$ Squaring $T^2 = \left[2\pi\sqrt{\frac{l}{g}}\right]^2$

or $T^2 = 4\pi^2 \times \frac{l}{g}$ Isolating g $g = \frac{4\pi^2 \times l}{T^2}$

TIP: Gravitational Field

The gravitational field strength at a point is the gravitational force exerted per unit mass placed at that point.

Putting values $g = \frac{4(3.14)^2 \times 0.500m}{(2.30s)^2}$

Therefore $g = 3.73\, m/s^2 = 3.73\, N/kg$ [down]. —— Answer

The gravitational field strength at the surface of mercury is 3.73 N/kg

ASSIGNMENT 10.5: GRAVITATIONAL FIELD STRENGTH AT EVEREST

What is the gravitational field strength at the top of Mount Everest at an altitude of 8954.0 m, if a pendulum with a length of 1.00 m has a period of 2.01 s?

LAB WORK

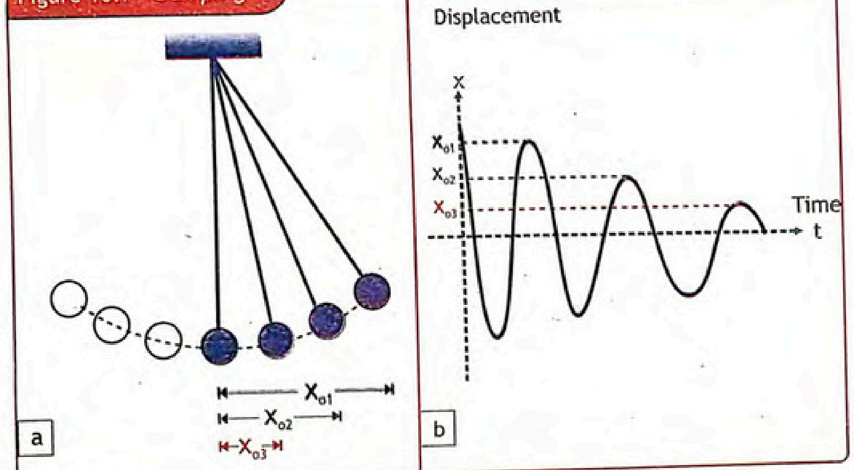
To prove that time period of a simple pendulum is independent of (i) mass of the pendulum (ii) amplitude of the vibration.

10.5 DAMPING

Any effect that tends to reduce the amplitude of vibrations is called damping.

The oscillatory motions we have considered so far have been for ideal systems that is, systems that oscillate indefinitely under the action of a linear restoring force.

Figure 10.7 : Damping



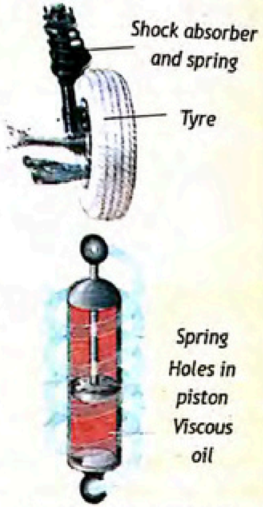
However in many real systems, resistive forces, such as friction, reduce the motion. As a result, the amplitude progressively decreases with time, and the motion is said to be damped. The motion of pendulum eventually stops if it is left untouched because the pendulum loses energy by doing work on the surrounding forces, such as air resistance and friction. The energy of the system decreases with time and eventually falls to zero and pendulum comes to rest as shown in figure 10.7.

INFO

SHOCK ABSORBERS

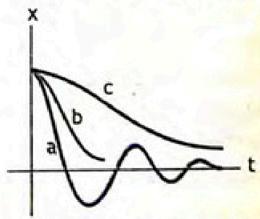
Well-designed damping is needed for certain kinds of applications. The concept of damping system is used in the car suspension system for comfortable ride.

One widely used application of damped harmonic motion is in the suspension system of an automobile. Figure shows a shock absorber attached to a main suspension spring of a car. A shock absorber is designed to introduce damping forces, which reduces the vibrations associated with a bumpy ride. As the drawing shows, a shock absorber consists of a piston in a reservoir of oil. When the piston moves in response to a bump in the road, holes in the piston head permit the piston to pass through the oil. Viscous forces that arise during this movement cause the damping.



