St Ninian's HS

Higher Physics

Skills & Uncertainties

Pupil Notes

SQA Course Specification Higher

Units, prefixes and scientific notation

- Appropriate use of units and prefixes.

- SI units should be used with all physical quantities, where appropriate. Prefixes should be used where appropriate. These include pico (p), nano (n), micro (μ), milli (m), kilo (k), mega (M), giga (G) and tera (T).

- Use of the appropriate number of significant figures in final answers. This means that the final answer can have no more significant figures than the value with least number of significant figures used in the calculation.

- Appropriate use of scientific notation.

- Awareness of typical command words and question types.

Units

In Physics we deal with quantities and measurements – units give meaning to these numbers.

A "distance of 5" could mean 5 mm, 5 miles, or 5 light years... Without units (and context) the number is meaningless.

Many relationships between different quantities will only work with the correct (or at least consistent units).

For example, if calculating the distance travelled by a sound wave in air: $v = 340\ ms^{-1}$

Say we want to determine how far the sound wave travels in 1 minute.

Using $d = vt$, without converting 1 minute into seconds:

$$v\left[\frac{metres}{seconds}\right] \times t[minutes] \qquad = d\left[\frac{metres \times minutes}{seconds}\right]$$

These units are mismatched – they won't cancel out and we wouldn't be left with distance in metres. The number we get isn't correct for *any* unit.

If we convert the time from 1 minute to 60 seconds.

$$v\left[\frac{metres}{seconds}\right] \times t[seconds] \qquad = d\left[\frac{metres \times seconds}{seconds}\right] \qquad = d\ [metres]$$

These units match up – the seconds cancel out and we are left with a correct answer in metres.

Calculations make up a significant part of the Higher Physics course and the final examination – omission of units in final answers could significant decrease overall scores so be careful to always include units where appropriate!

Scientific Notation

In Physics we deal with measurements ranging from the subatomic to the astronomical. Writing these numbers out in full can be inconvenient and increases the chances of it being written down incorrectly, or typed into a calculator incorrectly.

For example:

Mass of an electron, $m_e = 0.000000000000000000000000000000911\ kg$

...is much more clearly written as $m_e = 9.11 \times 10^{-31}\ kg$

Mass of the Sun, $m_S = 1{,}989{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000\ kg$

...is much more clearly written as $m_S = 1.989 \times 10^{30}\ kg$

In Maths you may be familiar with *standard form* – where numbers are written a number between 1 and 10 multiplied by a power of 10 which could be positive or negative (like both numbers written above). Scientific notation is very useful but standard form is not a requirement in physics.

For example:

The radius of Earth, $r_E = 6370\ km$ can be written in metres as $r_E = 6370 \times 10^3\ m$.

This is equivalent, and equally as valid as writing $r_E = 6.370 \times 10^6\ m$. There is no need to take the extra step to express the quantity in standard form.

Prefixes

Unit prefixes can also be used to express the size of a number:

Prefix	***Prefix abbreviation***	***Prefix replaces***	***Multiple size***
tera-	T	$\times 10^{12}$	1,000,000,000,000
giga-	G	$\times 10^{9}$	1,000,000,000
mega-	M	$\times 10^{6}$	1,000,000
kilo-	k	$\times 10^{3}$	1,000
milli-	m	$\times 10^{-3}$	0.001
micro-	μ	$\times 10^{-6}$	0.000001
nano-	n	$\times 10^{-9}$	0.000000001
pico-	p	$\times 10^{-12}$	0.000000000001

The easiest way to deal with quantities with unit prefixes is to simply replace the *prefix abbreviation* with the corresponding $\times 10^{x}$.

For example:

The resistance of a resistor, $R = 25\ k\Omega$ can be written as $R = 25 \times 10^{3}\Omega$.

The speed of Voyager 1, $v_{V1} = 17\ kms^{-1}$ can be written as $v_{V1} = 17 \times 10^{3} ms^{-1}$.

The capacitance of a capacitor, $C = 350\ \mu F$ can be written as $C = 350 \times 10^{-6} F$.

The wavelength of red light, $\lambda_R = 656\ nm$ can be written as $\lambda_R = 656 \times 10^{-9} m$.

The distance from the Sun to Pluto, $d_{SP} = 4.4\ Tm$ can be written as $d_{SP} = 4.4 \times 10^{12} m$.

Significant Figures

In Higher Physics, you are expected to **round every single calculated value** to an **appropriate number of significant figures** – failing to do this will often result in losing the final mark in a calculation question.

Consider a calculation involving $V = IR$:

We are told that a lamp has a resistance of 45 Ω (this is 2 sig figs), *and a potential difference of 3.71 V* (this is 3 sig figs) *across it.*

Following our standard method for calculations, but not rounding our final answer enough might give us:

$$V = IR$$

$$3.71 = I \times 45$$

$$I = \frac{3.71}{45}$$

$$I = 0.082\dot{4}\ A$$ (this is *infinite* sig figs)

$$I = 0.082444\ A$$ (this is 5 sig figs)

The *correct* rounding of this answer would be $I = 0.082\ A$ (this is 2 sig figs).

To determine the ***appropriate*** **number of significant figures** in any final answer:

- Note the number of significant figures present in the values you are calculating with.
- Identify the value with the ***lowest number of significant figures*** used in the calculation. In the example above this was 2 significant figures (from *R = 45 Ω*).
- **Round your final answer** to the **same number of significant figures**.

There is some wiggle room given – marks for final answers are awarded for answers that have up to two figures more, or one figure fewer than the data given to the fewest significant figures. This is why marking schemes have a range of several accepted answers. In the example above, accepted answers would be $I = 0.08\ A$, $I = 0.082\ A$, $I = 0.0824\ A$, or $I = 0.08244\ A$.

Because of this common advice is: ***if in doubt, round to 3 sig figs****!*

Why does it matter?

The number of significant figures in the data we are given is a measure of the *precision* of that data. A *resistance of 45 Ω* could come from an ohmmeter reading, which gives resistance to the nearest 1 Ω. A *potential difference of 3.71 V* could come from a voltmeter reading, which gives the voltage to the nearest *0.01 V*. The true voltage, for example, may be *3.706 V*, or *3.71210 V*, but with the equipment available we cannot be that exact.

If we carry out the calculation using that data (*V = 3.71 V*) we cannot say for certain that the calculated value of current, $I = 0.082444\ A$, because that suggest a level of accuracy that we cannot be certain of.

If we had used *3.706 V*, or *3.71210 V* in our calculation we would get a different answer ($I = 0.0823555\ldots\ A$ or $I = 0.08249111\ldots\ A$). Both can be rounded to $I = 0.082\ A$; for the values we're working with, this is the level of accuracy with which we can state our final answer.

What figures are significant?

General rules:

- If it tells you ***how big or small*** a number is, it is insignificant. Can the digits be replaced by using scientific notation without changing the meaning? Then **insignificant**.
- If it tells you anything about the ***precision*** of a measurement – where it lies on a scale (regardless of the *size* of that scale) – then is it **significant**.

Actual rules:

- Non-zero digits are *always* significant.
  E.g. 4814 is 4sf, 3.9 is 2sf, 29.927 is 5 sf.
- Interior zeros (zeros *between* non-zeros) are significant.
  E.g. 404 is 3sf, 820402 is 6 sf.
- Leading zeros (zeros *before* non-zero digits) are not significant.
  E.g. 0.0000005 is 1sf, 0.0482 is 3 sf, 0.000401 is 3 sf.
- Trailing zeros after a decimal point are significant.
  E.g. 3.00 is 3sf, 340.0 is 4 sf.
- Trailing zeros in a whole number are not significant (unless stated otherwise).
  E.g. 190 is 2 sf, 375000 is 3 sf.

