

THEME A · SPACE, TIME AND MOTION

SL & HL ≈ 35 min read

IB Physics A.2 Forces and Momentum — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). A.2 has no additional HL content; the only SL/HL difference is that HL students must also handle collisions and explosions in two dimensions (see the HL box in the collisions section).

 SL A.2 questions HL A.2 questions Flashcards Circular motion simulation Collisions simulation Terminal velocity simulation

What this page covers

- ✓ Newton's three laws of motion, and forces as interactions between two bodies
- ✓ Drawing free-body diagrams and using them to find the resultant force
- ✓ Contact forces: normal force, static and dynamic friction, tension, the elastic force of a spring (Hooke's law), viscous drag on a small sphere and buoyancy
- ✓ Field forces: weight, and electric and magnetic forces
- ✓ Linear momentum and when it stays constant
- ✓ Impulse, force–time graphs, and impulse as change in momentum
- ✓ Why $F = \frac{\Delta p}{\Delta t}$ is more general than $F = ma$ (changing mass)
- ✓ Elastic and inelastic collisions, explosions, and what happens to kinetic energy in each
- ✓ Circular motion: angular velocity, centripetal acceleration and centripetal force

In one minute

- A body's velocity changes only if a **resultant** force acts on it; $F = ma$, or more generally $F = \Delta p / \Delta t$.
- Newton's third-law forces come in pairs that act on **different** bodies, so they never cancel each other.
- A free-body diagram shows every force on *one* body; add the forces as vectors to get the resultant.
- Static friction adjusts itself up to a maximum $\mu_s F_N$; once sliding, friction is $\mu_d F_N$.
- Impulse $J = F \Delta t$ equals change in momentum. Momentum is conserved in every collision and explosion of an isolated system; kinetic energy is conserved only in elastic collisions.
- Uniform circular motion has constant speed but changing velocity: a resultant (centripetal) force acts towards the centre, $F = \frac{mv^2}{r}$.

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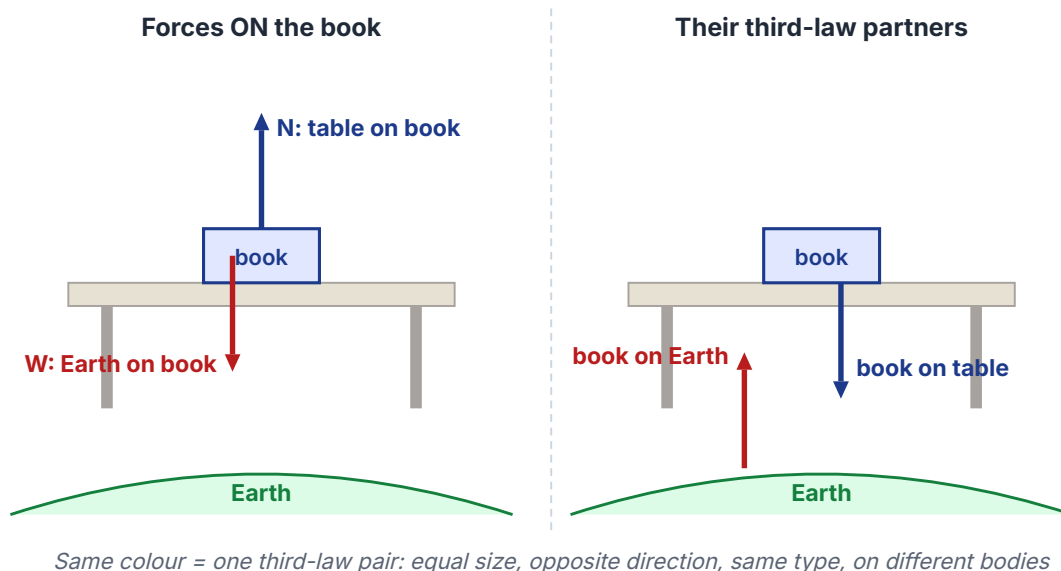
What are Newton's three laws of motion?

Kinematics (A.1) describes motion; dynamics explains it. A **force** is an interaction between two bodies — a push or a pull exerted *by* one body *on* another. It is a vector, measured in newtons (N), where $1 \text{ N} = 1 \text{ kg m s}^{-2}$.

Law	Statement (examinable wording)	What you use it for
First law	A body stays at rest or keeps moving with constant velocity unless a resultant external force acts on it.	Translational equilibrium: if the velocity is constant (including zero), the forces balance, $\Sigma F = 0$.
Second law	The resultant force on a body is equal to its rate of change of momentum, $F = \frac{\Delta p}{\Delta t}$. For constant mass this becomes $F = ma$.	Finding the acceleration from the resultant force, or the force from a measured acceleration.
Third law	If body A exerts a force on body B, then B exerts a force on A that is equal in magnitude and opposite in direction.	Identifying force pairs; explaining recoil, rockets, walking, swimming.

A resultant force causes acceleration, not motion. A body moving at constant velocity has zero resultant force on it — it does not need a force to “keep it going”.

- The first law defines **inertia**: a body resists changes to its velocity. Mass is the measure of inertia.
- In $F = ma$, F is always the **resultant** (net) force, and a is in the same direction as F .
- A Newton's third law pair has four properties: the two forces are **equal in size**, **opposite in direction**, of the **same type** (both gravitational, both contact, ...) and act on **different bodies**.



The normal force and the weight both act on the book, so they are not a third-law pair — even though they are equal and opposite here. The partner of the weight is the book's gravitational pull on the Earth.

How do you draw and use a free-body diagram?

A free-body diagram shows one body on its own with every external force acting on it, each drawn as a labelled arrow in the direction of the force and with a length proportional to its size.

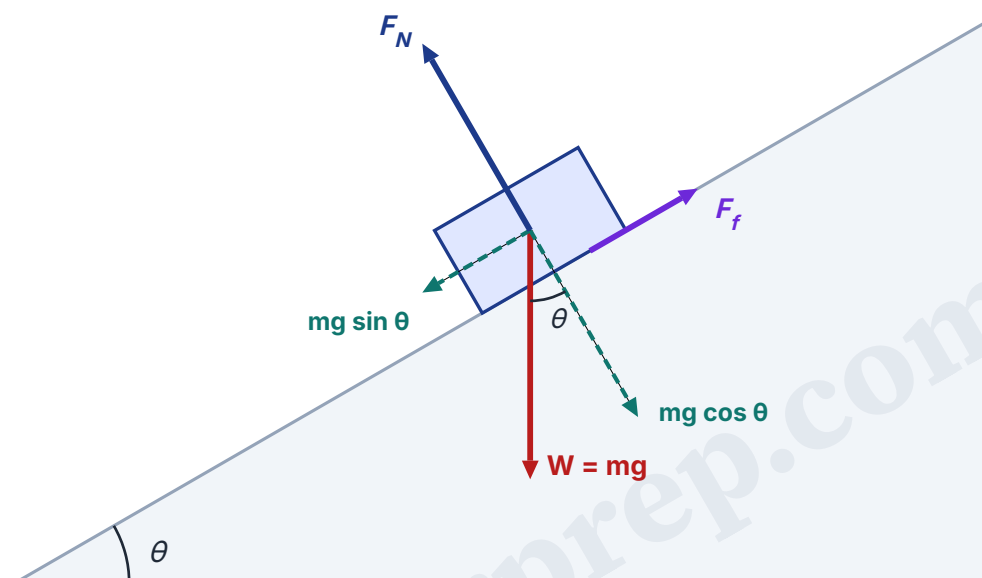
- Draw **one body only**. Forces that the body exerts on other things do not belong on its diagram.
- Start each arrow on the body (at the point of action, or at the centre for a point-particle model). Use standard labels: W or F_g , F_N , F_f , T , F_d , F_b .
- Make the arrow lengths consistent with the motion: equal and opposite if the body is in equilibrium, unequal in the direction of any acceleration.
- Never add "resultant force" or "centripetal force" as an extra arrow — the resultant is what the real forces *add up to*.

