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

Physical quantities and units AS

Read online at pastopic.com/cambridge/physics-9702/notes/physical-quantities-and-units

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What you need to know

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

1. **Say what a physical quantity is.** Every physical quantity is a number (its magnitude) together with a unit, such as 2.5 m or 300 K.
2. **Make sensible estimates** of the quantities in the course: the mass of a person, the speed of a car, the current in a kettle, the size of an atom, and so on.
3. **Recall the five SI base quantities and their units:** mass (kg), length (m), time (s), current (A) and temperature (K).
4. **Write any derived unit in base units** (for example the newton as kg m s^{-2}), and use the derived units of the quantities in the course.
5. **Check that an equation is homogeneous** by comparing the base units of each term, and use this to find the units of a constant or an unknown power.
6. **Recall and use the ten prefixes** from pico (p) to tera (T), on base and derived units alike.
7. **Explain systematic errors** (including zero errors) **and random errors**, and what each does to a set of readings.
8. **Tell precision from accuracy.**
9. **Find the uncertainty in a calculated quantity** by adding absolute uncertainties or adding percentage uncertainties.
10. **Tell scalars from vectors** and give examples of each from the course.
11. **Add and subtract vectors** in one plane.
12. **Split a vector into two perpendicular components.**

Understand it

A physical quantity is a number and a unit

"The rope is 12 long" tells you nothing: 12 m and 12 cm are very different ropes. A **physical quantity** is anything you can measure, and writing one down always needs both parts: a **numerical magnitude** and a **unit**. 7.0 N is a physical quantity. On their own, "kilogram" is only a unit and "3.0" or "40%" are only numbers.

The number does not have to be in standard form and the unit does not have to be SI or a base unit: 450 g and 0.450 kg are both complete.

SI base units

Scientists agree on a small set of **base quantities**, each with a **base unit**. Every other unit is built from them. In this course there are five:

Base quantity	Base unit	Symbol
mass	kilogram	kg
length	metre	m
time	second	s
electric current	ampere	A
temperature	kelvin	K

Keep the words apart: **time** is a base quantity, the **second** is its base unit. **Charge** is not a base quantity and the **coulomb** is not a base unit (charge = current × time, so C = A s). The base unit of temperature is the **kelvin**, not the degree Celsius, and the base unit of mass is the **kilogram**, not the gram.

Derived units

Every other quantity is defined by an equation, and its unit comes from that equation. To write a unit in base units, go back to the defining equation and substitute the base units of each quantity:

- speed $= \dfrac{\text{distance}}{\text{time}}$: m s^{-1}; acceleration $= \dfrac{\text{change in velocity}}{\text{time}}$: m s^{-2}
- force $= ma$: kg × m s^{-2} = kg m s^{-2} (the **newton**, N)
- work $= Fs$: kg m s^{-2} × m = kg m^2 s^{-2} (the **joule**, J)
- power $= \dfrac{\text{work}}{\text{time}}$: kg m^2 s^{-3} (the **watt**, W)
- pressure $= \dfrac{\text{force}}{\text{area}}$: kg m s^{-2} ÷ m^2 = kg m^{-1} s^{-2} (the **pascal**, Pa)
- charge $= It$: A s (the **coulomb**, C)
- potential difference $= \dfrac{\text{energy}}{\text{charge}}$: kg m^2 s^{-2} ÷ A s = kg m^2 s^{-3} A^{-1} (the **volt**, V)
- resistance $= \dfrac{V}{I}$: kg m^2 s^{-3} A^{-2} (the **ohm**, Ω)
- frequency $= \dfrac{1}{\text{period}}$: s^{-1} (the **hertz**, Hz)

Named units are just shorthand, so several combinations can mean the same thing. N m, J and W s are all units of energy; N s and kg m s^{-1} are both units of momentum.

Homogeneous equations

You can only add, subtract or equate things that have the same units: 3 kg + 2 s means nothing. An equation is **homogeneous** when every term has the same base units. For $s = ut + \frac{1}{2}at^2$:

- s: m
- ut: m s^{-1} × s = m
- $\frac{1}{2}at^2$: m s^{-2} × s^2 = m ($\frac{1}{2}$ is a pure number with no unit)

Every term is in metres, so the equation is homogeneous. Pure numbers such as 2, $\frac{1}{2}$ and π have no units, so they never affect homogeneity. That is also why a homogeneous equation can still be **wrong**: $s = ut + at^2$ is homogeneous too, but the missing $\frac{1}{2}$ makes it false. Homogeneity can prove an equation wrong, never right.

The same idea finds the units of a constant. If $F = kv^2$, then $k = \dfrac{F}{v^2}$, so its units are kg m s^{-2} ÷ m^2 s^{-2} = kg m^{-1}.

Prefixes

A prefix multiplies a unit by a power of ten.

Prefix	Symbol	Multiplier
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
deci	d	10^{-1}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}

So 350 nm $= 350 \times 10^{-9}$ m $= 3.5 \times 10^{-7}$ m, and 2.4 GHz $= 2.4 \times 10^{9}$ Hz. Capitals matter: m is milli, M is mega.

Squared and cubed units need the prefix squared or cubed. 1 cm $= 10^{-2}$ m, so 1 cm² $= (10^{-2})^2$ m² $= 10^{-4}$ m² and 1 cm³ $= 10^{-6}$ m³. Likewise 1 mm² $= 10^{-6}$ m². A density of 1 g cm^{-3} is $\dfrac{10^{-3}\ \mathrm{kg}}{10^{-6}\ \mathrm{m}^3} = 1000$ kg m^{-3}.