It can be useful to ask yourself *how would I write this number in Standard Form (scientific notation)?* If the zeros can be replaced by a $\times 10^x$, they were never significant.

Command Words

Command words such as *calculate*, *explain*, or *predict* indicate the specific action that is required to answer a question. This, alongside the number of available marks can help decipher what to do.

Command Word	***Action Required***
Calculate	Select the appropriate equation(s) from the relationship sheet and use to solve a given problem.
Determine	Use the information provided alongside appropriate equation(s) to calculate a specified value.
Show	Select the appropriate equation(s) from the relationship sheet and show how they can be used to obtain a given value.
State	Give a specific definition, say what will happen to a certain value or identify a certain quantity.
Describe	Provide a statement or explanation of characteristics and/or features.
Explain	State what will happen to a certain variable due to other, related variables changing. Often based on previously calculated values – follow the trail.
Suggest	Apply your knowledge and understanding to a given situation.
Justify	Give reasons to support a suggestion or conclusion via theory or calculation.
Estimate	Use the information available to determine an approximate value for a given quantity.
Sketch	Sketch a graph with appropriate axes but not to scale. Requires correct shape and often key numerical values.
Draw a graph of…	Draw an appropriate graph (generally a scatter graph with line/curve of best fit) to show the relationship between two variables.
Using your knowledge of physics…	Demonstrate your knowledge of the particular area(s) of **<u>Higher</u> Physics** involved in the question.

SQA Course Specification Higher

Uncertainties

- Knowledge of scale reading, random, and systematic uncertainties in a measured quantity.

- All measurements of physics quantities are liable to uncertainty, which should be expressed in absolute or percentage form.

- Scale reading uncertainty is an indication of how precisely an instrument scale can be read.

- Random uncertainties arise when measurements are repeated and slight variations occur. Random uncertainties may be reduced by increasing the number of repeated measurements.

- Use of an appropriate relationship to determine the approximate random uncertainty in a value using repeated measurements.

- Systematic uncertainties occur when readings taken are either all too small or all too large. This can arise due to measurement techniques or experimental design.

- The mean of a set of repeated measurements is the best estimate of the “true” value of the quantity being measured. When systematic uncertainties are present, the mean value will be offset. When mean values are used, the approximate random uncertainty should be calculated.

- Appropriate use of uncertainties in data analysis.

- When an experiment is being undertaken and more than one physical quantity is measured, the quantity with the largest percentage uncertainty should be identified and this may often be used as a good estimate of the percentage uncertainty in the final numerical result of an experiment. The numerical result of an experiment should be expressed in the form *final value ± uncertainty*.

Types of Uncertainty

Every measurement is subject to some uncertainty – our measuring devices may be limited, external factors we won't account for might affect our measurements, or even just unpredictable fluctuations we have no control over. When doing experimental work it is important to acknowledge these sources of uncertainties and their impacts, as they will affect our results.

There are 3 different types of uncertainty to consider:

- Scale reading uncertainty.
- Systematic uncertainty.
- Random uncertainty.

We generally express uncertainty after the measurement, either as an absolute value or as a percentage of the measurement e.g.:

$a = 9.8\,ms^{-2} \pm 0.3\,ms^{-2}$ or $R = (3.8 \pm 0.3\,)\,\Omega$ or $s = 1.5\,m \pm 3\%$

Accuracy vs Precision

When discussing and evaluating uncertainties and measurements within the context of an experiment it is important that we are able to understand and use appropriate language. Accuracy and precision are two terms which are easily mixed up.

Accuracy is how close a measurement or calculated quantity is to the ***true value***. This can be related to systematic uncertainties.

Precision can be used in two different contexts:

- How consistent repeated measurements are (related to random uncertainties).
- How *exact* measurements can be made (related to scale reading uncertainties).

Consider a measurement of the acceleration of an object in free fall – we know the true value should be 9.8 ms^{-2}. Visualise the *true value of 9.8* ms^{-2} as the bullseye on a target.

High accuracy, high precision.

E.g. *9.8* ms^{-2}, *9.7* ms^{-2}, *9.8* ms^{-2}, *9.6* ms^{-2}, *9.9* ms^{-2}.

High accuracy, low precision.

E.g. *8.7* ms^{-2}, *9.8* ms^{-2}, *10.9* ms^{-2}, *8.5* ms^{-2}, *11.1* ms^{-2}.

Low accuracy, high precision.

E.g. *4.2* ms^{-2}, *4.0* ms^{-2}, *4.1* ms^{-2}, *4.1* ms^{-2}, *4.2* ms^{-2}.

Low accuracy, low precision.

E.g. *4.6* ms^{-2}, *10.7* ms^{-2}, *7.2* ms^{-2}, *3.5* ms^{-2}, *5.8* ms^{-2}.

Scale Reading Uncertainty

This is a measure of how ***precise*** a measurement can be made. The **scale reading uncertainty** is applied differently for **digital measuring devices** (you read the number off a screen) and **analogue measuring devices** (you read the measurement off a scale yourself).

When doing **experimental work** you should **record the scale reading uncertainty** for **any value you measure** (for both independent and dependent variables).

Digital scale readings uncertainties:

$$\pm \textit{ the smallest division (units)}$$

E.g. a voltmeter

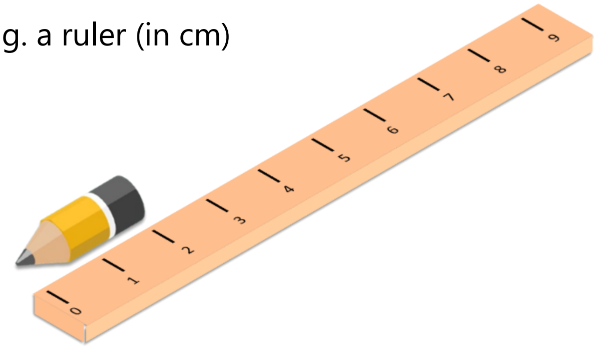
The **smallest division** here is ***0.01 V*** (the smallest amount our measurement could go up or down by).

The reading is ***1.12 V ± 0.01 V***.

Analogue scale reading uncertainties:

$$\pm \textbf{\textit{half}} \textit{ the smallest division (units)}$$

E.g. a ruler (in cm)



The **smallest division** here is **1 cm**.
Half the **smallest division** is **0.5 cm**.

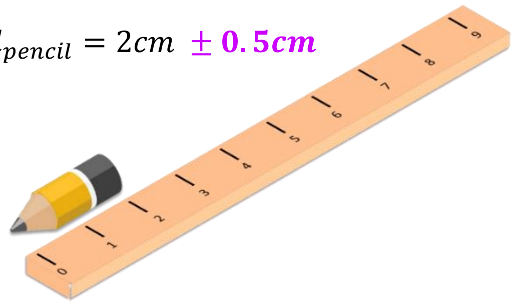
The reading is ***2 cm ± 0.5 cm***.

How would the scale reading uncertainty be reduced?