Shock absorber and spring

The graph shows three types of damped motions, with curve (a) representing under-damped oscillation. Whereas the curve (b) shows that if the fluid viscosity is increased, the object returns rapidly to equilibrium after it's released and doesn't oscillate. In this case, the system is said to be critically damped. If the viscosity is increased further, the system is said to be over-damped. In this case the time required to reach equilibrium is greater than in critical damping, as illustrated by curve (c).



Graphs of displacement versus time for (a) an underdamped oscillator, (b) a critically damped oscillator, and (c) an overdamped oscillator.

10.6 NATURE OF WAVES AND THEIR TYPES

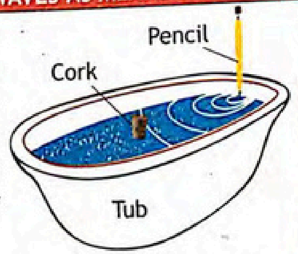
A wave is a disturbance that moves outward from its point of origin, transferring energy by means of vibrations with little or no transport of medium.

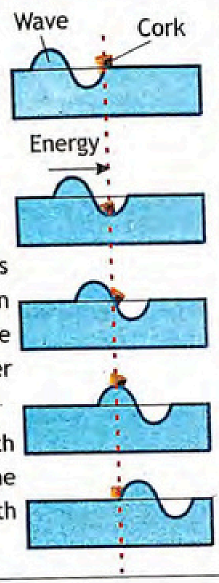
There are two common features to all waves:

1. A wave is a traveling disturbance.
2. A wave carries energy from place to place.

ACTIVITY: WATER WAVES AS MEANS OF ENERGY TRANSFER

Take a tub full of water, move a pencil up and down at one edge of the tub. Waves are produced on the water surface which move away from the point of impact of the pencil.





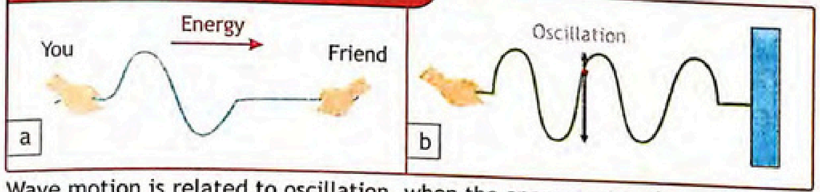
Place a cork in the middle of the tub. You can see that as the waves passes through the cork it will move up and down about its place. The energy which is spent in moving the pencil up and down reaches the cork by means of water waves due to which it is also moves up and down.

Notice that during this process the cork does not move with waves, it only moves up and down which shows that the particles of matter (water) does not move forward with waves instead they oscillate about their mean position.

A wave is a disturbance that transfers energy through a medium. While the disturbance and the energy that it carries, moves through the medium, the matter does not experience net movement. Instead, each particle in the medium vibrates about some mean (or rest) position as the wave passes.

Both particles and waves carry energy but there is an important difference in how they do this. Think of a ball as a particle. If you toss the ball to a friend, the ball moves from you to your friend and carries energy, this is not wave motion because matter is transported. However, if you and your friend hold the ends of a rope and you give your end a quick shake, the rope remains in your hand and the energy can be felt by your friend on the other end of the rope. Even though no matter is transferred, the rope still carries energy through the wave that you created as shown in figure 10.8 (a).

Figure 10.8 - *Simple Harmonic Motion*



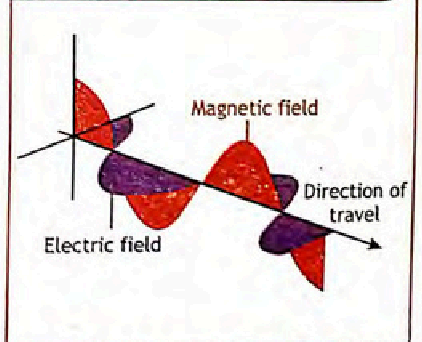
Wave motion is related to oscillation, when the energy moves through the wave the particles of the medium executes simple harmonic motion about their equilibrium position. For example, take a rope and color a part of it. Attach one end of the rope to the wall and wiggle the other end regularly and continuously. The number of waves will be produced forming a wave train. Observe the color marking, it will execute oscillations about certain mean position, as shown in figure 10.8 (b).

When a stone is dropped in a pond water, ripples (waves) are seen on the surface of water. The particles of water that absorb energy and start oscillating from the impact of the stone. These particles transfer some of its energy to the neighboring particles which also start vibrating. In this way gradually other particles on the water surface also start oscillating and energy is spread out throughout the water pond.