Estimating

An estimate is a sensible value to one significant figure, or just the right power of ten. Build it from a few values you know and a simple formula. Useful values:

Quantity	Rough value
mass of an adult	70 kg (weight about 700 N)
height of an adult	1.7 m
walking speed; car in town; car on a motorway	1.5 m s^{-1}; 15 m s^{-1}; 30 m s^{-1}
mass of a small car	1000 kg
density of water (a person's body is close to it)	1000 kg m^{-3}
density of most metals	3000 to 9000 kg m^{-3}
diameter of an atom	10^{-10} m
wavelength of visible light	400 nm (violet) to 700 nm (red)
mains voltage (in many countries); kettle power	230 V; 2 to 3 kW
room temperature	290 K to 300 K
thickness of a sheet of paper	0.1 mm

For example, the kinetic energy of a small car in town is about $\frac{1}{2} \times 1000 \times 15^2 \approx 1 \times 10^5$ J. The number of atoms in 1 cm^3 of metal is about $\dfrac{10^{-6}\ \mathrm{m}^3}{(10^{-10}\ \mathrm{m})^3} = 10^{24}$, since each atom takes up a cube about 10^{-10} m across.

Errors: systematic and random

No measurement is perfect. The difference between a reading and the true value is an **error**, and there are two kinds.

A **systematic error** shifts every reading the **same way by the same amount** (or the same fraction). Causes include:

- a **zero error**: the instrument does not read zero when it should, such as a balance that shows 0.3 g with nothing on it;
- a wrongly calibrated scale, such as a ruler whose marks are too far apart;
- always reading a scale from the same wrong angle.

Repeating and averaging does **not** remove a systematic error, because every reading is off in the same way. You remove it by finding it: check the zero before you start and subtract any zero error, or calibrate against a known value.

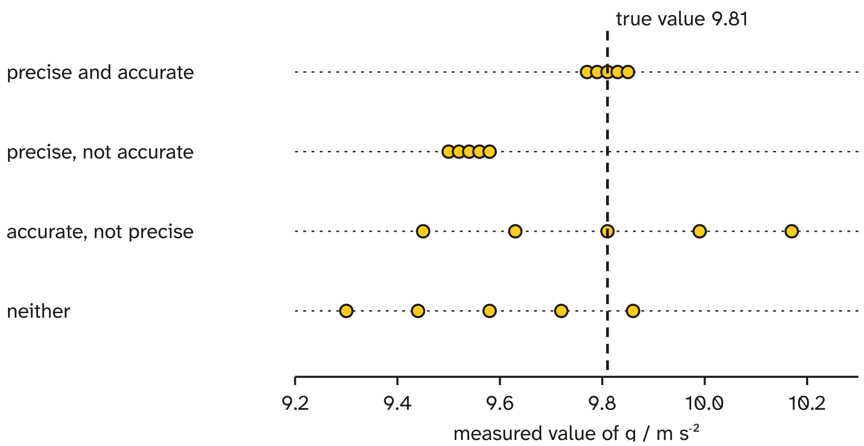
For example, if a ruler's marks are 2.0% too close together, each "millimetre" on it is really 0.98 mm. A rod that measures 250 mm on this ruler is really $250 \times 0.98 = 245$ mm long. Every reading is too **large**, by the same fraction.

A **random error** makes readings **scatter on both sides** of the true value, by different amounts each time. Causes include human reaction time with a stopwatch, a reading that fluctuates, and judging where a pointer sits between two marks. Taking several readings and **averaging** reduces the effect of random errors.

Precision and accuracy

- A set of readings is **precise** if the readings are **close to each other** (a small spread). Precision is about random error.
- A reading or set of readings is **accurate** if it is **close to the true value**. Accuracy is about systematic error.

The two are independent, as the diagram shows. Precise readings can all be wrong by the same amount, and scattered readings can average out to the true value.

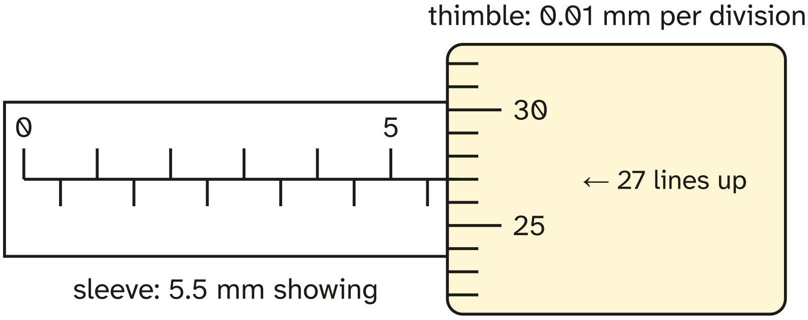


The number of decimal places an instrument shows (its **resolution**) is not the same as accuracy: a digital balance reading to 0.01 g can still have a zero error.

Zero errors and reading a micrometer

A **micrometer screw gauge** measures small lengths, such as the diameter of a wire, to 0.01 mm. The **sleeve** has a millimetre scale above its datum line and half-millimetre marks below it. The **thimble** turns once for every 0.50 mm and has 50 divisions, so each division is 0.01 mm.