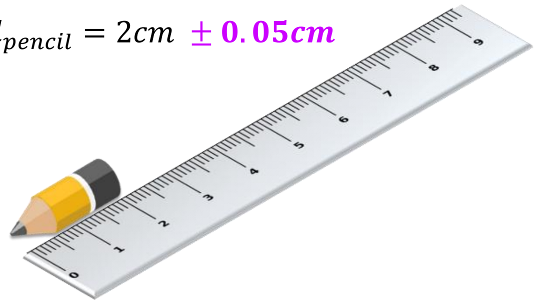
If the scale reading uncertainty is the largest source of uncertainty in our measurements, we could improve our experimental procedures by using a device that measures in smaller increments. This would decrease the size of the scale reading uncertainty and make our measurements more *precise*.

E.g. for our measurement of the length of the pencil:

$l_{pencil} = 2cm \ \pm \mathbf{0.5cm}$



$l_{pencil} = 2cm \ \pm \mathbf{0.05cm}$

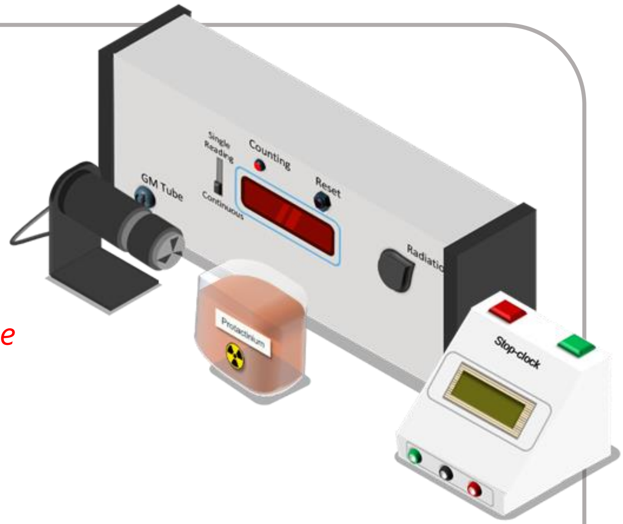


We have identified a large scale reading uncertainty and made our measurement ***more precise***.

Systematic Uncertainty

A systematic uncertainty is a consistent, repeatable error in experimental measurements, caused by errors in the experimental set up/procedure.

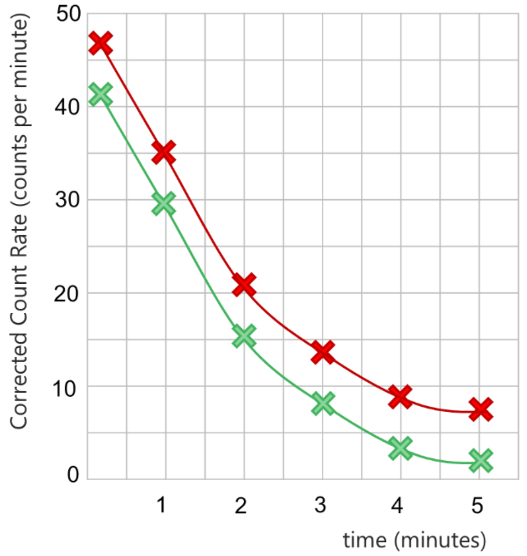
An example from N5 Physics:



If a physicist wants to measure the *activity of the radioactive source* they need account for the background radiation.

The physicists needs to plot the *activity/count rate of the radioactive source* over *time*, not the *activity/count rate of the radioactive source + the background radiation* over *time*.

Let's compare:



Note: these graphs show us the **general trend** (activity decreases over time) ***but <u>not</u> a relationship between activity and time***. At Higher level, this be an insufficient conclusion to draw – we generally adapt our data such that it gives us a straight line graph (and therefore a $y = mx + c$ relationship).

The true values of activity/count rate ***from the source*** are shown in green. Whilst the red line shows the same trend, each value of corrected count rate is too large by the same amount. To remove the systematic uncertainty in this experiment we measured the background count and subtracted it from each measurement of count rate we made (hence the *corrected* count rate).

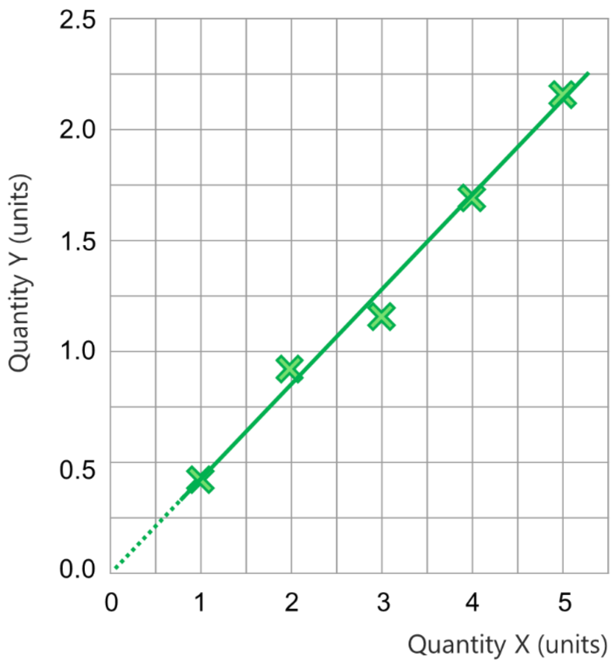
How do I know if my data shows a systematic uncertainty?

For most of the experiments that feature in Higher Physics, we plot our processed data as a scatter graph and expect that the line of best fit would be a straight line, often intersecting with the origin $(0,0)$. If the line of best fit *should* intersect the origin, but it *doesn't* that could mean a systematic uncertainty in the data.

Generally, we are aiming to do one of two things:

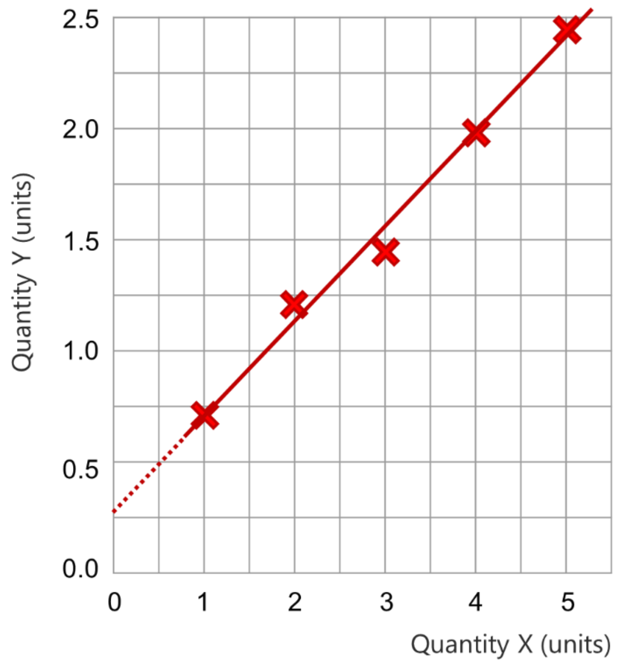
- Determine a constant value from the gradient of the line of best fit (systematic uncertainty won't affect the gradient).
- Determine the relationship between two quantities (systematic uncertainty will change the way the relationship can be described).

Consider these two graphs of Quantity Y vs Quantity X:



The **line of best fit** is a **straight line** that **intersects the origin**.

This data shows that **X and Y are directly proportional**.



This **line of best fit** is a **straight line** but it **does not intersect the origin**.

This does not show that X and Y are directly proportional, but we could say there is a **linear relationship between X and Y**.

