Revision Guide for Chapter 2

Contents

Revision Checklist

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I can show my understanding of effects, ideas and relationships by describing and explaining:

how electric currents are a flow of charged particles *e.g. an electron beam in an X-ray tube, electrons in a metal, electrons and holes in a semiconductor* Revision Notes: electric current and charge, electron beam	
the idea of potential difference in an electric circuit, as energy per unit charge Revision Notes: potential difference Summary Diagrams: Rivers and electric currents	
what resistance and conductance mean Revision Notes: conductance and resistance	
what happens to potential difference and current in circuits with components connected in series and in parallel using the ideas of resistance and conductance as appropriate Revision Notes: parallel circuit, series circuit Summary Diagrams: Conductors in parallel and series, Series and parallel rivers	
what electromotive force (emf) means Revision Notes: electromotive force, see also potential difference	
what is meant by internal resistance and the effect of internal resistance in a circuit Revision Notes: internal resistance Summary Diagrams: Sources and internal resistance	
the idea of power in electric circuits as *energy dissipated or transferred per second* Revision Notes: electrical power	
the relation between current and potential difference in ohmic resistors *i.e. resistors which follow Ohm's law so that the ratio V / I stays the same when external conditions (such as temperature) stay the same* Revision Notes: Ohm's law, non-ohmic conductors	
the action of a potential divider *e.g. in sensor applications such as to sense position or angle, reduce a potential difference, produce a potential difference from a change in resistance* Revision Notes: potential divider	

I can use the following words and phrases accurately:

with reference to electric circuits: *emf, potential difference, current, charge, resistance, conductance, series, parallel, internal resistance, load* Revision Notes: electric current and charge, potential difference, conductance and resistance, parallel circuit, series circuit, electromotive force, internal resistance	
with reference to instrumentation: *resolution, sensitivity, stability, response time, calibration, systematic error, zero error* Revision Notes: resolution, sensitivity, response time, systematic error, random variation	

I can sketch and interpret:

simple circuit diagrams Revision Notes: parallel circuit, series circuit, potential divider	
graphs of current against potential difference; graphs of resistance or conductance against temperature Revision Notes: Ohm's law, non-ohmic conductors	

I can calculate:

the conductance G of a circuit or a component using the relationship $G = I / V$ and rearrange the equation to calculate other quantities Revision Notes: conductance and resistance	
the resistance R of a circuit or a component using the relationship $R = V / I$ and rearrange the equation to calculate other quantities Revision Notes: conductance and resistance	
charge flow in a circuit or component using the relationships $Q = I\ t$, $Q = W / V$ and rearrange the equations to calculate other quantities Revision Notes: electric current and charge, potential difference, electrical power	
current, circuit resistance and potential differences in series circuits using the resistances of components *e.g. total resistance = sum of component resistances* Revision Notes: conductance and resistance, series circuit	
currents, circuit resistance and potential differences in parallel circuits using the conductances of components *e.g. total conductance = sum of component conductances* Revision Notes: conductance and resistance, parallel circuit	
the power dissipated in a circuit using the relationship $P = I\ V$ and rearrange the equation to calculate other quantities Revision Notes: electrical power	
power, current, resistance and potential difference in circuits and components using the relationships $P = I^2 R$, $P = V^2 / R$ and rearrange the equations to	

calculate other quantities Revision Notes: electrical power	
energy dissipated in a circuit $W = V I t$ Revision Notes: electrical power	
current, potential difference and resistance in circuits with internal resistance, e.g. using the relationships $V = \varepsilon - I r_{internal}$ and $V = I R_{load}$ and rearrange the formulae to calculate other quantities Revision Notes: potential difference, electromotive force, internal resistance	
the effects produced by potential dividers in a circuit *e.g. when an LDR or thermistor is used in a sensing application* Revision Notes: potential divider	

I can show my ability to make better measurements by:

identifying and estimating the largest source of uncertainty in measurements with sensors and electrical instruments Revision Notes: accuracy and precision, uncertainty	
taking account of properties of sensors and instruments: resolution, sensitivity, stability, response time, and calibration, systematic and zero error Revision Notes: resolution, sensitivity, response time, calibration, uncertainty, systematic error	
using dot-plots or histograms of repeated measurements to estimate mean and range of values, and identify possible outliers Revision Notes: random variation, uncertainty	
plotting graphs including uncertainty bars, using them to estimate uncertainty in gradient or intercept Revision Notes: uncertainty, graphs	
considering ways to reduce the largest source of uncertainty in an experiment Revision Notes: accuracy and precision, uncertainty	

I can show an appreciation of the growth and use of scientific knowledge:

giving examples of and commenting on the applications of sensors Revision Notes: sensor	

Revision Notes

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Electric current and charge

Electric current is charge flow per unit time:

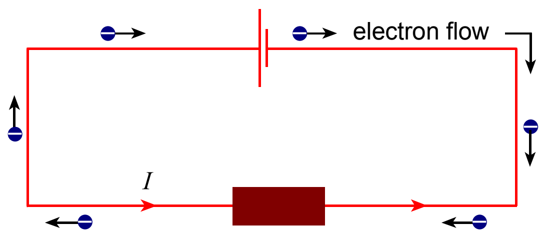
$$I = \frac{\Delta Q}{\Delta t}$$

where I is current and ΔQ is the charge flow in time Δt.

The SI unit of electric current is the ampere (symbol A). The SI unit of charge is the coulomb (symbol C). One coulomb passes a point in a circuit each second when the current is one ampere.

The direction of electric current is conventionally shown as from positive to negative, which is the direction in which positively charged particles would flow. Long after the convention was established, it was discovered that the carriers most often responsible for electric currents, electrons, are negatively charged. Electrons therefore flow in a circuit from negative to positive.

Current and charge



charge passing through in time t, $Q = It$

An electric current is a flow of charge carriers. Thus a beam of electrons in an X-ray set carries a current, as does a beam of moving ions.

Conduction in metals is due to the movement of conduction electrons. These are electrons that are free to move through the metal because they are not bound to any one ion in the metal.

With no potential difference across the conductor, charge carriers move about at random. Under a potential difference, the charge carriers drift along the conductor.

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Electron beam

Electron beams are used in television and x-ray tubes, VDU tubes and oscilloscopes.

An electron beam is usually produced in a vacuum tube by thermionic emission from a heated cathode. The electrons are accelerated from the cathode to an anode by a potential difference. The anode has a small hole in it which allows some electrons through. These electrons are then focused into a beam by further electrodes or coils.

An electron beam is usually controlled using electric and magnetic fields. The kinetic energy and speed of an electron in an electron beam depend on the anode potential V_A as the work done on each electron by the anode gives the electron its kinetic energy. Since the work done = eV_A, the kinetic energy of an electron in the beam is equal to eV_A. Provided the speed v of the electron is much less than the speed of light, its kinetic energy = (1/2) $m\,v^2$, therefore

$$\frac{1}{2} m\,v^2 = eV_A .$$

The electrons in the beam have a small range of speeds because they are emitted from the cathode with a range of energies. But to a good approximation, all the electrons in the same beam have the same kinetic energy and speed and are therefore equally deflected by electric and magnetic fields. This makes sharp focusing possible.

In an oscilloscope tube, the beam is made to scan repeatedly along the same line, slowly in one direction then much more rapidly on return. A voltage waveform is displayed on the screen as a result of applying the voltage across a pair of parallel plates through which the beam passes.

Magnetic deflecting coils are used to control the beam in a TV, x-ray or VDU tube. The current in the coil is varied to alter the magnetic field strength as desired and so drive the electron beam across the screen as required.

Relationships

Kinetic energy of electron (1/2) $mv^2 = eV$, if its speed is much less than the speed of light.

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Potential difference

The potential drop across a component in an electrical circuit is like the pressure drop between the inlet and outlet of a radiator in a central heating system. The pressure difference drives water through the radiator. In the same way, a potential difference exists across the terminals of a component in an electric circuit, and drives a flow of charge through it. Potential difference is measured using a voltmeter.

The potential difference between two points is the energy gained or lost per unit charge by a small positive charge when it moves from one point to the other. The abbreviation 'p.d.' may be used in place of 'potential difference'. In speech, the word 'voltage' is commonly used. The potential drop across a component is the energy delivered per unit charge when a small charge passes through the component.

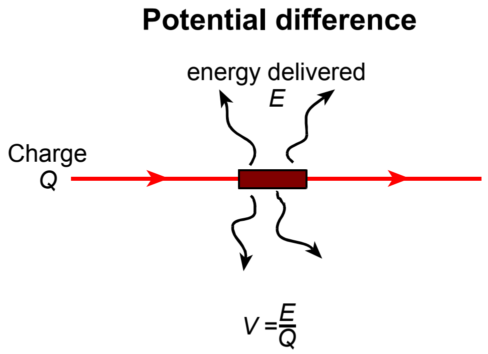
The SI unit of potential difference is the volt (V). 1 volt = 1 joule per coulomb.

Relationships

Potential difference

$$V \quad \frac{E}{Q}$$

where E is the energy delivered and Q is the charge passed.



