The Scientific Process

You'll need the skills covered in Topic 1 throughout your course, so make sure you're clear on everything that comes up on the next 12 pages, and can apply it to the physics you meet in the rest of your AS or A-level.

Scientists Come Up with **Theories** — Then **Test Them**...

Science tries to explain **how** and **why** things happen — it **answers questions**. It's all about seeking and gaining **knowledge** about the world around us. Scientists do this by **asking** questions, **suggesting** answers and then **testing** their suggestions to see if they're correct — this is the **scientific process**.

1) **Ask** a question about **why** something happens or **how** something works. E.g. what is the nature of light?
2) **Suggest** an answer, or part of an answer, by forming a **theory** (a possible **explanation** of the observations) — e.g. light is a wave. (Scientists also sometimes form a **model** too — a **simplified picture** of what's physically going on.)
3) Make a **prediction** or **hypothesis** — a **specific testable statement**, based on the theory, about what will happen in a test situation. For example, if light is a wave, it will interfere and diffract when it travels through a small enough gap.
4) Carry out a **test** — to provide **evidence** that will support the prediction (or help to disprove it). E.g. shining light through a diffraction grating to show diffraction and interference (p.84).

The evidence supported Quentin's Theory of Flammable Burps.

A theory is only scientific if it can be tested.

...Then They **Tell** Everyone About Their **Results**...

The results are **published** — scientists need to let others know about their work. Scientists publish their results as reports (similar to the lab write-ups you do in school) written up in **scientific journals**. Scientific journals are just like normal magazines, only they contain **scientific reports** (called papers) instead of the latest celebrity gossip.

1) It's important that the **integrity** (trustworthiness) of the reports published in scientific journals is checked. Scientists (like anyone else) might be **dishonest** or **biased**, or an investigation might have made **invalid** conclusions (see page 13).
2) The report is sent out to **peers** — other scientists that are experts in the **same area**. They examine the data and results, and if they think that the conclusion is reasonable it's **published**. This makes sure that work published in scientific journals is of a **good standard**. This process is known as **peer review**.
3) But peer review **can't guarantee** the science is **correct** — other scientists still need to **reproduce** it.
4) Sometimes **mistakes** are made and bad work is published. Peer review **isn't perfect** but it's probably the best way for scientists to self-regulate their work and to publish **quality reports**.

...Then **Other Scientists** Will **Test** the Theory Too

Other scientists read the published theories and results, and try to **test the theory** themselves. This involves:

- Repeating the **exact same experiments**.
- Using the theory to make **new predictions** and then testing them with **new experiments**.

If the **Evidence** Supports a Theory, It's **Accepted — for Now**

1) If all the experiments in all the world provide good evidence to back it up, the theory is thought of as **scientific 'fact'** (for now).
2) But it will never become **totally indisputable** fact. Scientific **breakthroughs or advances** could provide new ways to question and test the theory, which could lead to **new evidence** that **conflicts** with the current evidence. Then the testing starts all over again...

And this, my friend, is the **tentative nature of scientific knowledge** — it's always **changing** and **evolving**.

The Scientific Process

So scientists need evidence to back up their theories. They get it by carrying out experiments, and when that's not possible they carry out studies.

Evidence *Comes From* ***Controlled Lab Experiments...***

1) Results from **controlled experiments** in **laboratories** are **great**.
2) A lab is the easiest place to **control variables** so that they're all **kept constant** (except for the one you're investigating).

Pages 6-13 are all about how to design and carry out a lab experiment.

...That You can Draw ***Meaningful Conclusions*** *From*

1) You always need to make your experiments as **controlled** as possible so you can be confident that any effects you see are linked to the variable you're changing.
2) If you do find a relationship, you need to be careful what you conclude. You need to decide whether the effect you're seeing is **caused** by changing a variable (this is known as a **causal relationship**), or whether the two are just **correlated**. There's more about drawing conclusions on page 13.

Society ***Makes Decisions*** *Based on* ***Scientific Evidence***

1) Lots of scientific work eventually leads to **important discoveries** or breakthroughs that could **benefit humankind**.
2) These results are **used by society** (that's you, me and everyone else) to **make decisions** — about the way we live, what we eat, what we drive, etc.
3) All sections of society use scientific evidence to make decisions, e.g. politicians use it to devise policies and individuals use science to make decisions about their own lives.

Other factors can **influence** decisions about science or the way science is used:

1) **Economic factors:**
   Society has to consider the **cost** of implementing changes based on scientific conclusions — e.g. the cost of reducing the UK's carbon emissions to limit the human contribution to **climate change**.
   Scientific research is often **expensive**. E.g. in areas such as astronomy, the Government has to **justify** spending money on a new telescope rather than pumping money into, say, the **NHS** or **schools**.
2) **Social factors:**
   Decisions affect **people's lives** — e.g. when looking for a site to build a **nuclear power station**, you need to consider how it would affect the lives of the people in the **surrounding area**.
3) **Environmental factors:**
   Many scientists suggest that building **wind farms** would be a **cheap** and **environmentally friendly** way to generate electricity in the future. But some people think that because **wind turbines** can **harm wildlife** such as birds and bats, other methods of generating electricity should be used.