If we were expecting our experimental to give us the graph on the **left** but instead we plotted the graph on the **right**, we could identify a **systematic uncertainty** affecting all measured values of Y. This means that every single measured value of Y is greater than it should be (therefore inaccurate), and by the same amount. Measurements of X are not affected.

What should I do if my data shows a systematic uncertainty?

Where possible, seek to avoid systematic uncertainties. This could be simply positioning measuring tools properly (e.g. making sure measurements of length start at the 0 mark on a ruler) or correcting measurements where background readings are unavoidable (e.g. measuring the background radiation to find the corrected count rate as above).

When carrying out data analysis and making conclusions, consider the aim of any experiment being carried out and whether the systematic uncertainty has a significant effect on the outcome:

- If the aim of an experiment is linked to the gradient of a line of best fit only, then the systematic uncertainty will not impact the outcome.
- If the aim of an experiment is to determine a relationship between two quantities then the systematic uncertainty will impact the outcome (the expected conclusion may be incorrect).

Random Uncertainty

Random uncertainty in measurements is caused by random, unpredictable fluctuations in experimental conditions that cannot be controlled.

For example:

- For a swinging pendulum, small changes in room temperature or air currents could affect the air resistance experienced by the mass, or textures in the string could affect the friction it experienced as it swings. Slight variations in how quickly the button on the stopwatch is pressed will affect measurements of the pendulums period.
- For an electrical component, small change in room temperature will affect the resistance of a component and therefore the current measured through it.

The random uncertainty in any repeated measured value can be calculated by:

$$random\ uncertainty = \frac{max.value - min.value}{number\ of\ values}$$

The same relationship can be written out as:

$$\Delta R = \frac{R_{max} - R_{min}}{n}$$

And adapted to whatever quantity is being measured.
E.g. for repeated measurements of distance, d:

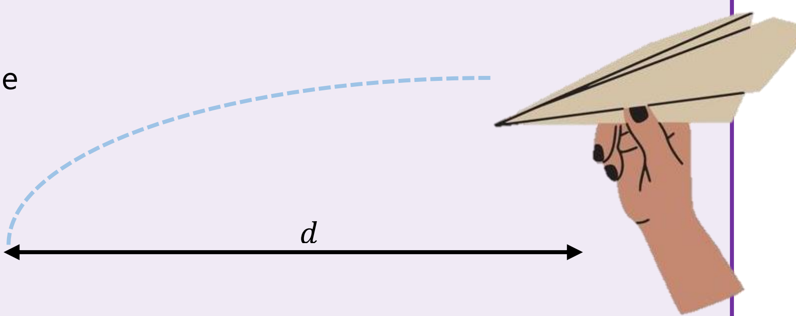
$$\Delta d = \frac{d_{max} - d_{min}}{n}$$

The random uncertainty in a measured value can be minimised by **repeating the measurement** a greater number of times.

Worked Example: The Paper Plane

An aeromechanical engineer wants to measure the range, d, of their paper plane.

To ensure they quote a reliable measurement, they repeat their measurements and calculate a mean range:



d_1 (m)	d_2 (m)	d_3 (m)	d_4 (m)	$\bar{d}$ (m)
10.51	6.84	13.01	12.40	**10.69**

Calculate the random uncertainty in the mean value of the range.

$$\Delta d = \frac{d_{max} - d_{min}}{n} \qquad \Delta d = \frac{13.01 - 6.84}{4} \qquad \Delta d = \pm 1.54\ m$$

Percentage Uncertainties

There are two ways to express the uncertainty of a measured value:

- The absolute uncertainty, which is expressed in the same units as the measurement.
  E.g. $l_{pencil} = 2cm \pm \mathbf{0.5cm}$
- The percentage uncertainty, which is expressed as a proportion of the measurement.
  E.g. $l_{pencil} = 2cm \pm \mathbf{25}\ \%$

Both shows the range in which the true value lies.

To calculate an absolute uncertainty as a percentage of a measurement:

$$percentage\ uncertainty\ in\ x = \frac{absolute\ uncertainty}{measured\ value} \times 100 \qquad \%\Delta x = \frac{\Delta x}{x} \times 100$$

Worked Example: The Wind Turbines

A renewables engineer is reporting the average energy output per turbine per day, E, for a cluster of 6 wind turbines.

Calculate the percentage uncertainty in the mean value of E.

turbine	*E (GJ)*
1	*62*
2	*53*
3	*87*
4	*52*
5	*53*
6	*72*
mean	***63***

First find the absolute random uncertainty in E:

$$\Delta E = \frac{E_{max} - E_{min}}{n} \qquad = \frac{87 - 52}{6} \qquad = \pm 5.8\ GJ$$

Then determine the percentage uncertainty in E:

$$\%\Delta E = \frac{\Delta E}{\bar{E}} \times 100 \qquad = \frac{5.8}{63} \times 100 \qquad = \pm\ 9.2\ \%$$

For some previous examples:

measurement	*value ± absolute uncertainty*	*type of uncertainty*	*value ± percentage uncertainty*
voltmeter reading, V	$1.12\ V\ \pm 0.01\ V$	scale reading (digital)	$1.12\ V\ \pm 0.89\ \%$
length of pencil, l_{pencil}	$2\ cm\ \pm 0.05\ cm$	scale reading (analogue)	$2\ cm\ \pm 2.5\ \%$
range of paper plane, d	$10.69\ m\ \pm 1.54\ m$	random	$10.69\ m\ \pm 14\ \%$

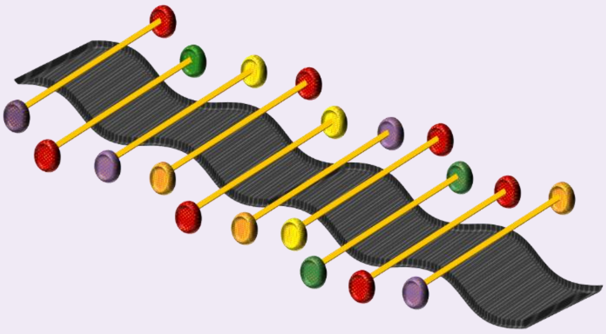
There is not set rule on what an acceptable level of uncertainty is – as a general rule of thumb, aim to keep uncertainties under 10% to ensure reliable results. For the data shown above we can see that $\%\Delta d > 10\%$ - to reduce the random uncertainty in this measurement we would suggest taking more repeated measurements of the same value.

Calculating Uncertainties in Final Values

Often in Higher Physics you will carry out an experiment to determine some constant value (such as acceleration due to gravity, internal resistance of a cell, refractive index of a medium, Planck's constant, wavelength of a laser).

When an experiment requires more than one physical quantity to be measured (e.g. height and time taken for a ball to fall through that height) the quantity with the **largest percentage uncertainty** should be identified, and can be applied to the final calculated value.

Worked Example: The Wave Machine



An S3 pupil builds a Fruit Pastille Wave Machine.

They create a wave at one end and using a stopclock to measure how long it takes it to travel to the other side:

length of wave machine, $d = (3.10 \pm 0.005)\ m$
time taken, $t = (5.03 \pm 0.01)\ s$

Calculate the speed of the wave, and include the absolute uncertainty in the final value.

