IB DP PHYSICS · THEME A SPACE, TIME AND MOTION · A.2 · ~12 MIN READ

A.2 Forces and momentum

Newton's three laws, free-body diagrams, every contact and field force (friction, Hooke's law, Stokes drag, buoyancy), momentum, impulse, collisions and explosions, and circular motion.

Newton's laws | Free-body diagrams | Friction & Hooke's law | Drag & buoyancy | Momentum & impulse | Collisions | Circular motion

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No tag = **SL and HL** HL ONLY HL students only DATA BOOKLET given in the exam

M1 A1 how marks are awarded highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

- A **force** is an interaction between two bodies. **Newton's first law:** no resultant force, no change in velocity. **Second law:** F = ma, or more generally F = Δp/Δt. **Third law:** forces come in equal and opposite pairs acting on different bodies.
- **Free-body diagrams** show every force on one body. Resolve them, add them up, and the resultant gives the acceleration.
- **Momentum p = mv** is conserved when no resultant external force acts. **Impulse J = FΔt = Δp** is the area under a force–time graph.
- **Circular motion** needs a resultant force towards the centre, F = mv^2/r. It changes the direction of the velocity, not the speed.
- **A.2 is the same at SL and HL.** There is no additional higher level content.

BY THE END YOU CAN

- State and apply Newton's three laws, and identify third-law pairs correctly.
- Draw free-body diagrams and find resultant forces, including on slopes and in lifts.
- Use friction, Hooke's law, viscous drag and buoyancy equations.
- Apply conservation of momentum to collisions and explosions, and decide whether a collision is elastic.
- Use impulse and force–time graphs.
- Analyse uniform circular motion with v = ωr and a = v^2/r.

1 Newton's laws

The three laws

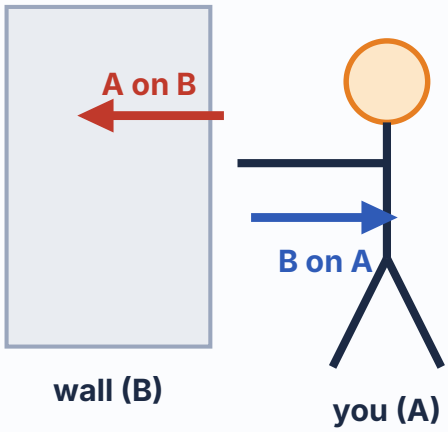
First law — a body stays at rest or moves with constant velocity unless a resultant force acts on it. Balanced forces do NOT mean "not moving".

Second law — the resultant force equals the rate of change of momentum, F = Δp/Δt. For constant mass this becomes F = ma.

Third law — if body A exerts a force on body B, then B exerts an equal and opposite force of the same type on A.

$$F = ma$$ DATA BOOKLET

F is the RESULTANT force, in N; a in m s^{-2}



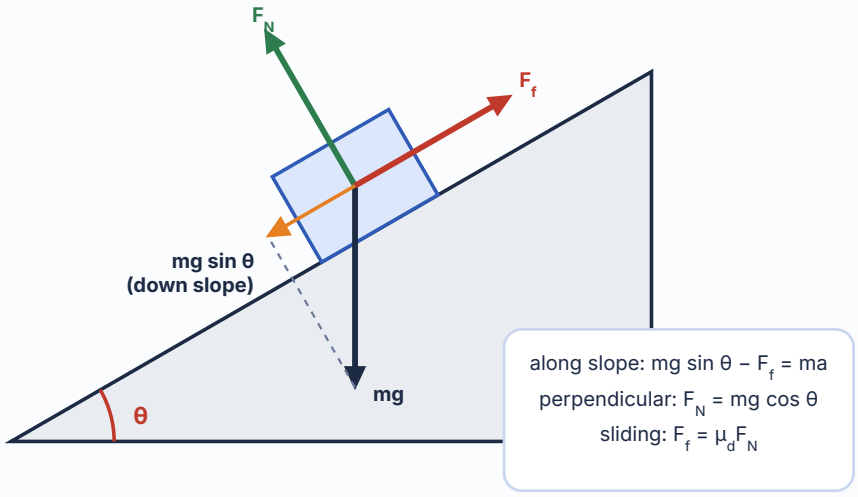
Newton's third law pair:
same size, opposite direction,
same type of force,
acting on DIFFERENT bodies.
Weight and normal reaction on a
book are NOT a third-law pair.

The two forces in a third-law pair act on different bodies, so they never cancel each other.