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Conductance and resistance

Conductance is a measure of how well a component in a circuit conducts electricity. Conductance is defined as

$$G = \frac{\text{current}}{\text{potential difference}} = \frac{I}{V}$$

The symbol for conductance is *G*. The SI unit of conductance is the siemens (symbol S), equivalent to A V $^{-1}$. One siemens is the conductance of a conductor through which the current is one ampere when the potential difference across it is one volt.

The conductance of a sample of material depends on the number of charge carriers present and on how easily the carriers move through the material.

Resistance is a measure of how badly a component in a circuit conducts electricity. Resistance is defined as:

$$R = \frac{\text{potential difference}}{\text{current}} = \frac{V}{I}$$

The symbol for resistance is *R*. The SI unit of resistance is the ohm (symbol Ω), equivalent to V A^{-1}.

Thus conductance and resistance are simply alternative ways of describing the same thing. Each is the reciprocal of the other.

$$G = \frac{1}{R} \text{ and } R = \frac{1}{G}$$

The choice of which to use is a matter of convenience. Perhaps conductance is rather more fundamental, expressing effect (current) per unit of cause (potential difference). The term resistance unfortunately suggests that a conductor 'fights' the flow of current, when in fact the flow is mainly determined simply by whether or not there are any mobile charge carriers.

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Parallel circuit

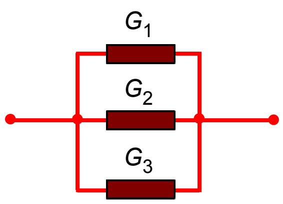
In a parallel circuit, charge flows from one point to another along alternative paths.

Circuit rules:
1. The potential difference across components in parallel is the same for each component.
2. The current through a parallel combination is equal to the sum of the currents through the individual components.

Components in parallel can be switched on or off independently by a switch in series with each component. For example, appliances connected to a ring main circuit are in parallel with each other between the live and the neutral wires of the ring main. This is so they can be switched on or off without affecting each other. Light sockets connected to a lighting circuit are also connected in parallel with each other so they can be switched on or off independently.

Where two or more components are in parallel with one another in a d.c. circuit, the current is greatest in the component with the highest conductance. The potential difference is the same across each component and the total current entering the combination is the sum of the individual currents. Since conductance is proportional to current, the total conductance of the combination is therefore the sum of the individual conductances for components in parallel.

Conductance in parallel



Combined conductance

$G = G_1 + G_2 + G_3$

Since $G=1/R$ this can also be written:

$1 / R = 1 / R_1 + 1 / R_2 + 1 / R_3$

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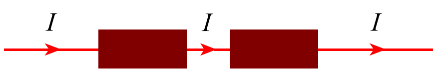
Series circuit

In a series circuit, charge flows along one path through every component in sequence. Thus the whole current passes through each component.

Circuit rules:
1. The current through components in series is the same for each component.
2. The potential difference across a series combination is equal to the sum of the potential differences across the individual components.

The current passing through two or more components in series is the same because the electrons pass through each component in turn.

Resistors in series



Components in series are all switched on or off together by a single switch in series with the components. A fuse in a plug is always in the live wire in series with the appliance element or motor so that the appliance is disconnected from the live wire if the fuse blows.

For two or more resistors R_1, R_2, R_3, etc in series their combined resistance $R = R_1 + R_2 + R_3$.

Because $R = 1/G$ their combined conductance G is given by $1 / G = 1 / G_1 + 1 / G_2 + 1 / G_3$.

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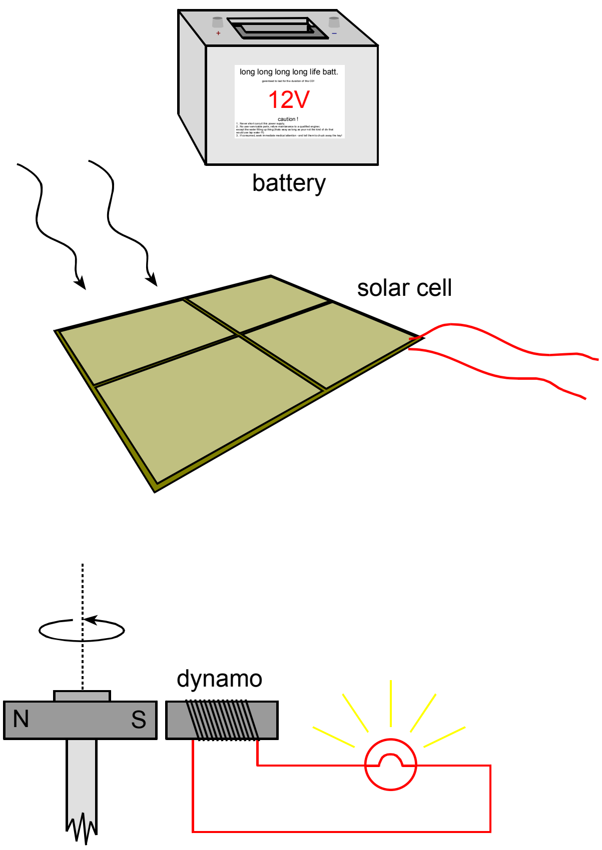
Electromotive force (emf)

Electromotive force (abbreviated to emf) is the energy a source can provide for every coulomb of charge flowing round a circuit. It is equal to the work done per unit charge, when a small positive charge goes round the whole circuit.

The SI unit of emf is the volt (symbol V). A source with an emf of one volt provides one joule of energy for every coulomb of charge flowing round a circuit.

Electrical sources of energy include batteries, solar cells, thermocouples and dynamos.

Sources of emf



Relationships

1. Electromotive force ε = energy provided / charge delivering this amount of energy.
2. Energy E provided by a source is given by $E = \Delta Q\, \varepsilon$ where ε is the source emf and ΔQ is the charge delivered.

3. Since the charge passing through a source in time Δt is $\Delta Q = I\,\Delta t$, where I is the current, then the energy provided $E = I\,\Delta t\;\varepsilon$.

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Internal resistance

Internal resistance is the resistance internal to a source of emf.

The energy provided by a source is delivered to the components of the circuit by charge flowing round the circuit. Some of this energy is dissipated inside the source due to the source's internal resistance. This causes the potential difference across the terminals of the source to be less than the emf of the source.

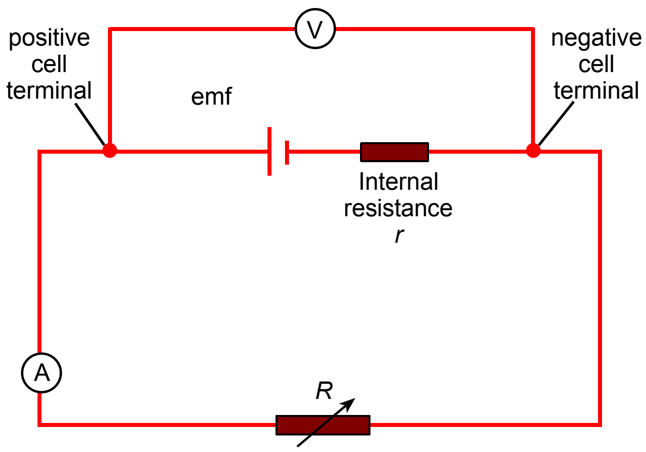
The lost p.d. in the source is the energy dissipated per unit charge inside the source due to its internal resistance. The lost p.d. depends on the current and on the internal resistance of the source.

For a source of emf ε with internal resistance r connected to a load of resistance R, as shown in the circuit below

$\varepsilon = I\,R + I\,r$

where IR is the potential difference across the load resistance and Ir is the lost p.d.

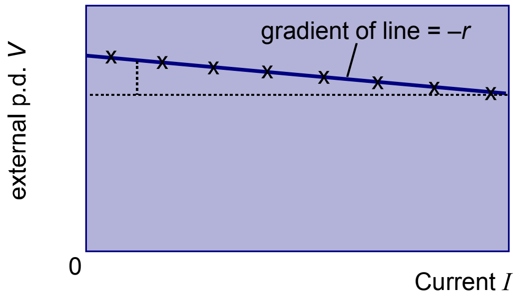
Measuring internal resistance



The external p.d. $V = I\,R = \varepsilon - Ir$. The graph below shows how the external p.d. V varies with the current drawn. This graph has a gradient $-r$ and a y-intercept equal to ε.

Note that the p.d. V falls as the current increases. This is why the output potential difference of an electrical source of energy (including a power supply unit) falls if more current is drawn from the source. The headlights of a car often dim for a moment as you operate the starter motor.

Results



Relationships

$\varepsilon = I R + I r$

$V = \varepsilon - Ir$

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Electrical power

Electrical power is the rate at which energy is provided by an electrical supply or used by an electrical appliance.

The SI unit of power is the watt (symbol W). One watt is a rate of transfer of energy of one joule per second.

1 kilowatt = 1000 watts.

Mains electricity is priced in kilowatt hours (kW h) where 1 kW h is the energy delivered in 1 hour at a rate of 1 kilowatt. Note that 1 kW h = 3.6 MJ.

