Isaac Essential Physics

Explaining Physics

Isaac Physics Team
Isaac Physics Project

PERIPHYSEOS
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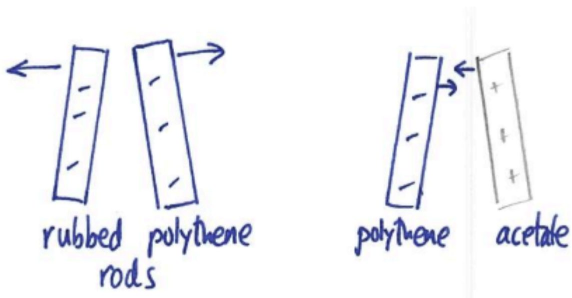
Electricity

1 Charges

The ancient Greeks noticed that lamps made of amber (fossilized tree resin) attracted dust. When they rubbed the lamps, they attracted even more dust.

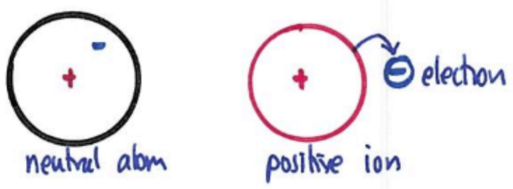
The Greek word for amber was electron, and this gives its name to everything electric, and the name of the particle responsible for most of it. When we rub many materials they can also attract dust. We say that they are charged.

If you rub two identical plastic rods with the same cloth, hang one up, and hold the other close to it, you notice them push apart or repel. However if you rub two different plastics, and bring them near to each other, sometimes the rods pull together or attract.



It follows that there must be at least two different kinds of electric charge. If there were only one type of charge, then you would always get the same effect when you brought two charged objects together. Given that one of these types can cancel out the other, we say that there are only two types of charge and we call one positive and the other negative.

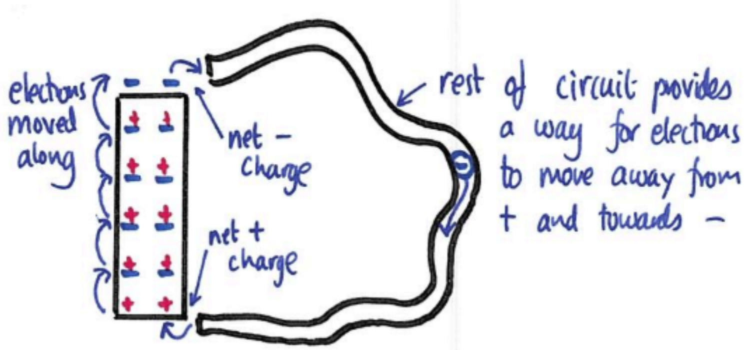
When two objects are charged with the same kind of charge (both positive or both negative) they push apart. However when they are charged with different charges (one $+$ and one $-$) then they pull together. These forces are at the root of all that happens electrically.



Within the last 100 years, we saw evidence that everything is made of atoms. Atoms have positive and negative parts, and the negative parts can sometimes be pulled off and made to move about separately. As these negative parts are responsible for most of what we see as electricity, they were named electrons. Anything which is negatively charged has too many electrons, and anything positively charged has too few.

Electric circuits - Separation

When we make an electric circuit, and put it to use, there are two things going on. In one part of the circuit there is charge separation. Something which would otherwise have been neutral has its positive and negative parts separated so that you have an excess of electrons at one end and a shortage of them at the other. Given that pulling a negative charge away from a positive one takes some force and effort, separating charge is a way of storing energy, and accordingly, this can't be done without an input of energy from some other store.



In a battery or cell, a chemical reaction separates the charge, and the store of chemical energy is reduced as the charge is separated. In a generator, magnets allow energy involved in the motion to be used to separate the charge; and in a solar cell light itself is used to separate the charge. So the charge separator is the electrical supply.

We are now ready to make an electric circuit by connecting something to our battery.

Completing the circuit

The simplest circuit is made when one end of a metal wire is fixed to the positively charged end of a battery, and the other end of the wire is fixed to the negatively charged end of the battery. Very rapidly, the wire heats up. If the wire is thin enough, it even gets hot enough to glow.

If you repeat our experiment with a piece of string instead of a wire, you find that it does not heat up. Both string and wire, being made of atoms, contain positively charged parts and negatively charged parts (electrons). In string, all of these charged parts are held in place by strong forces. In a metal, all of the positively charged parts, and most of the electrons are also held in place. However some of the electrons are free to move within the wire. When the wire is connected to the battery, these electrons move. This makes an electric current, and as we shall see later, this causes the wire to get hotter.

If it were not for the chemical reaction in the battery, the electrons' motion would neutralise the charge on the terminals of the battery. The excess of electrons at the $-$ end would have moved round to the $+$ where they would have remedied the deficit. However, as this charge moves round the circuit, the chemical reaction in the battery separates more charge, ensuring that there is always an excess of electrons at the $-$ end and a shortage of them at the $+$ end. This keeps the charge flowing through our circuit until the chemical reaction in the battery stops for lack of reactant.

Energy transfer

We might have explained why a piece of string wire won't complete an electric circuit, but we haven't explained why a metal wire might hot. To do this, we have to look inside the wire and see what the electrons are up to. Frequently they hit something else within the wire and bounce off it. When the electron bounces off, it gives some of its motion and some of its energy away. Consequently the electron loses some of its energy – it bounces off with a lower speed than before the collision. At the same time, the parts of the wire which have been hit gain energy, and so the wire itself gains energy and heats up.

So far, so good. The battery makes the electrons move, and the electrons give that energy to the metal of the wire when they slow down as a result of hitting things. This is perfectly correct, however there is a further complication.

If the electrons slow down as they pass along the wire from the battery, then surely they must emerge from the other end of the wire more slowly than they went in. If this is true, then there must be two consequences. Firstly, the current emerging from the end of the wire must be less than the current entering it. Secondly, as more electrons are entering the wire than leaving it, there must be a build-up of electrons within the wire. This must give the wire a negative charge which increases as time passes.

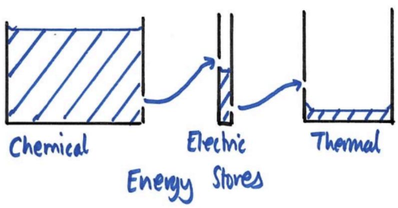
The problem is that neither of these two consequences is observed. The current entering the wire (measured by an ammeter) is identical to that leaving it at the other end. And the wire remains stubbornly neutral.

