8 MOTION

INTRODUCTION

- In physics, change with time of the position or orientation of a body. Motion along a line or a curve is called translation. Motion that changes the orientation of a body is called rotation. In both cases all points in the body have the same velocity (directed speed) and the same acceleration (time rate of change of velocity). The most general kind of motion combines both translation and rotation.
- All motions are relative to some frame of reference. Saying that a body is at rest, which means that it is not in motion, merely means that it is being described with respect to a frame of reference that is moving together with the body.
- For example, a body on the surface of the Earth may appear to be at rest, but that is only because the observer is also on the surface of the Earth. The Earth itself, together with both the body and the observer, is moving in its orbit around the Sun and rotating on its own axis at all times.
- As a rule, the motions of bodies obey Newton's laws of motion. In this chapter we will study translation and rotational motion of the body around us.

1 MOTION AROUND US

We observe many types of motion around us in everyday life like:

(1) Vehicles moving on a road
(2) Birds flying in the sky
(3) Movement of the needles of a watch
(4) Circulation of blood through veins and arteries
(5) The movement of the planets around the Sun

A body is said to be in motion if its position changes with time and its surroundings. Motion and rest are always relative but never absolute.

2 SCALAR AND VECTOR QUANTITIES

2.1. Scalar Quantities

A physical quantity which is defined only by magnitude is known as a scalar quantity.

Examples: Temperature, mass, distance.

2.2. Vector Quantities

A physical quantity which is defined by magnitude as well as direction is known as a vector quantity.

Examples: Force, weight, displacement.

3 VARIOUS TERMS RELATED TO MOTION

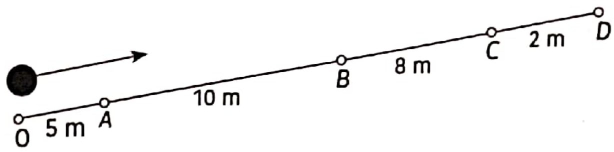
3.1. Position

The position is defined as the location of an object with respect to a particular point. The particular point about which the position of an object is measured is known as the reference point or the origin.

3.2. Distance

The distance covered by an object is the total length of the path covered by the object. It is a scalar quantity and its SI unit is meter.

Example: Consider the motion of an object moving along a straight path as shown below.

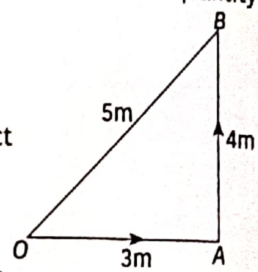


Let the object start its motion from point O and move through point A, B, C and reach up to point D. Then the total distance covered by the object will be:

Distance = $OA + AB + BC + CD$ = 5m + 10m + 8m + 2m = 25m

3.3. Displacement

The displacement of an object is the shortest distance between the initial and final point of the object's path. It is a vector quantity and its SI unit is meter.



Example: Suppose an object starts moving from point O and reaches to point B, passing through A.

O is the initial position of the object and B is the final position of the object. The displacement of the object will be the distance OB.

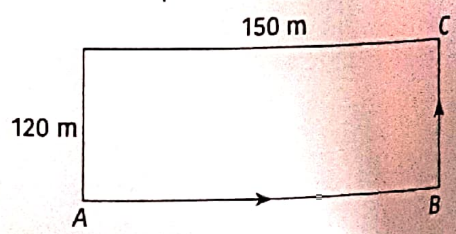
$$OB = \sqrt{OA^2 + AB^2} = \sqrt{3^2 + 4^2} = \sqrt{25} = 5\text{m}$$

Since, it is a vector quantity, the displacement of the object is said to be 5 m from point O towards point B.

3.4. Difference between Distance and Displacement

S. No.	Distance	Displacement
(1)	It is the length of the actual path covered by an object, irrespective of its direction of motion.	Displacement is the shortest distance between the initial and final positions of an object in a given direction.
(2)	Distance is a scalar quantity.	Displacement is a vector quantity.
(3)	Distance covered can never be negative. It is always positive or zero.	Displacement may be positive, negative or zero.
(4)	Distance between two given points may be same or different for different path chosen.	Displacement between two given points is always the same.

Example 1: A jogger jogs along one length and breath of a rectangular park. If the dimensions of the park are 150m × 120m, then find the distance travelled and the displacement of the jogger.



Solution: According to the question,

Length of the rectangular park, l = 150 m

Breadth of the rectangular park, b = 120 m

Let us assume that the jogger starts at point A and jogs to point C via point B.