The equation power = current × potential difference follows from two facts:

1. Current is charge per second flowing through the component or device.
2. Potential difference is the energy delivered per unit charge to the component or device.

Therefore:

$$\text{current} \times \text{potential difference} = \frac{\text{charge}}{\text{time}} \times \frac{\text{energy}}{\text{charge}} = \frac{\text{energy}}{\text{time}} = \text{power}$$

Relationships

$P = I V$

Since $V = I R$ then also:

$P = I^2R$

Alternatively, since $I = V/R$ then:

$P = V^2/R$

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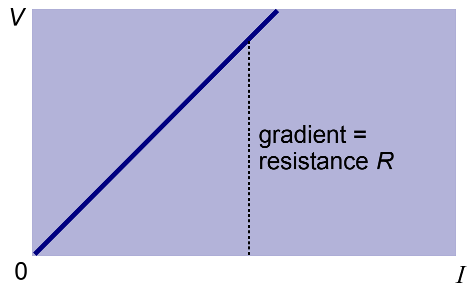
Ohm's law
Ohm's law states that the current through a conductor is proportional to the potential difference across it, provided that other physical conditions, notably temperature, are constant.

Many conductors do not obey Ohm's law. Materials that do obey Ohm's law, including many metallic conductors, are called 'ohmic conductors'.

A graph of potential difference against current for an ohmic conductor is shown below. The graph is linear and passes through the origin. That is, the current is directly proportional to the potential difference. The gradient of the straight line is equal to the resistance of the conductor. Thus the resistance of an ohmic conductor is independent of the current.

V-I for a wire



The relationship $R = V / I$ is used to calculate the resistance at any current (or p.d.), whether the conductor is ohmic or not. If the resistance R is constant, the graph is linear and passes through the origin, and the conductor is ohmic. Thus for an ohmic conductor, the resistance R is equal to the constant slope of the graph of V against I.

Relationships
$R = V / I$ whether the conductor is ohmic or not (R not necessarily constant).

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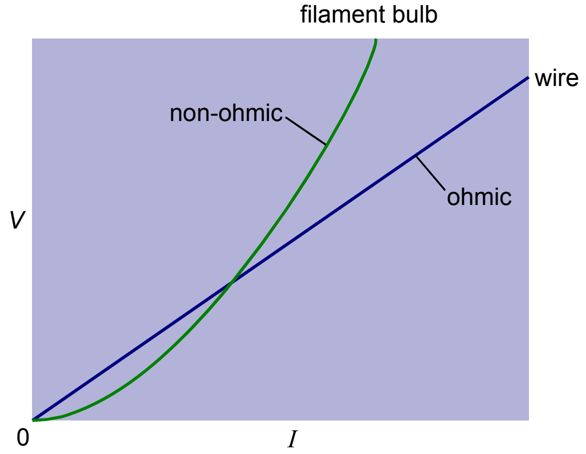
Non-ohmic conductors
An ohmic conductor (e.g. a metal wire at constant temperature) is a conductor that obeys Ohm's law. The graph of potential difference (on the *y*-axis) against current for the resistor is linear and passes through the origin, so its resistance is constant.

By contrast, a filament lamp's resistance increases as the current increases so the filament lamp is non-ohmic. The resistance increases because the filament gets hot. This is because as the temperature increases, the conduction electrons become less mobile, due to increased scattering from vibrations of the lattice of atoms.

Ohmic and non-ohmic conductors



A neon lamp is another example of a non-ohmic conductor. It does not obey Ohm's law because as the p.d. increases, ions get enough energy to ionise more atoms by collision, so increasing the supply of charge carriers and increasing the conductance.

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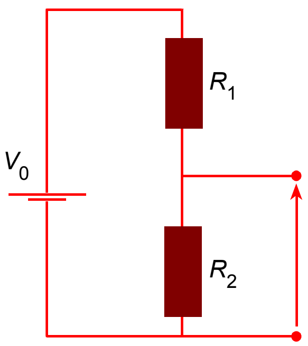
Potential divider

A potential divider consists of two (or more) resistors in series connected to a power supply or battery, as shown below. The resistances of the resistors are chosen so that the potential difference from the power supply is shared by (or 'divided between') the resistors as required.

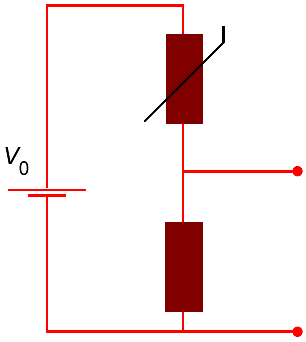
A potential divider



$$V_2 = \frac{R_2}{R_1 + R_2} V_0$$

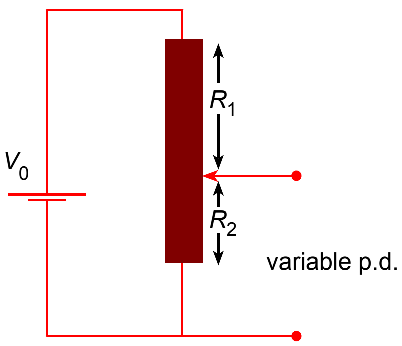
A temperature sensor can consist of a potential divider with one of its resistors replaced by a thermistor, as shown below. When the temperature changes, the potential difference across the fixed resistance changes. This change of potential difference can be used to activate an electronic system such as an alarm circuit.

Using a thermistor



A **potentiometer** is a potential divider that can be used to supply a variable potential difference. Resistors R_1 and R_2 are sections of a single uniform resistance wire or track divided by a sliding contact. By moving the contact along the wire, the ratio of R_1 to R_2 is changed. A fixed potential difference is applied between the ends of the wire so that the potential difference between the sliding contact and either end can be changed smoothly by moving the contact along the track.

potentiometer



Relationships
For a potential divider consisting of two resistors R_1 and R_2 connected as above to a power supply with an output potential difference V_0, the potential difference V_1 across R_1 is given by:

$$V_1 \quad \frac{R_1}{R_1 \quad R_2} V_0$$

and the potential difference V_2 across R_2 is given by:

$$V_2 \quad \frac{R_2}{R_1 \quad R_2} V_0$$

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Resolution

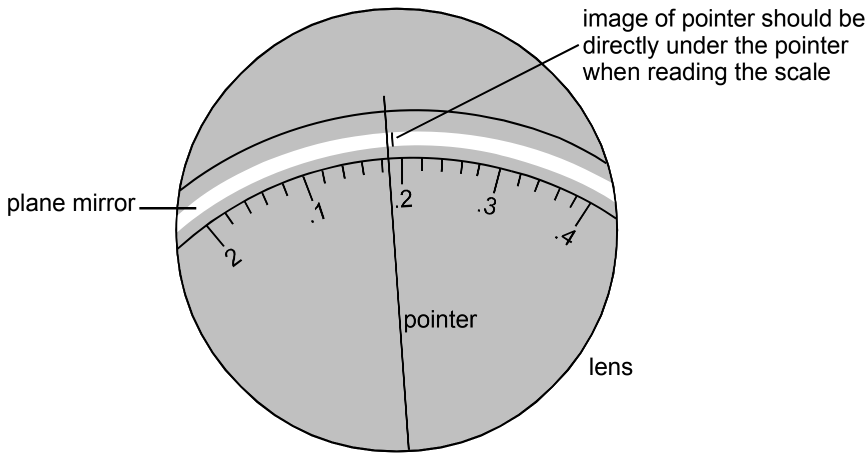
The term resolution can apply to both instruments and images.

The resolution of an instrument is the smallest change of the input that can be detected at the output.

The output of a digital instrument is a numerical display. The resolution is the smallest change of input the instrument can display. For example, a digital voltmeter that gives a three-digit read-out such as 1.35 V has a resolution of 0.01 V since the smallest change in p.d. it can display is 0.01 V.

For an analogue instrument, the output is the position of a pointer on a scale. Its resolution is the smallest change in input that can be detected as a movement of the pointer. The resolution of an analogue instrument can be improved using a magnifying lens to observe movement of the pointer.

Reading a scale



The resolution of an image is the scale of the smallest detail that can be distinguished. The size of the pixels sets a limit to the resolution of a digital image. In an ultrasound system, the pixel dimensions may correspond to about one millimetre in the object imaged. A high-quality CCD may have an array about 10 mm × 10 mm consisting of more than 2000 × 2000 light-sensitive elements, each about 5 μm in width. In a big close-up picture of a face 200 mm across, the width of each pixel would correspond to 1 / 10 mm in the object photographed.

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Sensitivity

The sensitivity of a measuring instrument is the change of its output divided by the corresponding change in input.

A temperature sensor whose output changes by 100 mV for a change of 2 K in its input has a sensitivity of 50 mV per kelvin.

A silicon photocell with an output of 500 mV when illuminated by light of intensity 1000 lux has a sensitivity of 0.5 mV per lux.

A very sensitive instrument gives a large change of output for a given change of input.

In a linear instrument, the change of output is directly proportional to the change of the input. Thus a graph of output against input would be a straight line through the origin. The gradient of the line is equal to the sensitivity, which is constant. Thus a linear instrument has a sensitivity that is independent of the input.