To read it: take the last mark the thimble edge has uncovered on the sleeve (including a half-millimetre mark if one shows), then add the thimble division that lines up with the datum line, times 0.01 mm.



reading = 5.5 mm + 27 × 0.01 mm = 5.77 mm

Before measuring, close the jaws and read the gauge. If it reads $+0.03$ mm, that is a **zero error** of $+0.03$ mm, and every reading is 0.03 mm too large: a reading of 5.77 mm means a true diameter of $5.77 - 0.03 = 5.74$ mm. If the closed reading is below zero, say -0.02 mm, **add** 0.02 mm to each reading instead. In general, **true value = reading − zero error**.

A ruler reading is found the same way from two ends: a length is (end reading) − (start reading), and each end has its own uncertainty.

Uncertainty

Every measurement has an **uncertainty**: a range that the true value probably lies within. Write it three ways:

- **absolute uncertainty**: $l = (25.0 \pm 0.5)$ cm, in the same unit as the value;
- **fractional uncertainty**: $\dfrac{\Delta l}{l} = \dfrac{0.5}{25.0} = 0.02$;
- **percentage uncertainty**: $0.02 \times 100\% = 2\%$.

For a set of repeated readings, use the **mean** as the value and **half the range** as the absolute uncertainty. Readings of 2.46, 2.51, 2.49 and 2.54 s give (2.50 ± 0.04) s.

When you calculate a quantity from measured ones, the uncertainties combine by two rules. Both are **additions**, whether you add or subtract the values, or multiply or divide them.

Adding or subtracting quantities: add the absolute uncertainties. A spring's pointer moves from (250 ± 2) mm to (318 ± 2) mm, so the extension is (68 ± 4) mm. The uncertainty grows even though the values were subtracted. As a percentage, $\frac{4}{68} = 5.9\%$, far more than either reading's (under 1%): the difference of two close values is always much less certain.

Multiplying or dividing quantities: add the percentage (or fractional) uncertainties. For $\rho = \dfrac{m}{V}$, the percentage uncertainty in ρ is (% in m) + (% in V).

A power multiplies the percentage uncertainty by the power. x^2 has twice the percentage uncertainty of x, x^3 three times, $\sqrt{x}$ half and $\frac{1}{x^2}$ twice (the sign of the power doesn't matter; always add). For a circle of radius $r = (4.0 \pm 0.1)$ cm, r has 2.5% uncertainty, so $A = \pi r^2$ has $2 \times 2.5\% = 5\%$. For $E = \frac{1}{2}mv^2$ with m to $\pm 2\%$ and v to $\pm 3\%$, E is uncertain by $2\% + 2 \times 3\% = 8\%$.

Exact numbers have no uncertainty. π, $\frac{1}{2}$ and 4 in a formula add nothing. Multiplying a value by an exact number multiplies its absolute uncertainty by the same number, so its percentage stays the same.

Then turn the percentage back into an absolute uncertainty: absolute $=$ value $\times \frac{\text{percentage}}{100}$. Give the absolute uncertainty to **one significant figure** and round the value to the **same decimal place**: 7921 ± 235 kg m^{-3} becomes $(7.9 \pm 0.2) \times 10^3$ kg m^{-3}.

Scalars and vectors

A **scalar** has magnitude only. A **vector** has magnitude **and direction**. Both kinds still need a unit.

Scalars	Vectors
distance, speed, time, mass	displacement, velocity, acceleration
energy (every kind), work, power	force (including weight, tension, upthrust, drag, friction)
pressure, density, volume, area	momentum
temperature, charge, potential difference, resistance	
frequency, wavelength, period	

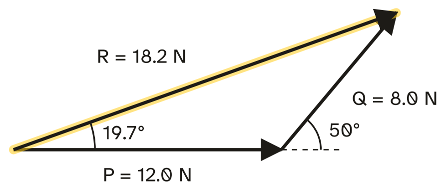
A minus sign is not a direction: -5 °C is a scalar, and so is a negative charge. Some combinations are worth knowing:

- a vector times (or divided by) a scalar is a vector: mass × acceleration = force, velocity × time = displacement, pressure × area = force;
- work is force × displacement **in the direction of the force**, and it is a scalar: it has no direction of its own.

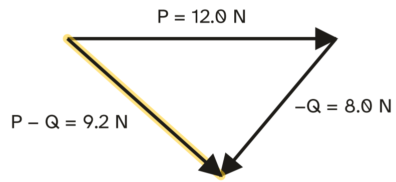
Adding and subtracting vectors

To **add** two vectors, draw them **tip to tail**: draw the first, then start the second at the tip of the first. The **resultant** is the arrow from the start of the first to the tip of the second. To **subtract** a vector, reverse it and add: $\mathbf{P} - \mathbf{Q} = \mathbf{P} + (-\mathbf{Q})$, where $-\mathbf{Q}$ has the same size as $\mathbf{Q}$ but points the opposite way.

P + Q: tip to tail



P − Q = P + (−Q)



You can find the resultant three ways:

- **Scale drawing**: draw the triangle to scale, then measure the resultant's length and angle.
- **Pythagoras** when the two vectors are perpendicular. 6.0 N east and 8.0 N north give $\sqrt{6.0^2 + 8.0^2} = 10.0$ N at $\tan^{-1}\frac{8.0}{6.0} = 53.1^\circ$ north of east.
- **Components** (next section) or the **cosine and sine rules** for any other angle.

