

# Measurement and Units

Matthew Williams • Physics • May 20, 2026

## Measurement and Units

### Galileo and the Scientific Method

**Galileo Galilei** (1564-1642) is credited with establishing the modern scientific method in physics. Before Galileo, natural philosophers (including Aristotle) relied on reasoning and observation without controlled testing. Galileo's key contributions were:

- **Hypothesis and experiment:** he formed a testable prediction, then designed experiments to check it.
- **Controlled variables:** he changed one factor at a time and measured the outcome quantitatively.
- **Mathematical description:** he expressed results as equations rather than qualitative statements.
- **Evidence over authority:** his conclusions were based on measured data, not tradition.

His investigation of free fall showed that all objects (regardless of mass) accelerate at the same rate under gravity, directly contradicting Aristotle. His study of pendulum motion led to the discovery that the period depends on length, not on the mass of the bob.

### The Simple Pendulum

A simple pendulum consists of a mass (the **bob**) on a string of fixed length, swinging from a pivot. The **period  $T$**  is the time for one complete swing (there and back).

#### Factors investigated:

Factor	Effect on period
Length of string ( $L$ )	Longer string 'longer period ( $T \propto \sqrt{L}$ )
Mass of bob ( $m$ )	No effect
Angle of displacement ( $\theta$ )	No effect for small angles (less than about $10^\circ$ )

Only the length of the string affects the period. This is the conclusion Galileo first observed.

### Graphing the data:

- A graph of  $T$  against  $L$  gives a curved (square-root) shape.
- A graph of  $T^2$  against  $L$  gives a **straight line through the origin**, confirming  $T^2 \propto L$ . The gradient equals  $4\pi^2/g$ , so the graph can be used to determine  $g$ .

When plotting, use crosses or circled dots for data points, draw the line of best fit that passes closest to all points (not dot-to-dot), and use a triangle covering at least half the line to calculate the gradient.

Physics is built on measurement. Every physical quantity has a numerical value and a unit, without the unit, a number is meaningless. The system used internationally is the SI (Système International d'Unités).

## Physical Quantities

A **physical quantity** is anything that can be measured. Every quantity is either fundamental or derived.

**Fundamental quantities** cannot be defined in terms of other physical quantities. The SI defines seven, of which five appear throughout CSEC Physics:

Quantity	SI Unit	Symbol
Mass	kilogram	kg
Length	metre	m
Time	second	s
Temperature	kelvin	K
Electric current	ampere	A

**Derived quantities** are combinations of fundamental ones. They come with derived units:

Quantity	Definition	SI Unit
Area	length $\times$ length	$m^2$
Volume	length <sup>3</sup>	$m^3$
Density	mass / volume	$kg\ m^{-3}$

Speed	distance / time	$\text{m s}^{-1}$
Force	mass $\times$ acceleration	$\text{N} (= \text{kg m s}^{-2})$
Pressure	force / area	$\text{Pa} (= \text{N m}^{-2})$
Energy	force $\times$ distance	$\text{J} (= \text{N m})$
Power	energy / time	$\text{W} (= \text{J s}^{-1})$

## SI Prefixes

When quantities are very large or very small, prefixes scale the base unit:

Prefix	Symbol	Multiplier
mega-	M	$10^6$
kilo-	k	$10^3$
centi-	c	$10^{-2}$
milli-	m	$10^{-3}$
micro-	$\mu$	$10^{-6}$
nano-	n	$10^{-9}$

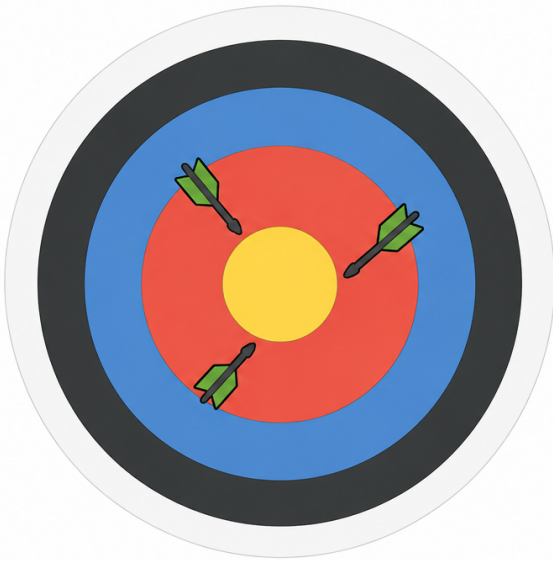
## Precision and Accuracy

These two are easy to confuse.

**Accuracy** describes how close a measurement is to the true value. An accurate measurement is correct; an inaccurate one contains systematic error.