Finding the resultant force

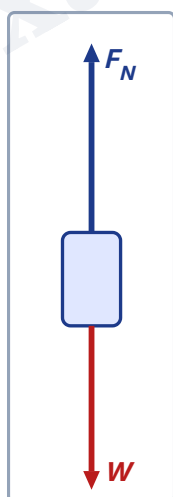
- In one dimension, choose a positive direction and add the forces with signs.
- In two dimensions, resolve every force into two perpendicular components (usually parallel and perpendicular to the motion or the surface), then add

each set separately: ΣF_x and ΣF_y .

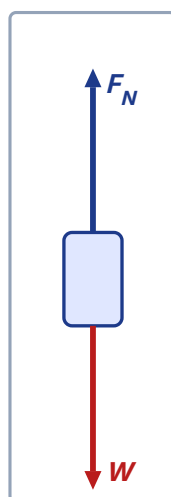
- For a body on a slope of angle θ , the weight resolves into $mg \sin \theta$ **down the slope** and $mg \cos \theta$ **into the slope**.
- **Translational equilibrium** (Newton's first law): $\Sigma F_x = 0$ and $\Sigma F_y = 0$.



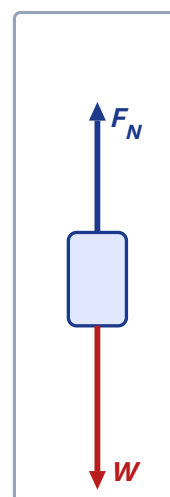
Block at rest on a rough slope. The dashed arrows are the components of the weight; they replace the weight in calculations — they are not extra forces. Perpendicular to the slope $F_N = mg \cos \theta$; along the slope $F_f = mg \sin \theta$.



accelerating upwards
 $a = 1.5 \text{ m s}^{-2} \uparrow$
 $F_N > W$



constant velocity
 $a = 0$
 $F_N = W$



accelerating downwards*
 $a = 2.0 \text{ m s}^{-2} \downarrow$
 $F_N < W$

A person standing on scales in a lift. The scales read the normal force, not the weight.

*"Accelerating downwards" includes moving upwards while slowing down — it is the direction of the acceleration that matters, not of the velocity.

WORKED EXAMPLE 1 Easy · Calculate

A student of mass 62.0 kg stands on bathroom scales in a lift. Calculate the reading of the scales, in newtons, when the lift (a) accelerates upwards at 1.5 m s^{-2} , (b) moves upwards at a constant speed, (c) slows down at 2.0 m s^{-2} as it approaches the top floor.

Forces on the student: F_N up (the scale reading) and $W = mg$ down. Take **up as positive**: $F_N - mg = ma \Rightarrow F_N = m(g + a)$.

(a) $a = +1.5$: $F_N = 62.0(9.8 + 1.5) = \mathbf{701 \text{ N}}$

(b) $a = 0$: $F_N = 62.0 \times 9.8 = \mathbf{608 \text{ N}}$ (equal to the weight)

(c) Moving up but slowing down, so the acceleration is downwards: $a = -2.0$. $F_N = 62.0(9.8 - 2.0) = \mathbf{484 \text{ N}}$

EXAM TIP — APPARENT WEIGHT

“Feeling heavier” in a lift means the normal force is larger than the weight. The weight mg itself does not change. State this explicitly: the scale reading is the *normal force* exerted by the scales on the person.

Which contact forces do you need to know?

Contact forces arise when bodies touch. At the microscopic level they are electromagnetic forces between the atoms of the two surfaces.

Normal force F_N

The normal force is the component of the contact force that acts perpendicular to the surface, pushing the body away from the surface.

- It is **not** always equal to mg : on a slope $F_N = mg \cos \theta$; in an accelerating lift $F_N = m(g + a)$; if someone pushes down on a box, F_N increases.

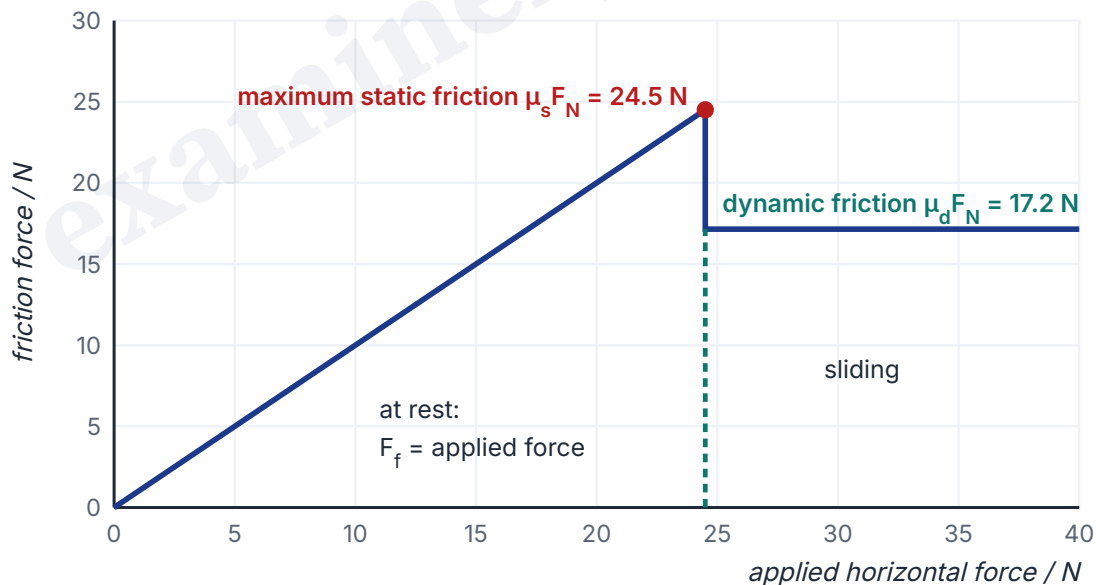
- F_N becomes zero when the body loses contact with the surface.

Friction F_f

Surface friction acts parallel to the surface of contact and opposes the relative motion (or the tendency to relative motion) of the two surfaces.

$$F_f \leq \mu_s F_N \quad (\text{static, body at rest}) \qquad F_f = \mu_d F_N \quad (\text{dynamic, body sliding})$$

- μ_s = coefficient of static friction; μ_d = coefficient of dynamic friction (no units). Usually $\mu_d < \mu_s$.
- F_N = normal force (N). Both equations are in the data booklet.
- Static friction is **only as large as it needs to be** to stop sliding. $\mu_s F_N$ is its *maximum* value, reached just before the body starts to slide.
- Friction can act in the direction of motion: the road pushes a driven car's tyres *forwards*, and friction makes you walk.



A 5.0 kg block on a horizontal floor with $\mu_s = 0.50$ and $\mu_d = 0.35$ ($F_N = 49$ N). While the block is at rest the friction matches the applied force; once it slides, friction drops to the constant dynamic value.

WORKED EXAMPLE 2 Medium · Determine

A crate of mass 12 kg rests on a loading ramp inclined at 25° to the horizontal. Between the crate and the ramp $\mu_s = 0.55$ and $\mu_d = 0.40$.

- (a) Determine the magnitude and direction of the friction force on the crate.
 (b) The ramp is raised to 35° . Show that the crate now slides, and determine its acceleration.

(a) Component of weight down the slope: $mg \sin 25^\circ = 12 \times 9.8 \times \sin 25^\circ = 49.7 \text{ N}$.

Maximum static friction: $\mu_s F_N = 0.55 \times 12 \times 9.8 \times \cos 25^\circ = 58.6 \text{ N}$.

Since $49.7 \text{ N} < 58.6 \text{ N}$ the crate stays at rest, and friction balances the down-slope component exactly: **$F_f \approx 50 \text{ N up the slope}$** . (Not 58.6 N — static friction only reaches its maximum when sliding is about to start.)

(b) At 35° : $mg \sin 35^\circ = 67.5 \text{ N}$ but $\mu_s F_N = 0.55 \times 12 \times 9.8 \times \cos 35^\circ = 53.0 \text{ N}$. The down-slope component exceeds the maximum static friction, so the crate slides.

Sliding: $F_f = \mu_d F_N = 0.40 \times 96.3 = 38.5 \text{ N}$.

$$a = \frac{67.5 - 38.5}{12} = \mathbf{2.4 \text{ m s}^{-2} \text{ down the slope}}$$

Mass cancels: $a = g(\sin \theta - \mu_d \cos \theta) = 9.8(\sin 35^\circ - 0.40 \cos 35^\circ) = 2.41 \text{ m s}^{-2}$.