The distance (s) covered by the jogger is:

$$s = AB + BC = 150\text{m} + 120\text{m} = 270\text{m}$$

The displacement of the jogger will be the shortest distance between A and C which is the distance AC.

$$AC = \sqrt{AB^2 + BC^2} = \sqrt{150^2 + 120^2} = 30\sqrt{41}\text{m}$$

Thus the distance covered by the jogger is 270 m and his displacement is $30\sqrt{41}$ m from A towards C.

4 UNIFORM AND NON-UNIFORM MOTION

Motion of any body can be divided into two categories based on the distance covered in time intervals. These are discussed and compared below.

Uniform Motion	Non-Uniform Motion
A body is said to be in uniform motion if the body covers equal distances in equal intervals of time.	A body is said to be in non-uniform motion if the body covers unequal distances in equal intervals of time. The length of the time interval is irrelevant.
The distance covered during uniform motion linearly increases.	The distance covered during non-uniform motion does not linearly increase.
Example: If a car is moving along a straight line path, it is covering equal distances in equal intervals of time.	Example: If a car is moving through traffic, it is covering unequal distances in equal intervals of time.

5 RATE OF MOTION

The ratio of distance travelled by an object to the time taken is called rate of motion. The various terms required to measure the rate of motion are discussed below.

5.1. Speed

Speed of an object is defined as the distance travelled by the body per unit time.

$$\text{Speed}(v) = \frac{\text{Distance}(s)}{\text{Time}(t)}$$

5.2. Properties of Speed

(1) Speed is a scalar quantity.

(2) The SI unit of speed is metre per second (m/s).

(3) The distance travelled by an object is either positive or zero, so the speed may be positive or zero but never negative.

5.3. Types of Speed

The classification for speed is given below:

(1) **Uniform Speed:** If a moving body covers equal distances in equal intervals of time, it is said to have uniform speed. It is also known as constant speed.

(2) **Non - Uniform Speed:** If a moving body covers unequal distances in equal intervals of time, it is said to have non-uniform speed. It is also known as variable speed.

(3) **Average Speed:** Average speed is defined as the ratio of the total distance travelled by a body to the total time taken. It is expressed as:

$$\text{Average Speed} = \frac{s_{total}}{t_{total}} = \frac{s_1 + s_2 + s_3 + \dots}{t_1 + t_2 + t_3 + \dots}$$

(4) **Instantaneous Speed:** The speed of an object at any particular instant of time or at a particular point along its path is called the instantaneous speed of the object.

Example 1: The odometer of a bike reads 1600 km at the start of the trip and 2000 km at the end of the trip. If the bike took 16 hrs to complete the trip, calculate the average speed of the bike in km/h and m/s.

Solution: The distance covered by the bike is, s = 2000 – 1600 = 400 km

Time taken to complete the trip, t = 16 hrs

The average speed of the bike is: $\text{Average Speed} = \frac{s}{t} = \frac{400}{16} = 25\text{km/hr}$

The average speed can now be converted to m/s:

$$\text{Average Speed} = 25\text{ km/hr} = 25 \times \frac{5}{18} = 6.9\text{ m/s}$$

Example 2: An object travels 14 m in 4 s and then another 16 m in 2 s. What is the average speed of the object?

Solution: According to the question, First distance covered, $s_1 = 14$ m, Time taken to cover s_1, $t_1 = 4$ s

Second distance covered, $s_2 = 16$ m, Time taken to cover s_2, $t_2 = 2$ s

The average speed of this object can be found as: $\text{Average Speed} = \frac{\text{Total Distance}}{\text{Total Time}} = \frac{s_1 + s_2}{t_1 + t_2} = \frac{14+16}{4+2} = 5\ \text{m/s}$

- **A speedometer is a device used to measure the instantaneous speed of an object.**

5.4. Velocity

Velocity of an object is defined as the displacement of the body per unit time. Velocity is the speed of an object moving in a definite direction. It is expressed as:

$$\text{Velocity}(v) = \frac{\text{Displacement}(d)}{\text{Time}(t)}$$

5.5. Properties of Velocity

(1) Velocity is a vector quantity.

(2) The SI unit of velocity is meter per second (m/s).

(3) The velocity of an object can be changed by changing the object's speed, direction of motion or both.

5.6. Types of Velocity

The classification for velocity is given below:

(1) **Uniform Velocity:** If an object covers equal displacements in equal intervals of time, without changing direction, then its velocity is known as uniform velocity or constant velocity.

(2) **Non - Uniform Velocity:** If an object covers unequal displacements in equal intervals of time, then its velocity is known as non-uniform velocity or variable velocity.

