

## **Fundamentals of Mechanical Motion: Theory, Formulas, and Practical Examples**

Mechanical motion is one of the fundamental concepts in physics used to describe how and why the position of bodies changes in space over time. Classical mechanics is built entirely on this foundation. To understand what mechanical motion is, it's essential not only to grasp the fact of changing position but also how we measure it, how we classify different types of motion, and why studying this phenomenon is so important.

### **What Is Motion?**

Motion is the process of changing the position of a body relative to other bodies. However, to understand this fully, we must clarify: relative to what? For example, if you sit inside a moving train and look at the adjacent seat, it appears stationary. Yet, to an observer standing on the platform, the train and everything inside it is moving. Hence, motion is always a relative concept.

### **Frame of Reference — The Basis for Describing Motion**

To talk meaningfully about motion, it's necessary to define a frame of reference. It consists of three main components.

The first is the reference body — the object relative to which we measure the motion of another body. Examples include the Earth, a wall, or a vehicle.

The second is the coordinate system, which allows us to determine the position of a body in space. Usually, this involves three mutually perpendicular axes (X, Y, and Z), through which we assign coordinates to points. Coordinates enable us to precisely specify the location of an object.

The third is a time-measuring device (a clock). Since motion is a change of position over time, we must record the exact time to understand how fast and in what direction the body is moving.

Without choosing a frame of reference, it is impossible to describe motion because motion always occurs relative to something. For instance, when we travel in a car, relative to the road we are moving, but relative to the car's interior, we may be at rest.

### **Material Point — A Simplified Model of a Body**

In physics, to simplify the study of motion, a body is often considered as a material point. This means we ignore the size, shape, and internal structure of the object and

represent it as a single point in space possessing mass.

This approach simplifies calculations and the analysis of motion, especially when the body's size is negligible compared to the distances it covers. For example, describing the Earth's orbit around the Sun is convenient by considering Earth as a material point, since Earth's diameter is negligible compared to the distance to the Sun.

However, in some problems, it is important to consider the actual size and shape of the body, such as when studying a planet's rotation around its axis, aircraft aerodynamics, or the ballistics of a projectile.

### Trajectory, Path, and Displacement — Key Kinematic Concepts

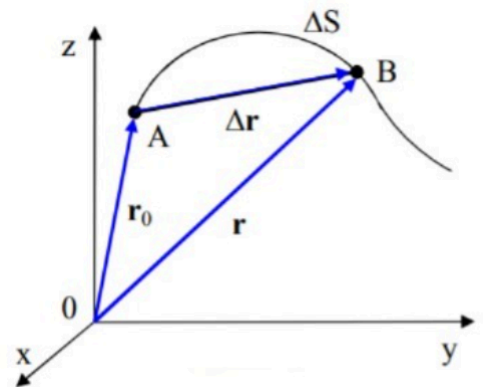
The trajectory is the line that a body traces in space as it moves. It can have various shapes — straight, curved, circular, or spiral. The trajectory represents the “trace” of motion.

The path is a scalar quantity equal to the length of the trajectory traveled. The path is always positive because it measures the total distance traveled regardless of direction.

Displacement is a vector connecting the initial and final positions of the body. Unlike the path, displacement accounts for direction and can be zero (if the body returns to its starting point) or have a specific magnitude and direction.

Let the position of the body in space be represented by the position vector  $\vec{r}(t)$ , where  $t$  is time. Then the displacement over the time interval from  $t_1$  to  $t_2$  is

$$\Delta \vec{r} = \vec{r}(t_2) - \vec{r}(t_1).$$



### Types of Mechanical Motion

Motion can be classified by various criteria.

By trajectory shape:

- **Rectilinear motion** — movement along a straight line. This is the simplest type of motion. Examples include a train moving on a straight track or a ball rolling on a flat surface.

- **Curvilinear motion** — movement along a curved path. Examples include a car turning a corner or a planet orbiting the Sun.

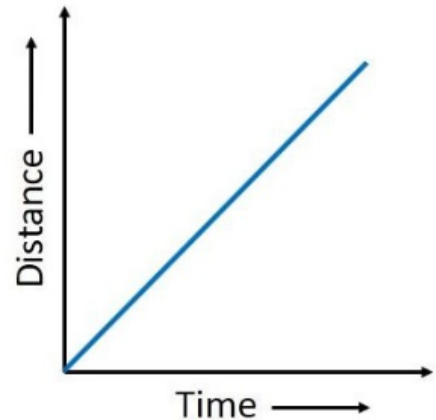
By velocity behavior:

- **Uniform motion** — the velocity of the body remains constant over time. In uniform motion, the path is proportional to time:

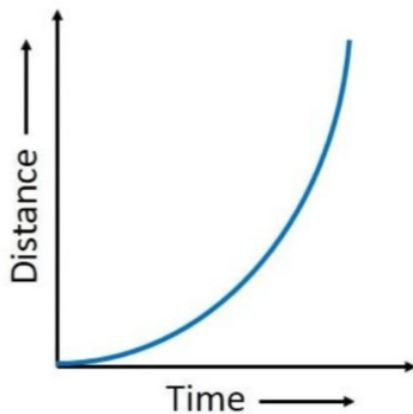
$$s = v \cdot t,$$

where  $v$  is the velocity and  $t$  is time.

### Uniform Motion



### Non-Uniform Motion



- **Non-uniform motion** — the velocity changes with time. This is the more common type of motion in nature and technology.

By the nature of the body's motion:

- **Translational motion** — all points of the body move the same way, maintaining their relative positions. An example is a car moving along a road.
- **Rotational motion** — points of the body move along circles around an axis of rotation. An example is a car wheel rotating around its axle.

Sometimes these motions combine: the car moves forward (translational motion) while its wheels rotate (rotational motion).

## Acceleration and Motion with Changing Velocity

To describe motion with changing velocity, acceleration is introduced as the rate of change of velocity over time:

$$\vec{a} = \frac{\vec{v} - \vec{v}_0}{t}$$

For rectilinear motion with constant acceleration, the velocity and displacement are given by the equations:

$$v = v_0 + at,$$
$$s = v_0t + \frac{1}{2}at^2,$$

where  $V_0$  is the initial velocity,  $a$  is acceleration, and  $t$  is time.

## Laws of Motion and Causes of Change in Position

Kinematics studies motion without considering the causes. The causes of motion are studied in dynamics, the branch of mechanics examining forces and their effects.

According to Newton's second law, the change in motion of a body is caused by the force applied to it, which causes the body to accelerate, decelerate, or change direction. Acceleration is proportional to the force and inversely proportional to the mass:

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

where  $F$  is force,  $m$  is mass, and  $a$  is acceleration.

Thus, the motion of any body results from interactions with other bodies via forces such as gravity, friction, elasticity, and others.

## Examples of Mechanical Motion in Life and Technology

Mechanical motion surrounds us everywhere. Movement of cars, trains, airplanes, ships — all these are examples of mechanical motion. In nature, examples include Earth's

rotation, planetary orbits, and flows of water and air.

In biology, muscle and skeletal movements enable organisms to move. In technology, understanding mechanics allows creation of complex devices from simple machines to robots.

In astronautics, mechanics helps calculate spacecraft trajectories, velocities, and travel times.