

Motion and forces

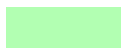
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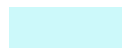
Revision notes for one topic, free to download.

These are the summary notes only. The full edition of this booklet also carries the worked examples, the required practicals and the formula sheets, with every topic in one place.

Colour Codes



Definitions



Diagrams



Notes and warnings



Sub-topic headings

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Define Distance / displacement

- how far an object has travelled (scalar) / its straight-line distance from start to finish in a stated direction (vector).

Define Acceleration

- change in velocity per second; a negative acceleration is a deceleration.

Define Resultant force

- the single force with the same effect as all the forces on an object.

Define Weight / mass

- the force on an object due to a gravitational field, in newtons / the quantity of matter in it, in kilograms.

HIGHER TIER

Define Momentum HT ONLY

- mass $\times$ velocity; a vector, in kg m/s.

Define Braking distance

- distance travelled while the brakes decelerate the vehicle.

Define Stopping distance

- thinking distance + braking distance.

Define Scalar / vector quantity

- one with magnitude (size) but no specific direction / one with both magnitude and a specific direction.

Define Speed / velocity

- distance travelled per second (scalar) / speed in a stated direction (vector).

Define Free fall

- motion under gravity alone; the acceleration g in free fall is 10 m/s^2 .

Define Newton's laws

- first: a body stays at rest or at constant velocity unless a resultant force acts; second: resultant force = mass $\times$ acceleration; third: two interacting objects exert equal and opposite forces on each other.

HIGHER TIER

Define Inertial mass HT ONLY

- how difficult it is to change an object's velocity; the ratio of force over acceleration.

Define Thinking distance

- distance travelled while the driver reacts, before the brakes are applied.

2.1 Scalars and vectors (2.1–2.5)

A **scalar quantity** has magnitude (size) but **no specific direction** (2.1); a **vector quantity** has both magnitude and a **specific direction** (2.2). That is the difference you must explain (2.3).

	Scalar	Vector
Magnitude / direction	Yes / no	Yes / yes
Written as	A number and a unit	A number, a unit and a direction
Drawn as	—	An arrow: length = magnitude, way it points = direction

You must **recall which quantities are vectors and which are scalars** (2.4):

The spec pairs them as displacement/distance, velocity/speed and weight/mass; the vector is first in each pair.

Velocity is speed in a stated direction (2.5): 5 m/s is a speed, 5 m/s due north is a velocity. A car going round a roundabout at a steady 8 m/s has constant *speed* but changing *velocity*.

Likewise, walk 40 m east then 30 m west: the **distance** is 70 m, but the **displacement** is 10 m east. Return to your start and the displacement is zero however far you walked.

Scalar	Vector
Distance	Displacement
Speed	Velocity
Mass	Acceleration
Energy	Force
Time	Weight
	Momentum HT ONLY

WATCH OUT

"Negative" does not mean "small". For a vector a minus sign is a **direction** — the opposite way to whichever you chose as positive. A velocity of -6 m/s is just as fast as $+6$ m/s.

2.2 Distance, speed and time (2.6, 2.11–2.12)

Speed is rarely constant, so this gives an **average**: total distance $\div$ total time — not the average of the separate speeds.

Motion	Typical speed
Walking	1.5 m/s
Running	3 m/s
Cycling	6 m/s
Car (town)	13 m/s (about 30 mph)
Car (motorway)	30 m/s (about 70 mph)
Train	55 m/s
Aeroplane (cruising)	250 m/s
Wind (gentle breeze to gale)	5–20 m/s
Sound in air	330 m/s

Typical speeds (2.12)

You must **recall some typical speeds encountered in everyday experience** for wind and sound, and for walking, running, cycling and other transport systems. Real values vary enough that a range is acceptable.

Laboratory methods for measuring speed (2.11)

You must be able to **describe a range of laboratory methods for determining the speeds of objects**.

- **Light gates and a data logger** — a card of measured length breaks an infrared beam; the logger times the interruption, and speed = card length $\div$ interruption time. Two gates a known distance apart give the speed at two points, and so the acceleration. Most reliable, as it removes human reaction time.
- **Ticker-tape timer** — 50 dots per second, so each gap is 0.02 s; gap length $\div$ 0.02 s = speed, and lengthening gaps mean accelerating.
- **Stopwatch and metre rule** — simple, but human reaction time (≈ 0.25 s) makes it unreliable for short times; use a long distance to cut the percentage error.
- **Video with a timer in shot, or a motion sensor** — played back frame by frame.

