PERIOD–II

P10CH2

Topic 2

Velocity and Acceleration

2.1. INTRODUCTION TO MOTION

Suppose a bus is standing at point C in front of a house at a particular time. Here house is a stationary object and is taken as a reference. The stationary object or fixed point taken for measuring the position of body is known as reference point. Suppose after two seconds bus is at a new position, say C′, which is away from the house as shown in Fig. 2.1. Call out during these two seconds, as the position of the bus was changing with respect to the stationary house. Hence we can say that this bus was in motion.

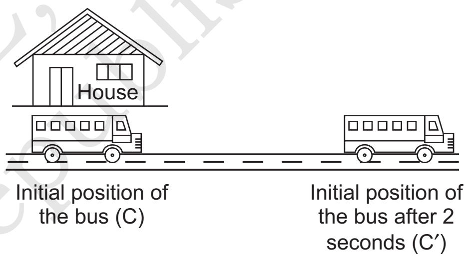

Fig. 2.1. Motion of bus

A body is said to be in motion when its position changes continuously with respect to a reference point.

*If the position of a body with respect to its surroundings does not change with time, the body is said to be at **rest**.*

2.1.1. Types of Motion-Uniform and Non-Uniform Motion

In motion, the moving body covers some distance in certain interval of time.

*If a body covers equal distances in equal interval of time (however small the interval may be) its motion is said to be **uniform**.* For example, a bus running at a constant speed of 20 m/sec will cover equal distance of 20 m in every second and hence motion of the bus is uniform. The distance-time graph of a body having uniform motion is a straight line.

*If a body covers unequal distances in equal interval of time, its motion is said to be **non-uniform (variable)**.* For example, if a ball is dropped

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from the roof of a tall building then ball covers unequal distances in equal intervals of time. It covers 4.9 metres in first second, 14.7 metres in second second, 24.5 metres in third second and so on. Distance-time graph for a body having non-uniform motion is a curved path.

2.2. DISTANCE AND DISPLACEMENT

In physics, distance and displacement have different meanings. Let us understand the difference by taking an example.

Suppose a boy moves from point A to B, then B to C as shown in Fig. 2.2, he moves along the path ABC. The sum of length of path AB and BC gives us the actual distance travelled by the boy.

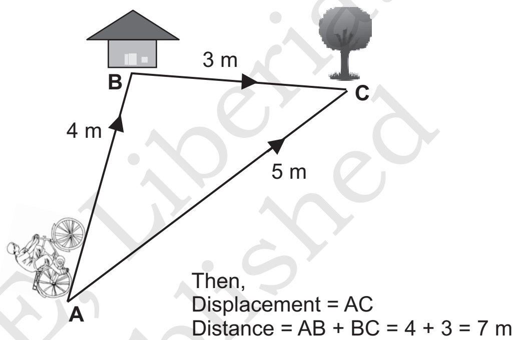

Fig. 2.2. Distance and displacement

Thus, the distance travelled by a body is the total length of the path covered by a moving body irrespective of the direction.

The path-length between the initial and final positions of the body gives the distance covered by the body.

The length of path AC, that is 5 m, is the displacement.

Hence, we can define the displacement as: *whenever a body moves from one position to other then shortest distance between the initial position and final position of a body is called displacement.* Distance covered by a body has magnitude only whereas displacement has magnitude as well as direction.

Example 2.1: *In a long distance race the athletes were expected to take four rounds of the track such that the line of finish was same as the line of start. Suppose the length of the track was 200 m.*

(a) What is the total distance to be covered by the athletes ?

(b) What is the displacement, of the athletes when they touch the finish line ?

(c) Is the motion of the athletes uniform or non-uniform ?

(d) Is the displacement of an athlete and the distance moved by him at the end of the race equal ?

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Solution:

(a) Total distance covered = 4 × 200 m = 800 m

(b) As the athletes finish at the starting line, hence displacement is zero.

(c) As the direction of motion of the athlete is changing while running on the track, hence motion is non-uniform.

(d) Displacement and distance moved are not equal.

2.3. SPEED

The distance covered per unit time, is called speed. (It measures the time rate of change of position in any direction). It is a scalar quantity. It is represented by the symbol v.

$$\text{Speed} = \frac{\text{distance taravelled}}{\text{time taken}}$$

If a body covers a distance S in time t, speed, $v = \frac{S}{t}$

If a car covers a distance of 100 km in 2 hours, speed of this car is given by

$$\text{Speed} = \frac{100 \text{ km}}{2 \text{ hours}} = 50 \text{ km/hour}$$

2.3.1. Uniform Speed

The speed of a body is said to be **uniform**, if it covers equal distances in equal intervals of time, however small these intervals may be. (A uniform speed is also called a **constant speed**).

2.3.2. Average Speed

In case, speed is not uniform (constant), we can obtain average speed by dividing the total distance covered by the total time taken.

i.e., $$\text{Average speed} = \frac{\text{Total distance travelled}}{\text{Total time taken}}$$

2.3.3. Unit of Speed

Unit of speed depends upon unit of distance and time. The S.I. units of

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distance and time are metre (m) and second (s) respectively. Hence, S.I. unit of speed becomes, $\frac{\text{metre}}{\text{second}}$ *i.e.*, m s^{-1}.

$$\text{Conversion : } \frac{1 \text{ km}}{1 \text{ h}} = \frac{1000 \text{ m}}{3600 \text{ s}} = \frac{5}{18} \text{ m s}^{-1} \text{ i.e., } \quad 1 \text{ km h}^{-1} = \frac{5}{18} \text{ m s}^{-1}.$$

2.4. VELOCITY

Velocity *of a body is the distance travelled by the body per unit time in a given direction.* That is,

$$\text{Velocity} = \frac{\text{Distance travelled in a given direction}}{\text{Time taken}}$$

As the distance travelled in a given direction is called displacement, hence,

$$\text{Velocity} = \frac{\text{Displacement}}{\text{Time taken}}$$

If a body travels a distance S in a given direction in time t i.e., if displacement of the body is S after time t, velocity v of the body is given by,

$$v = \frac{S}{t}$$

2.4.1. Velocity is a Vector Quantity

Direction of velocity is same as that of displacement.

2.4.2. Uniform Velocity

The velocity of a body is said to be uniform, if it always moves in same direction and covers equal distances in equal intervals of time, however smaller these intervals may be.

The velocity of a body can be changed in two ways :

- By changing speed of the body, and
- By keeping the speed constant and changing the direction.

2.4.3. Average Velocity

Total displacement divided by total time, is called **average velocity**.

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It is denoted by v_{av}.

Thus, $$v_{av} = \frac{S}{t} \quad \text{or} \quad S = v_{av} \times t$$

i.e., Total displacement = Average velocity × time

If the velocity of a body always goes on changing at a uniform rate, average velocity is given by the arithmatic mean of initial velocity and final velocity for a given time.

Hence, average velocity (v_{av}) may also be given as

$$v_{av} = \frac{\text{Initial velocity + Final velocity}}{2}$$

If u is the initial velocity and v is the final velocity, average velocity is given by

$$v_{av} = \frac{u+v}{2}$$

2.4.4. Unit of Velocity

Velocity has same unit as the speed has. It is so, because the unit is concerned with the magnitude, which has same value for a speed or a velocity in a particular case.

2.4.5. Difference between Speed and Velocity

Some important points of difference between speed and velocity are given in the following table.

Table 2.1. Distinction between Speed and Velocity

	Speed	Velocity
1.	It is time rate of change of position in any direction.	It is time rate of change of position in a definite-(specified) direction only.
2.	Direction of motion of the body is not specified.	Here, direction of motion of the body is specified.
3.	It is measured as distance travelled per unit time.	It is measured as displacement made per unit time.
4.	It is a scalar quantity.	It is a vector quantity.

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Example 2.2: *Rita takes 20 minutes to cover a distance of 3.2 km on a bicycle. Calculate her velocity in units of km/min, m/min and km/h.*

Solution:

Here,

Distance covered,

$$S = 3.2 \text{ km} = 3200 \text{ m}$$

Time taken,

$$t = 20 \text{ minutes} = \frac{1}{3} \text{ h}$$

Velocity, v = ? (to be calculated)

From relation, for uniform speed

$$= \frac{\text{Distance travelled}}{\text{Time taken}}$$

We have, $v = \dfrac{S}{t}$

Substituting various values, we get,

$$v = \frac{3.2 \text{ km}}{20 \text{ min}}$$

$$= 0.16 \text{ km/min}$$

$$v = 0.16 \text{ km min}^{-1}$$

Also, $v = \dfrac{3200 \text{ m}}{20 \text{ min}}$

$$= 160 \text{ m/min}$$

or $v = 160 \text{ m min}^{-1}$

Further,

$$v = \frac{3.2 \text{ km}}{1/3 \text{ h}}$$

$$= 9.6 \text{ km/h}$$

or $v = 9.6 \text{ km h}^{-1}$

Example 2.3: *The velocity of a car is 18 m s^{-1}. Express this velocity in km h^{-1}.*

Solution:

Here, $v = 18 \text{ m s}^{-1}$

$v = ? \text{ km h}^{-1}$ (to be calculated)

As, 1 km per hour

$$= \frac{1000}{60 \times 60} \text{ m/sec}$$

$$= \frac{5}{18} \text{ m/sec}$$

$$\therefore \quad 1 \text{ m s}^{-1} = \frac{18}{5} \text{ km h}^{-1}$$

Hence

$$18 \text{ m s}^{-1} = 18 \times \frac{18}{5} \text{ km h}^{-1}$$

$$= \frac{324}{5} \text{ km h}^{-1}$$

$$= 64.8 \text{ km h}^{-1}$$

i.e., Velocity, $v = 64.8 \text{ km h}^{-1}$

Example 2.4: *A body is moving with a velocity of 10 m s^{-1}. If the motion is uniform, what will be the velocity after 10 s ?*

Solution:

Since the motion is uniform, velocity will remain same.

i.e., velocity = 10 m s^{-1}

Example 2.5: *An electric train is moving with a velocity of 120 km h^{-1}. How much distance will it cover in 30 s ?*

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Solution:

Here,

Velocity, $v = 120 \text{ km h}^{-1}$

$= 120 \times \frac{5}{18}$ m/sec $= \frac{100}{3}$ m s^{-1}

$\left[\because 1 \text{ km/hour} = \frac{5}{18} \text{ m/sec}\right]$

Time, t = 30 s

Distance, S = ? (to be calculated)

From relation,

$$S = vt$$

we get, $S = \frac{100}{3} \text{ m s}^{-1} \times 30 \text{ s}$

$= 1000$ m,

i.e., Distance, S = 1 km

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2.5. ACCELERATION

Acceleration of a body is defined as the rate of change of velocity of the body with time i.e., change of velocity per unit time is called acceleration. It is denoted by a and it is a ***vector quantity***.

i.e., $$\text{acceleration} = \frac{\text{Change in velocity}}{\text{Time taken for change}}$$

But, change in velocity = Final velocity – Initial velocity

$$\therefore \quad \text{Acceleration} = \frac{\text{Final velocity} - \text{Initial velocity}}{\text{Time taken for change}}$$

If velocity of the body changes from u to v in time t, then, $a = \frac{v-u}{t}$

The acceleration is **positive**, when the velocity increases with time and the acceleration is **negative**, when the velocity decreases with time.

If a body moves with uniform velocity, then $v = u$ and, acceleration is zero *i.e.*, $a = 0$ *i.e.*, acceleration of body moving with uniform velocity is zero.