To calculate the speed of the wave:

$$v = \frac{d}{t} \qquad = \frac{3.10}{5.03} \qquad = 0.616\ ms^{-1}$$

Then to know which uncertainty to use we need to express each as a %Δ:

$$\%\Delta d = \frac{\Delta d}{d} \times 100 \qquad \%\Delta t = \frac{\Delta t}{t} \times 100$$

$$\%\Delta d = \frac{0.005}{3.10} \times 100 \qquad \%\Delta t = \frac{0.01}{5.03} \times 100$$

$$\%\Delta d = \pm 0.16\ \% \qquad \%\Delta t = \pm 0.20\ \%$$

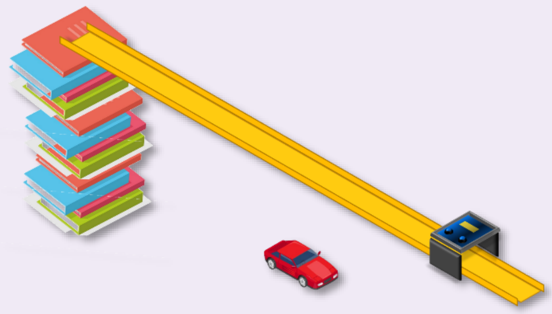
The biggest percentage uncertainty in the values used to calculate speed is 0.20 %, so to find the absolute uncertainty in the calculated speed we need to find 0.20 % of 0.616 ms^{-1}:

$$v = 0.616\ ms^{-1} \ \pm 0.20\ \%$$

$$v = 0.616\ ms^{-1} \ \pm\ 0.0012\ ms^{-1}$$

Worked Example: The Hot Wheels Car

A physics teacher is investigating how much energy is lost to the surroundings (mostly via friction) as his hot wheels car travels down a ramp.



The hot wheels car is released from rest at the top of the ramp, from a known height (measured with a metre stick with cm increments). The mass of the hot wheels car is measured with a digital balance. The speed of the hot wheels car at the bottom of the ramp is measured with a BeeSpi V light gate.

The teacher repeats the procedure several times and records the following measurements and uncertainties.

mass of hot wheels car, $m = (0.15 \pm 0.01)\ kg$
height of ramp, $h = (0.75 \pm 0.005)\ m$
speed of hot wheels car, $v_1 = 6.17\ ms^{-1}$ $\quad v_2 = 7.51\ ms^{-1}$ $\quad v_3 = 7.95\ ms^{-1}$

(a) **Calculate** the mean speed of the car at the bottom of the ramp.

$$\bar{v} = \frac{\sum v}{n} \qquad = \frac{6.17 + 7.51 + 7.95}{3} \qquad = \pm\, 7.21\ \ ms^{-1}$$

(b) **Calculate** the approximate random uncertainty in the mean value of speed.

$$\Delta v = \frac{v_{max} - v_{min}}{n} \qquad = \frac{7.95 - 6.17}{3} \qquad = \pm\, 0.59\ \ ms^{-1}$$

(c) **Determine** which of the quantities; mass m, height h, or mean speed v, has the largest percentage uncertainty.

$$\%\Delta m = \frac{\Delta m}{m} \times 100 \qquad \%\Delta h = \frac{\Delta h}{h} \times 100 \qquad \%\Delta v = \frac{\Delta v}{\bar{v}} \times 100$$

$$\%\Delta m = \frac{0.01}{0.15} \times 100 \qquad \%\Delta h = \frac{0.005}{0.75} \times 100 \qquad \%\Delta v = \frac{0.59}{7.21} \times 100$$

$$\%\Delta m = \pm\, 6.7\ \% \qquad \%\Delta h = \pm 0.67\ \% \qquad \%\Delta v = 8.2\ \%$$

The quantity with the largest % uncertainty is the speed (± 8.2 %). For any calculations using these values, an uncertainty of ± 8.2 % should be applied.

SQA Course Specification Higher

Experimental Skills

- Planning experimental procedures/practical investigations to meet the requirements of the aim (e.g. verification of a relationship or measurement of a constant).

- Recording detailed observations and collecting data from experiments/practical investigations.

- Presenting information appropriately in a variety of forms (including properly tabulated data and the creation of scatter graphs with appropriately drawn lines of best fit).

- Drawing valid conclusions and giving explanations supported by evidence/justification.

- Communicating findings/information effectively.

- Evaluating experimental procedures and data, and suggesting relevant improvements.

Experimental Aims

Before considering equipment, experimental procedure, or data gathering, it is important to ensure that the **aim** of an experiment is **clear and concise**.

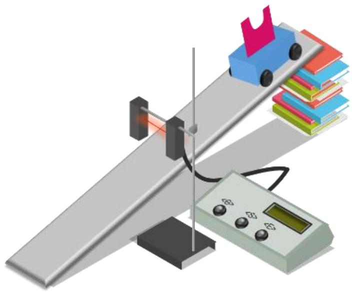
In Higher Physics experimental aims will be structured one of two ways:

- To measure the value of a constant, typically calculated from the gradient of a line of best fit (e.g. "*to measure the value of [constant]*").
- To determine the relationship between two quantities, typically based on the best fit (e.g. "*to determine the relationship between [Y] and [X]*").

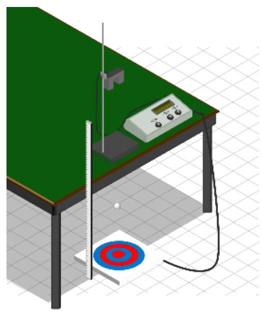
It is important to keep the experimental aim in mind when drawing conclusions, finding comparative data, and making evaluative statements – these must be relevant to the experimental aim.

There are 5 experiments *required* by the Higher Physics Course Specification (though you will likely encounter others throughout the course):

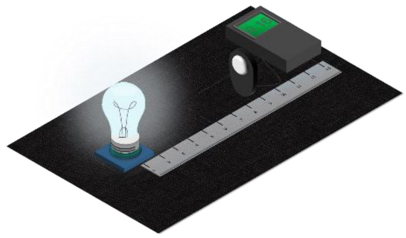
- Description of an experiment to measure the acceleration of an object down a slope.



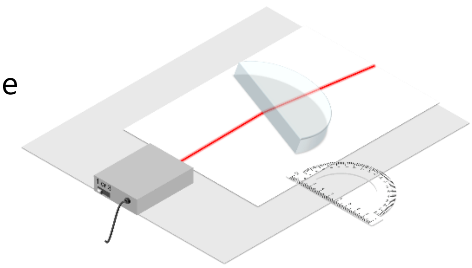
- Description of an experiment to measure the acceleration of a falling object.



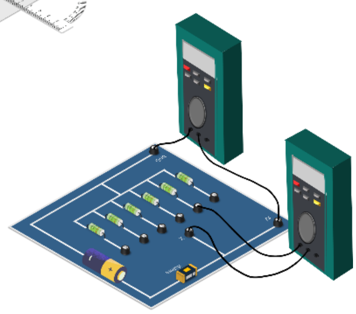
- Description of an experiment to verify the inverse square law for a point source of light.



- Description of an experiment to determine the refractive index of a medium.



- Description of an experiment to measure the EMF and internal resistance of a cell.



