National 5 Physics

Electricity

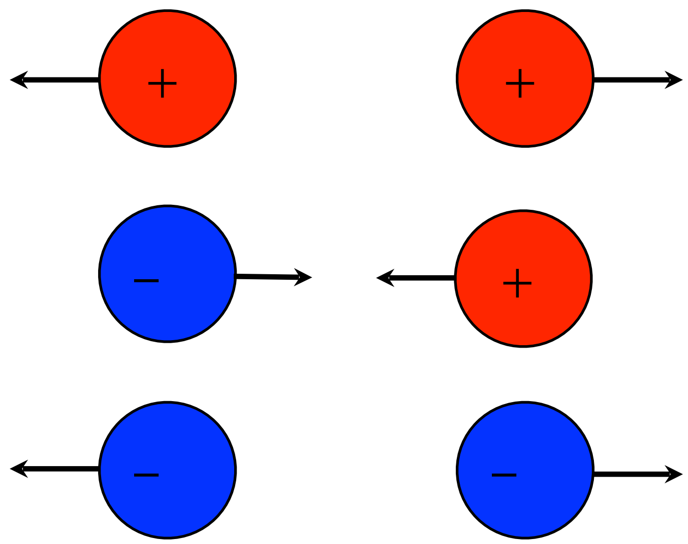
ELECTRICAL CHARGE CARRIERS AND CURRENT

Electrical Charge

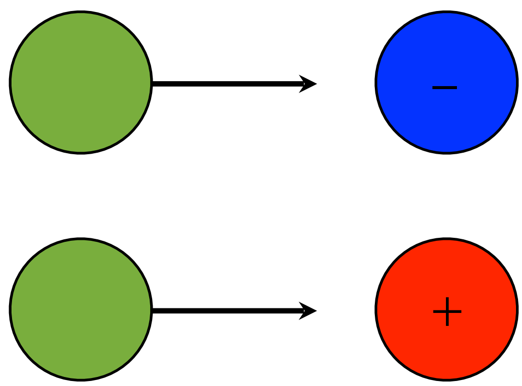
Electrical charge exists in two distinct types — **positive** charge and **negative** charge. It is also possible for an object or particle to have no electrical charge at all, we call these objects electrically **neutral**.

Positively charged objects will repel other positively charged particles. However they will be attracted to negatively charged objects. Similarly negatively charged objects will repel other negatively charged particles but they will be attracted to positively charged objects. This can be remembered as two simple rules:

- Like charges **repel**
- Opposite charges **attract**

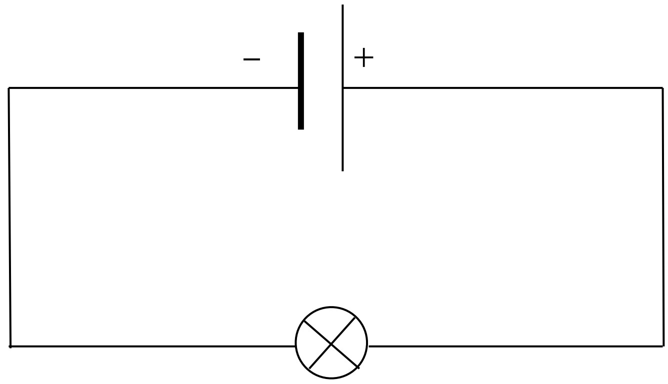


Neutrally charged objects are attracted to **both** positively charged and negatively charged objects.

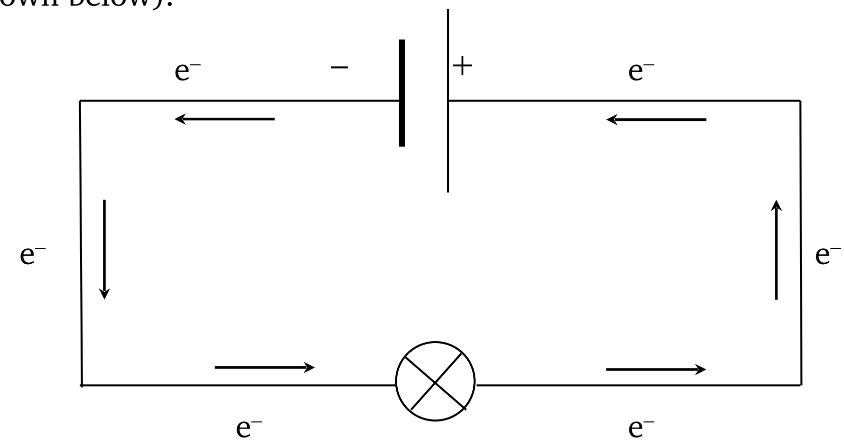


Current

Electrical current is simply the flow of charge carriers. In a standard electrical circuit the charge carriers are **electrons**. As an example consider the circuit below:



Electrons are **repelled** away from the negative terminal of the battery and **attracted** to the positive terminal of the battery. To move from the negative terminal to the positive terminal they need to move around the circuit through the lamp (as shown below).



We call this negative to positive current **electron flow** or more usually just **current**. However scientists used to think that charges flowed from positive to negative. If these scientists were alive today they would probably argue that they were still correct and that an absence of an electron (or hole) flows from positive to negative. Nevertheless it was thought that current flows from positive to negative for many years and circuit symbols and diagrams often make more sense if you do think about current flowing from positive to negative. Today we call this **conventional current**. At National 5 we will only ever talk about electron flow but if you look at English or American materials they almost exclusively use conventional current. Remember:

- **Current (Electron Flow)** — negative to positive
- **Conventional Current** — positive to negative

Current, Charge, Time Formula

We define current as the amount of charge flowing past a point in a circuit per second. Current is measured in amperes, or amps for short. One amp is equal to one coulomb (the unit of charge) per second. The formula for this is on the formula sheet and is given below:

$$Q = It$$

Charge measured in coulombs (C)

Current measured in amperes or amps (A)

Time measured in seconds (s)

Example

A lamp has a current of 1.5 amperes flowing through it while lit. How much charge flows through the lamp in 50 seconds?

Practice Problems

1. The current in a heater is 7 amperes. How many Coulombs of charge flow through the heater in 30 seconds?

2. The total charge that flows in a circuit is 12 C. The time taken for this charge to flow is 6 s. What is the current flowing in the circuit?

3. A car headlamp uses a current of 2 A. How long must the lamp be switched on for 10 C to pass through it?

4. A hair dryer is switched on for 5 minutes and the current flowing is 3 A. How much charge flows through the hairdryer in this time?

5. What is the current when 4 C of charge passes a point in 0.4 s?

6. How much charge passes through a cow if it touches an electric fence and receives a pulse of 20 milliamperes (mA) for 0.1 seconds?

