CIE International A Level Physics

Topic 3

Dynamics

Revision Booklet

This booklet covers:

- Mass, Force and Newton's Laws of Motion
- Linear Momentum and Impulse
- Non-Uniform Motion and Terminal Velocity
- Conservation of Momentum
- Elastic and Inelastic Collisions

Mass, Force and Newton's Laws of Motion

Mass

Mass is the property of an object that resists change in motion (inertia). It is a scalar quantity measured in kilograms (kg). A larger mass requires a larger force to produce the same acceleration.

Newton's First Law

An object remains at rest or continues to move with **constant velocity** unless acted upon by a **resultant (net) force**.
Equivalently: if the resultant force on an object is zero, its acceleration is zero.

Newton's Second Law

The **resultant force** on an object is directly proportional to its **rate of change of momentum**, and acts in the same direction as the rate of change of momentum:

$$F = \frac{\Delta p}{\Delta t} = \frac{\Delta(mv)}{\Delta t}$$

For constant mass this simplifies to:

$$F = ma$$

- F: resultant force (N); m: mass (kg); a: acceleration (m s^{-2}).
- The resultant force and acceleration are always in the **same direction**.
- 1 N: the force that gives a mass of 1 kg an acceleration of 1 m s^{-2}.

Newton's Third Law

If object A exerts a force on object B, then object B exerts an **equal and opposite force** on object A.
These forces are:

- Equal in magnitude.
- Opposite in direction.
- Of the **same type** (e.g. both gravitational, both contact).
- Acting on **different objects** — they never cancel because they act on different bodies.

Newton's Third Law Pairs

A common error is to confuse Newton's third law pairs with forces in equilibrium. Two forces balance (sum to zero) when they act on the *same* object; Newton's third law pairs act on *different* objects. For example: weight (mg downward on book) and normal contact force (N upward on book) are *not* a Newton's third law pair — they are equilibrium forces on the same object. The Newton's third law pair of the book's weight is the gravitational pull the book exerts on the Earth.

Weight

The **weight** of an object is the gravitational force acting on it due to a gravitational field:

$$W = mg$$

- $g = 9.81$ m s^{-2}: gravitational field strength / acceleration of free fall.
- Weight acts at the object's **centre of gravity**.
- Weight is a vector (downward); mass is a scalar.

Linear Momentum and Impulse

Linear Momentum

The **linear momentum** of an object is the product of its mass and velocity:

$$p = mv$$

- Unit: kg m s^{-1} (or N s).
- Momentum is a **vector** — direction matters.
- Always state or define the positive direction when solving problems.

Force as Rate of Change of Momentum

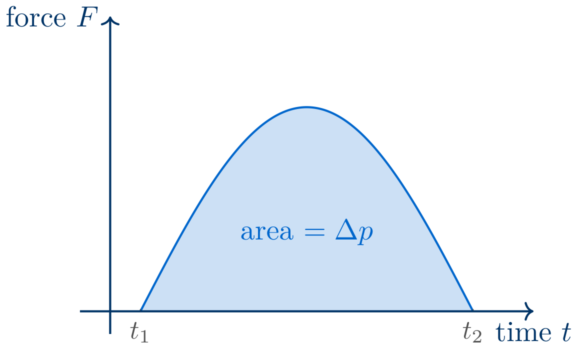
Newton's second law in its most general form:

$$F = \frac{\Delta p}{\Delta t}$$

Rearranging: $F\,\Delta t = \Delta p$
The product $F\,\Delta t$ is called the **impulse**:

$$\text{Impulse} = F\,\Delta t = \Delta p = mv - mu$$

- Unit: N s $\equiv$ kg m s^{-1}.
- Impulse equals the **change in momentum**.
- For a variable force, impulse = area under a force–time graph.