Gathering Sufficient Data

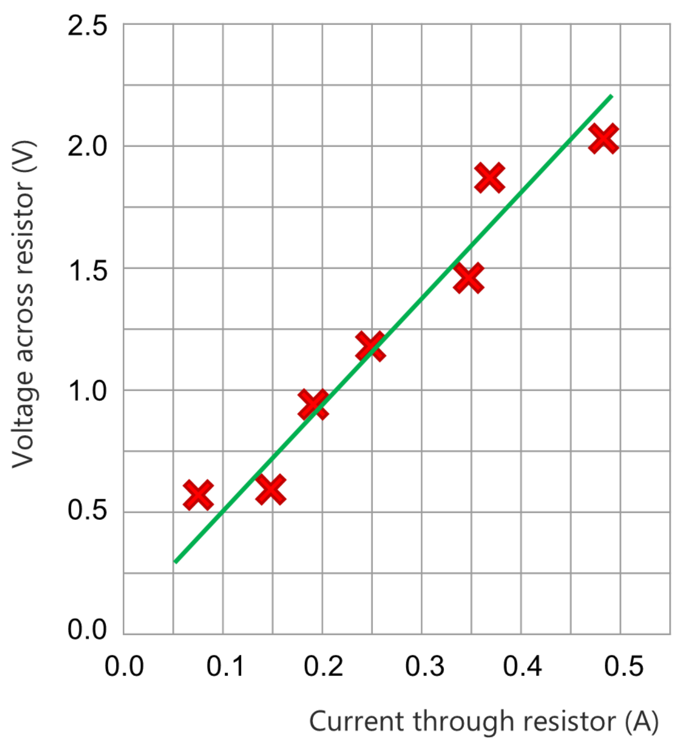
Once the experimental aim has been decided, the experimental procedure can be planned. To calculate a value or determine a relationship we **must gather sufficient data** to allow a scatter graph to be plotted and a line of best fit drawn:

- To draw a reliable line of best fit, **at least 5 sets of data** are required – a line drawn from fewer than 5 data points is much more likely to be difficult to place correctly.
- To minimise the effect of random uncertainties, **repeated measurements of any dependent variable** must be taken.
- For **any measured value** (whether an independent or dependent variable) the **scale reading uncertainty** must be noted.
- Depending on the equipment available you may have to decide for yourself on the **range of data** – for this consider how uncertainties may affect the values you expect to measure (e.g. for a moving object, air resistance would have a greater effect at high speeds so choose a range of values that wouldn't result in excessive speeds; for small values of current (as in Worked Example: The Lamp below) the scale reading uncertainty in the ammeter is significant, so choose a range of data for which you'd expect greater currents).

Why bother plotting a graph at all?

Measurements in the real-world are rarely perfect. In the Physics lab we can always expect some random uncertainty and scale reading uncertainty. Gathering sufficient data and using a line of best fit allows us to average out experimental errors, and smooths out our data.

Consider the data below, from an experiment which aims to measure the resistance of a resistor:



The individual data points (✖) are a little messy – not all in a neat line.

The line of best fit goes through the *centre of the data*. (As a quick check that it's positioned correctly - there should be roughly the same number of data points above as below.)

If we had used an individual data point to calculate the resistance ($R = \frac{V}{I}$) the values would vary significantly.

Calculating the gradient from the line of best fit (here $m = R$) provides one value that takes into account *all of the data* – and is therefore more likely to provide the true value of resistance.

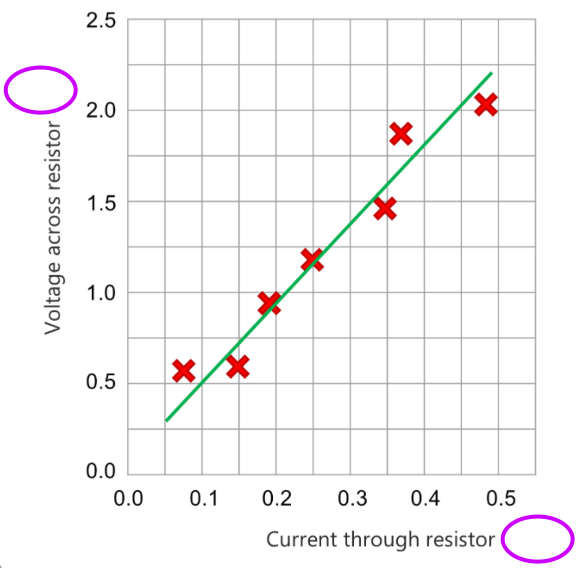
Graphing and Analysing Data

Once sufficient data has been gathered and that data has been processed (averages and any required derived values calculated), a graph is plotted. Every graph should have:

- **Labels and units** where appropriate (these can generally be taken straight from table headings).
- **Scales**, appropriate to data (scales need to start at 0 if seeking to verify a relationship that is directly proportional, but otherwise this isn't necessary).
- **Accurately plotted data points** (tolerance of ½ the smallest division of the graph paper) – best marked with a small "x".
- **Line of best fit** (through the centre of the data).

What makes a graph bad?

Error with *labels and units*:



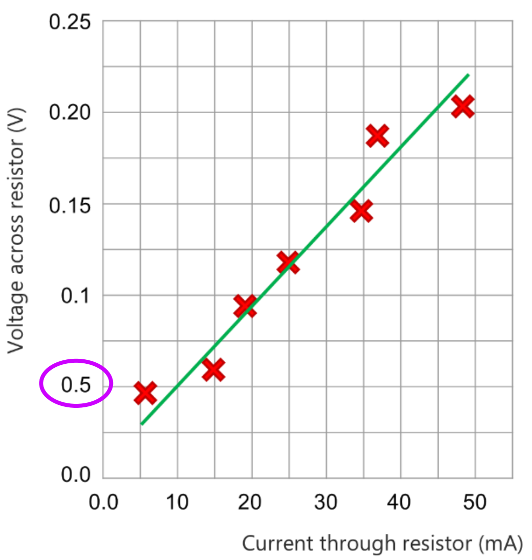
This graph has labels but no units.

We do encounter quantities that don't require units (AKA *dimensionless*), but current and voltage both require units.

Without units, the numbers have no meaning. We could calculate the gradient of the line but could not determine the value of resistance if the units of voltage and current are unknown (they could be V and A, or kV and mA – we don't know).

Similarly with no labels the scales would just be numbers with no meaning.

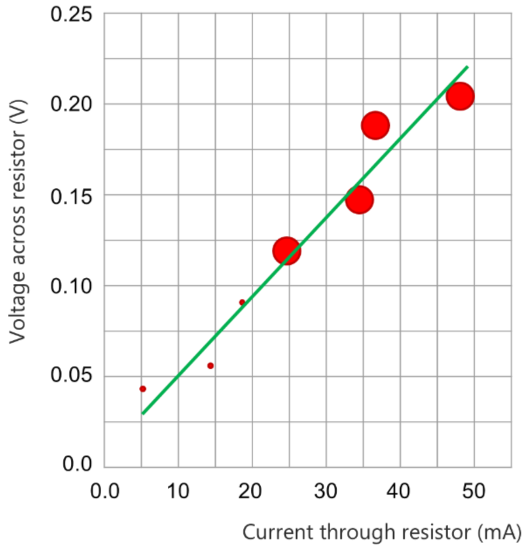
Error with *scales*:



This graph has a *non-linear scale* (the y-axis scale does not go up in even intervals).

This kind of error means that the scale is incorrect, but also since the mistake occurs within the range of plotted data the plot is also incorrect *and* the line of best fit is incorrect. Any further values based off of the line of best fit would also be incorrect.