Practice Questions

Q1 What is peer review?

Q2 Explain why a theory supported by a paper published in a scientific journal is not necessarily scientific 'fact'?

Q3 Explain why considering scientific evidence alone is not enough when making decisions in society.

Exam Question

Q1* A scientist has developed a proposal for a power station which generates electricity renewably from the energy of the tides, without producing greenhouse gases that can lead to climate change. The proposed location of the power station is off a stretch of scenic coastline that attracts a lot of tourism. She claims that her evidence suggests that if built in this location, the power station would produce sufficient electricity to entirely replace a nearby coal-fired power station that uses non-renewable fossil fuels and produces greenhouse gases. Discuss the economic, social and environmental factors that need to be considered by decision-makers considering her proposal. [6 marks]

* The quality of your extended response will be assessed in this question.

No. Borrowing your friend's homework to 'check' it is not peer review...

Hopefully these pages have given you a nice intro to the scientific process, e.g. what scientists do to provide you with 'facts'. You need to understand this, as you're expected to know how science works yourself — for the exam and for life.

Quantities and Units

Learning Physics is a lot like building a house — both involve drinking a lot of tea. Also, both have important foundations — if you skip this stuff everything else is likely to go a bit wrong. So, here goes brick-laying 101...

A *Physical Quantity* has both a *Numerical Value* and a *Unit*

1) Every time you measure or calculate a quantity you need to give the **units**.
2) There are seven **base quantities** from which all the other quantities you'll meet can be **derived**. These other quantities are called **derived quantities**.
3) The **Système International** (SI) includes a set of **base units** for the seven base quantities. The base quantities and their SI base units are:

Quantity	SI base unit
mass	kilogram, kg
length	metre, m
time	second, s
current	ampere, A
temperature	kelvin, K
amount of a substance	mole, mol
luminous intensity	candela, cd

Kilograms are a bit odd — they're the only SI unit with a scaling prefix (see the next page).

You're more likely to see temperatures given in °C.

4) The units for **derived quantities** can be derived from these base units. E.g. **force** is a derived quantity, with the SI derived unit of newtons, N. **1 N** is defined as equivalent to **1 kgms^{-2}**.
5) The derived quantities and SI derived units you'll need will be covered throughout the book and you need to remember them.
6) You also need to have a rough idea of the size of each SI base unit and SI derived unit in this book, so that you can **estimate quantities** using them.

Remembering how SI derived units are defined will help you make sure the other quantities in your equations are in the right units.

Example: A man drops a ball from the first floor window of his house. It takes 1 s to hit the ground. Estimate the average speed of the ball.

A first floor window of a normal house is about 6 m above the ground, so s = 6 m.

speed = distance ÷ time = 6 m ÷ 1 s = 6 ms^{-1}

You Can *Work Out* Derived Units *Mathematically*

The units in any equation must always be the **same on both sides**.
You can use this rule to work out some of the simpler SI derived units, like speed:

Example: Show that the SI derived unit for speed is ms^{-1} (speed = distance ÷ time).

Distance is a length, so its SI base unit is the metre, m. The base unit of time is the second, s.
To find the unit for speed, just put the units for distance and time into the equation for speed: **m ÷ s = ms^{-1}**

Some SI derived units have **special names**, like the newton. You can work out what they're **equivalent** to in **SI base units** using the same method as above.

Example: Charge, Q, is measured in coulombs, C, and given by the equation charge = current × time. What is one coulomb equivalent to in SI base units?

The SI base unit for current is the ampere, A, and the SI base unit for time is the second, s.
Charge = current × time, so 1 C = 1 A × 1 s = **1 As**

Quantities and Units

Prefixes Let You Scale Units

Physical quantities come in a **huge range** of sizes. Prefixes are scaling factors that let you write numbers across this range without having to put everything in standard form.

These are the most common prefixes you'll come across:

prefix	femto (f)	pico (p)	nano (n)	micro (μ)	milli (m)	centi (c)	deci (d)	kilo (k)	mega (M)	giga (G)	tera (T)
multiple of unit	1×10^{-15}	1×10^{-12}	1×10^{-9}	1×10^{-6}	0.001 (1×10^{-3})	0.01 (1×10^{-2})	0.1 (1×10^{-1})	1000 (1×10^{3})	1×10^{6}	1×10^{9}	1×10^{12}

If you're a bit uncertain about moving directly between these scaling factors, then convert quantities into the standard unit before you do anything else with them:

Example 1: Convert 1869 picometres into nanometres.

First, convert the value to metres: 1869 pm = 1869×10^{-12} m

Then divide by 1×10^{-9} to convert to nanometres: $1869 \times 10^{-12} \div 1 \times 10^{-9}$ = **1.869 nm**

Or, you can convert between prefixes directly:

Example 2: Convert 0.247 megawatts into kilowatts.

1 MW = 1×10^{6} W and 1 kW = 1×10^{3} W

So the scaling factor to move between MW and kW is:

$(1 \times 10^{6}) \div (1 \times 10^{3}) = 1 \times 10^{3}$.