COMMON MISTAKE

Calling weight and the normal reaction 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**.

Free-body diagrams and resolving



Draw only the forces acting ON the block. Resolve along and perpendicular to the slope.

- **Rules:** one body, every force as an arrow from the body, labelled with its type. No "forces of motion" and no forces the body exerts on other things.
- **Slopes:** the weight splits into **mg sin θ** down the slope and **mg cos θ** into the slope.

WORKED EXAMPLE

A 5.0 kg block slides down a 30° slope with μ_d = 0.20. Find its acceleration.

1. $F_N = mg\cos 30° = 5.0 \times 9.8 \times 0.866 = 42.4$ N **M1**
2. $F_f = 0.20 \times 42.4 = 8.49$ N up the slope **M1**
3. resultant down the slope = $5.0 \times 9.8 \times 0.5 - 8.49 = 16.0$ N **M1**
4. **$a = 16.0/5.0 = 3.2$ m s^{-2}** **A1**

WORKED EXAMPLE

A 60 kg student stands on scales in a lift accelerating upwards at 1.5 m s^{-2}. What do the scales read?

1. up is +: $F_N - mg = ma$ **M1**
2. $F_N = 60(9.8 + 1.5) =$ **678 N** **A1**
3. **the scales read more than her weight (588 N); moving down at constant speed they would read 588 N**

WORKED EXAMPLE

Masses of 3.0 kg and 2.0 kg hang on either side of a light frictionless pulley. Find the acceleration and the tension.

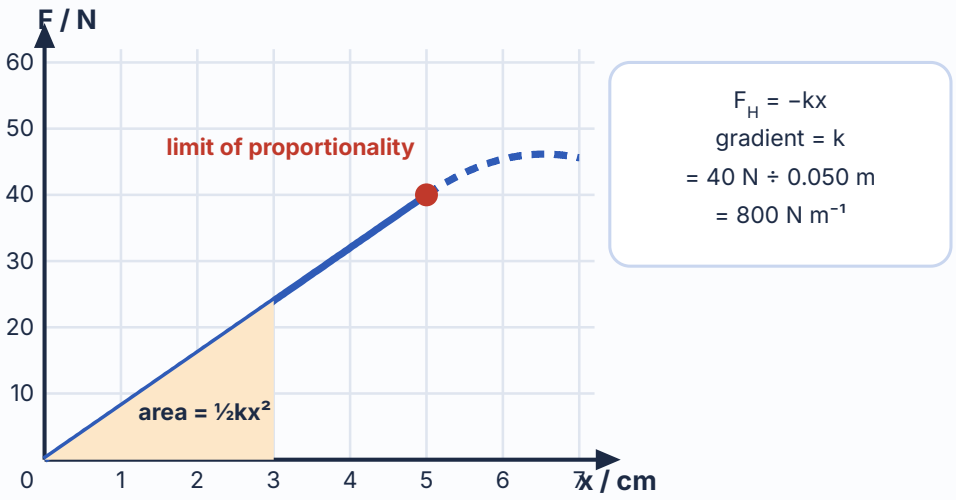
1. whole system: $(3.0 - 2.0)g = (3.0 + 2.0)a \Rightarrow a =$ **1.96 m s^{-2}** **M1** **A1**
2. for the 2.0 kg mass: $T - 2.0g = 2.0a$ **M1**
3. **$T = 2.0(9.8 + 1.96) = 23.5$ N** **A1**

2 The forces you need

Force	Equation	Notes
weight	$F_g = mg$	$g = 9.8$ N kg^{-1} near Earth
static friction	$F_f \le \mu_s F_N$	grows to match the push, up to a maximum
dynamic friction	$F_f = \mu_d F_N$	while sliding; $\mu_d < \mu_s$
elastic (Hooke)	$F_H = -kx$	minus: the force opposes the extension
viscous drag	$F_d = 6\pi\eta rv$	Stokes: small sphere, slow, smooth flow
buoyancy	$F_b = \rho Vg$	ρ and V of the displaced FLUID

- All of these are in the data booklet DATA BOOKLET. Field forces (gravitational, electric, magnetic) act at a distance and are covered in theme D.

