Cambridge AS & A Level · Physics (9702) · Notes

Dynamics AS

Read online at pastopic.com/cambridge/physics-9702/notes/dynamics

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Read first: Kinematics, Physical quantities and units

What you need to know

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

1. **Understand mass** as the property of an object that resists a change in its motion.
2. **Recall and use** $F = ma$, knowing that the acceleration is always in the same direction as the resultant force.
3. **Define and use linear momentum**: momentum = mass × velocity.
4. **Define and use force** as the rate of change of momentum.
5. **State and apply Newton's three laws of motion.**
6. **Describe and use weight** as the effect of a gravitational field on a mass, and recall that weight = mass × acceleration of free fall ($W = mg$).
7. **Explain friction and drag (air resistance) qualitatively**: they oppose motion, and drag grows as the speed grows. No formulas or coefficients are needed.
8. **Describe and explain how an object moves in a uniform gravitational field when there is air resistance.**
9. **Understand terminal velocity**: an object moving against a resistive force can reach a constant velocity.
10. **State the principle of conservation of momentum.**
11. **Apply conservation of momentum** to elastic and inelastic collisions and explosions, in one and in two dimensions.
12. **Recall that in an elastic collision** the total kinetic energy is conserved, and the relative speed of approach equals the relative speed of separation.
13. **Understand that momentum is always conserved** in an interaction, while kinetic energy may change.

Kinematics describes motion; this topic explains it with forces. The coefficient of restitution and coefficients of friction and viscosity are not needed.

Understand it

Mass and Newton's first law

Mass is how hard it is to change an object's motion: to start it, stop it, speed it up or turn it. A full shopping trolley is harder to get moving and harder to stop than an empty one, because it has more mass. Mass is a scalar, measured in kg, and it is the same wherever the object is.

Newton's first law: an object stays at rest, or keeps moving at a constant velocity, unless a resultant force acts on it. So "constant velocity" and "zero resultant force" always go together. A car cruising at a steady 25 m s^{-1} on a straight road still has forces on it (the driving force and the resistive forces), but they cancel.

Momentum and Newton's second law

Linear momentum is mass × velocity:

$$p = mv$$

Units: kg m s^{-1}, which is the same as N s. Momentum is a **vector**, in the direction of the velocity. A 1500 kg car at 20 m s^{-1} has momentum $1500 \times 20 = 30\,000$ kg m s^{-1}; driving the other way at the same speed it has $-30\,000$ kg m s^{-1}.

Newton's second law: the resultant force on an object is proportional to its rate of change of momentum, and acts in the direction of that change. With SI units the constant is 1, which is how the newton is defined, so

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

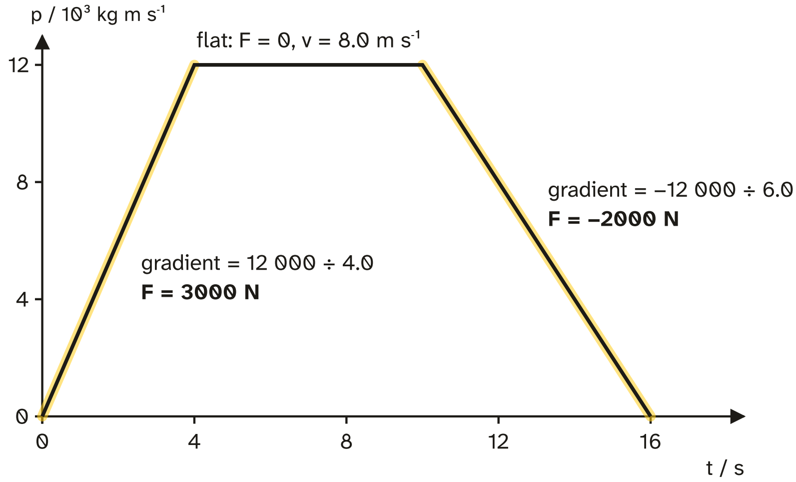
This **is** the definition of force: the rate of change of momentum. When the mass is constant, $\Delta p = m\,\Delta v$, so $F = m\dfrac{\Delta v}{\Delta t} = ma$. That is the familiar $F = ma$, a special case for constant mass. Two things follow:

- **The acceleration is always in the direction of the resultant force.** A car braking while moving forwards has a resultant force, and an acceleration, backwards.
- **Force × time = change in momentum**: $F\Delta t = \Delta p$. The same change in momentum can come from a big force for a short time or a small force for a long time. That is why a crumple zone or a bent knee on landing reduces the force.

When the mass changes (a rocket burning fuel, water from a hose), use the momentum form. A hose that sends out 1.5 kg of water every second at 12 m s^{-1} gives the water $1.5 \times 12 = 18$ kg m s^{-1} of momentum per second, so it pushes the water with 18 N, and the water pushes back on the hose with 18 N.

Reading a momentum–time graph

Since $F = \dfrac{\Delta p}{\Delta t}$, the **gradient of a momentum–time graph is the resultant force**, and the **area under a force–time graph is the change in momentum**.



