Tools and Inquiries reference guide

Skills in the study of physics

The skills and techniques you must experience through the course are encompassed within the tools. These tools support the application and development of the inquiry process in the delivery of the physics course.

Tools

- **Tool 1:** Experimental techniques
- **Tool 2:** Technology
- **Tool 3:** Mathematics

Inquiry process

- **Inquiry 1:** Exploring and designing
- **Inquiry 2:** Collecting and processing data
- **Inquiry 3:** Concluding and evaluating

Throughout the programme, you will be given opportunities to encounter and practise the skills; instead of stand-alone topics, they will be integrated into the teaching of the syllabus when they are relevant to the syllabus topics being covered.

Tools

Tool 1: Experimental techniques

Skill: Addressing safety of self, others and the environment

Recognize and address relevant safety, ethical or environmental issues in an investigation

While the safety of students (and teachers) in a physics laboratory is always an important concern, it should not be a major issue if your behaviour is appropriate. Most schools will have a list of expected behaviours of students in a laboratory. The few accidents which occur are usually a result of inattention or carelessness.

Experimental situations requiring particular attention include the following:

- **Electrical equipment which is connected to the mains supply (110–230 V).** Such equipment should have regular safety checks and never be used close to water. Bare wires connected to the mains should not be used for experimentation. The laboratory should have appropriate circuit breakers and an RCCB which can cut off the electrical supply very quickly, protecting lives.
- **High voltage supplies (for example, 5000 V)** may be needed for a few teacher demonstrations, but they are provided with protection due to the very high internal resistance included deliberately in their design.
- **Electrostatic high voltage generators** can be used for interesting and dramatic demonstrations. They are very safe to use, but people with serious medical conditions are usually advised not to take part.
- **Hazardous chemicals** are not usually used in physics experiments.
- **Equipment made from glass** must be treated carefully to avoid breakage. Goggles should be worn.
- **Containers with a gas at high or low pressure** should have a shield around them for protection in the unlikely event of an explosion or implosion.

- **Radioactive sources** are usually used by teachers only, although some schools allow students to use such sources under close supervision. Sources should be labelled and stored securely and used for as short a time as possible. Students should not be allowed too close to the experiments and the sources should be shielded and never directed towards students.
- **The light from a laser** (or other very intense light source) should not be allowed to shine into anyone's eyes.
- **High temperatures** are required for a few experiments. Appropriate care is needed, especially when very hot water is involved.

Skill: Measuring variables

Understand how to accurately measure quantities to an appropriate level of precision

You should understand how to measure the following variables:

- mass
- time
- length
- volume
- temperature
- force
- electric current
- electric potential difference
- angle
- sound and light intensity

Comments about measuring these specific variables have been included at appropriate places in the coursebook, in the Tools Boxes.

Tool 2: Technology

Skill: Applying technology to collect data

Use sensors

Electronic sensors respond to a particular physical quantity by producing a corresponding voltage. That voltage must be converted to digital form before it can be understood, processed and displayed by appropriate software. This conversion can be done in different ways, including by a separate data logger/interface that is connected between the sensor and a computer.

Identify and extract data from databases

A database is information (often extensive) which is stored electronically in a structured and organised way. Many databases are continually updated with new data. There are many different types and sizes of database, which may be accessed in different ways. Some databases are only available to certain people (information within a school, for example).

Generate data from models and simulations

Many situations in physics can be reduced to simplified mathematical *models*. Such models provide the essential basis for understanding; they can be expanded later to include more details.

Many computer simulations are available to visually represent mathematical models – for example, the movement of a mass bouncing up and down on the end of a spring (Topic C1). These simulations can be very useful in supporting the learning process, especially if they allow you to investigate the effects of changing the variables (for example, mass on the spring, stiffness of the spring, air resistance, and so on). While virtual experiments should not replace actual experimental work, they are guaranteed to quickly produce results which are consistent with the physics theory and they enable students to carry out a wider range of tests than would usually be possible in a laboratory.

Carry out image analysis and video analysis of motion

Observation and measurement of fast-moving objects presents many technical difficulties. In the 1870s and 1880s, Eadweard Muybridge was the first to try to analyse motion (most notably of horses) by using quickly taken photographs.

The time between photographs was known and the position of the horse could be judged from the lines in the background. Using this information, Muybridge was able to calculate the average speed of the horse between consecutive pictures (and, if relevant, the horse's acceleration). The pictures also revealed previously unconfirmed information about how a horse's legs moved.

The same principles apply to video analysis using a modern video camera or a smartphone app. The motion to be analysed should take place just in front of a suitable measurement grid. The video can be replayed in slow motion, or frame-by-frame. Alternatively, a software programme can be used to track and measure the position of a videoed object.

Skill: Applying technology to process data

Use spreadsheets to manipulate data

You should be familiar with creating a spreadsheet (using Excel, for example) which is suitable for entering data from an investigation or another source of information. You can then process the data to determine if there is a mathematical relationship between the variables. Often, the last step in the analysis involves producing a graph (or graphs), which may be hand-drawn or computer generated. Spreadsheets are particularly useful in propagating uncertainties in processed data.

Represent data in graphical form

This is covered in detail later, in the 'Graphing' skill in Tool 3: Mathematics.

Use computer modelling

Powerful computers can be used to make predictions about the future, using the latest available data with complex models. Examples include: climate warming, global energy resources, the spread of a pandemic, the weather, flight simulators, response of buildings to extreme weather and earthquakes.

Tool 3: Mathematics

Skill: Applying general mathematics

Mathematics is used on nearly every page of the coursebook. It is a fundamental tool of the physicist. The rest of this section will provide information about the most important mathematical processes and how they apply to physics. Further examples can be found in the Tools Boxes within the coursebook; most of these boxes have been placed where the processes are first encountered, in the early chapters. The Tools Boxes also contain some additional material not included in this section.

Skill: Using units, symbols and numerical values

Apply and use SI prefixes and units

An internationally agreed system of units is used by scientists around the world. This is called the **SI system** (from the French 'Système International'). SI units are used throughout this course.

In everyday language, we use the words 'thousand' and 'million' to represent large numbers. The scientific equivalents are the prefixes kilo- and mega-. For example, a kilowatt is one thousand watts, while a megajoule is one million joules. Similarly, a thousandth and a millionth are represented scientifically by the prefixes milli- and micro-. The table below shows the standard prefixes you will encounter in physics.

Prefix	Abbreviation	Value
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deca	da	10^{1}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}

Work with fundamental units

There are seven fundamental (basic) units in the SI system: kilogram, metre, second, ampere, mole, kelvin (and candela, which is not part of this course). These units are called 'fundamental' because their definitions do not involve combinations of other units (unlike 'metres per second', for example). You are not expected to learn the definitions of these units.

The table below shows the quantities, names and symbols for the fundamental SI units.

Quantity	Name	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	kelvin	K
amount of substance	mole	mol

Express derived units in terms of SI units

All other units in science are combinations of the fundamental units. For example, the unit for volume is m^3 and the unit for speed is $m\ s^{-1}$. Combinations of fundamental units are known as **derived units**.

Some derived units are also given their own name, shown in the table below. For example, the units of force are $kg\ m\ s^{-2}$, but it is usually called the newton, N. All derived units are introduced and defined when they are needed during the course.

Derived unit	Quantity	Combined fundamental units
newton (N)	force	$kg\ m\ s^{-2}$
pascal (Pa)	pressure	$kg\ m^{-1}\ s^{-2}$
hertz (Hz)	frequency	s^{-1}
joule (J)	energy	$kg\ m^2\ s^{-2}$
watt (W)	power	$kg\ m^2\ s^{-3}$
coulomb (C)	charge	As
volt (V)	potential difference	$kg\ m^2\ s^{-3}\ A^{-1}$
ohm (Ω)	resistance	$kg\ m^2\ s^{-3}\ A^{-2}$
weber (Wb)	magnetic flux	$kg\ m^2\ s^{-2}\ A^{-1}$
tesla (T)	magnetic field strength	$kg\ s^{-2}\ A^{-1}$
becquerel (Bq)	radioactivity	s^{-1}

Note that you are expected to write and recognise units using superscript format (such as $m\ s^{-1}$) rather than m/s, with which you may be familiar from earlier courses. The unit for acceleration, for example, should be written $m\ s^{-2}$, not m/s^2.

Check an expression using dimensional analysis of units

In any equation, the units in each expression must be equivalent to each other.

For an example (from Topic B3), consider the equation $PV = nRT$. The pressure of a gas, P, multiplied by its volume, V, equals an amount of gas, n, multiplied by a constant, R, multiplied by the temperature, T.

The units on the left-hand side are: $kg\ m^{-1}\ s^{-2} \times m^3 = kg\ m^2\ s^{-2}$. As you can see from the table above, these are the units of energy – joules, J.

The units on the right-hand side are: mol × units of R × K. For the units to be the same in both expressions, the units of R must be $J\ mol^{-1}\ K^{-1}$.

You can also use this kind of analysis to check if a suggested equation could be correct. It is a simplified version of what is known as **dimensional analysis**.

Use scientific notation

When writing and comparing very large or very small numbers, it is convenient to use scientific notation (sometimes called *standard form*).

In scientific notation, every number is expressed in the form $a \times 10^b$, where a is a decimal number larger than 1 and less than 10, and b is a whole number (**integer**) called the **exponent**. For example, in scientific notation the number 434 is written as 4.34×10^2; similarly, 0.000 316 is written as 3.16×10^{-4}.

Scientific notation is useful for making the number of **significant figures** clear (see below). It is also used for entering and displaying large and small numbers on calculators. The letter E, or $\times 10^x$, is often used on calculators to represent 'times ten to the power of…'. For example, 4.62E3 represents 4.62×10^3, or 4620.