The problem is solved straight away when we realise that although the slowing down is happening throughout the wire, so is the speeding up. The battery sets up an electric field which exists along the whole wire. All of the electrons in the wire experience a force pulling them towards the $+$ end. All of the electrons, let me stress, not just the ones nearest the battery. This force causes all of the electrons to speed up. As they speed up, they hit things more often, and lose energy at a faster rate. Each time an electron hits something, it slows down a bit, but its speed is rapidly restored by the electric force provided by the battery's electric field, and it carries on speeding up until it hits something else.

Very quickly indeed an equilibrium is reached where electrons, on average, have just attained their previous speed when they undergo their next collision. At this time electrons gain just as much energy from the field in between successive collisions as they lose during one collision. If they try going too fast, they collide more frequently than this, and slow down; if they go too slowly, they collide less frequently, and speed up – either way the equilibrium is soon restored.

Accordingly, we see that the transfer of energy from the electric field to the warmth of the wire is occurring directly at all points along the wire, and the average speed of the electrons is the same at all points in the wire.

If we wish to use a picture of energy stores to understand what is going on, there is a small store of electrical potential energy in the separation of charge. If we think of this store as a tank, the chemical energy store is used to keep this tank topped up, and it is this store which is able to provide what we need to keep the charge moving and indeed to increase the thermal energy store as electrons collide with ions.

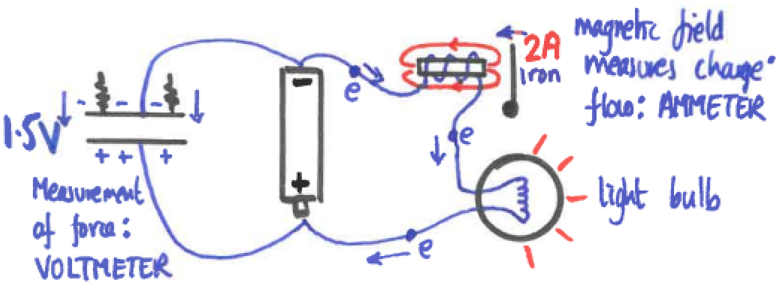


2 Measuring electricity

All of electricity concerns charges. Charge is electrical stuff, and we get our symbol Q for electric charge from the French who simply call it quantity. Perhaps unsurprisingly given the French connection, we measure charge in units called coulombs C, named after a French scientist. When you rub a balloon so it can stay on the ceiling, the charge is very small (about a billionth of a coulomb), so a coulomb is a very large amount of electrical stuff.

It is very difficult to measure charge itself. However we can make measurements of two things charge does, as shown in figure 2. One is to measure it flowing around the circuit. As we will see, a moving charge creates a magnetic field, and this enables the charge flow to be monitored. This flow is called a current. Current is given the symbol I because the French called it intensity. It is measured in units called amps A, named after a different French scientist. The device which measures current is called an ammeter.

The other way to measure it is to measure the force causing the charge to flow around the circuit. The device for doing this is called a voltmeter. The measurement itself is known by several names, including electromotive force (e.m.f.), potential difference (p.d.) and voltage. It is given the symbol V and measured in units called volts, named after an Italian.



You can measure the current at a point in a circuit (the charge passing that point each second). However you can only measure the potential difference between two points (you need two numbers before you can work out the difference between them).

Sometimes we choose a reference point (usually the negative terminal of the battery) and call this a zero volt point. We can then use a voltmeter to measure the potential difference between our location on the circuit and this reference point. That reading is called the potential of our location.

Contrasting current and potential difference (voltage)

The difference between current and potential difference can cause confusion to students, and they might wonder why we need two measurements (V and I) rather than just one. When we studied energy transfers and work done, we learned that the energy transferred depended on two things — the force applied and also the distance moved. The power, that is the energy transferred each second, then depended on the force applied and the speed. Sometimes one can be traded off against the other for practical reasons, such as choosing a low gear when cycling uphill. This is because in this situation, you are willing to push the pedals very quickly if it means you don't have to push them as hard. However when cycling at speed on a flat smooth road, you choose a high gear so that by putting a larger force on the pedals, you don't have to move your legs up and down as frequently.

There is a similar situation with electricity, where the force is related to the potential difference (voltage) and the speed is related to the current (charge flow rate). Electronic components as found in most gadgets are damaged if the electrical forces are too great. This limits the potential difference (voltage) which can be used. To get the job done, in compensation, more charge will have to move, so we will need a larger current. On the other hand, when connecting your town or village to the nearest power station we don't want the charge to move too fast — if we do, the wires get really hot and energy is wasted. In this case we choose to use a high potential difference (voltage).

Force is the most visual way of picturing potential difference. However the volt does not quantify force directly, but rather the energy transfer involved with charge as it passes from one side of a component to the other. If the potential difference across a light bulb is 3 V then during the time when one coulomb of charge has been pushed through it, there will be 3 J of energy transfer within it. Thinking back to the tank of electric potential energy on page 5, the potential difference is the height to which we keep the electric tank filled.

Power

The rate of transferring energy mechanically is called the power and can be worked out by multiplying velocity and force. In a similar way, we can calculate electrical power to measure the energy transferred by an electric circuit each second.

The formula is

$$\text{Power} = \text{Current} \times \text{Potential difference}, \quad \text{in symbols:} \quad P = IV.$$

Given that that the current is related to the speed the charges move and the potential difference (also known as the electromotive force) is related to the force on the charges, this formula makes sense.

We can justify the formula further. The potential difference measures the energy transferred for each unit of charge (coulomb) flowing. So the total energy transfer will be given by

$$\text{Energy transfer} = \text{Potential difference} \times \text{Charge}.$$

The energy transfer each second is given by

$$\text{Power} = \frac{\text{Energy transfer}}{\text{Time}} = \frac{\text{Potential difference} \times \text{Charge}}{\text{Time}}.$$

Now current measures the charge flow each second, so

$$\text{Power} = \text{Potential difference} \times \frac{\text{Charge}}{\text{Time}},$$

so

$$\text{Power} = \text{Potential difference} \times \text{Current}.$$

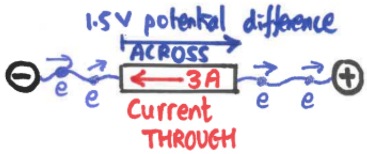
Power is measured in watts (symbol: W) in an electrical circuit, just as it is in a mechanical system, in the same way that we always measure energy transfers in joules regardless of the process going on.

