Motion and Dynamics

Matthew Williams • Physics • May 20, 2026

Motion and Dynamics

Distance, Displacement, Speed, Velocity

These four quantities form two scalar-vector pairs. Distinguishing them precisely is important in physics.

Scalar	Vector	Definition
Distance	Displacement	**Distance** is the total path length travelled. **Displacement** is the straight-line distance from start to finish in a specified direction.
Speed	Velocity	**Speed** is the distance travelled per unit time. **Velocity** is the displacement per unit time (or rate of change of displacement); it has direction.

$$\text{velocity} = \frac{\text{displacement}}{\text{time}} \qquad v = \frac{s}{t}$$

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

Both speed and velocity use units of m s{.

Acceleration is the rate of change of velocity, or the change in velocity per unit time:

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

where u is initial velocity and v is final velocity. Units: m s{.

Motion Graphs

Displacement-Time Graphs

The gradient of a displacement-time graph equals velocity.

- Horizontal line: stationary (zero velocity)
- Straight line with positive gradient: constant positive velocity
- Curve with increasing gradient: acceleration

Velocity-Time Graphs

The gradient of a velocity-time graph equals acceleration. The **area under** a velocity-time graph equals displacement.

- Horizontal line: constant velocity (zero acceleration)
- Straight line with positive gradient: constant acceleration
- Negative gradient: deceleration

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📝 **Exam Tip**
To find displacement from a v-t graph, calculate the area of each region geometrically (rectangle for constant velocity, triangle for acceleration/deceleration). Areas below the time axis represent motion in the opposite direction and count as negative displacement.

Aristotle's View of Motion

Aristotle (4th century BC) argued that a continuous force is needed to keep an object moving: the faster the force applied, the faster the object moves (
$v \propto F$
). He believed that objects naturally come to rest and that rest is the natural state of all things.

This view was eventually shown to be wrong. The reason everyday objects slow down is friction and air resistance, not a fundamental tendency to stop. Newton later showed that a force changes velocity, not velocity itself.

Newton's Three Laws of Motion

First Law

An object remains at rest or continues moving at constant velocity unless acted on by a resultant external force. This is the law of **inertia**, objects resist changes to their state of motion.

<JustInCase>

Inertia is the tendency of an object to resist any change in its state of rest or uniform motion. A more massive object has greater inertia; it requires a larger force to produce the same acceleration.

</JustInCase>

The practical consequence: if something is accelerating, there must be a non-zero resultant force. If it moves at constant velocity, the forces are balanced.

Second Law

The resultant force on an object equals its mass multiplied by its acceleration:

$$F = ma$$

where F is in newtons, m in kilograms, and a

in m s{^{2}. The acceleration is in the same direction as the resultant force.

Third Law

Every force has an equal and opposite reaction force, acting on a different object. The two forces in an action-reaction pair are equal in magnitude, opposite in direction, and act on different bodies, they cannot cancel each other.

<NewtonThirdLawDiagram />

Common examples of Newton's Third Law in dynamic systems:

- **Rocket propulsion** — hot gases are expelled backward at high speed; by the Third Law the rocket is pushed forward with an equal and opposite force.
- **Garden sprinkler** — water is pushed out through the nozzles; the reaction force spins the sprinkler arms in the opposite direction.
- **Trampoline** — when a gymnast lands, they push down on the trampoline; the trampoline pushes back up on the gymnast with an equal force, propelling them upward.

Newton's laws applied, crash test (2015 Paper 02, Q4)

A 70 kg test dummy is in a car travelling at 26 m s{. The car crashes and stops in 0.1 s.

Part (i), Initial momentum:

$$p = mv = 70 \times 26 = 1\,820\text{N s}$$

Part (ii), Force from seatbelt:

The dummy decelerates from 26 m s{ to 0 in 0.1 s.

$$a = \frac{\Delta v}{\Delta t} = \frac{0 - 26}{0.1} = -260\text{m s}^{-2}$$

$$F = ma = 70 \times 260 = 18\,200\text{N}$$

The seatbelt exerts a force of 18,200 N on the dummy.

Linear Momentum

Momentum is the product of mass and velocity:

$$p = mv$$

Units: kg m s{ (equivalent to N s).

Momentum is a vector, it has the same direction as the velocity.

Newton's Second Law in Terms of Momentum

Force equals the rate of change of momentum:

$$F = \frac{\Delta p}{\Delta t} = \frac{mv - mu}{t}$$

This form is more general than $F = ma$ because it works even when mass changes.

Conservation of Linear Momentum

In a closed system (no external forces), the total momentum before a collision equals the total momentum after:

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

This holds for all collisions, elastic and inelastic, as long as no external forces act.

Conservation of momentum, collision (2016 Paper 02, Q2)

An 8 kg ball moving east at 10 m s{ collides with a 2 kg ball moving west at 5 m s{. After the collision they stick together. Find their common velocity.

Take east as positive.

Total momentum before:

$$p_{\text{before}} = (8 \times 10) + (2 \times -5) = 80 - 10 = 70\text{kg m s}^{-1}$$

After collision (combined mass = 10 kg):

$$70 = 10v$$

$$v = 7\text{m s}^{-1}\text{east}$$

📝 **Exam Tip**

Assign a positive direction at the start of every momentum problem and stick to it. A velocity in the opposite direction gets a negative sign. If your final velocity comes out negative, the object is moving in the direction you called negative.