So 0.247 MW = $0.247 \times 1 \times 10^{3}$ = **247 kW**

It's really easy to get muddled up when you're converting between prefixes. The rule is, if you're moving to the right in the table above, your number should get smaller, and if you're moving to the left the number should get larger. If your answer doesn't match the rule, you've made a mistake.

Don't use these prefixes in the middle of calculations — they'll change the units of your final answer, and could get you in a mess. You should generally convert to the units you need to use before you do any calculations, or once you've got a final answer.

Practice Questions

Q1 What is meant by a base quantity and a derived quantity?

Q2 What is the SI unit of mass?

Q3 What is meant by an SI base unit and an SI derived unit?

Q4 What is: a) 20 000 W in kilowatts
b) 2×10^{-6} W in milliwatts
c) 1.23×10^{7} W in gigawatts?

Aliona preferred scaling frozen waterfalls.

Exam Question

Q1 The density, ρ, of a material gives its mass per unit volume. It is given by $\rho = m / V$, where m = mass and V = volume.

a) Express the units of density in terms of SI base units. [1 mark]

b) Calculate the density of a cube of mass 9.8 g, and side length 11 mm.
Give your answer in the units stated in part a). [2 marks]

c) A bath tub is filled with water. Given that the density of water is approximately 1000 kg m^{-3}, estimate the mass of the water in the bath tub. [2 marks]

What's the SI base unit for boring...

Not the most exciting pair of pages these, I'll admit, but it's important that you have the basics down, or else you're leaving yourself open to simple little mistakes that'll cost you marks. So make sure you've memorised all the SI base units in the table, then try and write down all the prefixes and their scaling factors. If you don't get them all first time, keep trying until you can. Remember, you need to know the units for every derived quantity you meet in this book, too.

Planning and Implementing

Science is all about getting good evidence to support (or disprove) your theories, so scientists need to be able to spot a badly designed experiment, interpret the results of an experiment or study, and design their own experiments too...

You Might have to **Design an Experiment** to Answer a **Question**

1) You might be asked to design a physics experiment to **investigate** something or answer a question.
2) It could be a **lab experiment** that you've seen before, a **new experiment** you aren't familiar with, or it could be something **applied**, like deciding which building material is best for a particular job.
3) Whatever you're asked, you'll be able to use the physics you know and the skills covered on the next few pages to figure out the best way to do the investigation.

A **Variable** is Anything that has the Potential to **Change** in an Experiment

1) First, you need to identify your **independent** and **dependent variables**:

The **independent** variable is the thing you **change**.
The **dependent** variable is the thing you **measure**.

Example 1: If you're investigating how changing the potential difference across a component affects the current through it, the **independent variable** is the **potential difference**, and the **dependent variable** is the **current**.

2) Apart from the independent and dependent variables, **all other variables** should stay the same during your experiment. If not, you can't tell whether or not the independent variable is responsible for any changes in your dependent variable, so your results won't be **valid** (p.12). This is known as **controlling variables**. It might be worth **measuring control variables** that are likely to change during your experiment to check that they really are under control.

Example 1 (continued): In the example above, you need to use the same **circuit components**, and to keep the **temperature** of the apparatus **constant** — e.g. by letting the circuit cool down between readings.

Example 2: If you're investigating the value of **acceleration due to gravity** by dropping an object and timing its fall, **draughts** in the room could really mess up your results. Picking an object that is more **resistant** to being blown about (like a ball-bearing) will help make your results more **precise** (p.12).

Select Appropriate **Apparatus** and **Techniques**

1) You need to think about what **units** your measurements of the independent and dependent variables are likely to be in before you begin (e.g. millimetres or metres, milliseconds or hours).
2) Think about the **range** you plan on taking measurements over too — e.g. if you're measuring the effect of increasing the force on a spring, you need to know whether you should increase the force in steps of 1 newton, 10 newtons or 100 newtons. Sometimes, you'll be able to **estimate** what effect changing your independent variable will have, or sometimes a **pilot experiment** might help.
3) Considering your measurements before you start will also help you choose the most appropriate **apparatus** and **techniques** for the experiment:

There's a whole range of apparatus and techniques that could come up in your exam. Make sure you know how to use all the ones you've come across in class.

Example:

- If you're measuring the length of a **spring** that you're applying a force to, you might need a **ruler**. If you're measuring the diameter of a **wire**, you'd be better off with a set of **callipers**.
  If the wire **doesn't stretch** easily, you may need to use a **very long wire** to get an extension that's big enough to measure, so you might need to use a **pulley** like in the Young modulus experiment on p.60.
- If you're measuring a **time interval**, you could use a **stopwatch**. If the time is **really short** (for example if you're investigating acceleration due to gravity), you might need something more sensitive, like **light gates**.

4) Whatever apparatus and techniques you use, make sure you use them **correctly**. E.g. if you're measuring a length, make sure your eye is level with the ruler when you take the measurement.
5) While you're planning, you should also think about the **risks** involved in your experiment and how to manage them — e.g. if you're investigating a material that might snap, wear safety goggles to protect your eyes.