Sliding starts when $\tan \theta = \mu_s$, here at 28.8° .

Tension T

- Tension is the pulling force exerted by a stretched string, rope, cable or rod on the body attached to it. It acts **along** the string, away from the body.
- For a light (massless) string, the tension is the same all along it — also over a frictionless pulley.
- A string can only pull, never push. If the calculated tension is negative, the string has gone slack.

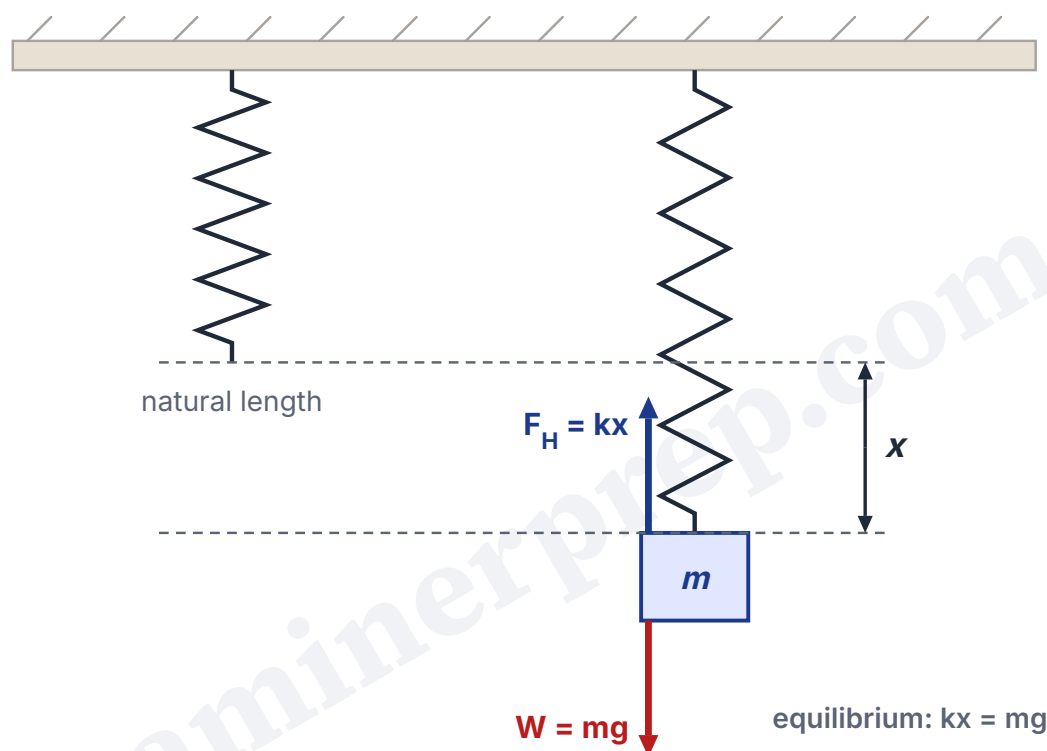
Elastic restoring force F_H — Hooke's law

Hooke's law: the elastic restoring force of a spring is proportional to its extension and acts in the opposite direction to it, $F_H = -kx$.

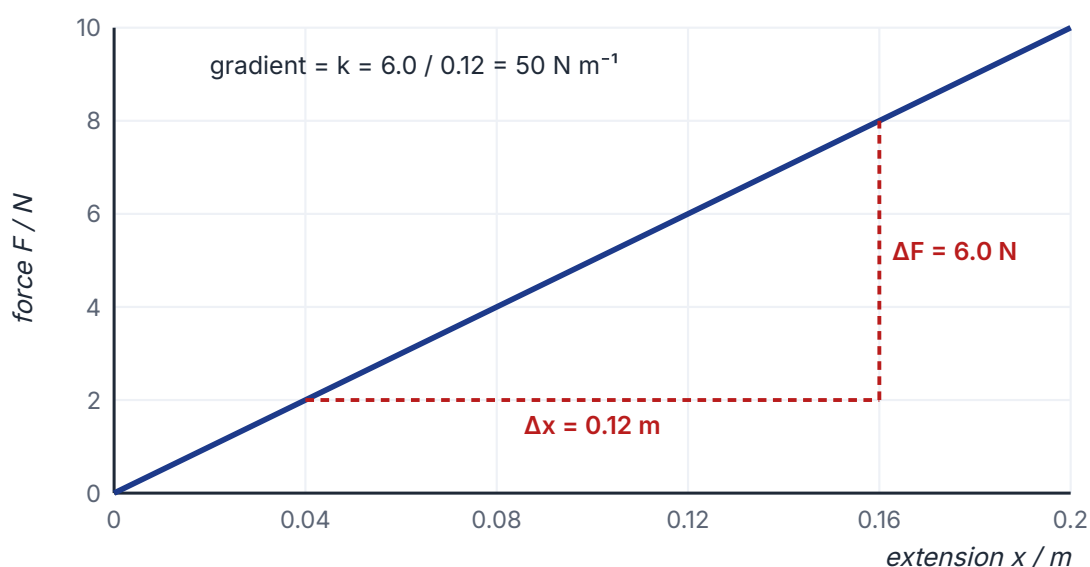
- k = spring constant (N m^{-1}), x = extension or compression from the natural length (m). The minus sign shows that the force opposes the displacement —

it restores the spring towards its natural length.

- When you only need the size, use $F = kx$. On a graph of applied force against extension, k is the gradient.
- A stiffer spring has a larger k . The law holds only up to the limit of proportionality.



A mass hanging in equilibrium on a spring: the upward elastic force kx balances the weight mg .



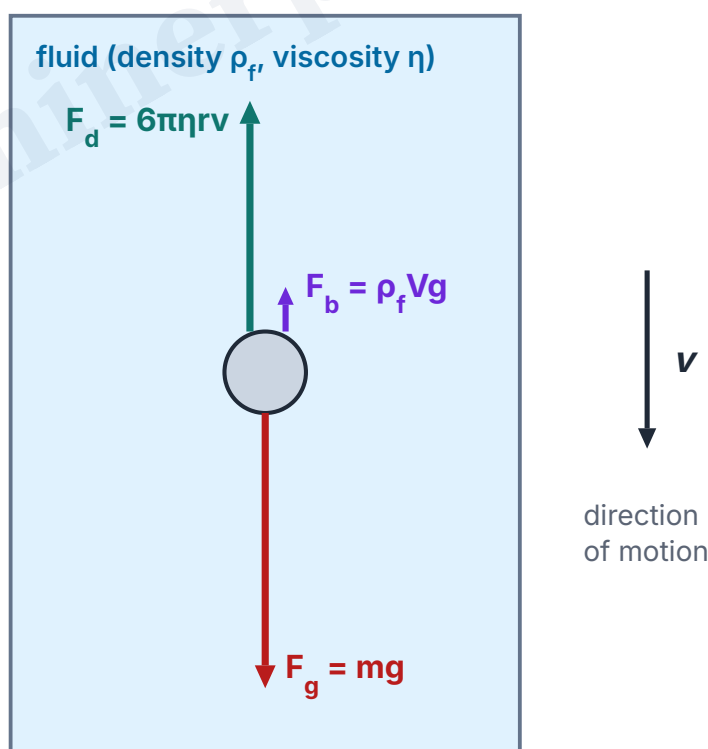
Force against extension for a spring with $k = 50 \text{ N m}^{-1}$. The graph is a straight line through the origin, and its gradient is the spring constant.

Viscous drag F_d and buoyancy F_b

$$F_d = 6\pi\eta rv$$

$$F_b = \rho Vg$$

- η = viscosity of the fluid (Pa s), r = radius of the sphere (m), v = speed of the sphere relative to the fluid (m s^{-1}).
- ρ = density of the **fluid** (kg m^{-3}), V = volume of fluid **displaced** (m^3) — the submerged volume of the body.
- $F_d = 6\pi\eta rv$ (Stokes' law) applies to a **small sphere moving slowly** so that the flow is smooth. Drag opposes the velocity and grows with speed.
- Buoyancy (upthrust) equals the weight of fluid displaced and acts upwards. A floating body displaces its own weight of fluid: $F_b = W$.
- For a sphere falling at terminal speed: $F_d + F_b = F_g$, so $6\pi\eta rv_t = (\rho_s - \rho_f)Vg$.