(3) **Average Velocity:** Average velocity is defined as the ratio of total displacement of the object to the total time taken. It is expressed as:

$$_{avg} \quad \frac{\text{Total Displacement}}{\text{Total time}}$$

If the velocity of an object changes at a uniform rate, then the average velocity can be found as:

$$V_{avg} = \frac{\text{Initial Velocity(u)+Final Velocity }(v)}{2}$$

(4) **Instantaneous Velocity:** The velocity of an object at a particular instant of time or at a particular point of its path is called its instantaneous velocity.

- If a body is moving in a straight line then the magnitude of its speed and velocity will be equal.
- Average speed of a moving object can never be zero but the average velocity of a moving object can be zero.

Example 3: Rajeev went from Delhi to Chandigarh and returned to Delhi on his motorbike. The odometer on the bike had a reading of 4200 km at the start of the trip and 4460 km at the end of his trip. If Rajeev took 4 h 20 min to complete his trip, find the average speed and average velocity in km/h as well as in m/s.

Solution: The total distance covered by Rajeev will be, s = final odometer reading – initial odometer reading = 4460 – 4200 = 260 km.

Total time taken to complete the trip, t = 4 hrs 20 min = 4.33hrs

The average speed can now be found as:

$$\text{Average Speed} = \frac{s}{t} = \frac{260}{4.33} = 60\ \text{km/hr} = 60 \times \frac{5}{18} = 16.67\ \text{m/s}$$

The displacement for this trip is 0 m since he started in Delhi and finished in Delhi.

Therefore, the average velocity is:

$$v_{avg} = \frac{s}{t} = \frac{0}{4.33} = 0\text{km/hr}.$$

5.7. Difference between Speed and Velocity

S. No.	Speed	Velocity
(1)	Speed is described as the distance traveled by an object per unit time.	Velocity is described as the distance traveled by an object per unit time in a particular direction.
(2)	Direction of the motion of the object is not specified.	Direction of the motion of the object is specified.
(3)	Speed is a scalar quantity as a result it only has magnitude.	Velocity is a vector quantity as result it has both magnitude and direction.

5.8. Acceleration

It is defined as the rate of change of velocity with respect to time. It is expressed as:

$$a = \frac{\text{Chane in velocity } (\Delta v)}{\text{Change in Time} (\Delta t)}$$

If in a given time interval (t), the velocity of a body changes from u to v then the acceleration (a) is expressed as:

$$a = \frac{\text{Final velocity } (v) - \text{Initial velocity } (u)}{\text{Time interval } (t)}$$

$$a = \frac{v-u}{t}$$

5.9. Properties of Acceleration

This kind of motion is known as accelerated motion.

(1) The SI unit of acceleration is m/s^2.

(2) It is a vector quantity.

(3) The acceleration is taken to be positive if it is in the direction of velocity, negative if it is opposite to the direction of velocity and zero when the object is moving with a constant velocity.

- If the velocity of an object decreases with time, then it is said to have negative acceleration. Negative acceleration is also called **deceleration or retardation.**

5.10. Types of Acceleration

The classification for acceleration is given below:

(1) **Uniform Acceleration:** If an object travels in a straight line and its velocity increases or decreases by equal amounts in equal intervals of time, then it is known as uniform acceleration.

Examples: Motion of a freely falling body, Motion of a ball rolling down an inclined plane

(2) **Non-uniform acceleration:** If the velocity of an object increases or decreases by unequal amounts in equal intervals of time, then it is known as non-uniform acceleration.

Examples: Motion of a car in traffic, Motion of a train entering or leaving a platform

Example 4: Starting from rest, a car attains a velocity of 5 m/s in 20 s. Then, the driver of the car applies a brake such that the velocity of the car comes down to 3 m/s in the next 6 s. Calculate the acceleration of the car in both the case

Solution: Case 1:

Initial velocity of the car, $u = 0$ m/s, Final velocity of the car, $v = 5$ m/s,

Time interval, $t = 20$ s

The acceleration in this case is: $a = \frac{v-u}{t} = \frac{5-0}{20} = 0.25 m/s^2$

Case 2:

Initial velocity of the car, $u = 5$ m/s, Final velocity of the car, $v = 3$ m/s

Time interval, $t = 6$ s

The acceleration in this case is: $a = \frac{v-u}{t} = \frac{3-5}{6} = -0.33 m/s^2$. The negative sign shows that the particle is decelerating.

8 UNIFORM CIRCULAR MOTION

If an object moves in a circular path with uniform speed, then its motion is called uniform circular motion. Here are some of its properties:

(1) When an object moves along a circular path, its direction of motion keeps changing continuously. The velocity changes due to continuous change in direction and thus, motion along a circular path is said to be accelerated.