Hooke's law

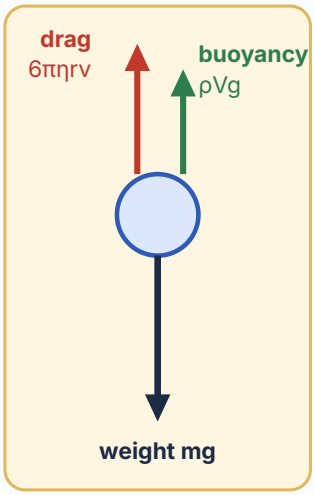


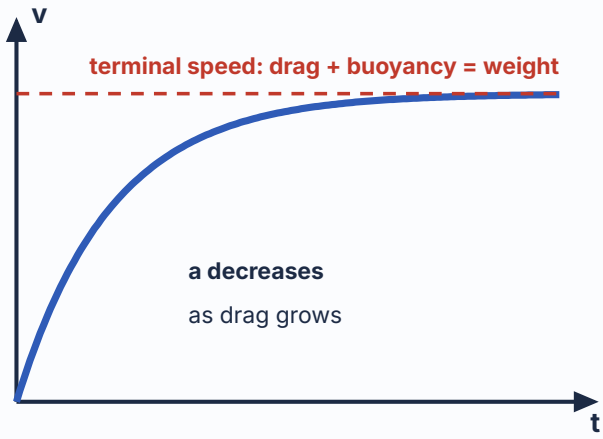
$F_H = -kx$
gradient = k
= 40 N ÷ 0.050 m
= 800 N m^{-1}

Up to the limit of proportionality the force is proportional to the extension. The gradient is the spring constant.

- **Springs in series** are easier to stretch (smaller overall k); **springs in parallel** are stiffer. Work it out from the force on each spring rather than memorising a rule.

Drag, buoyancy and terminal speed





As the ball speeds up, drag grows until the forces balance. From then on it falls at a constant terminal speed.

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WORKED EXAMPLE

A steel ball of radius 1.0 mm falls through oil (η = 0.80 Pa s, ρ_{oil} = 900 kg m^{-3}; ρ_{steel} = 7800 kg m^{-3}). Find its terminal speed.

1. $V = \frac{4}{3}\pi(1.0 \times 10^{-3})^3 = 4.19 \times 10^{-9}$ m^3 M1
2. weight − buoyancy = $(7800 - 900) \times 4.19 \times 10^{-9} \times 9.8 = 2.83 \times 10^{-4}$ N M1
3. at terminal speed this equals $6\pi\eta rv$ M1
4. **$v = 2.83 \times 10^{-4} \div (6\pi \times 0.80 \times 1.0 \times 10^{-3}) = 0.019$ m s^{-1}** A1

COMMON MISTAKE

Using the density of the ball in $F_b = \rho Vg$. Buoyancy uses the density of the **fluid** that is pushed aside.

3 Momentum and impulse

$$p = mv$$ DATA BOOKLET

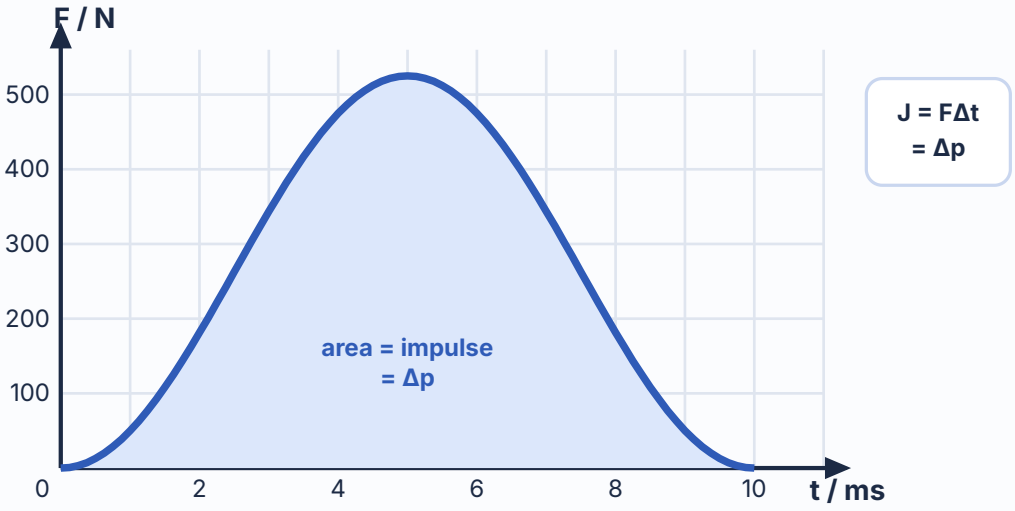
a vector, in kg m s^{-1} (or N s)

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

works even when the mass changes (rockets, conveyor belts)

$$J = F\Delta t = \Delta p$$ DATA BOOKLET

impulse, in N s



A longer contact time (padding, bending your knees) gives the same Δp with a smaller force.