Express quantities to an appropriate number of significant figures

The more precise a measurement is, the greater the number of significant figures (digits) that can be used to represent it. For example, an electric current stated to be 4.20 A (as distinct from 4.19 A or 4.21 A) suggests a greater precision than a current stated to be 4.2 A.

Significant figures are all the digits used in data to carry meaning, whether they are before or after a decimal point. This includes zeros.

Zeros are often used without thought or meaning, and this can lead to confusion. For example, if you are told that it is 100 km to the nearest airport, you might be unsure whether it is approximately 100 km or 'exactly' 100 km. This is a good example of why scientific notation is useful. Using 1.00×10^3 km makes it clear that there are three significant figures. In contrast, 1×10^3 km represents much less precision.

When answering questions or processing experimental data, the result of a calculation cannot be more precise than the data used to produce it. As a general (and simplified) rule, the result should have the same number of significant figures as the data used. If the number of significant figures is not the same for all pieces of data, then the number of significant figures in the answer should be the same as the least precise of the data (which has the fewest significant figures).

Understand orders of magnitude

Physics is the fundamental science that tries to explain how and why everything in the universe behaves as it does. Physicists study everything from the smallest parts of atoms to distant objects in our galaxy and beyond.

Measurements and calculations commonly relate to the world that we can see around us (the macroscopic world), but our observations may require microscopic explanations, often including an understanding of molecules, atoms, ions and subatomic particles. Astronomy is a branch of physics that deals with the other extreme − quantities that are very much bigger than anything we experience in everyday life.

The study of physics therefore involves dealing with both very large and very small numbers. When numbers are so different from our everyday experiences, it can be difficult to appreciate their true size. For example, the age of the universe is believed to be about 10^{18} s, but just how big is that number? The only sensible way to answer that question is to compare the quantity with something else with which we are more familiar. For example, the age of the universe is about 100 million human lifetimes.

When comparing quantities of very different sizes (magnitudes), for simplicity we often make approximations to the nearest power of 10. When numbers are approximated and quoted to the nearest power of 10, it is called giving them an order of magnitude. For example, when comparing the lifetime of a human (the worldwide average is about 70 years) with the age of the universe (1.4×10^{10} y), we can use the approximate ratio $10^{10}/10^2$. We can say that the age of the universe is about 10^8 human lifetimes, or that there are eight orders of magnitude between the values.

Here are three further examples:

- The mass of a hydrogen atom is 1.67×10^{-27} kg. To an order of magnitude, this is 10^{-27} kg.
- The distance to the nearest star (Proxima Centauri) is 4.01×10^{16} m. To an order of magnitude, this is 10^{17} m. (Note: log of $4.01 \times 10^{16} = 16.60$, which is nearer to 17 than to 16.)
- There are 86 400 seconds in a day. To an order of magnitude, this is 10^5 s.

The table below lists the range of masses that occur in the universe.

Object	Mass/kg
the observable universe	10^{53}
our galaxy (the Milky Way)	10^{42}
the Sun	10^{30}
the Earth	10^{24}
a large passenger plane	10^{5}
a large adult human	10^{2}
a large book	1
a raindrop	10^{-6}
a virus	10^{-20}
a hydrogen atom	10^{-27}
an electron	10^{-30}

The table below lists the range of distances that occur in the universe.

Distance	Size/m
distance to the edge of the visible universe	10^{27}
diameter of our galaxy (the Milky Way)	10^{21}
distance to the nearest star	10^{16}
distance to the Sun	10^{11}
distance to the Moon	10^{8}
radius of the Earth	10^{7}
altitude of a cruising plane	10^{4}
height of a child	1
how much a human hair grows by in one day	10^{-4}
diameter of an atom	10^{-10}
diameter of a nucleus	10^{-15}

The table below lists the range of times that occur in the universe.

Time period	Time interval/s
age of the universe	10^{18}
time since dinosaurs became extinct	10^{15}
time since humans first appeared on Earth	10^{13}
time since the pyramids were built in Egypt	10^{11}
typical human lifetime	10^{9}
one day	10^{5}
time between human heartbeats	1
time period of high-frequency sound	10^{-4}
time for light to travel across a room	10^{-8}
time period of oscillation of a light wave	10^{-15}
time for light to travel across a nucleus	10^{-23}

Use estimation

Sometimes, you will not have the data needed for accurate calculations, or you may need to make calculations quickly. Sometimes a question is so vague that an accurate answer is simply not possible. The ability to make sensible estimates is a very useful skill that needs plenty of practice.

When making estimates, different people will produce different answers and it is usually sensible to use only one (maybe two) significant figures. Sometimes only an order of magnitude is needed.

Determine rates of change

The **rate of change** of a quantity is a measure of how quickly it is changing with respect to time. A simple example might be that the temperature of some water being heated changes from 17 °C to 35 °C in 60 s.

The Greek letter delta, Δ, is used to represents a change in a quantity. Typically, Δ is used for relatively small changes. In the example of the water being heated, $\Delta\Theta = 18$ °C (using the symbol Θ for temperature) and $\Delta t = 60$ s (using the symbol t for time).

The *average* rate of change of temperature with time $= \frac{\Delta\Theta}{\Delta t} = \frac{18}{60} = 0.30\ °\text{C s}^{-1}$.

Rates of change are often determined from graphs of a quantity against time. The *gradient* of a straight line graph represents a constant rate of change. If a rate of change is changing, the graph will be curved and the *instantaneous* rate of change at any particular time can be determined from the gradient of a tangent to the curve at that time. This is explained later in this guide.

Understand direct and inverse proportionality

The simplest possible relationship between two variables is that they are **directly proportional** to each other (often just called *proportional*). If two variables, say x and y, are directly proportional, this means that if x doubles, y also doubles; if y is divided by five, then x is divided by five; if x is multiplied by 17, then y is multiplied by 17; and so on. In other words, the ratio of the two variables ($\frac{x}{y}$ or $\frac{y}{x}$) is constant. Proportionality is shown using the symbol ∝.

If two variables show direct proportionality, you can write: $y \propto x$ **or** $\frac{x}{y} = \text{constant}$

To check if two variables are proportional to each other, you can either:

- calculate their ratios for different values to confirm that they are constant (as shown in the table below; the data in either of the last two columns confirms $y \propto x$, allowing for experimental uncertainties); or
- draw an x–y graph to determine if it is a straight line through the origin (as discussed in the graphs section of this reference guide).

x	y	$\frac{x}{y}$	$\frac{y}{x}$
0	0	-	-
0.32	1.6	0.20	5.0
0.81	4.2	0.19	5.2
1.4	6.9	0.20	4.9
2.5	12.8	0.20	5.1
6.4	30.0	0.21	4.7
10.9	55.2	0.20	5.1

If one variable increases while the other decreases, this is an *inverse relationship*. The simplest inverse relationship between two variables, say x and y, is that when x doubles, y halves; if y is divided by five, then x is multiplied by five; if x is multiplied by 17, then y is divided by 17; and so on. In other words, the ratio of the two variables xy is constant. This is called **inverse proportionality**.

If two variables show inverse proportionality, you can write: $y \propto \frac{1}{x}$ or xy = constant

To check if two variables are inversely proportional to each other, you can either:

- calculate values for when they are multiplied together, to confirm that they are constant (as shown in the table below; the data in the last column confirms $y \propto \frac{1}{x}$, allowing for experimental uncertainties); or
- draw an x–$\frac{1}{y}$ graph to determine if it is a straight line through the origin (as discussed in the graphs section of this reference guide).

x	y	xy
0	0	-
2.0	17	34
11	3.1	34
22	1.6	35
37	0.94	35
43	0.79	34
64	0.55	35

Understand scalars and vectors

Everything that you measure has a **magnitude** (size) and a unit. For example, you might measure the mass of a book to be 640 g. Here, 640 g is the magnitude of the measurement, but mass has no direction.

All physical quantities can be described as scalars or vectors.

- Quantities that have only magnitude, and no direction, are called **scalars**.
- Quantities that have both magnitude and direction are called **vectors**.

Most quantities are scalars. Some common examples of scalars used in physics are mass, length, time, energy, temperature and speed.

However, when using the following quantities you need to know both the magnitude and the direction in which they are acting, so they are vectors:

- displacement (distance in a specified direction)
- velocity (speed in a given direction)
- force (including weight)
- acceleration
- momentum and impulse
- field strength (gravitational, electric and magnetic).

In diagrams, vectors are shown with straight arrows, pointing in a certain direction from the correct point of application. The length of the arrow is proportional to the magnitude of the vector.

Add two vectors in the same plane

When two or more scalar quantities are added together (for example, masses of 25 g and 50 g), there is only one possible answer: 75 g. When vector quantities are added, however, there is a range of possible results, depending on the directions involved.

When two forces are acting in the same direction, it is easy to determine the combined effect of the two vectors (forces). The two vectors are simply added together, for example: 3 N + 5 N = 8 N. The value of 8 N is called the **resultant force**.

A resultant vector is the single vector which has the same effect as the combination of separate vectors.

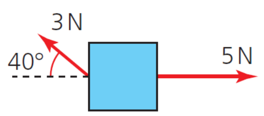
When forces act in opposite directions, the resultant force is still found by *adding* the two vectors. However, you must consider the opposite directions of the forces by describing one direction as positive and the other as negative.

- If a force to the right is described as positive: (+5) + (−3) = 2 N
- If you prefer to describe a force to the left as positive: (−5) + (3) = −2 N

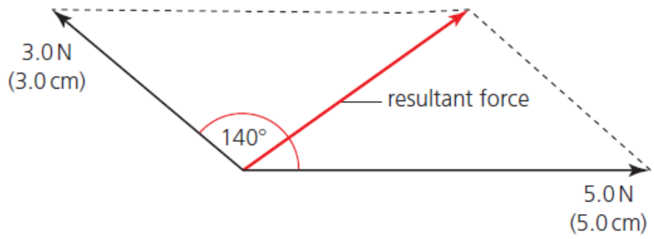
To determine the result of two vectors which are not aligned, there are two possible methods: by scale drawing (a graphical method) or by using trigonometry.