2.5.1. Uniform Acceleration

The acceleration of a body is said to be uniform, *if it always moves in same direction and its velocity changes by equal amount in equal intervals of time, however small these intervals may be.*

Some examples of uniformly accelerated motion are :

(i) motion of a freely falling body.

(ii) motion of a ball rolling down an inclined plane.

(iii) if wind resistance is negligible, motion of a bicycle going down the slope on a road (provided cyclist is not pedalling).

Non-uniform acceleration : If the velocity of a body changes at non-uniform rate, acceleration of the body is non-uniform. Movement of car on a crowded city road is an example of non-uniform acceleration, as speed of the car changes continuously there.

Retardation (Deceleration) : Velocity of a body may increase or decrease with time. If the velocity of a body increases with time, then acceleration is positive. *If velocity of body decreases with time, acceleration is negative and body is said to have* ***retardation***.

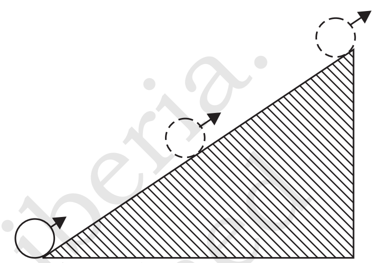

Fig. 2.3. Retardation

$$\text{Retardation} = \frac{\text{Change in velocity}}{\text{Time taken}}$$

2.5.2. Units of Acceleration

Unit of acceleration depends upon unit of velocity and time.

If velocity is in $\frac{\text{metre}}{\text{second}}$ and time is in second, i.e., in S.I. system, unit of acceleration is :

$$\frac{\text{metre/second}}{\text{Second}} = \frac{\text{metre}}{(\text{Second})^2} = \frac{\text{m}}{\text{s}^2} = \text{m s}^{-2}$$

Unit of retardation, is also metre per second^2 i.e., m/sec^2

Example 2.6: *A car starting from a station and moving with uniform acceleration, attains a speed 60 km h^{-1} in 10 minutes. Find its acceleration.*

Solution:

Here,

$$u_1 = 0 \text{ (Starting from rest)}$$

$$u_2 = 60 \text{ km h}^{-1} = 60 \times \frac{5}{18} = \frac{50}{3}$$

$$= 16.7 \text{ m sec}^{-1}$$

$$t = 10 \text{ min} = 600 \text{ sec.}$$

Acceleration, a = ? (to be calculated)

From relation $$a = \frac{u_2 - u_1}{t} = \frac{16.7 - 0}{600}$$

$$= 0.0278 \text{ m sec}^{-2}$$

2.6. EQUATIONS OF MOTION

The equations relating various quantities in a motion with uniform acceleration, are called equations of motion.

Various quantities involved in equations of motion are:

Initial velocity = u

Uniform acceleration = a

Final velocity = v

Time taken = t

Displacement (distance in the direction of velocity) = S

1. First Equation of Motion

Initial velocity = u

Final velocity = v

Change in velocity = $v - u$

Time taken for the change = $t - 0 = t$

Rate of change of velocity = $\frac{v - u}{t}$

By definition, $$a = \frac{v - u}{t}$$

or $$v - u = at$$

or $$v = u + at \qquad \text{...(1)}$$

This equation gives the expression for velocity acquired by the body in time t.

2. Second Equation of Motion

Initial velocity = u

Final velocity = v

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Average velocity, $v_{av} = \frac{v+u}{2}$

By relation, $S = v_{av} \times t$

We have, $S = \left(\frac{u+v}{2}\right) \times t$ ...(2)

From eqn. (1), $v = u + at$

From eqns. (1) and (2), we get

$\therefore$ $S = \frac{u+(u+at)}{2} \times t = \left(u + \frac{at}{2}\right)t$

We have, $S = ut + \frac{1}{2}at^2$ ...(3)

This equation gives the expression for distance travelled by the body in time *t*.

In above calculation, if we put, $u = v - at$, in eqn. (1), we would get

$$S = vt - \frac{1}{2}at^2$$

3. Third Equation of Motion

From eqn. (1), $v = u + \text{at}$ or $v - u = at$

From eqn. (2), $S = \left(\frac{u+v}{2}\right)t$

or $v + u = \frac{2S}{t}$

Multiplying $(v - u)$ and $(v + u)$, we get

$$v^2 - u^2 = at \times \frac{2S}{t}$$

or $v^2 = u^2 + 2aS$ ...(4)

This equation gives the expression for velocity acquired by the body when it has travelled through a distance S.

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Example 2.7: *As ship is moving at a speed of 56 km h^{-1}. One second later, it is moving at a speed of 58 km h^{-1}. What is its acceleration?*

Solution: Here

Initial speed,

$$u = 56 \text{ km h}^{-1}$$

$$= 56 \times \frac{5}{18} \text{ m s}^{-1}$$

$$= \frac{140}{9} \text{ m s}^{-1}$$

$$= 15.55 \text{ m s}^{-1}$$

Final speed,

$$v = 58 \text{ km h}^{-1}$$

$$= 58 \times \frac{5}{18} \text{ m s}^{-1}$$

$$= \frac{145}{9} \text{ m s}^{-1}$$

$$= 16.11 \text{ m s}^{-1}$$

Time taken, $t = 1$ s

Acceleration $a = ?$

From equation, $v = u + at$

We have, $a = \dfrac{v - u}{t}$

Substituting various values, we get

$$a = \frac{(16.11 - 15.55)\,\text{m s}^{-1}}{1\,\text{s}}$$

$$= 0.56 \text{ m s}^{-2}$$

or $a = 0.56 \text{ m s}^{-2}$.

Example 2.8: *An object undergoes an accelerations of 8 m s^{-2} starting from rest. Find the distance travelled in one second.*

Solution: Here,

Initial velocity,

$$u = 0$$

(object starts from rest)

Acceleration, $a = 8 \text{ m s}^{-2}$

Time taken, $t = 1$ s

Distance covered, S = ?

From formula, $S = ut + \frac{1}{2} at^2$

we get,

$$S = \left[0 \times 1 + \frac{1}{2} \times 8 \times (1)^2\right] \text{m}$$

S = 4 m.

Example 2.9: *A train is travelling at a speed of 90 km per hour. Brakes are applied so as to produce a uniform acceleration of – 0.5 m s^{-2}. Find how for the train will go before it is brought to rest.*

Solution: Here,

Initial velocity of the train,

$$u = 90 \text{ km h}^{-1} = 25 \text{ m s}^{-1}$$

$$\left[\because 1 \text{ km h}^{-1} = \frac{5}{18} \text{ m s}^{-1}\right]$$

Final velocity of the train,

$$v = 0$$

(Finally train is brought to rest)

Uniform acceleration,

$$a = -0.5 \text{ m s}^{-2}$$

From equation of motion,

$$v^2 = u^2 + 2aS$$

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we have,

$$S = \frac{v^2 - u^2}{2a}$$

Substituting various values, we get

$$S = \frac{0-(25\ ms^{-1})^2}{2\times(-0.5\ ms^{-2})}$$

$$= \frac{25\times 25\ m^2\ s^{-2}}{1\ m\ s^{-2}}$$

$$= 625\ m.$$

Example 2.10: *A trolley while going down an inclined plane has an acceleration of 2 cm s^{-2}. What will be its velocity 3 seconds after the start?*

Solution: Here,

Initial velocity of the trolley,

$$u = 0$$

Uniform acceleration,

$$a = 2\ cm\ s^{-2}$$

Time taken, $t = 3$ s

Final velocity of the trolley,

$$v = ?$$

In relation, $v = u + at$

Substituting various values, we get

$$v = 0 + 2\ cm\ s^{-2} \times 3\ s$$

$$= 6\ cm\ s^{-1}.$$

2.7. GRAPHICAL ANALYSIS OF UNIFORM MOTION

Graphs are generally plotted on a paper ruled in millimetre or squares.

To understand that how a graph can be plotted, do the following activity.

ACTIVITY 2.1

Consider a car moving on a level road along a straight line path. The distance moved by the car in every twelve minutes is given in the following table.

Distance Covered by a Car at Regular Intervals of Time

Time (min) →	0	12	24	36	48	60
Distance moved from starting point (km) →	0	10	20	30	40	50

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Procedure

1. Choice of a graph paper

We choose a cm graph paper and mark the axes.

2. Choice of axes

We take time along *X*-axis, because it is **independent variable**.

We take distance along *Y*-axis, because it is **dependent variable**.

3. Choice of scale

For time, we take 6 minutes = 1 cm

For distance, we take 10 km = 1 cm

4. Marking of quantities on the axes

We mark 0, 12, 24, 36, 48 and 60 at 0, 2 cm, 4 cm, 6 cm, 8 cm and 10 cm points on the *X*-axis.

We mark 0, 10, 20, 30, 40 and 50 at 0, 1 cm, 2 cm, 3 cm, 4 cm and 5 cm points on the *Y*-axis.

5. Marking points on the graph paper

Perpendicular lines on the axes represent the quantity of the point on which they are perpendicular. Point of intersection of these lines gives the point corresponding to one set of observation. The points of intersection and the quantities represented by them are given below:

	Quantity	
Point	**Time (min)**	**Distance (km)**
O	0	0
A	12	10
B	24	20
C	36	30
D	48	40
E	60	50

6. Drawing of curve

A continuous line is drawn which passes through all the points.

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In this particular case, the line is a straight line representing a uniform motion (Fig. 2.4).

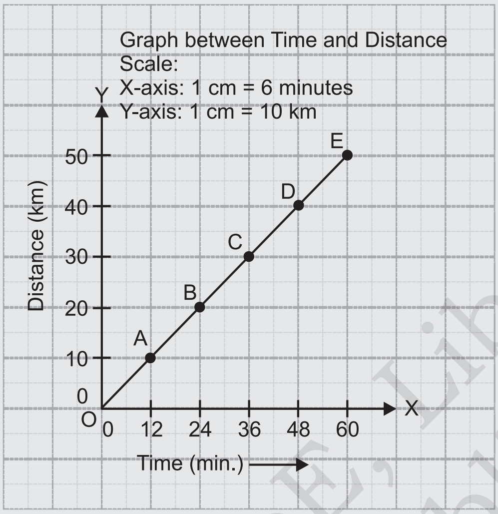

Fig. 2.4. Distance-time graph for a car moving with a uniform speed

2.7.1. Graphical Representation of Uniform Motion

Graphs drawn for studying the nature of motion of an object, are called **kinematic graphs**.

The three main types of kinematic graphs are as follows.

1. Position-time graph 2. Distance (displacement)-time graph

3. Speed velocity-time graph.

These graphs represent the nature of the motion of the body.

1. Position–time graph

This graph is plotted between position and time.

It is easy to analyze and understand motion of an object if it is represented graphically. To draw graph of the motion of an object, its position at different times are shown on *Y*-axis and time on *X*-axis.

Case I : When the body is at rest.

When position of the body does not change with time then it is said to be at rest.

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Suppose a car is at rest. The position of car at different times are given in the table below.

Time (s)	0	1	2	3	4
Position (m)	40	40	40	40	40

If we plot corresponding position-time data, we get a straight line parallel to *X*-axis (time-axis) as shown in Fig. 2.5.