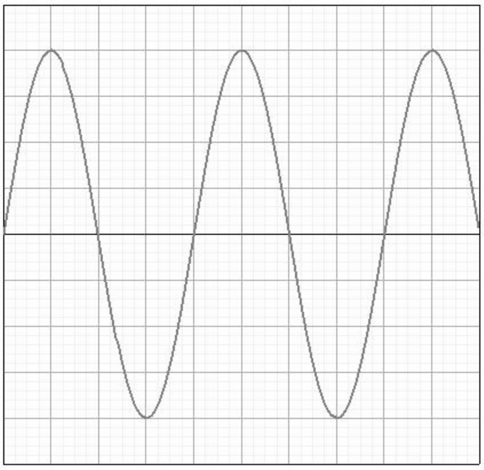
7. A torch lamp passes 720 C of charge in 1 hour. What is the current in the lamp?

Alternating and Direct Current (a.c./d.c.)

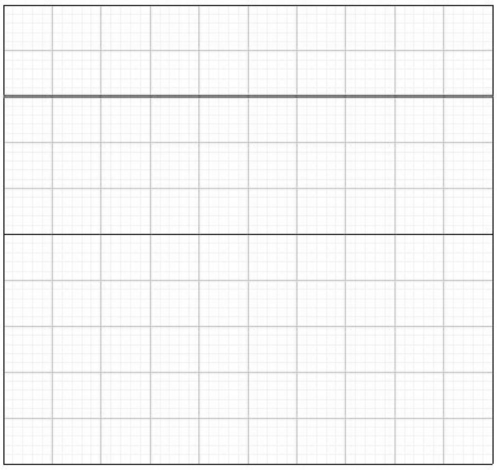
When current flows from negative to positive we call this **direct current**. Direct current is supplied by batteries and some specialist power supplies. However the electricity in a mains socket does not have a positive and negative terminal — instead it uses **alternating current**.

Alternating current does not have a positive and negative, instead the direction of the current changes, usually many times a second. In the United Kingdom mains electricity uses alternating current with a frequency of 50Hz. This means that in one second the current changes from flowing in one direction to another and back 50 times.

Below is what ideal alternating current (on the left) and direct current (on the right) sources would look like when connected to an oscilloscope:



sinusoidal a.c. waveform



constant d.c. waveform

Circuits that use alternating current do not have positive and negative terminals, instead they use **live** and **neutral** terminals and wires. Some high voltage circuits will also include an **earth** wire as a safety measure. In the U.K. there is a common standard defining the colour of insulation on these wires:

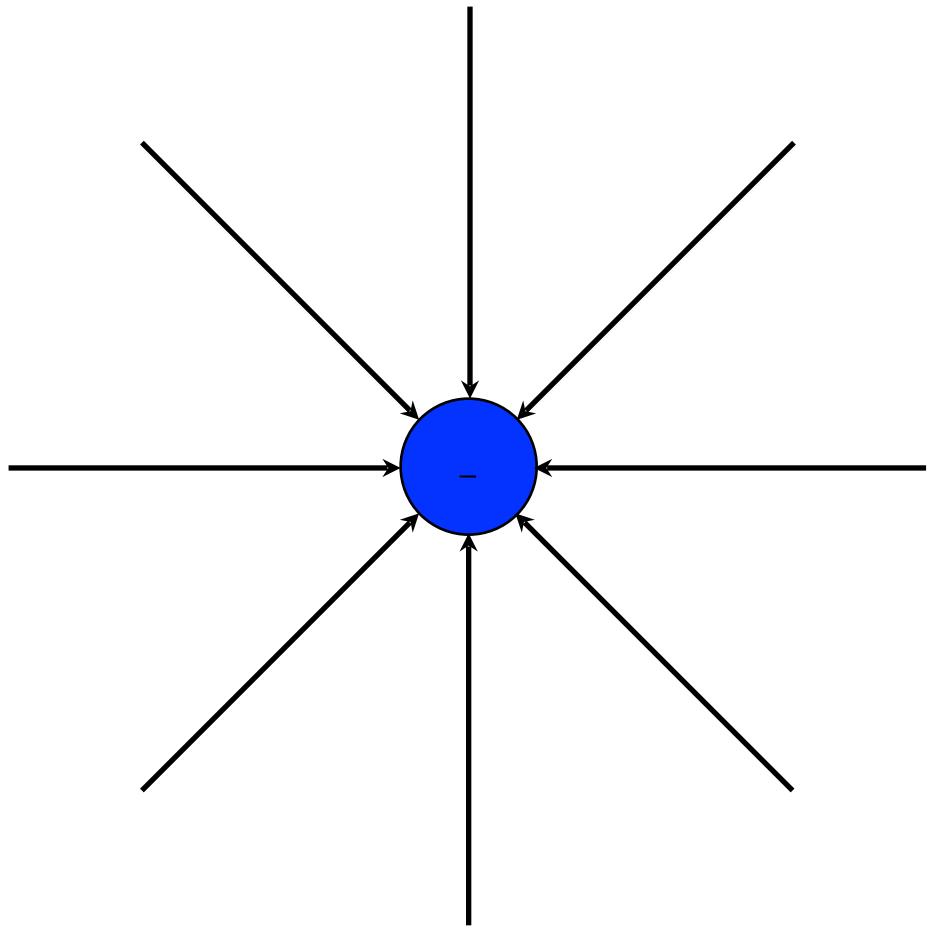
- Live — **Brown**
- Neutral — **Blue**
- Earth — Yellow and **Green** stripes

Electric Fields and Potential Difference

Any electrically charged object emits an **electric field**. The strength of the electric field depends on how much charge the object has — and how far away from the object you are. The shape of the field is determined by the shape of the object. These fields can exert a force on other charged particles. We can visualise electric fields by drawing arrows showing what direction an imaginary **positive** test charge would travel. Any charge particle will experience a **force** in an electric field. This will cause the charge particle to **accelerate** due to Newton's Second Law[1].