At terminal speed: $F_d + F_b = F_g$

Forces on a small sphere falling at terminal speed in a viscous liquid, drawn to scale for worked example 3: drag and buoyancy together balance the weight.

WORKED EXAMPLE 3 Hard · Show that / Explain

A steel ball-bearing of radius 1.5 mm and density 7800 kg m^{-3} is released from rest in a tall tube of glycerol. Glycerol has density 1260 kg m^{-3} and viscosity 1.5 Pa s .

(a) Calculate the weight of the ball and the buoyancy force on it. (b) Show that the terminal speed of the ball is about 0.021 m s^{-1} . (c) Explain why the initial acceleration of the ball is less than g .

(a) $V = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi(1.5 \times 10^{-3})^3 = 1.414 \times 10^{-8} \text{ m}^3$

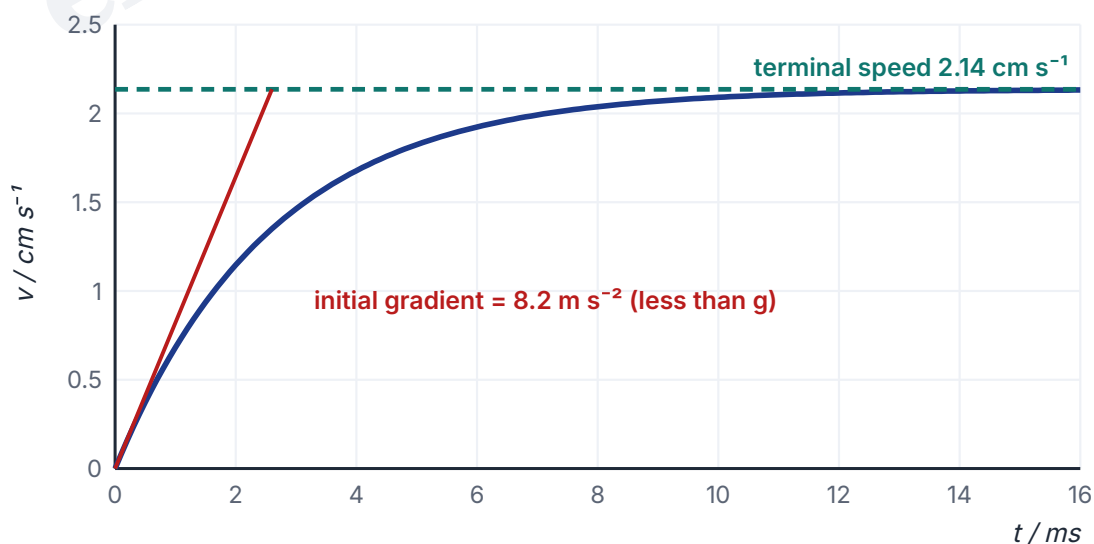
$F_g = \rho_s V g = 7800 \times 1.414 \times 10^{-8} \times 9.8 = \mathbf{1.08 \times 10^{-3} \text{ N}}$

$F_b = \rho_f V g = 1260 \times 1.414 \times 10^{-8} \times 9.8 = \mathbf{1.75 \times 10^{-4} \text{ N}}$

(b) At terminal speed the resultant force is zero: $F_d = F_g - F_b = 1.081 \times 10^{-3} - 1.75 \times 10^{-4} = 9.06 \times 10^{-4} \text{ N}$.

$v_t = \frac{F_d}{6\pi\eta r} = \frac{9.06 \times 10^{-4}}{6\pi \times 1.5 \times 10^{-3}} = \mathbf{0.0214 \text{ m s}^{-1}} \approx 0.021 \text{ m s}^{-1}$

(c) At release $v = 0$, so there is no drag, but buoyancy already acts upwards. The resultant force $F_g - F_b$ is smaller than the weight, so $a = \frac{F_g - F_b}{m} = \left(1 - \frac{\rho_f}{\rho_s}\right)g = 8.2 \text{ m s}^{-2}$, which is less than g .



Speed of the ball in worked example 3. It is within 2 % of its terminal speed after about 10 ms. The initial gradient is 8.2 m s^{-2} , not g , because of buoyancy.

TRY IT YOURSELF

A.2 Terminal Velocity simulation: change the mass, size and fluid and watch drag grow until the forces balance.

What are field forces?

Field forces act **at a distance**: the bodies do not need to touch. In A.2 you need to recognise them and include them correctly in free-body diagrams; their detailed treatment comes in Theme D.

Force	Acts on	Equation at this stage	Developed in
Gravitational force (weight) F_g	any body with mass	$F_g = mg$ (data booklet), with $g = 9.8 \text{ N kg}^{-1}$ near the Earth's surface	D.1
Electric force F_e	charged bodies	attractive or repulsive; acts along the electric field for a positive charge	D.2
Magnetic force F_m	moving charges and current-carrying conductors	perpendicular to both the velocity (or current) and the magnetic field	D.3

- Weight acts at the centre of mass and points towards the centre of the Earth (vertically downwards).
- Mass (kg) is a property of the body; weight (N) is a force that depends on the local gravitational field strength.

What are momentum and impulse?

Linear momentum is the product of mass and velocity, $p = mv$. It is a vector in the direction of the velocity, with unit kg m s^{-1} (equivalently N s).

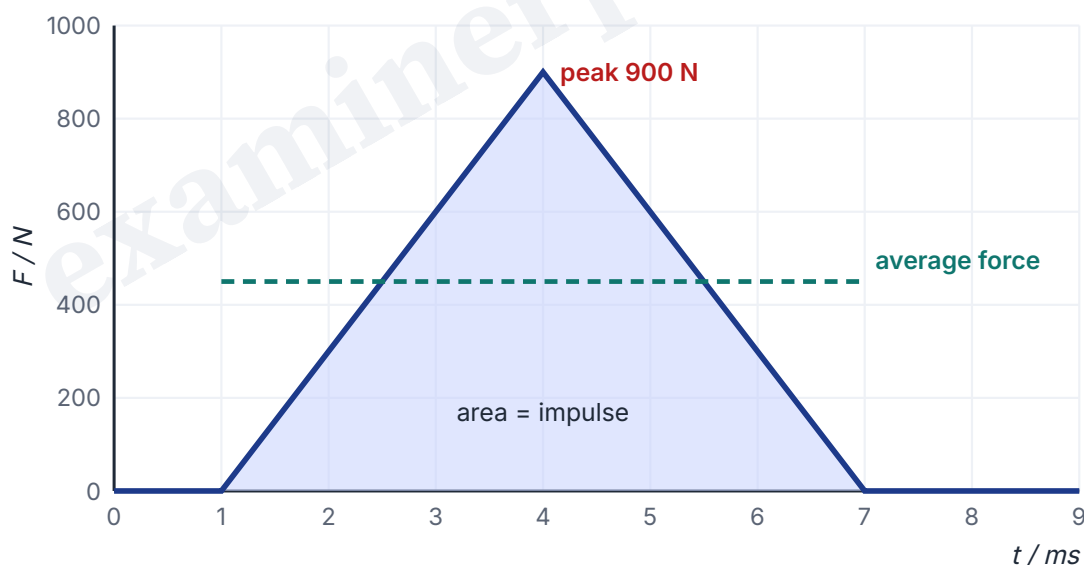
- The momentum of a system stays constant unless a **resultant external force** acts on the system.

- Newton's second law in its general form: $F = \frac{\Delta p}{\Delta t}$ — the resultant force equals the rate of change of momentum.

Impulse

Impulse is the product of the average resultant force and the time for which it acts, $J = F\Delta t$. The impulse applied to a body equals its change in momentum, $J = \Delta p$.

- J = impulse (N s), F = average resultant force (N), Δt = time of contact (s).
- For a force that varies, the impulse is the **area under the force–time graph**.
- For the same change in momentum, a longer contact time means a smaller average force. This is the physics of airbags, crumple zones and bending your knees on landing. Following through with a racket or bat works the other way round: it increases Δt , so the same force gives a larger impulse.