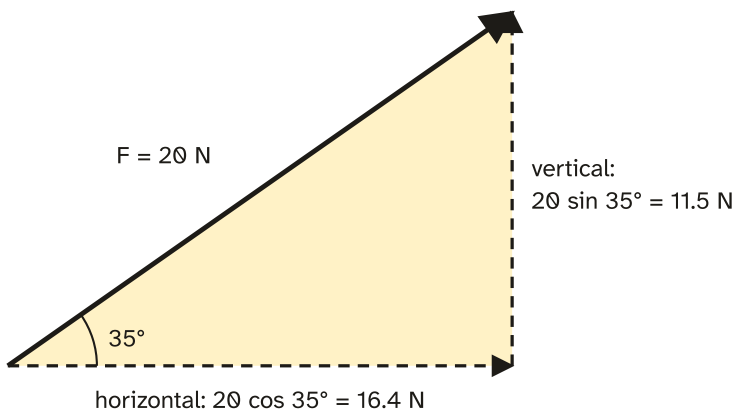
A **change** in a vector quantity is a subtraction: change in velocity $= \mathbf{v} - \mathbf{u}$. A ball moving at 5.0 m s^{-1} east that ends up moving at 5.0 m s^{-1} north has a change in velocity of $\sqrt{5.0^2 + 5.0^2} = 7.1$ m s^{-1} towards the north-west, not zero.

The resultant of two vectors is largest when they point the same way (sizes add) and smallest when they point opposite ways (sizes subtract). Forces of 3 N, 5 N and 10 N can give any resultant from $10 - 3 - 5 = 2$ N up to $3 + 5 + 10 = 18$ N, but never 0, because the 10 N force is bigger than the other two together.

Components

Any vector can be replaced by two **perpendicular components** that together have the same effect. For a vector of size F at angle θ to a direction:

- the component **along** that direction is $F\cos\theta$ (the side next to the angle);
- the component **at right angles** to it is $F\sin\theta$ (the side opposite the angle).



Components make adding any number of vectors easy: resolve each one in the same two directions, add all the components in each direction (with signs for opposite directions), then combine the two totals with Pythagoras and find the angle with $\tan^{-1}$.

Key facts and formulas

"Given" means it is on the data sheet in the exam. "Learn it" means you must remember it. Nothing in this topic is on the data sheet except the value of g.

Formula	Status
Physical quantity = numerical magnitude × unit	Learn it
Base units: kg, m, s, A, K	Learn it
Prefixes: p 10^{-12}, n 10^{-9}, μ 10^{-6}, m 10^{-3}, c 10^{-2}, d 10^{-1}, k 10^{3}, M 10^{6}, G 10^{9}, T 10^{12}	Learn it
N = kg m s^{-2}, J = kg m^2 s^{-2}, W = kg m^2 s^{-3}, Pa = kg m^{-1} s^{-2}, C = A s, V = kg m^2 s^{-3} A^{-1}, Ω = kg m^2 s^{-3} A^{-2}, Hz = s^{-1}	Learn it
Percentage uncertainty $= \dfrac{\Delta x}{x} \times 100\%$	Learn it
$y = a \pm b$: $\Delta y = \Delta a + \Delta b$	Learn it
$y = \dfrac{a^p b^q}{c^r}$: $\dfrac{\Delta y}{y} = p\dfrac{\Delta a}{a} + q\dfrac{\Delta b}{b} + r\dfrac{\Delta c}{c}$	Learn it
Repeated readings: value = mean, uncertainty = $\frac{1}{2}$ × range	Learn it
True value = reading − zero error	Learn it
Components of F at θ to a direction: $F\cos\theta$ along it, $F\sin\theta$ at right angles	Learn it
Perpendicular vectors: $R = \sqrt{X^2 + Y^2}$, angle $= \tan^{-1}\dfrac{Y}{X}$	Learn it
Cosine rule $a^2 = b^2 + c^2 - 2bc\cos A$; sine rule $\dfrac{a}{\sin A} = \dfrac{b}{\sin B}$	Learn it
Circle $A = \pi r^2$; sphere $V = \frac{4}{3}\pi r^3$; cylinder $V = \pi r^2 l$; cuboid $V = lwh$	Learn it
$g = 9.81$ m s^{-2}	Given

How to do it

In the Paper 1 and Paper 2 questions we have tagged for this topic (163 different questions, 2021–2025; 5 more appear on two papers), the types came up this often. 17 of the 163 questions mix two or three types, so the counts add up to more than 163.

Question type	Questions
SI base units, derived units and homogeneity	47
Combining uncertainties	37
Identifying scalars and vectors	21
Errors, precision and accuracy	19
Estimates	17
Adding, subtracting and resolving vectors	16
What a physical quantity is	11
Prefixes and powers of ten	10
Reading instruments and zero errors	6

1. SI base units, derived units and homogeneity (47 questions)

Finding the base units of a quantity or a constant:

1. **Make the unknown the subject** of the equation.
2. **Write the base units of every other quantity**, using the defining equations (a force is kg m s^{-2}, a pressure kg m^{-1} s^{-2}, a power kg m^2 s^{-3}, and so on). Drop pure numbers such as 2, π and $\frac{4}{3}$.
3. **Collect the powers** of each base unit: add powers on top, subtract powers underneath.

