

CAIE Physics A-level

Topic 2: Measurement Techniques Notes

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2 - Measurement Techniques

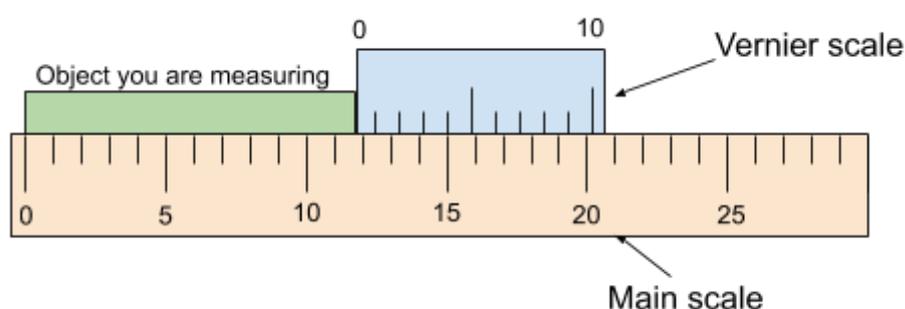
2.1 - Measurements

You must be able to carry out the following measurements using the instruments listed:

Measurement	Instrument(s)
Length	Ruler, vernier calipers, micrometers
Weight	Balance
Angle	Protractor
Time interval	Stopwatch, calibrated oscilloscope
Temperature	Thermometer
Current	Ammeter
Voltage	Voltmeter
Small electrical current (in null methods)	Galvanometer
Magnitude of magnetic field strength (A-level only)	Calibrated Hall probe (A-level only)

The **resolution** of an instrument is the smallest change in the quantity being measured that gives a recognisable change in reading.

Vernier calipers have a resolution of **0.1 mm**, which is better than that of a ruler which is 1 mm, meaning that they can be used to make more accurate measurements. Vernier calipers have two scales, the main scale and the vernier scale, as shown below:



In order to read any instrument with a vernier scale you must:

1. Find the **millimetre value from the main scale**, by taking the marked value below zero on the vernier scale. In the example above, this would be 12 mm.
2. Find the mark on the vernier scale which **aligns perfectly with a marked reading on the main scale**. In the example above, this would be the 4th mark along (note how the marks from both scales form a straight line), which represents 0.4 mm, as each mark on **the vernier scale represents a tenth of a millimeter**.
3. **Add your two measured values**: $12 + 0.4 = 12.4$ mm.



Micrometers work in a similar fashion to vernier calipers, however they have a higher resolution of **0.01 mm**, and are usually used to measure the diameter or thickness of an object. To use a micrometer you must:

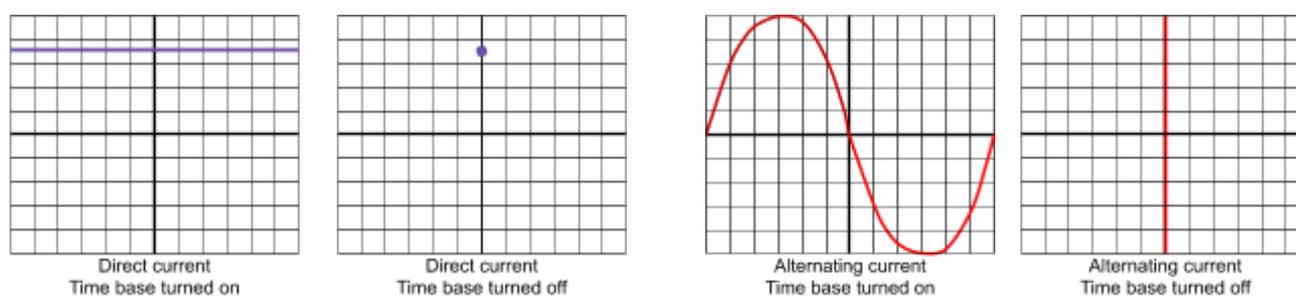
1. Place the object to be measured between the **jaw of the micrometer**.
2. The barrel of the micrometer has two scales, one which is horizontal (barrel scale) and one which is vertical (thimble scale). The barrel scale will give a reading of millimeters and half millimeters.
3. Read the barrel scale by looking at the edge of the **micrometer thimble** (this is the part that turns), if the thimble is over the 4th millimeter marking after 10 mm, you're reading 14 mm and if it is on/just over the half millimeter marking after 14mm, then the reading is 14.5 mm.
4. For more precise measurements, find where the **thimble scale** lines up exactly with the axis of the **barrel scale**. Each mark on the thimble scale represents 0.01 of a mm. If this is 33 then **add** 0.33 to the barrel scale reading (14.5 mm) to give a measurement of 14.83 mm.