For this 1500 kg car:

- 0 to 4.0 s: gradient $= \dfrac{12\,000}{4.0} = 3000$ N, the resultant forwards force (acceleration $\frac{3000}{1500} = 2.0$ m s⁻²).
- 4.0 to 10.0 s: flat line, so zero resultant force. The speed is $\dfrac{p}{m} = \dfrac{12\,000}{1500} = 8.0$ m s⁻¹.
- 10.0 to 16.0 s: gradient $= \dfrac{-12\,000}{6.0} = -2000$ N, so a resultant force of 2000 N backwards while it stops.

A straight line means a constant force. If a line crosses zero and carries on below the axis, the object stops and then moves the other way, with the same force still acting.

Newton's third law

Newton's third law: if body A exerts a force on body B, then B exerts a force on A that is equal in size and opposite in direction.

The two forces of a third-law pair:

- act on **different** bodies (so they never cancel each other out);
- are the **same type** of force (both gravitational, both contact, both electric);
- are equal in size and opposite in direction, and act for the **same time**.

The Earth pulls a book down with its weight W; the pair of that force is the book pulling the **Earth** up with a gravitational force W. The table pushing up on the book is **not** the pair of the weight: it is a contact force, and it acts on the same body. It equals W only because the book is in equilibrium, which is Newton's first law, not the third.

Weight

Weight is the force on a mass caused by a gravitational field:

$$W = mg$$

On the Earth $g = 9.81$ m s^{-2} (or 9.81 N kg^{-1}), so a 60 kg person weighs $60 \times 9.81 = 589$ N. On the Moon, where $g = 1.62$ m s^{-2}, the same person weighs $60 \times 1.62 = 97.2$ N, but their mass is still 60 kg. Mass stays the same; weight depends on where you are.

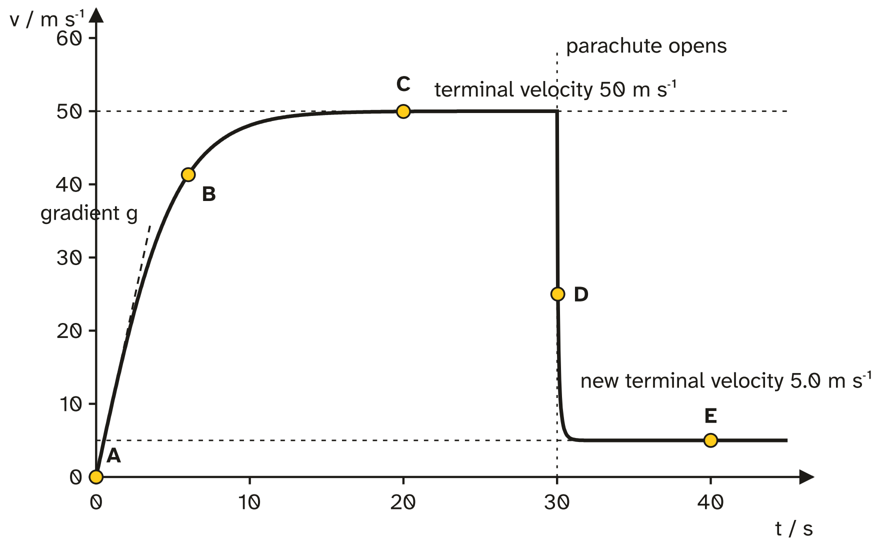
In a lift. The floor pushes up on a 60 kg person with a contact force R. Taking up as positive, $R - mg = ma$:

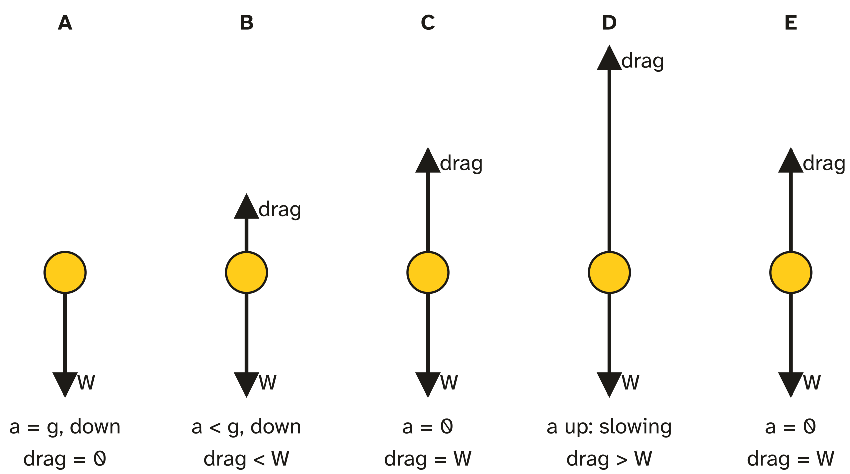
- accelerating up at 1.5 m s^{-2}: $R = 60(9.81 + 1.5) = 679$ N, and you feel heavier;
- accelerating down at 1.5 m s^{-2}: $R = 60(9.81 - 1.5) = 499$ N, and you feel lighter;
- moving at a steady speed either way: $R = 589$ N.

Your weight, mg, doesn't change in any of these; only the contact force does.

Friction, drag and terminal velocity

Friction acts where two surfaces slide, or try to slide, over each other, and it opposes that motion. **Drag** (air resistance in air, a viscous force in a liquid) opposes motion through a fluid, and it **increases as the speed increases**. That one idea explains every falling-object question.