Graphical method

The diagram below shows two misaligned vectors:

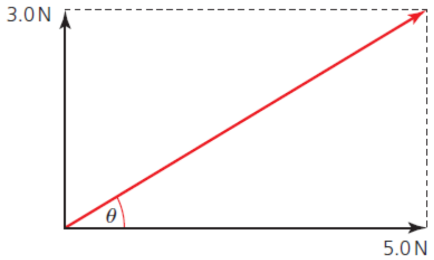


To determine the resultant of these two vectors by scale drawing, the vectors are drawn carefully to scale (for example, using 1 cm to represent 1 N), with the correct angle (140°) between them (as shown in the diagram below). They are considered to be acting at the same point. A parallelogram is then completed. The resultant force is the diagonal of the parallelogram, represented in this case by the line drawn in red. If the diagram has been drawn accurately, you can determine both the magnitude and the direction from it. In this example, the red line is 3.4 cm long, which represents a force of 3.4 N, at an angle of 36° to the 5.0 N force.



Trigonometric method

If two forces are at right angles to each other, a parallelogram drawn to represent these forces will be a rectangle, as shown in the diagram below.



You can find the magnitude of the resultant force, F, using Pythagoras's theorem:

$$F^2 = 3.0^2 + 5.0^2 = 34$$

$$F = 5.8\text{ N}$$

You can use trigonometry to determine the direction of this force:

$\tan\theta = \frac{3.0}{5.0}$ (θ is the angle that the resultant makes with the direction of the 5.0 N force)

$$\theta = 31°$$

You will not be expected to determine trigonometrical solutions if the parallelogram is not a rectangle.

Add three vectors

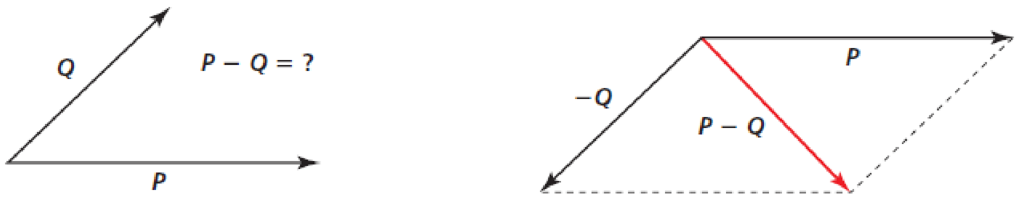
The most easily understood method of adding three vectors is to find the sum of two of them and then add this value to the third. Alternatively, the 'head to tail' method can be used. On a scale drawing, the three vectors are drawn in order. The resultant joins the start and the end.

Subtract vectors

Sometimes, you will need to find the difference between two vectors – for example, when you are considering by how much a vector quantity has changed. This is determined by subtracting one vector from the other, as shown in the diagram below.

When finding the difference between vectors P and Q, you add P to a reversed Q:

$$P - Q = P + (-Q)$$

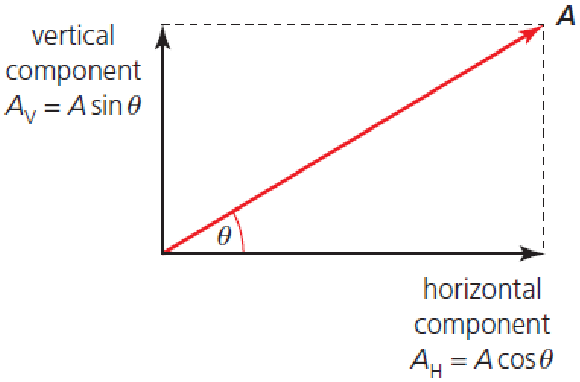


Resolve vectors

You have seen that you can combine two individual vectors mathematically to find a single resultant that has the same effect as the two separate vectors. You can also reverse this process: a single vector can be considered as having the same effect as two separate vectors. This is called **resolving a vector** into two **components**.

Resolving can be very useful because, if the two components are chosen to be perpendicular to each other (often horizontal and vertical), they will then be independent of each other. This means the two vectors can be considered separately.

The diagram below shows a single vector, A, acting at an angle θ to the horizontal.



If you want to know the effects of this vector in the horizontal and vertical directions, you can resolve A into two components:

$$\cos\theta = \frac{A_H}{A} \qquad \sin\theta = \frac{A_V}{A}$$

This means that: $\boldsymbol{A_H = A\cos\theta}$ **and** $\boldsymbol{A_V = A\sin\theta}$

In this example, the components chosen are horizontal and vertical, but the same ideas can be applied to other angles.

Skill: Processing uncertainties

Understand accuracy, uncertainties and errors

Although scientists are perceived as working towards finding 'exact' answers, an unavoidable **uncertainty** exists in *every* measurement. The results of all scientific investigations have uncertainties and errors, although good experimentation will try to keep these as small as possible.

When you receive numerical data of any kind (scientific or otherwise), you need to know how much belief you should place in that information. The presentation of the results of serious scientific research should always include an assessment of the uncertainties in the findings; this is an integral part of the scientific process.

No matter how hard we try, and no matter how good our measuring instruments, it is not possible to measure anything exactly. For one reason, the things we measure do not exist as perfectly exact quantities and there is no reason why they should.

This means that every measurement is an approximation. A measurement could be the most accurate ever made – for example, the width of a ruler might be stated as 2.283 891 03 cm – but that is still not perfect, and even if it was, we would not know because we would need a more accurate instrument to check it! In this example, we have the added complication that when measurements of length become very small, we have to deal with the atomic nature of the objects that we are measuring.

A measurement is **accurate** if it is close to its true value. For example, if you weigh a mass of 90.1 g and the result is 90.1 g, then the measurement can be described as accurate. However, you should be aware that in scientific research, 'true' values are rarely known.

If the same mass (90.1 g) was measured by a different method, or by a different person, and the result was 89.8 g, then there is a clear **error** in the measurement. An error has occurred if the measurement is different from its true value (using an appropriate number of significant figures for the comparison).

Significant errors are usually due to faulty apparatus or poor experimental skills. It is often possible to correct the source of such errors.

A **systematic error** occurs because there is something consistently wrong with the measuring instrument or the method used. A reading with a systematic error is always either bigger or smaller than the correct value, by the same amount. Common causes of systematic errors are instruments that have an incorrect scale (wrongly calibrated), or instruments that have an incorrect value to begin with. If a meter displays a reading when it should read zero, this is called a *zero offset error*. For example, a thermometer that records 0.5 °C when the temperature is 0 °C will produce systematic errors when used to measure other temperatures.

Uncertainties in measurements are an indication of the amount of variation seen in the readings taken (without considering their accuracy). For example, if you weigh the same (unknown) mass five times, you might get the following results: 53.2 g, 53.4 g, 52.9 g. 53.0 g, and 53.1 g. The results are not all the same, so there is clearly some *random uncertainty* in the measurements. The uncertainty in the use of the measuring instrument itself is usually assumed to be equal to the smallest division on its scale/display. In this example, this is ±0.1 g.

All experimental data has uncertainties. Sometimes, uncertainties arise because of difficulties in taking measurements. For example, human reaction times affect measurements made when using a stopwatch, and it can be difficult to measure the distance moved by something that is moving quickly.

It is usually not possible to reduce uncertainties using the same apparatus and techniques.

In science, the word **precise** means that measurements have low uncertainty. If measurements are repeated, they will produce similar results. Consider groups of arrows shot at two unmarked boards. You do not know where the target is on each board, so you cannot tell whether the arrows were shot accurately or not. However, if one board has a grouping of arrows in a small area, while the other board has arrows spread across a wide area, you can say the arrows on the first board were shot with more precision than on the second board.

When assessing experimental data, we are more concerned with uncertainties than with errors (which may be unknown and which we hope are not present!).

If a single measurement is made of a particular quantity, you may have no way of knowing how close it is to the correct result; that is, you will not know the size of any uncertainty in measurement. However, if the same measurement is repeated and the results are similar (low uncertainty, high precision), you will gain some confidence in the results of the experiment, especially if you have checked for any possible causes of systematic error.

The most common way of reducing the effects of random uncertainties is to repeat measurements and calculate a *mean value*. This mean value should be closer to the correct value than most, or all, of the individual measurements. Any unusual (**anomalous**) values ('outliers') should be checked and probably excluded from the calculation of the mean.

Many experiments involve taking a range of measurements, under different experimental conditions, so that a graph can be drawn to show the pattern of the results. (For example, changing the voltage in an electric circuit to see how it affects the current as in Topic B.5.) Increasing the number of pairs of measurements made also reduces the effects of uncertainties because the line of best fit can be placed with more confidence.

Wherever possible, experiments should be designed to produce large values. Consider measurements of length. A metre ruler might only be readable to the nearest millimetre, so all measurements made with such a ruler will only be accurate to the nearest millimetre. When measuring a length of 90 cm, this uncertainty will probably be considered acceptable (it is a percentage error of 1.1%). When measuring a length of 2 mm, however, the percentage error is 50%, which is unacceptable. The larger a measurement (made with a particular measuring instrument), the smaller the percentage uncertainty should be. If it is not possible to increase the size of the values to be measured, then the measuring instrument might need to be changed to one with smaller divisions.

It is possible to carry out an experiment carefully with good quality instruments, but still have large random uncertainties. There could be many different reasons for this and the experiment may have to be redesigned to resolve the problems. Using a stopwatch to time the fall of an object dropped from a hand to the floor, or measuring the height of a bouncing ball, are two examples of simple experiments which may have significant random uncertainties.