For example, the energy stored in a stretched spring is $E = \frac{1}{2}kx^2$, so $k = \dfrac{2E}{x^2}$, with units $\dfrac{\mathrm{kg\,m^2\,s^{-2}}}{\mathrm{m^2}} = $ kg s^{-2}.

Variations you will meet:

- **"Use the definition of ... to show that the base units are ..."**: write the defining equation in words or symbols first (power = work done ÷ time), then substitute. The first mark is for the equation.
- **Temperature differences** such as $(T_1 - T_2)$ have units K, and pressure differences have the units of pressure. A difference is never unitless.
- **Constants with no units.** Show that the base units on both sides are the same, so the constant's units cancel completely.
- **Find the power** n in an equation such as $v = k\left(\dfrac{p}{\rho}\right)^n$, where p is a pressure, ρ a density and k a number. Write the units of the bracket (kg m^{-1} s^{-2} ÷ kg m^{-3} = m^2 s^{-2}), then choose n so that both sides match: $(\mathrm{m^2\,s^{-2}})^n = \mathrm{m\,s^{-1}}$, so $n = \frac{1}{2}$. With more than one base unit, match the powers of each in turn.

- **Which equation is homogeneous?** Work out the base units of each side for each option.
- **Which quantity has these units?** Or **which two units are the same?** Reduce everything to base units and compare. W s m^{-1} = kg m^2 s^{-3} × s ÷ m = kg m s^{-2}, a force.
- **Base quantity or base unit?** Pick from lists: current is a base quantity, ampere is a base unit; charge, force and energy are neither; coulomb, newton and degree Celsius are not base units.

2. Combining uncertainties (37 questions)

1. **Get each percentage uncertainty.** Percentage $= \dfrac{\text{absolute}}{\text{value}} \times 100\%$. If the question gives percentages already, use them.
2. **Multiply each by its power** in the formula (2 for a square, 3 for a cube or a volume from a length, $\frac{1}{2}$ for a square root). Ignore pure numbers such as π.
3. **Add them all**, even for quantities that divide.
4. **If an absolute uncertainty is asked for**, multiply the calculated value by the percentage ÷ 100. Give it to 1 significant figure and the value to the same decimal place.

For example, $g = \dfrac{2s}{t^2}$ with s to 1% and t to 2% gives $1\% + 2 \times 2\% = 5\%$.

Variations you will meet:

- **Sums and differences**, such as an extension, a temperature rise, or a wall thickness from two diameters: add the absolute uncertainties first, then work out the percentage if needed. Halving a value (radius from diameter, wall thickness from the difference of two diameters) halves its absolute uncertainty too.
- **Volumes and areas from lengths**: a sphere's volume from its diameter has $3\times$ the diameter's percentage uncertainty; the cross-sectional area of a wire has $2\times$.
- **Radius from a volume** ($r = \sqrt[3]{3V/4\pi}$): the percentage uncertainty in r is $\frac{1}{3}$ of that in V.
- **Which measurement contributes most?** Work out each term's contribution (percentage × power) and compare. A small reading, such as a wire's diameter or a short extension, usually has the biggest percentage, and squaring it doubles it.
- **Working back from the answer**: "W has 8% uncertainty; which formula links it to X (2%) and Y (4%)?" Check each option by the rules.
- **Two results with uncertainties**: "Could the two cubes be made of the same material?" Work out each range (value ± absolute uncertainty). If the ranges overlap, they could be the same; if not, they are different.
- **A fluctuating reading plus a meter's stated accuracy**: take the middle of the fluctuation as the value, half the fluctuation as one uncertainty, the meter's percentage of the reading as the other, and add them.

3. Identifying scalars and vectors (21 questions)

1. Ask: **does this quantity have a direction?** If so, it is a vector; if not, a scalar.
2. Know the lists in "Understand it". Weight, upthrust and momentum are vectors; energy, power, pressure, temperature and charge are scalars.

Variations you will meet:

- **Tables to tick**, or a list that is "all scalars".
- **Definitions**: a scalar has magnitude only; a vector has magnitude and direction. Both have a magnitude and a unit.
- **"Which calculation gives a vector?"** A vector combined with a scalar gives a vector (for example final displacement – initial displacement, or mass × acceleration); work (force × displacement along it) and energy are scalars.
- **Statements with wrong reasons**: temperature is not a vector because it can be negative, and time is not a vector because it only goes forward.

4. Errors, precision and accuracy (19 questions)

1. **Precision**: look at how close the readings are **to each other**.
2. **Accuracy**: look at how close the readings (or their mean) are **to the true value**.
3. **Systematic error**: same shift every time, not reduced by averaging; zero errors and bad calibration are examples. **Random error**: scatter both ways, reduced by averaging.

Variations you will meet:

- **Sets of readings and a true value** (for example readings of 503, 504 and 503 mm when the true value is 500 mm): the readings are close together, so precise to within 1 mm, but all 3 to 4 mm high, so not accurate to within 1 mm.
- **A single value with an uncertainty**, such as (9 ± 1) m s^{-2} for g: it is accurate (the true 9.81 lies inside the range) but not precise (the range is wide).
- **Wrongly spaced scale marks**: marks too far apart make every reading too **small**; too close together make it too **large**. Correct the reading by the same percentage.
- **"Explain what is meant by accuracy"**: how close a measured value is to the true value.
- **"Suggest why the results are precise but not accurate"** or **"suggest a cause of the systematic error"**: name something that shifts every reading the same way, such as a zero error on the balance or a consistent reaction-time delay. "Human error" is too vague to earn a mark.