**Precision** describes how repeatable a measurement is. Precise measurements cluster together, even if they are all slightly wrong. A well-calibrated instrument gives high accuracy; a sensitive instrument gives high precision. Both qualities are desirable but independent.

## accuracy



## precision



A common analogy for accuracy vs precision is arrows shot at a target: accurate arrows cluster around the bullseye, precise arrows cluster tightly together regardless of where they land

## Significant Figures

**Significant figures** (s.f.) express the precision of a measurement. The number of significant figures is the number of meaningful digits, starting from the first non-zero digit:

- 4.52 m has 3 s.f.
- 0.0063 kg has 2 s.f.
- 1500 could be 2, 3, or 4 s.f., use standard form to remove ambiguity (e.g.  $1.5 \times 10^3$ )

When calculating, the answer should match the lowest number of significant figures in the data. Rounding further than your data warrants gives a false impression of precision.

<JustInCase>

**Standard form** is a way of writing a number as  $A \times 10^n$ , where  $1 \leq A < 10$  and  $n$  is an integer. For example, 0.0045 in standard form is  $4.5 \times 10^{-3}$ .

</JustInCase>

## Sources of Error

**Random errors** affect individual measurements unpredictably. Taking multiple readings and averaging reduces their effect.

**Systematic errors** shift all readings in the same direction by the same amount. Averaging does not remove them. A classic systematic error is a **zero error**, when an instrument reads a non-zero value before any measurement is taken. Check for zero errors before using any instrument and subtract the offset from all readings.

**Parallax error** occurs when you read a scale at an angle rather than directly in front of it. Always position your eye so it is level with the scale marking.

## Measuring Instruments

Different instruments suit different ranges and required precision.

**Metre rule:** measures lengths to  $\pm 1$  mm. Suitable for objects 1 cm to 1 m.

A metre rule marked in centimetres

**Vernier caliper:** measures lengths to  $\pm 0.1$  mm. The vernier scale gives the fractional millimetre by finding which vernier division lines up with a main scale division.

A labelled diagram of a vernier caliper showing outside jaws, inside jaws, depth probe, main scale, and vernier scale

**Micrometer screw gauge:** measures diameters and small lengths to  $\pm 0.01$  mm. One full rotation of the thimble moves the spindle 0.5 mm. Read the sleeve, then add the thimble reading.

A labelled diagram of a micrometer screw gauge showing the anvil, spindle, sleeve, thimble, and ratchet

**Balance:** measures mass to varying precision depending on type. An electronic balance gives a direct reading; a beam balance compares the unknown mass to known masses.

**Stopwatch:** measures time intervals. Human reaction time ( $\sim 0.2$  s) limits its precision. For short events, use a motion sensor or light gate.

**Thermometer:** measures temperature. A liquid-in-glass thermometer relies on thermal expansion; a thermocouple converts a temperature difference to a small voltage and suits rapidly changing or extreme temperatures.

**Exam Tip**

In Paper 02, questions sometimes ask you to state the most suitable instrument for a measurement and justify your choice. The justification usually refers to the range (is the quantity within the instrument's scale?) and the precision (does the instrument read finely enough for the context?).

## Density

**Density** is mass per unit volume:

$$\rho = \frac{m}{V}$$

where  $\rho$  is density in  $\text{kg m}^{-3}$ ,  $m$  is mass in kg, and  $V$  is volume in  $\text{m}^3$ .

Density is an intrinsic property of a material; it does not change with the size of the sample. A 1 kg block of iron and a 10 kg block of iron have the same density.

To measure density:

- 1. Measure mass using a balance.
- 2. Measure volume. For regular objects, calculate from dimensions. For irregular solids, use a displacement method: fill a measuring cylinder with water, record the volume, fully submerge the object, and record the new volume. The difference is the object's volume.

**Density calculation (2019 Paper 02, Q2)**

A concrete block has dimensions  $0.4 \text{ m} \times 0.3 \text{ m} \times 0.2 \text{ m}$  and a mass of 160 kg.


**Step 1:** Find the volume.

$$V = 0.4 \times 0.3 \times 0.2 = 0.024 \text{ m}^3$$

**Step 2:** Apply the density formula.

$$\rho = \frac{m}{V} = \frac{160}{0.024} = 6\,667 \text{ kg m}^{-3}$$

The density is approximately  $6\,700 \text{ kg m}^{-3}$  (3 s.f.).

 **Exam Tip**

Density questions sometimes give volume in  $\text{cm}^3$  and mass in grams. You can work in  $\text{g cm}^3$  throughout (water has density  $1 \text{ g cm}^3$ ), but if the question asks for SI units, convert:  $1 \text{ g cm}^3 = 1000 \text{ kg m}^3$ .

Study Vault