10.6.1 Types of waves: The waves are mainly of two kinds: mechanical waves, and electromagnetic waves.

i. Mechanical waves: *The waves produced by oscillation of material particles are called mechanical waves.* Mechanical waves are very familiar; common examples include water waves, sound waves, seismic waves, etc. These waves can exist only within a material medium.

Figure 10.9 - *Electromagnetic waves*



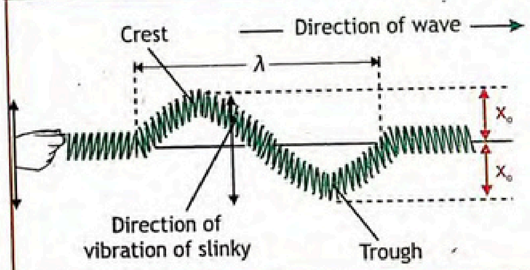
ii. Electromagnetic waves: *The waves that propagate by oscillation of electric and magnetic fields are called electromagnetic waves, they do not require material medium for their propagation.* The wave is a combination of travelling electric and magnetic fields.

The fields vary in value and are directed at right angles to each other and to the direction of travel of the wave, as shown by the representation in Figure 10.9. The common examples of electromagnetic waves are visible and ultraviolet light, radio waves, microwaves, x-rays etc.

Waves can also be classified as transverse and longitudinal in terms of the directions of disturbance or displacement in the medium and that of the propagation of wave.

i. **Transverse waves:** *A transverse wave is one in which the disturbance occurs perpendicular to the direction of motion of the wave.* Radio waves, light waves, and microwaves are transverse waves. Transverse waves also travel on the strings of instruments such as guitars and banjos.

Figure 10.10 - *Transverse wave in slinky*



Crest: *The part of wave above the equilibrium position is called crest.*

Trough: *The part of wave below the equilibrium position is called trough.*

Figure 10.10 shows transverse wave can be generated using a Slinky*(a long loosely coiled spring)*. If one end of the Slinky is jerked up and down, an upward pulse is sent traveling toward the right. If the end is then jerked down and up, a downward pulse is generated and also moves to the right.

TIP: AM and FM

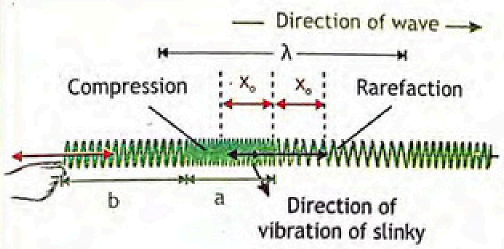
AM and FM radio waves are transverse waves consisting of electric and magnetic disturbances traveling at a speed of 3.00×10^8 m/s.

If the end is continually moved up and down in simple harmonic motion, an entire wave is produced.

ii. **Longitudinal wave:** *A longitudinal wave is one in which the disturbance occurs parallel to the line of travel of the wave.* A sound wave is a longitudinal wave.

A longitudinal wave can also be generated with a slinky, as shown in Figure 10.11. When one end of slinky is pushed forward and backward along its length (i.e., longitudinally) two regions are formed.

Figure 10.11 - *Longitudinal Waves in slinky*



Compressions: *The regions of high density and pressure relative to the equilibrium density or pressure of the medium are termed as compressions.*

Rarefactions: *The regions of low density and pressure relative to the equilibrium density or pressure of the medium are termed as rarefactions.*

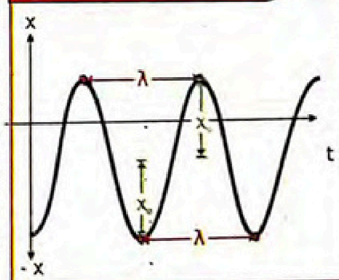
The region where the parts of slinky are compressed together (called compression) is seen moving towards the right. The region where the parts of slinky are stretched apart (called rarefaction) is also seen moving towards the right.