Point Charge

Below is the electric field around a negatively charged sphere, like an electron:

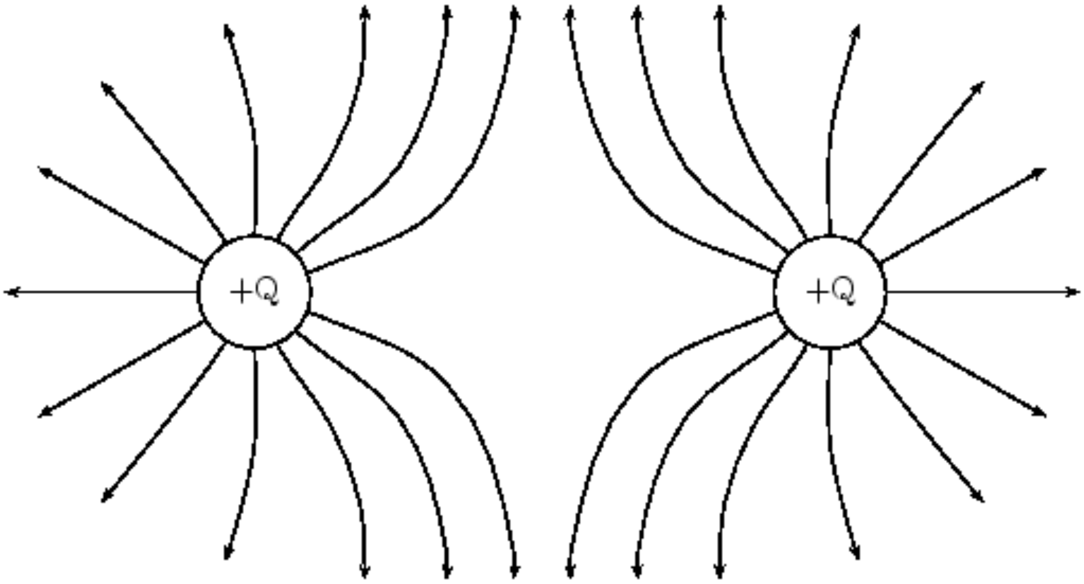


A positive charge placed anywhere around this negatively charged sphere would be attracted towards it — just as we would expect. A positively charged sphere, like a Van der Graaf generator would have the same shape of field but the arrows would point in the **opposite** direction.

[1] See the Mechanics topic for more detail on Newton's Second Law.

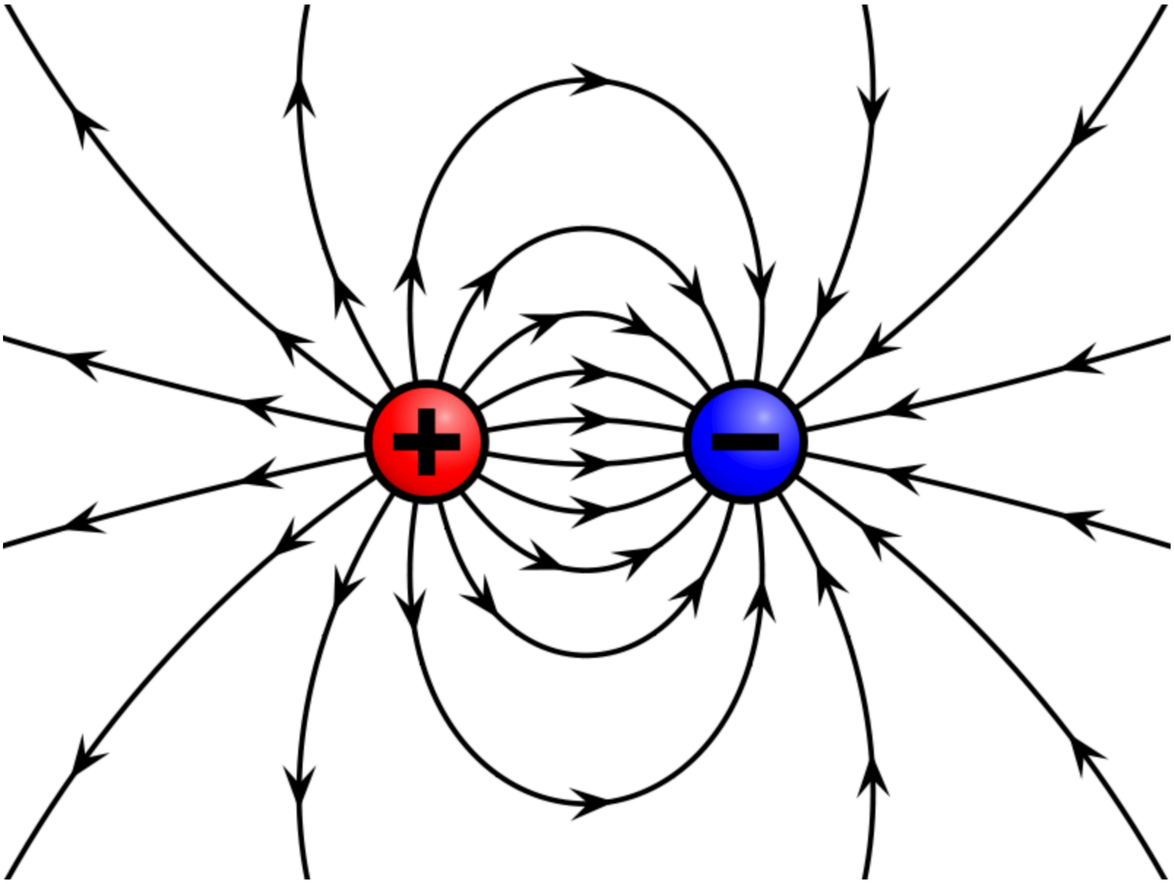
Two Like Charges

Below is the electric field around two negatively charged spheres, such as two protons:



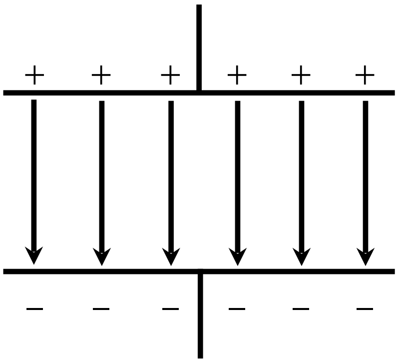
Two Opposite Charges

Below is the electric field around two oppositely charged spheres, such as a positron and an electron:



Parallel Plates

There is a special type of electric field that we can create when we set up two metal plates (one positive and one negative or neutral) parallel to each other and separated by an insulator. The field between this arrangement of parallel plates looks like this:

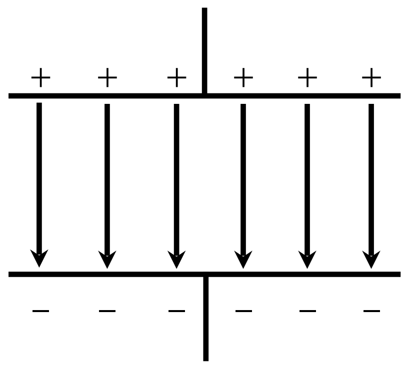


A positive charge anywhere between the two plates will be attracted towards the negative plate and repelled from the positive plate. In other words a positively charged particle would move towards the negative plate. Conversely a negatively charge particle would move towards the positive plate.

Imagine that you could put a negatively charged particle (say an electron) on the negative plate. It would want to move towards the positive plate. If it was allowed to travel across the gap it would gain kinetic energy. However if it cannot move across the gap it will try to find another route to the positive plate — for instance through an electrical circuit.