If the change of output is not proportional to the change of the input, the graph would be a curve. In this case, the sensitivity would vary with input. Many instruments, such as light meters, have a logarithmic dependence of output on light input.

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Response time

Response time is the time taken by a system to change after a signal initiates the change.

In a **temperature-control system**, the response time is the time taken for the system to respond after its temperature changes. For example, a home heating system with a response time that is too long would not start to warm the building as soon as its temperature fell below the desired level.

In an electronic measuring instrument, the response time is the time taken by the instrument to give a reading following a change in its input. If the response time is too long, the instrument would not measure changing inputs reliably. If the response time is too short, the instrument might respond to unwanted changes in input.

Reasons for slow response times include the inertia of moving parts and the thermal capacity of temperature sensors.

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Systematic error

Systematic error is any error that biases a measurement away from the true value.

All measurements are prone to systematic error. A systematic error is any biasing effect, in the environment, methods of observation or instruments used, which introduces error into an experiment. For example, the length of a pendulum will be in error if slight movement of the support, which effectively lengthens the string, is not prevented, or allowed for.

Incorrect zeroing of an instrument leading to a **zero error** is an example of systematic error in instrumentation. It is important to check the zero reading during an experiment as well as at the start.

Systematic errors can change during an experiment. In this case, measurements show trends with time rather than varying randomly about a mean. The instrument is said to show **drift** (e.g. if it warms up while being used).

Systematic errors can be reduced by checking instruments against known standards. They can also be detected by measuring already known quantities.

The problem with a systematic error is that you may not know how big it is, or even that it exists. The history of physics is littered with examples of undetected systematic errors. The only way to deal with a systematic error is to identify its cause and either calculate it and remove it, or do a better measurement which eliminates or reduces it.

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Random variation

Random variation has to do with small unpredictable variations in quantities.

Truly random variation may be rather rare. However, variations due to a number of minor and unrelated causes often combine to produce a result that appears to vary randomly.

Random variation can be due to uncontrollable changes in the apparatus or the environment or due to poor technique on the part of an observer. They can be reduced by redesigning the apparatus or by controlling the environment (e.g. the temperature). Even so, random variation can still remain. The experimenter then needs to use the extent of such variation to assess the range within which the true result may reasonably be believed to lie.

First, accidental variations with known causes need to have been eliminated, and known systematic errors should have been allowed for. Then, variations of measurements around an average value are often treated as random.

The simplest approach is to suppose that the true result lies somewhere in the range covered by the random variation. This is a bit pessimistic, since it is more likely that the true result lies fairly near the middle of the range than near the extremes.

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Accuracy and precision

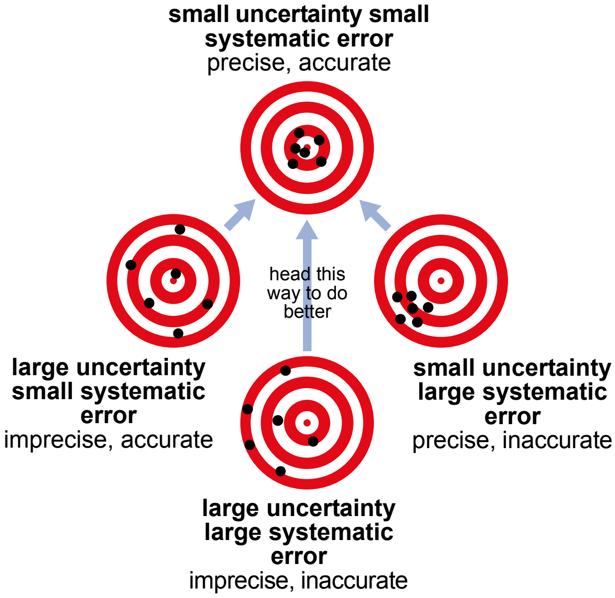
A measurement is accurate if it is close to the true value. A measurement is precise if values cluster closely, with small uncertainty.

A watch with an accuracy of 0.1% could be up to five minutes astray within a few days of being set. A space probe with a trajectory accurate to 0.01 % could be more than 30 km off target at the Moon.

Think of the true value as like the bullseye on a target, and measurements as like arrows or darts aimed at the bullseye.

Uncertainty and systematic error

Think of measurements as shots on a target. Imagine the 'true value' is at the centre of the target



An accurate set of measurements is like a set of hits that centre on the bullseye. In the diagram above at the top, the hits also cluster close together. The uncertainty is small. This is a measurement that gives the true result rather precisely.

On the left, the accuracy is still good (the hits centre on the bullseye) but they are more scattered. The uncertainty is higher. This is a measurement where the average still gives the true result, but that result is not known very precisely.

On the right, the hits are all away from the bullseye, so the accuracy is poor. But they cluster close together, so the uncertainty is low. This is a measurement that has a systematic error, giving a result different from the true result, but where other variations are small.

Finally, at the bottom, the accuracy is poor (systematic error) and the uncertainty is large.

A statement of the result of a measurement needs to contain two distinct estimates:

1. The best available estimate of the value being measured.
2. The best available estimate of the range within which the true value lies.

Note that both are statements of belief based on evidence, not of fact.

For example, a few years ago discussion of the 'age-scale' of the Universe put it at 14 plus or minus 2 thousand million years. Earlier estimates gave considerably smaller values but with larger ranges of uncertainty. The current (2008) estimate is 13.7 ± 0.2 Gy. This new value lies within the range of uncertainty for the previous value, so physicists think the estimate has been improved in precision but has not fundamentally changed.

Fundamental physical constants such as the charge of the electron have been measured to an astonishing small uncertainty. For example, the charge of the electron is $1.602\,173\,335 \times 10^{-19}$ C to an uncertainty of $0.000\,000\,005 \times 10^{-19}$ C, better than nine significant figures.

There are several different reasons why a recorded result may differ from the true value:

1. **Constant systematic bias**, such as a zero error in an instrument, or an effect which has not been allowed for.

   Constant systematic errors are very difficult to deal with, because their effects are only observable if they can be removed. To remove systematic error is simply to do a better experiment. A clock running slow or fast is an example of systematic instrument error. The effect of temperature on the resistance of a strain gauge is an example of systematic experimental error.

2. **Varying systematic bias**, or drift, in which the behaviour of an instrument changes with time, or an outside influence changes.

   Drift in the sensitivity of an instrument, such as an oscilloscope, is quite common in electronic instrumentation. It can be detected if measured values show a systematic variation with time. Another example: the measured values of the speed of light in a pipe buried in the ground varied regularly twice a day. The cause was traced to the tide coming in on the nearby sea-shore, and compressing the ground, shortening the pipe a little.

3. **Limited resolution of an instrument**. For example the reading of a digital voltmeter may change from say 1.25 V to 1.26 V with no intermediate values. The true potential difference lies in the 0.01 V range 1.25 V to 1.26 V.

   All instruments have limited resolution: the smallest change in input which can be detected. Even if all of a set of repeated readings are the same, the true value is not exactly equal to the recorded value. It lies somewhere between the two nearest values which can be distinguished.

4. **Accidental momentary effects**, such as a 'spike' in an electrical supply, or something hitting the apparatus, which produce isolated wrong values, or 'outliers'.

   Accidental momentary errors, caused by some untoward event, are very common. They can often be traced by identifying results that are very different from others, or which depart from a general trend. The only remedy is to repeat them, discarding them if further measurements strongly suggest that they are wrong. Such values should never be included in any average of measurements, or be used when fitting a line or curve.

5. **Human errors**, such as misreading an instrument, which produce isolated false recorded values.

Human errors in reading or recording data do occur, such as placing a decimal point wrongly, or using the wrong scale of an instrument. They can often be identified by noticing the kinds of mistake it is easy to make. They should be removed from the data, replacing them by repeated check observations.

6. **Random fluctuations**, for example noise in a signal, or the combined effect of many unconnected minor sources of variation, which alter the measured value unpredictably from moment to moment.

   Truly random variations in measurements are rather rare, though a number of unconnected small influences on the experiment may have a net effect similar to random variation. But because there are well worked out mathematical methods for dealing with random variations, much emphasis is often given to them in discussion of the estimation of the uncertainty of a measurement. These methods can usually safely be used when inspection of the data suggests that variations around an average or a fitted line or curve are small and unsystematic. It is important to look at visual plots of the variations in data before deciding how to estimate uncertainties.

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Uncertainty

The uncertainty of an experimental result is the range of values within which the true value may reasonably be believed to lie. To estimate the uncertainty, the following steps are needed.

