ELECTRICITY AND MAGNETISIUM
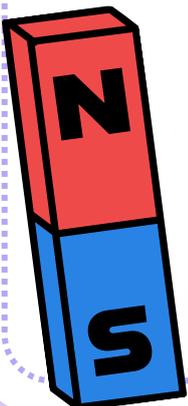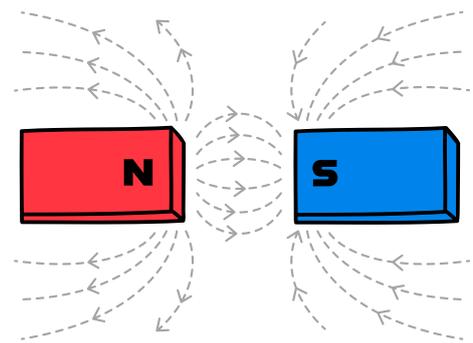
Content

- Syllabus (0625)
- Notes by cognito
- Cambridge O Level Physics book section for extra explanation

4   Electricity and magnetism

4.1   Simple phenomena of magnetism

Core

1   Describe the forces between magnetic poles and between magnets and magnetic materials, including the use of the terms north pole (N pole), south pole (S pole), attraction and repulsion, magnetised and unmagnetised

2   Describe induced magnetism

3   State the differences between the properties of temporary magnets (made of soft iron) and the properties of permanent magnets (made of steel)

4   State the difference between magnetic and non-magnetic materials

5   Describe a magnetic field as a region in which a magnetic pole experiences a force

6   Draw the pattern and direction of magnetic field lines around a bar magnet

7   State that the direction of a magnetic field at a point is the direction of the force on the N pole of a magnet at that point

8   Describe the plotting of magnetic field lines with a compass or iron filings and the use of a compass to determine the direction of the magnetic field

9   Describe the uses of permanent magnets and electromagnets

Supplement

10   Explain that magnetic forces are due to interactions between magnetic fields

11   Know that the relative strength of a magnetic field is represented by the spacing of the magnetic field lines

4.2   Electrical quantities

4.2.1 Electric charge

Core

1   State that there are positive and negative charges

2   State that positive charges repel other positive charges, negative charges repel other negative charges, but positive charges attract negative charges

3   Describe simple experiments to show the production of electrostatic charges by friction and to show the detection of electrostatic charges

4   Explain that charging of solids by friction involves only a transfer of negative charge (electrons)

5   Describe an experiment to distinguish between electrical conductors and insulators

6   Recall and use a simple electron model to explain the difference between electrical conductors and insulators and give typical examples

Supplement

7   State that charge is measured in coulombs

8   Describe an electric field as a region in which an electric charge experiences a force

9   State that the direction of an electric field at a point is the direction of the force on a positive charge at that point

10   Describe simple electric field patterns, including the direction of the field:

    (a) around a point charge

    (b) around a charged conducting sphere

    (c) between two oppositely charged parallel conducting plates (end effects will **not** be examined)

4.2.2 Electric current

Core

1   Know that electric current is related to the flow of charge

2   Describe the use of ammeters (analogue and digital) with different ranges

3   Describe electrical conduction in metals in terms of the movement of free electrons

4   Know the difference between direct current (d.c.) and alternating current (a.c.)

Supplement

5   Define electric current as the charge passing a point per unit time; recall and use the equation

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

6   State that conventional current is from positive to negative and that the flow of free electrons is from negative to positive

4.2   Electrical quantities continued

4.2.3 Electromotive force and potential difference

Core

1   Define electromotive force (e.m.f.) as the electrical work done by a source in moving a unit charge around a complete circuit

2   Know that e.m.f. is measured in volts (V)

3   Define potential difference (p.d.) as the work done by a unit charge passing through a component

4   Know that the p.d. between two points is measured in volts (V)

5   Describe the use of voltmeters (analogue and digital) with different ranges

Supplement

6   Recall and use the equation for e.m.f.

$$E = \frac{W}{Q}$$

7   Recall and use the equation for p.d.

$$V = \frac{W}{Q}$$

4.2.4 Resistance

Core

1   Recall and use the equation for resistance

$$R = \frac{V}{I}$$

2   Describe an experiment to determine resistance using a voltmeter and an ammeter and do the appropriate calculations

3   State, qualitatively, the relationship of the resistance of a metallic wire to its length and to its cross-sectional area