Potential Difference/Voltage

Consider again the two parallel plates:



Imagine we tried to drag a positively charged particle from the negative plate to the positive plate. Energy had to be given to the charged particle to move it against the direction of the electric field. In Physics we would say work is done (we will revisit the idea of work in the Dynamics and Space unit).

Imagine that the particle is now released from the positive plate. Before the charged particle is released it has electrical potential energy and when it is released this is converted to kinetic energy.

We say that the plates have a **voltage** across them or **potential difference** between them. If a potential difference is applied to either end of a conductor electrons will flow towards the positive end and away from the negative end — causing a current.

When electrons move through an electrical component (such as a lamp) they may convert some of their electrical energy into other forms (such as light). This means they will 'loose' some electrical energy and so their voltage will be less. This can be measured and the amount of potential difference or voltage across a component is linked to the amount of energy lost by the electrons in the component. The higher the voltage the more energy lost by the electrons.

Extension — Voltage formula

Voltage can be thought of as the amount of energy a charged particle has per coulomb of charge. One volt is defined as one joule per coulomb. There is a formula for this, though it is **not** needed at National 5 for calculations it can be useful when answering "explain" type questions.

$$V = E \div Q$$

Voltage measured in volts (V) or joules per coulomb (JC^{-1})

Electrical energy (or work) measured in joules (J)

Charge measured in coulombs (C)

Ohm's Law

Resistance

Resistance is a measure of how hard it is for electrons to flow through a component or wire. Resistance is measured in ohms (Ω). It was discovered and named when Georg Ohm noticed that the gradient of a V/I graph is constant when the voltage and current across a wire is measured.

Lots of things can affect the resistance of a component or wire. For an ordinary conducting wire the following factors affect resistance:

- Length — the **longer** wire the **higher** the resistance
- Area — the **smaller** the cross sectional area of a wire the **higher** the resistance
- Material — some conductors are better than others!
- Temperature — the **higher** the temperature the **higher** the resistance

The relationship between temperature and resistance is particularly important as some components heat up in use, changing their resistance. Some materials can be cooled so much that their resistance drops to zero — becoming a **superconductor**.

Georg Ohm (16 March 1789 – 6 July 1854)

Ohm’s Law Formula

Today we summarise Georg Ohm’s work on voltage and current as a formula stating that the voltage across a component (or conductor) is equal to the current flowing though the component multiplied by the resistance of the component. It appears on the formula sheet and is given below:

$$V = IR$$

Voltage measured in volts (V)

Current measured in amps (A)

Resistance measured in ohms (Ω)

Example

A battery supplies a lamp of resistance 10 Ω with a current of 0.2 A. What is the voltage supplied by the battery?

Practice Problems

1. A current of 2 A flows through a heating element of resistance 60 Ω. What is the voltage supplied to the element?

2. A bulb is rated at 2.2 V and 0.2 A. What is its resistance when it is used at its correct rating?

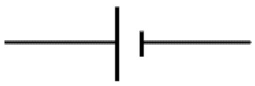
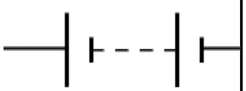
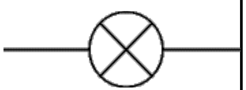
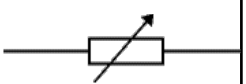
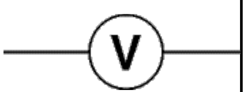
3. An electrical supply of 12 V is supplied to a 10 kΩ resistor. What current flows in the resistor?

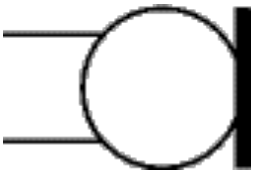
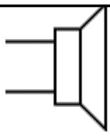
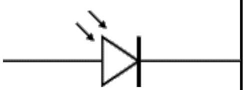
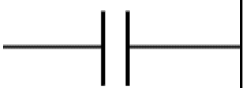
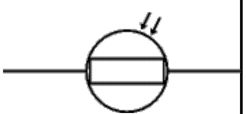
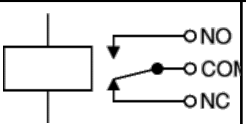
4. The voltage supply to a circuit is doubled but the resistance is kept the same. How does this affect the amount of current that flows in the circuit?

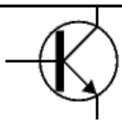
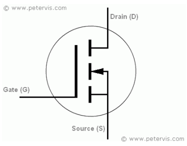
Practical Circuits

Circuit Symbols

It would be impractical and confusing to draw an electrical circuit as a picture. Instead all electrical components are represented by unique and standardised symbols connected with lines (representing wires) in a **circuit diagram**. Below are the symbols you will need to recognise, what they represent, what that component does and an example use.

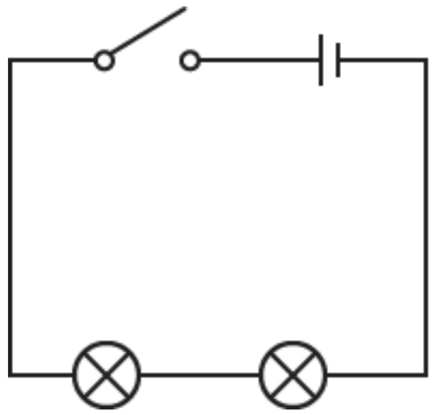
Symbol	Component	Function	Example Application
	cell	providing voltage	combining into a battery
	battery	providing voltage	powering circuits
	lamp	producing light	lighting
	switch	controlling current (on/off)	various
	resistor	controlling resistance (fixed)	potential dividers
	variable resistor	controlling resistance (variable)	dimmer switch
	voltmeter	measuring voltage	fault finding
	ammeter	measuring current	electrical safety

Symbol	Component	Function	Example Application
	diode	controlling current direction	a.c. to d.c adapters
	light emitting diode (LED)	producing light	on/off indicator lights
	microphone	converting sound to electrical signals	telephone
	loudspeaker	producing sound	headphones
	photodiode	detecting light	light gate
	fuse	limiting current	standard U.K. plug
	capacitor	storing charge, smoothing, time delays	various
	thermistor	detecting temperature changes	thermostats
	light dependant resistor (LDR)	detecting light changes	street lighting
	relay	circuit connecting switch	car ignition

Symbol	Component	Function	Example Application
	NPN transistor	controllable switch	logic gates, computers
	MOSFET transistor	controllable switch	logic gates, computers
	motor	producing rotational motion	electric car

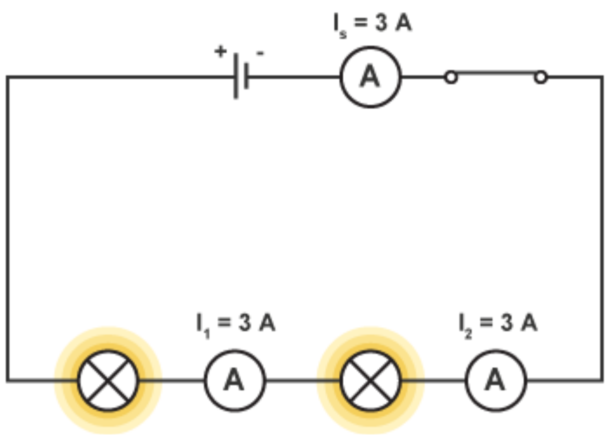
Series Circuits

Series circuits are constructed by 'daisy chaining' components together. The circuit shown below is an example of a typical series circuit:



Current in a Series Circuit

The current in a series circuit is the **same** at every point in the circuit.



