## KINEMATICS

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**Classical Mechanics** - Classical mechanics is the branch of Physics which deals with the study of state of rest as well as motion of material objects.

**Kinematics** - Kinematics is the branch of Classical Mechanics which deals with the study of motion of point objects, bodies and system of bodies without taking into account the mass of each or the cause of motion.

**Rest and Motion are Relative Terms**

A person sitting in a moving train is at rest with respect to fellow passengers but is in motion with respect to objects outside the train. So, rest and motion are relative terms.

An object is said to be **at rest** if it does not change its position with respect to an observer, and is said to be **in motion** if it changes its position with respect to an observer.

**Note:**
- Observer does not necessarily mean a human. An observer can be the surroundings or any inanimate object.
- In rectilinear motion, there is no movement of an object in lateral direction.

**Motion in One, Two or Three Dimensions**

The position of an object in space is expressed in terms of three rectangular coordinates $x$, $y$ and $z$. When these coordinates change with time, then the object is said to be **in motion**. However, it is not necessary that all the three coordinates change with time. Even if one or two coordinates change with time, the object is said to be **in motion**.

(a) **Motion in One Dimension**:

When an object moves along a straight line, its motion is said to be **one dimensional motion**. It is also called **rectilinear motion or linear motion**.
For example:
- a car moving along a straight road
- a train moving on a straight track
- a ball thrown vertically up or dropped from a certain height
- a mass oscillating from a vertical spring i.e. oscillatory motion

In this type of motion, only one of the three rectangular coordinates \((x, y, z)\) change with time. Consider one-dimensional motion along x-axis. When the particle moves from A to B, the x-coordinate changes from \(x_1\) to \(x_2\).

(b) **Motion in Two Dimensions:**
An object moving along a curved path in a plane has two-dimensional motion. In this type of motion, two of the three rectangular coordinates change with time. Thus, two rectangular coordinate axes are required for the description of two-dimensional motion.

When the particle moves from A to B the coordinates change from \((x_1, y_1)\) to \((x_2, y_2)\).
(c) Motion in Three Dimensions:

An object moving in space has **three-dimensional motion**. In this type of motion, all the three rectangular coordinates change with time. In order to describe three-dimensional motion, we require all the three rectangular coordinates. When the particle moves from A to B, the rectangular coordinates change from \((x_1, y_1, z_1)\) to \((x_2, y_2, z_2)\).

**Distance**

Distance is defined as the length of path traversed by an object. It is a scalar quantity. It is to be noted that the path may not be straight.

**Unit**: The SI unit of distance is metre (m).

**Displacement**

Displacement is the shortest straight line distance between the initial and the final position of an object. Displacement is a vector quantity. Thus, the numerical value is its **magnitude**. It is directed from the initial position to the final position. It is represented by the symbol \(\vec{s}\).

**Unit**: The SI unit of displacement is metre (m) which is the same as distance.
**Representation of a Vector**

A vector is represented by a directed line segment (a line segment of fixed length with an arrow). The length of the segment gives the magnitude of the vector on a suitable scale. The arrow-head gives the direction of the vector.

**Displacement Representation**

The displacement, being a vector, is represented in the above manner.

**Example** : The vector \( \overrightarrow{AB} \) represents 50 m displacement in easterly direction. The scale taken is 1 cm = 10 m (displacement). ‘A’ is the initial position also known as the origin and ‘B’ is the final position of the object.

\[
\begin{align*}
\text{A} & \quad \text{B} \\
1 & \quad 2 \quad 3 \quad 4 \quad 5 \\
\text{(in cm)} &
\end{align*}
\]

**Characteristics of Displacement**

(i) Displacement in any interval of time may be zero, positive or negative. **The displacement can be zero even if the distance is not zero.** If an object, after travelling, comes back to its starting point, the displacement is zero but the distance travelled is not zero.

(ii) **The magnitude of displacement is either equal to or less than the distance.** If motion is along a fixed direction, the magnitude of displacement is equal to that of distance, but if motion is along a curve or if the direction of motion changes, the magnitude of displacement is less than that of distance. **The magnitude of displacement can never be greater than the distance travelled by the object.**

(iii) The displacement of an object gives no information about the actual path of the object nor does it convey whether the motion is uniform, accelerated or circular.

(iv) The displacement of an object between two points has a unique value.

(v) The magnitude of the displacement of an object between two points is the shortest distance between these points.
**Speed**

The speed is defined as the rate of change of distance with time.

It is a scalar quantity. It tells us how fast the object is moving, i.e. it tells us how much distance is covered by the moving object in each second. But it does not indicate the direction of motion.

\[
\text{speed} = \frac{\text{distance}}{\text{time}}
\]

Speed can be either positive or zero. It can never be negative because it is independent of the direction of motion.