Follow the skydiver, taking down as positive:

- **A (just after jumping)**: the speed is zero, so there is no drag. The only force is the weight, so the acceleration is g.
- **A to B**: as the speed rises, the drag rises. The resultant force $W - D$ gets smaller, so the acceleration gets smaller: the v–t curve gets less steep.
- **C (terminal velocity)**: the drag has grown to equal the weight. The resultant force is zero, so the acceleration is zero and the velocity stays at 50 m s^{-1}. For an 80 kg skydiver, the drag is then $80 \times 9.81 = 785$ N.
- **D (parachute opens)**: the parachute's large area makes the drag at 50 m s^{-1} far bigger than the weight. The resultant force is **upwards**, so the acceleration is upwards: the skydiver **slows down but is still moving down**. The deceleration is largest at the instant the parachute opens, because that's when the drag is largest.
- **D to E**: as the speed falls, the drag falls, so the deceleration gets smaller.
- **E**: the drag equals the weight again, at a lower terminal velocity of 5.0 m s^{-1}.

At both terminal velocities the drag is the same size, the weight. What changed is the speed needed to make that much drag.

What affects terminal velocity. An object reaches terminal velocity when the drag (plus any upthrust) equals its weight. So a heavier object of the same shape and size must reach a higher speed before the drag equals its weight: it has a higher terminal velocity, and a larger area (a parachute, a snowflake, sitting upright on a bike) means the same drag is reached at a lower speed. A dense ball in a liquid has a higher terminal velocity than a light one; the height it is dropped from doesn't matter.

In a liquid there is also upthrust (from Forces, density and pressure), which acts upwards and doesn't change with speed. At terminal velocity: weight = drag + upthrust.

Thrown upwards with air resistance. On the way up, the weight and the drag both act downwards, so the deceleration is **more than** g. On the way down, the drag acts upwards against the weight, so the acceleration is **less than** g. The ball reaches a lower height than it would in a vacuum, takes less time to get there, and comes back slower than it was thrown. The resultant force is largest at the start (fastest, so most drag, and both forces act the same way) and decreases as the ball slows.

Conservation of momentum

The principle of conservation of momentum: the total momentum of a system of objects stays constant, provided no resultant external force acts on the system (an **isolated system**).

Why it works: in a collision, A pushes B and B pushes A with equal and opposite forces (third law) for the same time. So B gains exactly the momentum that A loses: $\Delta p_A = -\Delta p_B$, and the total doesn't change.

Using it in a straight line: choose a positive direction, give every velocity a sign, and write

$$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2.$$

For example, a 3.0 kg trolley moving at 4.0 m s^{-1} hits a 1.0 kg trolley at rest and they stick together: $3.0 \times 4.0 = 4.0v$, so $v = 3.0$ m s^{-1}.

Explosions start with zero total momentum, so they end with zero total. If two trolleys of 0.20 kg and 0.30 kg are pushed apart by a spring and the 0.30 kg one moves off at 2.0 m s^{-1}, then $0 = 0.30 \times 2.0 + 0.20v$ and $v = -3.0$ m s^{-1}: 3.0 m s^{-1} the other way. The lighter part always moves faster. The same idea explains why a gun recoils and why a nucleus recoils when it emits an α-particle.

Elastic and inelastic collisions

Momentum is conserved in **every** collision and explosion in an isolated system. Kinetic energy, $E_k = \frac{1}{2}mv^2$, is not always:

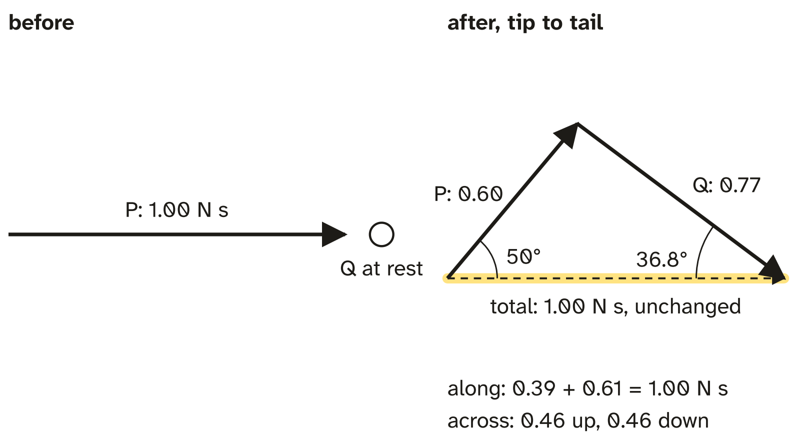
- **Elastic collision**: the total kinetic energy is conserved. It's also true that the **relative speed of approach equals the relative speed of separation**.
- **Inelastic collision**: some kinetic energy is transferred to other forms (thermal energy, sound, permanent deformation). The total **energy** is still conserved; only the kinetic part goes down. Objects that stick together always have an inelastic collision.

In the sticking-trolleys example, the kinetic energy before is $\frac{1}{2} \times 3.0 \times 4.0^2 = 24$ J and after is $\frac{1}{2} \times 4.0 \times 3.0^2 = 18$ J, so 6.0 J was transferred to other forms: 25% of it. In an explosion the kinetic energy goes **up**, supplied by the chemical or elastic energy stored.