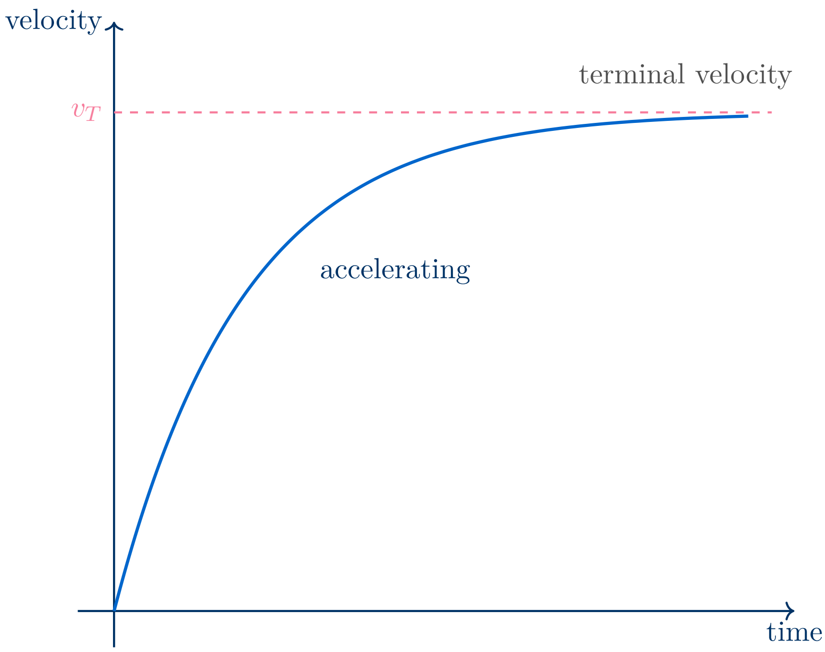
Non-Uniform Motion and Terminal Velocity

Friction and Drag Forces

- **Friction**: contact force opposing relative motion between surfaces.
- **Viscous drag / air resistance**: resistive force on an object moving through a fluid. A simple model: drag force **increases as speed increases**.
- Both forces act opposite to the direction of motion.

Terminal Velocity

An object falling through a fluid **reaches terminal velocity** when the **drag force equals the driving force** (weight for a falling object). At this point the resultant force is zero and acceleration is zero — the object moves at constant velocity.

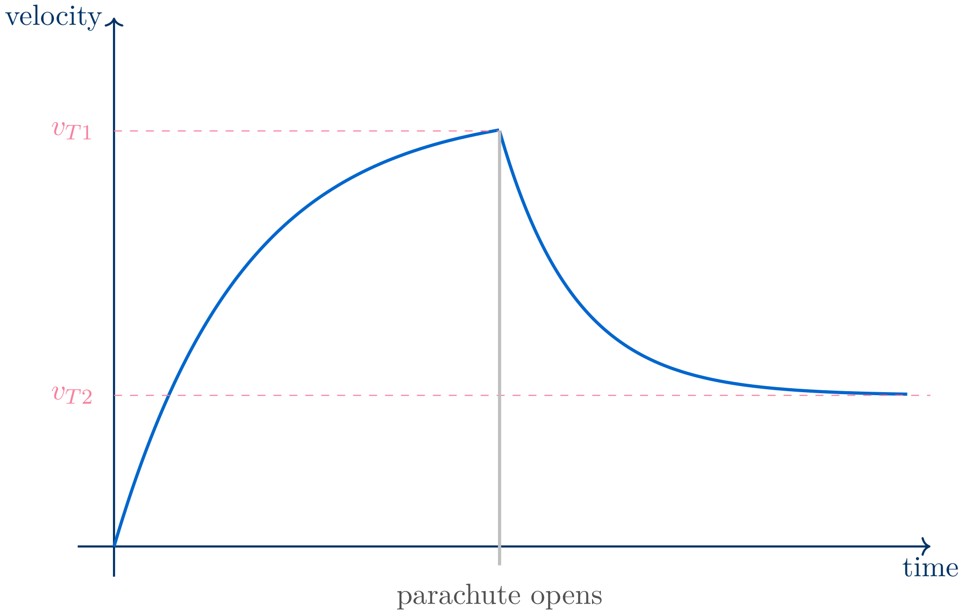


Stages of Free Fall with Air Resistance

1. **Initially**: velocity = 0, drag = 0. Resultant force = mg downward. Acceleration = g.
2. **As speed increases**: drag increases. Resultant force decreases. Acceleration decreases (gradient of v–t graph decreases).
3. **At terminal velocity** v_T: drag = mg. Resultant force = 0. Acceleration = 0. Constant velocity.