5. Estimates (17 questions)

1. **Pick the formula** that links the quantity to things you know.
2. **Put in rough values** from the table in "Understand it", to one significant figure.
3. **Choose the option with the right power of ten.**

For example, the weight of an adult is about $70 \times 9.81 \approx 700$ N, so 7×10^2 N.

Variations you will meet:

- **Mass from size and density**: mass $=$ density × volume. A 10 cm cube of aluminium ($\rho \approx 2700$ kg m^{-3}) has mass $2700 \times 10^{-3} = 2.7$ kg.

- **Counting atoms**: volume of the object ÷ volume of one atom (about 10^{-30} m³).
- **Kinetic energy** of a runner, a car or a train: $\frac{1}{2}mv^2$ with rough values; convert km h^{-1} to m s^{-1} first (divide by 3.6).
- **Current from power**: a kettle takes about $\frac{2300}{230} = 10$ A.
- **"Which is not a reasonable estimate?"** Check each option; the wrong one is usually off by a power of ten or more, often because of a prefix.

6. Adding, subtracting and resolving vectors (16 questions)

1. **Resolve** each vector into components along two perpendicular directions: $F\cos\theta$ along, $F\sin\theta$ across, where θ is the angle to the direction you resolve along.
2. **Add** the components in each direction, taking one way as positive.
3. **Combine** with Pythagoras, and find the direction with $\tan^{-1}$. State the angle and what it is measured from.

Variations you will meet:

- **Two vectors at an angle**: use components, or the cosine rule on the tip-to-tail triangle. Two equal vectors F at an angle θ to each other have resultant $2F\cos\frac{\theta}{2}$, so two 8.0 N forces at 90° give 11.3 N.
- **Subtraction and change in velocity**: reverse the vector being subtracted, then add tip to tail. Pick the diagram that shows $\mathbf{P} + (-\mathbf{Q})$.
- **A boat crossing a river** (or an aircraft in a wind) that must travel straight across: aim upstream so the current is cancelled. $\sin\theta = \dfrac{\text{current speed}}{\text{boat speed}}$, and the speed straight across is $\sqrt{\text{boat}^2 - \text{current}^2}$.
- **A resultant velocity with wind or current** at an angle: add the components of the two velocities.
- **Possible resultants of several forces**: the largest is the sum; the smallest is zero only if the biggest force is no more than the sum of the others.

7. What a physical quantity is (11 questions)

1. A physical quantity is something measurable, and it is written as a **number with a unit**.
2. Reject anything that is only a unit (metre, kelvin, pascal), only a number (3.0, 40%), or not measurable (flavour).

Variations you will meet:

- **"What must all physical quantities have?"** A magnitude and a unit. Not a direction, not an SI or base unit, and not standard form.
- **"Which is a physical quantity?"** A named measurable, such as potential difference or spring constant, or a value with a unit, such as 7.0 N.
- **Nonsense units**: a value is a possible measurement only if its unit simplifies to the unit of a real quantity.

8. Prefixes and powers of ten (10 questions)

1. **Replace the prefix by its power of ten.**
2. **To change to another prefix**, divide by the new prefix's power: 5.2 GW $= 5.2 \times 10^9$ W $= \dfrac{5.2 \times 10^9}{10^6}$ MW $= 5.2 \times 10^3$ MW.

Variations you will meet:

- **Squared and cubed units**: 0.25 mm² $= 0.25 \times 10^{-6}$ m²; 1 g cm⁻³ $= 1000$ kg m⁻³. For N mm⁻², multiply by 10^6 to get N m⁻².
- **Ordering prefixes** by size, or finding the largest and smallest unit.
- **Ratios**: 1 mA is $\dfrac{10^{-3}}{10^{-6}} = 1000$ times 1 μA.
- **Checking combinations**, such as current × resistance = voltage with mA and kΩ: $10^{-3} \times 10^3 = 1$, so mA × kΩ gives volts.

9. Reading instruments and zero errors (6 questions)

1. **Micrometer**: sleeve reading (whole and half millimetres) + thimble division × 0.01 mm.
2. **Correct for the zero error**: true value = reading − zero error (subtracting a negative zero error adds it).
3. **Uncertainties**: the corrected value comes from two readings, so add their absolute uncertainties.

Variations you will meet:

- **An analogue meter**: work out what each small division is worth (range ÷ number of divisions), then count divisions.
- **Thickness of one sheet**: measure a whole stack with a ruler and divide by the number of sheets. The reading is (end − start), and dividing by the number of sheets divides the uncertainty too.
- **Naming an instrument**: vernier calipers for lengths of a few centimetres to 0.01 cm; a micrometer for diameters of wires and small balls to 0.01 mm.