Relative speed is how fast the gap between the objects closes or opens. Moving towards each other at 5 and 3 m s^{-1}, they approach at 8 m s^{-1}. Moving the same way at 5 and 3 m s^{-1}, the faster one catches up at 2 m s^{-1}. For an elastic collision the gap opens again at the same rate afterwards. This gives a second equation that is much easier to use than the kinetic-energy one.

Momentum in two dimensions

Momentum is a vector, so it is conserved **in each direction separately**. Resolve every momentum along the original line of motion and at right angles to it, and conserve each set of components.



Here puck P has momentum 1.00 N s and hits puck Q, which is at rest. Afterwards P has 0.60 N s at 50° to its old line:

- **Along the line**: $1.00 = 0.60\cos 50^\circ + p_Q \cos\phi$, so $p_Q \cos\phi = 1.00 - 0.386 = 0.614$ N s.

- **Across the line**: before, zero. So $0 = 0.60 \sin 50^\circ - p_Q \sin\phi$, giving $p_Q \sin\phi = 0.460$ N s.
- So $p_Q = \sqrt{0.614^2 + 0.460^2} = 0.77$ N s at $\phi = \tan^{-1}\dfrac{0.460}{0.614} = 36.8^\circ$ on the other side of the line.

The vector picture says the same thing: the momentum arrows after the collision, joined tip to tail, must end where the arrow before the collision ends.

Key facts and formulas

"Given" means it is on the data sheet in the exam. "Learn it" means you must remember it.

Formula	Status
Momentum $p = mv$ (a vector; units kg m s^{-1} = N s)	Learn it
Force = rate of change of momentum, $F = \dfrac{\Delta p}{\Delta t}$	Learn it
$F = ma$ (resultant force, constant mass; a in the direction of F)	Learn it
Change in momentum $\Delta p = F\Delta t$ = area under a force–time graph	Learn it
Gradient of a momentum–time graph = resultant force	Learn it
Force from a steady stream (jet, rocket, hose): $F = \dfrac{\Delta m}{\Delta t} v$	Learn it
Weight $W = mg$	Learn it
$g = 9.81$ m s^{-2}	Given
Conservation of momentum: $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$ (isolated system)	Learn it
Kinetic energy $E_k = \frac{1}{2}mv^2$; also $E_k = \dfrac{p^2}{2m}$	Learn it
Elastic collision: total E_k conserved; relative speed of approach = relative speed of separation	Learn it
At terminal velocity: resultant force $= 0$ (weight = drag, plus upthrust in a fluid)	Learn it
Upthrust $F = \rho g V$ (from Forces, density and pressure)	Given
$v^2 = u^2 + 2as$, $s = ut + \frac{1}{2}at^2$ (from Kinematics)	Given

How to do it

In the Paper 1 and Paper 2 questions we have tagged for this topic (195 different questions, 2021–2025; 6 more appear on two papers), the types came up this often. 27 of the 195 questions mix two or more types, so the counts add up to more than 195.

Question type	Questions
Newton's laws, $F = ma$ and third-law pairs	49
Drag, air resistance and terminal velocity	48

Question type	Questions
Force as rate of change of momentum	44
Mass, weight and the definitions	36
Conservation of momentum in a straight line	23
Elastic and inelastic collisions	23
Conservation of momentum in two dimensions	12

1. Newton's laws, $F = ma$ and third-law pairs (49 questions)

1. **Draw the object and every force on it**: weight down, contact or tension forces, driving force, friction and drag against the motion.
2. **Choose a positive direction**, usually the direction of the acceleration.
3. **Write resultant force** $= ma$: (forces in the positive direction) – (forces the other way) $= ma$.
4. **Solve** for the unknown, then check the sign: a negative acceleration means it points the other way.

For example, a 1200 kg car with a driving force of 3000 N and a resistive force of 600 N accelerates at $\frac{3000-600}{1200} = 2.0$ m s^{-2}.

Variations you will meet:

- **Rockets and lifts**: upward force minus weight $= ma$. So thrust $= W + ma = W + \dfrac{W}{g}a$. The contact force from a lift floor is $m(g+a)$ going up faster and $m(g-a)$ going down faster.
- **Connected objects** (a car and trailer, two blocks on a string over a pulley, blocks pushed together): first treat everything as one object to get the acceleration, using only the **external** forces and the **total** mass. Then write $F = ma$ for one object on its own to get the tension or contact force between them (Example 1).
- **A new force suddenly acts**: the resultant force changes at once, and so does the acceleration. A string holding a hanging mass is cut: the spring above now pulls up with the whole old tension, so the remaining mass accelerates upwards.
- **"Which pair is a Newton's third law pair?"** Both forces must be the same type and act on different bodies. The pair of an object's weight is its gravitational pull on the **Earth**. The pair of a road pushing a wheel forwards is the wheel pushing the road backwards.
- **Balanced forces**: if the resultant force is zero the object is at rest **or** moving at a constant velocity; you can't tell which from the forces alone.
- **From a velocity–time graph**: the gradient is a, so $F = m\times$ gradient. Check the units (cm s^{-1}, km h^{-1}). A graph of resultant force against time has the same shape as the gradient of the v–t graph: flat where v–t is straight, zero where it is flat.
- **Constant force, mass falling** (a spacecraft or rocket burning fuel): $a = \dfrac{F}{m}$ rises as m falls, so the speed–time graph is a curve that starts from zero speed and gets steeper, not a straight line.