10.6.2 Characteristic Wave Parameters: There are many ways to describe or measure a wave. Some characteristics depend on how the wave is produced, whereas others depend on the medium through which the wave travels. Certain characteristic wave parameters and their definitions are given as under.

i. **Wavelength 'λ':** *The shortest distance between points where the wave pattern repeats itself is called the wavelength, its symbol is the Greek letter lambda 'λ'.*

The unit of wavelength is '*m*'. The wavelength is the repeated distance of the wave pattern—a shift of the wave pattern by one wavelength to the right (or the left) reproduces the original wave pattern. The wave length may be the distance between two successive crests or troughs as shown in figure 10.10 and figure 10.12, or it may be the distance between two successive compressions as shown in figure 10.11.

Figure 10.12 - *Wavelength*



Amplitude x_o or A: *The amplitude A of a wave is the magnitude of the maximum displacement of the elements of wave from their equilibrium positions as the wave passes through them.* Amplitude is represented by x_o or *A* and the unit of amplitude is *m*. As shown in figure 10.10, figure 10.11 and figure 10.12.

Wave Cycle: *As a wave passes a given point along its path, that point undergoes cyclic motion. The point is displaced first in one direction and then in the other direction. Finally, the point returns to its original equilibrium position, thereby completing one cycle.*

Frequency f: *The number of wave cycles (N) passing through a certain point (P) in unit time (t) is called frequency.* The unit of frequency is hertz (Hz).

$$f = \frac{N}{t} \quad \text{——— } \boxed{10.10}$$

Figure 10.13: Frequency

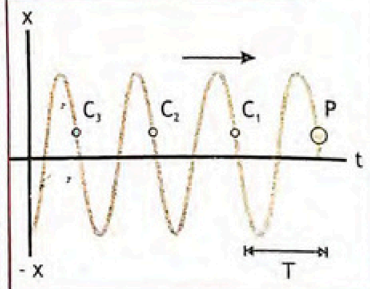


Figure 10.13 shows three cycles C_1, C_2 and C_3 approaching point P if these cycles cross point P in one second then frequency will be 3 hertz.

Time Period T: *The time required for one wave cycle to pass through a certain point is called Time Period T.* The unit of time period is seconds (s).

It is the time any vibrating element of wave takes to move through one complete oscillation as shown in figure 10.13. Time period is the reciprocal of frequency.

$$T = \frac{1}{f} \quad \text{——— } \boxed{10.11}$$

POINT TO PONDER

Earthquake waves under Earth's surface also have both longitudinal and transverse components (called compressional or P-waves and shear or S waves, respectively). These components propagate at different speeds. For example, earthquakes also have surface waves that are similar to surface waves on water.

Wave Speed: The distance traveled by wave in unit time is called wave speed '*v*'.

$$v = \frac{\text{distance}}{\text{time}} = \frac{\Delta s}{\Delta t} \quad \text{——— } (1)$$

The distance traveled by wave equal to one wavelength 'λ' ($\Delta s = \lambda$) is covered in time equal to time period T ($\Delta t = T$), therefore equation 1 can be written as

$$v = \frac{\lambda}{T} \quad \text{——— } (2)$$

Since time period 'T' and frequency 'f' are reciprocal of each other, therefore

$$f = \frac{1}{T} \quad \text{——— } (3)$$

putting equation 3 in equation 2, we get

$$v = f\lambda \quad \text{——— } \boxed{10.12}$$

Equation 10.12 is also called universal wave equation as it applies to all waves and gives the wave speed in terms of frequency f and wavelength λ.

EXAMPLE 10.6: WAVE SPEED

A student vibrates the end of a spring at 2.6 Hz. This produces a wave with a wavelength of 0.37 m. Calculate the speed of the wave.

GIVEN

frequency 'f' = 2.6 Hz

wavelength 'λ' = 0.37 m

REQUIRED

speed 'v' = ?

SOLUTION: By universal wave equation $v = f\lambda$

putting values $v = 2.6s^{-1} \times 0.37m$

Hence $v = 0.962ms^{-1}$ ——— Answer

The answer validates; as reasonable speed for wave in a spring is about 1 m/s.

ASSIGNMENT 10.6: WAVELENGTH OF SOUND

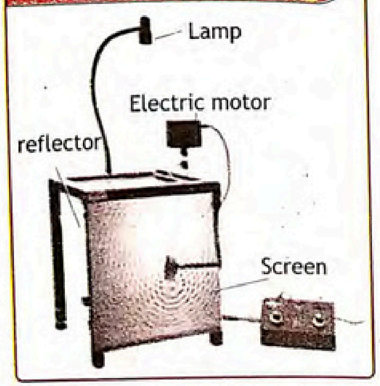
A sound wave of wavelength 1.7×10^{-2} m. Calculate the frequency of sound if its velocity is $343.4\ ms^{-1}$.