(2) When a body takes one round of a circular path, then it travels a distance equal to its circumference which is 2pr, where r is the radius of the circular path.

8.1 Angular Displacement (θ)

The angle turned by a body moving on a circle from some reference line is called angular displacement.

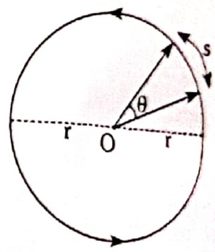
$$\text{Angular Displacement} = \frac{\text{Arc}(s)}{\text{Radius}(r)}$$

8.2 Angular velocity (ω)

Angular velocity is a vector quantity and is described as the rate of change of angular displacement which specifies the angular speed or rotational speed of an object and the axis about which the object is rotating.

$$\omega = \frac{\text{Total Angular displacement}}{\text{Total time taken}}, \omega = \frac{2\pi}{T} = 2\pi n.$$

Where, T = Time, n = Frequency,



Important Figure

8.3 Relation between angular velocity and linear velocity $v = r\omega$

Where, r = radius, v = velocity.

Some examples of uniform circular motion are given here:

(1) A piece of stone tied to a thread and rotated in a circle with a uniform speed.

(2) The motion of blades of an electric fan around the axle.

(3) The motion of the moon and the earth.

(4) A satellite in a circular orbit around the earth.

(5) A car moving on a circular path with constant speed. Some other examples are as follows;

Example 1: The minute hand of a wall clock is 10 cm long. Find its displacement and the distance covered from 10:00 am to 10:30 am.

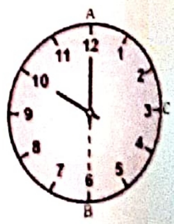
Solution: Length of the minute hand, l = 10 cm = r

The displacement of the minute hand from 10:00 to 10:30 is the diameter AB.

Therefore, Displacement $= 2r = 2 \times 10 = 20$ cm

The total distance covered by the minute hand is the circumference of the semicircle.

Therefore, Displacement $= \pi r = 3.14 \times 10 = 31.4$ cm



Example 2: A body moves in a circular path of radius 20 cm, if it completes two and half revolutions along the circular path, then find distance and the displacement of the body.

Solution: According to the question, the body moves in a circular path of radius 20 cm. So, during one complete revolution the distance (s) covered by the body is equal to the circumference of the circular path, i.e., $2\pi r$. For two and a half revolutions, the distance covered will be $s = 2 \times 2\pi r + \pi r = 5\pi r = 5 \times 3.14 \times 20 = 314$cm

We know that the displacement is the minimum distance between the initial and final positions of the body. After two and a half revolutions the final position of the body will be 180° opposite to its initial position. The shortest distance between two opposite points on a circle is the diameter. i.e., $2 \times r = 2 \times 20 = 40$ cm.

This displacement is directed from the initial position towards the final position.

Chapter at Glance

(1) An object is said to be in **motion** if its position changes with time.

(2) The **distance** travelled by a body is the actual length of the path covered by it, irrespective of the direction in which the body travels. It is a scalar quantity. Its SI unit is metre.

(3) The shortest distance between the initial and final position of the moving object is called the **displacement** of the object. It is a vector quantity. Its SI unit is meter.

(4) The ratio of distance travelled by an object to the time taken is called **rate of motion.**

(5) **Speed** of an object is defined as the distance travelled by it in unit time.

$$\text{Speed}(v) = \frac{\text{Distance}(s)}{\text{Time}(t)}$$

It is a scalar quantity. Its SI unit is metre per second (m/s).

(6) Velocity of an object is defined as the displacement of the body per unit time.

$$\text{Velocity}(v) = \frac{\text{Displacement}(d)}{\text{Time}(t)}$$

It is a vector quantity. Its SI unit is metre per second (m/s).

(7) **Acceleration** is defined as the rate of change of velocity with respect to time.

$$a = \frac{\text{Change in velocity}(\Delta v)}{\text{Change in Time}(\Delta t)}$$

It is a vector quantity. Its SI unit is metre per second square (m/s^2).

(8) If the velocity of an object changes by an equal amount in equal intervals of time, then the acceleration of the object is known as **uniform acceleration.**

(9) If the velocity of an object changes by an unequal amount in equal intervals of time then the acceleration of the object is known as **non-uniform acceleration.**

(10) There are three **equations of motion** relating distance (s), initial velocity (u), final velocity (v), acceleration (a) and time (t). These are given below:

- $v = u + at$
- $s = ut + \frac{1}{2}at^2$
- $v^2 - u^2 = 2as$

(11) When an object moves in a circular path with uniform speed, its motion is called uniform circular motion.