Force–time graph for a ball in contact with a racket for 6.0 ms. The shaded area is the impulse; a rectangle at the average force over the same 6.0 ms has the same area.

WORKED EXAMPLE 4 Medium · Determine (graph)

A tennis ball of mass 58 g travels horizontally towards a racket at 18 m s^{-1} . The graph above shows how the force exerted by the racket on the ball varies with time. The ball leaves along the same line in the opposite direction.

Determine (a) the impulse on the ball, (b) the speed with which the ball leaves the racket and (c) the average force exerted by the racket on the ball.

(a) Impulse = area of the triangle = $\frac{1}{2} \times (6.0 \times 10^{-3}) \times 900 = \mathbf{2.7 \text{ N s}}$
(away from the racket).

(b) Take the direction away from the racket as positive, so $u = -18 \text{ m s}^{-1}$.
 $J = m(v - u) \Rightarrow 2.7 = 0.058(v - (-18)) \Rightarrow v = \frac{2.7}{0.058} - 18 = \mathbf{29 \text{ m s}^{-1}}$ (28.6 m s⁻¹)

(c) $F = \frac{J}{\Delta t} = \frac{2.7}{6.0 \times 10^{-3}} = \mathbf{450 \text{ N}}$

The common error is to use $\Delta v = 29 - 18$. When a body reverses, the magnitudes of the velocities add: $\Delta v = 28.6 + 18 = 46.6 \text{ m s}^{-1}$.

When mass changes: why $F = \Delta p / \Delta t$ is more general than $F = ma$

$F = ma$ assumes the mass of the body is constant. $F = \frac{\Delta p}{\Delta t}$ also works when mass is being gained or lost — a rocket ejecting exhaust gas, sand falling onto a conveyor belt, or a jet of water hitting a wall. In these cases $\frac{\Delta p}{\Delta t} = v \frac{\Delta m}{\Delta t}$, where $\frac{\Delta m}{\Delta t}$ is the mass flow rate and v is the change in velocity given to that mass (for example, from rest to the exhaust speed, or from the jet speed to rest).

Example. A hose sends 2.5 kg of water per second horizontally at 12 m s^{-1} against a wall, where it stops. Each second the water loses momentum $2.5 \times 12 = 30 \text{ kg m s}^{-1}$, so the wall exerts 30 N on the water and, by Newton's third law, the water exerts **30 N** on the wall.

How is momentum conserved in collisions and explosions?

The law of conservation of linear momentum: the total momentum of a system is constant provided no resultant external force acts on it.

- During a collision the two bodies exert equal and opposite forces on each other (third law) for the same time, so they receive equal and opposite impulses. The momentum one gains, the other loses.
- External forces such as friction are usually negligible during the very short collision time, so the system can be treated as isolated.
- **Method:** choose a positive direction; write total momentum before = total momentum after, with signs; solve.

Event	Momentum	Total kinetic energy	Energy transfer
Elastic collision	conserved	conserved	none overall (kinetic energy is temporarily stored as elastic energy during contact)
Inelastic collision	conserved	decreases	kinetic energy → internal (thermal) energy, sound, permanent deformation
Bodies stick together (totally inelastic)	conserved	largest possible decrease	as above; the bodies move off with a common velocity
Explosion	conserved (often zero before and after)	increases	chemical or elastic potential energy → kinetic energy

- Kinetic energy and momentum are linked by $E_k = \frac{p^2}{2m}$ (data booklet, A.3). In an explosion from rest the pieces have equal and opposite momenta, so the **lighter piece gets more kinetic energy**.
- When two equal masses collide elastically head-on and one is initially at rest, they exchange velocities (think of Newton's cradle).
- You will not be asked to solve simultaneous momentum and energy equations for an elastic collision; you may be asked to *check* whether kinetic energy is conserved.

WORKED EXAMPLE 5 Medium · Calculate / Determine

Trolley A (mass 0.80 kg) moves at 0.60 m s^{-1} towards trolley B (mass 1.20 kg), which is at rest. They collide and stick together.

(a) Calculate the velocity of the trolleys after the collision. (b) Determine the fraction of the initial kinetic energy that is transferred to other forms. (c) Determine the impulse exerted on A by B.

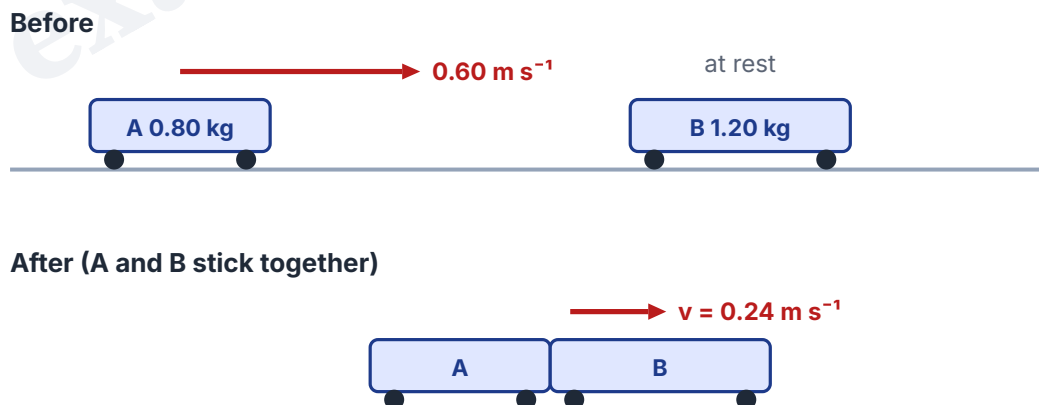
(a) Momentum before = momentum after: $0.80 \times 0.60 + 1.20 \times 0 = (0.80 + 1.20)v \Rightarrow v = \frac{0.48}{2.00} = \mathbf{0.24 \text{ m s}^{-1}}$ in A's original direction.

(b) E_k before = $\frac{1}{2}(0.80)(0.60)^2 = 0.144 \text{ J}$; E_k after = $\frac{1}{2}(2.00)(0.24)^2 = 0.0576 \text{ J}$.

Fraction transferred = $\frac{0.144 - 0.0576}{0.144} = \mathbf{0.60 \text{ (60 \%)}}$, mainly to internal energy and sound.

(c) $J_A = m_A(v - u) = 0.80(0.24 - 0.60) = \mathbf{-0.29 \text{ N s}}$ (0.288 N s, opposite to A's original motion).

Check with the third law: the impulse on B is $1.20 \times 0.24 = +0.288 \text{ N s}$ — equal and opposite, as it must be.



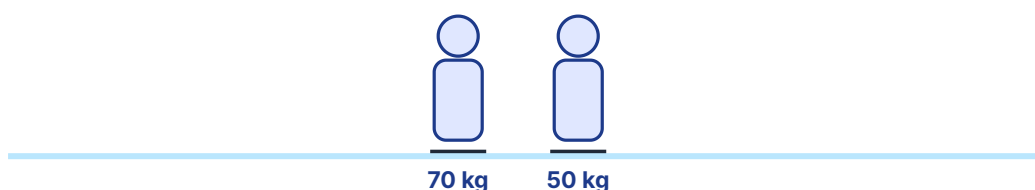
Before and after a collision in which the two trolleys couple together (worked example 5). Velocity arrows are drawn to the same scale.

Explosions

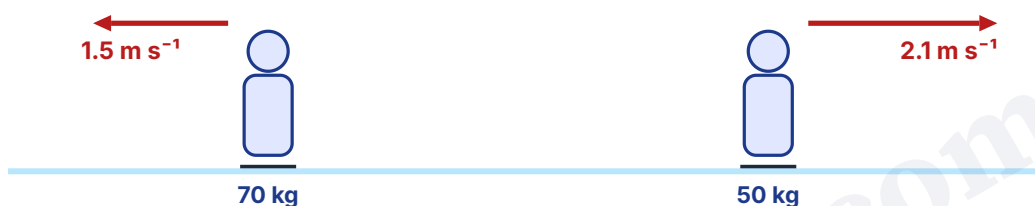
In an explosion a system that starts at rest has zero total momentum, so afterwards the momenta of the parts must still add to zero: the parts fly apart in

opposite directions. The kinetic energy comes from a store of chemical or elastic potential energy.

