H2 Physics (9749)

Dynamics (Forces & Momentum) — LECTURE + EXAM Notes

A-Level 2027 Syllabus

Newton's Laws of Motion

Syllabus Learning Outcomes

By the end of this topic, you should be able to:

- State and apply Newton's three laws of motion
- Define inertia and relate it to Newton's First Law
- Apply $F = ma$ to solve problems involving constant mass
- Understand that force is a vector quantity and draw free body diagrams
- Apply Newton's Third Law to identify action-reaction pairs

Core Concepts

Newton's Laws form the foundation of classical mechanics. They describe the relationship between a body and the forces acting upon it, and its motion in response to those forces.

Newton's First Law (Law of Inertia)

Definition

Newton's First Law: A body continues in a state of rest or uniform motion in a straight line unless acted upon by a net external force.

This law introduces the concept of **inertia** — the tendency of a body to resist changes in its state of motion. The greater the mass, the greater the inertia.

Warning

Inertia is NOT the same as momentum. Inertia is a property of matter (mass); momentum is the quantity of motion a body possesses.

The First Law leads to the concept of **equilibrium** — when the net external force on a body is zero:

- A stationary body remains stationary
- A moving body continues at constant velocity

Mathematically: $\sum F = 0 \Rightarrow \frac{dv}{dt} = 0$

Newton's Second Law (Law of Acceleration)

Derivation

Derivation of $F = ma$ Starting from the definition of momentum:

$$p = mv \tag{1}$$

Newton's original formulation states that the rate of change of momentum is proportional to the net force:

$$F \propto \frac{dp}{dt} = \frac{d(mv)}{dt} \tag{2}$$

For constant mass:

$$\frac{d(mv)}{dt} = m\frac{dv}{dt} = ma \tag{3}$$

Thus:

$$F = ma \tag{4}$$

where F is the net force, m is the mass, and a is the acceleration.

Definition

Newton's Second Law: The net external force acting on a body is equal to the rate of change of momentum of that body, and acts in the direction of the change in momentum.

Key points:

- $F = ma$ applies when mass is constant
- Force is a **vector** — direction matters
- 1 N is defined as the force that gives a mass of 1 kg an acceleration of 1 m s^{-2}
- This law is the basis for most dynamics problems in A-Level

Example

Worked Example A car of mass 1200 kg accelerates from rest to 20 m s^{-1} in 8.0 s. Find the net force acting on the car.
Solution:

$$\begin{aligned} v &= u + at \\ 20 &= 0 + a(8) \\ a &= 2.5\text{ms}^{-2} \\ F &= ma = 1200 \times 2.5 = 3000\text{N} \end{aligned}$$

Newton's Third Law (Action and Reaction)

Definition

Newton's Third Law: For every action, there is an equal and opposite reaction.

This means:

- Forces ALWAYS occur in pairs
- The action and reaction are equal in magnitude but opposite in direction
- They act on **different bodies** — never on the same body

Warning

Common misconception: The action-reaction pair cancel each other out. **WRONG!** They act on different bodies, so they cannot cancel.

Exam Tip

When identifying action-reaction pairs, ask: "What exerts the force on what?"

Example

Identifying Action-Reaction Pairs A book rests on a table. Identify the action-reaction pairs.
Solution:

1. **Book on table** (weight): The book exerts a force on the table (downward). The table exerts an equal and opposite force on the book (upward) — this is the **normal force**.
2. **Table on Earth**: The table pulls the Earth upward (via gravity). The Earth pulls the table downward with equal force.

Note: The book's weight and the normal force are NOT an action-reaction pair because they act on the same body (the book).

Linear Momentum

Syllabus Learning Outcomes

- Define linear momentum as $p = mv$
- State the principle of conservation of momentum
- Apply conservation of momentum to solve collision problems
- Understand impulse as change in momentum

Core Concepts

Definition of Momentum

Definition

Linear momentum (p) is the product of mass and velocity:

$$p = mv \tag{5}$$

Momentum is a **vector** quantity with the same direction as velocity. SI unit: **kg m s^{-1}** (or Ns).

Momentum is a measure of the "quantity of motion" a body possesses. It depends on both mass and velocity:

- A heavy truck moving slowly can have the same momentum as a light car moving fast
- Both a stationary mass and a fast-moving light mass have zero momentum

Warning

Momentum has direction! Always specify direction when solving problems.

Impulse

Core Concepts

When a force acts on a body, it changes the body's momentum. The change in momentum depends on both the magnitude of the force and the time during which it acts.