Planning and Implementing

Figure Out *how to* ***Record*** *your Data Before you* ***Start***

Before you get going, you'll need a **data table** to record your results in.

P.d. / V	Current / A			
	Trial 1	Trial 2	Trial 3	Average
1.00	0.052	0.047	0.050	0.050
1.50	0.079	0.075	0.077	0.077
2.00	0.303	0.098	0.097	...
2.50	0.129	0.125	0.130	...
3.00	0.149	0.151	0.145	...
...	...	...	...	...

1) It should include space for your **independent variable** and your **dependent variable**. You should specify the **units** in the headers, not within the table itself.
2) The readings of the **independent variable** should be taken at **evenly spaced intervals**.
3) Your table will need enough room for repeated measurements. You should aim to **repeat** each measurement at least **three times**. Taking repeat measurements can reduce the effect of random errors in your results (see p.12) and makes spotting **anomalous** results, like this one, much easier. If there's no way to take repeat readings, then you should **increase** the **total number** of readings that you take.
4) There should be space in your table for any data processing you need to do, e.g. calculating an **average** from repeated measurements, or calculating speed from measurements of distance and time.
5) Most of the time, your data will be **quantitative** (i.e. you'll be recording numerical values). Occasionally, you may have to deal with **qualitative** data (data that can be observed but not measured with a numerical value). It's still best to record this kind of data in a table, to keep your results **organised**, but the layout may be a little **different**.

You Could be Asked to ***Evaluate*** *An* ***Experimental Design***

If you need to evaluate an experimental design, whether it's your own or someone else's, you need to think about these sorts of things:

- Does the experiment **actually test** what it sets out to test?
- Is the method **clear** enough for someone else to follow?
- Apart from the **independent** and **dependent variables**, is everything else going to be **properly controlled**?
- Are the **apparatus** and **techniques appropriate** for what's being measured? Will they be used correctly?
- Are enough **repeated measurements** going to be taken?
- Is the experiment going to be conducted **safely**, for those involved and those **nearby**?
- Are there any other **ethical considerations**? For example, does the experiment produce **harmful waste products**? Is the apparatus being used in a way that won't **damage it**?

Greta was paying the price for not planning her experiment properly.

Practice Questions

Q1 What is meant by the term independent variable? What is a dependent variable?

Q2 Why do you need to plan to control all of the other variables in an experiment?

Q3 What do you need to consider when selecting your apparatus?

Q4 Why should you take repeated measurements in an experiment?

Exam Question

Q1 A student is investigating the effect of the light level on the resistance of an LDR (light-dependent resistor). The student connects the LDR to a power supply, and measures the resistance of the LDR at various distances from a light source using a multimeter.

a) State the independent and dependent variables for this experiment. [1 mark]

b) State two variables that the student needs to control in order to ensure his results are valid. [2 marks]

The best-planned experiments of mice and men...

...often get top marks. The details of planning and carrying out an experiment will vary a lot depending on what you're investigating, but if all this stuff is wedged in your brain you shouldn't go far wrong, so make sure you've got it learned.

Analysing Results

You've planned an experiment, and you've got some results (or you've been given some in your exam). Now it's time to look into them a bit more closely...

Do any **Calculations** You Need to **First**

1) Before you calculate anything, check for any **anomalous results.** If there's something in the results that's **clearly wrong**, then don't include it in your calculations — it'll just **muck everything up**. Be careful though, you should only exclude an anomalous result if you have **good reason** to think it's wrong, e.g. it looks like a decimal point is in the **wrong place**, or you suspect that one of the control variables **changed**. And you should talk about any anomalous results when you're evaluating the experiment (pages 12-13).
2) For most experiments, you'll at least need to calculate the mean (average) of some **repeated measurements**:

$$\text{mean (average) of a measurement} = \frac{\text{sum of your repeated measurements}}{\text{number of repeats taken}}$$

In class, you could use a spreadsheet to process your data (and plot graphs), but it's important that you know how to do it by hand for the exam.

3) Calculate any quantities that you're interested in that you haven't **directly measured** (e.g. pressure, speed).

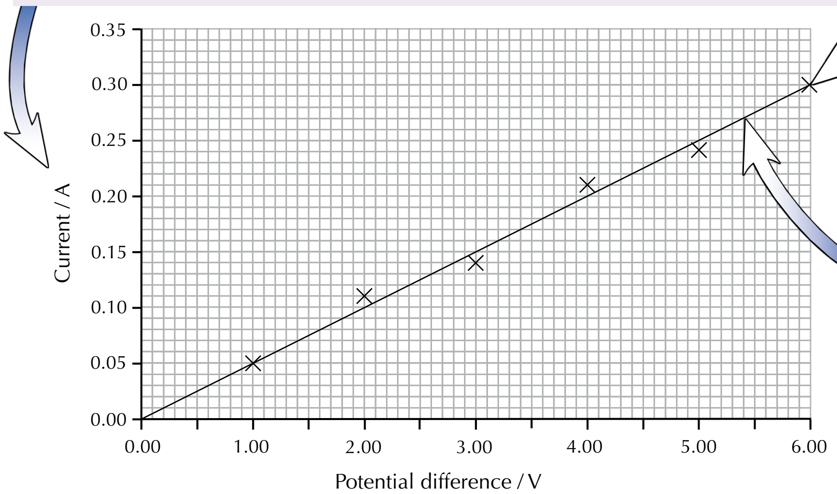
You should try to give any values you calculate to the **same number of significant figures** as the data value with the **fewest significant figures** in your calculation. If you give your result to too many significant figures, you're saying your final result is more **precise** than it actually is (see p.12).