- **Stopping distance with a constant force**: find a from $v^2 = u^2 + 2as$, then $F = ma$. Or use work: $Fs = \frac{1}{2}mv^2$.

2. Drag, air resistance and terminal velocity (48 questions)

1. **List the forces**: weight (down, constant), drag (against the motion, growing with speed) and, in a liquid, upthrust (up, constant).
2. **Resultant force** = the forces in the direction of motion minus the others.
3. **Explain with a chain**: speed changes → drag changes → resultant force changes → acceleration changes (Newton's second law).
4. **At terminal velocity**: resultant force is zero, so weight = drag (+ upthrust).

Variations you will meet:

- **Describe and explain the motion** (the skydiver above): acceleration g at first, then decreasing as drag increases, zero at terminal velocity. Name the cause **and** the effect: "drag increases, so the resultant force decreases, so the acceleration decreases."
- **Forces at a point on the graph**: on the curved part, drag < weight; on the flat part, drag = weight; just after a parachute opens, drag > weight.
- **Graph shapes**: v–t is a curve that starts with gradient g (the same gradient as falling in a vacuum) and levels off. a–t starts at g and curves down to zero. Drag against v is a curve that rises, starting from the origin. On a distance–time graph, terminal velocity is the part that is a straight line.
- **Calculations at terminal velocity**: drag $= mg$, or drag $= W - U$ in a liquid. With a given drag formula such as $F = 6\pi\eta rv$, set it equal to $W - U$ and solve for v or the constant.
- **Acceleration at a given instant**: resultant force ÷ mass. For a skydiver of 68 kg with 1800 N of drag: $a = \frac{1800-667}{68} = 16.7$ m s^{-2} **upwards**.
- **Thrown upwards in air**: going up, weight and drag both act down, so the deceleration is more than g and decreases as it slows; it reaches a lower height sooner than in a vacuum.
- **Comparing objects**: same size and shape, heavier one → higher terminal velocity. Same mass, larger area → lower terminal velocity, reached sooner.
- **Why a force can't be drag**: drag depends on speed, so a force that stays constant while the speed changes, or that is still there when the object is momentarily at rest, is not drag.

3. Force as rate of change of momentum (44 questions)

1. **Choose a positive direction.** A velocity the other way is negative.
2. **Change in momentum** $\Delta p = mv - mu$, with signs. A ball hitting a wall at u and bouncing back at v has $|\Delta p| = m(u + v)$, not $m(u - v)$.
3. **Average force** $F = \dfrac{\Delta p}{\Delta t}$. Convert ms to s.
4. **Direction**: the force on the object is in the direction of Δp. The force on the wall or bat is equal and opposite (third law).

Variations you will meet:

- **Momentum–time graph**: gradient = resultant force. If another force (friction, drag) also acts, the applied force = resultant + resistive force.
- **Force–time graph**: area = change in momentum. Divide by the mass for the change in velocity. The velocity–time graph rises while the force acts and is flat once the force is zero.
- **A steady stream** (hose, fan, rocket exhaust, drone rotor): $F = \dfrac{\Delta m}{\Delta t} v$. For a jet of density ρ, area A and speed v, the mass per second is $\rho A v$, so $F = \rho A v^2$. For a hovering drone, F equals its weight.
- **Change in momentum at an angle**: momentum is a vector, so subtract vectors. A ball hitting a surface at angle θ and bouncing off at the same speed and angle changes momentum only at right angles to the surface: $\Delta p = 2p\sin\theta$. Turning through 90°: $\Delta p = \sqrt{p_1^2 + p_2^2}$.
- **Constant force, find the time**: $\Delta t = \dfrac{\Delta p}{F}$. A 2000 kg van at 15 m s⁻¹ stopped by 6000 N takes $\frac{30\,000}{6000} = 5.0$ s.
- **Momentum and kinetic energy together**: $E_k = \dfrac{p^2}{2m}$, so $m = \dfrac{p^2}{2E_k}$ and $v = \dfrac{2E_k}{p}$.
- **Sketching from a momentum–time graph**: velocity $= \frac{p}{m}$, so its graph has the same shape. Displacement–time: its gradient follows p, so it curves over and has a maximum where $p = 0$.

4. Mass, weight and the definitions (36 questions)

Learn these word for word in meaning:

- **Mass**: the property of an object that resists a change in its motion.
- **Weight**: the force on a mass due to a gravitational field; $W = mg$.
- **Momentum**: the product of mass and velocity.
- **Force**: the rate of change of momentum. ("Mass × acceleration" is how to work out a resultant force for a constant mass, not the definition.)
- **Newton's second law**: the resultant force is proportional to the rate of change of momentum (and in its direction).
- **Principle of conservation of momentum**: the total momentum of a system is constant, provided no resultant external force acts on it.

Variations you will meet:

- **Mass and weight on another planet**: the mass is unchanged; the weight scales with g. An object that weighs 3.0 N on a planet where g is a quarter of the Earth's weighs 12 N on the Earth, with the same mass.
- **Finding g from a weight and a mass**: $g = \frac{W}{m}$. Convert g to kg and mN to N first.
- **"Which statement is correct?"**: watch for mass given a direction (it is a scalar), weight described as resisting motion (that is mass), or the principle given without "isolated system" or "no external force".
- **Weight in a moving spacecraft**: the gravitational force mg doesn't depend on how the spacecraft accelerates; only the contact force does.