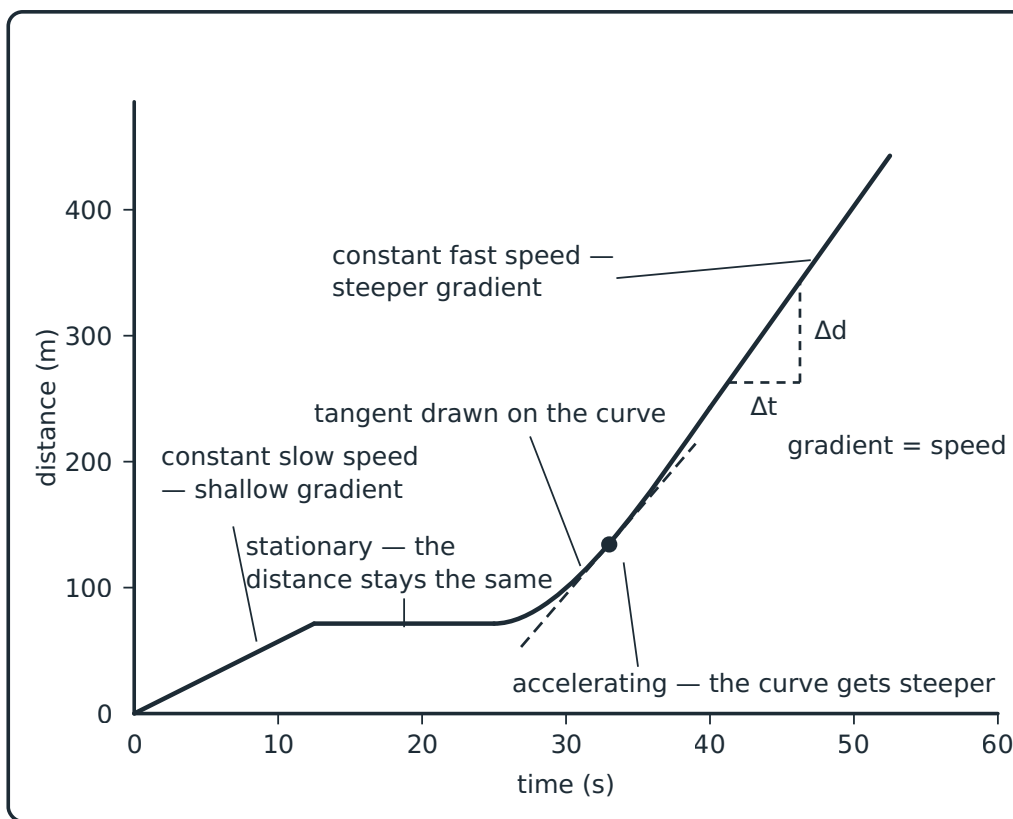
2.3 Distance–time graphs (2.7)

You must analyse distance/time graphs including determination of speed from the gradient.

- Distance is on the y-axis, time on the x-axis.
- A horizontal line means stationary; a straight sloping line means constant speed; a steeper line means a greater speed.
- A curve getting steeper means accelerating; a curve getting shallower means decelerating.
- The gradient is the speed: $\text{gradient} = \frac{\text{change in distance (rise)}}{\text{change in time (run)}}$.
- For a curve, draw a tangent at the point you want; the gradient of the tangent is the speed at that instant.

Take the rise and run from as large a triangle as possible, using easy grid lines, and check the axis units.

Reading a distance–time graph



How to read it

- flat line = stationary
- steeper line = faster
- gradient = speed
- speed = distance $\div$ time
- a curved line means the speed is changing
- to find the speed at an instant on a curve, draw a tangent and find its gradient

2.4 Acceleration and velocity–time graphs (2.8, 2.10, 2.13)

Free fall (2.13). Recall that the acceleration g in free fall is 10 m/s^2 , and **estimate the magnitudes of everyday accelerations**: a car pulling away $\approx 2 \text{ m/s}^2$; a sprinter off the blocks $\approx 5 \text{ m/s}^2$; a dropped object 10 m/s^2 ; an emergency stop $\approx 6\text{--}8 \text{ m/s}^2$.