Students often find it easy to see the sense in this equation by making an analogy. For example, the number of tins of soup you bring into your home each year depends partly on how often you shop and partly on how many tins you bring home each time.

A high power could be achieved with a small potential difference providing the current is high enough. A factory canteen could buy its soup one tin at a time, but someone will have to go to the shop many times each day. It would make more sense to have a small number of deliveries with vans or even trucks carrying many tins at a time. This would be equivalent to a circuit of high power with low current but a high potential difference. The potential difference used on the National Grid, which can be $440\,000$ V is equivalent to a delivery using an extremely large truck, or perhaps even a train load of soup!

Direction of current and potential difference

To keep the distinction between current and potential difference (voltage) in mind, always think about the potential difference across the component (the force externally applied to it to make the electrons move) contrasting with the current through.



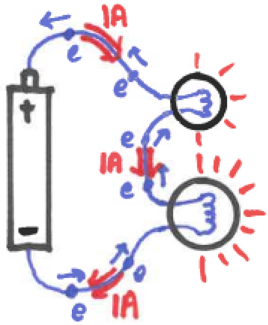
This diagram shows the conventions we use for directions when we study electric circuits. Firstly potential differences are measured as shown by the blue arrow.

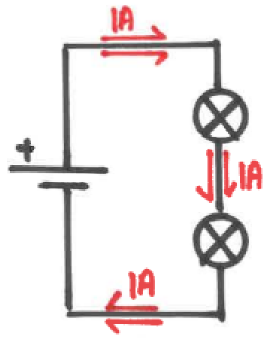
We now know that in wires electrons move, and these are negatively charged, so they move from $-$ to $+$ outside of the battery. However, some positive particles can also move in electric circuits (for example, sodium ions in a salt solution). These would move the other way, from $+$ to $-$ when outside of the battery. Given we want to label a direction without having to know what is carrying the charge, we pretend when labelling diagrams that it is only $+$ charge which moves. Accordingly, our diagrams will show the current direction as flowing from $+$ to $-$, even though any moving electrons are actually going the other way.

3 Circuit rules

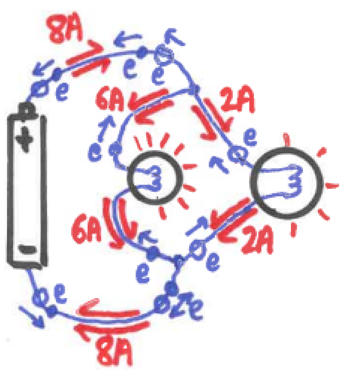
We can explain what is going on in a circuit, for example predicting which light bulb is going to be brightest, if we know the rules which relate currents and potential differences. For each case, we will have two diagrams. The ones on the left give an idea what the circuit will actually look like. However, standard circuit diagrams are clarified versions which show the connections correctly, but use tidier shapes. These are shown on the right in each case.

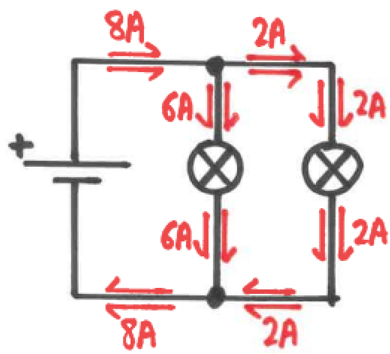
Rules about current





For every electron which goes into a wire at one end, another electron comes out the other end, albeit with some energy transfers having happened along the way. This is because the wire can not make (or destroy) electrons. This means that the if you measure the current in amps on both sides of the same component at the same time, you will get the same answer. Current is not used up as it travels around a circuit.

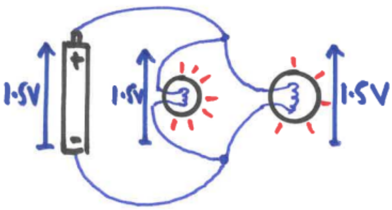


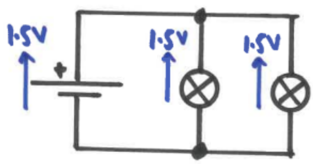


If a circuit has junctions, then this rule still applies, and so for each electron arriving at the junction, another one leaves. This is known as the conservation of charge. If 8 C in total enters a junction each second we say the current entering is 8 A. It follows that 8 A must also leave it. If there are two routes out of the junction, then the current will be shared between them. If the two routes are identical, then it will be a fair sharing and there will be 4 A flowing each way. However if the routes are not the same, then the current will be split unequally, perhaps 6 A along one route and 2 A along the other. But the total must still be 8 A.

Potential difference in parallel circuits

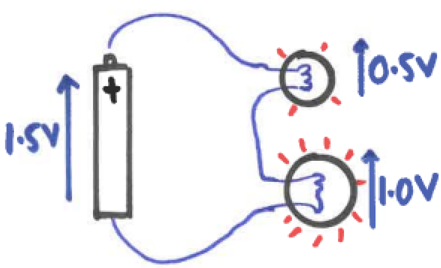
Charge is not the only quantity to be conserved in an electric circuit. Energy is also conserved. Suppose that we have a 1.5 V battery powering a light bulb. This means that for each coulomb of charge which flows through the circuit, 1.5 J is transferred from the battery to the bulb.

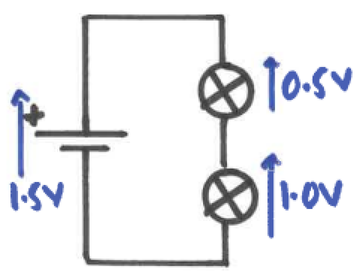




Now let us imagine that the battery is connected to two light bulbs in parallel. Each charge coming from the battery must go through the one light bulb or the other. However either way, the energy it gained by being separated in the battery will be passed to the bulb it goes through. The reduction in energy stored by the battery must be the same as the energy transferred to that light bulb. Now, potential difference measures the energy transfer associated with one coulomb of charge. So a 1.5 V battery transfers 1.5 J to a light bulb for each coulomb which flows through that bulb. Accordingly, the potential difference across each lamp is 1.5 V. So although the charge is shared (you could equally well say that the current is divided), the potential difference is not. Put more bluntly voltage does not split at junctions.