Record uncertainties in raw data

The term **raw data** is used to describe measurements made directly in an investigation, which have not been processed in any way.

The uncertainty in a measurement is the range, above and below a stated value, within which we expect any repeated measurements to fall.

Consider a student who wants to measure the greatest height to which a ball bounces after being dropped from a height of 2.0 m. There is no 'true', accepted value for this kind of measurement, so the student cannot know for sure if her measurements are accurate.

To check the quality of her measurements, the student repeats them (the more times the better, within reason). Her readings suggest that her measurements have uncertainties. To quantify the uncertainty, she calculates an average, as follows:

$$\text{average from six measurements} = \frac{1.32+1.32+1.37+1.28+1.34+1.30}{6} = 1.3216\ldots \text{ m}$$

The average value should be stated to the same number of significant figures (and/or decimal places) as the original data: 1.32 ± 0.05 m

The uncertainty is recorded as ±0.05 m because this is the largest difference between the average and any of the individual measurements: 1.37 − 1.32 = 0.05). Note that, because of experimental difficulties, this uncertainty is greater than the smallest division on the measuring instrument used (±0.1 m).

This type of value, expressed in this way and based on raw data, is known as **absolute uncertainty**.

If the student had recorded the six height measurements as 1.3 m, 1.2 m, 1.5 m, 1.2 m, 1.3 m, 1.4 m, with an average of 1.3166… m, the result would be recorded as 1.3 ± 0.2 m.

Uncertainties can be expressed as absolute, fractional (relative), or as a percentage.

Continuing with the first set of measurements from the example above:

$$\textbf{fractional uncertainty} = \frac{0.05}{1.32} = \pm 0.038$$

$$\textbf{percentage uncertainty} = 0.038 \times 100 = \pm 3.8\%$$

Percentage (and fractional) uncertainties are need to process data, as explained below.

Ideally, uncertainties should be quoted for all experimental measurements. However, this can be repetitive and tedious in a learning environment, so they are often omitted unless being taught specifically.

It is usually easy to determine the size of an absolute uncertainty associated with a single measurement taken with a particular measuring instrument: it is usually assumed to be equal to the smallest division on the scale of the instrument. However, the overall uncertainty in a measurement – allowing for all experimental difficulties – is sometimes more difficult to determine. For example, a hand-operated stopwatch might display times to the nearest 0.01 s, but the uncertainty in its measurements will be much greater because of human reaction times.

Propagate uncertainties in processed data

The term **processed data** is used to describe the results obtained after calculations have been made using raw data. In this section, we will consider how uncertainties in raw data affect the results of processed data.

Processed data should not have more significant figures than the raw data used to calculate it.

Consider a simple example. A trolley moving with constant speed was measured to have travelled a distance of 76 cm ± 2 cm (±2.6%) in a time of 4.3 s ± 0.2 s (±4.7%).

The speed can be calculated as follows:

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{76}{4.3} = 17.674\ldots$$

This is 18 m s^{-1} when rounded to two significant figures (consistent with the experimental data).

To determine the uncertainty in this answer, you need to consider the uncertainties in distance and time.

- The largest possible value for speed is $\frac{\text{largest distance}}{\text{shortest time}} = \frac{78}{4.1} = 19.024\ldots$ cm s^{-1}.
- The smallest possible value for speed is $\frac{\text{smallest distance}}{\text{longest time}} = \frac{74}{4.5} = 16.444\ldots$ cm s^{-1}.

The speed is therefore between 16.444 cm s^{-1} and 19.024 cm s^{-1}. (The numbers will be rounded at the end of the calculations.) The value 19.024 has the greater difference (1.350) from 17.674. Therefore, the final result can be expressed as 17.674 ± 1.350 cm s^{-1}, which is a maximum uncertainty of 7.6%. Rounding to two significant figures, the more realistic result is 18 ± 1 cm s^{-1}.

Uncertainty calculations like this can be very time-consuming and, for this course, approximate methods are acceptable. For example, in the speed calculation shown above, the uncertainty in the data was ±2.6% for distance and ±4.7% for time. We can approximate the percentage uncertainty in the final result by adding the percentage uncertainties in the data: 2.6 + 4.7 = 7.3%. This gives approximately the same result as the calculations using the largest and smallest possible values for speed.

Use the following rules to find uncertainties in calculated results:

- For quantities that are added or subtracted: add the absolute uncertainties.
  If $y = a \pm b$, then $\Delta y = \Delta a + \Delta b$
- For quantities that are multiplied or divided: add the individual fractional or percentage uncertainties
  If $y = abc$, then $\frac{\Delta y}{y} = \frac{\Delta a}{a} + \frac{\Delta b}{b} + \frac{\Delta c}{c}$
- For quantities that are raised to a power, n:
  If $y = a^n$, then $\frac{\Delta y}{y} = |n\left(\frac{\Delta a}{a}\right)|$
- For other functions (such as trigonometric functions, logarithms, or square roots): calculate the highest and lowest absolute values possible and compare with the mean value. Note, however, that although such calculations can occur in connection with laboratory work, they will not be required in examinations.

Use computer spreadsheets to calculate uncertainties

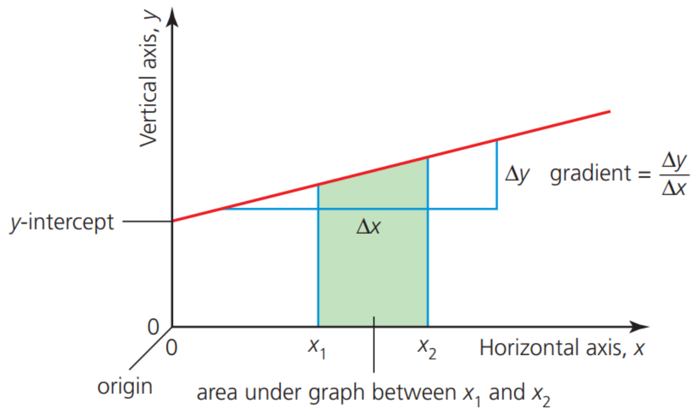
Computer spreadsheets can be very helpful when you need to make multiple calculations of uncertainties in experimental results. For example, the resistivity, ρ, of a metal wire can be calculated using the equation $\rho = \frac{R\pi r^2}{l}$, where r and l are the radius and length of the wire, and R is its resistance (from Topic B.5). Raw data from an experiment to measure the resistance of various wires of the same metal is added to a spreadsheet. The spreadsheet can then be used to make calculations to determine resistivity and the uncertainty in the result. A computer program can also be used to draw a suitable graph of the results, including uncertainty bars (explained later).

Skill: Graphing

Construct graphs

There are many quantities that can be measured in a physics experiment. Usually, all but two of them are controlled so they do not change during the course of the experiment. Of the remaining two quantities, one (called the independent variable) is deliberately varied or changed while the effect on the other (called the dependent variable) is investigated.

The best way to analyse the results of such experiments is usually to plot (draw) a graph. Looking at a graph is a good way to identify a pattern, or trend, in numerical data. Graphs can also provide extra information – gradients (slopes), intercepts and the areas under graphs often have important meanings. The next diagram illustrates the terminology associated with graphs.



The drawing of good-quality graphs is a very important skill in physics, even if computers can do much of the work. When drawing a graph, it is important to remember the following points:

- The larger a graph is, the more precisely the points can be plotted. A simple rule is that the graph should occupy at least half of the available space (in each direction).
- Each axis should be labelled with the quantity and the unit used (e.g. force/N, speed/m s^{-1}). Lists of results in tables should be similarly labelled. For example, if you want to record a mass of 5 g as the number 5 on the axis of a graph, then labelling the axis as ‘mass/g’ indicates that you have divided 5 g by g to get 5.
- The independent variable is usually plotted on the horizontal axis and the dependent variable on the vertical axis. Sometimes, decisions about what to plot on each axis are made so that the gradient of the graph has a particular meaning. If time is one of the variables, it is nearly always plotted on the horizontal axis.
- The scales chosen should make it easy to plot the points and interpret the graph. For example, five divisions might be used to represent 10 or 20, but not 7 or 12.
- Usually, both scales should start at zero, so the origin (0, 0) is included on the graph. This is often important when interpreting a graph. However, this is not always sensible, especially if it would

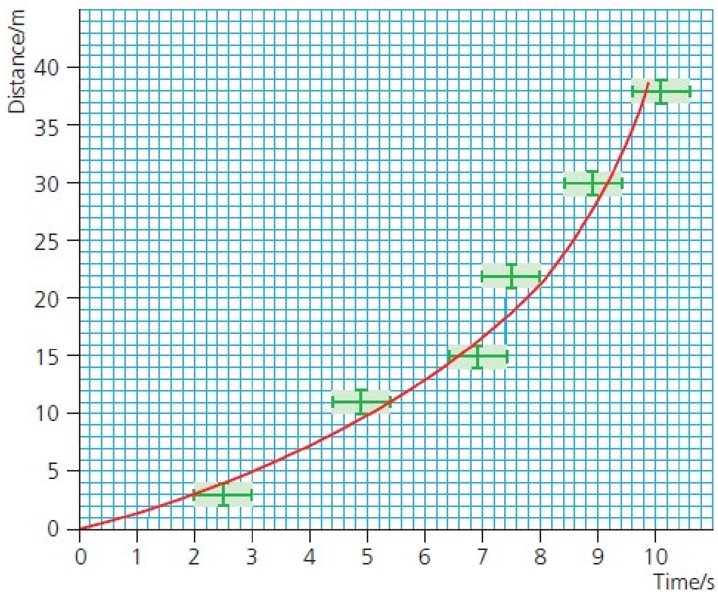
mean that all the readings were restricted to a small part of the graph. Temperature scales in °C do not usually need to start at zero.