Velocity–time graphs (2.10)

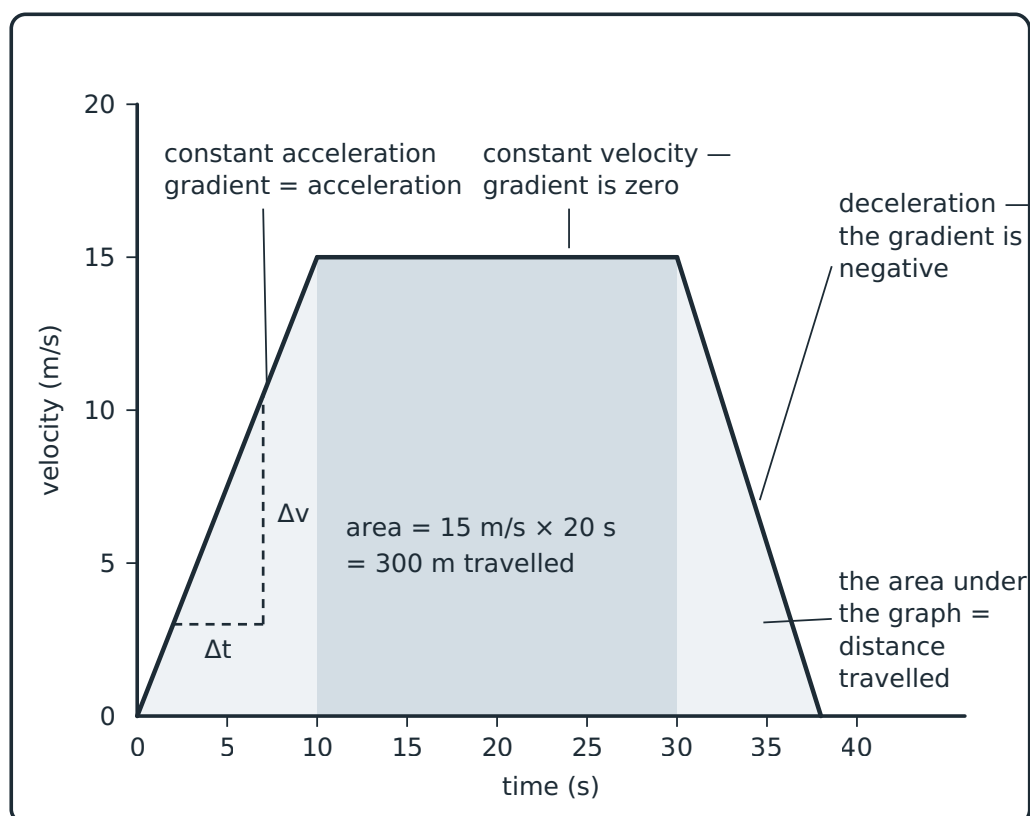
You must **analyse velocity/time graphs** to do three things.

a — Compare acceleration from gradients qualitatively. The steeper the line the greater the acceleration: sloping up = accelerating, horizontal = constant velocity, sloping down = decelerating.

b — Calculate the acceleration from the gradient (uniform acceleration only): gradient = change in velocity $\div$ change in time, which is $a = (v - u) \div t$.

c — Determine the distance travelled using the area between the graph line and the time axis (uniform acceleration only). Split it into rectangles (time $\times$ velocity) and triangles ($\frac{1}{2} \times$ time $\times$ change in velocity) and add the parts. The answer is a **distance in metres**, since $\text{m/s} \times \text{s} = \text{m}$.

Reading a velocity–time graph



How to read it

- gradient = acceleration
- flat line = constant velocity
- downward slope = deceleration
- area under the graph = distance travelled
- split the area into triangles and rectangles, or count squares

WATCH OUT

A horizontal line on a **distance**–time graph means *stopped*; on a **velocity**–time graph it means *moving at a steady speed*. Check the y-axis label before describing the motion.