For a parachutist who opens their parachute after reaching terminal velocity:

- Drag suddenly increases greatly ⇒ resultant force is now *upward* ⇒ deceleration.
- Speed decreases ⇒ drag decreases until a new, lower terminal velocity is reached.



Conservation of Linear Momentum

Principle of Conservation of Momentum

The **total linear momentum** of a system of objects remains constant provided **no external resultant force** acts on the system.

$$\sum p_{\text{before}} = \sum p_{\text{after}}$$

This follows directly from Newton's second and third laws.

Applying Conservation of Momentum

1. Define a **positive direction**.
2. Write down total momentum **before** the collision/explosion.
3. Write down total momentum **after**, using + or − for direction.
4. Set before = after and solve.

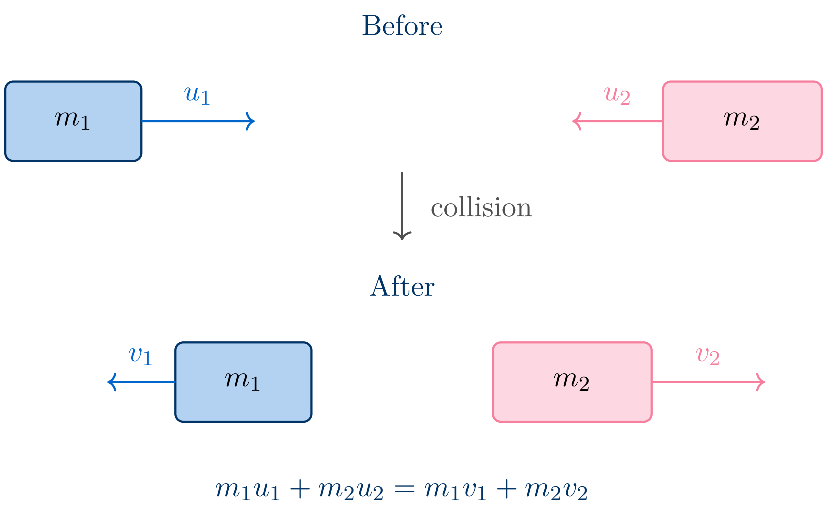
For a two-body collision:

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

For an explosion starting from rest (total initial momentum = 0):

$$0 = m_1v_1 + m_2v_2 \implies m_1v_1 = -m_2v_2$$

The two objects move in **opposite directions**.



Elastic and Inelastic Collisions

Elastic Collision

In an **elastic collision**:

- Total **momentum** is conserved (always).
- Total **kinetic energy** is conserved.
- The **relative speed of approach** equals the **relative speed of separation**:

$$u_1 - u_2 = v_2 - v_1$$

Perfectly elastic collisions are rare in practice (e.g. collisions between gas molecules, some subatomic particles).

Inelastic Collision

In an **inelastic collision**:

- Total **momentum** is conserved (always).
- Total **kinetic energy is not conserved** — some is converted to heat, sound, or deformation.
- In a **perfectly inelastic** collision, the objects **stick together** and move as one — maximum kinetic energy is lost (but momentum is still conserved).

	Elastic	**Inelastic**
Momentum conserved	**Yes**	**Yes**
Kinetic energy conserved	**Yes**	**No**
Relative speed: approach = separation	**Yes**	No
Objects stick together	No	Possibly (perfectly inelastic)

Checking for Elastic Collision

To determine whether a collision is elastic:

1. Apply conservation of momentum to find unknown velocities.
2. Calculate total KE before: $\sum \frac{1}{2}mv^2$ (using initial speeds).
3. Calculate total KE after: $\sum \frac{1}{2}mv^2$ (using final speeds).
4. If KE before = KE after $\Rightarrow$ **elastic**. If KE is lost $\Rightarrow$ **inelastic**.
5. Alternatively, check if $u_1 - u_2 = v_2 - v_1$.