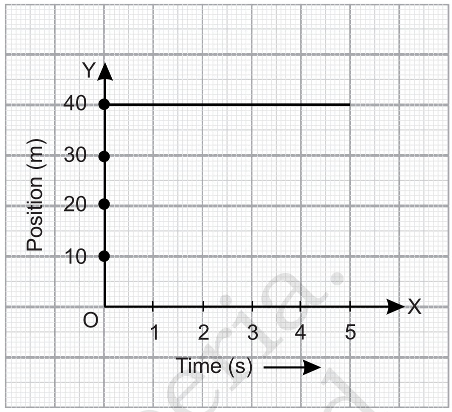

Fig. 2.5. Position–time graph for body at rest

Case II: When the body is in the motion with uniform (constant) motion

When the position of the body changes by equal amounts in equal intervals of time then body is said to be moving with constant speed.

Suppose a car is moving at a constant speed. The positions of car at different times are given in the table below.

Time (s)	0	1	2	3	4	5	6	7
Position (m)	0	10	20	30	40	50	60	70

If we plot corresponding position-time data, we get a straight line. This line represents the position-time graph of the motion as shown in Fig. 2.6.

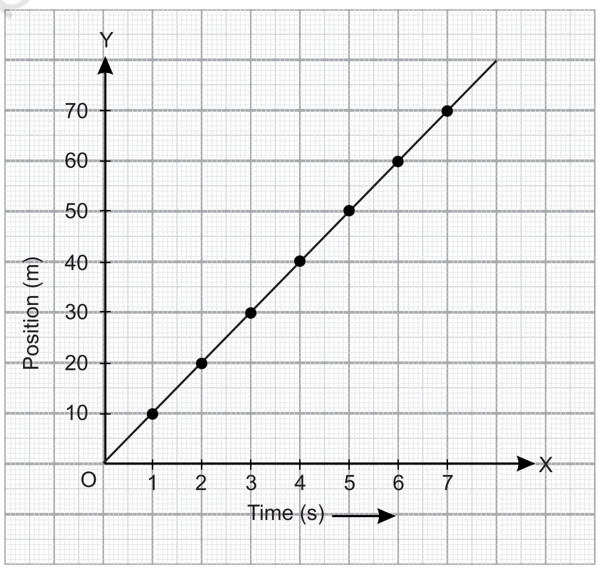

Fig. 2.6. Position-time graph for car with uniform motion

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Case III: When the body is in non-uniform motion

Consider a car that is moving with increasing acceleration.

The position of car at different time are given in the table below.

Time (s)	0	1	2	3	4	5
Position (m)	0	2	8	18	32	50

If we plot corresponding position-time data, we get a curve. The curve represents the position-time graph of the motion with increasing acceleration.

In such case, the position-time graph is not a straight line, but is a curve as shown in figure 2.7.

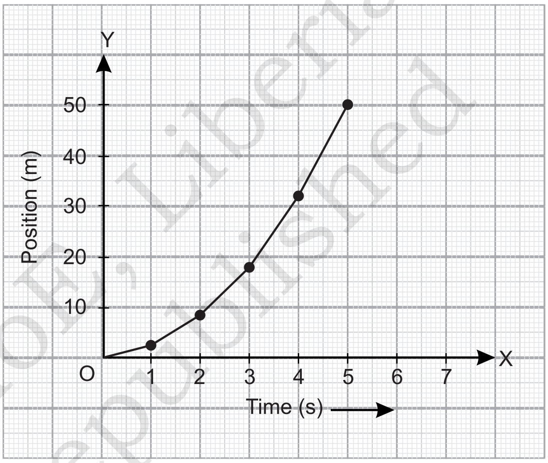

Fig. 2.7. Non-uniform motion, rate of charge in position is increasing

If the car is moving with decreasing acceleration *i.e.*, retardation of while the position of car at different times are given in table below.

Time (s)	0	1	2	3	4
Position (m)	80	70	40	10	0

If we plot corresponding position-time data, we get a curve. The curve in Fig. 2.8 represents the position-time graph of the motion with decreasing acceleration or retardation.

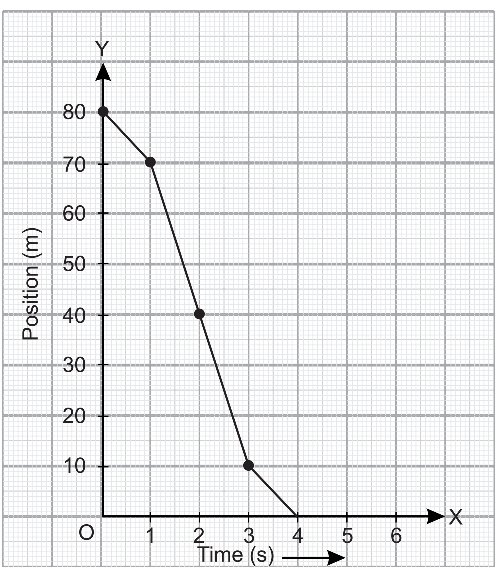

Fig. 2.8. Non-uniform motion, rate of charge in position is decreasing

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2. Distance (Displacement)-Time Graph

This graph is plotted between the time taken and the distance covered. The time taken is taken along the X-axis and the distance covered is taken along the Y-axis

Since, $$\text{speed} = \frac{\text{distance}}{\text{time}}$$

The slope of the distance-time graph gives the speed of the body.

The slope of the displacement-time graph gives the **velocity** of the body.

Case I. When the body is at rest

When position of the body does not change with time then it is said to be stationary. The distance-time graph of such a body is a straight line parallel to X-axis (time-axis), as shown in Fig. 2.9.

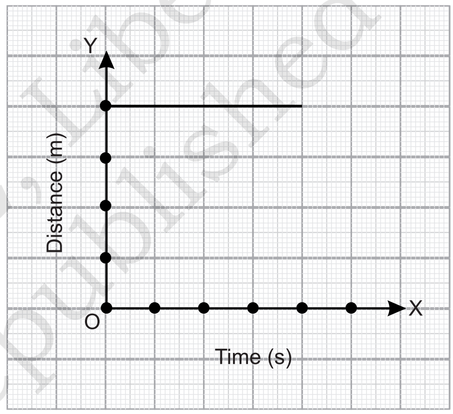

Fig. 2.9. Distance-time graph for a stationary body

Case II. When the body is in the motion with uniform (constant) speed

When the position of the body changes by equal amounts in equal intervals of time then body is said to be moving with uniform speed. The distance-time graph of such a body is a straight line, inclined to X-axis (time-axis) as shown in Fig. 2.10.

Suppose a car-taxi is moving on a straight path with a uniform speed. Let the following table represent the distance of the taxi from its starting point with respect to time.

Time (hours) →	1	2	3	4	5	6	7	8	9	10
Distance covered (km) →	50	100	150	200	250	300	350	400	450	500

The distance-time graph plotted is shown in figure 2.10.

In Fig. 2.10, taking time along X-axis and distance along Y-axis, the graph comes to be a straight line, passing through the origin O.

As a straight line has a constant slope, this graph represents a constant (uniform) speed.

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Speed of taxi = slope of line OR

$$= \frac{QS}{PS} = \frac{(400 - 200)\text{ km}}{(8 - 4)} = \frac{200\text{ km}}{4} = 50\text{ km h}^{-1}$$

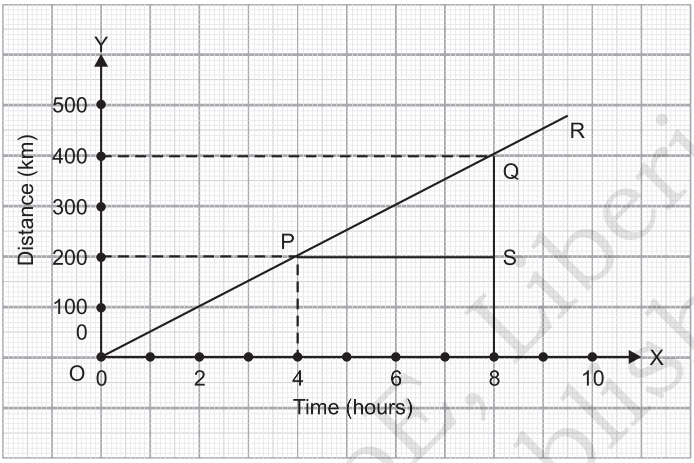

Fig. 2.10. Distance-time graph of car-taxi moving with uniform speed

Case III. When the body is in motion with a non-uniform (variable) speed

In such case, the time graph is not a straight line, but is a curve, as shown in Fig. 2.11.

As the line has different slopes at different values of time, its speed is variable. At point P, slope is less, hence speed is less. At point Q, slope is more hence speed is more.

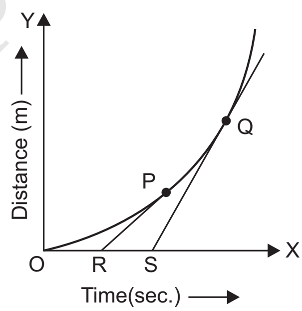

Fig. 2.11. Distance-time graph for a body moving with non-uniform speed

3. Speed (Velocity)-Time Graph

Speed (velocity)-time graph is plotted between the time taken and the speed (velocity) acquired. Time taken is plotted along X-axis and the speed (velocity) acquired is taken along Y-axis.

Since, acceleration $= \dfrac{\text{Speed (or velocity)}}{\text{Time}}$

Hence the slope of the speed (or velocity)-time graph, gives the acceleration of the body.

Since, distance = speed × time, hence area enclosed between the speed-time graph line and the *X*-axis (time-axis) gives the distance covered by the body. Similarly, area enclosed between the velocity-time graph line and the *X*-axis gives the displacement of the body.

Case I. When the body is moving with a uniform speed (velocity)

Since the speed (velocity) of the body is uniform hence the magnitude remains same. This graph is a straight line parallel to X-axis (time-axis) as shown in Fig. 2.12.

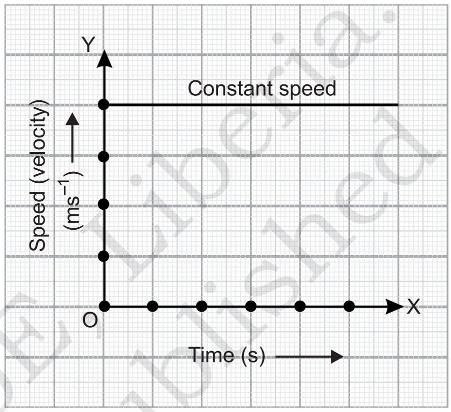

Fig. 2.12. Speed (velocity)-time graph for a body with uniform speed (velocity)

Case II. When the body is moving with a uniform acceleration

Here, the speed (velocity) is changing by equal amounts in equal intervals of time. The speed (velocity)-time graph of such body is a straight line inclined to X-axis (time-axis) as show in Fig. 2.13.

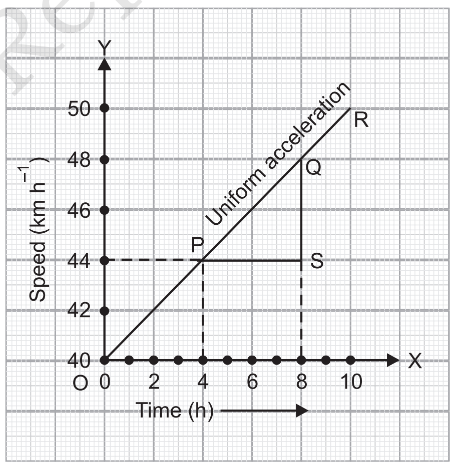

Fig. 2.13. Speed (velocity)-time graph for a bus moving with uniform acceleration

Suppose a bus is moving on a straight path with a uniform acceleration.