5. Conservation of momentum in a straight line (23 questions)

1. **Draw before and after**, and choose a positive direction.
2. **Write total momentum before = total momentum after**, with a sign on every velocity.
3. **Solve** for the unknown velocity. The sign of the answer gives its direction.
4. **If asked about energy**, work out the total kinetic energy before and after separately; the difference is the energy transferred.

Variations you will meet:

- **Objects stick together**: $m_1u_1 + m_2u_2 = (m_1 + m_2)v$.
- **Explosions and recoil** (fireworks, springs, α-decay): total momentum before is zero, so $m_1v_1 = -m_2v_2$. The pieces move in opposite directions with speeds in the inverse ratio of their masses. A nucleus that was at rest can't stay at rest after emitting a particle, because the particle has momentum.
- **Kinetic energy from an explosion**: for two pieces from rest, the kinetic energies are in the **inverse** ratio of the masses.
- **Something dropped into a moving cart**: horizontal momentum is conserved, so the cart slows: same momentum, larger mass, less kinetic energy.
- **Two stages**: a pellet embeds in a block (momentum), then the block rises (energy: $h = \frac{v^2}{2g}$). Don't use energy for the collision itself: it is inelastic.
- **Percentage of kinetic energy lost** $= \frac{E_{\text{before}} - E_{\text{after}}}{E_{\text{before}}} \times 100\%$.
- **Contact force during the collision**: the change in momentum of **one** object ÷ contact time.

6. Elastic and inelastic collisions (23 questions)

1. **What is conserved?** Momentum: always (isolated system). Total energy: always. Kinetic energy: only in an elastic collision.
2. **To decide elastic or inelastic**, compare the total kinetic energy before and after, or compare the relative speeds of approach and separation.
3. **To find two unknown velocities after an elastic collision**, use two equations:
   - momentum: $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$;
   - relative speed: $u_1 - u_2 = v_2 - v_1$ (approach = separation).
4. **Solve simultaneously**: rearrange the second for v_1 and substitute into the first.

Variations you will meet:

- **Equal masses, one at rest, elastic**: they swap velocities; the moving one stops and the other moves off at its speed.
- **Light object hits a heavy one at rest, elastic**: the light one bounces back more slowly than it arrived; the heavy one moves off slowly. A heavy one hitting a light one: both move forwards, the light one faster.

- **"Which row / which diagram is possible?"** Check both: the momentum totals must match, and for "elastic" the relative speeds must match too. For an inelastic collision the kinetic energy after must be **less** (not more) than before.
- **Bouncing ball**: rebound speed less than impact speed → inelastic.
- **A statement that is wrong**: "relative speed of approach + relative speed of separation = 0", "kinetic energy is reduced in an elastic collision", "momentum is conserved only in elastic collisions" are all wrong.

7. Conservation of momentum in two dimensions (12 questions)

1. **Choose two directions** at right angles, usually along the original line of motion and across it.
2. **Resolve every momentum** into components: $p\cos\theta$ along and $p\sin\theta$ across.
3. **Conserve each direction separately.** Across the line the total before is often zero, so the components after are equal and opposite.
4. **Combine** the components with Pythagoras and $\tan^{-1}$ for the size and direction.

Variations you will meet:

- **Given both angles, find the speeds**: use the across-the-line equation to link the two speeds, then the along-the-line equation (Example 4 works the other way round).
- **Explosion into three pieces from rest**: the momenta form a closed triangle. If two are at right angles, the third has size $\sqrt{p_1^2 + p_2^2}$.
- **Two objects meeting at angles and sticking together**: add the momentum vectors; the combined object moves along the resultant.
- **Vector-diagram options**: the arrows after, placed tip to tail, must start and end where the arrow (or arrows) before start and end.
- **"Which diagram is impossible?"**: one where every piece after moves to the same side of the original line, so the momentum across the line can't cancel.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

A car of mass 1200 kg tows a trailer of mass 400 kg along a straight, level road. The driving force on the car is 3000 N. The resistive force on the car is 400 N and on the trailer is 200 N. The tow bar is horizontal.

(a) Calculate the acceleration of the car and trailer. **[2]**

(b) Calculate the tension in the tow bar. **[2]**

(c) State the size and direction of the force that the trailer exerts on the car, and name the law you used. **[2]**

Solution

(a) Treat the car and trailer as one object. Resultant force $= 3000 - 400 - 200 = 2400$ N. **M1** $a = \dfrac{2400}{1600} = 1.5$ m s^{-2}. **A1**

(b) For the trailer alone: $T - 200 = 400 \times 1.5$ **M1**, so $T = 800$ N. **A1** Check with the car alone: $3000 - 400 - 800 = 1800 = 1200 \times 1.5$. ✓

(c) 800 N **B1**, backwards (opposite to the motion), by Newton's third law: the car pulls the trailer forwards with 800 N. **B1**

Example 2

A tennis ball of mass 0.058 kg hits a vertical wall at 24 m s^{-1} at right angles and bounces straight back at 18 m s^{-1}. It is in contact with the wall for 12 ms.