- Data points should be neat and small. If points are used (rather than crosses), drawing a small circle around them can ensure that they are not overlooked, especially if the line goes through them.
- The more points are plotted, the more precisely the line representing the relationship can be drawn. At least six points are usually needed, although this may not always be possible.
- When all the points have been plotted, a pattern will usually be clear and a line of best fit – or trend line – can be drawn. Trend lines may be straight (drawn with a ruler) or curved. (A straight line represents a linear relationship.) The line should be smooth and thin. A bumpy line that tries to pass through, or near, all the points shows that the person drawing the line does not understand that points cannot be perfectly placed: there is uncertainty in all measurements. Typically, there will be about as many points above the line of best fit as there are below the line. Points on a graph should never be joined by a series of straight lines.
- Drawing graphs by hand is an important skill that you should practise. However, knowing how to use a computer program to plot graphs is also a very valuable and time-saving skill (especially for investigation work). A graph generated by a computer (or graphic display calculator) must be judged by the same standards as a hand-drawn graph and it is important to recognise that computer-generated best-fit lines are not always well placed.

Represent uncertainties on graphs: uncertainty bars

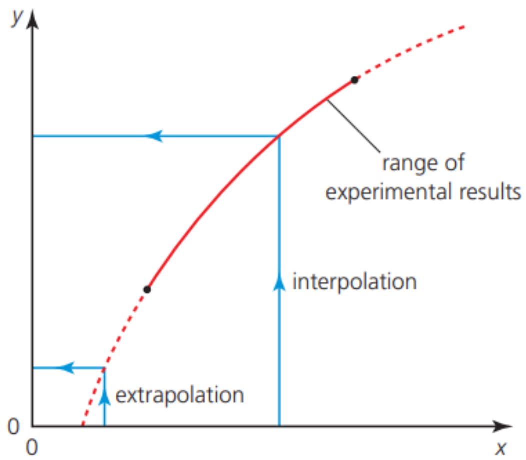
The range of random uncertainty in a measurement or a calculated result can be represented on a graph by the use of crossed lines to mark the point (rather than crosses or dots). Look at the example graph below, which shows distance against time for the motion of a train. Vertical and horizontal lines have been drawn through each data point to represent the uncertainties in the two measurements. In this example, the uncertainty in time is ±0.5 s and the uncertainty in distance is ±1 m. These lines, which usually have small lines to indicate clearly where they end, are called **uncertainty bars**. In the example, the space outlined by each error bar has been shaded for emphasis – it is expected that a line of best fit should pass somewhere through each shaded area.

In some experiments, the error bars are so short and insignificant that they are not included on the graph. For example, a mass could be measured as 347.46 ± 0.01 g. The uncertainty in this reading would be too small to show as an error bar on a graph. (Note that error bars are not expected for trigonometric or logarithmic functions.)



Extrapolate and interpolate graphs

A line of best fit is usually drawn to cover a specific range of measurements recorded in an experiment, as shown in the example below. If you want to predict other values within that range, you can usually do so with confidence. The diagram shows how values for y can be determined for a chosen value of x. This is called **interpolation**.



If you want to predict what might happen outside the range of measurements (**extrapolation**), you need to extend the line of best fit. Lines are often extrapolated to see if they pass through the origin, or to find a y-intercept.

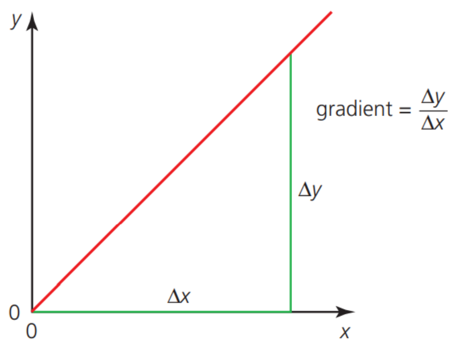
Predictions made by extrapolation should be treated with care: it may be wrong to assume that the behaviour seen within the range of measurements also applies outside that range.

Work with proportionality in graphs

Many basic physics experiments aim to investigate whether there is a **proportional relationship** between two variables. This is usually best checked by drawing a graph.

If two variables are (directly) proportional, their graph will be a straight line passing through the origin.

The graph below represents a proportional relationship. It is important to note that a linear graph that does *not* pass through the origin does *not* represent proportionality.



Calculate and use gradients of lines

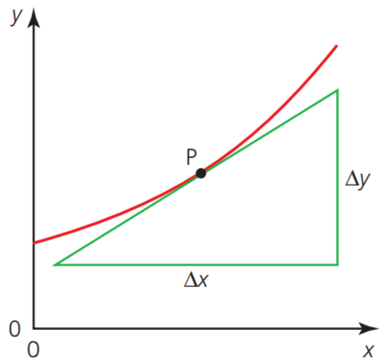
The gradient of a line is often given the symbol m and, for an x–y graph, it is calculated by dividing a change in y, Δy, by the corresponding change in x, Δx, as shown in the diagram above.

$$\text{gradient of } x\text{–}y \text{ graph, } m = \frac{\Delta y}{\Delta x}$$

When determining the gradient of a line, it is important to use the largest triangle possible because the percentage uncertainty will be less when using larger values.

The gradients of many lines have a physical meaning, for example, the gradient of a mass–volume graph equals the density of the material. The gradient of a graph of any quantity against time represents the *rate of change* of that quantity.

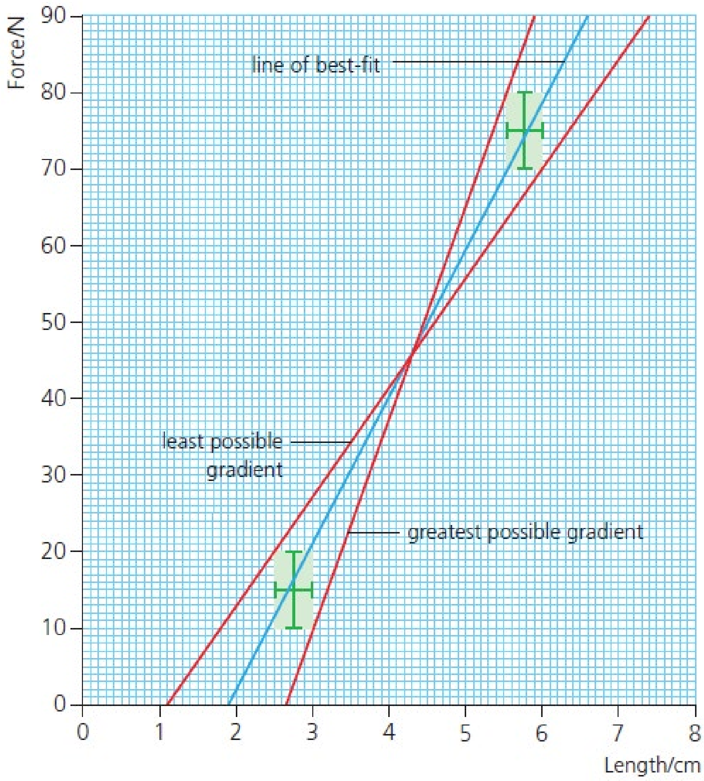
The gradient of a curved line, such as that shown in the diagram below, is constantly changing. You can determine the gradient of the curve at a point, P, by finding the gradient of a tangent drawn to the curve at that point. (In mathematics, if the equation of a line is known, the gradient at any point can be determined by a process called differentiation.)



Calculate uncertainty in gradients and intercepts

It is often possible to draw a range of straight lines, all of which pass through the uncertainty bars representing experimental data.

We usually assume that the best fit line is midway between the lines of maximum possible gradient and minimum possible gradient. An example is shown below. (For simplicity, *only the first and last error bars are shown*; in practice, all the error bars need to be considered when drawing a line of best fit.)



This graph shows how the length of a metal spring changed as the force applied was increased (Topic A.2). We know that the measurements were not very precise because the uncertainty bars are long. The line of best fit has been drawn midway between the other two lines (least possible gradient and greatest possible gradient). This is a linear graph (a straight line) and it is known that the gradient of the graph represents the force constant (stiffness) of the spring, while the horizontal intercept represents the original length of the spring. Taking measurements from the best fit line, we can make the following calculations:

- force constant = gradient = $\frac{90-0}{6.6-1.9}$ = 19 N cm^{-1}
- original length = horizontal intercept = 1.9 cm

To determine the uncertainty in the calculations of gradient and intercept, we need only consider the range of straight lines that could be drawn through the first and last error bars. The uncertainty is the maximum difference between the extreme values obtained from graphs of maximum and minimum possible gradients and the value calculated from the best fit line. In this example, it can be shown that:

- force constant is between 14 N cm^{-1} and 28 N cm^{-1}
- original length is between 1.1 cm and 2.6 cm.

The final result can be quoted as:

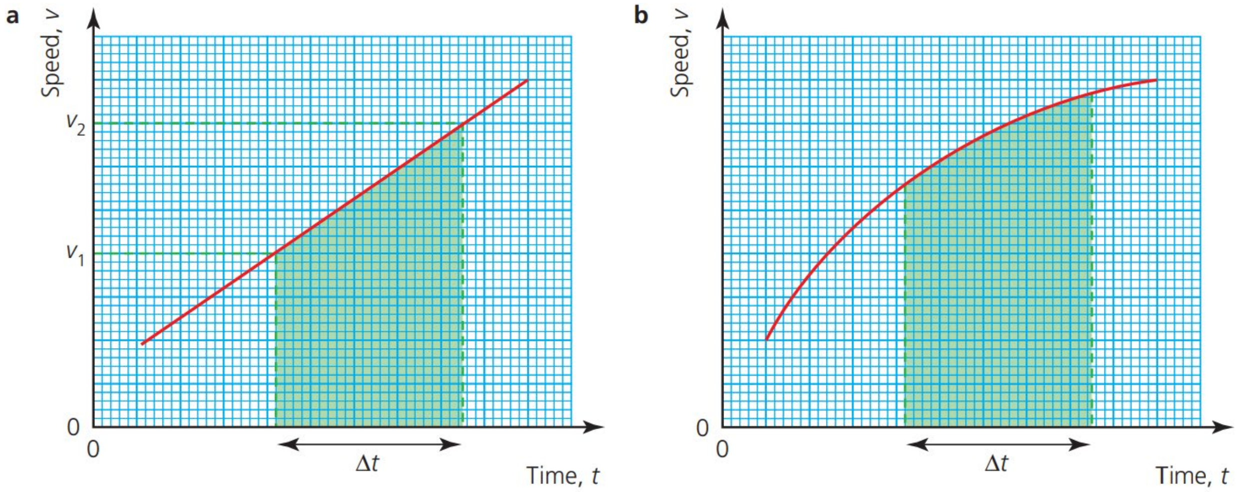
- force constant = 19 ± 9 N cm^{-1}
- original length = 1.9 ± 0.8 cm.