For a changing force, the impulse is the area under the force–time graph.

WORKED EXAMPLE

A 0.15 kg ball hits a wall at 20 m s^{-1} and rebounds at 15 m s^{-1}. Contact lasts 10 ms. Find the impulse and the mean force.

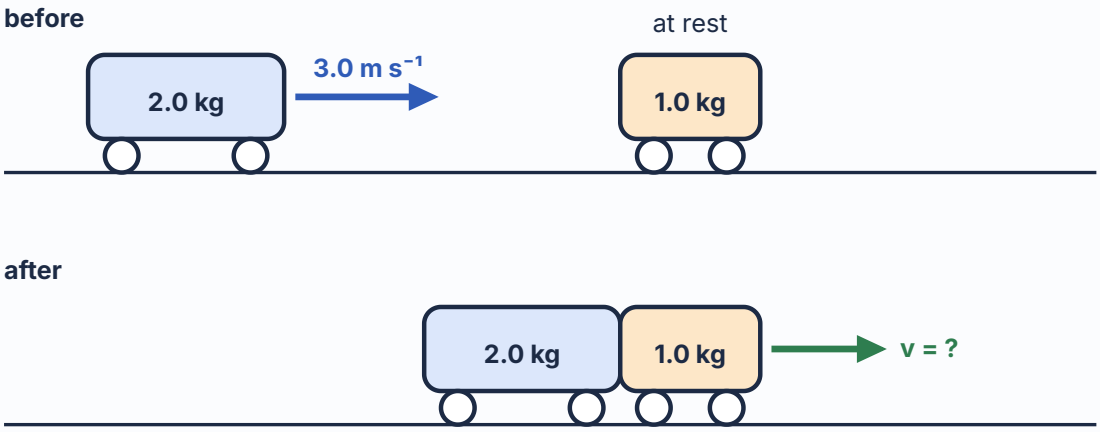
1. towards the wall is +: $\Delta p = 0.15(-15) - 0.15(20) = -5.25$ N s M1 A1
2. impulse **5.3 N s** away from the wall
3. **$F = \Delta p/\Delta t = 5.25/0.010 = 525$ N** A1

COMMON MISTAKE

Forgetting the change of direction: $\Delta p = 0.15(20 - 15) = 0.75$ N s is wrong. The velocity changes from +20 to −15, a change of 35 m s^{-1}.

Conservation of momentum

- **In a closed system** (no resultant external force), total momentum before = total momentum after. This comes straight from Newton's third law.



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

The trolleys stick together, so they share one final velocity.

WORKED EXAMPLE

In the diagram, is the collision elastic?

1. E_k before = ½ × 2.0 × 3.0^2 = 9.0 J M1
2. E_k after = ½ × 3.0 × 2.0^2 = 6.0 J M1
3. **kinetic energy is lost (3.0 J becomes internal energy and sound), so the collision is inelastic** R1

Elastic collision — total kinetic energy is conserved (momentum is always conserved).

Inelastic collision — kinetic energy is lost. "Perfectly inelastic" means the bodies stick together.

Explosion — total momentum stays zero (if it started at rest), but kinetic energy increases, coming from chemical or elastic energy.

WORKED EXAMPLE

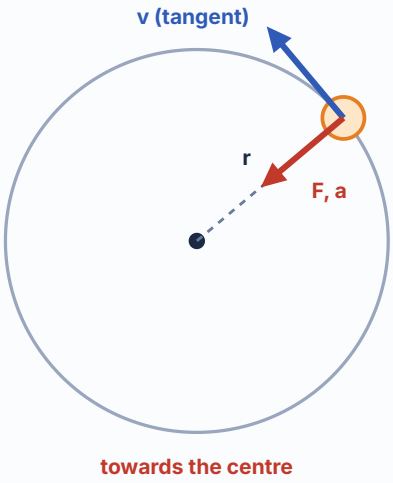
Two skaters push off each other from rest: 60 kg and 40 kg. The 40 kg skater moves off at 1.5 m s^{-1}. Find the other skater's velocity.