Let the following table represent the speed (velocity) of the bus with respect to time.

Time (hours)	0	1	2	3	4	5	6	7	8	9	10
Speed (km h^{-1})	40	41	42	43	44	45	46	47	48	49	50

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Taking time along X-axis and speed (velocity) along Y-axis, the graph, comes to be a straight line passing through the origin O (Fig. 2.13).

As a straight line has a constant slope, the graph represents a constant (uniform) acceleration.

$$\text{Acceleration of bus} = \text{slope of line OR} = \frac{QS}{PS}$$

$$= \frac{(48 - 44)\ \text{km h}^{-1}}{(8 - 4)\ \text{h}}$$

$$= \frac{4\ \text{km h}^{-1}}{4\ \text{h}} = 1\ \text{Kmh}^{-2}$$

$$\therefore \quad \text{Acceleration} = 1\ \text{km h}^{-2}.$$

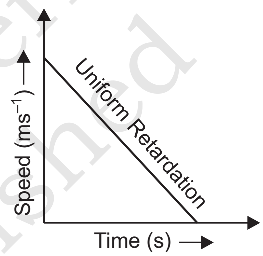

Fig. 2.14.

Speed-time graph of a body slopping downward (Fig. 2.14) indicates uniform retardation.

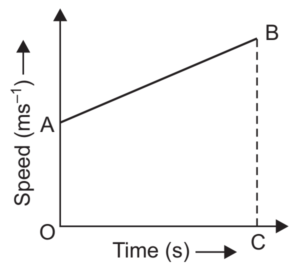

Fig. 2.15.

When the initial speed of the body is not zero then speed-time graph does not start from origin as shown in Fig. 2.15. In this figure, OA represents initial speed and AB represents uniform acceleration from A to B.

To find the acceleration in such cases, initial speed OA is subtracted from the final speed and is then divided by the time given by OC.

Case III. When the body is moving with a non-uniform (variable) acceleration

In such a case, the speed (velocity)-time graph is not a straight line but is a curve as shown in Fig. 2.16.

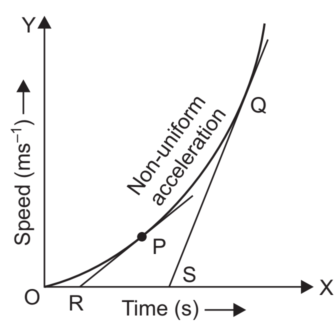

Fig. 2.16. Speed (velocity)-time graph for a body moving with non-uniform acceleration

As this curve has different slopes at different times, hence acceleration is variable. At point P, slope is less, hence acceleration is less. At point Q, slope is more, hence acceleration is more.

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Example 2.11: *The position-time graph of a person is shown below. Read the graph and answer the question that follow.*

(a) *When did the person reach 12 m beyond the starting point?*

(b) *Where was the person after 2 seconds?*

(c) *Find the displacement in the time interval 3s to 4s.*

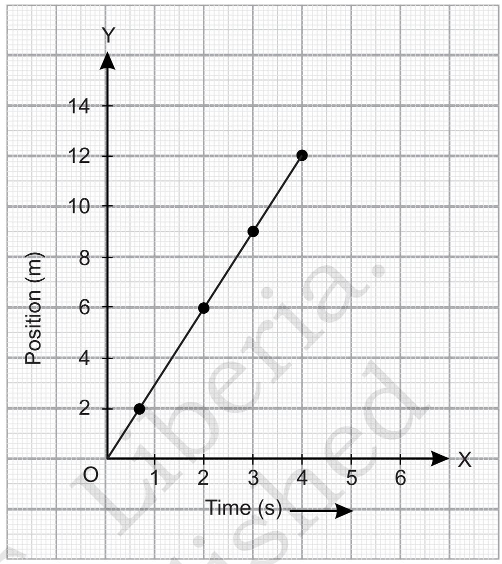

Fig. 2.17.

Solution:

(a) From the graph, at position y = 12 m, the time is exactly t = 4s.

(b) From the graph at t = 2s the position of a person is exactly 6 metres.

(c) From the graph the position of person at t = 3 s is 9m and the position of person at t = 4 s is 12 m.

So the total displacement = (12 – 9) m = 3 m.

Example 2.12: *The following is the distance-time table of a moving car:*

Time	10 : 05 a.m.	10 : 25 a.m.	10 : 40 a.m.	10 : 50 a.m.	11 : 00 a.m.	11 : 10 a.m.	11 : 25 a.m.	11 : 40 a.m.
Distance	0 km	5 km	12 km	22 km	26 km	28 km	38 km	42 km

(a) *Use a graph paper and plot the distance travelled by the car versus time.*

(b) *When was the car travelling at the maximum speed?*

(c) *What is the average speed of the car?*

(d) *What is the speed between 11 : 25 a.m. and 11 : 40 a.m.?*

(e) *During a part of the journey, the car was forced to slow down to 12 km h^{-1}. At what distance did this happen?*

Solution: Figure 2.18 represents the distance time graph of the car.

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(a) The graph plotted on a graph paper shows time along the X-axis and the distance along the Y-axis.

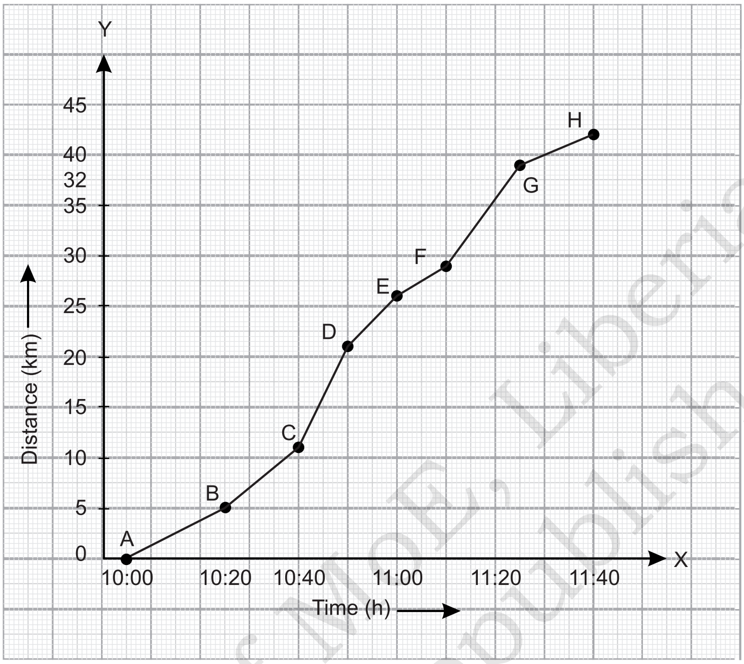

Fig. 2.18. Distance-time graph of a car

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(b) The slope of distance-time line represents speed. The line with maximum slope will represent maximum speed.

Line CD represents the maximum (greatest) speed between 10 : 40 a.m. and 10 : 50 a.m.

(c) As given,

Total distance travelled

= 42 km

Total time taken

= (11 : 40 a.m.) – (10 : 05 a.m.)

= 1 h 35 minutes = 95 minutes

$= \frac{95}{60}$ hours = 1.58 h

From relation,

$$v_{av} = \frac{\text{Total distance}}{\text{Total time}}$$

$$= \frac{42 \text{ km}}{1.58 \text{ h}}$$

$$= 26.58 \text{ km/h}$$

or $v_{av} = 26.6 \text{ km h}^{-1}$.

(d) Between 11 : 25 a.m. and 11:40 a.m.

Distance travelled

= (42 – 38) km = 4 km

Time taken

= (11 : 40 a.m.) – (11 : 25 a.m.)

$= 15 \text{ minutes} = \frac{15 \text{ h}}{60} = 0.25 \text{ h}$

$$\text{As speed} = \frac{\text{Distance}}{\text{Time}}$$

$$\therefore \quad v = \frac{4 \text{ km}}{0.25 \text{ h}} = 16 \text{ km/h}$$

$$\text{or} \quad v = 16 \text{ km h}^{-1}.$$

(*e*) Slowing down must give the car minimum speed. This is represented by line EF.

For this part of journey,

distance covered = (28 – 26) km

= 2 km

Time taken

= (11 : 10 a.m.) – (11 : 00 a.m.)

$= 10 \text{ minutes} = \frac{1}{6} \text{ h}.$

$$\text{As Speed} = \frac{\text{Distance}}{\text{Time}}$$

$$v = \frac{2 \text{ km}}{1/6 \text{ h}} = 12 \text{ km/h}$$

$$\text{or} \quad v = 12 \text{ km h}^{-1}.$$

Example 2.13: *The driver of a car, travelling at 52 km h^{-1} applies the brakes and decelerates uniformly. The car stops in 5 seconds. Another driver going at 34 km h^{-1} applies his brakes slower and stops after 10 seconds. On the same graph paper, plot the speed versus time graph for two cars. Which of the two cars travelled farther after the brakes were applied?*

Solution: First, we convert the speed from k mh^{-1} into m s^{-1} using conversion formula.

$$1 \text{ km h}^{-1} = \frac{1 \text{ kilometre}}{1 \text{ hour}}$$

$$= \frac{1000 \text{ metre}}{3600 \text{ sec}}$$

$$= \frac{5}{18} \text{ m s}^{-1}$$

Hence,

$$52 \text{ km h}^{-1} = 52 \times \frac{5}{18} \text{ m s}^{-1}$$

$$= \frac{130}{9} \text{ ms}^{-1}$$

$$= 14.4 \text{ m s}^{-1}$$

and

$$34 \text{ km h}^{-1} = 34 \times \frac{5}{18} \text{ m s}^{-1}$$

$$= \frac{85}{9} \text{ m s}^{-1}$$

$$= 9.4 \text{ m s}^{-1}$$

The speed-time path for the two cars is plotted as shown in Fig. 2.19.

First we take a point *P* on *Y*-axis to represent a speed of 14.4 m s^{-1}.

Then we take a point *Q* on *X*-axis to represent a time of 5 s.

We join *PQ*. Line *PQ* represents speed-time graph for first driver.

Next we take a point *R* on *Y*-axis to represent a speed of 9.4 m s^{-1}. Then we take a point S on *X*-axis to represent a time of 10 s.

We join *RS*. Line *RS* represents speed-time graph for second driver.

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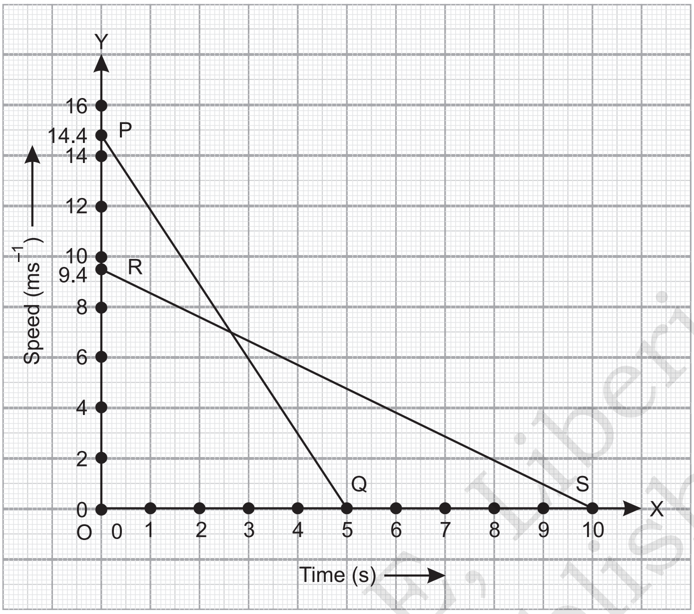

Fig. 2.19. Speed-time graph for the drivers.