The large uncertainties in these results confirm that the experiment lacked precision.

Interpret areas under graphs

The area under many graphs has a physical meaning. As an example, consider diagram **a** below, which shows part of a speed–time graph for a vehicle moving with constant acceleration. The area under the graph (the shaded area) can be calculated from the average speed, given by $\frac{(v_1+v_2)}{2}$, multiplied by the time, Δt.

The area under the graph is therefore equal to the distance travelled in time Δt. In diagram **b** below, a vehicle is moving with changing (decreasing) acceleration. In this case, the graph is curved, but the same rule applies: the area under the graph (shaded) represents the distance travelled in time Δt.



The area in diagram **b** can be estimated in a number of different ways – for example, by counting small squares, or by drawing a rectangle that appears (as judged by eye) to have the same area. (If the equation of the line is known, it can be calculated using the process of integration.)

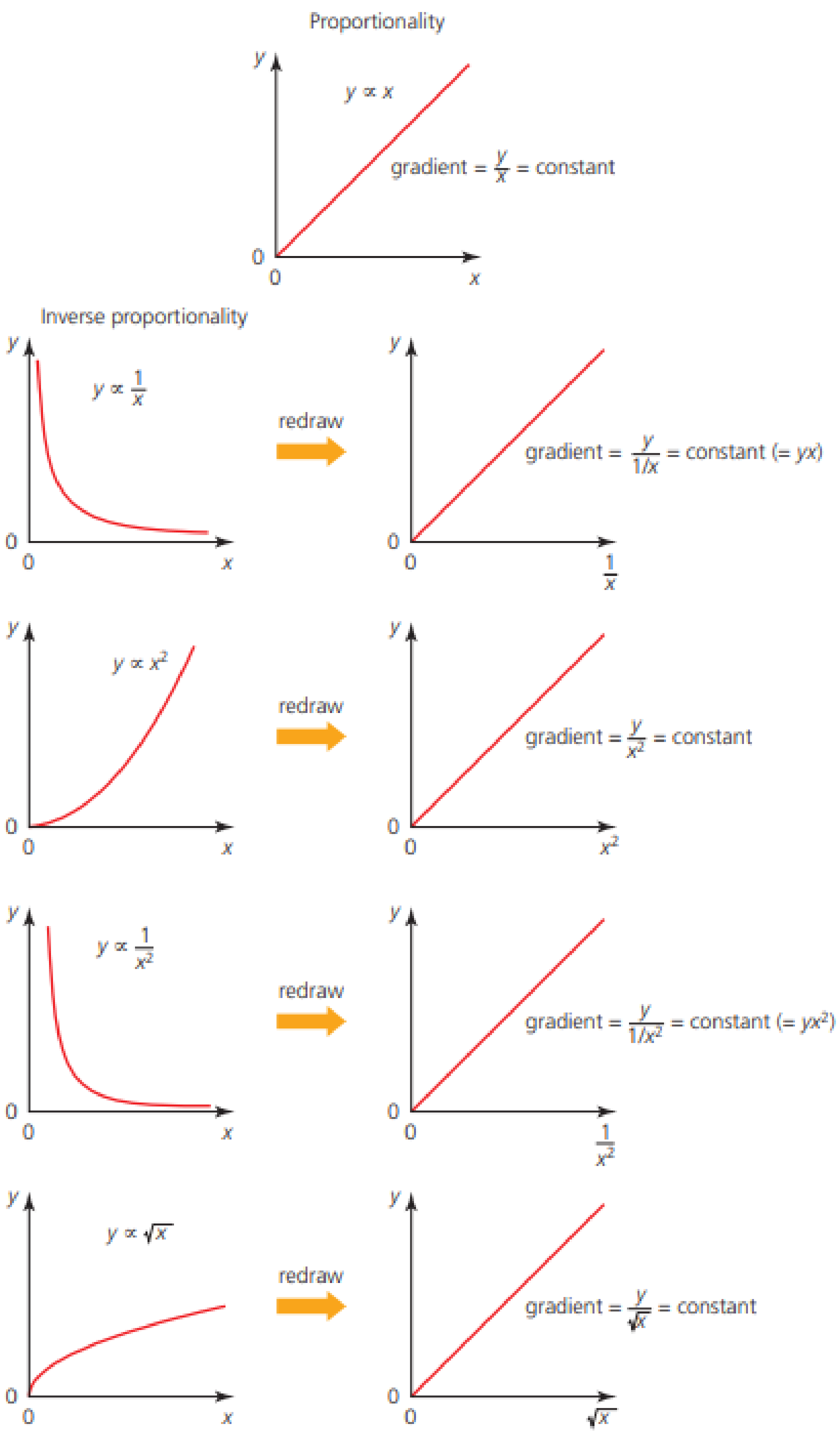
Linearize graphs

Straight lines are much easier to understand and analyse than curved lines, but when raw experimental data are plotted against each other (x and y, for example), the lines are often curved rather than linear.

Data that give an x–y curve can be used to draw other graphs to check different possible relationships. For example:

- If a graph of y against x^2 is a straight line through the origin, y is *proportional* to x^2.
- If a graph of y against $\frac{1}{x}$ is a straight line through the origin, y is proportional to $\frac{1}{x}$. In this case, x and y are said to be *inversely proportional* to each other.
- If a graph of y against $\frac{1}{x^2}$ is a straight line through the origin, this represents an *inverse square relationship*.

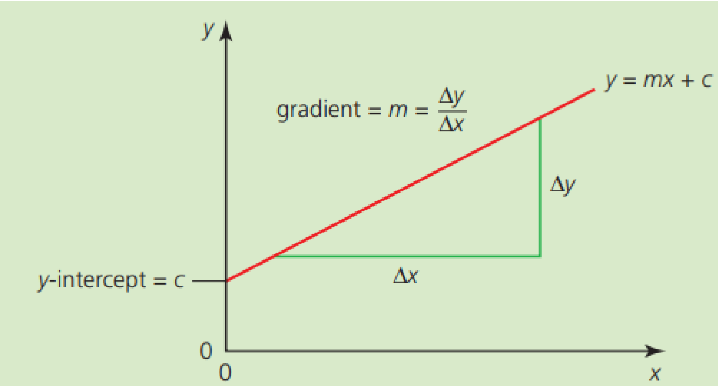
The diagram below shows some graphs of the most common relationships.



Find the equation of a straight line

All linear graphs can be represented by an equation of the form $y = mx + c$

where m is the gradient and c is the value of y when $x = 0$, known as the y-intercept (see diagram below).



Once a linear graph has been drawn, values for the gradient and the y-intercept can be determined. These values can be used to produce a mathematical equation to describe the relationship.

Work with power laws and logarithmic graphs

Sometimes there is no 'simple' relationship between two variables, or you may have no idea what the relationship could be. In general, you can write that the variables x and y are connected by a relationship of the form:

$$y = kx^p$$

where k and p are unknown constants. That is, y is proportional to x to the power p.

Taking logarithms of this equation, you get:

$$\log y = (p \times \log x) + \log k$$

Compare this with the equation for a straight line, $y = mx + c$.

If you draw a graph of $\log y$ against $\log x$, it will have a gradient p and a y-intercept of $\log k$.

Using this information, you can write a mathematical equation to describe the relationship. Note that logarithms to the base 10 have been used in the above equation, but natural logarithms (ln) could be used instead.

Inquiry process

Inquiry 1: Exploring and designing

Skill: Exploring

Demonstrate independent thinking, initiative and insight

Many of the best physics investigations begin with a personal interest of the student. This could be a particular area of the syllabus, or an interest outside the classroom. There are many possibilities, for example: music, sport, some feature of the local environment, or renewable energy.

An investigation which is only a straightforward extension of laboratory work already covered in the course may be an easy and 'safe' choice, but it does not show much imagination or initiative. Also, wherever possible, an investigation should be linked to a real-world application, rather than 'pure physics'.

You need to consider carefully whether your choice of an imaginative and interesting investigation will also enable you to demonstrate the skills necessary for a good assessment; that is, will your investigation cover most, or all, of the points discussed in the rest of this chapter?

Consult a variety of sources / Select sufficient and relevant sources of information

After deciding on a general area of interest, you will often need to research other sources of information for background knowledge and any relevant physics which is beyond the IB course (if appropriate). Teachers should be an excellent source of advice and information and, obviously, the internet has multiple sources (of various quality). Physics books, science magazines and books from libraries can be additional sources of information and inspiration.

Your intended investigation should be both interesting and unusual, but also realistic in terms of the apparatus that is available in the school, and the time available. It would be wise to consult with teachers about whether your intended investigation is sensible under the circumstances.

All sources of information should be acknowledged in your investigation report, including those which were researched but not used (with a reason given).