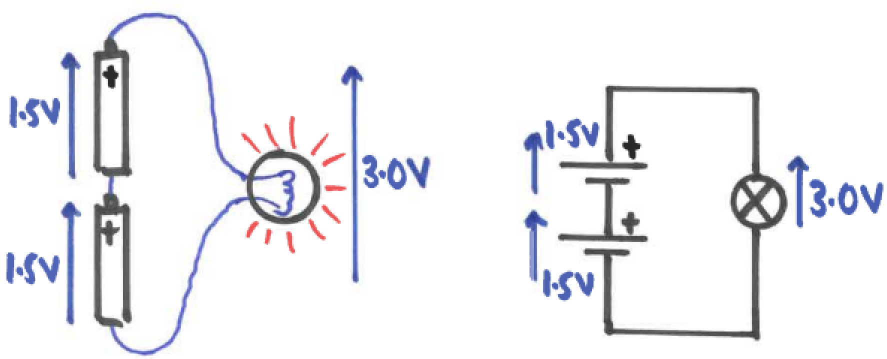
Potential difference in series circuits





On the other hand, if the two light bulbs are connected to the 9 V battery in series, then all of the charge which flows must go through both bulbs. It will go through one and [then] the other. During the time taken for one coulomb to flow, there will be 1.5 J of energy transferred from the battery to the bulbs. However as the total energy can not change, this energy must be shared between the bulbs. So if one bulb received 0.5 J, the other must have received 1.0 J. Given that potential difference (or voltage) is energy transfer for each coulomb flowing through, this means that there will be a potential difference of 0.5 V across one bulb and 1.0 V across the other.

More than one battery

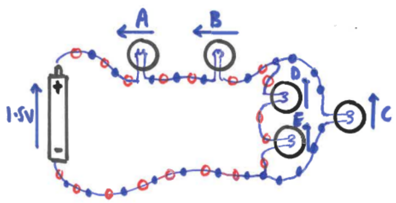


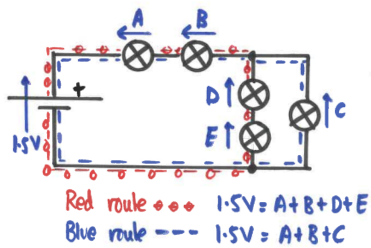
If two batteries are connected in series to a light bulb, then all of the charge which will flow through the bulb will have gone through both batteries. During the time taken for one coulomb to flow, each battery will have contributed 1.5 J to the energy transfer, and accordingly the bulb will receive 3.0 J. The potential difference across the bulb in this case will therefore be $1.5\,\text{V} + 1.5\,\text{V} = 3.0\,\text{V}$.

If one of the batteries had been connected the other way round, then its potential difference would be in the other direction. In our diagram, that means its arrow would point the other way. The result is that the force applied to the charges by the batteries would cancel out $1.5\,\text{V} - 1.5\,\text{V} = 0\,\text{V}$, there would be no current flowing and the bulb would not light.

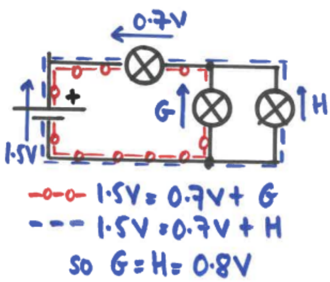
If two opposing batteries have different potential differences, then they will not be able to completely cancel each other out. A 3 V battery opposing a 2 V battery will leave 3 V $-$ 2 V $=$ 1 V potential difference to push a small current around the circuit

Rule for potential differences





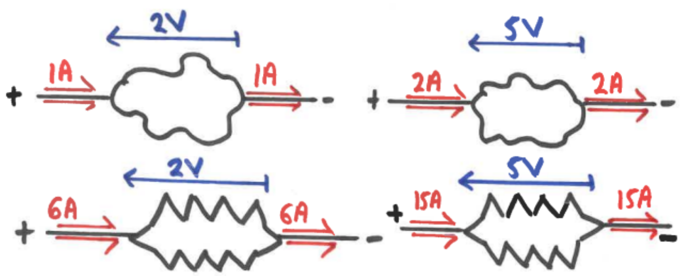
If you choose any route through the circuit from one end of the battery to the other (choosing any direction you like at any junctions you reach), and add up the potential differences across the components you go through on your journey, you will get the potential difference of the battery.



Suppose two components are in parallel with each other. Given that choosing one or the other does not affect the rest of the route (or the potential difference across the battery), it must be that the potential difference across those two components must be the same. It is in general true that components in parallel with each other will have the same potential difference.

4 Resistance

Applying a certain potential difference across an object, say two volts $(2\,\mathrm{V})$, won't always lead to the same current flowing. It depends how well the object conducts electricity. In the diagram below, the spiky sample conducts electricity better than the rounded sample. You can tell this, because for both $2\,\mathrm{V}$ and $5\,\mathrm{V}$ of potential difference, it has a larger current than the rounded specimen. We say that the better conductor (here the spiky sample) has a lower resistance than the rounded sample.



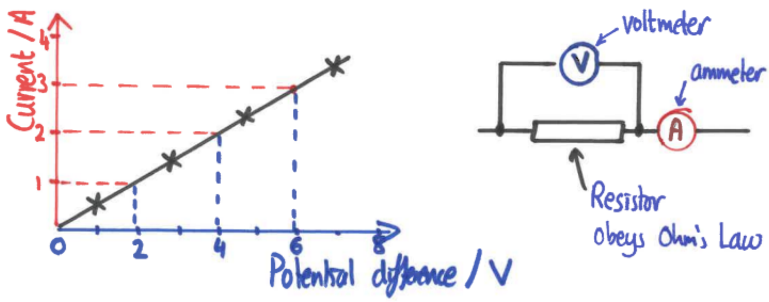
When you apply a larger potential difference across something in a circuit, you put a larger force on the electrons to push them around the circuit. You would therefore expect them to move faster, leading to a larger current through the circuit. This is true for both the rounded and spiky examples in the diagram.

For many materials, we find that doubling the potential difference (or voltage), and so doubling the force on the electrons, leads to a doubling in the speed and therefore the current. These materials are said to obey Ohm's law.

In our diagram, the rounded sample does not obey Ohm's law: to make the current get twice as large we needed to more than double the potential difference. The spiky sample, however does obey Ohm's law: when the potential difference was made $2.5\times$ larger, the current also got $2.5\times$ larger.

Characteristic graph

The graph we might plot to see if something obeys Ohm's law is called its characteristic. The current through it is plotted against the potential difference across it. The component drawn in the diagram, a resistor, does obey Ohm's law. The circuit diagram shows how you would connect a resistor to a voltmeter and ammeter so that the potential difference across it and the current through it can be measured. This little circuit would be attached to batteries of different potential differences to obtain the data in the graph.