10.7 PROPERTIES OF WAVES

The basic properties of two dimensional waves, such as water waves can be described with the help of ripple tank.

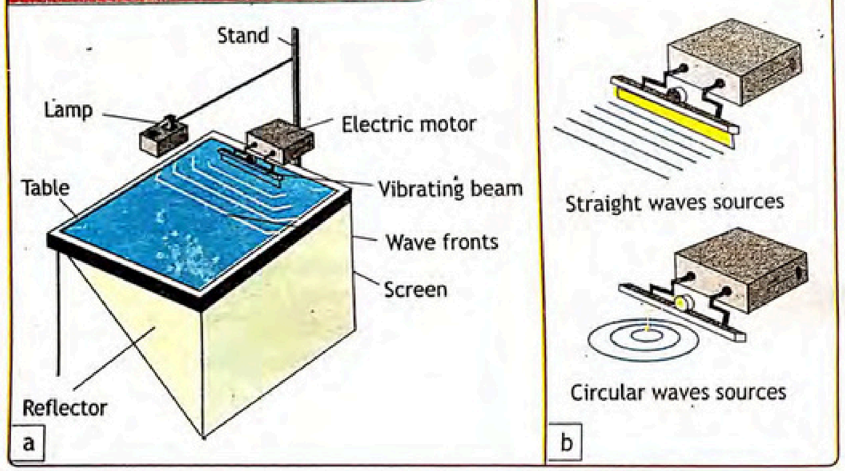
The schematic diagram and the image of ripple tank are shown in the figure 10.14. Ripple tank is an experimental setup to study the two dimensional features or characteristics of wave mechanics such as reflection, refraction and diffraction. It consist of shallow tray of water with a transparent base, usually illuminated from above, so that light shines through the water. The ripples on the water show up as shadows (bright and dark lines) on the screen underneath the tank.

Figure 10.14 - Ripple Tank



Sometimes for easy visualization, a reflector is used to project the screen on front base of the ripple tank as shown in figure 10.15 (a). Straight waves can be set up by using a straight dipper, while circular waves can be formed by using a spherical dipper. Both dipper are vibrated up and down by an electric motor as shown in figure 10.15 (b).

Figure 10.15 - Ripple Tank Illustration



For a two or three dimensional wave, such as a water wave, we are concerned with wave fronts, by which we mean all the points along the wave forming the wave crest (what we usually refer to simply as a "wave" at the seashore). A line drawn in the direction of wave motion, perpendicular to the wave front, is called a ray, as shown in Figure 10.16.

Figure 10.16 - Wavefront

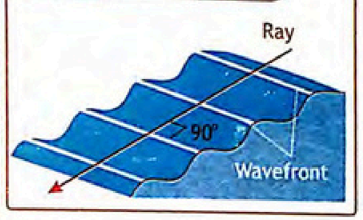
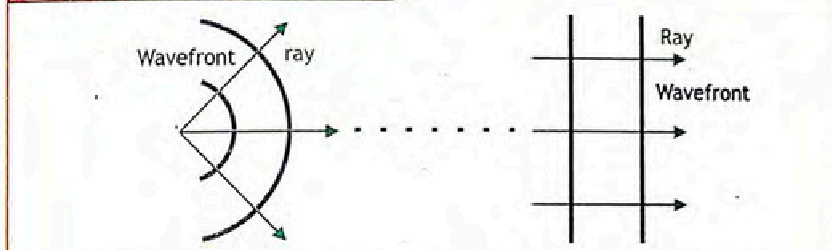


Figure 10.17 - Rays and wavefronts

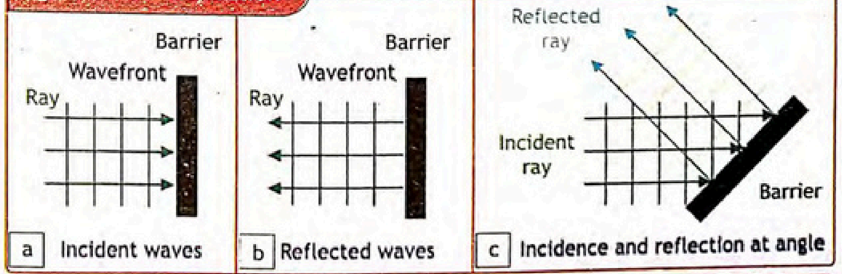


Rays, signifying the direction of wave motion, are always perpendicular to the wave fronts (wave crests). (a) Circular or spherical waves near the source. (b) Far from the source, the wave fronts are nearly straight or flat, and are called plane waves.