Image source: [Lucasbosch, CC BY-SA 3.0](https://www.lucasbosch.com/), labels are added to the image

Any type of current can be displayed on an **oscilloscope**, which shows the variation of voltage with time. However, it is possible to turn off the **time-base**, which will cause the trace to **show all the possible voltages at any time in one area**, which is useful for taking measurements. For a **direct current**, the trace will show a **straight line parallel to the axis**, at the height of the output voltage. If time-base is turned off, then only a dot will be seen on the screen, at the height of the output voltage.

For an **alternating current**, the trace will show a repeating **sinusoidal waveform** which shows the variation of output voltage with time. If the time-base is switched off, then a straight vertical line will appear on the screen, showing all the possible voltages.

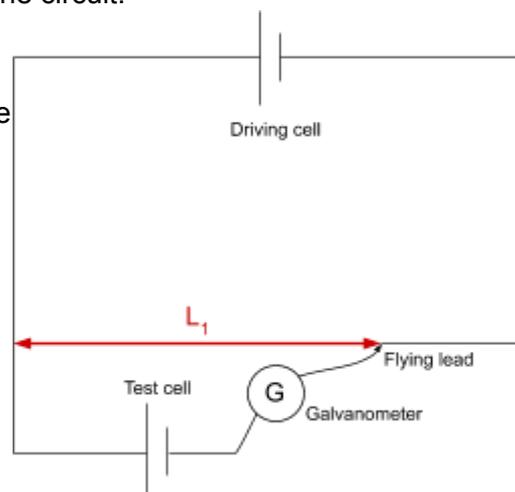


An oscilloscope will have a fixed grid on its display however, **you can adjust the scale of both axes to make measurements easier**. To change the scale of the Y-axis, you can select the number of volts per division using a **Y-gain control dial**, which will be marked on the oscilloscope. To change the scale of the X-axis, you can adjust the time **base**, which again will be marked on the oscilloscope.

In order to take measurements from an oscilloscope you will need to **count the number of divisions** (adjusting the axes to make this easier), and **multiply them by either the volts per division or the time base**, depending on what you are measuring.

A **galvanometer** detects and measures small electric currents. It is often used in **null methods**, which is where an unknown value is measured by adjusting a circuit until the reading on the galvanometer is zero. This is useful because no current flows through the galvanometer meaning the circuit is left undisrupted, giving **very accurate measurements**, whereas a real ammeter will not have infinite input resistance, so will affect the current in the circuit.

For example, a galvanometer can be used to compare the emf of two cells, using a potential divider circuit as seen in the diagram on the right. A **potential divider** is a circuit with **several resistors in series connected across a voltage source**, used to **produce a required fraction of the source potential difference**. In this case, the resistors are the lengths of uniform resistance wire.



The length of the wire L_1 is adjusted by changing the connection of the flying lead to the circuit, which will in turn change the resistance and so potential across that stretch of wire (as $V=IR$ and resistance increases with length).

Once the galvanometer reads zero, the potential across the test cell from the driving cell is equal and opposite to the test cell's potential difference, which is why no current can flow. This method is repeated with a test cell of known potential and the original test cell's potential can be calculated using ratios.

A **Hall probe** (A-level only) is used to measure magnetic field strength, and must be used **perpendicular** to the field being investigated to prevent it from only measuring a component of magnetic field strength.

An instrument, such as a weighing scale, may have a **digital display** or **analogue scale**. Digital displays are usually **more precise, easier to use and provide a higher resolution**, however will only provide a snapshot of the value being measured whereas analogue scales can show a **range of possible values** as well as **demonstrating any fluctuations** (for example in voltage). One disadvantage of analogue scales is that they are affected by **parallax errors**, which are measurement errors caused by looking at a scale from different angles.



Below are the displays of a digital (left) and analogue multimeter (right).



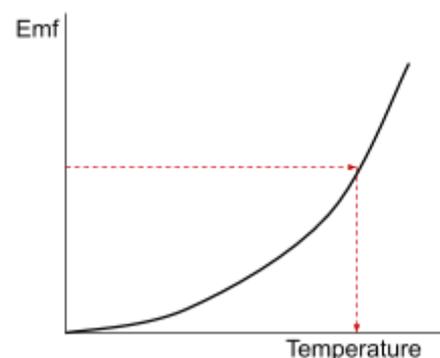
Image source (left): [Cjp24, CC BY-SA 3.0](#)



Image source (right): [Loadmaster, CC BY-SA 3.0](#)

Calibration curves are used alongside instruments whose outputs are not proportional to the value they are measuring. An example of such an instrument is a **thermocouple thermometer**, which **produces an emf which varies with temperature**.

In order to use this device you must record the measured value of emf and find where the calibration curve is equal to this. This can be done by drawing a horizontal line across from the y-axis, where emf is on this axis, until you reach a point on the curve. Then draw a vertical line down from this point on the curve, until you reach the x-axis. Where the line crosses the x-axis will give you the measured temperature.



The **calibration curve** of a thermocouple thermometer, for example, would be produced by measuring its emf output when exposed to known values of temperature. This process is similar for all instruments which require a calibration curve.