(a) Calculate the change in momentum of the ball. **[2]**

(b) Calculate the average force exerted on the ball by the wall. **[1]**

(c) State and explain whether the collision is elastic. **[2]**

(d) State the average force exerted on the wall by the ball. **[1]**

Solution

Take the direction the ball bounces back as positive, so $u = -24$ m s^{-1} and $v = +18$ m s^{-1}.

(a) $\Delta p = mv - mu = 0.058 \times 18 - 0.058 \times (-24)$ **M1** $= 0.058 \times 42 = 2.44$ N s, away from the wall. **A1**

(b) $F = \dfrac{\Delta p}{\Delta t} = \dfrac{2.436}{0.012} = 203$ N away from the wall. **A1**

(c) The speed after is less than the speed before, so the kinetic energy decreased (from 16.7 J to 9.40 J): the collision is **inelastic**. **B1 B1**

(d) 203 N towards the wall (Newton's third law). **B1**

Example 3

A trolley A of mass 0.60 kg moves at 2.5 m s^{-1} along a straight, frictionless track towards a trolley B of mass 0.40 kg, which is at rest. After they collide, A moves on in the same direction at 0.50 m s^{-1}.

(a) State the principle of conservation of momentum. **[2]**

(b) Calculate the velocity of B after the collision. **[2]**

(c) Show that the collision is elastic, using relative speeds. **[2]**

(d) The trolleys are in contact for 0.050 s. Calculate the average force on B. **[2]**

Solution

(a) The total momentum of a system stays constant **M1**, provided no resultant external force acts (an isolated system). **A1**

(b) $0.60 \times 2.5 + 0 = 0.60 \times 0.50 + 0.40v$ **M1** $1.50 = 0.30 + 0.40v$, so $v = 3.0$ m s^{-1} in A's original direction. **A1**

(c) Relative speed of approach $= 2.5 - 0 = 2.5$ m s^{-1}. **M1** Relative speed of separation $= 3.0 - 0.50 = 2.5$ m s^{-1}. They are equal, so the collision is elastic. **A1** (Check: kinetic energy before $= \frac{1}{2} \times 0.60 \times 2.5^2 = 1.875$ J; after $= \frac{1}{2} \times 0.60 \times 0.50^2 + \frac{1}{2} \times 0.40 \times 3.0^2 = 0.075 + 1.80 = 1.875$ J.)

(d) Δp of B $= 0.40 \times 3.0 = 1.2$ N s **M1**; $F = \dfrac{1.2}{0.050} = 24$ N. **A1**

Example 4

On a frictionless air table, a puck X of mass 0.20 kg moving at 3.0 m s^{-1} hits a puck Y of mass 0.30 kg, which is at rest. After the collision X moves at 1.8 m s^{-1} at 60° to its original direction.

(a) Calculate the components of the momentum of Y after the collision, along and at right angles to X's original direction. **[3]**

(b) Calculate the speed of Y and its direction. **[2]**

(c) Determine whether the collision is elastic. **[2]**

Solution

(a) Along: $0.20 \times 3.0 = 0.20 \times 1.8\cos 60^\circ + p_{\text{along}}$ **M1** $0.60 = 0.18 + p_{\text{along}}$, so $p_{\text{along}} = 0.42$ N s. **A1** Across: $0 = 0.20 \times 1.8\sin 60^\circ - p_{\text{across}}$, so $p_{\text{across}} = 0.312$ N s, on the other side of the line from X. **A1**

(b) $p_Y = \sqrt{0.42^2 + 0.312^2} = 0.523$ N s, so $v_Y = \dfrac{0.523}{0.30} = 1.74$ m s^{-1}. **A1** Angle $= \tan^{-1}\dfrac{0.312}{0.42} = 36.6^\circ$ to X's original direction. **A1**

(c) Kinetic energy before $= \frac{1}{2} \times 0.20 \times 3.0^2 = 0.90$ J. **M1** After $= \frac{1}{2} \times 0.20 \times 1.8^2 + \frac{1}{2} \times 0.30 \times 1.74^2 = 0.324 + 0.456 = 0.78$ J. Less than before, so it is **inelastic** (0.12 J transferred to other forms). **A1**

Common mistakes

- **Defining force as "mass × acceleration".** Examiner reports say this every year. The definition is **rate of change of momentum**; $F = ma$ is how to calculate a resultant force when the mass is constant.