Formulate research questions and hypotheses

After deciding on the broad topic for an investigation, you need to be specific about the aims of your intended work. A research 'question' is needed. At the end of a successful investigation, you should be able to give a clear answer to the original question, or a justifiable reason why you are not able to do this.

Investigations should usually involve taking quantitative measurements. There are certainly other interesting possibilities – for example, videoing the motions of paper aeroplanes – but without numerical data to process, it is unlikely that you will be able to show a full range of investigational skills. Without numerical data, it is also unlikely that your research question and its answer will be satisfactory.

Your hypothesis is your prediction about the probable conclusion of your investigation, with a provisional scientific explanation. For example:

'I think that the power output from a solar cell will be proportional to the light intensity. This is because intensity $= \frac{\text{power}}{\text{area}}$ and the area is constant. I expect that the efficiency of the energy transfer is constant.'

Of course, you may not know exactly what to expect. Indeed, it can be argued that this would contribute to a more interesting investigation. Nevertheless, you should be able to discuss possible outcomes in advance of your investigation.

State and explain predictions using scientific understanding

Your hypothesis does not have to be correct, but it must be reasonable and justified. You should explain your prediction/hypothesis using a level of physics understanding which is appropriate to the IB physics course.

Some investigations may require an understanding of physics which is beyond the content of the IB Physics course. While this may be generally creditable, it is not a necessary feature for a good assessment.

Skill: Designing

The report of the design of a good quality investigation will have the following characteristics:

- The research question is described within a specific and appropriate context.
- Methodological considerations associated with collecting relevant and sufficient data to answer the research question are explained.
- The description of the methodology for collecting or selecting data allows for the investigation to be reproduced.

Demonstrate creativity in the designing, implementation and presentation of the investigation

It is rare that a student plans a completely original investigation. However, the most impressive investigations are often those which demonstrate a student's imagination and individuality of approach to a familiar situation. For example, if you are interested in scuba diving, you could investigate the loss of thermal energy from objects submerged in cold water.

Develop investigations that involve hands-on laboratory experiments, databases, simulations and modelling

Most investigations will involve individual laboratory experiments. However, you may consider other possibilities, including:

- extracting and evaluating data from a range of sources, including databases
- working in collaboration with one or two other students (if appropriate)
- using computer models and simulations, when the equivalent laboratory work is not possible
- field-work (gathering data outside a laboratory environment).

Identify and justify the choice of dependent, independent and control variables

In all physics experiments, you should identify all the factors (variables) that could change the outcome of the process being studied. The simplest investigations have only two significant inter-dependent variables. Some processes have numerous variables, which makes them more interesting but also more difficult to investigate.

Usually, one variable (the independent variable) is deliberately changed while the effect on another variable (the dependent variable) is recorded. It is important that all other variables are controlled – that is, they are not allowed to change. Otherwise, it will be very difficult to interpret the results of the investigation. In your investigation design, you need to explain how you will control these other variables, or why they are not expected to change.

If you are using databases and/or the internet as sources of numerical data, 'identifying and justifying the choice of dependent, independent and control variables' will seem less appropriate. However, you must still be very clear about which factors you intend to consider.

Justify the range and quantity of measurements

The range of values chosen for the independent variable in an experiment should usually be as large as is practicable with the available apparatus. Students commonly, and unnecessarily, restrict the range of their measurements; you should avoid this.

If you decide to change the range of experimental readings during your investigation, you may need to use a different measuring instrument or technique. In this case, you should be aware that some unwanted inconsistencies may occur.

In elementary work, you may have learned that it is acceptable to use six different values for the independent variable – that this is enough to draw a basic graph. However, in many experiments, this would not be ideal. There are many factors to consider, including time available, difficulty in making measurements, and whether the experiment is central to the investigation or just one of a number of aspects. As a guiding principle, you should aim to use your time in the laboratory well; the number of measurements you make should reflect that aim.

The need to repeat measurements and take an average is well-understood, but the number of repetitions needed may depend on the variations seen in your results. Usually, each reading should be taken at least three times (where applicable). Sometimes, however, there will be no reason to repeat measurements – for example, when reading the value of a steady electric current with an ammeter. Under such circumstances, it is usually sensible to take a greater number of *different* readings. Generally, if time is available, more repetitions of measurements can only improve your investigation.

The plan for your investigation is likely to involve taking measurements at regular intervals within the chosen range (for example, every 10 cm over a range of 1 metre). However, you may need to change this aspect of your plan during the practical work if the pattern of measurements of the dependent variable suggests you need a different strategy.

Design and explain a valid methodology

Your investigation plan and report should list the apparatus used, with supporting diagrams where appropriate. Use standard symbols to ensure diagrams are clear. Whenever you have made a choice between different items of apparatus, explain and justify your decision.

If your intended research involves computer modelling, databases, spreadsheets etc. (rather than practical laboratory work), state clearly how you will select your sources and list all resources fully within your report.

Ensure your original plan for the investigation is realistic and will fully utilise the total time available for its completion.

You need to describe how you carried out your investigation, including enough detail that any reader of the report would be able to exactly repeat the experiment(s). In particular, you should describe clearly how the independent and dependent variables were measured and changed, and the degree of precision expected.

In many cases, investigations do not go to plan. You should expect changes and have the flexibility to adapt. Any changes (from your original plan) made during the course of the investigation should be described and justified in your report.

Your plan should explain in detail how the resources you have chosen will be used to answer the research question. This includes how you will control variables other than the chosen independent and dependent variables, or why these variables can be assumed to be constant.

You should recognise any relevant safety, ethical or environmental issues. If appropriate, you must explain how you considered these aspects, when describing the design of the investigation.

The quantity and range of the intended measurements is discussed in the next section.

Pilot methodologies

You may be unsure whether your intended investigation is realistic. In such cases, it is advisable to complete a quick trial experiment (a pilot), to determine a suitable method or check whether an investigation is worth pursuing.

For example, a student may decide that they want to investigate the angles at which models of ladders on different surfaces can lean up against a vertical wall before they slip. However, the student will probably be unsure of the best way of approaching this investigation until they have tried out a few possibilities.

Pilot studies, and their conclusions, should be summarised in the investigation report.

Skill: Controlling variables

The following information is included at appropriate points within the Topic chapters:

- calibrate measuring apparatus, including sensors
- maintain constant environmental conditions of systems
- insulate against heat loss or gain
- reduce friction
- reduce electrical resistance
- take background radiation into account.

Inquiry 2: Collecting and processing data

Skill: Collecting data

Identify and record relevant qualitative observations

Almost all physics investigations should involve quantitative measurements of numerical data. Occasionally, non-numerical (qualitative) observations may also be relevant.

In some experiments, you may observe changes that cannot be measured, but which may be important when you are reaching conclusions or making evaluations. You should include all qualitative observations that may be relevant to the investigation in your report.

Collect and record sufficient relevant quantitative data

You must record raw data (direct measurements) for all relevant variables. If readings are repeated, you must show *all* values in an appropriate table(s) of results, not just averages. If *differences* in distance, temperature, etc. are important, you must show the original data from which the differences were calculated. For example, if a temperature rose from 21.5 °C to 26.0 °C, you must record these two values as well as the temperature difference of 4.5 °C.

The range and quantity of measurements has been discussed above.

The table below is an example of how results should be recorded in a table. As part of her investigation, a student wanted to investigate the effects of air resistance on a small ball dropped from a wide range of different heights.

Height from which ball was dropped / m ±0.05 m	Times taken to reach the ground / s ±0.25 s
5.00	4.65, 4.51, 4.55, 4.49, 4.48
4.50	3.60, 3.69, 3.67, 3.75, 3.67
4.00	3.00, 2.93, 3.03, 2.97, 2.78
3.50	2.39, 2.40, 2.50, 2.45, 2.37
3.00	1.94, 1.91, 1.86, 1.89, 1.99
2.50	1.44, 1.45, 1.49, 1.51, 1.39
2.00	1.11, 1.04, 1.05, 0.98, 1.04
1.50	0.78, 0.79, 0.86, 0.83, 0.80
1.00	0.62, 0.55, 0.51, 0.64, 0.53
0.50	0.31, 0.32, 0.28, 0.59, 0.42

Note the following points.

- The headings *fully* describe the quantities being measured. Headings such as 'Height' and 'Time' would be insufficient: the units of measurement should also be included in the heading. SI units should usually be used.
- Each measurement was repeated five times (and the student should later calculate mean values). This experiment can be repeated quickly, so five repetitions is a reasonable number – especially since there are significant uncertainties in time measurements.
- The number shown in red is anomalous: it does not fit the pattern shown by other readings. It may be described as an 'outlier'.

- The uncertainty of a measuring instrument when making a single measurement is often quoted as the smallest division of the scale used (where applicable).
- The uncertainty of the measuring *instrument* may be different from the uncertainty of the measuring *process* using that instrument, because of other factors.
- The number of significant figures used for the data is consistent with the quoted uncertainties.
- The table headings show values for the *absolute uncertainty* in the measurements. Although the student used a stopwatch which shows values to the nearest 0.01 s, they have assumed a much greater uncertainty because of delays due to human reaction times.
- More generally, you can assess the uncertainty in measurements by looking at the amount of variation seen in repeated readings (without considering their accuracy, which is probably unknown).

Identify and address issues that arise during data collection

In the course of your experiment, it may become clear that your plan needs some changes. This is not (necessarily) a criticism of the plan. In fact, the ability to adapt to changing circumstances is a valuable skill. For example, the student who recorded the results in the table above may decide that the uncertainties in the time measurements are too large (over 90% in the shortest times), so they need to think about another way of taking time measurements (perhaps using light gates rather than a hand-held stopwatch).

It is possible that a whole experiment will not produce satisfactory data and needs to be redesigned. Alternatively, you may simply need to adjust the quantity and/or range of measurements, based on the initial results obtained.

