Mechanics

Lecture 3: Rectilinear Motion of a Particle
Newton's Laws of Motion

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1 Introduction to Classical Mechanics

Classical mechanics is the branch of physics that deals with the motion of macroscopic objects under the influence of forces. It provides a systematic framework to describe motion, analyze causes, and predict future behavior. In medical physics, classical mechanics is essential for understanding the motion of patients, diagnostic equipment, laboratory instruments, and biomechanical systems.

Mechanics is divided into:

- **Kinematics**: Description of motion without considering its causes.
- **Dynamics**: Study of motion together with the forces causing it.

2 Rectilinear Motion of a Particle

Rectilinear motion refers to the motion of a particle along a straight line. This is the simplest type of motion and forms the foundation for more complex two- and three-dimensional motion.

The position of a particle is completely described by a single coordinate $x(t)$.

2.1 Position and Displacement

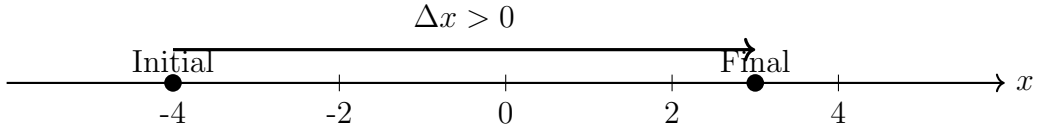
The position vector of a particle moving along the x-axis is:

$$\vec{r}(t) = x(t)\hat{i}$$

Displacement is defined as the change in position:

$$\Delta x = x_2 - x_1$$

Displacement is a vector quantity and can be positive, negative, or zero.



Solved Example 1

A particle moves from $x_1 = -8$ m to $x_2 = 5$ m.

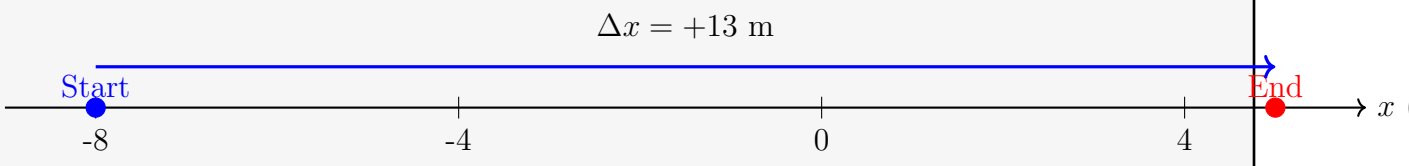


Figure: Graphical representation of displacement for Solved Example 1.

Solution:

$$\Delta x = x_2 - x_1 = 5 - (-8) = 13 \text{ m}$$

The positive value of displacement indicates that the particle moves in the positive direction along the x-axis.

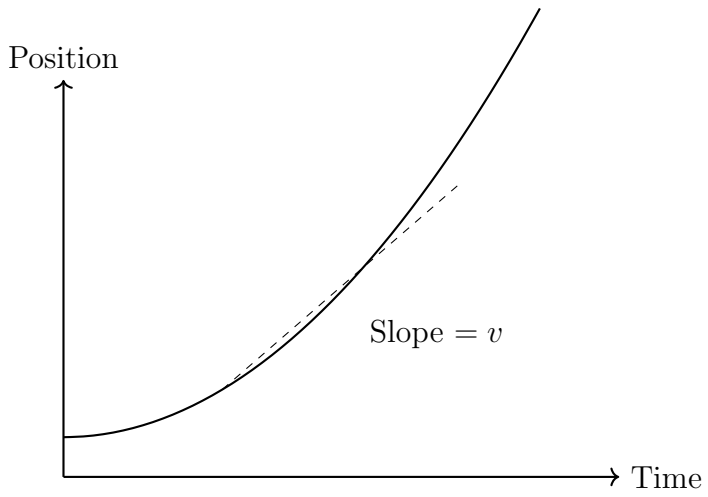
2.2 Velocity

Velocity describes how fast and in which direction the position changes. The average velocity is:

$$v_{\text{avg}} = \frac{\Delta x}{\Delta t}$$

The instantaneous velocity is:

$$v = \frac{dx}{dt}$$



Solved Example 2

The position of a particle is given by $x(t) = 3t^2 - 6t + 4$.

