A LEVEL PHYSICS 9702 · AS LEVEL · TOPIC 3 · ~9 MIN READ

Dynamics

Mass and inertia, Newton's three laws, force as rate of change of momentum, weight, drag and terminal velocity, and conservation of momentum in elastic and inelastic collisions in one and two dimensions.

Mass & inertia | Newton's laws | F = ma | Momentum | F = Δp/Δt | Weight | Drag & terminal velocity | Conservation of momentum

RS by Riyaz Sir
mentorriyaz.in

Paper tag = **where it is examined** DATA & FORMULAE given in the exam C1 A1 B1 how marks are awarded

highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

- **Mass** is the property of an object that resists changes in its motion. **Weight** is the effect of a gravitational field on a mass: W = mg.
- **Force is the rate of change of momentum,** F = Δp/Δt. For constant mass this is F = ma, and the acceleration is in the direction of the resultant force.
- **Momentum is always conserved** in an interaction when no resultant external force acts. Kinetic energy is conserved only in an **elastic** collision.
- **In an elastic collision,** the relative speed of approach equals the relative speed of separation.
- **Objects falling through air** speed up until drag equals weight: then the resultant force is zero and they move at **terminal velocity**.

BY THE END YOU CAN

- State and apply Newton's three laws, with correct third-law pairs.
- Define linear momentum and force as rate of change of momentum.
- Describe qualitatively how drag affects falling objects and explain terminal velocity.
- Apply conservation of momentum to elastic and inelastic collisions in one and two dimensions.

1 Newton's laws

The laws

Newton's first law — an object stays at rest or moves with constant velocity unless a resultant force acts on it.

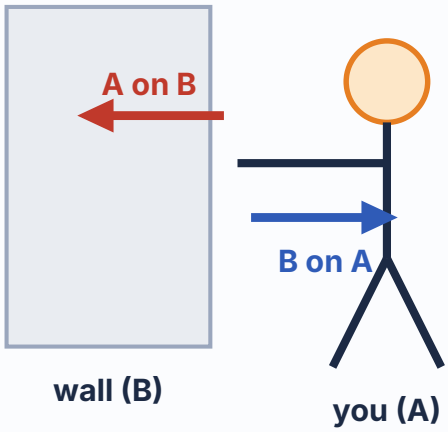
Newton's second law — the rate of change of momentum of an object is proportional to the resultant force acting on it, and takes place in the direction of the force (F = Δp/Δt; F = ma for constant mass).

Newton's third law — if body A exerts a force on body B, then B exerts a force on A that is equal in magnitude, opposite in direction, and of the same type.

Linear momentum — the product of mass and velocity, p = mv (vector, unit kg m s^{-1} or N s).

$$F = \Delta p/\Delta t = ma$$

F is the RESULTANT force; 1 N gives 1 kg an acceleration of 1 m s^{-2}



Newton's third law pair:
same size, opposite direction,
same type of force,
acting on DIFFERENT bodies.
Weight and normal reaction on a
book are NOT a third-law pair.

A third-law pair acts on two different bodies, so the forces never cancel each other.

COMMON MISTAKE

Calling weight and the normal contact force on a resting book a third-law pair. They act on the same body and are different types of force. The partner of the book's weight is the book's gravitational pull on the Earth. The 2024 Paper 1 report noted that Newton's third law was poorly understood.

Using F = ma

- **Draw a free-body diagram** of one object, with a ruler, every force labelled ("weight", not "gravity"). Then resultant force = mass × acceleration.

WORKED EXAMPLE

A lift of mass 800 kg accelerates upwards at 1.5 m s^{-2}. Find the tension in the cable.

1. resultant force = T − mg = ma C1
2. **T = 800 × (9.81 + 1.5) = 9048 N = 9.0 kN** A1

WORKED EXAMPLE

A tennis ball of mass 0.15 kg hits a wall at 20 m s^{-1} and rebounds at 15 m s^{-1} along the same line. Contact lasts 0.050 s. Find the average force on the ball.