Now, we calculate the distance travelled by each car, using these speed-time graphs. Distance travelled by first car

$$= \text{Area under the line } PQ$$

$$= \text{Area of } \Delta POQ$$

$$= \frac{\text{Height} \times \text{Base}}{2}$$

$$= \frac{14.4\ \text{ms}^{-1} \times 5\ \text{s}}{2} = 36\ \text{m}$$

Distance travelled by second car

$$= \text{Area under the line } RS$$

$$= \text{Area of } \Delta ROS$$

$$= \frac{\text{Height} \times \text{Base}}{2}$$

$$= \frac{9.4\ \text{ms}^{-1} \times 10\,\text{s}}{2} = 47\ \text{m}.$$

It is very clear that the second car travelled farther after the brakes were applied.

2.8. NEWTON'S LAWS OF MOTION

To describe the motion of the bodies, Newton has given three laws. These laws are known as Newton's laws of motion.

2.8.1. Newton's First Law of Motion

Newton's first law states that "*everybody continues to remain in its state of rest or of uniform motion along a straight line, unless it is compelled to change its states of rest or of uniform motion, by some external force*".

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2.8.1.1. Inertia of a Body

The inherent property of a body, by virtue of which (due to which) a body at rest tends to remain at rest and a body in motion tends to continue moving with same velocity in same direction, is called ***inertia*** *(tendency to remain as such, is called* ***inertness****).*

For examples

(i) A man sitting on the horse back falls behind when the horse starts moving suddenly.

(ii) The passengers fall backward when their bus starts moving suddenly.

(iii) When a bus takes sharp turn, passengers tend to fall sideway.

2.8.1.2. Momentum

ACTIVITY 2.2

Take a heavy cricket ball and a light tennis ball. Throw them with same velocity.

1. Which of these ball will stop with less effort?
2. Do you think the same cricket ball moving slowly can easily be stopped than when it was moving fast?

The effort needed to stop a moving object is a measure of amount of motion present in the object.

The amount of motion present in a moving object, is called the ***momentum*** *of the object.* It is represented by the symbol p. It is a vector quantity.

For a body of mass m moving with velocity v, it is found by experience that

Momentum $\propto$ mass and momentum $\propto$ velocity

Mathematically, $p \propto m$ and $p \propto v$ or $p \propto mv$

$\therefore$ $p = kmv$

In S.I. unit, $k = 1$

$\therefore$ $p = mv$

i.e., Momentum is measured as the product of mass and velocity

In vector form, $\vec{p} = m\vec{v}$

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Momentum of a body depends on the mass of the body and its velocity. A cricket ball although having small mass but when thrown with high velocity possesses large momentum.

Every moving body possesses momentum.

S.I. unit of momentum is kg m s^{-1}. C.G.S. unit of momentum is g cm s^{-1}.

2.8.2. Newton's Second Law of Motion

Newton's second law states "the *rate of change of momentum of a body is directly proportional to the applied force and takes place in the direction of force*". Mathematically, this law can be expressed as

$$\text{Applied force} \propto \frac{\text{Change in momentum}}{\text{Time taken}}$$

If a body of mass m has initial velocity u, then initial momentum of the body will be mu. Suppose a force F acts on this body for a time t resulting in a change in its velocity to v, then final momentum of the body becomes mv.

Thus, change in momentum of the body = $mv - mu$.

Then, from the definition of second law of motion we can write

$$F \propto \frac{mv - mu}{t} \quad \text{or} \quad F \propto m\frac{(v-u)}{t}$$

But, we know that, $a = \dfrac{v-u}{t}$

$\therefore$ $F \propto ma$

Thus, force acting on a body is directly proportional to the product of the mass of the body and acceleration produced in the body by the application of the force.

i.e., $F \propto ma$ or $F = kma$ ...(1)

where k is a constant of proportionality.

In SI units, value of k is 1.

$\therefore$ Equation (1) becomes, $\mathbf{F = ma}$

i.e., **Force = mass × acceleration** ...(2)

Vector form of Newton's second law of motion is

$$\vec{F} = m\vec{a}$$

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Thus we can say that acceleration produced in a body is directly proportional to the force acting on the body and inversely proportional to the mass of the body.

2.8.2.1. Units of Force

(i) The S.I. unit of force is netwon (N).

One newton is that force which when applied on a body of mass 1 kg, produces in it an acceleration of 1 m s^{-2}.

i.e., $$1 \text{ newton} = 1 \text{ kilogram} \times 1 \text{ m s}^{-2}$$

or $$1 \text{ N} = 1 \text{ kg} \times 1 \text{ m s}^{-2}$$

(ii) The C.G.S. unit of force is dyne.

One dyne is that force which when applied on a body of mass 1 g, produces in it an acceleration of 1 cm s^{-2}.

i.e., $$1 \text{ dyne} = 1 \text{ gram} \times 1 \text{ cm s}^{-2}$$

or $$1 \text{ dyne} = 1 \text{ g} \times 1 \text{ cm s}^{-2}$$

(iii) Relation between dyne and newton

$$\begin{aligned} 1 \text{ N} &= 1 \text{ kg} \times 1 \text{ m s}^{-2} \\ &= 1000 \text{ g} \times 100 \text{ cm s}^{-2} \\ &= 10^5 \text{ g cm s}^{-2} \end{aligned}$$

or $$\mathbf{1 \text{ N} = 10^5 \text{ dyne}}$$

2.8.2.2. Applications of Newton's Second Law of Motion

Some important applications of Newton's second law of motion in our daily life are given below:

(i) Jumping on a heap of sand: If someone jumps from a height on a heap of sand, his feet move inside the sand very slowly. His momentum changes slowly requiring a lesser force of reaction from the sand. Thus man is not injured.

(ii) Springs in vehicles: The vehicles are fitted with springs to reduce the hardness of the shocks. When vehicles move over an uneven road, they experience impulses exerted by the road. The springs increase the duration of impulse and hence reduce the force.

(iii) Springs in seats: The seats are also fitted with springs to reduce their hardness. When we sit on them all of a sudden, the seats

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are compressed. The compression increases duration of our coming to rest on the seat. The reaction force of seats becomes negligible.

(iv) **Athletes** are advised to stop slowly after finishing a fast race.

In general, all changes of momentum must be brought slowly to involve lesser forces of action reaction and this avoids injury.

Example 2.14: *What is the acceleration produced by a force of 12 newtons exerted on an object of mass 3 kg?*

Solution: Here,

Force, F = 12 N

Mass, m = 3 kg.

Acceleration, a = ? (to be calculated)

From relation, F = ma

we have, $a = \dfrac{F}{m}$

Substituting various values, we get,

$$a = \frac{12}{3}\ \text{m s}^{-2}$$

Acceleration, $a = 4\ \text{m s}^{-2}$

Example 2.15: *What force would be needed to produce an acceleration of 4 m s^{-2} in a ball of mass 6 kg?*

Solution: Here,

Mass, m = 6 kg

Acceleration, $a = 4\ \text{m s}^{-2}$

Force, F = ? (to be calculated)

From relation, F = ma

we get, F = 6 × 4 N or F = 24 N

Example 2.16: *Two blocks made up of different metals, identical in shape and size are acted upon by equal forces which cause them to slide on a horizontal surface. The acceleration of second block is found to be 5 times that of the first. What is the ratio of the mass of the second block to the first block?*

Solution:

Let, force on both blocks = F

Suppose, mass of first block = m_1

Mass of second block = m_2

Acceleration of first block = a_1

Acceleration of second block = a_2

Ratio of accelerations, $\dfrac{a_2}{a_1} = 5$ (given)

Ratio of masses, $\dfrac{m_2}{m_1}$ = ? (to be calculated)

From relation, F = ma

i.e., $F = m_1a_1 = m_2a_2$ (given)

We have, $\dfrac{m_2}{m_1} = \dfrac{a_1}{a_2}$

Putting values, we get, $\dfrac{m_2}{m_1} = \dfrac{1}{5}$

Ratio of masses = 1 : 5

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2.8.3. Newton's Third Law of Motion

Newton's third law states that "*whenever one body exerts a force on another body, the second body also exerts an equal and opposite force on the first body*". The force exerted by the first body on the second body is called **'action'** and force exerted by the second body on the first body is called **reaction**.

Newton's third law of motion can be explained with the help of following activity:

ACTIVITY 2.3

Take two similar spring balances A and B and join them hook to hook as shown in Fig. 2.20. Attach second end of the spring B to a hook rigidly fixed on rigid wall.

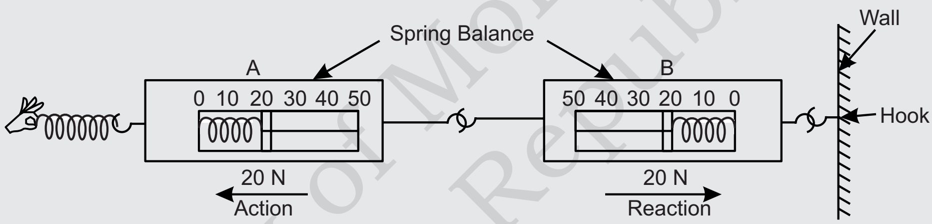

Fig. 2.20. Demonstration of Newton's third law of motion

Pull the other end of the spring A to the left. Do you observe that the spring balances show the same reading say 20 N for the applied force?

The pulled balance A exerts a force of 20 N on the balance B. It acts as action. B pulls the balance A in opposite direction with a force of 20 N. This force is the force of reaction.

Thus, we conclude that action and reaction force are equal and opposite and act on two different bodies. Newton's third law can be defined as *for every action there is an equal and opposite reaction.*

Some examples of Newton's third law of motion are:

(i) Hammer Hits a Nail: A hammer hits a nail, driving the nail downwards (action) into a piece of wood. The "reaction" is the force of the nail pussing upwards on the hammer, which stops the hammer.

Fig. 2.21.

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(ii) Swimming of a Man: Man pushes water in the backward direction (action) and water pushes man in the forward direction (reaction). In this way man swims.

(iii) Flight of Jet or Rocket: The burnt gases are exhausted from behind with high speed giving the gases backward momentum (action). The exhausted gases impart the jet or rocket a forward momentum (reaction). The jet or rocket moves.

2.9. NEWTON'S UNIVERSAL LAW OF GRAVITATION

Universal law of gravitation also known as Newton's law of gravitation.

The law states that *every entity in this universe attracts every other intity with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centres.*

The force is **mutual** and direction of the force is along the line joining the centres of the two bodies.

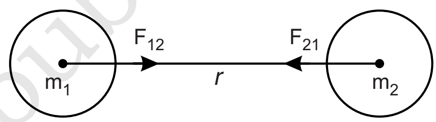

Fig. 2.22. Gravitational force between two bodies

Suppose two bodies of masses m_1 and m_2 lie with their centres at distance r apart (Fig. 2.22).

Suppose force of attraction between these bodies is F.