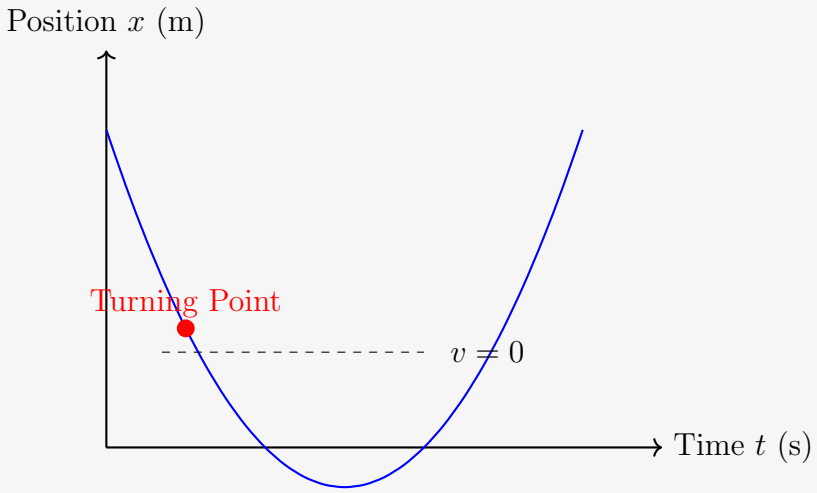


Figure 2: Position–time graph showing turning point where velocity becomes zero (Solved Example 2).

Solution:

$$v(t) = \frac{dx}{dt} = 6t - 6$$

The particle stops when $v = 0$:

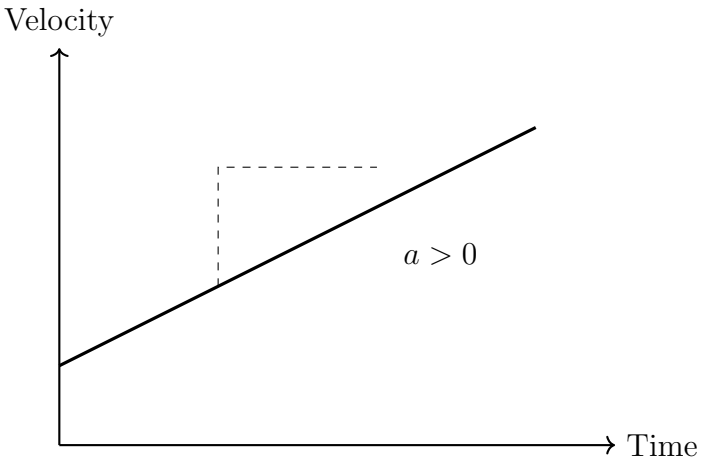
$$6t - 6 = 0 \Rightarrow t = 1 \text{ s}$$

2.3 Acceleration

Acceleration is the rate of change of velocity:

$$a = \frac{dv}{dt}$$

Acceleration can exist even if velocity is zero.



Solved Example 3

Given $v(t) = 10 - 2t$, find the acceleration and stopping time.

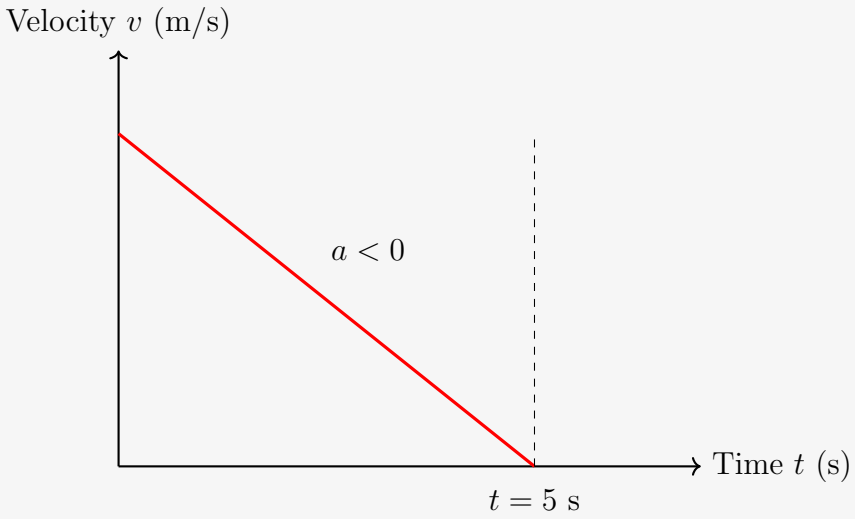


Figure 3: Velocity–time graph showing deceleration and stopping time (Solved Example 3).