2.2 - Errors and Uncertainties

Random errors affect **precision**, meaning they cause differences in measurements which causes a spread about the mean. You **cannot** get rid of all random errors.

An example of random error is **electronic noise** in the circuit of an electrical instrument.

To reduce random errors:

- Take **at least 3 repeats** and calculate a **mean**, this method also allows **anomalies to be identified**
- Use **computers/data loggers/cameras** to reduce human error and enable **smaller intervals**
- Use **appropriate equipment**, e.g a micrometer has higher resolution (0.1 mm) than a ruler (1 mm)

Systematic errors affect **accuracy** and occur due to the apparatus or faults in the experimental method. Systematic errors cause all results to be **too high or too low by the same amount** each time.

An example is a balance that isn't zeroed correctly (**zero error**) or reading a scale at a different angle (this is a **parallax error**).



To reduce systematic error:

- **Calibrate** apparatus by measuring a known value (e.g. weigh 1 kg on a mass balance), if the reading is inaccurate then the systematic error is easily identified
- In radiation experiments correct for **background radiation** by measuring it beforehand and subtracting it from the final results
- Read the **meniscus** (the central curve on the surface of a liquid) **at eye level** (to reduce parallax error) and use **controls** in experiments

You must understand the difference between precision and accuracy:

Precision	Precise measurements are consistent, they fluctuate slightly about a mean value - this doesn't indicate the value is accurate.
Accuracy	A measurement close to the true value is accurate.

The **uncertainty** of a measurement is the bounds in which the accurate value can be expected to lie e.g. $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$, the true value could be within $18\text{-}22^{\circ}\text{C}$.

Absolute Uncertainty: uncertainty given as a fixed quantity e.g. $7 \pm 0.6 \text{ V}$

Fractional Uncertainty: uncertainty as a fraction of the measurement e.g. $7 \pm \frac{3}{35} \text{ V}$

Percentage Uncertainty: uncertainty as a percentage of the measurement e.g. $7 \pm 8.6\% \text{ V}$

To reduce percentage and fractional uncertainty, you can measure larger quantities.

Readings are when **one value** is found (e.g. reading a thermometer). Measurements are when the **difference between 2 readings** is found, since both the starting point and end point are judged (e.g. a ruler).

The **uncertainty in a reading** is **\pm half the smallest division**,
 e.g. for a thermometer the smallest division is 1°C so the uncertainty is $\pm 0.5^{\circ}\text{C}$

The **uncertainty in a measurement** is **at least ± 1 smallest division**,
 e.g. a ruler, must include **both** the uncertainty for the start and end value, as each end has $\pm 0.5\text{mm}$, they are added so the uncertainty in the measurement is $\pm 1\text{mm}$

When pieces of measured data are used in calculations, their uncertainty will also affect the result of the calculations, therefore you must be able to combine uncertainties as shown below:

- **Adding / subtracting data - ADD ABSOLUTE UNCERTAINTIES**

E.g. A thermometer with an uncertainty of $\pm 0.5 \text{ K}$ shows the temperature of water falling from $298 \pm 0.5 \text{ K}$ to $273 \pm 0.5 \text{ K}$, what is the difference in temperature?

$$298 - 273 = 25\text{K} \quad 0.5 + 0.5 = 1\text{K (add absolute uncertainties)} \quad \text{difference} = 25 \pm 1 \text{ K}$$



- **Multiplying / dividing data - ADD PERCENTAGE UNCERTAINTIES**

E.g. a force of 91 ± 3 N is applied to a mass of 7 ± 0.2 kg, what is the acceleration of the mass?

$$a = F/m = 91/7 = 13 \text{ m s}^{-2}$$

$$\text{percentage uncertainty} = \frac{\text{uncertainty}}{\text{value}} \times 100$$

$$\text{Work out \% uncertainties } \frac{3}{91} \times 100 + \frac{0.2}{7} \times 100 = 3.3\% + 2.9\% \quad \text{add \% uncertainties}$$

$$= 6.2\%$$

$$\text{So } a = 13 \pm 6.2\% \text{ m s}^{-2} \quad 6.2\% \text{ of } 13 \text{ is } 0.8$$

$$a = 13 \pm 0.8 \text{ m s}^{-2}$$

- **Raising to a power - MULTIPLY PERCENTAGE UNCERTAINTY BY POWER**

The radius of a circle is 5 ± 0.3 cm, what is the percentage uncertainty in the area of the circle?

$$\text{Area} = \pi \times 25 = 78.5 \text{ cm}^2$$

$$\text{Area} = \pi r^2$$

$$\% \text{ uncertainty in radius} = \frac{0.3}{5} \times 100 = 6\% \quad \% \text{ uncertainty in area} = 6 \times 2 \text{ (2 is the power from } r^2 \text{)}$$

$$= 12\%$$

$$78.5 \pm 12\% \text{ cm}^2$$