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) Use the definition of potential difference to show that the SI base units of the volt are kg m^2 s^{-3} A^{-1}. **[2]**

(b) The rate P at which thermal energy passes through a window is given by $P = UA\,\Delta T$, where A is the area of the window and ΔT is the temperature difference between the two sides. Determine the SI base units of U. **[2]**

Solution

(a) Potential difference $=$ energy transferred per unit charge, $V = \dfrac{W}{Q}$. **B1** Energy (force × distance) has units kg m s^{-2} × m $=$ kg m^2 s^{-2}, and charge $= It$ has units A s, so the volt is $\dfrac{\mathrm{kg\ m^2\ s^{-2}}}{\mathrm{A\ s}}$ $=$ kg m^2 s^{-3} A^{-1}. **B1**

(b) $U = \dfrac{P}{A\,\Delta T}$. P is a power: kg m^2 s^{-2} ÷ s $=$ kg m^2 s^{-3}. A is in m^2 and ΔT in K. **M1**

$$U : \frac{\mathrm{kg\ m^2\ s^{-3}}}{\mathrm{m^2 \times K}} = \mathrm{kg\ s^{-3}\ K^{-1}} \quad \mathbf{A1}$$

Example 2

The speed v of waves on deep water is given by $v = C(g\lambda)^n$, where g is the acceleration of free fall, λ is the wavelength and C is a constant with no units.

(a) Use base units to find n. **[2]**

(b) $C = 0.40$. Calculate v for waves of wavelength 2.5 m. **[1]**

(c) A student says that checking the base units proves that $C = 0.40$ is correct. Explain why the student is wrong. **[1]**

Solution

(a) $g\lambda$ has units m s^{-2} × m $=$ m^2 s^{-2}, and v has units m s^{-1}. **M1** $(\mathrm{m^2\ s^{-2}})^n = \mathrm{m\ s^{-1}}$ needs $2n = 1$, so $n = \frac{1}{2}$. **A1**

(b) $v = 0.40 \times \sqrt{9.81 \times 2.5} = 0.40 \times 4.95 = 2.0$ m s^{-1}. **B1**

(c) C has no units, so any value of C gives a homogeneous equation; homogeneity cannot test a pure number. **B1**

Example 3

A student measures a solid metal cylinder:

Quantity	Measurement
diameter d	(2.40 ± 0.02) cm
length l	(6.00 ± 0.05) cm

Quantity	Measurement
mass m	(215 ± 1) g

(a) Calculate the density of the metal in kg m^{-3}. **[2]**

(b) Calculate the percentage uncertainty in the density. **[3]**

(c) State the density with its absolute uncertainty, to an appropriate number of significant figures. **[1]**

Solution

(a) Radius $= 1.20$ cm, so $V = \pi r^2 l = \pi \times 1.20^2 \times 6.00 = 27.14$ cm^3. **M1** $\rho = \dfrac{215}{27.14} = 7.92$ g cm^{-3} $= 7920$ kg m^{-3}. **A1**

(b) d: $\dfrac{0.02}{2.40} \times 100 = 0.83\%$, doubled because V depends on d^2: 1.67%. **M1** l: $\dfrac{0.05}{6.00} \times 100 = 0.83\%$; m: $\dfrac{1}{215} \times 100 = 0.47\%$. **M1** Total: $1.67 + 0.83 + 0.47 = 2.97\% \approx 3.0\%$. **A1**

(c) Absolute uncertainty $= 7921 \times 0.0297 = 235$ kg m^{-3}, which is 200 to 1 significant figure. So $\rho = (7.9 \pm 0.2) \times 10^3$ kg m^{-3}. **B1**

Example 4

Two forces act on a point. Force $\mathbf{P}$ is 12.0 N due east. Force $\mathbf{Q}$ is 8.0 N at 50° north of east.

(a) Calculate the east and north components of $\mathbf{Q}$. **[2]**

(b) Determine the magnitude and direction of the resultant of $\mathbf{P}$ and $\mathbf{Q}$. **[3]**

(c) Determine the magnitude of $\mathbf{P} - \mathbf{Q}$. **[2]**

Solution

(a) East: $8.0 \cos 50^\circ = 5.14$ N. **B1** North: $8.0 \sin 50^\circ = 6.13$ N. **B1**

(b) Total east $= 12.0 + 5.14 = 17.14$ N; total north $= 6.13$ N. **M1** $R = \sqrt{17.14^2 + 6.13^2} = 18.2$ N **A1**, at $\tan^{-1} \dfrac{6.13}{17.14} = 19.7^\circ$ north of east. **A1**

(Check with the cosine rule: the angle inside the triangle between $\mathbf{P}$ and $\mathbf{Q}$ drawn tip to tail is $180^\circ - 50^\circ = 130^\circ$, so $R^2 = 12.0^2 + 8.0^2 - 2(12.0)(8.0)\cos 130^\circ = 331.4$ and $R = 18.2$ N.)

(c) $\mathbf{P} - \mathbf{Q}$: east $= 12.0 - 5.14 = 6.86$ N; north $= 0 - 6.13 = -6.13$ N. **M1** Magnitude $= \sqrt{6.86^2 + 6.13^2} = 9.2$ N. **A1**