Then according to Newton's law of gravitation, force of attraction between them is proportional to the product of their masses.

i.e., $$F \propto m_1 m_2 \quad \text{...(1)}$$

Also force of attraction between these two bodies is inversely proportional to the square of the distance between them

i.e., $$F \propto \frac{1}{r^2} \quad \text{...(2) (Inverse square law)}$$

Combining eqs. (1) and (2), we get $F \propto \dfrac{m_1 m_2}{r^2}$ or $F = G\,\dfrac{m_1 m_2}{r^2}$

where G is constant of proportionality. It is called **Universal Gravitational Constant**.

Value of G does not depend on the medium between the two bodies and is also independent of the masses of the bodies and the distance between them.

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Newton's law of gravitation is a universal law as it is true for all bodies whether terrestrial or celestial and whether they are big or small. It is also true at all times and at all locations of the bodies. It is found to be independent of the nature of the medium existing between them. It also acts in vacuum.

2.9.1. Importance of Newton's Law of Gravitation

This law explains successfully several unconnected phenomena. Some of these are:

1. The force that surrounds us from all sides.
2. The force that keeps us bound to the earth.
3. The force that binds moon to the earth and makes it move round the earth.
4. The force that makes planets move around the sun.
5. The tides due to the moon and the sun.

2.9.2. Units of G

From relation, $$F = \frac{Gm_1m_2}{r^2}$$

we have, $$G = \frac{Fr^2}{m_1m_2}$$

In S.I. unit, $$G = \frac{\text{N m}^2}{\text{kg kg}} = \text{N m}^2\ \text{kg}^{-2}$$

Value of G is 6.67 × 10^{-11} N m^2 kg^{-2} everywhere.

2.10. FORCE OF GRAVITATION OF THE EARTH (GRAVITY)

Attraction between two bodies having masses of same order is called gravitation and the force of attraction between them is called ***force of gravitation***. Forces involved are very small and the attracting bodies do not move towards each other.

Force with which earth attracts a body towards its centre is called force of gravity.

Thus, gravity becomes a special case of gravitation in which small bodies move towards huge planets.

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If M represent mass of the earth and m represent mass of a body.

Then, force of gravity acting on the body is

$$F = \frac{GMm}{r^2}$$

Force of gravity is responsible for holding the atmosphere above the surface of the earth, flow of water in rivers, rainfall, etc. We can keep us firmly on ground (without floating) because of the gravity of the earth.

2.10.1. Acceleration Due to Gravity

When we drop a stone from some height, it moves downward toward the earth. As it moves downward its velocity increases at a constant rate. Hence we can say that when an object is dropped from some height, a uniform acceleration is produced in the object due to the gravitational pull of the earth and this acceleration is independent of the mass of the object and its value is 9.8 ms^{-2}. Thus, *acceleration produced in a body due to the force of gravity (gravitational pull of the earth) is called acceleration due to gravity.* It is represented by the symbol 'g'.

2.10.2. Calculation of the Value of Acceleration Due to Gravity (g)

Force of gravity between the earth having mass M and radius R and body of mass m, when the body lies on the surface of the planet, is given by

$$F = \frac{GMm}{R^2} \qquad \text{...(1)(Here } r = R\text{)}$$

Force exerted by the earth on the body produces acceleration in the body. Thus, acceleration of the body = $\dfrac{\text{Force on the body}}{\text{Mass of the body}}$

i.e., $$a = \frac{F}{m} \quad \text{or} \quad F = ma \qquad \text{...(2)}$$

From Equations (1) and (2), we get,

$$ma = \frac{GMm}{R^2} \quad \text{or} \quad a = \frac{GM}{R^2}$$

This acceleration produced in the body is called acceleration due to gravity and is represented by g.

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$$\therefore \qquad g = \frac{GM}{R^2}$$

On the surface of the earth or near the surface of the earth, value of g is calculated below:

$$M = 6 \times 10^{24} \text{ kg}, \qquad R = 6.4 \times 10^6 \text{ m}$$

$$G = 6.67 \times 10^{-11} \text{ Nm}^2 \text{ kg}^{-2}$$

Hence,

$$g = \frac{6.67 \times 10^{-11} \times 6 \times 10^{24}}{(6.4 \times 10^6)^2} \text{ m sec}^{-2}$$

$$= 9.8 \text{ m sec}^{-2} \quad \textit{i.e.,} \quad g = 9.8 \text{ ms}^{-2}$$

The body moves towards the earth with this acceleration. To make the calculations easy, sometimes value of g is taken as 10 ms^{-2}.

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Example 2.17: *Suppose you and your friend have mass 50 kg each. Suppose both of you are standing such that your centres of gravity are 1 m apart. Calculate the force of gravitation between you and your friend. Also calculate the force of gravity acting on you using equation.*

Force of gravity $= \dfrac{GMm}{R^2}$. *(Take M* $= 6 \times 10^{24}$ *kg, R* $= 6.4 \times 10^6$ *m)*

Solution:

Here, $m_1 = m_2 = 50$ kg,

$r = 1$ m

In relation,

$$F = \frac{Gm_1m_2}{r^2}$$

Substituting various values, we get,

$$F = \frac{6.67 \times 10^{-11} \times 50 \times 50}{(1)^2}$$

N = 1.67×10^{-7} N

Force of gravitation,

$$F = 1.67 \times 10^{-7} \text{ N}$$

Also, $M = 6 \times 10^{24}$ kg and

$R = 6.4 \times 10^6$ m

In relation,

$$F = \frac{GMm}{\text{R}^2}$$

Substituting various values, we get,

$$F = \frac{6.67 \times 10^{-11} \times 6 \times 10^{24} \times 50}{(6.4 \times 10^6)^2} \text{ N}$$

$$= \frac{6.67 \times 3 \times 10^{15}}{6.4 \times 6.4 \times 10^{12}} \text{ N}$$

$$= 0.4885 \times 10^3 \text{ N}$$

or Force of gravity,

$$F = 488.5 \text{ N}$$

By direct calculations,

$$F = mg = 50 \times 9.8 \text{ N}$$

$$= 490 \text{ N}$$

$$F = 490 \text{ N}$$

Example 2.18: *The earth's gravitational force causes an acceleration of 5 m s^{-2} in a 1 kg mass somewhere in space. How much will the acceleration of a 3 kg mass be at the same place?*

Solution:

Relation, $g = \dfrac{GM}{r^2}$

in independent of the mass of the body.

Hence, acceleration of 3 kg mass will also be 5 ms^{-2}.

Example 2.19: *A space ship is at a distance equal to twice the radius of earth from the centre of the earth, find the gravitational acceleration.*

Solution:

We know that, $g = \dfrac{\text{GM}}{r^2}$

Here, $r = R + R = 2R$

Hence, $g = \dfrac{GM}{(2R)^2} = \dfrac{GM}{4R^2}$

$$= \frac{1}{4}\left(\frac{GM}{R^2}\right) = \frac{9.8}{4}\,\text{ms}^{-2}$$

$$= 2.45 \text{ m s}^{-2}$$

$\therefore \quad g = 2.45 \text{ m s}^{-2}$

2.10.3. Mass and Weight

Mass

Quantity of matter possessed by a body is called the ***mass*** *of the body.* It is represented by the symbol *m*. Mass of a body is constant and does not change from place to place. It is a scalar quantity.

SI unit of mass is kilogram and is written in short from as *kg*.

Mass of a body can never be zero.

Weight

The force with which a body is attracted towards the centre of the earth, is called the ***weight*** *of the body*. In other words we can say that *force of earth's gravity acting on a body is called its weight*. It is represented by the symbol *W*.

It is a **vector quantity** having direction towards the centre of the earth.

Downward force acting on a body of mass *m* is given by,

$$\text{Force} = \text{mass} \times \text{acceleration due to gravity}$$
$$= m \times g$$

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But from the definition of weight we know that force acting on a body due to the attraction of the earth is called its weight.

Hence, $W = m \times g$

where g is acceleration due to gravity.

SI unit of weight is same as that of force *i.e.*, Newton and is denoted by N.

From relation, $W = mg$

If m = 1 kg, then W = 9.8 N

Hence a 1 kg body has a weight of 9.8 N

Example 2.20: *Mass of an object is 10 kg. What is its weight on the earth?*

Solution: Here,

Mass of the object,

$$m = 10 \text{ kg}$$

Acceleration due to gravity,

$$g = 9.8 \text{ m s}^{-2}$$

Weight of the object,

$$W = ? \quad \text{(to be calculated)}$$

From relation,

$$W = mg$$

we get, $W = 10 \text{ kg} \times (-9.8) \text{ m s}^{-2}$

$$= -98 \text{ kg m s}^{-2}$$

orWeight, $W = 98$ N

(It acts downward)

Example 2.21: *What is the mass of an object whose weight is 49 N?*

Solution:

Here, weight W = – 49 N

Acceleration due to gravity,

$$g = -9.8 \text{ m s}^{-2}$$

Mass of the object,

$$m = ? \quad \text{(to be calculated)}$$

From relation,

$$W = mg$$

We have, $m = \dfrac{W}{g}$

Substituting various values, we get,

$$m = \frac{-49}{-9.8} \text{ kg}$$

$$= 5 \text{ kg}$$

i.e., m = 5 kg

Mass of object is 5 kg

2.10.4. Free Fall

When a body is dropped from some height, it falls downward toward the earth due to the gravitational force of the earth. Falling down of a body from some height with no other force acting on the body (except the gravitational force of the earth) is called free fall and the body which is falling down is called freely falling body.

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Acceleration of an object falling freely towards the earth does not depend on the mass. Hence in the absence of any frictional force (in vacuum) a feather or a coin, or a ball or a stone when dropped from same height all fall towards the earth with the same rate. In other words, we can say that *acceleration produced in the freely falling bodies is same for all bodies and is independent of the mass of the falling body.*

2.11. EQUATION OF MOTION UNDER GRAVITY

Corresponding to equations for accelerated motion on horizontal surfaces, we can have equation of motion under gravity.

General equations of motion	Equations of motion under gravity (for a freely falling body)
$v = u + at$	$v = u + gt$
$S = ut + \frac{1}{2} at^2$	$h = ut + \frac{1}{2} gt^2$
$v^2 = u^2 + 2aS$	$v^2 = u^2 + 2gh$

Some important useful points for solving numerical problems are :

(i) For a dropped body, $u = 0$
(ii) For a body thrown up, $v = 0$
(iii) For a body going downward, $a = g = +9.8\ m/s^{-2}$
(iv) For a body going upward, $a = g = -9.8\ m/s^{-2}$
(v) Time for upward journey = Time for downward journey
(vi) Velocity of return = Velocity of throw

[Through the value of g is 9.8 m/s^2, sometimes it is taken as 10 m/s^2 to make calculations simple.]

Example 2.22: *A stone is dropped from a cliff. Calculate its speed after it has fallen 100 m.*

Solution: Here,

$$u = 0,\ g = 9.8\ m/s^2,$$
$$h = 100$$
$$v = \text{? (to be calculated)}$$

From equation of motion,

$$v^2 = u^2 + 2gh$$

Putting values, we get,

$$v^2 = 0 + 2 \times 9.8 \times 100$$
$$= 1960$$

or $$v = 44.2\ m/s$$

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Example 2.23: *A stone dropped from the roof of a building takes 4 s to reach the ground. Find height of the building.*

Solution: Here,

$$u = 0,\ g = 9.8 \text{ m/s}^2,$$
$$t = 4 \text{ s}$$
$$h = ? \text{ (to be calculated)}$$

From equation of motion,

$$h = ut + \frac{1}{2} gt^2$$

Putting values, we get,

$$h = 0 \times 4 + \frac{1}{2} \times 9.8 \times (4)^2$$
$$= 4.9 \times 16$$
$$= 78.4 \text{ m}$$

Example 2.24: *A stone is dropped from the edge of the roof. It passes a window 2 metre high in 0.1 second. How far is the roof above the top of the window?*

Solution: Let edge of the roof be h m above the window and t be the time taken by the stone to fall his height.