1. Removing from the data **outlying** values which are reasonably suspected of being in serious error, for example because of human error in recording them correctly, or because of an unusual external influence, such as a sudden change of supply voltage. Such values should not be included in any later averaging of results or attempts to fit a line or curve to relationships between measurements.
2. Estimating the possible magnitude of any **systematic error**. An example of a constant systematic error is the increase in the effective length of a pendulum because the string's support is able to move a little as the pendulum swings. The sign of the error is known (in effect increasing the length) and it may be possible to set an upper limit on its magnitude by observation. Analysis of such systematic errors points the way to improving the experiment.
3. Assessing the **resolution** of each instrument involved, that is, the smallest change it can detect. Measurements from it cannot be known to less than the range of values it does not distinguish.
4. Assessing the magnitude of other small, possibly random, unknown effects on each measured quantity, which may include human factors such as varying speed of reaction. Evidence of this may come from the spread of values of the measurement conducted under what are as far as possible identical conditions. The purpose of repeating measurements is to decide how far it appears to be possible to hold conditions identical.
5. Determining the combined effect of possible **uncertainty** in the result due to the limited resolution of instruments (3 above) and uncontrollable variation (4 above).

To improve a measurement, it is essential to identify the largest source of uncertainty. This tells you where to invest effort to reduce the uncertainty of the result.

Having eliminated accidental errors, and allowed for systematic errors, the range of values within which the true result may be believed to lie can be estimated from (a) consideration of the resolution of the instruments involved and (b) evidence from repeated measurements of the variability of measured values.

Most experiments involve measurements of more than one physical quantity, which are combined to obtain the final result. For example, the length L and time of swing T of a simple pendulum may be used to determine the local acceleration of free fall, g , using

$$T = 2\pi\sqrt{\frac{L}{g}}$$

so that

$$g = \frac{4\pi^2 L}{T^2}.$$

The range in which the value of each quantity may lie needs to be estimated. To do so, first consider the resolution of the instrument involved – say ruler and stopwatch. The uncertainty of a single measurement cannot be better than the resolution of the instrument. But it may be worse. Repeated measurements under supposedly the same conditions may show small and perhaps random variations.

If you have repeated measurements, 'plot and look', to see how the values vary. A simple estimate of the variation is the $\text{spread} = \pm\frac{1}{2}\,\text{range}$.

A simple way to see the effect of uncertainties in each measured quantity on the final result is to recalculate the final result, but adding or subtracting from the values of variables the maximum possible variation of each about its central value. This is pessimistic because it is unlikely that 'worst case' values all occur together. However, pessimism may well be the best policy: physicists have historically tended to underestimate uncertainties rather than overestimate them. The range within which the value of a quantity may reasonably be believed to lie may be reduced somewhat by making many equivalent measurements, and averaging them. If there are N independent but equivalent measurements, with range R, then the range of their average is likely to be approximately R divided by the factor $\sqrt{N}$. These benefits are not automatic, because in collecting many measurements conditions may vary.

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Calibration

A measuring instrument needs to be calibrated to make sure its readings are accurate.

Calibration determines the relation between the input and the output of an instrument. This is done by measuring known quantities, or by comparison with an already calibrated instrument. For example, an electronic top pan balance is calibrated by using precisely known masses. If the readings differ from what they should be, then the instrument needs to be recalibrated.

Important terms used in the calibration of an instrument include:

The **zero reading** which should be zero when the quantity to be measured is zero. Electrical instruments are prone to drift off-zero and need to be checked for zero before use.

A **calibration graph**, which is a graph to show how the output changes as the input varies.

Linearity, which is where the output increases in equal steps when the input increases in equal steps. If the output is zero when the input is zero, the output is then directly proportional to the input, and its calibration graph will be a straight line through the origin. An instrument with a linear scale is usually easier to use than an instrument with a non-linear scale. However, with the advent of digital instruments, linearity has become less important. Given the output, the instrument simply looks up the correct value of the input to record, in a 'look-up' table. The 'look-up' table is the equivalent of a calibration graph.

The **resolution** of the instrument, which is the smallest change of the input that can be detected at the output.

The **sensitivity** of the instrument, which is the ratio of change in output for a given change in input. If the calibration graph is curved, then the sensitivity - the slope of the graph - varies across the range.

The **reproducibility** of its measurements, which is the extent to which it gives the same output for a given input, at different times or in different places. Reproducibility thus includes zero drift and changes in sensitivity.

Most instruments are calibrated using secondary standards which themselves are calibrated from primary standards in specialist laboratories.

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Graphs

Graphs visually display patterns in data and relationships between quantities.

A graph is a line defined by points representing pairs of data values plotted along perpendicular axes corresponding to the ranges of the data values.

Many experiments are about finding a link between two variable quantities. If a mathematical relationship between them is suggested, the suggestion can be tested by seeing how well the graph of the experimental measurements corresponds to the graph of the mathematical relationship, at least over the range of values of data taken. For example, a graph of the tension in a spring against the extension of the spring is expected to be a straight line through the origin if the spring obeys Hooke's law, namely tension = constant × extension. But if the spring is stretched further, the graph of the experimental results is likely to become curved, indicating that Hooke's law is no longer valid in this region.

Many plots of data yield curved rather than straight-line graphs. By re-expressing one or both variables, it may be possible to produce a graph which is expected to be a straight line, which is easier to test for a good fit. Some of the curves and related mathematical relationships met in physics are described below:

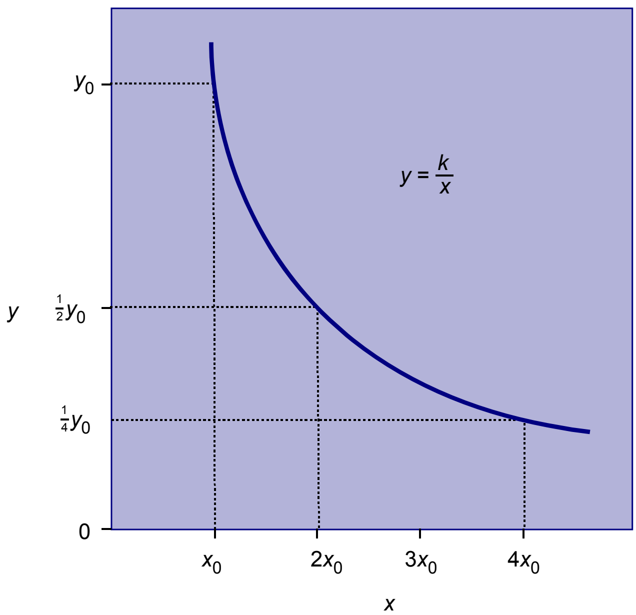
Inverse curves are asymptotic at both axes. The mathematical form of relationship for an inverse curve is

$$y \quad \frac{k}{x^n}$$

where n is a positive number and k is a constant.

n* = 1: *y* =*k* / *x

An inverse curve



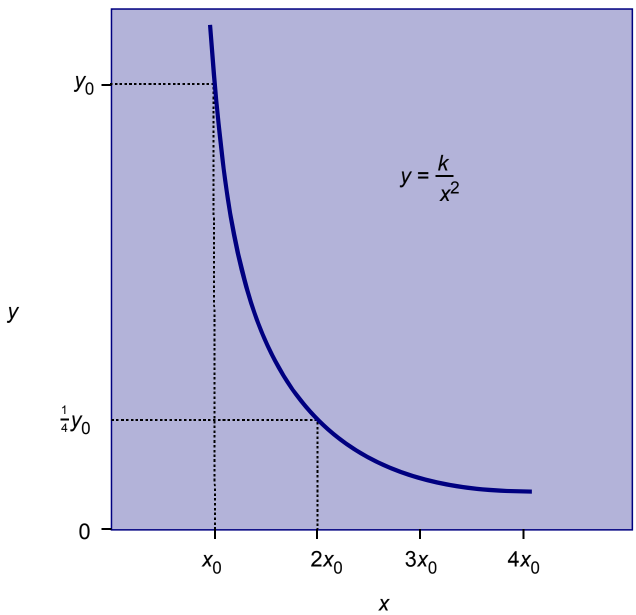
Examples:
Pressure = constant / volume for a fixed amount of gas at constant temperature.

Gravitational potential = constant / distance for an object near a spherical planet.

Electrostatic potential = constant / distance for a point charge near a large charge.

***n* = 2: *y* =*k* / x^2**

An inverse square curve



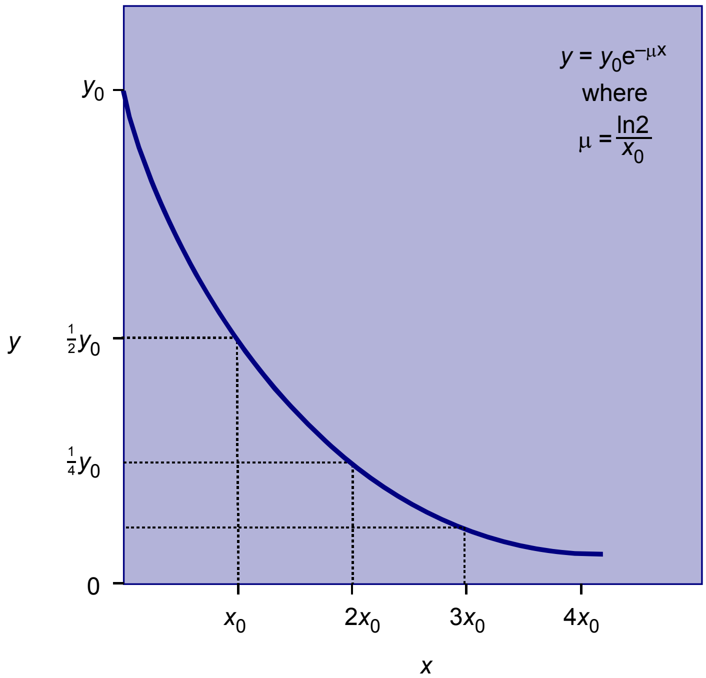
Examples:
Gravitational force between two points masses = constant / distance^2.