Notice in this case that

- For each point on the graph, the potential difference in volts is always twice as big as the current in amps: Potential difference in volts $=$ Current in amps $\times 2$.
- For each point on the graph, the current in amps is always half as big as the potential difference in volts: Current in amps $=$ Potential difference in volts $\div 2$.
- To make the current increase by 1 A, you need to increase the potential difference by 2 V.
- If you increase the potential difference by 1 V, the current increases by 0.5 A.

We can summarize all of these points by writing an equation for the current through the resistor.

$$\text{Current} = \frac{\text{Potential difference}}{\text{Resistance}} \quad \text{in symbols:} \quad I = \frac{V}{R}$$

The resistance here will be 2 units, indicating that for each extra amp you need to increase the potential difference by 2 V. So the resistance is 2 volts per amp or 2 V/A.

Now the 'volt per amp' has a special name, the Ohm. We can't use O as the symbol for Ohm as this could be confused with a zero, so we use the Greek letter O instead, namely omega Ω.

The better something is at conducting electricity, the smaller its resistance will be.

Resistance and Temperature

A sample of a material obeys Ohm's law if its resistance does not change as the current increases providing the temperature is kept steady. Metals fit this very well. Ordinary wires in circuits containing light bulbs and other components tend not to become noticeably warmer when small currents pass, and so these obey Ohm's law as well.

Resistors obey Ohm's law because it is in their job description and they would be sacked and thrown away if they did not. However if you read a resistor's employment contract carefully (sorry, I mean its specification sheet), it does specify a maximum power. If you exceed that power, two potentially nasty things happen. Firstly, the temperature will rise enough to affect the resistance of the resistor significantly. Secondly, it may get sufficiently hot as to pose a hazard. That said, high power resistors are designed to cope with dissipating energy (raising the energy stored thermally in the surroundings) - the high temperature won't hurt *them*, but they may still be too hot to touch.

Light bulbs contain thin filaments of wire which are designed to rise to high temperatures when a current passes. This is what enables them to glow and give off light. At these temperatures, their resistance is much higher than it was when they were unlit. Within the metal is a regular grid of metal ions (eg. Cu^{+}), and just the right number of free electrons (electrons not attached to a particular ion or atom) to keep the sample electrically neutral.

At room temperature, the ions oscillate or wobble. An electron can hit a wobbling ion in such a way that it loses kinetic energy. To get moving again, it relies on the energy store of the electric field set up by the battery, which sets up a force pulling it towards the $+$ terminal. This is the origin of resistance and dissipation of energy in a wire. As the temperature increases, the ions wobble more, causing more disruption to the electron motion, thereby making a bigger resistance, a smaller current, providing more warmth to the surroundings, and leading the store of energy in the battery to be used up more quickly.

Silicon and other semiconductors behave differently. In these materials there are electrons which are not *quite* free to move, but which do not require much energy to liberate them. As you raise the temperature of silicon, the energy stored in the oscillating atoms has an increased likelihood of freeing those electrons, which can then carry current. Accordingly, for semiconductors, an increase in temperature is usually accompanied by a rise in current and a drop in resistance. This is what is going on in a thermistor.

For safety reasons, never connect a thermistor directly to a battery without some other resistor in series with it (unless you have an active and effective way of cooling it - such as being in water). While things may start off ok, a vicious cycle soon sets in - the resistance of the thermistor causes it to get hot, which in turn lowers its resistance, so it carries more current, enabling it to get even hotter, lowering its resistance still further enabling it to get hotter still until it melts or causes other hazards. A suitable [ordinary] resistor in series with it effectively limits the current which can flow, protecting the thermistor, and also preventing your students getting hurt.

Light emitting diodes (LEDs) also contain very small pieces of semiconductor material, which are easily damaged by high currents. They also get better at conducting as they carry more current, so they also need to be put in series with a suitable resistor for their protection.

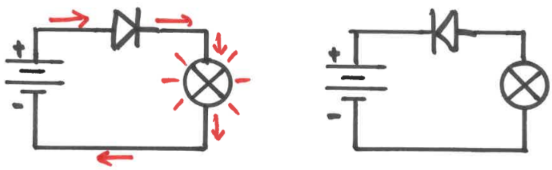
You can estimate the resistance of the safety resistor using

$$\text{resistance} = \frac{\text{battery potential difference}}{\text{maximum safe current}}$$

For LEDs, you would want to limit the current to about 20 mA unless it is a high brightness LED. When working with small thermistors, you would want smaller currents such as 5 mA to prevent them warming up too much.

Diodes

A diode is a clever component which only lets current flow one way through it, and even then only if the voltage is higher than a threshold. The threshold voltage for most diodes is about 0.6 V, but is considerably higher for light emitting diodes (LEDs).

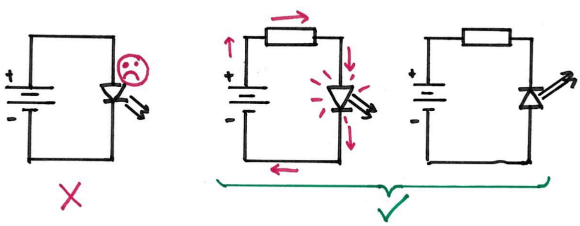


The symbol for a diode, shown in the circuit diagram above, is an arrow. The arrow indicates the direction of the allowed current (on its way from $+$ to $-$). A diode connected the other way round acts almost like a break in the circuit. Even a diode connected the right way round will let negligible current flow through it if the potential difference across it is lower than the threshold voltage.

An explanation of how diodes work is given on page 26.

More Diodes and LEDs

Some diodes are designed to light up when a current passes through them. These are called light emitting diodes (LEDs).



Remember, when connecting a circuit with a battery and an LED, to include a current-limiting resistor as explained on page 17. If you don't do this, and the diode is connected the correct way for charge to flow through it, the current becomes large enough to damage the very small crystal of semiconductor, which then breaks. The LED will not work again, ever.

Assuming a current-limiting resistor has been included in the circuit, a nice demonstration can be made in which if the battery is one way round, the LED lights, and if it is the other way round, the LED does not light.

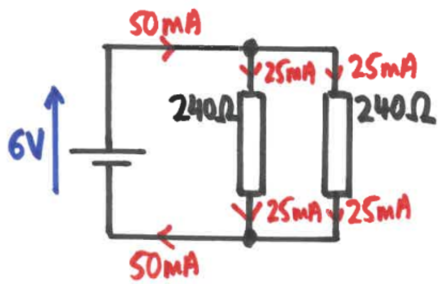
An explanation of how an LED works is given on page 28.