1. taking the rebound direction as positive: Δp = 0.15 × 15 − 0.15 × (−20) = 5.25 N s C1
2. **F = Δp/Δt = 5.25/0.050 = 105 N** A1 **(in the rebound direction)**

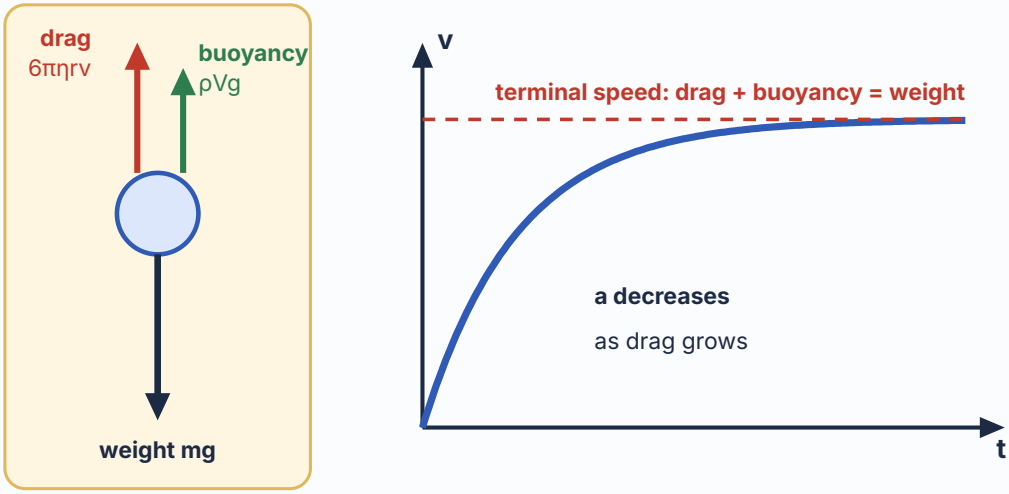
COMMON MISTAKE

Using the change in speed (20 − 15) instead of the change in velocity (15 − (−20)). Also, F = p/t is wrong: the force is the **change** in momentum over time. Both errors appear in the 2024 reports.

2 Drag and terminal velocity

Non-uniform motion

- **Friction** opposes relative motion between surfaces. **Drag** (air resistance) opposes motion through a fluid and increases with speed.
- **Falling from rest:** at first, drag is zero, so a = g. As speed rises, drag rises, the resultant force falls, and so the acceleration falls. When drag = weight, a = 0: **terminal velocity**.



Speed–time graph for a falling object with air resistance: the gradient (acceleration) falls to zero.

- **A ball thrown upwards with air resistance:** drag and weight both act downwards on the way up, so the deceleration is greater than g; on the way down they act in opposite directions, so the acceleration is less than g. Don't reuse the falling-from-rest graph for upward motion, as some 2024 candidates did.

EXAM TIP

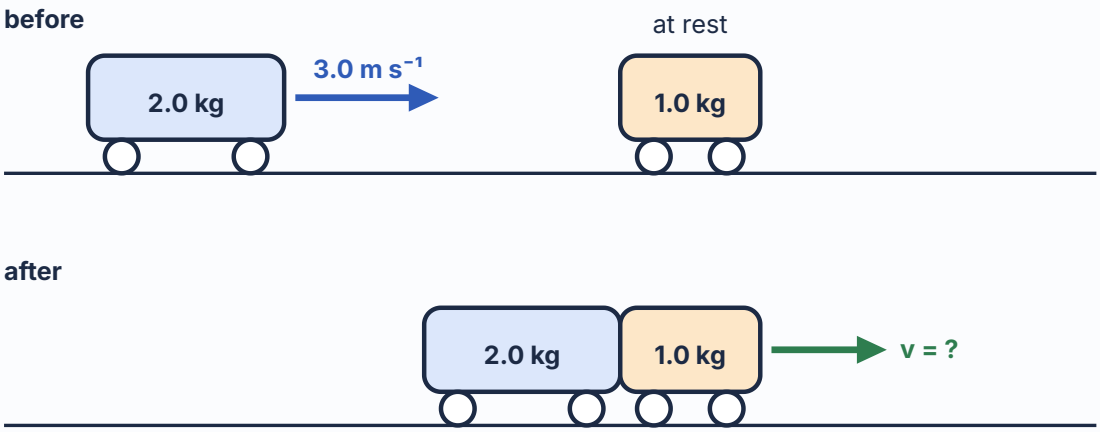
"Explain why the acceleration decreases" needs the chain: speed increases ⇒ drag increases ⇒ resultant force (weight – drag) decreases ⇒ acceleration decreases (a = F/m).

3 Conservation of momentum

The principle

Principle of conservation of momentum — for a system of interacting objects, the total momentum remains constant, provided no resultant external force acts on the system.

- **Why it follows from Newton's laws:** during a collision A pushes B and B pushes A with equal and opposite forces for the same time. So the momentum gained by one equals the momentum lost by the other.
- **Write "total" or "sum of"** in the statement: examiners in 2024 penalised "momentum is conserved" with no reference to the total.



p before = p after: 2.0 × 3.0 = 3.0v, so v = 2.0 m s^{-1}

The trolleys stick together: total momentum before = total momentum after.