Electric field intensity = constant / distance^2.

Intensity of gamma radiation from a point source = constant / distance^2.

Exponential decay

Exponential decrease



Exponential decay curves are asymptotic along one axis but not along the other axis.
Exponential decay curves fit the relationship

$I \quad I_0\, e^{\;ct}$

where I_0 is the intensity at $t = 0$ and c is a constant.

Examples:
Radioactive decay

$N = N_0\, e^{-\lambda t}$.

Capacitor decay

$Q = Q_0\, e^{-t/CR}$.

Absorption of x-rays and gamma rays by matter

$I = I_0\, e^{-\alpha x}$.

In general, to establish a relationship between two variables or to find the value of a constant in an equation, the results are processed to search for a straight-line relationship. This is because a straight line is much easier to recognise than a specific type of curve. To test a proposed relationship between two variables, the variables are re-expressed if possible to yield the equation for a straight line $y = m x + c$. For example, a graph of y = pressure against x = 1 / volume should give a straight line through the origin, thus confirming that the gas under test obeys Boyle's law. In the case of a test for an exponential decay curve of the form

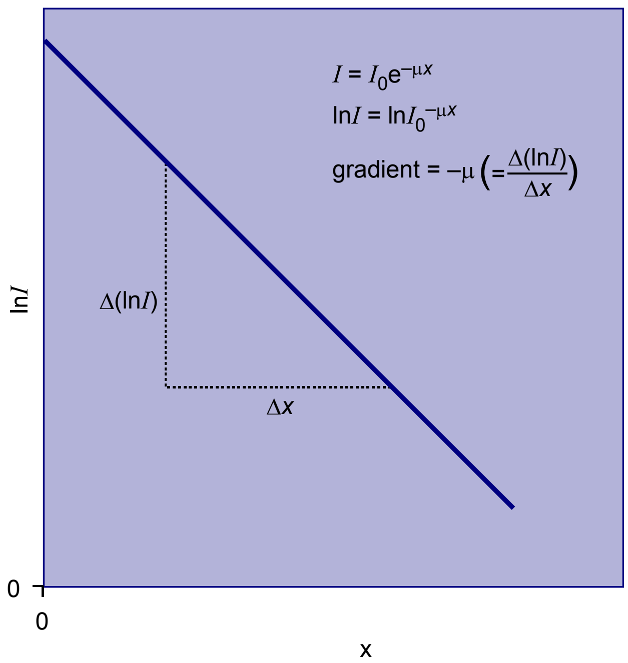
$$I = I_o \, e^{-\alpha x}$$

the variable I is re-expressed as its natural logarithm ln I, giving

$$\ln I = \ln I_0 - \alpha x.$$

A graph of ln I against x is now expected to be a straight line.

ln$I$ against x for $I = I_0 e^{-\mu x}$



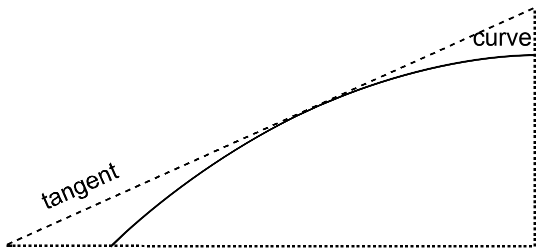
Graphs are a means of communication. To communicate clearly using graphs follow these rules:

1. Always choose a scale for each axis so that the points spread over at least 50% of each axis.
2. Obtain more points by making more measurements where a line curves sharply.
3. Label each axis with the name and symbol of the relevant quantity, and state the appropriate unit of measurement (e.g. pressure *p* / kPa).
4. Prefer graph areas which are wider than they are long ('landscape' rather than 'portrait').
5. Put as much information as possible on the graph, for example labeling points informatively.
6. When using a computer to generate graphs, always try several different formats and shapes. Choose the one which most vividly displays the story you want the graph to tell.
7. Label every graph with a caption which conveys the story it tells, for example 'Spring obeys Hooke's law up to 20% strain', not 'extension against strain for a spring'.

To measure the **gradient** of a curve at a point on the curve, draw the tangent to the curve as shown below and measure the gradient of the tangent by drawing a large 'gradient triangle'.

To measure the gradient of a straight line, draw a large gradient triangle with the line itself as the hypotenuse of the triangle then measure the gradient.

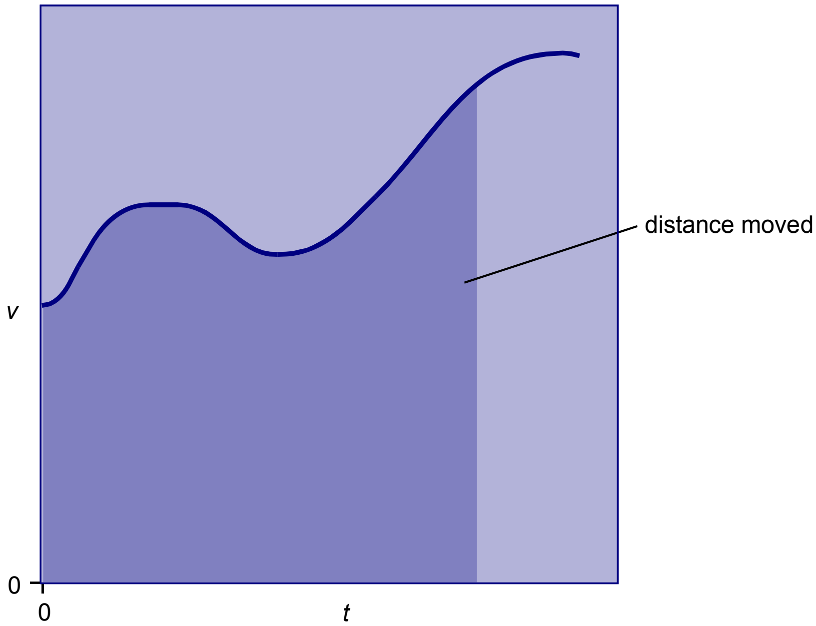
Drawing a tangent



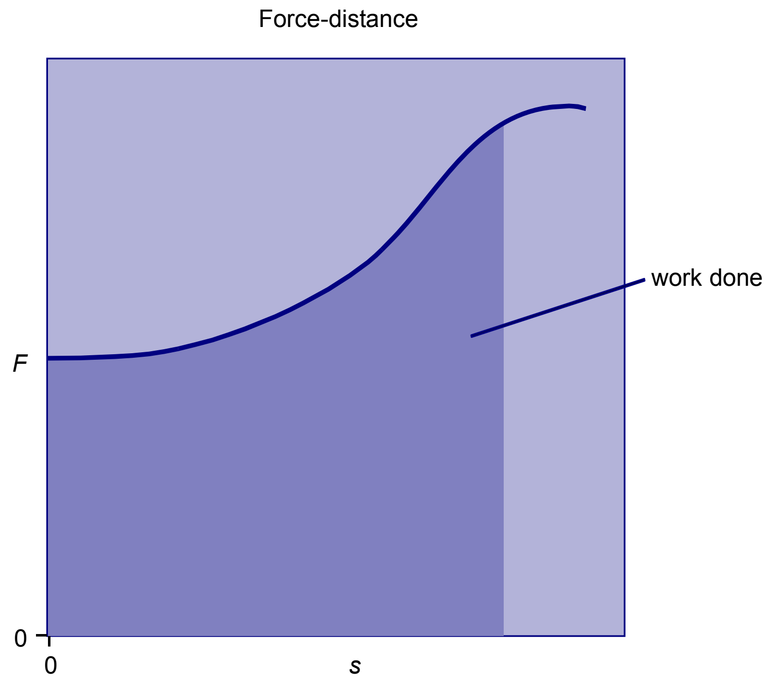
The **area under a curve** is usually measured by counting the grid squares, including parts of squares over half size as whole squares and disregarding parts of squares less than half size. Graphs in physics where areas are useful include:

speed–time graphs (where area represents distance moved)