The SI unit of speed is \( \text{m} \text{s}^{-1} \) respectively.

**Uniform speed**: An object is said to move with uniform speed if it covers equal distances in equal intervals of time throughout the motion, however small the time intervals may be.

**Variable speed**: An object is said to move with variable speed if it covers equal distances in unequal intervals of time or unequal distances in equal intervals of time, however small the time intervals may be.

**Average speed**: The average speed of an object is the ratio of the total distance travelled by an object to the total time taken.

OR

It can also be defined as the constant speed with which the object covers the same distance in a given time as it does while moving with variable speed during the same time.

\[
\text{Average speed} = \frac{\text{Total path length traversed}}{\text{Corresponding time interval}}
\]

If \( \Delta x \) is the distance travelled in time \( \Delta t \), then the average speed is given by

\[
v_{av.} \quad \text{or} \quad v = \frac{\Delta x}{\Delta t}
\]

**Instantaneous speed**: When the speed of an object changes continuously, then the speed of the object at a given instant of time is called the instantaneous speed.
Instantaneous speed = \( \frac{\text{Distance travelled in a short time interval}}{\text{Time interval}} \)

It can also be defined as the limit of the average speed as the time interval becomes infinitesimally small.

If \( \Delta x \) is the distance travelled in time interval \( \Delta t \), then

\[
\text{Instantaneous speed, } v = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt}
\]

The speedometer of a vehicle measures the instantaneous speed.

**Note:** In case of an object moving with uniform speed, the instantaneous speed and the average speed are equal (same as the uniform speed)

**Velocity**

Velocity is defined as the rate of change of displacement with respect to time. It can also be defined as the time rate of change of position of an object in a particular direction.

In simple words, speed in a particular direction is called velocity.

It is a vector quantity, i.e., it possesses both magnitude and direction. For velocity, both its magnitude and direction must be known. It is represented by the symbol \( \vec{u} \) or \( \vec{v} \). Velocity can be positive, negative or zero. If an object does not change its direction of motion, then the magnitude of velocity \( \vec{v} \) is known as speed \( v \).

\[ v = |\vec{v}| \]

**Uniform Velocity:** An object is said to be move with uniform velocity if it covers equal displacement in equal intervals of time, however small these time intervals may be.

**OR**

If an object travels equal distances in equal intervals of time along a particular direction, the object is said to be moving with uniform velocity.

If an object moves with a uniform velocity \( \vec{v} \), the displacement \( \vec{s} \) of the object in time interval \( t \) is given as \( \vec{s} = \vec{v} \cdot t \).

**Note:**

- Uniform velocities are always on a straight line path and in the same direction.
- The magnitude of velocity is equal to speed.
- The average velocity is equal to instantaneous velocity.
An object moving with uniform velocity has no acceleration. The acceleration is zero and so the net force on the object is zero.

Two objects are said to be moving with same velocities if both of them move with the same speed in the same direction.

**Note:** A vector quantity (e.g. velocity, acceleration, momentum, force) has both magnitude and direction. If either magnitude or the direction of the physical quantity changes, then the physical quantity is not uniform but variable.

**Non-uniform or Variable Velocity:** If an object moves unequal distances in a particular direction in equal intervals of time or it moves equal distances in equal intervals of time but its direction of motion does not remain the same, however small these time intervals may be, then the velocity of the object is said to be variable (or non-uniform).

Simply said, if these objects move with the same speed but in different directions or with different speeds in the same direction, they are moving with different velocities.

**Example:**
- A freely falling object has variable velocity because although the direction of motion of the object does not change, its speed continuously increases on account of gravity.
- Uniform circular motion is another example of variable velocity because even though the object is moving with uniform speed, its direction of motion continuously changes with time. In fact, it can be said that the velocity changes at a uniform rate. At any instant, the direction of velocity is along the tangent to the circular path at that point.

![Diagram](image)

**Average Velocity:** The average velocity of an object is defined as the ratio of the total displacement of the object to the total time taken.
Multiple Choice Questions

(1) The instantaneous velocity of an object can be measured
   (a) Graphically   (b) Vectorially   (c) By speedometer
   (d) None of these

(2) What is the relation between displacement, time and acceleration for an object having uniform acceleration?
   (a) \( s = ut + \frac{1}{2}at^2 \)  (b) \( s = (u + a)t \)  (c) \( s = v^2 - 2as \)
   (d) \( s = at - v \)

(3) Consider a tennis ball falling to the ground and bouncing back. Directions of which of these (acceleration, velocity and displacement) will change in the process
   (a) Velocity only
   (b) Displacement and velocity
   (c) Acceleration, velocity and displacement
   (d) Displacement and acceleration

(4) The acceleration of a moving object can be found from
   (a) Area under velocity-time graph
   (b) Area under distance-time graph
   (c) Slope of the velocity-time graph
   (d) Slope of distance-time graph

(5) The numerical ratio of displacement to the distance covered is always
   (a) Less than one
   (b) Equal to one
   (c) Equal to or less than one
   (d) Equal to or greater than one

(6) Acceleration of a particle changes when
   (a) Direction of velocity changes  (b) Magnitude of velocity changes
   (c) Both (a) and (b)  (d) Speed changes
(34) The displacement-time graph of moving particle is shown below.