Supplement

4   Sketch and explain the current–voltage graphs for a resistor of constant resistance, a filament lamp and a diode

5   Recall and use the following relationship for a metallic electrical conductor:

   (a) resistance is directly proportional to length

   (b) resistance is inversely proportional to cross-sectional area

4.2.5 Electrical energy and electrical power

Core

1   Understand that electric circuits transfer energy from a source of electrical energy, such as an electrical cell or mains supply, to the circuit components and then into the surroundings

2   Recall and use the equation for electrical power

$$P = IV$$

3   Recall and use the equation for electrical energy

$$E = IVt$$

4   Define the kilowatt-hour (kW h) and calculate the cost of using electrical appliances where the energy unit is the kW h

Supplement

4.3   Electric circuits continued

4.3.3 Action and use of circuit components

Core

1   Know that the p.d. across an electrical conductor increases as its resistance increases for a constant current

Supplement

2   Describe the action of a variable potential divider

3   Recall and use the equation for two resistors used as a potential divider

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

4.4   Electrical safety

Core

1   State the hazards of:

(a) damaged insulation

(b) overheating cables

(c) damp conditions

(d) excess current from overloading of plugs, extension leads, single and multiple sockets

when using a mains supply

2   Know that a mains circuit consists of a live wire (line wire), a neutral wire and an earth wire and explain why a switch must be connected to the live wire for the circuit to be switched off safely

3   Explain the use and operation of trip switches and fuses and choose appropriate fuse ratings and trip switch settings

4   Explain why the outer casing of an electrical appliance must be either non-conducting (double-insulated) or earthed

5   State that a fuse without an earth wire protects the circuit and the cabling for a double-insulated appliance

Supplement

4.5   Electromagnetic effects

4.5.1 Electromagnetic induction

Core

1   Know that a conductor moving across a magnetic field or a changing magnetic field linking with a conductor can induce an e.m.f. in the conductor

2   Describe an experiment to demonstrate electromagnetic induction

3   State the factors affecting the magnitude of an induced e.m.f.

Supplement

4   Know that the direction of an induced e.m.f. opposes the change causing it

5   State and use the relative directions of force, field and induced current

4.5.2 The a.c. generator

Core

Supplement

1   Describe a simple form of a.c. generator (rotating coil or rotating magnet) and the use of slip rings and brushes where needed

2   Sketch and interpret graphs of e.m.f. against time for simple a.c. generators and relate the position of the generator coil to the peaks, troughs and zeros of the e.m.f.

4.5.3 Magnetic effect of a current

Core

1   Describe the pattern and direction of the magnetic field due to currents in straight wires and in solenoids

2   Describe an experiment to identify the pattern of the magnetic field (including direction) due to currents in straight wires and in solenoids

3   Describe how the magnetic effect of a current is used in relays and loudspeakers and give examples of their application

Supplement

4   State the qualitative variation of the strength of the magnetic field around straight wires and solenoids

5   Describe the effect on the magnetic field around straight wires and solenoids of changing the magnitude and direction of the current

4.5   Electromagnetic effects continued

4.5.4 Force on a current-carrying conductor

Core

1   Describe an experiment to show that a force acts on a current-carrying conductor in a magnetic field, including the effect of reversing:

(a) the current

(b) the direction of the field

Supplement

2   Recall and use the relative directions of force, magnetic field and current

3   Determine the direction of the force on beams of charged particles in a magnetic field

4.5.5 The d.c. motor

Core

1   Know that a current-carrying coil in a magnetic field may experience a turning effect and that the turning effect is increased by increasing:

(a) the number of turns on the coil

(b) the current

(c) the strength of the magnetic field

Supplement

2   Describe the operation of an electric motor, including the action of a split-ring commutator and brushes

4.5.6 The transformer

Core

1   Describe the construction of a simple transformer with a soft iron core, as used for voltage transformations

2   Use the terms primary, secondary, step-up and step-down

3   Recall and use the equation

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

where p and s refer to primary and secondary

4   Describe the use of transformers in high-voltage transmission of electricity
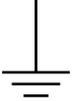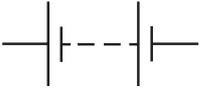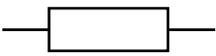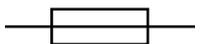
5   State the advantages of high-voltage transmission
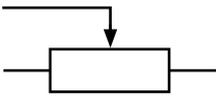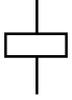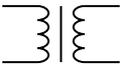
Supplement