Here, $u = 0,\ g = 9.8 \text{ m/s}^{-2}$

From equation of motion,

$$h = ut + \frac{1}{2} gt^2 = \frac{1}{2} gt^2 \qquad (\because u = 0)$$

For journey above the window,

$$h = \frac{1}{2} gt^2 \qquad \ldots(1)$$

For journey up to the bottom of the window,

$$(h + 2) = \frac{1}{2} g(t + 0.1)^2 \qquad \ldots(2)$$

Now subtracting equation (1) from equation (2) we have,

$$2 = \frac{1}{2} g\,[(t + 0.1)^2 - t^2]$$
$$= \frac{1}{2} g[t^2 + 0.2t + 0.01 - t^2]$$
$$= \frac{1}{2} \times 9.8\ [0.2t + 0.01]$$
$$= 4.9\ [0.2t + 0.01]$$
$$= 0.98t + 0.049$$

or $0.98t = 2 - 0.049$

$$= 1.951 \text{ or } t = \frac{1.951}{0.98}$$
$$= 1.99$$

Now, $h = \frac{1}{2} \times g \times t^2$

$$= \frac{1}{2} \times 9.8 \times (1.99)^2 \text{m}$$

or $h = 19.4$ m

The roof is 19.4 m above the window.

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GLOSSARY

Acceleration: Change in velocity of an object per unit time or rate of change of velocity of a substance.

Average speed: It is defined as the total distance travelled in the total time.

Displacement: The shortest distance measured from the initial to final position of an object.

Distance: The length of the space between two points.

Friction: It is the force resisting the relative motion of solid surfaces and material elements sliding against each other.

Gravity: The force of gravitation due to the earth is called gravity.

Instantaneous speed: It is the speed of an object at any given instant of time.

Inertia: The natural tendency of objects to resist a change in their state of rest or of uniform, motion is called inertia.

Kinematics: It is the study of the relationship between displacement, velocity, acceleration and time of a given motion without considering the forces that cause the motion.

Linear motion: Motion along a straight line.

Line graph: A graph which shows dependence of our physical quantity, such as distance or velocity, on another quantity such as time.

Mass: It refers to the amount of matter in an object.

Momentum: The momentum of an object is the product of its mass and velocity and has the same direction as that of the velocity Its SI unit is kg m s^{-1}.

Net force: The overall force acting on an object. It is also called resultant force.

Newton's first law of motion: An object continues to be in a state of rest or of uniform motion along a straight line unless acted upon by an unbalanced force.

Newton's second law of motion: The rate of change of momentum of an object is proportional to the applied unbalanced force in the direction of the force.

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Newton's third law of motion: To every action, there is an equal and opposite reaction and they act on two different bodies.

Non-uniform motion: When an object covers unequal distances in equal intervals of time.

Non-uniform speed: A body is said to be moving with non-uniform speed if it covers unequal distances in equal intervals of time.

Rest: When a body does not change its position with respect to time, then it is said to be at rest.

Speed: Distance travelled per unit time. Its SI unit is m/s.

Uniform motion: When an object covers equal distances in equal intervals of time.

Uniform Speed: A body is said to be moving with uniform speed if it covers equal distances in equal interval of time.

Universal law of gravitation: The law of gravitation states that the force of attraction between any two objects is proportional to the product of their neasses and inversely proportional to the square of the distance between them. The law applies to objects anywhere in the universe. Such a law is said to be universal.

Velocity: Displacement of an object per unit time. Its SI unit is m/s.

Weight: The weight of a body is the force with which the earth attracts it.

$$W = m.g \ (m = \text{mass}, \ g = \text{gravity})$$

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REVIEW EXERCISES

Do the review exercises in your notebook.

A. Choose the correct option.

1. When a body remains in one position for a long time, the body is said to be at ________.

(a) motion (b) rest

(c) stationary (d) none of the above

2. The change in position of a body with respect to time is said to be ________.

(a) rest (b) stationary
(c) motion (d) none of the above

3. Which of the following is a type of motion?
(a) Circular (b) Rectilinear
(c) Periodic (d) All of these

4. Motion in a straight line is known as ________.
(a) Rectilinear motion (b) Periodic motion
(c) Circular motion (d) None of the above

5. What is known as the change in position of an object?
(a) displacement (b) speed
(c) velocity (d) none of the above

6. Rate of change of displacement with respect to time is known as _____.
(a) speed (b) acceleration
(c) velocity (d) none of the above

7. The velocity of a body at a given instant is called
(a) instantaneous velocity (b) uniform velocity
(c) non-uniform velocity (d) none of the above

8. For uniform speed, a graph of distance travelled against time is a ________.
(a) straight line (b) curved line
(c) both (a) and (b) (d) none of these

9. Which of the following relations is correct?
(a) Speed = Distance × Time (b) Speed = $\frac{\text{Distance}}{\text{Time}}$
(c) Speed = $\frac{\text{Time}}{\text{Distance}}$ (d) Speed = $\frac{1}{\text{Distance} \times \text{Time}}$

10. The basic unit of speed is:
(a) km/min (b) m/min
(c) km/h (d) m/s

11. Inertia is ________.
(a) a property of matter (b) a type of force
(c) the speed of an object (d) none of these

12. A and B are two objects with masses 100 kg and 75 kg respectively, then ________.
(a) both will have the same inertia (b) B will have more inertia
(c) A will have more inertia (d) both will have less inertia

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13. The resultant of balanced forces is ________.
(a) non zero
(b) equal to zero
(c) not equal to zero
(d) equal to the acceleration produced in the body

14. The physical quantity, which is the measure of inertia, is ________.
(a) density
(b) weight
(c) force
(d) mass

15. Name the property of matter due to which a body continues in its state of rest or uniform motion unless an external force acts on it.
(a) Inertia
(b) Elasticity
(c) Viscosity
(d) Density

16. When a force of 1 N acts on a mass of 1 kg that is free to move, the object moves with
(a) a speed of 1 m/s
(b) a speed of 1 km/s
(c) an acceleration 10 m/s^2
(d) an acceleration of 1 m/s^2

17. The acceleration in a body is due to
(a) balanced force
(b) unbalanced force
(c) mass
(d) electrostatic force

18. When an object undergoes acceleration
(a) its speed always increases
(b) its velocity always increases
(c) it always falls towards the Earth
(d) a force always acts on it

19. A force of 10 N is acting on an object of mass 10 kg. What is the acceleration produced in it?
(a) 1 m/s^2
(b) 1 m/s
(c) 100 m/s^2
(d) 100 m/s

20. The physical quantity, which is equal to change in momentum, is
(a) force
(b) impulse
(c) acceleration
(d) velocity

21. What is the momentum of a man of mass 100 kg when he walks with a uniform velocity of 2 m/s?
(a) 200 kg m/s
(b) 200 N
(c) 200 kg m/s^2
(d) 50 kg m/s

22. The two factors on which the momentum of a body depends are ______ and _________.
(a) velocity, time
(b) mass, weight
(c) mass, distance
(d) mass , velocity

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B. Fill in the blanks.

1. A car moving at constant speed is an example of ________ motion.
2. The SI unit of speed is ________.
3. The speed at any given instant of time is known as ________ speed.
4. The SI unit of acceleration is ________.
5. The motion of a freely falling body is an example of ________ motion.
6. For every _______ there is an equal and opposite _______.
7. Newton's first law of motion is also known as Law of _______.
8. The momentum of an object is defined as the product of _______ and _______.
9. Impulse = Force × _______.
10. The force of gravitation due to the earth is _______.
11. The area under velocity-time graph represents _______ covered by the body.
12. In a velocity-time graph, uniform acceleration is represented by a _______ line inclined to x-axis (time axis).
13. Non-uniform acceleration in a velocity-time graph is represented by a _______ .
14. A _______ displacement-time graph represents uniform velocity.
15. A _______ displacement-time graph represents non-uniform velocity.
16. Newton's first law of motion gives the definition of _______ .
17. A heavier body having the same momentum will move with _______ speed compared to the speed of the lighter body.
18. If equal forces act on two bodies one heavier than another, the heavier one will have _______ acceleration than that of the lighter one.
19. The change of momentum of a body is called _______ .
20. The force of friction always _______ the applied force.

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C. State whether the following statements are true or false.

1. The acceleration is taken to be positive if it is in the direction of velocity.
2. In the case of non-uniformly accelerated motion, velocity-time graphs can have any shape.
3. A horizontal line on a speed-time graph represents a variable speed.
4. Deceleration is a type of acceleration where the speed of an object is decreasing with time.
5. A sloping line on a speed-time graph represents distance travelled.
6. An unbalanced force acting on an object brings it in motion.

7. An object maintains its motion under the continuous application of an unbalanced force.
8. Heavier objects offer larger inertia.
9. Momentum has both direction and magnitude.
10. All objects fall from a height at different rate.

D. Answer the following questions.

1. Define motion and list types of motion.
2. Distinguish between instantaneous speed and average speed.
3. Distinguish between velocity and acceleration.
4. Define:
   (a) Speed (b) Velocity
   (c) Acceleration (d) Distance
   (e) Displacement
5. When will you say a body is in:
   (a) uniform acceleration (b) non-uniform acceleration
6. Explain the following giving suitable reasons.
   (a) A passenger in a bus tends to fall backwards when bus starts suddenly.
   (b) A passenger in a bus tends to fall forward when it stops suddenly.
7. Explain the relationship between mass and inertia.
8. State Newton's first law of motion.
9. State Newton's second law of motion.
10. State Newton's third law of motion.
11. Explain the effect of force on the direction and state of the body.
12. Describe Newton's law of universal gravitation.
13. Define
   (a) Action and reaction (b) Inertia
   (c) Free Body Diagram.

E. Numericals.

1. What force would be needed to produce an acceleration of 4 m/s^2 on a ball of mass 6 kg?
2. What is the acceleration produced by a force of 12 N exerted on an object of mass 3 kg?
3. If an unbalanced force of 600 newtons acts on a body to accelerate it at +15 m/s^2, what is the mass of the body?

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4. If a car is traveling at 50 km/h along a straight line, how many meters does it travel in 10 seconds?

5. A force of 5000 newtons is applied to a 1200 kg car at rest. What is its acceleration?

6. A 10 kg body has an acceleration of 2 m/s^2. Find the net force acting on the body.

7. An empty truck with a mass of 2500 kg has an engine that will accelerate at a rate of 1.5 m/s^2. What will be the acceleration when the truck has an additional load of 1500 kg?

8. A box resting on a table has a mass of 5.0 kg.

(a) What is its weight?

(b) What will be its acceleration when an unbalanced horizontal force of 40 newtons acts on it?

9. A train starting from a railway station and moving with uniform acceleration attains a speed of 40 km/h in 10 minutes. Find its acceleration.

10. Akeelah takes 15 minutes from her house to reach her school on a bicycle. If the bicycle has a speed of 2 m/s, calculate the distance between her house and the school.

11. Show the shape of the distance-time graph for the motion in the following cases:

(a) A car moving with a constant speed.