Solution:

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

Stopping occurs when $v = 0$:

$$10 - 2t = 0 \Rightarrow t = 5 \text{ s}$$

3 Equations of Motion (Constant Acceleration)

For motion with constant acceleration:

$$v = v_0 + at \tag{1}$$

$$x = x_0 + v_0 t + \frac{1}{2}at^2 \tag{2}$$

$$v^2 = v_0^2 + 2a(x - x_0) \tag{3}$$

Solved Example 4

A particle starts from rest with $a = 3$ m/s^2. Find velocity and displacement after 4 s.

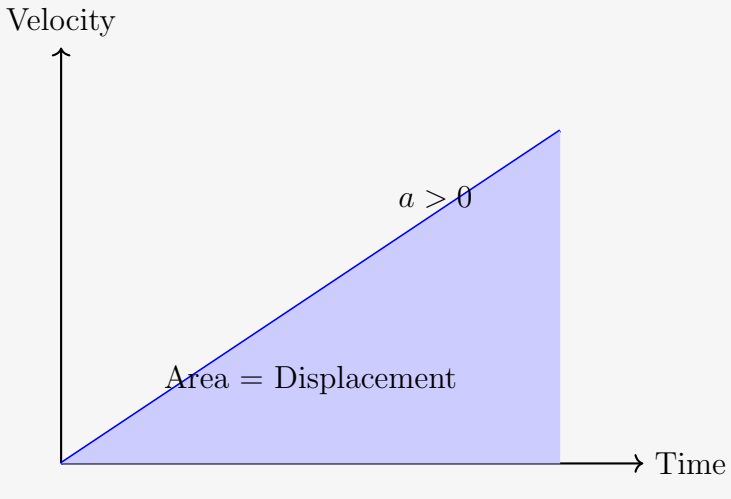


Figure 4: Velocity–time graph for constant acceleration showing displacement as area (Solved Example 4).

Solution:

$$v = at = 12 \text{ m/s}$$

$$x = \frac{1}{2}(3)(4^2) = 24 \text{ m}$$

Solved Example 5

A particle has $v_0 = 15$ m/s and $a = -5$ m/s^2. Find stopping distance.

Solution:

$$0 = 15^2 - 2(5)x \Rightarrow x = 22.5 \text{ m}$$

4 Newton's Laws of Motion

4.1 First Law (Law of Inertia)

A body remains at rest or moves with constant velocity in a straight line unless acted upon by a net external force. This law introduces the concept of inertia.

Example

A patient bed moving with constant speed experiences zero net force.

4.2 Second Law

The net external force is equal to mass times acceleration:

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

Solved Example 6

A 6 kg object is pulled by a force of 30 N.

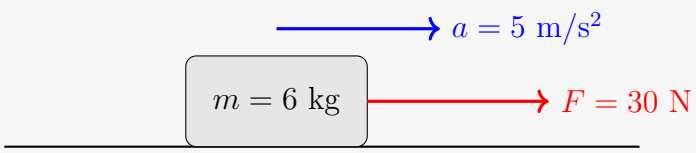


Figure 5: Force and resulting acceleration for Solved Example 6 (Newton's Second Law).

Solution:

$$a = \frac{30}{6} = 5 \text{ m/s}^2$$

Solved Example 7

Two forces act on a 4 kg mass: 20 N right, 4 N left.

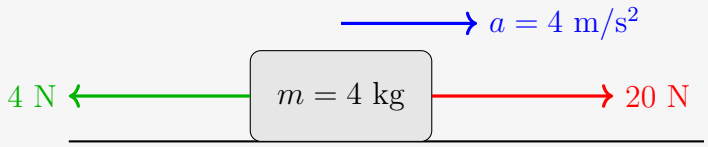


Figure 6: Net force and acceleration direction in Solved Example 7.

Solution:

$$F_{\text{net}} = 16 \text{ N} \quad \Rightarrow \quad a = 4 \text{ m/s}^2$$

4.3 Third Law

For every action, there is an equal and opposite reaction. These forces act on different bodies.

Solved Example 8

When a foot pushes the ground backward, the ground pushes the foot forward.

Solved Example: Newton's Third Law

A student pushes a laboratory cart with a horizontal force of 40 N to the right. Explain the action–reaction force pair and identify the bodies on which the forces act.

Solution:

According to Newton's Third Law, when one body exerts a force on another body, the second body simultaneously exerts a force of equal magnitude and opposite direction on the first body.

- **Action force:** The student exerts a force of 40 N on the cart (to the right).
- **Reaction force:** The cart exerts a force of 40 N on the student (to the left).

These two forces:

- Are equal in magnitude.
- Are opposite in direction.
- Act on **different bodies**.
- Do **not** cancel each other.