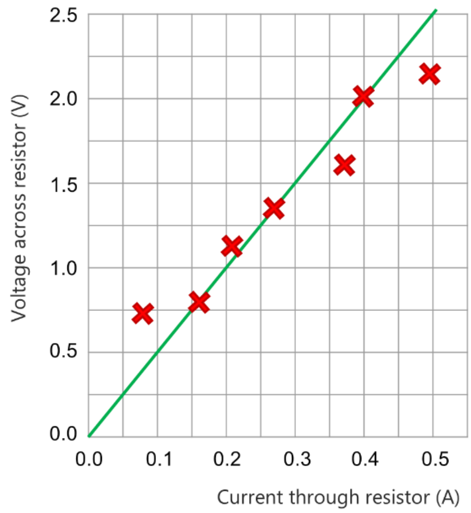
Error with *accurately plotted data points*:



The three data points on the left side of this graph marked with a small dot. This is fine here, but if the line of best fit lay right on top of them they could get lost underneath. For a hand drawn graph a small "x" (with the centre exactly on the data point) is the better option.

The four data points on the right side of this graph are marked with large dots. These dots are so large that they take up more than ½ a division on the graph paper, so they cannot be considered *accurate*.

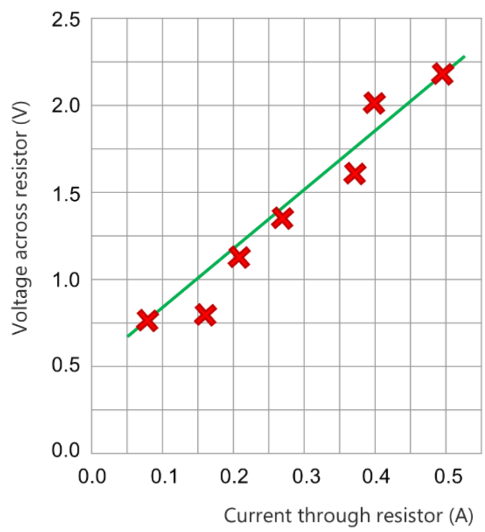
Errors with *line of best fit*:

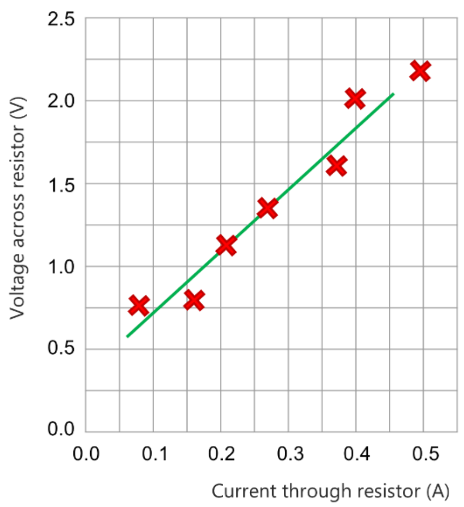


Although this line of best fit has 2 data points above and 2 below, it does not *fit* the data.

The line of best fit has been forced through the origin, at the expense of the data itself.

This line of best fit is too high – only one data point lies above the line and 4 lie below.





This line of best fit doesn't cover the whole range of data – it needs to be extended further to cover the data point that is further to the right. It is otherwise well placed.

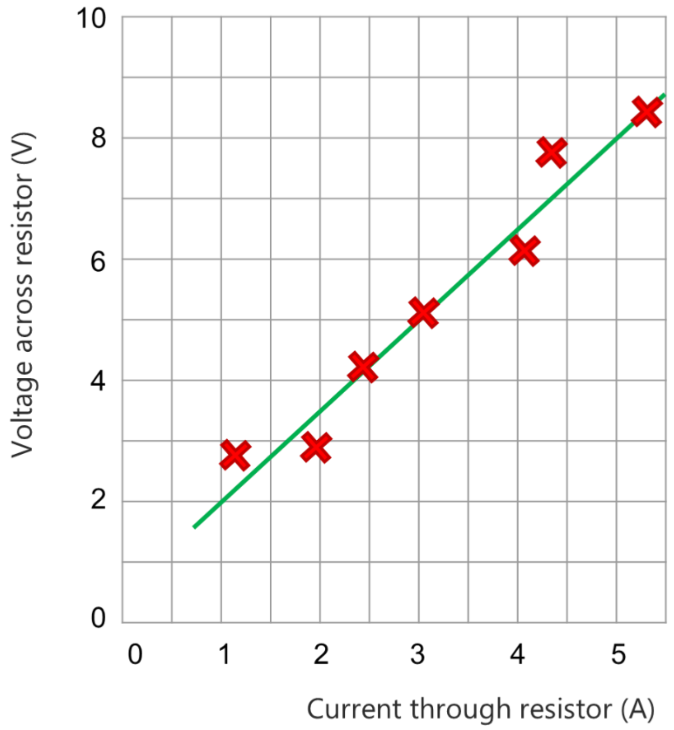
How do I use my graph to analyse my experimental data?

Whether aiming to determine a constant value or a relationship between two quantities, the gradient of the line of best fit, m, needs to be considered.

To calculate the **gradient** of a line, choose two points that are **on the line** – these don't need to be plotted data points (and unless the data points are *exactly* on the line then they *should not be*). Label these points as (x_1, y_1) and (x_2, y_2).

Then to determine the gradient of the line, $m = \frac{y_2 - y_1}{x_2 - x_1}$

For example:



(x_1, y_1) and (x_2, y_2)

(1,2) and (5, 8)

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

$$m = \frac{8 - 2}{5 - 1}$$

$$m = 1.5$$

The gradient of the line alone is meaningless – remember the point in drawing the graph would have been to determine a value or relationship.

Once we have the gradient of our line, we should need to state the significance of it. In the example above, the gradient of the line is equivalent to the resistance of the resistor, so…

gradient of the line, $m = 1.5 \therefore R_{resistor} = 1.5\ \Omega$

Note that we could not use this data to *prove* that $V = IR$. Comparing the equation of a straight line ($y = mx + c$) to the graph above gives us $V = RI + c$, not $V = IR$ (since the line doesn't quite go through the origin the y-intercept is >0). This does suggest that our data may suffer from a systematic error.

Using Uncertainties in Data Analysis

To identify areas of improvement for an experimental procedure we can look at which measurement has the greatest %Δ and suggest how to reduce this. Using percentage uncertainties allows us to compare uncertainties across different quantities, to find out which has the greatest impact on the results of an experiment.

Worked Example: The Lamp

A N5 Physics pupil carries out an experiment to determine the resistance of a lamp.

They use a variable power supply to adjust the voltage across the lamp to certain values (using a voltmeter) and they measure the current through the lamp (using an ammeter). Their raw data and processed results are shown below:

V_{lamp} (V)	I_{lamp} (A)			
	1	***2***	***3***	***Average***
1.00	0.04	0.05	0.03	0.04
2.00	0.09	0.08	0.08	0.083
3.00	0.12	0.11	0.10	0.11
4.00	0.15	0.18	0.16	0.16
5.0	0.19	0.20	0.19	0.193

(a) **State** the scale reading uncertainty for each measuring device.

Scale reading uncertainty for voltmeter is ± 0.01 V.
Scale reading uncertainty for ammeter is ± 0.01 A.

(b) **Calculate** the absolute random uncertainty for each repeated measurement.

V_{lamp} (V)	***Avg*** I_{lamp} (A)	ΔI_{lamp} (A)
1.00	0.04	± 0.0067
2.00	0.083	± 0.0033
3.00	0.11	± 0.0067
4.00	0.16	± 0.010
5.0	0.193	± 0.0033

(c) **Calculate** the percentage uncertainty for each measurement, and **identify** a way of improving the experimental procedure.