Formula Summary Sheet

Formula	Quantity	Units
$F = ma$	Newton's second law (constant mass)	N
$W = mg$	Weight	N
$p = mv$	Linear momentum	kg m s^{-1}
$F = \Delta p/\Delta t$	Force as rate of change of momentum	N
$F\,\Delta t = \Delta p$	Impulse	N s
$\sum p_{\text{before}} = \sum p_{\text{after}}$	Conservation of momentum	kg m s^{-1}
$u_1 - u_2 = v_2 - v_1$	Elastic collision condition	m s^{-1}

Newton's laws word-for-word:

1st: An object remains at rest or moves at constant velocity unless a resultant force acts.

2nd: Resultant force equals rate of change of momentum ($F = \Delta p/\Delta t$).

3rd: For every action there is an equal and opposite reaction (on a different object, same type of force).

Momentum is always conserved in all collisions (elastic and inelastic).
Kinetic energy is only conserved in elastic collisions.

Worked Examples

Example 1 — Newton's Second Law

Question: A car of mass 1200 kg accelerates from 8.0 m s^{-1} to 20 m s^{-1} in 6.0 s. The total resistive force is 400 N. Calculate (a) the acceleration, (b) the driving force.

Solution

(a) $a = \frac{v-u}{t} = \frac{20-8.0}{6.0} = \mathbf{2.0}$ m $\mathrm{s}^{\mathbf{-2}}$

(b) $F_{\text{net}} = ma = 1200 \times 2.0 = 2400$ N

$F_{\text{drive}} - F_{\text{resist}} = F_{\text{net}} \implies F_{\text{drive}} = 2400 + 400 = \mathbf{2800}$ N

Example 2 — Impulse and Change in Momentum

Question: A ball of mass 0.40 kg travelling at 12 m s^{-1} hits a wall and rebounds at 9.0 m s^{-1}. The collision lasts 0.025 s. Calculate (a) the impulse, (b) the average force on the ball.

Solution

Taking towards the wall as positive:

(a) $\Delta p = mv - mu = 0.40 \times (-9.0) - 0.40 \times 12 = -3.6 - 4.8 = -\mathbf{8.4}$ N s

Magnitude of impulse = 8.4 N s (directed away from wall).

(b) $F = \Delta p/\Delta t = -8.4/0.025 = -\mathbf{336}$ N

The average force on the ball is 336 N directed away from the wall.

Example 3 — Conservation of Momentum

Question: Trolley A (mass 2.0 kg, velocity +4.0 m s^{-1}) collides with stationary trolley B (mass 3.0 kg). After the collision, A moves at +1.0 m s^{-1}. Find the velocity of B and determine whether the collision is elastic.

Solution

Conservation of momentum (taking right as positive):

$p_{\text{before}} = 2.0 \times 4.0 + 3.0 \times 0 = 8.0$ kg m s^{-1}

$p_{\text{after}} = 2.0 \times 1.0 + 3.0 \times v_B = 2.0 + 3.0v_B$

$8.0 = 2.0 + 3.0v_B \implies v_B = \mathbf{2.0}$ m $\mathrm{s}^{\mathbf{-1}}$

Check for elastic collision:

KE before $= \frac{1}{2}(2.0)(4.0)^2 + 0 = 16.0$ J

KE after $= \frac{1}{2}(2.0)(1.0)^2 + \frac{1}{2}(3.0)(2.0)^2 = 1.0 + 6.0 = 7.0$ J

KE is not conserved ($16.0 \neq 7.0$) ⇒ the collision is **inelastic**.