6   Explain the principle of operation of a simple iron-cored transformer

7   Recall and use the equation for 100% efficiency in a transformer

$$I_p V_p = I_s V_s$$

where p and s refer to primary and secondary

8   Recall and use the equation

$$P = I^2 R$$

to explain why power losses in cables are smaller when the voltage is greater

Electrical symbols
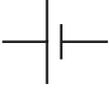
cell		switch	
battery of cells		earth or ground	
or			
power supply		junction of conductors	
d.c. power supply		lamp	
a.c. power supply		motor	
fixed resistor		generator	
variable resistor		ammeter	
thermistor		voltmeter	
light-dependent resistor		diode	
heater		light-emitting diode	
potential divider		fuse	
transformer		relay coil	
magnetising coil		electric bell	
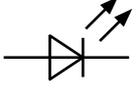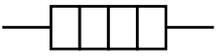
Core			Supplement		
Quantity	*Usual symbol*	*Usual unit*	*Quantity*	*Usual symbol*	*Usual unit*
potential difference/ voltage	V	V, mV, kV			
current	I	A, mA			
e.m.f.	E	V			
resistance	R	Ω			
charge	Q	C			
count rate		counts / s, counts / minute			
half-life		s, minutes, h, days, weeks, years			
			Hubble constant	H_0	s^{-1}

What Magnets Are & Drawing Magnetic Field Lines

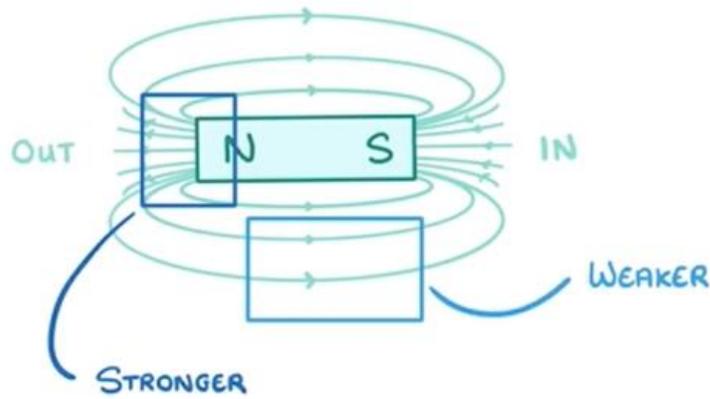This lesson covers:

1. The different types of magnets
2. How to draw magnetic field lines
3. What the magnetic field lines can tell us about the magnet