Putting resistors together in parallel

Suppose we have a 6 V battery and two $240\ \Omega$ resistors. If we just connect one of the resistors, the current would be

$$\text{current} = \frac{\text{potential difference}}{\text{resistance}} = \frac{6\ \text{V}}{240\ \Omega} = 0.025\ \text{A} = 25\ \text{mA}.$$

Now suppose we connect both resistors so that each one is connected across the whole battery. In this way, they are connected in parallel. Charge from the battery in effect chooses to go through one or the other, but can't go through both.



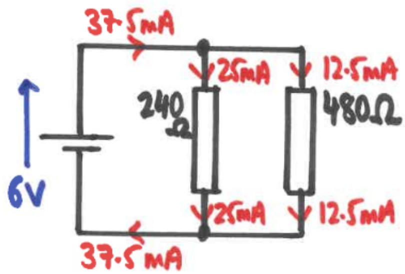
This will not affect the voltage of the battery, so each resistor carries 25 mA as before. The total current will be 50 mA. What this means is that the resistance of the circuit as seen from the battery is

$$\text{resistance} = \frac{\text{potential difference}}{\text{current}} = \frac{6\ \text{V}}{0.05\ \text{A}} = 120\ \Omega.$$

The effect of putting two identical resistors in parallel is that the combined resistance is half the resistance of the individual resistor.

Now let's connect two different resistors in parallel to our 6 V battery: a $240\ \Omega$ resistor and a $480\ \Omega$ resistor. The current through the $240\ \Omega$ resistor will be 25 mA as before. The current through the other resistor will be

$$\text{current} = \frac{\text{potential difference}}{\text{resistance}} = \frac{6\ \text{V}}{480\ \Omega} = 0.0125\ \text{A} = 12.5\ \text{mA}.$$



The total current is $25\ \text{mA} + 12.5\ \text{mA} = 37.5\ \text{mA}$. Notice that adding a new resistor increased the current as it provided a new route for the charge, even though the new resistor had a larger resistance.

If you wish, you can calculate the resistance of the new combination from this new total current:

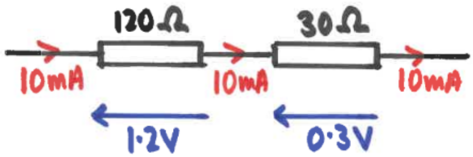
$$\text{resistance} = \frac{\text{potential difference}}{\text{current}} = \frac{6\ \text{V}}{0.0375\ \text{A}} = 160\ \Omega.$$

This overall resistance is less than the smaller individual resistance.

Putting resistors together in series

The rule when you put resistors in series (so the charge has to flow through one then the other - it can't choose) is much easier: **you just add the resistances.**

So if you put a $120\ \Omega$ resistor in series with a $30\ \Omega$ the circuit has an overall resistance of $120 + 30 = 150\ \Omega$.



Let's see why this works. Suppose the current in the circuit is 10 mA $= 0.01$ A. This current will pass through both resistors (one then the other), and the potential differences across the two resistors will be

$$\text{potential difference} = \text{current} \times \text{resistance} = 0.01\text{ A} \times 120\ \Omega = 1.2\text{ V}$$

$$\text{potential difference} = \text{current} \times \text{resistance} = 0.01\text{ A} \times 30\ \Omega = 0.3\text{ V}$$

The total potential difference across the circuit will be the sum $1.2 + 0.3 = 1.5$ V. In a series circuit like this, the current through each resistor is the same as the current supplied by the battery, but it is the potential difference which is shared between the resistors. The overall resistance of the circuit is

$$\text{resistance} = \frac{\text{potential difference}}{\text{current}} = \frac{1.5\text{ V}}{0.01\text{ A}} = 150\ \Omega.$$

We see that the overall resistance is indeed the sum of the original resistances.

Potential division

So, what will happen if we get our series circuit of $120\ \Omega$ and $30\ \Omega$ resistors and connect it to our 6 V battery?

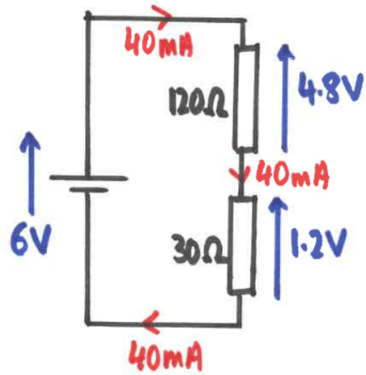
We already know that this combination acts like a $150\ \Omega$ resistor. So the current from the battery will be

$$\text{current} = \frac{\text{potential difference}}{\text{resistance}} = \frac{6\text{ V}}{150\ \Omega} = 0.04\text{ A} = 40\text{ mA}.$$

Now we know this, we can work out the potential difference across each resistor:

$$\text{potential difference} = \text{current} \times \text{resistance} = 0.04\text{ A} \times 120\,\Omega = 4.8\text{ V}$$

$$\text{potential difference} = \text{current} \times \text{resistance} = 0.04\text{ A} \times 30\,\Omega = 1.2\text{ V}.$$



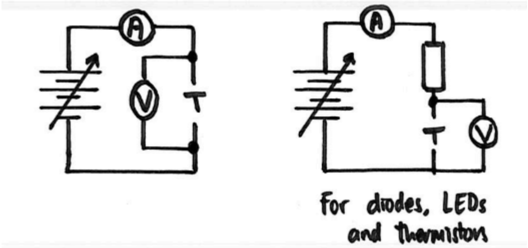
We see that the total potential difference $4.8 + 1.2 = 6$ V which correctly matches the battery potential difference. Notice, however, the way in which this potential difference is shared out between the resistors. One resistor had a resistance four times the other $120\,\Omega = 4 \times 30\,\Omega$. When they were put in series, the potential difference were shared in the same way $4.8\text{ V} = 4 \times 1.2\text{ V}$.

One resistor had one fifth of the total resistance $30/150 = \frac{1}{5}$, and it ended up with one fifth of the total potential difference $1.2/6.0 = \frac{1}{5}$. The other resistor, with four fifths of the total resistance ended up with four fifths of the potential difference.