NOTE

Tier check. The specification lists *interpret enclosed areas in velocity-time graphs* as a **Higher Tier** maths requirement, but statement 2.10c itself is untiered — both tiers can be asked for distance from the area, with simpler shapes at Foundation.

2.5 The equation $v^2 - u^2 = 2 \times a \times x$ (2.9)

Use this whenever a question gives a **distance instead of a time**. Square v and u **before** subtracting, take the square root at the end if you are finding v , and expect a negative a when the object slows down.

2.6 Forces as interactions, free body diagrams and resultant forces (9.1, 9.3–9.5)

NOTE

These are formally **Topic 9 — Forces and their effects (Paper 6)** statements, kept here because resultant force is needed for Newton's laws below. The numbers are Topic 9 numbers.

HIGHER TIER

How objects interact (9.1). A force is always an **interaction between two objects**, never something an object "has". Objects interact **at a distance, without contact**, through the **gravitational, electrostatic and magnetic** fields; or **by contact**, giving the **normal contact force** (the push of a surface, at right angles to it), **friction**, air resistance and tension. Either way the interaction produces a **pair of forces**, represented as **vectors**.

HT ONLY Free body force diagrams (9.4). Draw the object as a box or dot, then draw **only the forces acting on that one object** as labelled arrows pointing outward. Never draw forces the object exerts on other things.

HT ONLY Vector diagrams (9.3). Use them for the **resolution of forces**, a **net force** and **equilibrium** — **scale drawings only**, so you draw and measure rather than use trigonometry. Pick a scale (e.g. 1 cm = 10 N) and draw the vectors nose-to-tail; the resultant runs from the start of the first to the end of the last, and you measure its length and angle.

HT ONLY Resultant forces (9.5). Explain examples where several forces give a **resultant force**, and the special case of **balanced forces when the resultant is zero** (equilibrium). Forces in a straight line add or subtract: 500 N forward and 200 N backward gives 300 N forward.

2.7 Newton's first and second laws (2.14–2.15)

Newton's first law (2.14). A body remains at rest or continues at constant velocity unless acted on by a resultant force. Use it in two situations:

- **a — resultant force zero:** the body is at rest or moving at **constant velocity**. A car at a steady 25 m/s has driving force = drag; a skydiver at terminal velocity has weight = air resistance.
- **b — resultant force not zero:** the **speed and/or direction of the body change(s)**.

ANALOGY

Inertia. Stand on a bus. When it pulls away you lurch backwards; when it brakes you are thrown forwards — your body simply carries on doing what it was doing. Nothing pushed you; the bus changed velocity and you did not. That reluctance to change velocity is inertia.

2.8 Weight, mass and gravitational field strength (2.16–2.18)

Weight (2.16) is the force acting on an object due to a gravitational field. Mass does not change; weight does, because it depends on where the object is.

How weight is measured (2.17). With a **calibrated spring balance (newtonmeter)**: the object hangs from a spring that stretches in proportion to the force, on a scale marked in newtons. Kitchen scales measure weight but are calibrated to display mass in kg.

Weight and gravitational field strength (2.18). Weight is **directly proportional to mass**, the constant of proportionality being g , whose value depends on the object you are near and your distance from it: about 10 N/kg at the Earth's surface, 1.6 N/kg on the Moon. A 60 kg astronaut weighs 600 N on Earth and 96 N on the Moon, but has a mass of 60 kg in both. The whole weight acts at the **centre of mass**.

2.9 Core Practical 2.19 — force, mass and acceleration

2.10 Circular motion and inertial mass (2.20–2.22)

HIGHER TIER

HT ONLY An object moving in a **circular orbit at constant speed** has a **changing velocity** (qualitative only) — its speed is constant but its **direction** changes continuously, and velocity is a vector (2.20).

HT ONLY For motion in a circle there must therefore be a **resultant force**, the **centripetal force**, acting **towards the centre of the circle** (2.21). Examples: gravity on an orbiting planet, tension in the string of a whirled ball, friction between tyres and road on a bend.

HT ONLY **Inertial mass (2.22)** measures **how difficult it is to change the velocity of an object** (including from rest), and is defined as the **ratio of force over acceleration**, $m = F \div a$ — Newton's second law rearranged. A large inertial mass needs a large force for even a small acceleration.