Common mistakes

- **Calling the coulomb, the newton or the degree Celsius a base unit.** Examiner reports note the coulomb being picked in several years. Only kg, m, s, A and K are base units here, and "charge" is not a base quantity.
- **Writing a derived unit and calling it a base unit.** "Base units" means kg, m, s, A and K only; J, N, Pa and Hz must be broken down.
- **Treating a difference as unitless.** $(p_1 - p_2)$ is a pressure and $(T_1 - T_2)$ is a temperature; give them units.
- **Using hertz or amperes where they don't belong.** The base units of frequency are s^{-1}, and intensity (power per area) has no ampere in it.
- **Forgetting the power when combining uncertainties.** A diameter that is squared or cubed doubles or triples its percentage uncertainty, and a square root halves it. Multiplying the wrong quantity's uncertainty by the power is just as costly, so check which one carries the power.
- **Subtracting uncertainties.** Uncertainties always add, even when the quantities are divided or subtracted.
- **Mixing up absolute and percentage uncertainty.** Don't add a ± 0.1 cm to a $\pm 2\%$; convert first. And when turning a percentage into an absolute value, remember to divide by 100.
- **Giving the absolute uncertainty to too many figures,** or the value to a different decimal place from its uncertainty.
- **Saying averaging reduces a systematic error.** It only reduces random error.
- **Getting the direction of a calibration error wrong.** Marks too far apart make readings too small, not too large.
- **Confusing precision with the number of decimal places.** Precision is about the spread of repeated readings.
- **Squaring prefixes wrongly.** 1 mm² $= 10^{-6}$ m², not 10^{-3} m². Check that a final answer is a sensible size.
- **Adding vector sizes as if they were numbers.** 6 N and 8 N at right angles give 10 N, not 14 N. A change in velocity needs a vector subtraction.
- **Using sin for cos (or the reverse) when resolving.** The component next to the angle is $F\cos\theta$.

How to get the marks

- **"Define" and "use the definition of"**: give the defining word equation first (power $=$ work done ÷ time taken). The first mark is usually for that, before any units.
- **Base units**: show each quantity's base units before combining them, then give the final answer in the form kg m s^{-2} (powers, not fractions). In a "show that", every step must be visible and the last line must match the given units.
- **Uncertainty calculations**: the mark schemes give a method mark for a correct combination, such as $5 + 3 + 2 \times 4$, and the accuracy mark for the answer. Write the sum out.
- **Absolute uncertainty with a value**: 1 significant figure for the uncertainty (2 is usually allowed), and the value rounded to the same decimal place. $(6.4 \pm 0.2) \times 10^3$ kg m^{-3}, not $(6.382 \pm 0.19) \times 10^3$ kg m^{-3}.

- **Significant figures**: give a calculated value to the same number of significant figures as the least precise data, or one more. "Three significant figures" in a question is an instruction.
- **Explain precise/accurate**: refer to the data. "Precise because the values are close to each other; not accurate because they are all far from the true value of ...".
- **Vectors**: state the direction of a resultant with its reference (for example "19.7° north of east"). A magnitude alone loses the direction mark.
- **Physics mark schemes** also use a C1 mark: a mark for a correct step in the working, given automatically if the final answer is right. Showing your working earns it when the final answer slips. The worked examples above show these as **M1**.
- **Scalar/vector tables**: every tick must be right for the mark; one wrong row loses it.
- **"Suggest"**: a specific, relevant reason. "Human error" or "the equipment" earns nothing.

Quick check

1. Express the ohm in SI base units.
2. Convert (a) 0.40 mm² to m², (b) 7.5×10^4 μJ to J.
3. A student finds g from a pendulum using $g = \dfrac{4\pi^2 l}{T^2}$, with $l = (0.800 \pm 0.002)$ m and $T = (1.80 \pm 0.02)$ s. Calculate g and its absolute uncertainty.
4. Four measurements of g are 9.52, 9.55, 9.53 and 9.54 m s^{-2}. The true value is 9.81 m s^{-2}. Describe the precision and accuracy of the results, and state the kind of error most likely to be responsible.
5. A boat moves at 5.0 m s^{-1} in still water. It crosses a river 60 m wide that flows at 3.0 m s^{-1}, travelling straight across. Find the angle between the boat's heading and the line straight across, and the time taken to cross.

Answers

1. $R = \frac{V}{I}$, and the volt is kg m² s⁻³ A⁻¹ (Example 1(a)). So the ohm is kg m² s⁻³ A⁻¹ ÷ A $=$ kg m² s⁻³ A⁻².
2. (a) $0.40 \times 10^{-6} = 4.0 \times 10^{-7}$ m². (b) $7.5 \times 10^{4} \times 10^{-6} = 0.075$ J.
3. $g = \frac{4\pi^2 \times 0.800}{1.80^2} = 9.75$ m s⁻². Percentage uncertainty $= \frac{0.002}{0.800} \times 100 + 2 \times \frac{0.02}{1.80} \times 100 = 0.25 + 2.22 = 2.47\%$. Absolute uncertainty $= 9.75 \times 0.0247 = 0.24$, so $g = (9.7 \pm 0.2)$ m s⁻².
4. Precise: the readings differ by at most 0.03 m s⁻². Not accurate: the mean, 9.54 m s⁻², is 0.27 m s⁻² below the true value, far more than the spread. A **systematic** error (the same shift in every reading) is most likely, so averaging more readings would not help.
5. The upstream part of the boat's velocity must cancel the current: $\sin\theta = \frac{3.0}{5.0}$, so $\theta = 36.9^\circ$ upstream of straight across. Speed across $= \sqrt{5.0^2 - 3.0^2} = 4.0$ m s⁻¹, so the time is $\frac{60}{4.0} = 15$ s.

Past questions to try

- **9702/22/O/N/21 Q1**: prefixes, SI base units, and the percentage and absolute uncertainty in a resistivity.
- **9702/23/O/N/22 Q1**: the base units of a constant, then a value with its absolute uncertainty to the right figures.
- **9702/23/M/J/21 Q1**: scalars and vectors, velocity components and a resultant velocity with a current.
- **9702/11/M/J/21 Q5**: a micrometer reading corrected for a negative zero error, with its uncertainty.