The instantaneous velocity of the particle is negative at the point
(a) D  (b) F  (c) C  (d) E

(35) Two trains 127 m and 173 m in length are running in opposite directions at 40 and 32 km h⁻¹ respectively. They will completely pass each other in
(a) 15 s  (b) 37.5 s  (c) 2.3 s  (d) 23 s

**Theory Questions**

(1) Give one example of each type of following motion:
   (a) uniform velocity
   (b) variable velocity
   (c) variable acceleration
   (d) uniform retardation.

(2) The diagram below shows the pattern of the oil dripping on the road from a moving car. What information do you get from it about the motion of car?

(3) If a stone and a pencil are dropped simultaneously in vacuum from the top of a tower, which of the two will reach the ground first? Give a reason.

(4) Can displacement of an object be zero even if distance is not zero. Give an example to justify your answer.
Problems on Graphs

(1) ‘A’ starts travelling at 20 m s\(^{-1}\) and decelerates at a constant rate of \(-2.0\) m s\(^{-2}\) until it comes to rest.
(a) Sketch a velocity-time graph for the A’s motion. Calculate the distance travelled from the graph.
(b) Find the distance travelled using the equations of motion.

(2) The displacement-time graph shows the motion of two cars P and Q along a straight road in the same direction.

Answer the following:
(i) Which car started later? What was the time lag? How far away was the first car when the second started?
(ii) Which of the two has greater velocity?
(iii) When and where did one car overtake the other?

(3) The motion of an object is shown in the following graph.

(a) the acceleration at time, \(t = 1\) s, \(t = 8\) s, and \(t = 12\) s.
(b) the total distance travelled
Problems on Speed, Velocity, Acceleration and Equations of Motion

(1) Express the speed 72 km h\(^{-1}\) in m s\(^{-1}\).

(2) Express 25 m s\(^{-1}\) in km h\(^{-1}\).

(3) Arrange the following speeds in increasing order: 20 m s\(^{-1}\), 2 km min\(^{-1}\), 9 km h\(^{-1}\).

(4) A train takes 4 hours to travel from A to B with a uniform speed of 75 km h\(^{-1}\). Find the distance between the two cities.

(5) A car is moving in a straight line with speed 18 km h\(^{-1}\). It is stopped in 5 s by applying the brakes. Find:
   (i) the speed of car in m s\(^{-1}\)
   (ii) its deceleration
   (iii) the speed of car after 2 s.

(6) A train takes 3 hours to reach station B from station A, and then 4 hours to return from station B to station A. The distance between the two stations is 400 km. Find the average speed and the average velocity of the train.

(7) A car moving on a straight path covers a distance of 2 km due north in 200 s. What is the speed and the velocity of car?

(8) A car travels first 20 km with a uniform speed of 30 km h\(^{-1}\) and then next 20 km with a uniform speed of 45 km h\(^{-1}\) in the same direction. Calculate the total time of journey and the average speed of the car.

(9) A car travels from A to B at a speed of 30 km h\(^{-1}\) and back to A at a speed of 40 km h\(^{-1}\). Find its average speed for the journey.

(10) A motorbike starts from rest and moves with an acceleration of 2.5 m s\(^{-1}\). After traveling 25 m it crosses a bridge in 12.1 s.
   (a) What is the motorbike’s speed just after it leaves the bridge?
   (b) Find the length of the bridge.
Kinematics - Multiple Choice Answers

1. (c)

2. (a)

3. (b) Acceleration is always directed downwards.

4. (c)

5. (c)

6. (c) Acceleration is a vector which depends on magnitude and direction. So, it changes when the magnitude or direction or magnitude and direction both change.

7. (d)

8. (a)

9. (b) Kinetic Energy gets converted to Potential Energy. \( \frac{1}{2}mv^2 = mgh \)

10. (c) They possess the same acceleration i.e. acceleration due to gravity.

11. (b)

12. (d) When the object is thrown vertically upwards, its initial velocity is ‘\( u \)’ and final velocity \( v = 0 \). When the same object is falling down, its initial velocity \( u = 0 \) and final velocity is ‘\( v \)’.
   
   Due to law of conservation of energy \( v = u \).

13. (b) Use the equation \( v^2 = u^2 + 2as \), where \( v = 0 \), \( u = 19.6 \) and \( a = -9.8 \)