2.11 Newton's third law (2.23)

HIGHER TIER

Newton's third law: when two objects interact, the forces they exert on each other are **equal in size and opposite in direction**. Recall and apply it **to equilibrium situations** and **HT ONLY to collision interactions, relating it to the conservation of momentum in collisions**.

A third-law pair is always the same size, opposite in direction, the **same type** of force (both gravitational, both contact, both magnetic...) and acting on **two different objects**.

A book on a table: the table pushes up on the book and the book pushes down on the table with an equal force — a third-law pair. The book's **weight** and the normal contact force on the book are *not* a pair: they act on the same object and are the balanced forces of Newton's **first** law.

ANALOGY

Newton's third law. Push off a wall on a skateboard: you push the wall and the wall pushes you — you move because of the force *the wall exerts on you*, not the one you exert on the wall. **The pair acts on different objects**, so the two forces can never cancel out; if they acted on the same object, nothing could ever accelerate.

2.12 Momentum and collisions (2.24–2.26)

HIGHER TIER

HT ONLY Momentum in collisions (2.25). In a closed system **momentum is conserved**: total momentum before = total momentum after. This follows from Newton's third law — the objects exert equal and opposite forces on each other for the same time, so one gains exactly what the other loses. Examples to describe:

- Two trolleys collide and stick together: the combined mass moves off more slowly than the moving trolley did.
- A gun recoils backwards as the bullet goes forwards; total momentum stays zero.
- A snooker ball stops dead on striking an identical stationary ball, which moves off at the first ball's speed.
- For objects moving in **opposite** directions, give one a positive and one a negative velocity before adding.

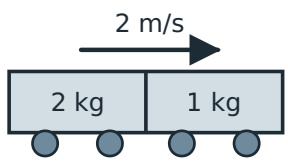
For a given change in momentum, **increasing the time reduces the force** — the physics behind the safety features in section 2.14.

Conservation of momentum in a collision

Higher tier only

Two trolleys collide and stick together

before: 
momentum before = $(2 \text{ kg} \times 3 \text{ m/s}) + (1 \text{ kg} \times 0 \text{ m/s})$
= 6 kg m/s

after: 
momentum after = $(2 \text{ kg} + 1 \text{ kg}) \times 2 \text{ m/s} = 6 \text{ kg m/s}$

total momentum before = total momentum after
momentum is conserved in a closed system

a closed system: no external forces act on the trolleys

Longer collision time, smaller force

$F = \text{change in momentum} \div \text{time}$
 $F = m \Delta v \div \Delta t$ (equation sheet)

The same change in momentum spread over a longer time gives a smaller force on the people.

Safety features

- crumple zones • air bags
- seat belts • crash mats
- cycle helmets
- cushioned playground surfaces



ANALOGY

Momentum and impulse. Catching a cricket ball, you pull your hands back as it arrives. The ball's momentum change is fixed — fast to stopped either way — but taking 0.4 s instead of 0.05 s makes the force on your hands eight times smaller. Crash mats, trampolines and bending your knees all work the same way.

2.13 Reaction time and stopping distance (2.27–2.30)

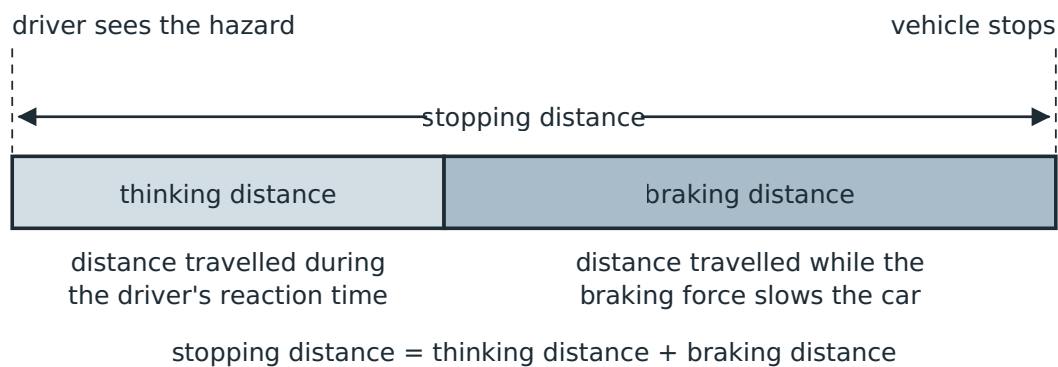
Measuring human reaction times (2.27). Explain the methods and recall typical results.