Present Your Results on a **Graph**

Make sure you know how to plot a graph of your results:

If you need to use your graph to measure something, select axes that will let you do this easily (e.g. by measuring the gradient or the intercept, see the next page).

1) Usually, the **independent variable** goes on the ***x*-axis** and the **dependent variable** goes on the ***y*-axis**. Both axes should be **labelled** clearly, with the quantity and **units**. The **scales** used should be sensible (i.e. they should go up in sensible steps, and should spread the data out over the full graph rather than bunching it up in a corner).



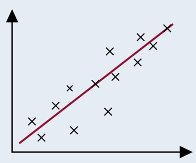
2) Plot your points using a **sharp pencil**, to make sure they're as **accurate** as possible.
3) Draw a **line of best fit** for your results. Around **half** the data points should be above the line, and half should be below it (you should ignore anomalous results). Depending on the data, the line might be **straight**, or **curved**.

Graphs can Show Different Kinds of **Correlation**

The **correlation** describes the relationship between the variables. Data can show:

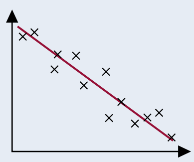
Remember, correlation does not necessarily mean cause — p.3.

Positive correlation:



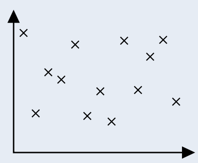
As one variable increases the other increases.

Negative correlation:



As one variable increases the other decreases.

No correlation:



No relationship between the variables.

Analysing Results

You Might Need to Find a **Gradient** or **Intercept**

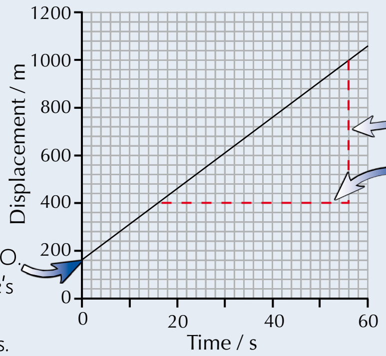
If the line of best fit is **straight**, then the graph is **linear**. This means a change in one always leads to a change in the other.
The **line of best fit** for a linear graph has the **equation**: $\boxed{y = mx + c}$

Where m is the **gradient** of the line and c is the **y-intercept**.

If the line of best fit goes through the origin (c is 0), you can say the variables are **directly proportional** to each other: $\boxed{y \propto x}$

$\propto$ just means 'is directly proportional to'.

Example: This graph shows displacement against time for a motorbike travelling west. Find the bike's velocity.



The y intercept is 160. This means the bike's displacement was 160 m at time 0 s.

For a displacement-time graph, the gradient gives the velocity (as velocity = displacement ÷ time).

$\Delta y = 1000 - 400 = 600$ m

$\Delta x = 56 - 16 = 40$ s

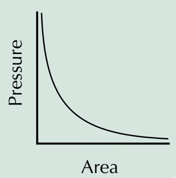
Δ means 'change in'.

$$\text{velocity} = \frac{\text{displacement}}{\text{time}} = \frac{\Delta y}{\Delta x} = 600 \div 40 = \mathbf{15\ ms^{-1}\ west}$$

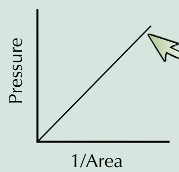
If a graph has a **curved** line of best fit, you can find the gradient of a given point on the line by drawing a **tangent** to the curve (see page 23). It's sometimes helpful to choose axes that turn a curved graph into a straight one:

Example:

For a given force, the graph of **pressure** applied against the **area** that the force is applied over looks like this:



If you plot pressure against **1 ÷ area**, the graph looks like this:



The **gradient** is:
pressure ÷ (1 ÷ area)
= pressure × area
= force applied (p.64)

pressure = force ÷ area.

Practice Questions

Q1 Describe what you should do with anomalous results when processing data.

Q2 How do you calculate an average of repeated results?

Q3 Sketch a graph showing a negative correlation.

Exam Question

Q1 An engineer is investigating the performance of a prototype car with a new kind of environmentally-friendly engine. The data below shows the speed of the car, going from stationary to over 70 kilometres per hour.
(In this question, you may use the formula: acceleration = change in speed ÷ time taken to change speed.)

Time / s	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0
Speed / km per hour	0	3	8	22	40	54	66	70

a) Draw a graph showing speed against time for this data. [4 marks]

b) State the times, to the nearest second, between which the graph is linear. [1 mark]

c) Using the graph, calculate the maximum acceleration of the car. [4 marks]

My level of boredom is proportional to the time I've spent on this page...