Derivation

Derivation of Impulse From Newton's Second Law:

$$F = \frac{dp}{dt} \tag{6}$$

Rearranging and integrating over time:

$$\int_{t_1}^{t_2} F\,dt = \int_{p_1}^{p_2} dp = p_2 - p_1 = \Delta p \tag{7}$$

The left side is the **impulse**.

Definition

Impulse (J) is the change in momentum, equal to the product of force and time:

$$J = F\Delta t = \Delta p = mv_2 - mv_1 \tag{8}$$

Impulse is also a vector quantity. SI unit: **N s** (equivalent to kg m s^{-1}).

Exam Tip

Impulse can be calculated in two ways:

1. $J = F\Delta t$ — use when force and time are given
2. $J = \Delta p = m(v_2 - v_1)$ — use when velocities are given

Both give the same answer.

Example

Worked Example A tennis ball (mass 0.058 kg) is hit from rest to 50 m s^{-1} in 0.040 s. Find: (a) The change in momentum (b) The average force exerted on the ball
Solution:

$$(a)\ \Delta p = m(v_2 - v_1) = 0.058 \times (50 - 0) = 2.9 \text{kgms}^{-1}$$
$$(b)\ F_{\text{avg}} = \frac{\Delta p}{\Delta t} = \frac{2.9}{0.040} = 73\text{N}$$

Conservation of Momentum

The Principle

Derivation

Derivation from Newton's Laws Consider two bodies A and B colliding. By Newton's Third Law:

$$F_{AB} = -F_{BA} \tag{9}$$

By Newton's Second Law:

$$F_{AB} = \frac{dp_A}{dt}, \quad F_{BA} = \frac{dp_B}{dt} \tag{10}$$

So:

$$\frac{dp_A}{dt} = -\frac{dp_B}{dt} \Rightarrow \frac{d}{dt}(p_A + p_B) = 0 \tag{11}$$

Thus:

$$p_A + p_B = \text{constant} \tag{12}$$

Exam Tip

Conservation of momentum applies when:

1. No external forces act on the system (isolated system)
2. External forces are negligible compared to internal forces during collision
3. For problems in A-Level: often stated as "assuming no external forces" or "isolated system"

Warning

Momentum is ALWAYS conserved in collisions/explosions (internal forces only). Kinetic energy may or may not be conserved — this determines whether the collision is elastic or inelastic.

Collisions

When two bodies interact (collide or explode), both momentum and (usually) energy are involved. The type of collision determines what quantities are conserved.

Elastic Collisions

Definition

An **elastic collision** is one in which both momentum and kinetic energy are conserved.

For two bodies A and B:

$$m_A u_A + m_B u_B = m_A v_A + m_B v_B \quad \text{(momentum)} \tag{13}$$

$$\frac{1}{2}m_A u_A^2 + \frac{1}{2}m_B u_B^2 = \frac{1}{2}m_A v_A^2 + \frac{1}{2}m_B v_B^2 \quad \text{(kinetic energy)} \tag{14}$$

Example

Worked Example - Elastic Collision A trolley A (mass 2.0 kg) moving at 3.0 m s^{-1} collides elastically with a stationary trolley B (mass 2.0 kg). Find their velocities after collision.
Solution: Let $u_A = 3$, $u_B = 0$, $v_A = ?$, $v_B = ?$
Momentum conservation:

$$2(3) + 2(0) = 2v_A + 2v_B \Rightarrow v_A + v_B = 3 \quad (1)$$

Kinetic energy conservation:

$$\frac{1}{2}(2)(3^2) = \frac{1}{2}(2)v_A^2 + \frac{1}{2}(2)v_B^2 \Rightarrow v_A^2 + v_B^2 = 9 \quad (2)$$

$$v_A + v_B = 3 \quad (1)$$

Substituting into equation (2):

$$(3 - v_B)^2 + v_B^2 = 9 \Rightarrow 9 - 6v_B + v_B^2 + v_B^2 = 9 \Rightarrow 2v_B^2 = 6v_B$$

$$v_B(2v_B - 6) = 0 \Rightarrow v_B = 0 \text{ or } v_B = 3$$

If $v_B = 0$, then $v_A = 3$ (no collision!) — reject.
So $v_B = 3\text{ms}^{-1}$, $v_A = 0\text{ms}^{-1}$.
Result: The trolleys exchange velocities completely.

In general, for equal masses in an elastic collision: velocities are exchanged.