1. $0 = 40(1.5) + 60v$ M1
2. **$v = -1.0$ m s^{-1}, so 1.0 m s^{-1} the opposite way** A1

$$E_k = \frac{p^2}{2m}$$ DATA BOOKLET

useful in explosions: equal momenta, so the lighter body gets more kinetic energy

4 Circular motion



$v = 2\pi r/T = \omega r$
$a = v^2/r = \omega^2 r = 4\pi^2 r/T^2$
$F = mv^2/r$
The force is at 90° to v, so it changes direction, not speed. No work done. Something must supply it: tension, friction, gravity...

The velocity is along the tangent. The acceleration and the resultant force point to the centre.

$$v = \frac{2\pi r}{T} = \omega r$$ DATA BOOKLET

ω is angular velocity in rad s^{-1}

$$a = \frac{v^2}{r} = \omega^2 r = \frac{4\pi^2 r}{T^2}$$ DATA BOOKLET

centripetal acceleration, towards the centre

- **Centripetal force is not a new force.** It is the name for the resultant force towards the centre. Always say which real force provides it: tension, friction, gravity, the normal force.

WORKED EXAMPLE

A 1200 kg car rounds a flat bend of radius 50 m at 15 m s^{-1}. Find the friction needed and the minimum μ_s.

1. $F = mv^2/r = 1200 \times 15^2/50 =$ **5400 N** M1 A1
2. **friction ≤ $\mu_s mg$, so $\mu_s \geq 5400/(1200 \times 9.8) = 0.46$** M1 A1

WORKED EXAMPLE

A 0.50 kg ball on a string moves in a vertical circle of radius 0.80 m. At the top its speed is 4.0 m s^{-1}. Find the tension there.

1. at the top both T and mg point down, towards the centre R1
2. $T + mg = mv^2/r$ M1
3. $T = 0.50 \times 16/0.80 - 0.50 \times 9.8 =$ **5.1 N** A1
4. **at the bottom $T - mg = mv^2/r$, so the string is tightest there**

COMMON MISTAKE

Adding "centripetal force" as an extra arrow on a free-body diagram. Draw only the real forces; their resultant is the centripetal force.

EXAM TIP

"Explain why the passenger feels pushed outwards" is a favourite. There is no outward force: the passenger's body tends to continue in a straight line (first law) and the door pushes them inwards.

LINKING QUESTION

Gravity provides the centripetal force for orbits. Set $GMm/r^2 = mv^2/r$ and you get the orbital speed in D.1.

IDEA FOR YOUR IA / EXPLORATION

Investigate how the terminal speed of a ball in a tall tube of glycerol (or washing-up liquid) depends on its radius. Stokes' law predicts $v \propto r^2$: test it with a log–log graph.

Test yourself — cover the answers first

QUICK CHECK

1. State Newton's first law.
2. A book rests on a table. What is the third-law partner of its weight?
3. What happens to the reading on lift scales when the lift accelerates downwards?
4. Give the unit of impulse in two forms.
5. What is conserved in every collision in a closed system?
6. Which way does the resultant force point for uniform circular motion?
7. Does a centripetal force do work?

EXAM-STYLE

8. A 2.0 kg box is pulled along a rough floor by a 15 N force at 30° above the horizontal; $\mu_d = 0.30$. Find the acceleration.
9. A 0.020 kg bullet at 400 m s^{-1} embeds itself in a 2.0 kg block on ice. Find the final speed and the kinetic energy lost.
10. A satellite moves in a circular orbit of radius 7.0×10^6 m with period 98 minutes. Find its centripetal acceleration.

Show answers

1. A body stays at rest or at constant velocity unless a resultant force acts on it.
2. the gravitational force of the book on the Earth
3. it is less than the weight
4. N s and kg m s^{-1}
5. momentum (kinetic energy only in elastic collisions)
6. towards the centre of the circle
7. No: it is perpendicular to the velocity.
8. $F_N = mg - 15 \sin 30° = 19.6 - 7.5 = 12.1$ N
   $F_f = 0.30 \times 12.1 = 3.63$ N
   resultant $= 15 \cos 30° - 3.63 = 13.0 - 3.63 = 9.36$ N
   $a = 9.36/2.0 =$ **4.7 m s^{-2}**
9. $0.020 \times 400 = 2.02v \Rightarrow v =$ **3.96 m s^{-1}**
   E_k before $= \frac{1}{2}(0.020)(400^2) = 1600$ J; after $= \frac{1}{2}(2.02)(3.96^2) = 15.8$ J
   lost ≈ **1580 J**
10. $T = 98 \times 60 = 5880$ s
    $a = 4\pi^2 r/T^2 = 4\pi^2(7.0 \times 10^6)/5880^2$
    $a =$ **8.0 m s^{-2}**

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