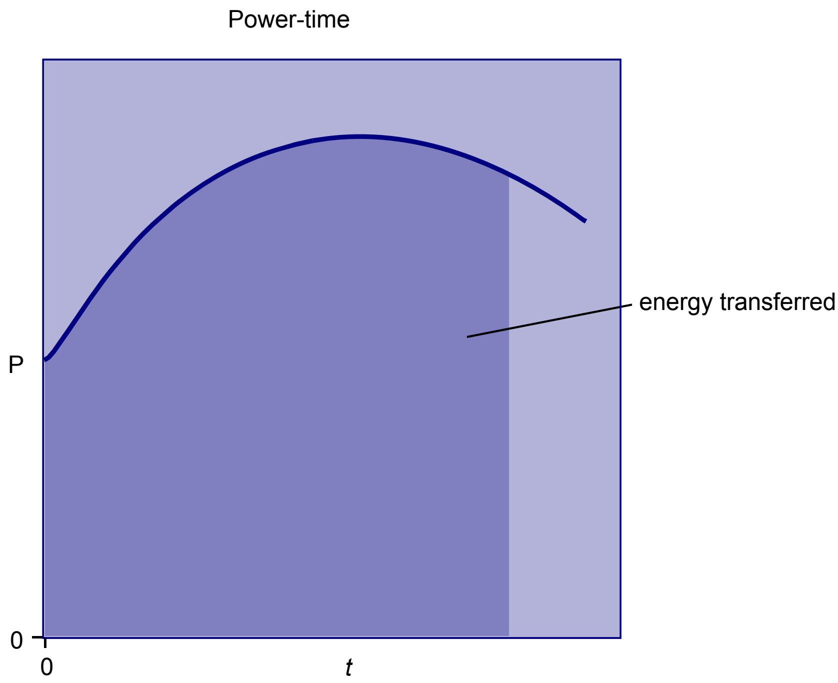
Speed-time



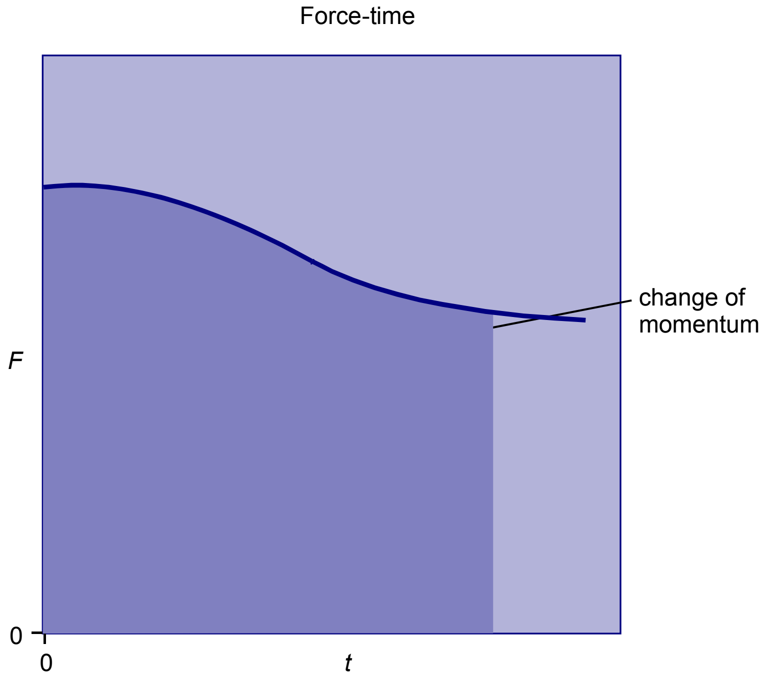
force–distance graphs (where area represents work done or energy transferred)



power–time graphs (where area represents energy transferred)



force–time graphs (where area represents change of momentum)



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Sensor

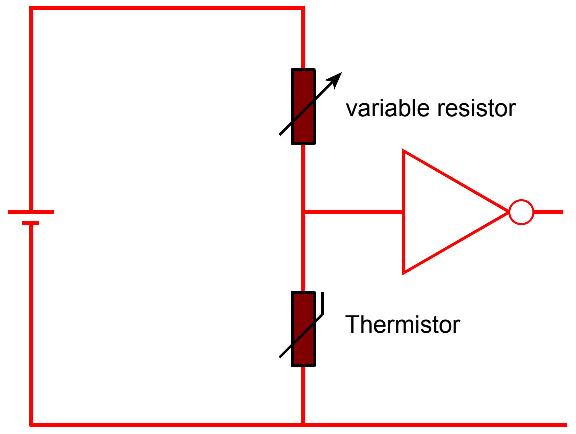
A sensor is a device designed to produce an electrical signal in response to a change in its surroundings

For example, a light sensor produces an electrical signal in response to a change in the light intensity falling on it. Many sensors rely on a change in a quantity such as resistance and so require a source of power to generate an output potential difference. These are **passive sensors**.

Some sensors contain a component that generates a voltage in response to a change of the input variable. For example, a pressure sensor may contain a piezoelectric disc which generates a potential difference when the disc is compressed. These are **active sensors**.

An example of a passive sensor is a thermistor used in a temperature-sensitive transducer. This could be a potential divider consisting of the thermistor in series with a variable resistor and a direct voltage supply. When the temperature of the thermistor changes, the potential difference across the resistor changes.

A temperature sensor



Output = 1 if the temperature is greater than a certain value determined by the setting of the variable resistor.

To make a light sensor, the thermistor can be replaced by a light-dependent resistor.

Some sensors work by emitting and detecting signals. For example, a sensor in an alarm system may emit infrared light, and detect changes in the light scattered back to it. Thus movement triggers the sensor, sounding an alarm or turning on a light.

Sensors are also used to control devices such as heaters, motors, solenoids, alarms and lighting systems.

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Summary Diagrams

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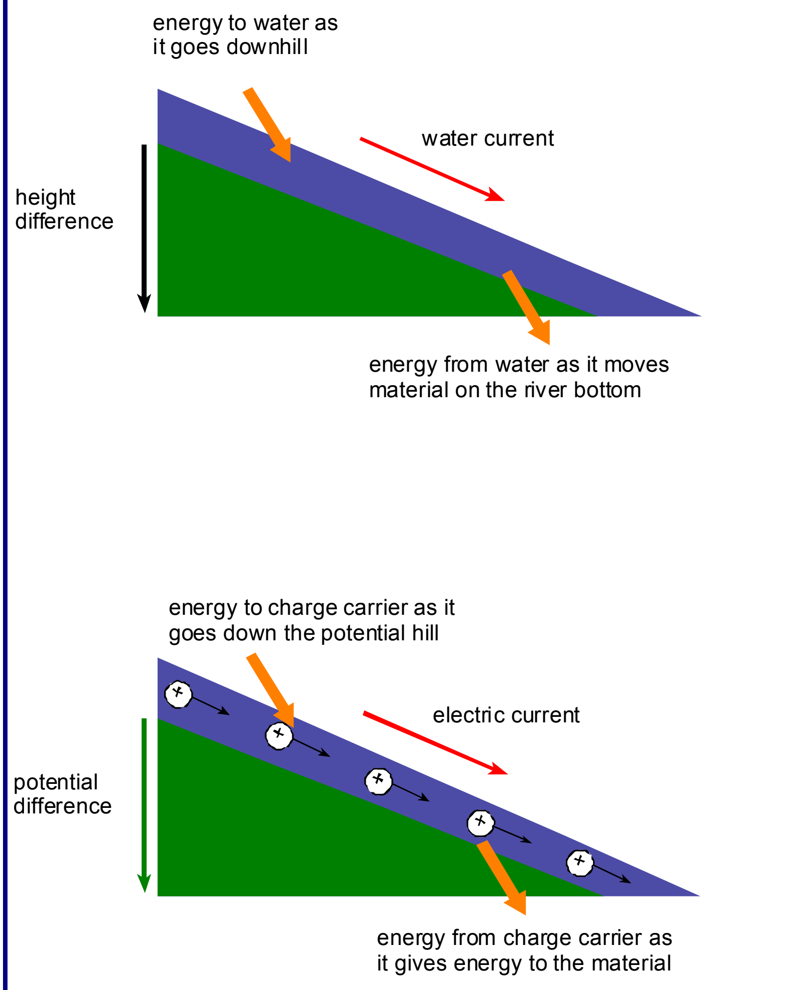
Rivers and electric currents

Here you can see how drop and flow in rivers can be used to model electric quantities.

Rivers and electric currents



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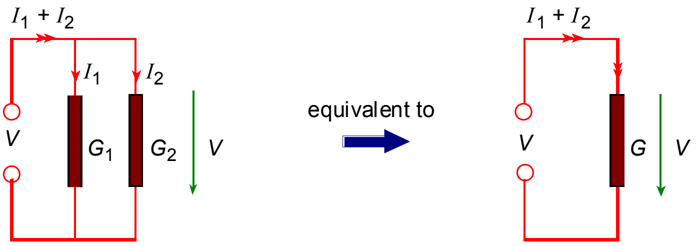
Conductors in parallel and series

Here you can see how conductance and resistance are used to describe parallel and series circuits.