- **Ruler drop test** — a partner holds a metre rule vertically between your open fingers and drops it without warning; the distance fallen before you catch it is converted to a time (using $g = 10 \text{ m/s}^2$). Typical result **0.2–0.3 s**.
- **Computer reaction timer** — click as soon as the screen changes colour; the computer times it, removing human timing error. Typical result about **0.25 s**.
- Repeat and take a mean; the person must not see the moment of release.

Factors affecting stopping distance (2.29). The spec lists the **mass** and **speed** of the vehicle, the **driver's reaction time**, the **state of the brakes**, the **state of the road** and the **amount of friction between the tyre and the road surface**.

Factor	Thinking distance	Braking distance
Greater speed	Increases ($\propto$ speed)	Increases much more ($\propto$ speed ²)
Longer reaction time — tiredness, alcohol, drugs, distractions	Increases	No effect
Greater mass of vehicle (load, passengers)	No effect	Increases
Worn brakes or worn tyres	No effect	Increases
Wet, icy, oily or gravelly road	No effect	Increases
Less friction between tyre and road	No effect	Increases

Thinking distance, braking distance and stopping distance



Factors affecting thinking distance

(the driver's reaction time)

- tiredness
- alcohol
- drugs
- distractions, eg using a phone

Typical reaction time: 0.2 s to 0.9 s.

Factors affecting braking distance

- the speed of the vehicle
- poor condition of the brakes
- poor condition of the tyres
- wet or icy road surface
- adverse weather, eg rain or ice

Greater speed → greater stopping distance.

Large decelerations are dangerous

- A greater braking force is needed to stop in a shorter distance, so the deceleration is larger.
- Work done by the friction force between the brakes and the wheel reduces the kinetic energy of the car, so the temperature of the brakes increases. Brakes may overheat and the driver may lose control.

Factors affecting reaction time (2.30): drugs, including alcohol and drowsiness-causing medicines, and **distractions** such as a mobile phone, loud music or passengers; tiredness and age also lengthen it. These increase the **thinking distance only** — but the stopping distance rises with it.

2.14 Large decelerations and vehicle collisions (2.31)

HIGHER TIER

Dangers of large decelerations (2.31). A large deceleration is a large change in momentum in a very short time, and therefore a very large force ($F = (mv - mu) \div t$). Large forces on the body cause serious injury — whiplash, broken bones, organ damage. Safety features **increase the time** taken for the momentum to change, reducing the force:

- **Crumple zones** — the front of the car deforms, extending the collision time.
- **Seat belts** — stretch, so the passenger decelerates over a longer time instead of hitting the windscreen.
- **Air bags** — inflate and squash, spreading the force over a longer time and a larger area.
- **Helmets, crash mats and escape lanes** — the same principle.

HT ONLY Estimating the forces involved (2.31). Use typical values — family car $\approx 1000\text{--}1500$ kg, town speed ≈ 13 m/s, motorway speed ≈ 30 m/s, collision lasting $\approx 0.1\text{--}1$ s — then apply $F = (mv - mu) \div t$, or estimate the deceleration and use $F = m \times a$. Quote the answer to one significant figure as an estimate.

HIGHER TIER

NOTE

Use of mathematics (Topic 2). Make calculations using ratios and proportional reasoning to convert units and compute rates; relate changes and differences in motion to distance–time and velocity–time graphs, and interpret lines and slopes; **HT ONLY interpret enclosed areas in velocity– time graphs**; and apply the formulae relating distance, time and speed for uniform motion and for motion with uniform acceleration, and calculate average speed for non-uniform motion.

NOTE

Suggested practicals (not core practicals). Investigate the acceleration g in free fall and the magnitudes of everyday accelerations; investigate conservation of momentum during collisions; investigate inelastic collisions (the objects staying together) and 'near' elastic collisions; investigate the relationship between mass and weight; investigate how crumple zones can be used to reduce the forces in collisions.