Example 4 — Perfectly Inelastic Collision and Explosion

Question: (a) A bullet of mass 0.020 kg travelling at 350 m s^{-1} embeds in a stationary block of mass 1.98 kg. Find their common velocity after impact.

(b) A stationary rocket of mass 800 kg explodes into two fragments. Fragment A (300 kg) moves at +120 m s^{-1}. Find the velocity of fragment B.

Solution

(a) Perfectly inelastic — objects stick together:

$$mu = (m + M)v \implies v = \frac{0.020 \times 350}{0.020 + 1.98} = \frac{7.0}{2.0} = \mathbf{3.5}\ \text{m s}^{\mathbf{-1}}$$

(b) Total initial momentum = 0 (at rest):

$$0 = 300 \times 120 + 500 \times v_B \implies v_B = \frac{-36000}{500} = -\mathbf{72}\ \text{m s}^{\mathbf{-1}}$$

Fragment B moves at 72 m s^{-1} in the opposite direction to A.

Practice Exam Questions

Section A — Short Answer Questions

Q1. State Newton's three laws of motion. For each law, give a practical example.

[6 marks]

Q2. Define linear momentum and state its unit. Explain what is meant by the impulse of a force and state how it relates to momentum.

[4 marks]

Q3. A skydiver of mass 75 kg (including equipment) falls from rest. Describe and explain the motion from the moment of jumping until a terminal velocity of 55 m s^{-1} is reached. Include reference to the forces acting throughout.

[5 marks]

Q4. Distinguish between an elastic and an inelastic collision. State which quantities are conserved in each.

[3 marks]

Section B — Longer Structured Questions

Q5. A force–time graph for a golf club striking a ball (mass 0.046 kg, initially at rest) shows a peak force of 2400 N over a contact time of 5.0×10^{-4} s. Assume the force–time graph is a triangle.

(a) Calculate the impulse given to the ball.

[2 marks]

(b) Hence calculate the speed of the ball immediately after impact.

[2 marks]

(c) Calculate the average force on the club from the ball during contact, and state its direction.

[2 marks]

Q6. Two ice skaters, A (mass 60 kg) and B (mass 80 kg), stand at rest facing each other on a frictionless ice rink. They push off from each other. After the push, skater A moves at 2.4 m s^{-1} to the left.

(a) Calculate the velocity of skater B after the push.

[3 marks]

(b) Calculate the total kinetic energy after the push. Explain whether this is consistent with conservation of energy.

[3 marks]

Q7. Ball P (mass 0.30 kg, velocity +6.0 m s^{-1}) collides head-on with ball Q (mass 0.50 kg, velocity −2.0 m s^{-1}). After the collision, ball P has velocity −1.5 m s^{-1}.

(a) Use conservation of momentum to find the velocity of Q after the collision.

[3 marks]

(b) Calculate the kinetic energy before and after the collision and determine whether the collision is elastic or inelastic.

[3 marks]

(c) Verify your answer to (a) using the elastic collision condition $u_1 - u_2 = v_2 - v_1$.

[2 marks]

Mark Scheme and Answers

Q1. 1st: object at rest/constant velocity unless resultant force acts [1]; e.g. book on table [1]. 2nd: resultant force = rate of change of momentum / $F = ma$ [1]; e.g. pushing a trolley [1]. 3rd: equal and opposite forces on different objects, same type [1]; e.g. swimmer pushing wall, wall pushes swimmer back [1].

Q2. Momentum = mass × velocity [1]; unit: kg m s^{-1} or N s [1]. Impulse = force × time = $F\Delta t$ [1]; impulse equals the change in momentum [1].

Q3. Initially only weight acts; acceleration = g = 9.81 m s^{-2} downward [1]. As speed increases, air resistance increases [1]; resultant force decreases, acceleration decreases [1]; gradient of v–t graph decreases [1]; at terminal velocity (55 m s^{-1}): drag = mg = $75 \times 9.81 = 736$ N, resultant = 0, acceleration = 0 [1].