Inelastic Collisions

Definition

An **inelastic collision** is one in which momentum is conserved but kinetic energy is NOT conserved. Some kinetic energy is converted to other forms (sound, heat, deformation).

For perfectly inelastic collisions (bodies stick together):

$$m_A u_A + m_B u_B = (m_A + m_B)v \quad (15)$$

Warning

In inelastic collisions, $KE_{\text{final}} < KE_{\text{initial}}$. Never use the kinetic energy conservation equation!

Example

Worked Example - Perfectly Inelastic Collision A bullet (mass 0.010 kg) traveling at 200 m s^{-1} embeds itself in a stationary block (mass 2.0 kg). Find the velocity of the block-bullet system after impact.
Solution:

$$\text{Momentum before} = 0.010 \times 200 + 2.0 \times 0 = 2.0\text{kgms}^{-1}$$
$$\text{Momentum after} = (0.010 + 2.0) \times v$$
$$2.0 = 2.01v$$
$$v = 0.995 \approx 1.0\text{ms}^{-1}$$

Coefficient of Restitution

The coefficient of restitution (e) quantifies how "bouncy" a collision is.

Definition

The coefficient of restitution is defined as the ratio of the relative speed of separation to the relative speed of approach:

$$e = \frac{\text{relative speed of separation}}{\text{relative speed of approach}} = \frac{v_B - v_A}{u_A - u_B} \tag{16}$$

- $e = 1$: Perfectly elastic collision
- $e = 0$: Perfectly inelastic collision (objects stick together)
- $0 < e < 1$: Real-world inelastic collision

Exam Tip

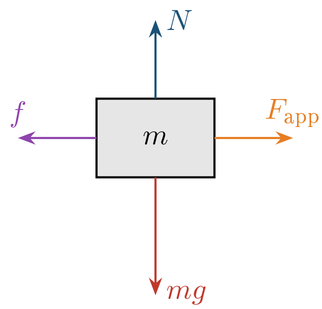
For one-dimensional collisions, always define direction clearly. Use positive for one direction, negative for the other.

Free Body Diagrams

A free body diagram (FBD) is essential for solving dynamics problems. It shows all forces acting on a body, drawn from the point of application.

Rules for drawing FBDs:

1. Isolate the body of interest
2. Represent the body as a point or simple shape
3. Draw each force as an arrow from the point, in the correct direction
4. Label each force with its magnitude or source (e.g., mg, N, F, f)
5. **NEVER** include forces that the body exerts on other bodies
6. Include weight (mg) unless stated otherwise



Warning

In the FBD above, mg and N are NOT an action-reaction pair! They both act on the same body (the block). The action-reaction pairs are: (1) block on Earth (Earth pulls block down), (2) Earth on block (block pulls Earth up), and (1) block on table (block pushes table down), (2) table on block (table pushes block up).

Exam Notes: Dynamics

Command Words & What They Require

Command Word

State Give a brief, concise answer — usually one word, phrase, or equation. No explanation required.

Example State

State Newton's Second Law of motion.

Answer: $F = ma$ *or "The net force equals mass times acceleration."*

Command Word

Define Give a precise meaning of a concept. Usually requires an equation where applicable.

Example Define

Define linear momentum.

Answer: Linear momentum is the product of mass and velocity: $p = mv$.

Command Word

Explain Give a reason for a phenomenon. Requires physics reasoning, not just stating facts.

Example Explain

Explain why a passenger in a car is thrown forward when the car suddenly stops.

Answer: Due to inertia, the passenger tends to continue in their state of motion. When the car stops, the passenger's body continues moving forward until restrained by the seatbelt.

Command Word

Calculate Show working and arrive at a numerical answer with appropriate units.

Example Calculate

Calculate the impulse delivered to a ball of mass 0.20 kg when it is hit from rest to 30 m s^{-1}.

Answer: $J = \Delta p = 0.20 \times 30 = 6.0\ N\ s$

Command Word

Determine Similar to calculate but may involve rearranging or solving equations.

Mark Allocation Patterns

In Dynamics questions, mark allocation typically follows patterns:

Marks	What Required	Example
1	State a fact, definition, or simple equation	State the equation for momentum
2	Apply a formula with substitution OR give a simple explanation	Calculate force given mass and a celeration.
3	Multi-step calculation OR explanation with reasoning	Explain why momentum is co served in an isolated system.
4-5	Complex problem with multiple steps OR detailed explanation	Solve a collision problem using bo momentum and energy consider tions.