Wave fronts far from the source have lost almost all their curvature (Figure 10.17) and are nearly straight, as ocean waves often are. They are then called plane waves.

A. **Reflection:** Reflection is the change in direction of a wave-front at an interface between two different media or rigid barriers so that the wave-front returns into the medium from which it is originated.

Figure 10.18 - Reflection

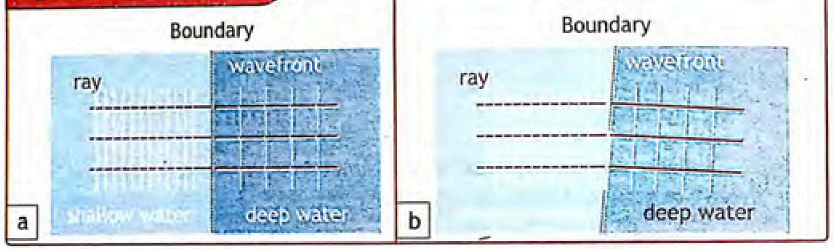


When waves run into a straight barrier, as shown in figure 10.18 (a), they are reflected back along their original path as shown in figure 10.18 (b). However, if a wave hits a straight barrier obliquely as shown in figure 10.18 (c), the wave-front is reflected at an angle to the barrier.

In ripple tank reflection can be demonstrated by placing an upright barrier in tray and the reflection of water can be seen.

A. Refraction: When waves travel from one medium into another, their speed changes. This phenomenon is called refraction. When a water wave enters a medium in which it moves more slowly, its wavelength decreases as well. This could have been predicted using the universal wave equation, since we can conclude that $\lambda \propto v$.

Figure 10.19 - *Refraction*



We can demonstrate this effect in water waves in ripple tank without even changing from water to another medium. Refraction occurs in water because the speed of waves in water is influenced by the depth of the water.

We can observe refraction occurring in the ripple tank if we place a thick sheet of plastic in the tray. When the wave travels from shallow to deep water, we can observe that its wavelength, and hence its speed, changes. If the wave crosses the boundary between the two depths straight on, no change in direction occurs. On the other hand, if a wave crosses the boundary at an angle, the direction of travel does change, again by equation $v = f\lambda$ as shown in figure 10.19.

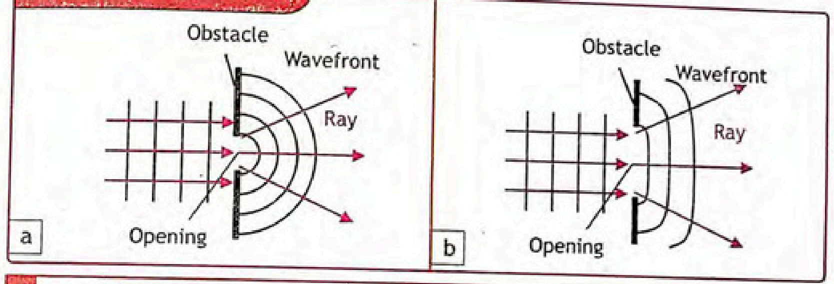
C. Diffraction: The bending of waves around corners of an obstacle is called diffraction. When waves pass through an aperture or opening it spreads out due to diffraction.

We can observe diffraction in water waves in ripple tank by generating straight waves and place two obstacles in such a way that the separation is comparable to the size of the wavelength.

After passing through the opening, waves spread out in every direction and turn into circular waves. This effect is greatest when the size of the opening is less than or equal to the size of the wavelength of generated waves. It must be noted that wavelength (or speed) of the wave is not affected by diffraction.

If the separation is large between obstacle compared to the wavelength, it can be seen that central part of the wave is not affected, only part of the wave at the edges diffract as shown in the figure 10.20.