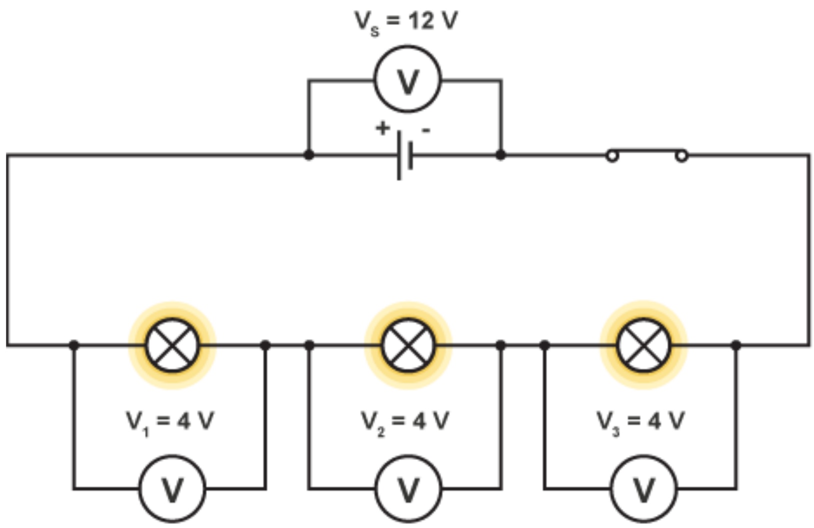
$$I_s = I_1 = I_2 = \ldots$$

Voltage in a Series Circuit

The voltages in a series circuit are ‘shared’ amongst the components. The voltages across all of the components in the circuit add up to the voltage of the supply. There is a formula to help you to remember this but it is not on the formula sheet:

$$V_S = V_1 + V_2 + \ldots$$

Below is an example of this rule in a series circuit:



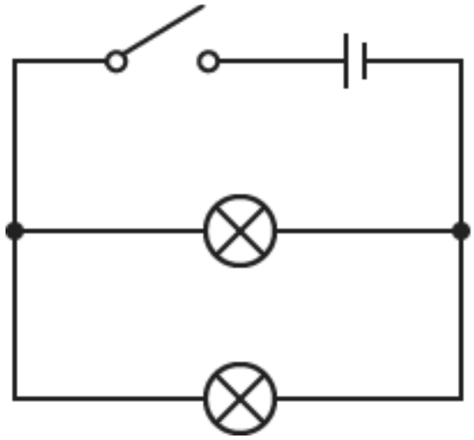
Resistance in a Series Circuit

The total resistance of a series circuit is equal to the sum of all of the resistances of the components. There is a formula for this and does appear on the formula sheet:

$$R_T = R_1 + R_2 + \ldots$$

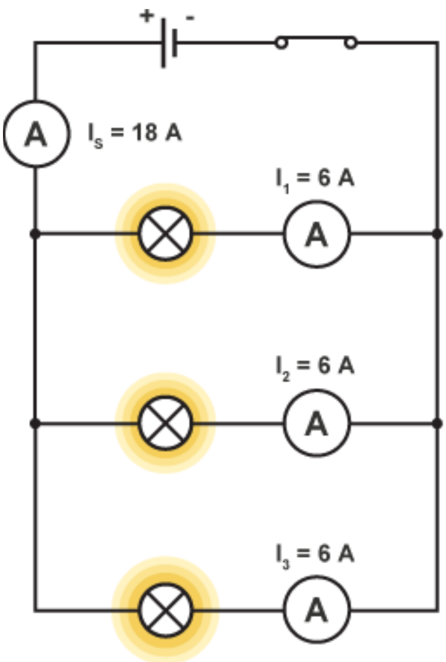
Parallel Circuits

Parallel circuits are constructed by placing each component on its own 'branch'. The circuit shown below is an example of a typical parallel circuit:



Current in a Parallel Circuit

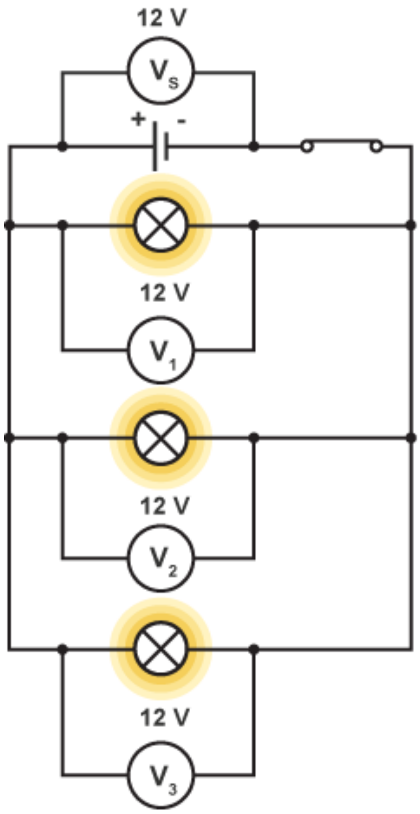
The currents in each of the branches add up to the current entering and leaving the power supply.



$$I_p = I_1 + I_2 + \ldots$$

Voltage in a Parallel Circuit

The voltage on every branch of a parallel circuit is the **same**. If the branches are connected directly to the power supply then the voltage in each branch will be the same as the voltage across the power supply.



$$V_p = V_1 = V_2$$

Resistance in a Parallel Circuit

The total resistance of a parallel circuit is a little tricky to calculate. **One over** the total resistance is equal to the sum of **one over** the resistance of each brach. The formula for this appears on the formula sheet and is given below:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

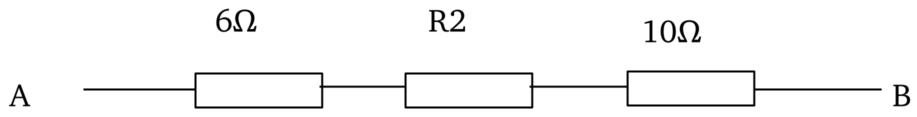
Practice Problems

1. A resistor of 3 Ω is in series with another resistor of 3 Ω. What is the total resistance?

2. The two 3 Ω resistors are now joined in parallel. What is the total resistance now?

3. The resistance of one Christmas tree light is 24 Ω. What is the total resistance of 20 lights in series?

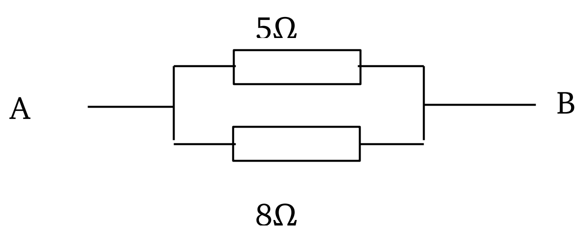
4. In the diagram below, the total resistance across AB is measured and found to be 25 Ω.