Q4. Elastic: both momentum and kinetic energy conserved [1]. Inelastic: momentum conserved, kinetic energy not conserved (converted to heat/sound/deformation) [1]. In all collisions, momentum is always conserved [1].

Q5(a). Triangular area: impulse = $\frac{1}{2} \times F_{\text{max}} \times t = \frac{1}{2} \times 2400 \times 5.0 \times 10^{-4} = \mathbf{0.60}$ N s [2].

Q5(b). $v = \Delta p/m = 0.60/0.046 = \mathbf{13}$ m s^{-1} [2].

Q5(c). By Newton's 3rd law, force on club = $0.60/5.0 \times 10^{-4}$ = **1200** N [1]; directed opposite to ball's motion (back toward the golfer) [1].

Q6(a). Initial total momentum = 0; $0 = 60 \times (-2.4) + 80 \times v_B$ [1]; $80v_B = 144$ [1]; $v_B = +\mathbf{1.8}$ m s^{-1} (to the right) [1].

Q6(b). KE = $\frac{1}{2}(60)(2.4)^2 + \frac{1}{2}(80)(1.8)^2 = 172.8 + 129.6 = \mathbf{302}$ J [2]. Initial KE = 0; energy is not conserved — the skaters' muscles do work (chemical energy converted to kinetic energy); this is an explosion, not a collision, so KE need not be conserved [1].

Q7(a). $p_{\text{before}} = 0.30 \times 6.0 + 0.50 \times (-2.0) = 1.8 - 1.0 = 0.80$ kg m s^{-1} [1]; $p_{\text{after}} = 0.30 \times (-1.5) + 0.50 \times v_Q = -0.45 + 0.50v_Q$ [1]; $0.80 = -0.45 + 0.50v_Q \implies v_Q = +\mathbf{2.5}$ m s^{-1} [1].

Q7(b). KE before = $\frac{1}{2}(0.30)(6.0)^2 + \frac{1}{2}(0.50)(2.0)^2 = 5.4 + 1.0 = 6.4$ J [1]; KE after = $\frac{1}{2}(0.30)(1.5)^2 + \frac{1}{2}(0.50)(2.5)^2 = 0.3375 + 1.5625 = 1.9$ J [1]; KE not conserved ⇒ **inelastic** [1].

Q7(c). $u_1 - u_2 = 6.0 - (-2.0) = 8.0$ m s^{-1}; $v_2 - v_1 = 2.5 - (-1.5) = 4.0$ m s^{-1} [1]; $8.0 \neq 4.0$ ⇒ confirms the collision is **inelastic** (elastic condition not satisfied) [1].

Revision Checklist

	Learning Objective	Confidence (1–3)
☐	Understand that mass is the property resisting change in motion	
☐	State and apply Newton's first law	
☐	Use $F = ma$ and $F = \Delta p/\Delta t$; know they are equivalent for constant mass	
☐	State and apply Newton's third law; identify Newton's third law pairs correctly	
☐	Define weight as $W = mg$ and locate it at the centre of gravity	
☐	Define momentum as $p = mv$ and state its unit	
☐	Define impulse as $F\Delta t = \Delta p$; find impulse from area under F–t graph	
☐	Describe qualitatively frictional and drag forces	
☐	Explain terminal velocity in terms of forces and draw v–t graph	
☐	Describe the motion of a parachutist opening their parachute	
☐	State the principle of conservation of momentum	
☐	Apply conservation of momentum to 1D and 2D collisions and explosions	
☐	Distinguish elastic and inelastic collisions by KE conservation	
☐	Use $u_1 - u_2 = v_2 - v_1$ to identify/verify an elastic collision	
☐	Understand that momentum is always conserved; KE only in elastic collisions	

Key: 1 = Need more work   2 = Getting there   3 = Confident

Good luck with your revision!

Dynamics is Newton's three laws working together. Everything from terminal velocity to collisions follows from $F = \Delta p/\Delta t$ and the simple rule that momentum is always conserved. Get those two ideas solid and you have the whole topic.