Conductors in parallel and series

Parallel



$I_1 = G_1 V$

$I_2 = G_2 V$

substitute for I_1, I_2

$G = \frac{I_1 + I_2}{V}$

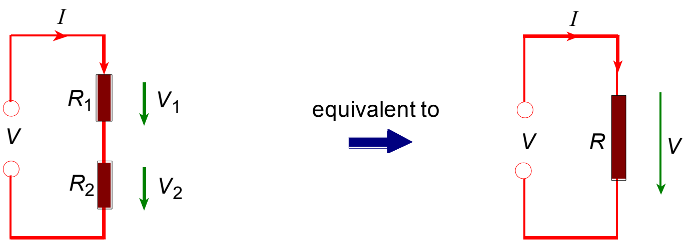
$G = G_1 + G_2$

$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$ (often used)

Currents add up, potential difference is the same for both: conductances add up

Example: lamps in domestic wiring

Series



$V_1 = R_1 I$

$V_2 = R_2 I$

substitute for V_1, V_2

$R = \frac{V_1 + V_2}{I}$

$R = R_1 + R_2$

$\frac{1}{G} = \frac{1}{G_1} + \frac{1}{G_2}$ (not often used)

Potential differences add up, current is the same for both: resistances add up

Example: potential divider

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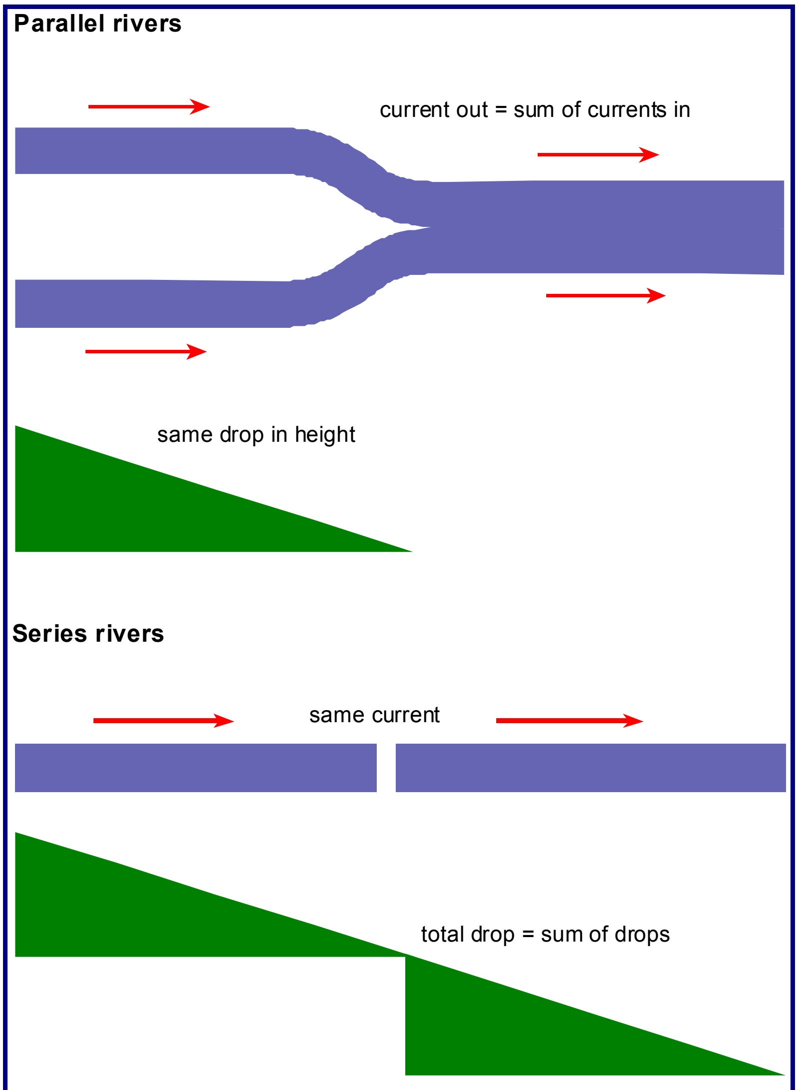
Series and parallel rivers

Here you can see how drop and flow in rivers can be used to model series and parallel circuits.



In parallel, currents add up. In series, potential differences add up

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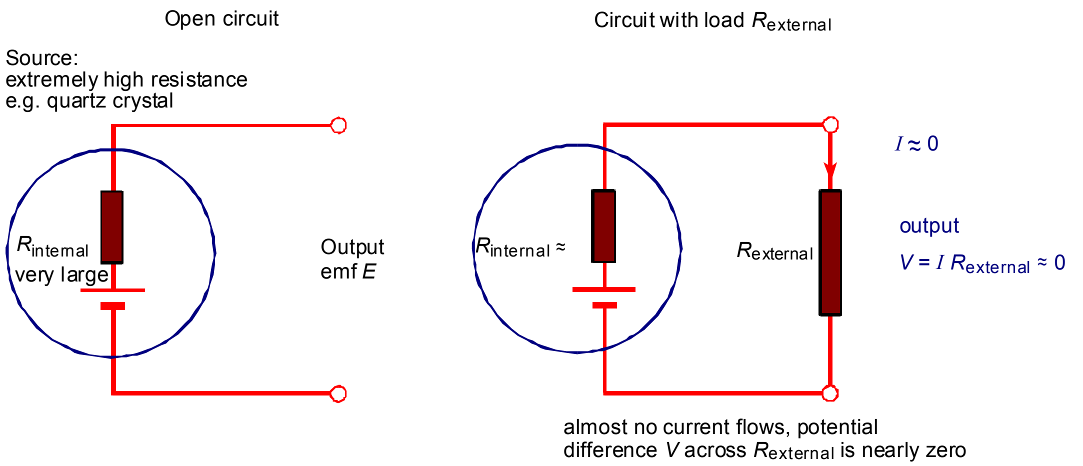
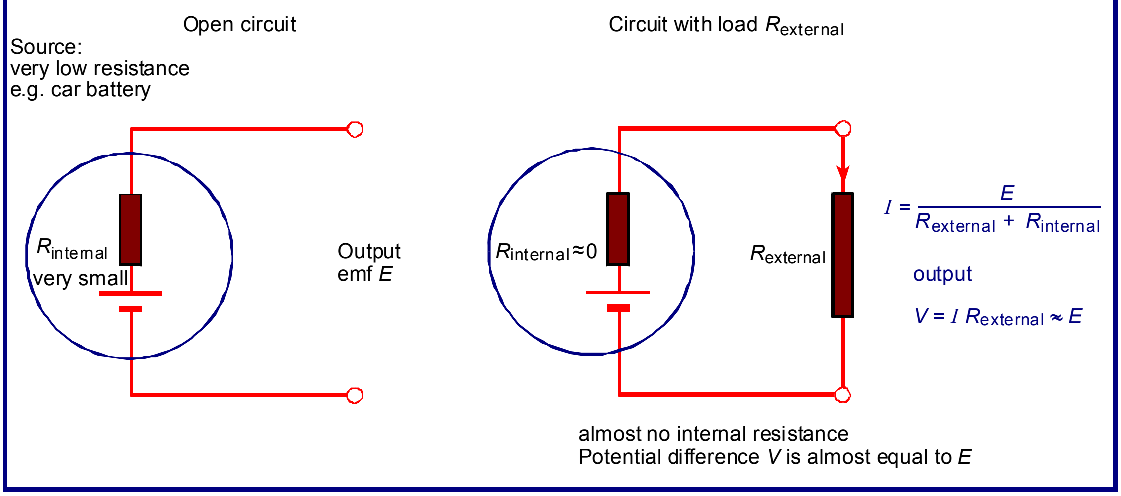
Sources and internal resistance

Open circuit behaviour is compared with behaviour under load, for different sources of emf.

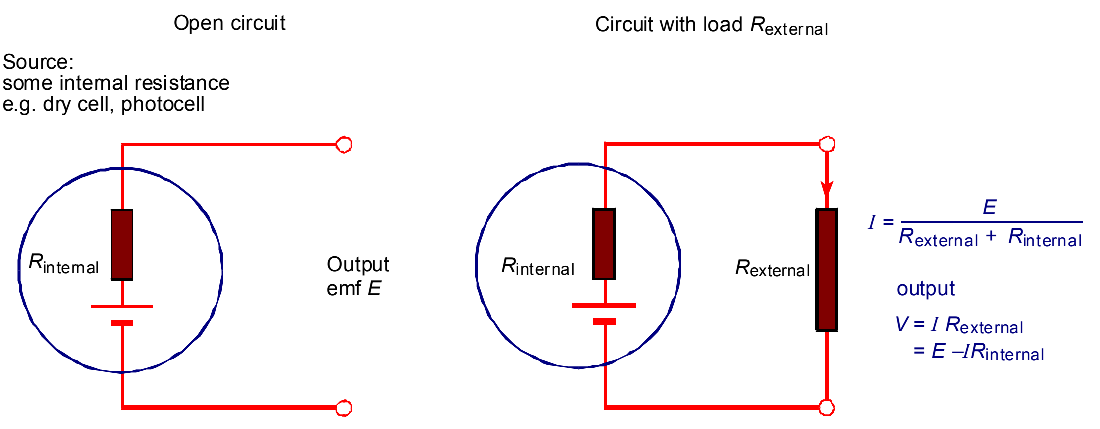
Internal resistance and emf



Internal resistance and emf



Internal resistance and emf



The electromotive force (emf) is equal to the potential difference from a source on an open circuit

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