Connecting the potentiometer

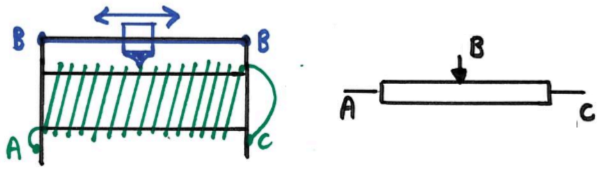
School experiments, including assessed practicals for examinable courses) often require the student to vary the potential difference across a component. There are three ways of doing this in a typical school laboratory.

The most straightforward way is if the school has power supplies with a variable voltage output. The circuits below can then be used to measure the current through and potential difference across a component.



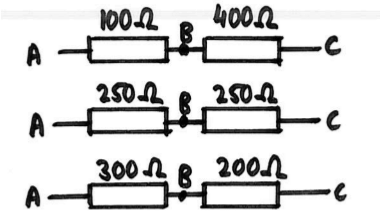
Notice that when investigating a diode, LED or thermistor, we must include a current-limiting resistor. Furthermore, we must set up our voltmeter so that it records the potential difference across the test component only (and not the resistor as well).

Many schools have heavy duty rheostats which often get called into service if variable voltage power supplies are not available.



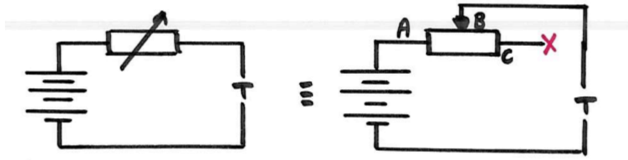
The rheostat is a large potentiometer. In other words, it contains one resistor which is split into two sections by a moving contact. This effectively makes it equivalent to two resistors in series where you can vary the resistance of the two parts subject to the constraint that the total resistance is always the same.

So a $500\ \Omega$ potentiometer (or pot for short) can be set to make any of the possibilities below.



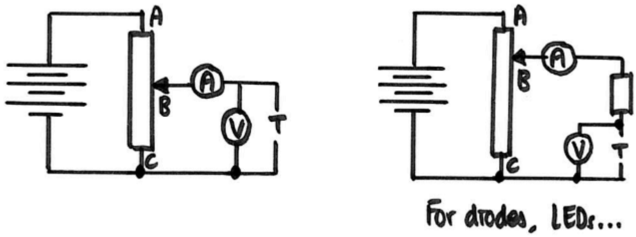
A potentiometer has three connections - the connections to the two ends (A and C in the diagram above), and the connection to the sliding contact (B).

The simplest way of connecting a rheostat (or other potentiometer) is as a variable resistor. In this circuit we use one of the fixed contacts and the sliding contact (eg contacts A and B only).



The disadvantage of this circuit is that while at one extreme it can put the entire potential difference of the battery across the test component, the maximum resistance may not be enough to reduce the potential difference across the test component sufficiently for a good characteristic curve to be drawn. If the test component is a light bulb, you might find that although you can dim the bulb, it never goes dark.

The situation is improved if you use all three of the connections as shown below. In this way, by adjusting the slider, you can deliver any potential difference to the test component from zero up to the battery voltage.



In this circuit, the two resistances of which the potentiometer is made form a potential divider circuit.

If the current taken by the test component is small, you will find that setting the sliding contact half way along the resistance will give half the battery voltage to the test component. However for larger currents drawn, the relationship between position of the slider and potential difference across the test component is not linear.

5 Appendix: Understanding at a deeper level

The content of this section is not needed by students or teachers at GCSE or A Level. However a bit more information about what is going on inside wires, diodes and LEDs as they carry current may well help us understand more of the wonderful mystery of the electric circuit.

The electron as a fermion

When a wire is lying on a table, disconnected, the electrons are not stationary, waiting in hope for a battery to liven up their day. They are already moving up and down the wire at high speed – bouncing off the sides, the ends, other electrons and the other parts inside the wire. You don't normally notice this, because just as many of them are moving one way as moving the other.

However, when you connect the wire to the battery, the motion of the electrons becomes measureable. The battery sets up an electric field in the wire because of its separation of charge. The electrons within the wire all experience this field and are attracted to the $+$ and repelled from the $-$ of the battery. The electrons which are already moving the right way (from $-$ to $+$) speed up. The ones moving the other way slow down. The ones which were going very slowly the wrong way are reversed. And now, we have a net motion of electrons – since more are going one way than the other.

But if the electrons are whizzing up and down the wire (equal numbers whizzing up and down) even before the battery is connected, how come they don't collide with things and lose energy until the battery is put in place? And why, exactly, are the electrons moving in the first place?

The answer goes to the root of what it is to be an electron. Electrons belong to the class of particles called fermions. Fermions are all observed to have a fascinating property – at no single point in time will you find two fermions without some distinguishing feature between them. So if you have two electrons in the same place at the same time, they might, for example, be different by virtue of having different velocities.

Not all electrons are free to move up and down the metal wire. Some are fixed in place. These are said to be localized electrons – they are fixed within a particular atom, and their position is marked as such. Accordingly, there is no problem with two apparently identical electrons being fixed within different atoms – they are obviously in different places.

However, the electrons which move, and therefore 'carry' the electric current, don't behave like this. In a sense, they all belong to the wire as a whole and act as a combined object flowing like a wave up and down the wire. In a sense, they are all in the same place – they are part of the same fluid or wave. Therefore they can only distinguish themselves from each other by having different velocities. This is why they can't all be stationary. If they were all stationary, they would all have the same velocity, so you could not tell them apart, and this is not allowed.

Consequently, the electrons usually take the lowest speeds allowed by this constraint. Yes, they do indeed collide with the fixed parts of the wire and each other before the battery is connected, but they can't lose energy during these collisions. For if an electron lost energy, it would also lose speed, which would mean that its velocity would change to some lower value. But it isn't allowed to have that value, because there is another electron in the wire which already has that lower velocity.

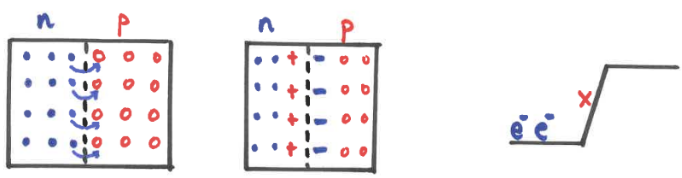
However, when the battery is connected, the electrons moving the 'right way' speed up a tiny bit, while the electrons moving the other way are slowed down by the same amount. This means that it is now possible for one of the fastest electrons moving the 'right way' to be bounced to a very slightly slower speed in the opposite direction and still have a unique velocity. Thus collisions involving a loss of electron energy can now occur. As we have explained earlier, the electron is soon sped up to its original speed by the electric field of the battery, so you don't notice a difference in the average velocity of the electrons at different points along the wire.