This stuff can get a bit fiddly, especially measuring the gradient of a curved line, but for the most part it's not too bad, and you should have seen a lot of it before. So dust off your pencil sharpener, and get to work...

Measurements and Uncertainties

There are errors and uncertainties in every measurement. You need to be aware of them.

All Results have Some *Uncertainty*

The smallest measuring interval on an instrument gives you its resolution.

1) **Every** measurement you take has an **experimental uncertainty**.
2) The smallest uncertainty you can have in a measurement is the uncertainty due to the **resolution** of your equipment. It's ± **half** of one division on the measuring instrument used. E.g. using a thermometer with a scale where each division represents 2 °C, a measurement of 30 °C will at **best** be measured to be 30 **± 1 °C**. And that's without taking into account any other errors that might be in your measurement.
3) The ± sign gives you the **range** in which the **true** length (the one you'd really like to know) probably lies. 30 ± 0.5 cm tells you the true length is very likely to lie in the range of 29.5 to 30.5 cm. The maximum difference between your value and the true value (here 0.5 cm) is sometimes called the **margin of error**.
4) There are two measures of uncertainty you need to know about:

Absolute uncertainty — the **total uncertainty** for a measurement.
Percentage uncertainty — the uncertainty given as a **percentage** of the measurement. Measuring **larger** values reduces the percentage uncertainty.

5) An uncertainty should also include a level of **confidence** or probability, to indicate how **likely** the true value is to lie in the interval. The **more variation** there is in your results, and the **fewer repeats** you have done, the **less confident** you can be.
6) The uncertainty on a **mean** (see p.8) of repeated results is the **largest difference** between the mean and any of the values used to calculate it. So if you take repeated measurements of a current and get values of 0.1 A, 0.4 A and 0.4 A, the mean current is 0.3 A, and the uncertainty on the mean is 0.3 – 0.1 = **± 0.2 A**. You can estimate the uncertainty on the mean as **half the range** — e.g. (0.4 – 0.1) ÷ 2 = **0.15 A**.
7) If no uncertainty is given for a value, the **assumed uncertainty** is **half the increment** of the **last** significant figure that the value is **given** to. E.g. 2.0 is given to 2 **significant figures**, so you would assume an uncertainty of 0.05. You should always assume the **largest** amount of uncertainty when doing an experiment.

Sometimes You Need to *Combine Uncertainties*

You have to combine the uncertainties of different measured values to find the uncertainty of a calculated result:

Adding or *Subtracting* Data — *ADD* the *Absolute Uncertainties*

Example: A wire is stretched from 4.3 ± 0.1 cm to 5.5 ± 0.1 cm. Calculate the extension of the wire.

1) First subtract the lengths without the uncertainty values: 5.5 – 4.3 = 1.2 cm
2) Then find the total uncertainty by adding the individual absolute uncertainties: 0.1 + 0.1 = 0.2 cm
So, the extension of the wire is **1.2 ± 0.2 cm**.

Multiplying or *Dividing* Data — *ADD* the *Percentage Uncertainties*

Example: A force of 15 N ± 3% is applied to a stationary object which has a mass of 6.0 ± 0.3 kg. Calculate the acceleration of the object and state the percentage uncertainty in this value.

1) First calculate the acceleration without uncertainty: $a = F \div m = 15 \div 6.0 = 2.5$ ms^{-2}
2) Next, calculate the percentage uncertainty in the mass: % uncertainty in $m = \frac{0.3}{6.0} \times 100 = 5\%$
3) Add the percentage uncertainties in the force and mass values to find the total uncertainty in the acceleration: Total uncertainty = 3% + 5% = 8%
So, the acceleration = **2.5 ms^{-2} ± 8%**

Raising to a Power — *MULTIPLY* the *Percentage Uncertainty* by the *Power*

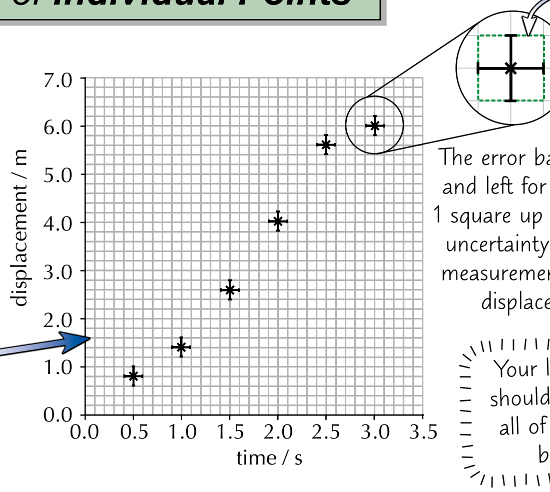
Example: The radius of a circle is r = 40 cm ± 2.5%. Find the percentage uncertainty in the circle's area (πr^2).