V_{lamp} (V)	$\%\Delta V_{lamp}$ ***scale***	***Avg*** I_{lamp} (A)	$\%\Delta I_{lamp}$ **scale**	$\%\Delta I_{lamp}$ ***random***
1.00	± 1.0 %	0.04	± 25 %	± 17 %
2.00	± 0.50 %	0.083	± 12 %	± 4.0 %
3.00	± 0.33 %	0.11	± 9.1 %	± 6.1 %
4.00	± 0.25 %	0.16	± 6.3 %	± 6.3 %
5.00	± 0.20%	0.193	± 5.2 %	± 1.7 %

The scale reading uncertainties for the ammeter are largest, so a more precise measuring device should be used to measure current.

The data range should be taken over higher values of V & I (the data set for 1 V has the highest uncertainties of all types).

Drawing Conclusions

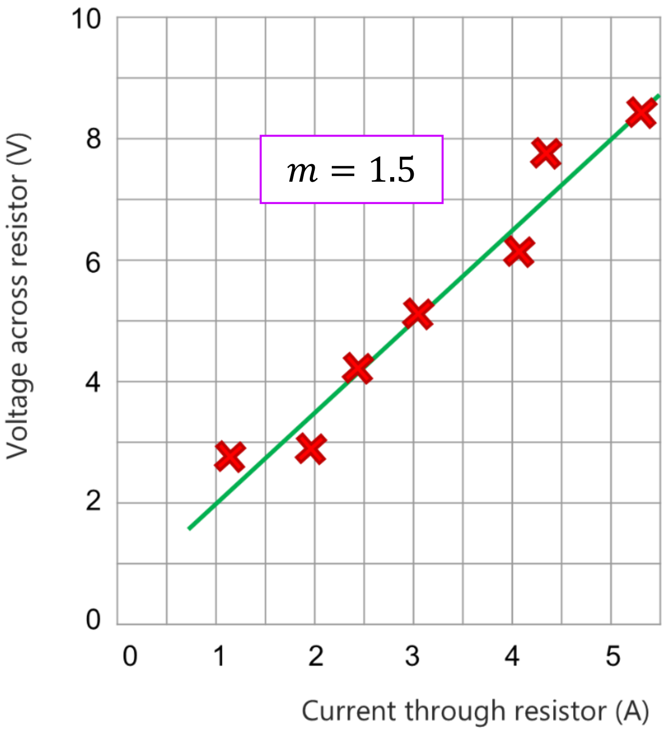
A conclusion should always respond directly to the experimental aim, and should be clear and concise.

Remember, in Higher Physics experimental aims will be structured one of two ways:

Aim	***Conclusion***
to measure the value of [constant]	value of [constant] from experimental data = _______
to determine the relationship between [Y] and [X]	the experimental data shows that [X] and [Y] are directly proportional *(if line of best fit goes through origin)* or the experimental data shows that [X] and [Y] have a linear relationship *(if line of best fit does not go through origin)*

Note that at Higher level we generally do look for a constant or a *relationship* – commenting on *trend* is not sufficient at this level.

For example:



If the aim of this experiment was *"to determine the resistance of the resistor"* then a conclusion stating "$R_{resistor} = 1.5\ \Omega$" is **correct**.

If the aim of this experiment was *"to determine the relationship between $V_{resistor}$ and $I_{resistor}$"* then a conclusion stating *"The voltage across the resistor and the current through the resistor have a linear relationship "* is **correct**.

If the aim of this experiment was *"to determine the relationship between $V_{resistor}$ and $I_{resistor}$"* then a conclusion stating *"As $I_{resistor}$ increases, $V_{resistor}$ increases"* is **insufficient**.

Evaluating Experimental Procedures

It is important to evaluate an experiment, to assess the reliability of our conclusion.

This can include evaluation of:

- Your experimental procedure (method)
- Your experimental data
- Any comparative data you have used

Your evaluative points should identify a **problem**, explain the **effects** of that problem, and **suggest a solution** to that problem that would improve your experiment. This could describe something you did already or something you would do if you were to repeat the experiment. It cannot be something that is a basic requirement at Higher level (e.g. taking repeats of measured values).

Evaluating Your Experimental Procedure

Consider the underlying physics related to your experiment, and the measurements you've made. Did you have to adapt your procedure at all when gather results?

Consider air resistance/friction for objects that move, or the effects of increasing temperature on objects that heat up. How could you plan your experimental procedure to avoid these affecting your measurements?

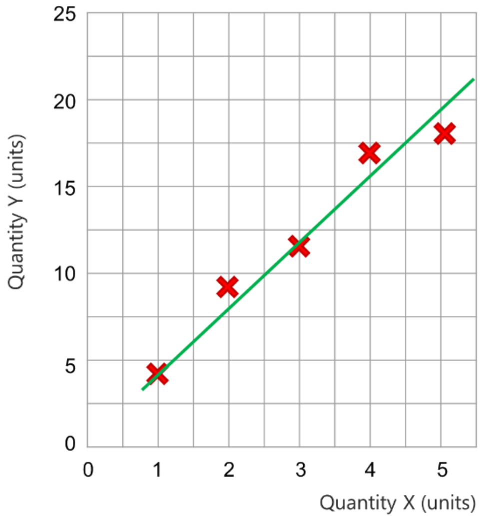
Evaluating Your Experimental Data

1. *Evaluate uncertainties in measured data*.

   Consider the most significant uncertainties (compare across different quantities using percentage uncertainties as above in *Worked Example: The Lamp*). Where are the most significant uncertainties? How could they be minimised?

   Note: an evaluative point on uncertainties is only valid if it would make a difference. E.g. if the scale reading uncertainty is ±1 % and the approximate random uncertainty is ±7 %, then reducing the scale reading uncertainty by using a more precise measuring device would have no effect on the overall uncertainty for that measurement (we would still be applying ±7 % as it's larger).

2. *Evaluate how easy it was to draw your line of best fit.*



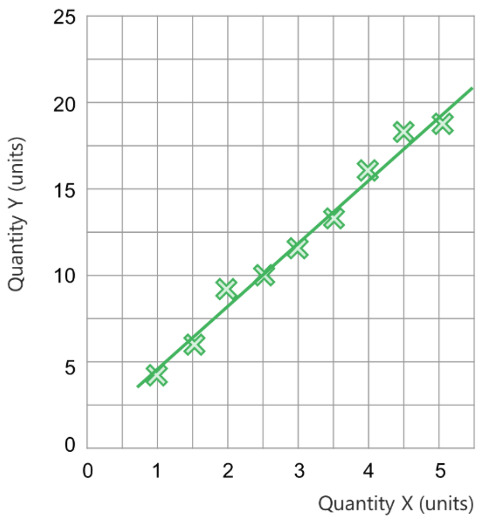
Consider the graph of Quantity Y vs Quantity X:

The data appears to curve – we could question whether the line of best fit here is appropriate.

Reasons for this could depend on the experiment - perhaps a moving object which would experience more air resistance at greater speeds (in this case the procedure should be adapted). Perhaps one or more of the points is simply a bit of an outlier.

More generally, we could take measurements in *smaller increments of Quantity X* – this would give us more data points and mean our line of best fit would be easier to place.

Repeating the experiment with this suggested improvement may lead to:



3. *Evaluate if your data gave you the results you expected.*

If your aim was to find a constant value, consider the magnitude of that value. Is it larger or smaller than you expected it to be? What could cause that?

If your aim was to determine a relationship between two quantities, consider how your results compare to what you expected. Is the data show a systematic uncertainty? What measurements are larger or smaller than expected? What could have caused that? How could you solve the problem?