How a diode works

The diode is made of a semiconducting material. This is a material like silicon or germanium which has very few free charge carriers available, and which has four electrons in its outer shell. The material can be doped by adding a small percentage of another element.

So called n-type semiconductor has a small amount of a material with five outer shell electrons like phosphorus added. This contributes more electrons to the material, and the 'fifth electron' is much freer to move around the material than the regular electrons in the semiconductor.

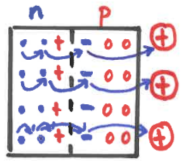
The opposite is when a small amount of boron (or some other material with three outer shell electrons) is added. This makes p-type semiconductor which has fewer electrons than pure silicon. This material can much more easily accept electrons than one without the added boron.

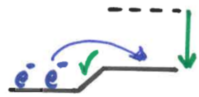


In a diode, thin layers of n-type and p-type semiconductor are joined, as shown in the diagram. Some of the especially mobile 'fifth electrons' from the n-type semiconductor move to join three-electron atoms in the p-type semiconductor.

This causes a charge difference at the barrier. The n-type region has lost electrons, so is now positively charged. The places where the electrons were are called holes. The p-type material has gained electrons so is negatively charged. This region near the junction with no 'fifth electrons' is called a depletion layer. Without mobile charge carriers it acts as an insulator, preventing further charge flow.

There are free electrons ('fifth electrons') in the n-type material further away from the boundary. However, because of the charge separation at the boundary, even if you could get them to cross it, you would have to push them hard to overcome the electrostatic force — you are trying, after all, to push them away from a $+$ charged region to a $-$ charged region. Effectively moving them would be like trying to push something uphill.





When we attach the diode to an electric circuit with the n-type semiconductor connected to the $-$ of the battery, two things happen. Electrons from the battery move through the n-type semiconductor to fill in the holes near the boundary. Meanwhile, the $+$ terminal of the battery attracts the free electrons in the p-type material away from the boundary. It is now possible for electrons to cross the boundary again.

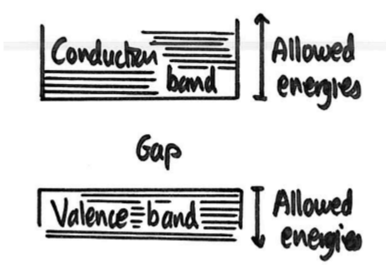
Another way of looking at it is to note that the electric field of the battery has reduced the energy required for an electron to move across the boundary, making the journey more accessible.

For a regular diode, the potential difference set up across the boundary by the depletion zone is about 0.6 V - hence the battery needs to overcome this before charge can flow.

How an LED works

In order to explain how an LED works, we are going to have to explore the energy levels of a semiconductor in more detail.

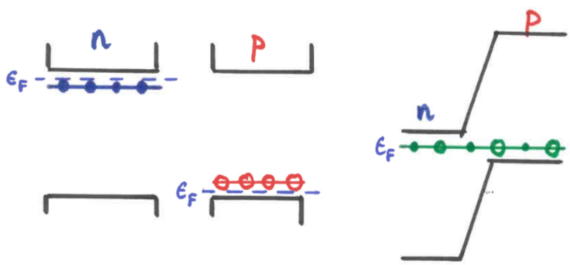
In a semiconductor, the allowed energies of electrons form two allowed regions, with a forbidden region (or gap) between them. The chance of an electron gaining enough energy to cross the gap is very much smaller than the chance of a single lottery ticket winning the jackpot, so the gap limits the ability of the material to conduct.



Usually the lower allowed region (the valence band) is full of electrons. They all move, but because just as many move one way as the other, there is no net current. The upper allowed region (the conduction band) has no electrons.

If an electron from the valence band were to be promoted, it would be free to move into any state of motion in the conduction band — so current could be carried. Furthermore, the vacancy it would leave behind in the valence band (the hole) would break the symmetry of the filled states there allowing the valence band to conduct too.

When we dope a semiconductor, we make extra energy levels. The fifth electrons in n-type semiconductor occupy a energy just below the conduction band. The three-electron atoms in the p-type semiconductor provides an energy level just above the valence band which can accept an electron from it.



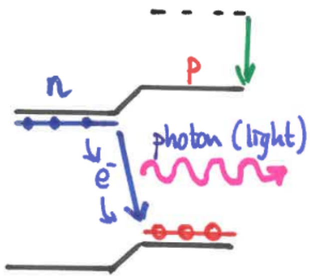
So, if we draw the energy level of the most energetic electrons, it will lie between the highest occupied electron energy and the lowest unoccupied electron energy.

In n-type semiconductor, this will lie between the 'fifth electron' level and the conduction band. In p-type semiconductor, it will lie between the valence band and the 'three electron atom' level.

Now if you use a piece of pipe to connect the bottoms of two buckets, and then pour water in, you notice that once things have settled, the water height in both buckets is the same. If it weren't the pressure difference would push water through the pipe until the levels were equal.

A similar thing happens when you stick a piece of n-type semiconductor next to a piece of p-type semiconductor. Things adjust to ensure the energy of the most energetic electrons on both sides of the boundary are the same.

This gives rise to the situation shown on the right in the diagram above. This is an alternative explanation of the depletion zone and the potential difference across it.



Now let's make the diode conduct by connecting a battery to counteract this potential. Notice that the effect of doing this is the energies of the most energetic electrons on either side of the boundary are now different as shown in the diagram above.

When an electron now passes from the n-type to p-type region, it will descend in energy. This will reduce its store of electric energy, and so this energy must be transferred somewhere. It is transferred as light. Each time an electron crosses the boundary, one packet (or photon) of light is produced.

Quantum physics has enabled us to find out that the energy of one of these photons is given by hf where h is a fixed number called the Planck Constant with a value of 6.63×10^{-34} Js and f is the frequency of the light in hertz.

The energy removed from the electrical store (and thus the chemical store of the battery) must equal the charge multiplied by the battery, hence qV where $q = 1.60 \times 10^{-19}$ C is the magnitude of charge on an electron.

Putting these two equations together tells you that for light to be emitted $qV > hf$, and so

$$V > \frac{hf}{q}.$$

Using this formula you can see that for a green LED to be lit, where green light has a frequency of about 6×10^{14} Hz, we must have a potential difference of more than 2.5 V.

A red LED requires a lower voltage as the frequency of red light is lower.