Before: both at rest, total momentum = 0



After pushing apart



$$70 \times (-1.5) + 50 \times (+2.1) = -105 + 105 = 0 \text{ kg m s}^{-1}$$

Two skaters at rest push apart. Their momenta are equal and opposite (105 kg m s^{-1} each). The lighter skater moves faster and receives more kinetic energy: 110 J against 79 J , a total of 189 J supplied by their muscles.

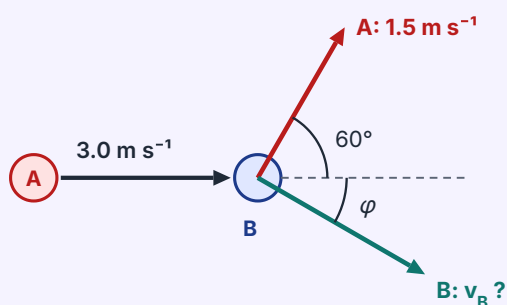
TRY IT YOURSELF

A.2 Momentum & Collisions simulation: set the masses and velocities, switch between elastic and inelastic collisions and compare total momentum and kinetic energy before and after.

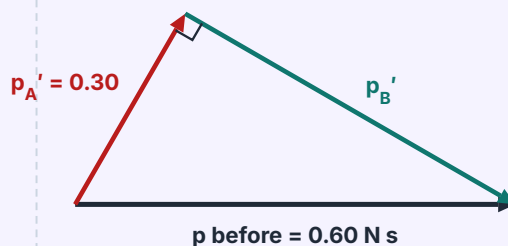
HL Collisions in two dimensions

At HL you need to treat collisions and explosions quantitatively in **two dimensions** (SL: one dimension only). Momentum is a vector, so it is conserved separately in each of two perpendicular directions: Σp_x before = Σp_x after, and Σp_y before = Σp_y after. Equivalently, the momentum vectors after the collision add (tip-to-tail) to the momentum vector before.

Top view



Momentum vectors (to scale)



$$p_A' + p_B' = p \text{ before (closed triangle)}$$

Puck A (0.20 kg , 3.0 m s^{-1}) strikes puck B (0.30 kg , at rest). A leaves at 1.5 m s^{-1} at 60° to its original line; B moves off at an angle φ on the other side of the original line. The momentum vectors after the collision form a closed triangle with the momentum before.

Solution. Before: $p_x = 0.20 \times 3.0 = 0.60 \text{ N s}$, $p_y = 0$.

A after: $p_x = 0.20 \times 1.5 \cos 60^\circ = 0.15 \text{ N s}$, $p_y = 0.20 \times 1.5 \sin 60^\circ = 0.26 \text{ N s}$.

B after: $p_x = 0.60 - 0.15 = 0.45 \text{ N s}$, $p_y = 0 - 0.26 = -0.26 \text{ N s}$, so
 $p_B = \sqrt{0.45^2 + 0.26^2} = 0.52 \text{ N s}$ at $\varphi = \tan^{-1}(0.26/0.45) = 30^\circ$ below the original line.

$v_B = \frac{0.52}{0.30} = 1.7 \text{ m s}^{-1}$ (1.73 m s^{-1}).

Kinetic energy: before 0.900 J ; after $\frac{1}{2}(0.20)(1.5)^2 + \frac{1}{2}(0.30)(1.73)^2 = 0.225 + 0.450 = 0.675 \text{ J}$. Kinetic energy decreased, so the collision is **inelastic**.

How do you describe and explain circular motion?

A body moving in a circle at **constant speed** is still accelerating, because the *direction* of its velocity is always changing. Newton's first law then tells us that a resultant force must act on it.

Describing the motion

Angular velocity ω is the rate of change of the angle swept out by the radius, $\omega = \frac{\Delta\theta}{\Delta t}$, measured in rad s^{-1} . In uniform circular motion one revolution (2π rad) takes one period T , so $\omega = \frac{2\pi}{T}$.

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

- v = linear (tangential) speed (m s^{-1}), r = radius of the circle (m), T = period, the time for one revolution (s), ω = angular velocity (rad s^{-1}).
- Frequency $f = \frac{1}{T}$, so also $\omega = 2\pi f$. Convert revolutions per minute to rad s^{-1} by multiplying by $\frac{2\pi}{60}$.
- The velocity is always **tangent** to the circle.

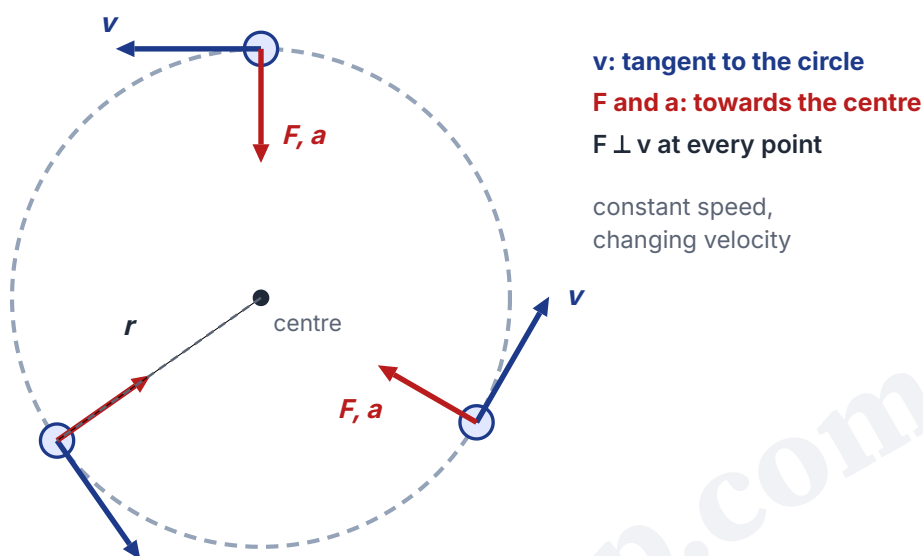
Centripetal acceleration and centripetal force

A body moving along a circular path at constant speed has a centripetal acceleration directed towards the centre of the circle, of magnitude $a = \frac{v^2}{r} = \omega^2 r = \frac{4\pi^2 r}{T^2}$.

- The resultant force that produces this acceleration is the **centripetal force**:

$$F = ma = \frac{mv^2}{r} = m\omega^2 r.$$
 (Only the acceleration is in the data booklet; combine it with $F = ma$.)
- The centripetal force acts **perpendicular to the velocity**. It changes the direction of motion but not the speed, and it does no work.
- "Centripetal" describes the direction of a resultant force; it is **not a new kind of force**. It is always provided by real forces, such as tension, friction, gravity, the normal force or a magnetic force.
- If the speed is changing (non-uniform circular motion), the resultant force also has a component along the velocity; the component towards the centre is still $\frac{mv^2}{r}$.

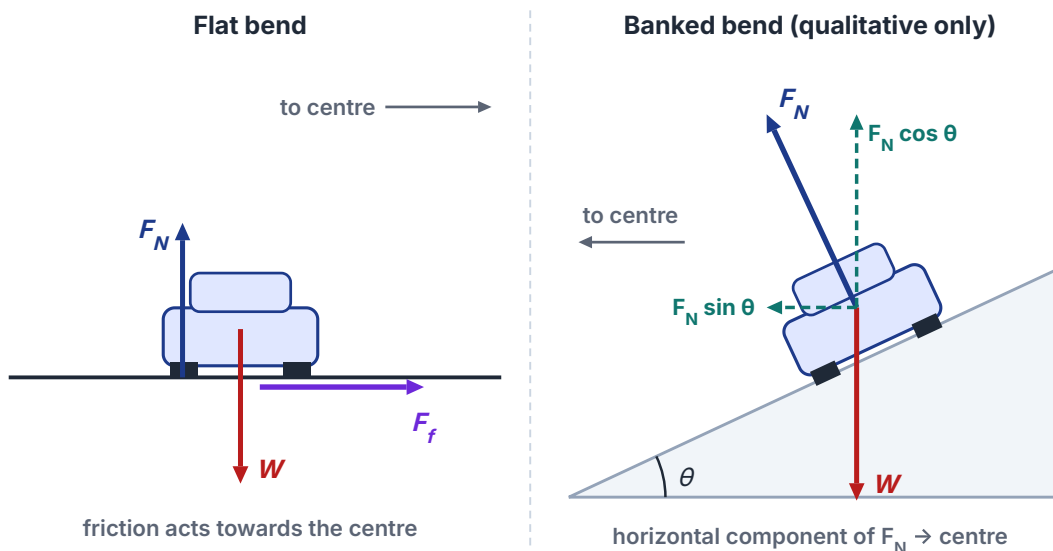
- If the centripetal force is removed, the body moves off along the tangent (Newton's first law) — not outwards along the radius.