What is the resistance of R_2?

5. Two 10Ω resistors are connected in parallel. What is their total resistance?

6. What is the total resistance across AB in the circuit below?



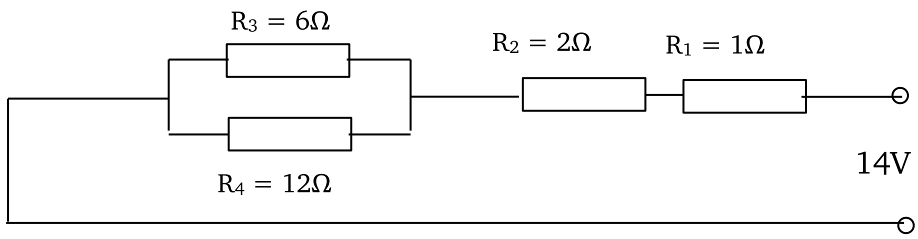
7. Two bars of an electric fire are joined in parallel. If each of the bars has a resistance of 1 kΩ.

   a) What is the total resistance?

   b) If the bars are connected to a 230 V power pack, what current will be supplied?

   c) What current will flow in each of the bars?

8. Four resistors are connected as shown in the circuit diagram below.



a) What is the total resistance of the resistors in parallel?

b) What is the total resistance in the circuit?

c) The current through R_1 is found to be 2A. What is the current flowing through R_2?

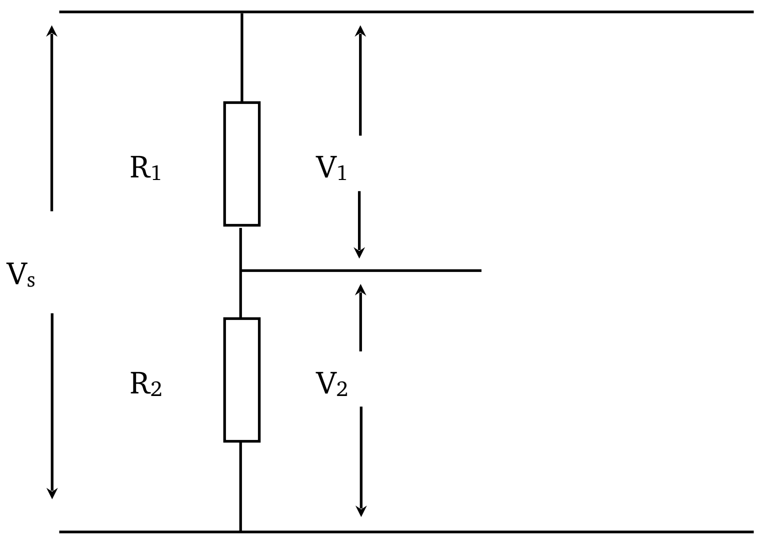
d) If the voltage across R_3 is 8V, what is the voltage across R_4?

e) What is the current flowing through R_3?

The Potential Divider aka The Voltage Divider

A potential divider provides a convenient way of obtaining a variable voltage from a fixed voltage supply.

Consider two fixed resistors, R_1 and R_2, connected in series across a supply with voltage V_s, as shown below:



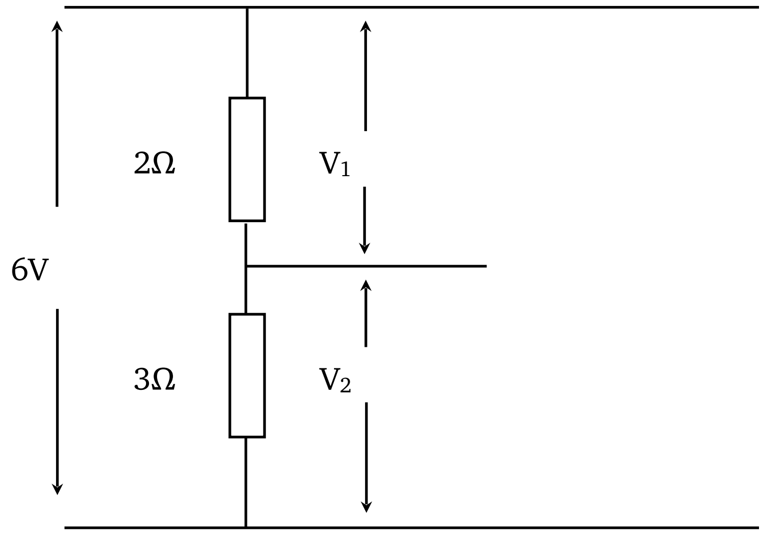
The current in the two resistors will be the same, however the voltage across the two resistors will be split. Whilst we could use Ohm's Law to calculate V_1 and V_2 (Or R_1 and R_2) there are two 'shortcut' formulae we can use. Both are on the formula sheet. The first, given below, is useful when you know 3 out of the 4 variables:

$$\frac{V_1}{V_2} = \frac{R_1}{R_2}$$

The second is useful when you know the supply voltage and the value of both resistors but not V_1 or V_2. This is a very handy formula that can save you much time when solving potential divider questions. It is given below:

$$V_2 = \left(\frac{R_2}{R_1 + R_2} \right) V_s$$

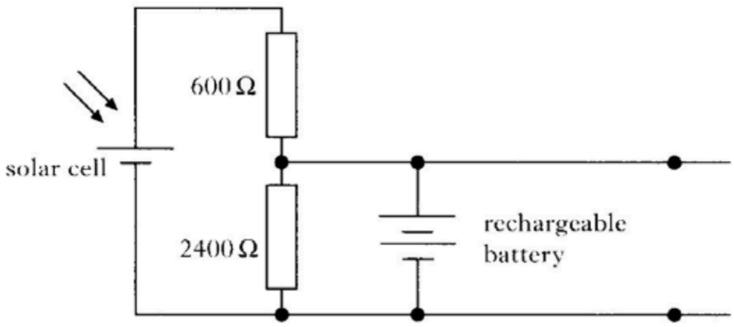
Example



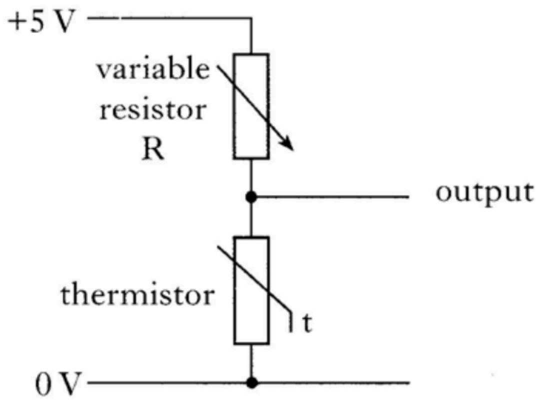
Find the values of V_1 and V_2

Practice Problems

1. Below is the circuit used in a solar powered battery charger. If the solar cell produces a voltage of 1.5 V what is the voltage across the rechargeable battery?