The radius is raised to the power of **2** to calculate the area. So, the percentage uncertainty is 2.5% × 2 = **5%**

Measurements and Uncertainties

Error Bars Show the Uncertainty of Individual Points

1) Most of the time, you work out the **uncertainty** in your **final** result using the uncertainty in **each measurement** you make.
2) When you're plotting a **graph**, you can show the uncertainty in **each measurement** by using **error bars** to show the **range** the point is likely to lie in.
3) You can have error bars for just one variable (see below), or **both** the dependent and the independent variable. Error bars on both variables give you an '**error box**' for each point.



This is an 'error box'. The true value of the data point could lie anywhere in this area.

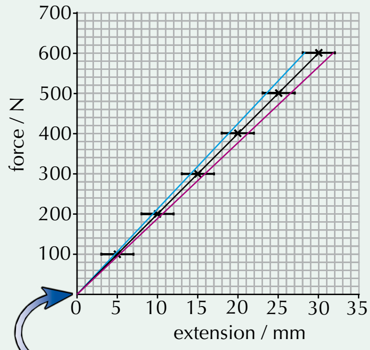
The error bars extend 1 square right and left for each measurement, and 1 square up and down. This gives an uncertainty of ± 0.1 s in each time measurement, and ± 0.2 m in each displacement measurement.

Your line of best fit (p.8) should always go through all of the error bars (see below) or boxes.

You Can Calculate the Uncertainty of Final Results from a Line of Best Fit

Normally when you draw a graph you'll want to find the **gradient** or **intercept** (p.9). For example, you can calculate *k*, the **force constant** of the object being stretched, from the **gradient** of the graph on the right — here it's about 20 000 Nm^{-1}. You can find the **uncertainty** in that value by using **worst lines**:

1) Draw lines of best fit which have the **maximum** and **minimum** possible slopes for the data and which should go through all of the **error bars** (see the pink and blue lines on the right). These are the **worst lines** for your data. If your data has errors in **both** the independent and dependent variables, then the worst lines should go through the **corners** of the **error boxes**.
2) Calculate the **gradients** of the worst lines. The blue line's gradient is about 21 000 Nm^{-1} and the pink line's gradient is about 19 000 Nm^{-1}.
3) The **uncertainty** in the gradient is given by half the **difference** between the **worst gradients** — here it's 1000 Nm^{-1}. So this is the uncertainty in the value of the force constant. For this object, the force constant is 20 000 ± 1000 Nm^{-1} (or 20 000 Nm^{-1} ± 5%).
4) Similarly, the uncertainty in the ***y*-intercept** is just half the **difference** between the **worst** intercepts (although there's no uncertainty here since the worst lines both go through the origin).



When the force is 0 N the extension is 0 mm — this is a measurement with no uncertainty.

Practice Questions

Q1 What is meant by experimental uncertainty? How does it relate to an instrument's resolution?

Q2 What are the rules for combining uncertainties?

Q3 What are worst lines? How could you use them to find the uncertainty in the intercept of a graph?

Exam Question

Q1 A student is investigating the acceleration of a remote controlled car. The car has an initial velocity of 0.52 ± 0.02 ms^{-1} and accelerates to 0.94 ± 0.02 ms^{-1} over an interval of 2.5 ± 0.5 s.

a) Calculate the percentage uncertainty in the car's initial speed. [1 mark]

b) Calculate the percentage uncertainty in the car's final speed. [1 mark]

c) Calculate the car's average acceleration over this interval. Include the absolute uncertainty of the result in your answer. (acceleration = change in velocity ÷ time taken). [4 marks]

My percentage uncertainty about these pages is 0.99%...

Uncertainties are a bit of a pain, but they're really important. Learn the rules for combining uncertainties, and make sure you know how to draw those pesky error bars, and what to do with them when you've got them.

Evaluating and Concluding

Once you've drawn your graphs and analysed your results, you need to think about your conclusions.

Evaluate the *Quality* of *Your Results*


Quality control — also important in construction.

Before you draw any conclusions, you should think about the quality of the results — if the quality's not great you won't be able to have much confidence in your conclusion. Good results are **valid**, **precise**, **repeatable**, **reproducible** and **accurate**.

1) **Valid measurements** measure what they're supposed to be measuring. If you haven't **controlled** all the variables (p.6) then your **results** won't be valid, because you won't just be testing the effect of the independent variable.
2) You can say your results are **precise** if the **range** that your repeated data is spread over is small. The precision of a result is only influenced by **random errors** (see below).
3) Results are **repeatable** if **you** can **repeat** an experiment multiple times and get the **same results**. You can measure the repeatability of your results by looking at their **precision**, and by comparing them to the results of other students in your class who have used exactly the same method and equipment.
4) For a result to be **reproducible**, it needs to be obtained by **different experimenters**, using **different equipment** and **different methods**. Testing whether a result is reproducible is a better test of its quality than testing whether it is repeatable, as it's less likely that the same **systematic errors** could have affected both methods (see below).
5) An **accurate result** is one that's really close to the **true value**. You often **can't know** the accuracy of a result, since you can never know the true value of what you're measuring. The exception to this is if you're measuring a **known constant**, like g, which has been **tested many times**, and is known to a good degree of certainty. In cases like this, you can assess how accurate your results are by **comparing** them to this known value. One way of doing this is by calculating the **percentage difference** — the difference between your result and the true value, expressed as a **percentage** of the **true value**.