- **Leaving out the condition in the conservation principle.** "Momentum before = momentum after" earns only part of the marks. Add "for an isolated system" or "provided no resultant external force acts". Don't confuse it with the principle of moments.
- **Wrong signs.** A ball that bounces back has a change in momentum of $m(u+v)$, not $m(u-v)$. In collisions, a block moving left must be given a negative momentum. Examiners see at least one wrong sign in many answers.
- **Using the wrong momentum for a force.** The force on one block during a collision is **its own** change in momentum ÷ time, not its final momentum and not the difference between the two blocks' momenta.
- **Change in momentum vs change in the size of momentum.** When the direction changes, subtract vectors: a ball turning through 90° from 0.12 to 0.050 N s has $\Delta p = \sqrt{0.12^2 + 0.050^2} = 0.13$ N s, not 0.070 N s.
- **Mixing up the resultant force with one of the forces.** For a block on a wire decelerating upwards, tension = weight – ma; adding ma, or taking the tension as the resultant force, are common slips. Find the resultant first, then the force asked for.
- **Wrong third-law pairs.** The weight of a book and the table's push on it are not a pair (different types, same body). The two forces of a pair act on different bodies, so they never cancel.
- **Explaining terminal velocity only halfway.** "The acceleration decreases" isn't enough; say **why**: "the drag increases as the speed increases, so the resultant force decreases". And at terminal velocity say the resultant force is **zero**, not that "the forces are balanced" without naming them.
- **Thinking the skydiver moves upwards when the parachute opens.** The acceleration is upwards; the velocity is still downwards, just smaller.
- **Forgetting upthrust in a liquid**, or putting the weight into the upthrust formula. Use $\rho g V$ with the density of the **liquid**.
- **Using kinetic energy instead of momentum** for a collision or explosion. Kinetic energy is only conserved when told the collision is elastic; momentum always is.
- **Treating mass as changing with g.** On the Moon the mass is the same; only the weight changes.

How to get the marks

- **"Define" and "state"**: give the precise wording. Force: "rate of change of momentum". Momentum: "product of mass and velocity". Mass: "property that resists change in motion". The conservation principle needs the condition. Newton's third law needs "equal and opposite" **and** "on different bodies".
- **Show the equation with numbers.** Physics mark schemes give a **C1** mark for the right physics with the numbers substituted (shown as **M1** in the examples above), then **A1** for the answer. A "show that" answer needs every step and one more significant figure than the value printed.
- **Vectors need directions.** For a force, velocity or change in momentum, "magnitude and direction" means give both. "Magnitude" alone means just the size.
- **"Describe and explain"** motion with drag: describe (the acceleration decreases to zero) **and** explain (drag increases with speed, so the resultant force decreases). Refer to Newton's second law if you can.
- **Force diagrams**: arrows start on the object, point the right way and are labelled (weight, drag, upthrust). Make the lengths sensible: at terminal velocity, drag + upthrust arrows should add up to the weight arrow.

- **Elastic or inelastic**: calculate the kinetic energy before and after (or compare relative speeds) and **state the conclusion**. A number without "so it is inelastic" loses the mark.
- **Sketches**: a straight line for a constant force; a curve that levels off for terminal velocity; start at the right value (for falling in air, the initial gradient is g).
- **Units**: momentum in kg m s^{-1} or N s; force in N. Convert g → kg, ms → s, cm s^{-1} → m s^{-1}.
- **Multiple choice**: work the numbers yourself first. The wrong options are usually a sign slip ($u - v$ instead of $u + v$), a forgotten third-law step (force on the wall vs on the ball) or kinetic energy used where momentum was needed.

Quick check

1. A resultant force of 5.0 N acts on a 2.0 kg trolley, initially at rest, for 3.0 s. Calculate its final momentum and speed.
2. A 4.0 kg rifle, initially at rest, fires a 0.010 kg bullet at 400 m s^{-1}. Calculate the recoil speed of the rifle.
3. A 70 kg skydiver falls at terminal velocity. State the drag force on her. When her parachute opens the drag force becomes 1500 N: calculate her acceleration and give its direction.
4. A 1.0 kg ball moving at 6.0 m s^{-1} has an elastic head-on collision with a 2.0 kg ball at rest. Calculate the velocities of both balls afterwards.
5. An astronaut's backpack has a mass of 12 kg. State its mass on the Moon and calculate its weight there ($g = 1.62$ m s^{-2}).

Answers

1. $\Delta p = F\Delta t = 5.0 \times 3.0 = 15$ N s, so the final momentum is 15 kg m s^{-1}. Speed $= \frac{15}{2.0} = 7.5$ m s^{-1}.
2. Total momentum is zero before, so $0 = 0.010 \times 400 + 4.0v$, giving $v = -1.0$ m s^{-1}: 1.0 m s^{-1} backwards.
3. At terminal velocity the resultant force is zero, so drag $= mg = 70 \times 9.81 = 687$ N. With the parachute open: $a = \frac{1500-687}{70} = 11.6$ m s^{-2}, **upwards** (she slows down while still falling).
4. Momentum: $6.0 = v_1 + 2.0v_2$. Elastic, so relative speeds: $6.0 = v_2 - v_1$. Adding: $12 = 3v_2$, so $v_2 = 4.0$ m s^{-1} forwards and $v_1 = -2.0$ m s^{-1}, i.e. 2.0 m s^{-1} back the way it came. (Check: kinetic energy 18 J before; $2.0 + 16 = 18$ J after.)
5. Mass 12 kg (it doesn't change). Weight $= 12 \times 1.62 = 19.4$ N.

Past questions to try

- **9702/21/M/J/23 Q3**: resultant force and applied force from a momentum–time graph, with friction.
- **9702/22/M/J/24 Q2**: a skydiver's velocity–time graph, the acceleration when the parachute opens and the change in momentum.
- **9702/23/O/N/24 Q2**: a collision where one ball stops, the kinetic energy change, and the forces each ball exerts on the other.
- **9702/21/M/J/24 Q3**: conservation of momentum in two dimensions, then a stopping force.