Exam Tip

In calculation questions:

- 1 mark: Correct equation
- 1 mark: Correct substitution with units
- 1 mark: Correct final answer with units
- Remaining marks: Working steps

Question Templates

Template 1: Newton's Laws Application

1. Identify all forces acting on the body
2. Draw a clear free body diagram
3. Resolve forces into components if needed
4. Apply $F = ma$ in the appropriate direction
5. Solve for the unknown

Template 2: Collision Problems

1. Define positive direction
2. Write momentum conservation equation: $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$
3. Determine if kinetic energy is conserved (elastic vs inelastic)
4. Write additional equation if needed
5. Solve simultaneous equations
6. Check direction of velocities

Template 3: Impulse Problems

1. Identify initial and final velocities
2. Calculate change in momentum: $\Delta p = m(v_2 - v_1)$
3. If force/time given: $J = F\Delta t$
4. Equate and solve

Answering Techniques: SUVA Framework

For structured physics questions, use the **SUVA** framework:

- **S**tate: State the relevant principle or equation
- **U**se: Use the equation (substitute values)
- **V**alue: Calculate the value
- **A**nswer: State final answer with units

Example

SUVA Application Question: A 5.0 kg block is pulled with a force of 20 N. If the coefficient of kinetic friction is 0.30, find the acceleration of the block.
Solution:

1. **S**tate: $F_{\text{net}} = ma$, $f_k = \mu_k N$
2. **U**se: $N = mg = 5.0 \times 9.8 = 49\text{N}$
   $f_k = 0.30 \times 49 = 14.7\text{N}$
   $F_{\text{net}} = 20 - 14.7 = 5.3\text{N}$
3. **V**alue: $a = 5.3/5.0 = 1.06\text{ms}^{-2}$
4. **A**nswer: $a = 1.1\text{ms}^{-2}$ (2 s.f.)

Timing Guide

Question Type	**Time per Mark**
State/Define (1m)	1 minute
Simple calculation (2-3m)	1.5 minutes per mark
Complex problem (4-6m)	2 minutes per mark
Essay/explanation (5-8m)	2 minutes per mark

Exam Tip

For a typical 25-mark paper:

- 25 minutes for Section A (multiple choice)
- 75 minutes for Section B (structured questions)
- Leave 5 minutes for checking

Common Errors to Avoid

Warning

Common Mistake 1: Forgetting to include direction Momentum and velocity are vectors. Always specify direction or use positive/negative signs.

Warning

Common Mistake 2: Using wrong conservation equation In inelastic collisions, kinetic energy is NOT conserved. Only use momentum conservation.

Warning

Common Mistake 3: Action-reaction pairs on same body The forces in an action-reaction pair act on DIFFERENT bodies. They never cancel.

Warning

Common Mistake 4: Using weight instead of mass $F = mg$ gives weight (a force), not mass. In $F = ma$, m is mass (kg), F is force (N).

Warning

Common Mistake 5: Forgetting to square velocities in KE Kinetic energy: $KE = \frac{1}{2}mv^2$. Many students forget the v^2 term in collision problems.

Warning

Common Mistake 6: Not considering initial conditions In collision problems, the initial velocities must be clearly defined. Watch for "initially at rest" or "moving at..."

Key Equations Summary

Equation	Name	When to Use
$F = ma$	Newton's Second Law	Constant mass, net force given
$p = mv$	Definition of momentum	Any momentum calculation
$J = F\Delta t = \Delta p$	Impulse-momentum theorem	Force and time known, or velocity change
$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$	Momentum conservation	Any collision/explosion problem
$e = \frac{v_B - v_A}{u_A - u_B}$	Coefficient of restitution	Determining elastic/inelastic nature
$KE = \frac{1}{2}mv^2$	Kinetic energy	Elastic collisions, energy considerations

Connections to Other Topics

Dynamics connects to many other topics in the H2 Physics syllabus:

- **Oscillations**: Simple harmonic motion derives from $F = -kx$, a type of force law
- **Gravitation**: Newton's laws applied to gravitational fields
- **Electric Fields**: Similar force laws (Coulomb's law parallels Newton's)
- **Momentum in Fluids**: Pressure and momentum transfer
- **Work, Energy, Power**: Energy methods as alternative to force-based analysis

The conservation of momentum principle extends to:

- Collisions and explosions
- Rocket propulsion
- Recoil of guns
- Angular momentum (in rotational dynamics)