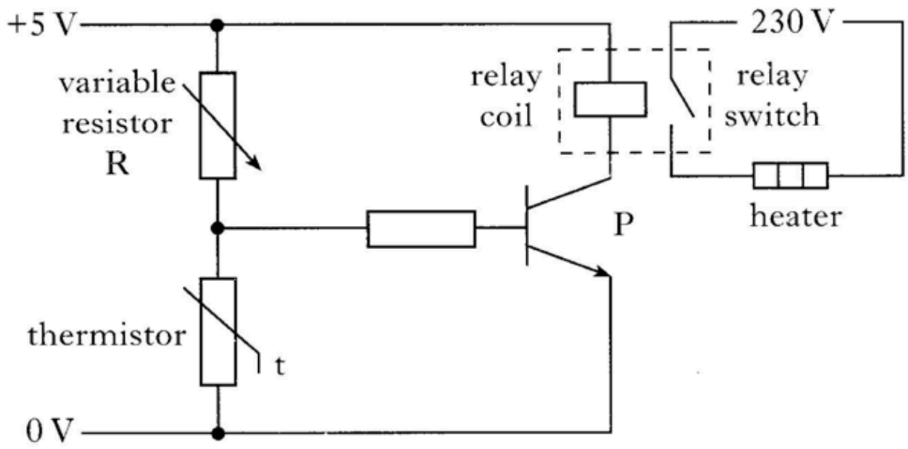


2. In the circuit below the variable resistor is set to 800 Ω. What is the resistance of the thermistor if the output voltage is 1.4 V?



Transistor Switching Circuits

Voltage dividers can be used to create automatic switching circuits by connecting the output voltage to a transistor. Below is an example circuit:



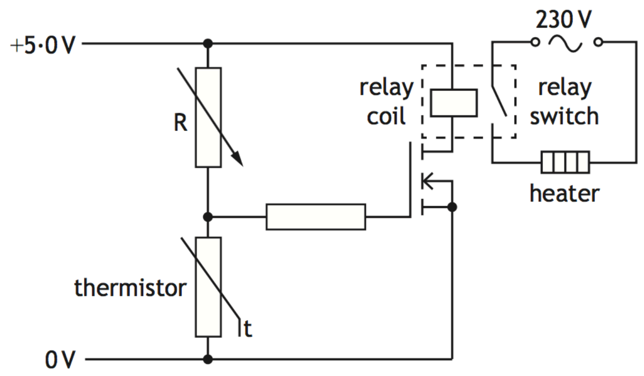
The circuit works as an automatic heater. The temperature that activates the circuit can be adjusted by changing the resistance of the variable resistor. The circuit operates like this:

1. As the temperature drops the resistance of the thermistor increases.
2. Because the thermistor is connected in a voltage divider circuit the voltage across the thermistor will increase.
3. Once the voltage across the thermistor reaches the switching voltage of the transistor the transistor will switch on. (This is 0.7 V for an NPN transistor and 1.4 V for an n-channel enhancement mode MOSFET).
4. When the transistor switches on it will allow current to flow through the relay coil.
5. The relay coil (which is an electromagnet) will energise and pull the relay switch shut.
6. This will switch the heater on.

Transistor switching circuits are extremely useful, allowing circuits to operate automatically and they form the basis of all computing.

Practice Problem

The variable resistor in the circuit below is set to 1050 Ω.



Explain how the circuit operates to switch on the heater when the temperature falls below a certain value (You must calculate the required voltage across the thermistor).

POWER

Power is defined in Physics as the amount of energy something uses every second. On electrical alliances the power of an appliance is given by its **power rating**. This can be found on the **rating plate**.

As you can see above the power rating of this appliance is 240 W. That means it uses 240 joules of energy every second. The W stands for watts — the units of power. 1 watt is equal to 1 joule per second. However power can be calculated for **any** form of energy not just electrical energy.

Power, Energy and Time Formula

Power is equal to energy divided by time. The formula appears on the formula sheet and is given below:

$$P = \frac{E}{t}$$

Energy measured in joules (J)

Power measured in watts (W) or joules per second ($J\,s^{-1}$)

Time measured in seconds (s)

Practice Problems

1. If a CD player supplies 100 J of sound energy per second, what is its power rating?

2. A heater supplies 3000 J of heat energy in 5 seconds. What is its power rating?

3. A miniature water heater is rated at 750 W. How many joules of heat energy will it produce each second?

4. A heater is rated at 3 kW. How much energy does it supply in one hour of use?

5. A miniature heater for making cups of tea is rated at 150 W. If it takes 45 kJ to boil the water, how long will this take?

6. A lamp converts 1000 J of electrical energy into light energy in 10 s.

   a) How much electrical energy does it convert every second?

   b) What is the power rating of the lamp?

7. If it requires 450 kJ of energy to boil a kettle of water, how long will this take if the power rating of a kettle is 2 kW?

8. An electric shower rated at 10 kW is switched on for 5 minutes. How much energy will it use up?

Electrical Power Formula

It is simple to calculate the amount of power an electrical appliance is using. The electrical power used is equal to the current multiplied by the voltage. The formula appears on the formula sheet and is given below:

$$P = IV$$

Power measured in watts (W) or joules per second ($J\,s^{-1}$)

Current measured in amperes (A)

Voltage measured in volts (V)

This is a very useful formula. For any appliance (such as the one on page 29) you can calculate the theoretical maximum current the appliance should use, this then lets you choose the correct fuse to use with the appliance. For mains appliances in the UK the following rule of thumb can be used:

- Appliances with a power rating of less than 720 W need a 3 A fuse.
- Appliances with a power rating of more than 720 W need a 13 A fuse.