Figure 10.20 - Diffraction



KEY POINTS

- **Oscillation:** The repeated motion back and forth about certain equilibrium (mean) position.
- **Simple Harmonic Motion:** The type of vibratory motion in which acceleration is directly proportional to displacement and is directed towards the mean position.
- **Time period:** Time required to complete one oscillation.
- **Frequency:** Number of cycles in unit time.
- **Wave:** Energy transfer mechanism without the transport of material medium.
- **Mechanical waves:** Wave that require material medium for their propagation.
- **Electromagnetic waves:** Waves which does not require material medium for its propagation.
- **Transverse waves:** The waves in which the particles of the medium oscillates perpendicular to the direction of motion of wave.
- **Longitudinal waves:** The waves in which the particles of the medium oscillates parallel to the direction of motion of wave.
- **Diffraction:** Bending of waves around the edges of an obstacle.

PRO

GROUP A 'EARTHQUAKE': Research earthquakes and different kinds of seismic waves. Also try to figure out the reason behind devastating earthquake that occurred at 08:50:39 Pakistan Standard Time on 8 October in Kashmir. Create a classroom presentation.

PROJECTS

GROUP B 'TWO SPRING-MASS SYSTEM': Design an experiment to compare the spring constant and period of oscillation of a system built with two (or more) springs connected in two ways: in series (attached end to end) and in parallel (one end of each spring anchored to a common point). If your teacher approves your plan, obtain the necessary equipment and perform the experiment, prepare a presentation to share your result with your class fellows.

GROUP C 'ANGLE IN SIMPLE PENDULUM': The rule that the period of a pendulum is determined by its length is a good approximation for amplitudes below 15°. Design an experiment to investigate how amplitudes of oscillation greater than 15° affect the motion of a pendulum. List what equipment you would need, what measurements you would perform, what data you would record, and what you would calculate. If your teacher approves your plan, obtain the necessary equipment and perform the experiment, prepare a presentation to share your result with your class fellows.

GROUP D 'TSUNAMI': Read litrature and search what are tsunamis, how they are formed. Also figure out the cause of destructing tsunami in 2004 at Indian Ocean. Write an article for school library.

GROUP E 'DEFINING TERMS': Make a chart of definitions of the terms used in oscillations and waves such as speed (v), frequency (f), wavelength (λ), time period (T), amplitude, crest, trough, cycle, wave front, compression and rarefaction and display it in your classroom.

EXERCISE

MULTIPLE CHOICE QUESTIONS

1. A transverse wave on a string has an amplitude A. A tiny spot on the string is colored red. As one cycle of the wave passes by, what is the total distance traveled by the red spot?
   A. A B. 2A C. $\frac{1}{2}$A D. 4A
2. Which of the following does not affect the period of the mass-spring system?
   A. mass B. spring constant
   C. amplitude of vibration D. All of the above affect the period.
3. An object of mass 'm' oscillates on the end of a spring. To double the period, replace the object with one of mass:
   A. 2 m B. m/2 C. 4 m D. m/4

4. A car mounted on shock absorbers is like a mass on a spring. If we ignore damping, how will the frequency of the oscillations change if passengers (or a heavy load) are added to the car? The frequency will
   A. increase B. decrease, C. stay the same D. be zero
5. If the pendulum completes exactly 12 cycles in 2.0 min, what is the frequency of the pendulum?
   A. 0.10 Hz B. 0.17 Hz C. 6.0 Hz D. 10 Hz
6. A certain pendulum has an iron bob. When the iron bob is replaced with lead bob of the same size, its time period will
   A. stay the same B. decrease C. increase D. be zero
7. A wave transports
   A. energy but not matter B. matter but not energy
   C. both energy and matter D. air
8. The bending of waves around the edges of the obstacle is
   A. reflection B. refraction C. diffraction D. damping

CONCEPTUAL QUESTIONS

Give a brief response to the following questions

1. Is every oscillatory motion simple harmonic? Give examples.
2. For a particle with simple harmonic motion, at what point of the motion does the velocity attain maximum magnitude? Minimum magnitude?
3. Is the restoring force on a mass attached to spring in simple harmonic motion ever zero? If so, where?
4. If we shorten the string of a pendulum to half its original length, what is the affect on its time period and frequency?
5. A thin rope hangs from dark high tower so that its upper end is not visible. How can the length of rope be determined?
6. Suppose you stand on a swing instead of sitting on it. Will your frequency of oscillation increase or decrease?
7. Explain the difference between the speed of a transverse wave traveling along a cord and the speed of a tiny colored part of the cord.
8. Why waves refract at the boundary of shallow and deep water?
9. What is the effect on diffraction if the opening is made small?