WORKED EXAMPLE

A 2.0 kg trolley moving at 3.0 m s^{-1} hits a 1.0 kg trolley at rest and they stick together. Find their common velocity and the kinetic energy lost.

1. 2.0 × 3.0 + 0 = 3.0v ⇒ **v = 2.0 m s^{-1}** C1 A1
2. KE before = ½ × 2.0 × 3.0^2 = 9.0 J; after = ½ × 3.0 × 2.0^2 = 6.0 J C1
3. **3.0 J lost (inelastic)** A1

Elastic and inelastic collisions

	Momentum	Kinetic energy	Relative speed
Elastic	conserved	conserved	approach = separation
Inelastic	conserved	not conserved (some becomes heat, sound, deformation)	separation < approach
Explosion (from rest)	total stays zero	increases (from chemical or stored energy)	—

WORKED EXAMPLE

A 1.0 kg ball moving at 4.0 m s^{-1} collides elastically head-on with a 3.0 kg ball at rest. The 1.0 kg ball rebounds at 2.0 m s^{-1}. Find the velocity of the 3.0 kg ball and show the collision is elastic.

1. momentum: 1.0 × 4.0 = 1.0 × (−2.0) + 3.0v ⇒ **v = 2.0 m s^{-1}** C1 A1
2. relative speed of approach = 4.0 m s^{-1}; of separation = 2.0 − (−2.0) = 4.0 m s^{-1}, equal ⇒ elastic B1
3. **(check: KE before 8.0 J, after 2.0 + 6.0 = 8.0 J)**

Collisions in two dimensions

- **Momentum is conserved in each direction separately.** Resolve every momentum into two perpendicular components, write one equation for each direction, then combine with Pythagoras and tan.

WORKED EXAMPLE

A 2.0 kg puck moving at 5.0 m s^{-1} hits a stationary 3.0 kg puck. Afterwards the 2.0 kg puck moves at 3.0 m s^{-1} at 60° to its original direction. Find the velocity of the 3.0 kg puck.

1. along the original line: 2.0 × 5.0 = 2.0 × 3.0 cos 60° + 3.0v_x ⇒ 3.0v_x = 7.0 **C1**
2. perpendicular: 0 = 2.0 × 3.0 sin 60° − 3.0v_y ⇒ 3.0v_y = 5.20 **C1**
3. 3.0v = √(7.0² + 5.20²) = 8.72 ⇒ **v = 2.9 m s^{-1}** **A1**
4. **direction: tan^{-1}(5.20/7.0) = 37° to the original line, on the other side** **A1**

COMMON MISTAKE

Writing the perpendicular equation with the wrong signs. Choose positive directions for both axes before writing anything. This caused errors in 2024 Paper 2.

LINKING QUESTION

The impulse idea F × Δt = Δp links to force–time graphs; the energy lost in collisions links to Work, energy and power; and momentum conservation in annihilation is used in Medical physics (PET).

Test yourself — cover the answers first

QUICK CHECK

1. Define linear momentum.
2. State Newton's second law in terms of momentum.
3. Is kinetic energy conserved in an inelastic collision?
4. A gun of mass 4.0 kg fires a 20 g bullet at 400 m s^{-1}. Find the recoil speed.
5. What is the resultant force on an object at terminal velocity?

EXAM-STYLE

6. Water leaves a hose at 15 m s^{-1} with mass flow rate 2.0 kg s^{-1} and hits a wall, stopping. Find the force on the wall.
7. Sketch and explain the velocity–time graph of a skydiver from leaving the plane until after the parachute opens.
8. A 0.50 kg ball at 6.0 m s^{-1} collides with a 1.5 kg ball moving at 2.0 m s^{-1} in the opposite direction. They stick together. Find their velocity.

Show answers

1. the product of mass and velocity
2. the resultant force is proportional to (equal to) the rate of change of momentum, in the same direction
3. no (momentum is)
4. $0.020 \times 400/4.0 = 2.0\ m\ s^{-1}$
5. zero
6. $F = \Delta p/\Delta t = 2.0 \times 15 = 30\ N$
7. speed rises with decreasing gradient to terminal velocity; parachute opens: drag > weight, so decelerates (gradient negative, decreasing in size) to a new, lower terminal velocity
8. $0.50 \times 6.0 - 1.5 \times 2.0 = 2.0v \Rightarrow v = 0$

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