Practice Problems

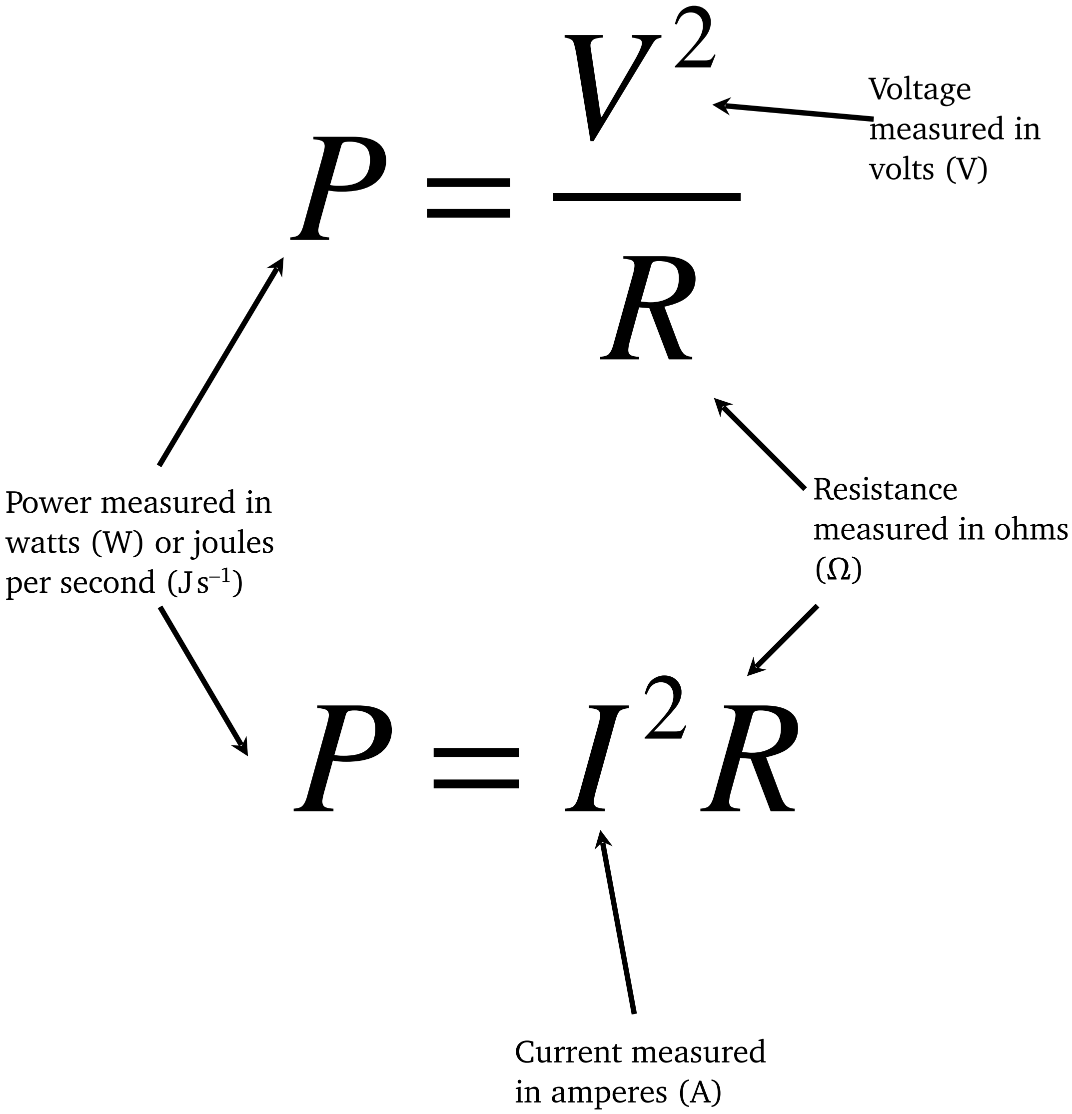
1. What is the power rating of a car sidelight that is supplied with 0.5 A of current from a 12 V supply?

2. An electric heater is rated at 3 kW and is connected to a mains supply of 230 V. What is the current that flows through it?

3. What is the supply voltage to a hairdryer which uses a power of 920 W and a current of 4 A?

More Power Formulae

We can combine P=IV and V=IR (Ohm's Law) to make two additional formulae for electrical power. Both are on the formula sheet and are given below:



Practice Problems

1. What is the power rating of a bulb of resistance 18 Ω if the correct current supply is 2 A?

2. An engineer is designing a fire and reads a data book stating that a 26.5 Ω resistor can safely handle a power of 2 kW. What is the maximum current it can safely handle?

3. The heating element of a hairdryer is supplied with 920 W of electrical power at a current of 4 A. What is the resistance of the element?

4. A 36 W bulb has a resistance of 9 Ω. What current flows through the bulb when it is operating at its correct power rating?

5. An electric fire operating at its correct power rating of 1 kW has an element with resistance of 53 Ω. What voltage is required to operate this appliance properly?

6. Find the power ratings of the following appliances:

   a) A 12 V bulb that takes a current of 1.5 A

   b) A 230 V drill that takes a current of 2.5 A

7. A 60 W car windscreen heater operates at 12 V. Find the current it uses.

8. A digital watch has a power rating of 0.12 W and takes a current of 0.08 A. What would be the voltage of the battery it uses?

9. A mains (230 V) operated electric oven has two power settings, 3 kW (low) and 5 kW (high). Calculate the current it uses at both low and high settings.

Electricity

You need to know:

	✓ ? ✘
That there are two types of charge; positive and negative	
That like charges repel each other	
That unlike charges attract one another	
That in an electric field a charged object will experience an unbalanced force	
How to use the Q = It formula	
That electrons are free to move in a conductor	
How to explain current in terms of moving charges	
That voltage is the energy per unit of charge	
What the circuit symbols, functions and applications of the following are: Cell, battery, resistor, variable resistor, fuse, switch, lamp, ammeter, voltmeter, LED, LDR, thermistor, transistor.	
If ammeters and voltmeters are connected in series or parallel and how to add them into a circuit diagram	
How to use Ohm's Law (the V = IR formula) and how to find resistance from a V/I graph	
That the resistance of a resistor can change if its temperature changes	
That in a series circuit the current is the same at all points in the circuit	
That all the voltages in a series circuit add up to the supply voltage	
That the currents in a parallel circuit add up to the supply current	

	✓ ? ✘
That the voltage across each ‘branch’ of a parallel circuit is the same as the supply voltage	
How to calculate the total resistance of series and parallel crcuits (the $R_T = R_1 + R_2$ and $1/R_T = 1/R_1 + 1/R_2$ formulae)	
The energy transformations in common electrical components	
That the resistance of a thermistor decreases as temperature increases	
That the resistance of an LDR decreases as the intensity of light increases	
That an LED will only light if connected a certain way round in a circuit	
That transistor can be used as a switch and how transistor circuits work	
The voltage divider shortcut formulae	
How to use the $P = IV$ formula	
How to use the $P = I^2R$ formula	
How to use the $P = V^2/R$ formula	