Most data is processed using graphs. If possible, you should draw a rough graph while the experiment is ongoing. This can provide an early indication of any issues that may be arising.

It is also possible that, in the process of carrying out your experiment, you may become aware of the possibilities for further, as yet unplanned experiments.

Your report should clearly explain any changes made during their investigation, and the reasons for making those changes.

Skill: Processing data

The data analysis in the report of a good quality investigation will have the following characteristics:

- The communication of the recording and processing of the data is both clear and precise.
- The recording and processing of data shows evidence of an appropriate consideration of uncertainties.
- The processing of data relevant to addressing the research question is carried out appropriately and accurately.

Carry out relevant and accurate data processing

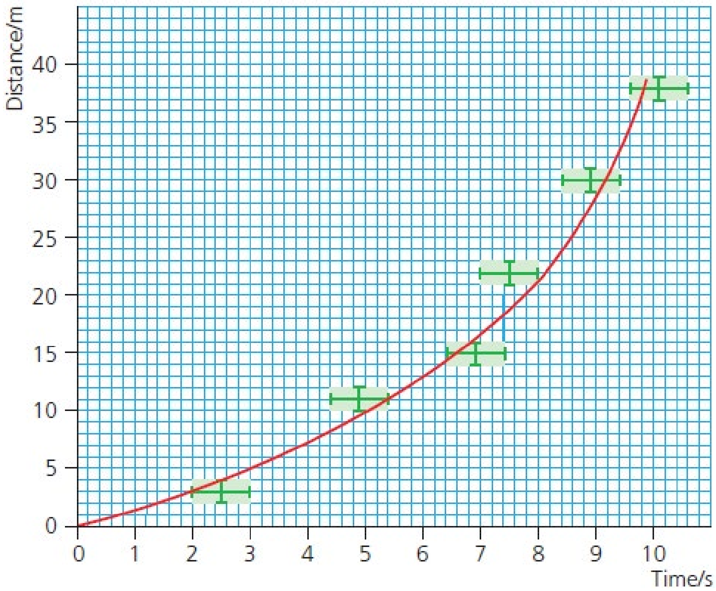
The processing of data (including uncertainties) has been discussed in detail in the Tools section earlier in this reference guide.

Data processing involves making calculations using raw data, determining the uncertainties in calculated data, and drawing appropriate graphs and charts. Graphs, charts and diagrams are almost always the best way of representing a set of data.

The axes of graphs should be labelled in the conventional way. Axes should usually begin at (0, 0); if they do not, you should explain why.

In your investigation report, it should be very clear how you have processed your numerical data – that is, what calculations you have made. Wherever possible, you should show raw data and processed data in the same table of results.

The graph below shows how a best-fit line can be drawn through uncertainty bars.



If a graph of results is a smooth curve, you may need to draw another graph to try to display a linear relationship. For example, the curved graph shown above could be redrawn as a distance–time^2 graph; if the new graph is a straight line through the origin, then distance is proportional to time squared.

Skill: Interpreting results

Interpret qualitative and quantitative data

You should comment on what you have learned from *all* the observations (numerical or otherwise) that are contained within your investigation report. This will usually – but not always – involve interpreting graphs or charts you have drawn using your raw or processed data.

The interpretation of graphs and diagrams of *quantitative* data is discussed in the next section.

Sometimes, quantitative data does not need to be represented graphically.

Interpret diagrams, graphs and charts, and Identify, describe and explain patterns, trends and relationships

Drawing and interpretation of graphs is covered in detail in the Tools section of this reference guide.

Your report will probably contain graphical representations which summarise the data you have collected and enable the reader to gain a quick impression of the results of the investigation. Your report should summarise what you have learned from any such graphs (and/or diagrams and charts, if relevant).

This may involve any, or all, of the following:

- discussing the quality and reliability of graphs
- identifying any relationship between the two variables
- if no precise relationship is apparent, describing and explaining any pattern or trend shown by a graph
- quoting values for intercepts and explaining their significance
- calculating gradients and explaining their significance
- calculating areas under graphs and explaining their significance
- identifying and explaining any maxima or minima (and other turning points).

Identify and justify the removal or inclusion of outliers in data

Anomalous readings are values that do not fit the pattern of other readings taken; they should not usually be rejected without being checked. The most common reason for an outlier is a simple error in measurement or recording, which will be evident if the measurement is repeated.

It is rare for an anomalous reading to be confirmed as correct. If this does happen, you should take additional measurements at slightly different values, to try to determine the extent of the anomaly.

If possible, you should try to identify the pattern of the data at the time of the experiment, probably by drawing a rough graph as you take your measurements. This will help you to identify anomalous readings when it is possible to repeat measurements if necessary. (If you do not notice an anomalous reading until you are processing your data, it may not be possible for you to check the measurement.)

Any outliers that have not been checked should be included in your report (and noted as such). You will need to use your judgement as to whether the outlier should affect your conclusions.

Assess accuracy, precision, reliability and validity

Accuracy, errors and precision have been discussed in the Tools section of this reference guide. It is essential that you understand the meaning of these terms:

- An *accurate* measurement is close to its true value. (Remember, however, that in many experiments, the 'true' values are not known, so known uncertainties are often more relevant than unknown accuracy.)
- An *error* has occurred if a measurement is different from its true value. That is, an error refers to inaccuracy (allowing for uncertainty and using a sensible number of significant figures).
- In science, *precise* measurements have low uncertainty. This is, if measurements are repeated, they will produce similar results. Precision is an indication of low uncertainty in measurements (or processed data).

Consider an experiment to determine the thermal conductivity of a certain type of wood. The value obtained by experimentation was 0.093 ± 0.005 W m^{-1} K^{-1}, compared to the 'true' (accepted) value of 0.0973 W m^{-1} K^{-1}. The uncertainty range of the experimental result includes the accepted value, so the experiment may be described as 'accurate'.

If the calculated thermal conductivity was 0.086 ± 0.005 W m^{-1} K^{-1}, you should conclude that either (i) the uncertainty had been underestimated, or (ii) there was an error in the experiment. The calculated result is precise, but inaccurate.

If the calculated thermal conductivity was 0.056 ± 0.050 W m^{-1} K^{-1}, you could reach no reliable conclusion about accuracy.

An experiment (as a whole) can be described as *reliable* if similar conclusions would be reached if it was repeated. A *valid* experiment is one which is relevant to the original research question. It is possible to complete a reliable experiment which is not valid, if your investigation is not relevant to the original question you wanted to answer.

When assessing the accuracy, precision, reliability and validity of your investigation, you must be honest and realistic.

Inquiry 3: Concluding and evaluating

Skill: Concluding

The report of the conclusion of a good quality investigation will have the following characteristics:

- The conclusion will be justified, relevant to the research question and fully consistent with the analysis presented.
- The conclusion will be justified through relevant comparison with the accepted scientific context.

Interpret processed data and analysis to draw and justify conclusions

A conclusion is a generalised statement which summarises what you have learned from your investigation. (This may be different from the interpretation of specific data and/or graphs.) Your conclusion(s) must be consistent with the results of your investigation. Your report should explain the reasoning behind your conclusion(s).

Some investigations will not lead to straightforward scientific conclusions. This may be acceptable, as long as your report explains and analyses the problems that arose during the process.

Compare the outcomes of an investigation to the accepted scientific context

Investigations may attempt to determine numerical values representing the physical properties of certain materials. For example, an investigation might aim to determine the specific heat capacity of concrete, or the thermal conductivity of a plastic.

If such experiments simply repeat techniques with which you are familiar, they are unlikely to offer you the opportunity to show a wide range of expertise. However, if it involves new or challenging techniques, such an investigation could be worthwhile. The results of investigations like this can be compared with data that is available online or in other reference sources. This allows you to assess the true accuracy of your conclusion – something which is not possible in most investigations.

Sometimes, an investigation may be related to broader scientific interests. Your interpretation of the results of such research may support, or contradict, accepted wisdom, and you should comment on any such comparisons in your report.

Relate the outcomes of an investigation to the stated research question or hypothesis

After processing and analysing the data, you should compare your conclusions with the research question and the hypothesis with which your investigation began.

Discuss the impact of uncertainties on the conclusions

We have already discussed the effect of uncertainties on processed data, including graphs. Clearly, the greater the uncertainties in your investigation, the less reliable your conclusions.

Skill: Evaluating

The report of the evaluation of a good quality investigation will have the following characteristics:

- The report explains the relative impact of specific methodological weaknesses or limitations.
- The report explains realistic improvements to the investigation, that are relevant to the identified weaknesses or limitations.

Evaluate hypotheses

After a successful investigation, it should be possible to judge (assess/evaluate) your original hypothesis. Such an evaluation should be included in your report.

Identify and discuss sources and impacts of random and systematic errors

Systematic errors are consistent variations from true values (so that, for example, all of your measurements are too large). Such errors occur because of a repeated mistake in the method used, or a 'zero-offset error' on the measuring instrument.

Ideally, you should identify and correct systematic errors during the course of your investigation. If you do not do this, however, it is often possible to make adjustments after the experiment has finished (if the systematic error has been confirmed).

Random uncertainties (and errors) produce a scattering of values around their mean value. Random uncertainties can only be reduced by using different apparatus and/or methods.

Evaluate the implications of methodological weaknesses, limitations and assumptions on conclusions

After an investigation, whether successful or not, it is usually possible to make some constructive criticisms of the methods and/or apparatus used. Common weaknesses are uncontrolled variables, insufficient data, or measurements not recorded with sufficient precision. You may also need to qualify your conclusion if it is only valid under certain conditions.

Explain realistic and relevant improvements to an investigation

It is possible to suggest improvements for every investigation, although some will be more necessary than others! Any suggested changes to the methodology, or the apparatus, should be sensible given the limits on the apparatus and time available. You should clearly explain the reasons for the suggested improvements.