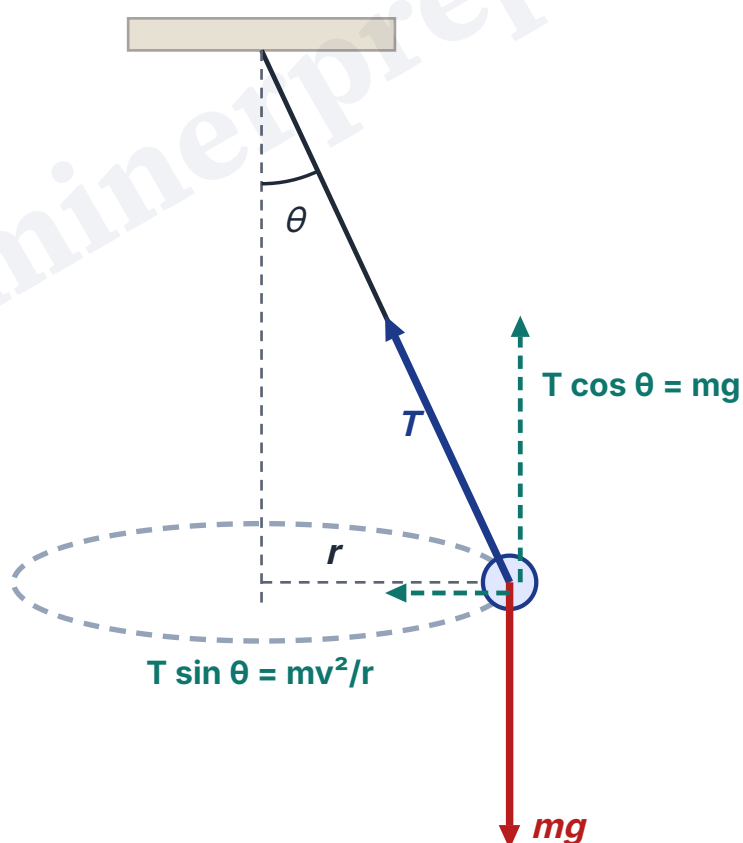
In uniform circular motion the velocity is tangential and the resultant force and acceleration point towards the centre, at right angles to the velocity at every point.

Quick example. A point on the rim of a wheel of radius 0.35 m makes one revolution every 0.50 s. Then $\omega = \frac{2\pi}{0.50} = 12.6 \text{ rad s}^{-1}$, $v = \omega r = 4.4 \text{ m s}^{-1}$ and $a = \omega^2 r = 55 \text{ m s}^{-2}$ towards the axle.

Situation	Force(s) providing the centripetal force
Ball whirled on a string in a horizontal circle	tension
Car on a flat bend	static friction between the tyres and the road
Car on a banked bend	horizontal component of the normal force (plus the horizontal component of any friction)
Conical pendulum	horizontal component of the tension
Satellite or moon in orbit	gravitational force
Charged particle moving perpendicular to a magnetic field	magnetic force



On a flat bend, friction alone provides the centripetal force, so the maximum safe speed is set by μ_s : $\mu_s mg = mv^2/r$. On a banked bend the normal force tilts towards the centre and its horizontal component helps. Banked bends are qualitative only in the 2025 guide.



A conical pendulum: the bob moves in a horizontal circle. The vertical component of the tension balances the weight; the horizontal component provides the centripetal force, giving $\tan \theta = \frac{v^2}{rg}$.

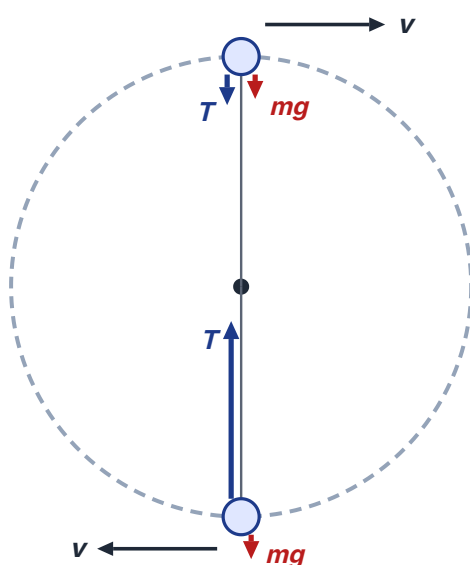
TRY IT YOURSELF

A.2 Circular Motion simulation: vary the speed, radius and mass and watch how the centripetal force and acceleration respond.

Non-uniform circular motion in a vertical circle

For a body whirled in a **vertical** circle the speed changes: gravity slows it on the way up and speeds it up on the way down. You only need to analyse the forces at the **top** and the **bottom**, where the resultant force is purely centripetal.

- **Top:** tension (or normal force) and weight both point towards the centre: $T + mg = \frac{mv^2}{r}$.
- **Bottom:** tension points up towards the centre, weight points away: $T - mg = \frac{mv^2}{r}$.
- The string stays taut at the top only if $v \geq \sqrt{gr}$. At this minimum speed the weight alone provides the centripetal force ($T = 0$).
- The same method (draw the forces, take "towards the centre" as positive) gives the normal force at the top or bottom of a roller-coaster loop or a hump-backed bridge. On top of a hump the normal force points *away* from the centre, so $mg - F_N = \frac{mv^2}{r}$: the car feels lighter.



Top: both forces point to the centre

$$T + mg = \frac{mv^2}{r}$$

slowest point → smallest T

Bottom: T up, mg down

$$T - mg = \frac{mv^2}{r}$$

fastest point → largest T

Forces on the ball in worked example 6, drawn to scale. At the top a small tension adds to the weight; at the bottom a large tension must overcome the weight and still provide the centripetal force.

WORKED EXAMPLE 6 Hard · Determine / Explain

A ball of mass 0.25 kg on a light string is whirled in a vertical circle of radius 0.80 m. Its speed is 7.0 m s^{-1} at the bottom of the circle and 4.2 m s^{-1} at the top.

(a) Determine the tension in the string at the top and at the bottom of the circle. (b) Determine the minimum speed at the top for which the string remains taut. (c) Explain why the string is most likely to break at the bottom.

(a) Top (towards centre = down): $T + mg = \frac{mv^2}{r} \Rightarrow T = \frac{0.25 \times 4.2^2}{0.80} - 0.25 \times 9.8 = 5.51 - 2.45 = \mathbf{3.1 \text{ N}}$

Bottom (towards centre = up): $T - mg = \frac{mv^2}{r} \Rightarrow T = \frac{0.25 \times 7.0^2}{0.80} + 2.45 = 15.3 + 2.45 = \mathbf{18 \text{ N}}$ (17.8 N)

(b) Taut condition: $T \geq 0$. At the limit $mg = \frac{mv^2}{r} \Rightarrow v = \sqrt{gr} = \sqrt{9.8 \times 0.80} = \mathbf{2.8 \text{ m s}^{-1}}$

(c) At the bottom the speed is greatest, so the required centripetal force mv^2/r is greatest; in addition the weight acts away from the centre, so the tension must exceed mv^2/r by mg . The tension is therefore largest at the bottom.

The two speeds are consistent with energy conservation (A.3): $v_{top}^2 = v_{bottom}^2 - 2g(2r) = 49 - 31.4 = 17.6$, so $v_{top} = 4.2 \text{ m s}^{-1}$.

Exam tips for A.2

EXAM TIP 1 — FREE-BODY DIAGRAMS ARE MARKED BY EYE

Arrows must start on the body, be labelled with recognised names or symbols, and have **lengths that match the physics**. If the body moves at constant velocity, upward and downward arrows must look equal; if it accelerates, the larger arrow must be in the direction of the acceleration.