Therefore, the cart accelerates forward, while the student experiences a backward force.

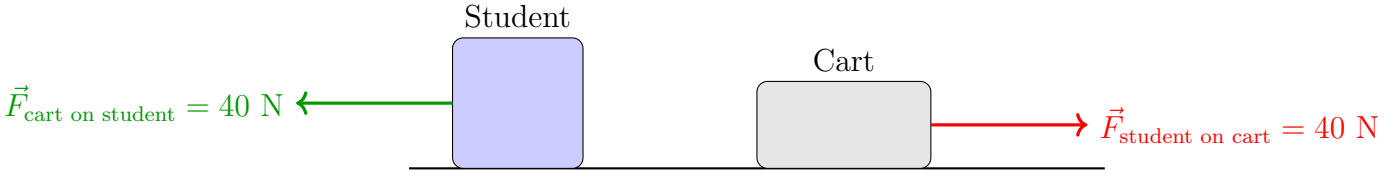


Figure: Action–reaction force pair illustrating Newton's Third Law.

5 Multiple Choice Questions (Old Style – 30 Questions)

1. Rectilinear motion occurs along:
   A- a curve
   B- a plane
   C- a straight line
   D- a circle
   E- none

2. Displacement is:
   A- scalar
   B- always positive
   C- vector
   D- distance
   E- speed

3. Velocity is defined as:
   A- dx/dt
   B- dv/dt
   C- d^2x/dt^2
   D- $|v|$
   E- none

4. Acceleration is:
   A- change in position
   B- change in velocity
   C- distance
   D- speed
   E- time

5. The slope of x–t graph gives:
   A- acceleration
   B- velocity
   C- displacement
   D- force
   E- mass

6. The slope of v–t graph gives:
   A- velocity
   B- displacement
   C- acceleration
   D- force
   E- mass

7. Area under v–t graph gives:
   A- velocity
   B- acceleration
   C- displacement
   D- force
   E- mass

8. If acceleration is zero, velocity is:
   A- increasing

B- decreasing
C- constant
D- zero
E- infinite

9. The SI unit of acceleration is:
   A- m/s
   B- m/s^2
   C- N
   D- kg
   E- J

10. Uniform motion means:
    A- constant speed
    B- constant velocity
    C- zero acceleration
    D- B and C
    E- none

11. Newton's First Law is the law of:
    A- force
    B- inertia
    C- acceleration
    D- momentum
    E- energy

12. Inertia depends on:
    A- velocity
    B- force
    C- mass
    D- acceleration
    E- time

13. Newton's Second Law is:
    A- $F = mv$
    B- $F = ma$
    C- $F = m/a$
    D- $F = va$
    E- none

14. The SI unit of force is:
    A- joule
    B- watt
    C- newton
    D- pascal
    E- kilogram

15. If net force is zero, motion is:
    A- accelerated
    B- uniform
    C- circular
    D- oscillatory
    E- none

16. Unbalanced forces cause:
    A- rest
    B- constant velocity
    C- acceleration
    D- equilibrium
    E- none

17. Action and reaction forces act on:
    A- same body
    B- different bodies
    C- same direction
    D- same point
    E- none

18. Mass is a measure of:
    A- force
    B- weight
    C- inertia
    D- momentum
    E- energy

19. Direction of acceleration depends on:
    A- velocity
    B- mass
    C- net force
    D- displacement
    E- time

20. Newton's laws apply in:
    A- all frames
    B- inertial frames
    C- rotating frames
    D- accelerating frames
    E- none

21. Which quantity is scalar?
    A- velocity
    B- displacement
    C- acceleration
    D- speed
    E- force

22. Which quantity can be negative?
    A- speed
    B- mass
    C- velocity
    D- time
    E- force

23. Force causes:
    A- displacement
    B- velocity

C- acceleration
D- mass
E- none

24. Newton's Third Law pairs are:
A- equal and same direction
B- equal and opposite
C- unequal and opposite
D- unequal and same
E- none

25. $v^2 = v_0^2 + 2ax$ is valid when:
A- v is constant
B- a is constant
C- x is constant
D- t is constant
E- none

26. If acceleration and velocity have same direction:
A- speed decreases
B- speed increases
C- speed is zero
D- motion stops
E- none

27. Kinematics studies:
A- forces
B- motion without causes
C- acceleration
D- energy
E- none

28. Dynamics studies:
A- motion only
B- forces only
C- motion and its causes
D- displacement
E- none

29. In medical physics, mechanics is important for:
A- decoration
B- safety and precision
C- cost only
D- aesthetics
E- none