(b) A car parked on a side road.

12. A car moves with a speed of 40 km/h for 15 minutes and then with a speed of 60 km/h for the next 15 minutes. Find the total distance covered by the car.

13. The graph (Fig. 2.23) shows the position of a body at different times. Calculate the speed of the body as it moves from:

(i) A to B

(ii) B to C, and

(iii) C to D.

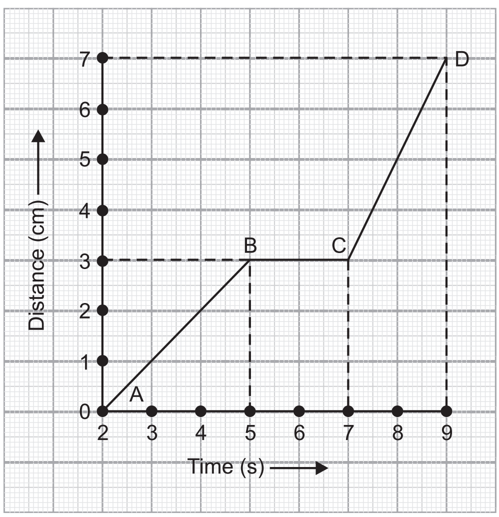

Fig. 2.23.

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14. A car travelling at 20 km h^{-1} speeds up to 60 km h^{-1} in 6 seconds. What is its acceleration?

15. A body starts to slide over a horizontal surface with an initial velocity of 0.5 m s^{-1}. Due to friction, its velocity decreases at the rate of 0.05 m s^{-2} (acceleration = – 0.05 m s^{-2}). How much time will it take for the body to stop?

16. Starting from a stationary position, Eric paddles his bicycle to attain a velocity of 6 m s^{-1} in 30 seconds. Then he applies brakes such that the velocity of the bicycle comes down to 4 m s^{-1} in the next 5 seconds. Calculate the acceleration of the bicycle in both the cases.

17. A train starting from rest, attains velocity of 72 km h^{-1} in 5 minutes. Assuming that the acceleration is uniform, find (i) the acceleration and (ii) the distance travelled by the train for attaining this velocity.

18. A train is travelling at a speed of 90 km per hour. Brakes are applied so as to produce a uniform acceleration of – 0.5 m s^{-2}. Find how far the train will go before it is brought to rest.

19. A trolley while going down an inclined plane has an acceleration of 2 cm s^{-2}. What will be its velocity 3 seconds after the start?

20. A stone is thrown in a vertically upward direction with a velocity of 5 m s^{-1}. If the acceleration of the stone during its motion is 10 m s^{-2} in the downward direction, what will be the height attained by the stone and how much time will it take to reach there?

21. Figure 2.24 shows the distance-time graph for the motion of two vehicles A and B. Which one of them is moving faster?

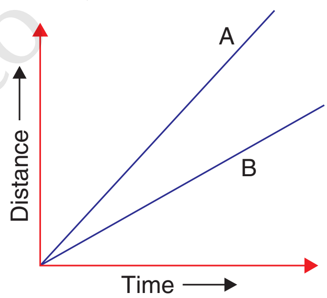

Fig. 2.24. Distance-time graph for the motion of two cars

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22. Which of the following distance-time graphs shows a truck moving with constant speed?

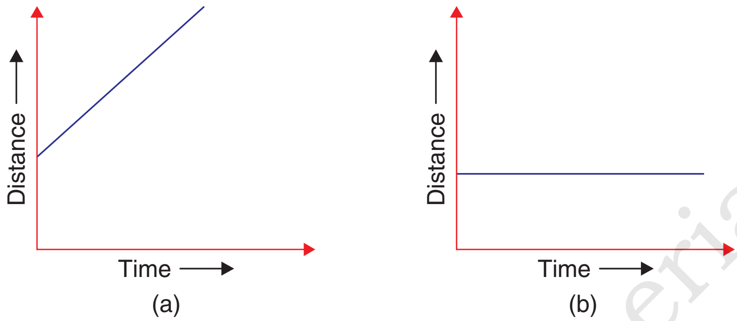

Fig. 2.25.

23. What type of motion is represented by each of the following speed-time graph:

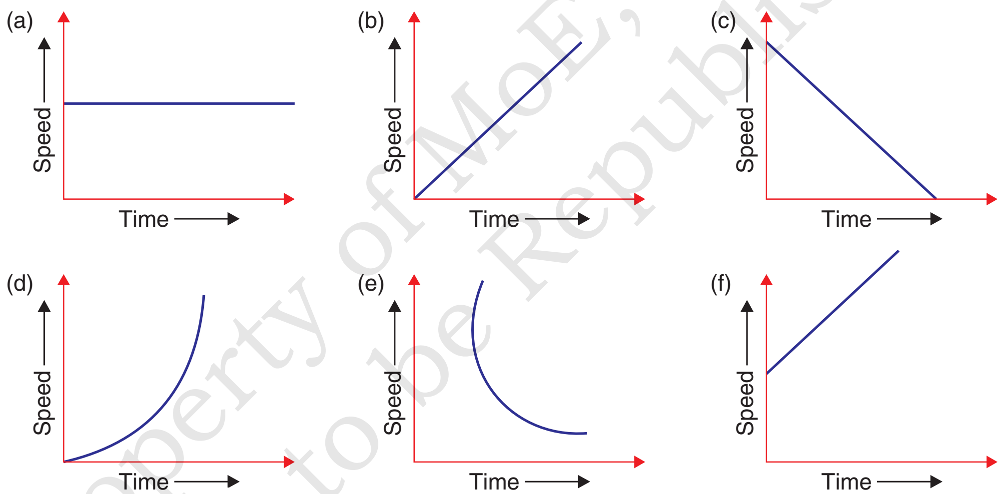

Fig. 2.26.

24. Which of the following graphs show a non-uniform motion?

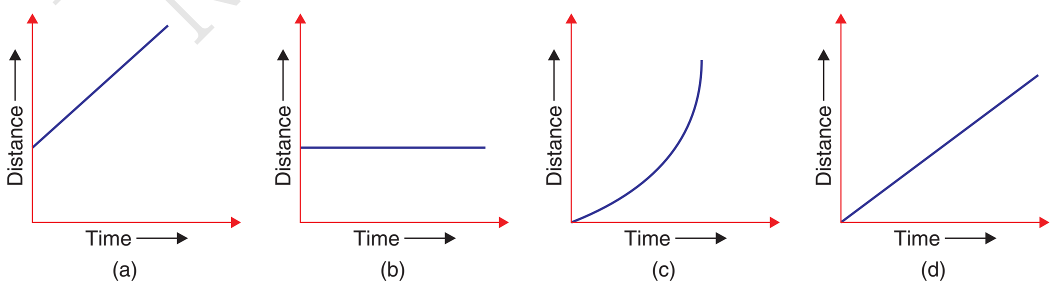

Fig. 2.27.

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25. Figure 2.28 shows the velocity time graph of the motion of an object.

State the type of motion in each of the following cases:

(i) OA

(ii) AB

(iii) CD

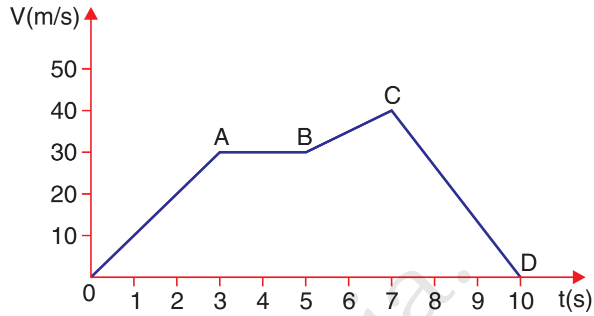

Fig. 2.28.

26. Plot and interpret the distance-time graph for the following data.

Time in s	0	1	2	3	4	5
Distance in m	25	25	25	25	25	25

27. Plot and interpret speed-time graph for the following data.

Time in s	0	1	2	3	4	5
Speed in m s^{-1}	0	4	8	12	16	20

28. Plot and interpret speed-time graph for the following data.

Time in s	0	1	2	3	4	5
Speed in m s^{-1}	0	2	5	9	14	20

29. The velocity-time graph represents the motion of an object for 350 s.

(a) Calculate the acceleration for the time interval 100 s < t < 200 s

(b) Calculate the displacement of the object in 0 to 350 s.

(c) Which type of motion is represented by BM in the velocity-time graph?

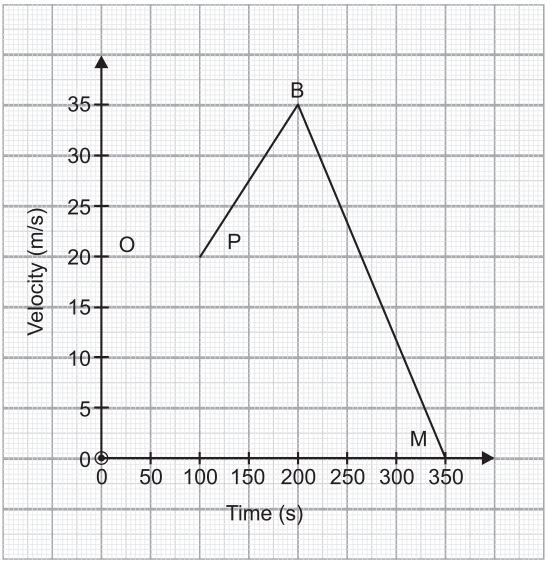

Fig. 2.29.

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30. The speed-time graphs of two cars are represented by P and Q as shown below:

(a) Find the difference in the distance travelled by the two cars (in m) after 4 s.

(b) Do they ever move with the same speed? If so, when?

(c) What type of motion car P and car Q are undergoing?

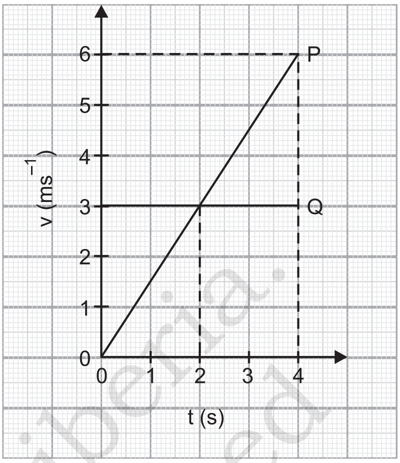

Fig. 2.30.

31. Calculate the force of gravitation between two objects of masses 25 kg and 40 kg respectively kept at a distance of 10 m from each other. (G = 6.67×10^{-11} Nm^2 kg^{-2}).

32. If the distance between two masses is increased 4 times, how many times, the mass of one of the body be changed to maintain the same gravitational force?

33. What is the force of gravity on a body of mass 300 kg lying on the surface of the earth? (Mass of earth = 6×10^{24} kg, radius of earth = 6.4×10^6 m. G = 6.7×10^{-11} N m^2 kg^{-2})

34. The earth's gravitational force causes an acceleration of 5 m/s^2 in a 1 kg mass somewhere in space. How much will the acceleration of a 3 kg mass be at the same place?

35. If a planet existed, whose mass and radius both are half those of the earth, find the acceleration due to gravity on its surface.

36. A stone is dropped from the edge of a roof

(a) how long does it take to fall 4.9 m?

(b) how fast does it move at the end of that fall?

(c) how fast does it move at the end of 7.9 metres?

(d) what is its acceleration after 1 s and after 2 s?

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