Unbalanced arrows on a body in equilibrium can cost the mark even when all the forces are named correctly.

EXAM TIP 2 — SIGNS IN A REBOUND

When a body bounces back, its momentum changes direction. Write $\Delta p = m(v - u)$ with a stated positive direction, so a ball arriving at 18 m s^{-1} and leaving at 29 m s^{-1} has $\Delta v = 47 \text{ m s}^{-1}$, not 11 m s^{-1} . This is the single most common error in impulse questions.

EXAM TIP 3 — STATE THE CONDITION

When you quote conservation of momentum, add the condition: "no resultant **external** force acts on the system". For an explosion or recoil from rest, say that the total momentum is **zero before and therefore zero after** — a common multiple-choice trap is to think the system gains momentum because it gains kinetic energy.

EXAM TIP 4 — "ELASTIC" MEANS KINETIC ENERGY

Define an elastic collision as one in which the **total kinetic energy** is conserved. "No energy is lost" is not accepted: total energy is conserved in every collision. To decide whether a collision is elastic, calculate the total E_k before and after.

EXAM TIP 5 — THE TOP OF A VERTICAL CIRCLE

At the top of a vertical circle, both the weight and the tension (or normal force) point **down**, towards the centre: $T + mg = mv^2/r$. Students often subtract mg here by copying the bottom-of-the-circle equation. Always draw the free-body diagram first and take "towards the centre" as positive.

Common misconceptions

Misconception	Why it is wrong	Correct idea
A moving body needs a resultant force to keep it moving.	Newton's first law: with zero resultant force the velocity stays constant.	A resultant force changes the velocity; it is not needed to maintain it.
Weight and normal force form a Newton's third law pair.	Both act on the same body, and they are different types of force.	Third-law pairs act on different bodies; the partner of the weight is the body's pull on the Earth.
Third-law forces cancel, so nothing can accelerate.	They act on different bodies, so they never appear on the same free-body diagram.	Only forces on the same body are added to find its resultant.
Static friction always equals $\mu_s F_N$.	$\mu_s F_N$ is only the maximum value.	Static friction equals whatever is needed to prevent sliding, up to $\mu_s F_N$.
Momentum is lost in an inelastic collision.	Momentum is conserved whenever no external force acts.	Only kinetic energy decreases in an inelastic collision.
A "centrifugal force" pushes a body outwards in circular motion.	No outward force acts on the body; the resultant force points inwards.	Without a centripetal force the body would move along the tangent.

How this topic connects

Circular motion and work: why a centripetal force transfers no energy

Work done is $W = Fs \cos \theta$ (A.3). In uniform circular motion the centripetal force is always perpendicular to the velocity, and therefore to each small displacement, so $\theta = 90^\circ$ and $\cos \theta = 0$. No energy is transferred: the kinetic

energy and the speed stay constant, and only the direction changes. (This is why a satellite in a circular orbit needs no fuel to stay in it.)

Slowing neutrons in a reactor: momentum conservation in the moderator

Fission neutrons are too fast to cause further fission efficiently. In the moderator they collide with light nuclei (such as hydrogen in water or carbon in graphite). Momentum is conserved in each collision, so each time the neutron passes momentum and kinetic energy to a nucleus. The transfer is largest when the target nucleus has a mass close to the neutron's, which is why light moderator nuclei are chosen. After many collisions the neutrons are slow ("thermal") enough to sustain the chain reaction (E.4).

From Hooke's law to oscillation: how a restoring force produces SHM

Hooke's law $F_H = -kx$ gives a force that is proportional to the displacement from equilibrium and always directed back towards it. By Newton's second law $a = -\frac{k}{m}x$: the acceleration is proportional to the displacement and opposite to it. This is the defining condition for simple harmonic motion (C.1), with $\omega^2 = k/m$.

Tools & inquiry — measuring forces in the lab (NOS: laws from uncertain data)

- **Coefficient of static friction:** tilt a board slowly until a block just starts to slide; at that angle $\mu_s = \tan \theta$. Repeat several times and use the spread of the angles to estimate the uncertainty.
- **Spring constant:** add masses, measure extensions and plot force against extension. The gradient of the line of best fit is k ; the steepest and shallowest lines through the error bars give its uncertainty.
- **Viscosity (falling-ball method):** time a ball-bearing between two marks well below the surface, after it has reached terminal speed. Then $\eta = \frac{2r^2(\rho_s - \rho_f)g}{9v_t}$ — derived from $F_d + F_b = F_g$ with the data-booklet equations; this result is not itself in the data booklet.
- Laws such as Hooke's law are accepted because data agree with a straight line *within their uncertainties* — a law is a model with a limited

range of validity, not an exact statement about every measurement.

Key equations

Equation	Use	In data booklet?
$F_f \leq \mu_s F_N, F_f = \mu_d F_N$	static and dynamic friction	yes
$F_H = -kx$	elastic restoring force of a spring	yes
$F_d = 6\pi\eta r v$	viscous drag on a small sphere	yes
$F_b = \rho V g$	buoyancy	yes
$F_g = mg$	weight	yes
$p = mv$	linear momentum	yes
$J = F \Delta t (= \Delta p)$	impulse	yes ($J = \Delta p$: learn it)
$F = ma = \frac{\Delta p}{\Delta t}$	Newton's second law	yes
$a = \frac{v^2}{r} = \omega^2 r = \frac{4\pi^2 r}{T^2}$	centripetal acceleration	yes
$v = \frac{2\pi r}{T} = \omega r$	speed and angular velocity	yes
$F = \frac{mv^2}{r} = m\omega^2 r$	centripetal force	no — combine $F = ma$ with $a = v^2/r$
$E_k = \frac{p^2}{2m}$	kinetic energy from momentum	yes (in A.3)

Check your understanding

1. A book rests on a table. Identify the Newton's third law partner of the book's weight.

The gravitational force exerted **by the book on the Earth**, acting upwards, with the same magnitude as the weight. (Not the normal force — that acts on the book too.)

2. A hose delivers 2.5 kg of water per second at 12 m s^{-1} horizontally onto a wall, where the water stops. Calculate the force on the wall.

$$F = \frac{\Delta p}{\Delta t} = \frac{\Delta m}{\Delta t} v = 2.5 \times 12 = 30 \text{ N, directed into the wall.}$$

3. A car goes round a flat bend of radius 40 m. The coefficient of static friction between the tyres and the road is 0.80. Calculate the maximum speed at which the car can take the bend without skidding.

$$\text{Friction provides the centripetal force: } \mu_s mg = \frac{mv^2}{r} \Rightarrow v = \sqrt{\mu_s gr} = \sqrt{0.80 \times 9.8 \times 40} = 18 \text{ m s}^{-1} \text{ (17.7 m s}^{-1}\text{). The mass cancels.}$$

4. Two trolleys of mass 0.50 kg and 1.5 kg are held together at rest with a compressed spring between them. When released, the 0.50 kg trolley moves off at 0.90 m s^{-1} . Calculate the velocity of the other trolley and the ratio of their kinetic energies.

Total momentum stays zero: $0.50 \times 0.90 = 1.5v \Rightarrow v = 0.30 \text{ m s}^{-1}$ in the opposite direction. Since the momenta are equal in size, $E_k = p^2/2m$ gives a ratio $E_{k,0.50} : E_{k,1.5} = 1.5 : 0.50 = 3 : 1$ (0.2025 J : 0.0675 J).

5. A conical pendulum bob moves in a horizontal circle of radius 0.30 m with its string at 25° to the vertical. Determine the speed of the bob and its period.

$$T \cos \theta = mg \text{ and } T \sin \theta = \frac{mv^2}{r}, \text{ so } \tan \theta = \frac{v^2}{rg} \Rightarrow v = \sqrt{0.30 \times 9.8 \times \tan 25^\circ} = 1.2 \text{ m s}^{-1} \text{ (1.17 m s}^{-1}\text{). Period} = \frac{2\pi r}{v} = \frac{2\pi \times 0.30}{1.17} = 1.6 \text{ s.}$$

Practise A.2 with exam-style questions

Original Paper 1A, 1B and 2 questions on forces, momentum and circular motion, with full mark schemes. Tick the questions you want and print them as your own test.

SL A.2 questions

HL A.2 questions

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