You'll Need to Think About Random *and* Systematic Errors

An error is the difference between your **measured value** and the **true value** of whatever you're trying to measure. There are two different kinds of error that could affect the quality of your results — **random errors** and **systematic errors**. You should think about these when you're planning your experiment (so you can minimise them) and when you're evaluating your results.

Systematic Errors

1) **Systematic errors** (including **zero errors**) are the same every time you repeat the experiment (they shift all the values by the same amount). They may be caused by the **equipment** you're using or how it's **set-up**, e.g. not lining up a ruler correctly when measuring the extension of a spring.
2) Systematic errors are really **hard to spot**, and they affect the **accuracy** of your results, but not the **precision** — so it can look like you've measured something **really well**, even if your results are actually **completely off**. Systematic errors might show up when you **compare results** with other people in your class who have done the **same experiment** if they're caused by a mistake you made, or when you compare your results with someone else who used a **different method** if there is something wrong with the procedure itself (i.e. when you check the reproducibility of your results).
3) It's always worth **checking your apparatus** at the start of an experiment, e.g. measure a few known masses to check that a mass balance is **calibrated** properly to make systematic errors less likely.

Random Errors

1) **Random errors** vary — they're what make the results a bit different each time you repeat an experiment. For example, if you measured the length of a wire 20 times, the chances are you'd get a slightly different value each time, e.g. due to your head being in a slightly different position when reading the scale. It could be that you just can't keep controlled variables (p.6) exactly the same throughout the experiment.
2) Unlike systematic errors, you can at least generally tell when random errors are there, as they affect your precision.
3) Using apparatus with a **better resolution** (p.10) can reduce the size of random errors in **individual measurements**.
4) Doing more **repeats** can also reduce the effect of random errors on **calculated results** like the mean (p.8).

Evaluating and Concluding

Draw **Conclusions** that Your Results **Support**

Your conclusion can't be more precise than the margin given by the uncertainty in your results.

1) A conclusion **explains** what the data shows.
   You can only draw a valid conclusion if you have valid data **supporting** it.
2) Your conclusion should be limited to the **circumstances you've tested** it under — if you've been investigating how the current flowing through a resistor changes with the potential difference across it, and have only used potential differences between 0 and 6 V, you can't claim to know what would happen if you used a potential difference of 100 V, or if you used a different resistor.
3) You also need to think about how much you can **believe** your conclusion, by evaluating the quality of your results (see previous page). If you can't believe your results, you can't form a **strong conclusion**.

Think About how the Experiment Could be **Improved**

Having collected the data, is there anything you think should have been done **differently**?
Were there any **limitations** to your method?

1) If the results aren't **valid**, could you change the experiment to fix this, e.g. by changing the data you're collecting?
2) If the results aren't **accurate**, what could have caused this?
   If there are **systematic errors** in your results, what could you do to prevent them?
3) Are there any changes you could make to the **apparatus** or **procedure** that would make the results more **precise**?

- There are some simple ways to reduce **random errors** or their effects (see p.12), including using the most **appropriate** equipment, (e.g. swapping a millimetre ruler for a micrometer to measure the diameter of a wire) and **increasing** the number of **repeats**.
- You can also use a **computer** to collect data — e.g. using light gates to measure a time interval rather than a **stopwatch.** This makes results more **precise** by reducing **human error**.

4) Are there any other ways you could have **reduced the errors** in the measurements?

Practice Questions

Q1 What is a valid result?

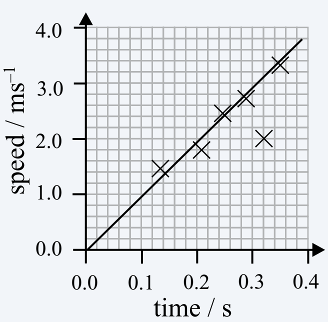
Q2 What is the difference between a repeatable result and a reproducible result?

Q3 What is the difference between saying the results of an experiment are precise and saying that they are accurate?

Q4 Give two examples of possible sources of random error and one example of a possible source of systematic error in an experiment. Which kind of error won't affect the precision of the results?

Q5 What should you think about when you are trying to improve an experimental design?

Exam Question



Q1 A student is investigating how the speed of a falling object is affected by how long it has been falling for. He drops an object from heights between 10 cm and 60 cm and measures its speed at the end of its fall, and the time the fall takes, using light gates. He plots a graph of the final speed of the object against the time it took to fall, as shown on the left.

a) Identify the anomalous result. [1 mark]

b) The student concludes that the speed of any falling object is always proportional to the time it has been falling for.
   Explain whether or not the results support this conclusion. [2 marks]

In conclusion, Physics causes headaches...

Valid, precise, repeatable, reproducible and accurate... you'd think they all mean the same thing, but they really don't. Make sure you know the difference, and are careful about which one you use, or you'll be throwing marks away.