MAGNETS

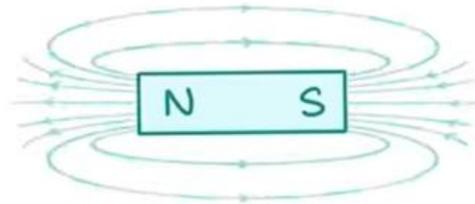└ ANY MATERIAL OR OBJECT THAT PRODUCES A MAGNETIC FIELD

BAR MAGNET

NORTH

EARTH

NORTH   SOUTH

SOUTH

FIELD LINES

SOUTH

NORTH

HORSESHOE MAGNET

MAGNETIC FIELDS

MAGNETS

└ ANY MATERIAL OR OBJECT THAT PRODUCES A MAGNETIC FIELD

OUT   N   S   IN

STRONGER

WEAKER
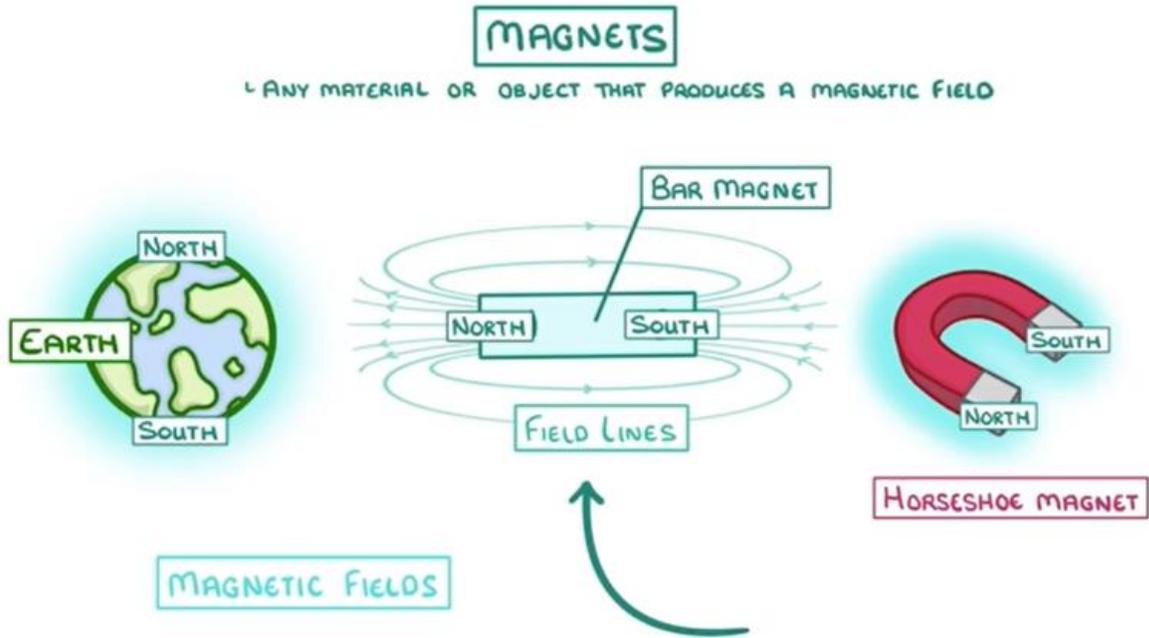
MAGNETS

TINY BAR MAGNET
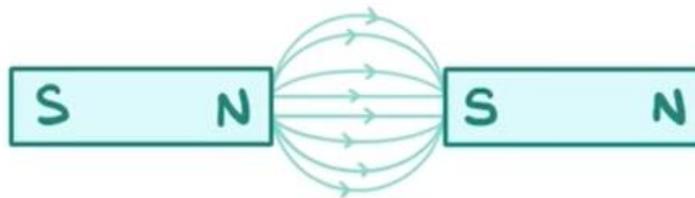
COMPASS

- LINE UP WITH THE FIELD LINES OF WHICHEVER MAGNETIC FIELD IT'S PUT IN
- POINT TOWARDS THE SOUTH POLE OF A MAGNET

INTERACTION BETWEEN TWO MAGNETS

electric / magnetic

A magnet is any material or object that produces a **magnetic** field.

⊙

Which of the following are examples of magnets?
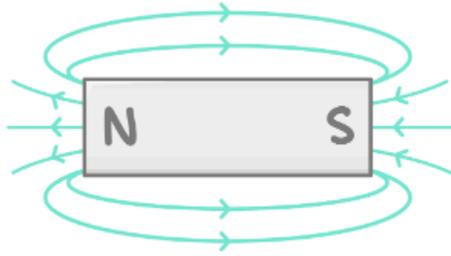(Select all that apply)

A horseshoe magnet

A charged rod

A bar magnet

The Earth

⊙

The above diagram shows a bar magnet and its magnetic field lines.

The arrows on the field lines always point:

Out from the south and into the north

Out from the north and into the south

1/1

thickness / colour / density

The strength of a magnetic field is shown by the **density** of the magnetic field lines.

1/1

Magnetic field lines can show:
(Select all that apply)

The density of the material

The strength of the magnet at a particular point

Whether two magnets would attract or repel

The direction that a small compass would point at that point

3/3
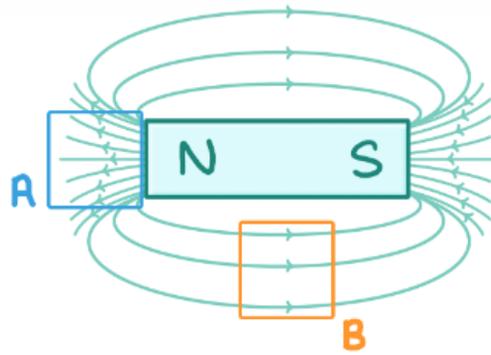
The above diagrams shows two regions of a bar magnet, labelled A and B.

Which region has a stronger magnetic field and why?

Region A because the field lines are further apart

Region A because the field lines are closer together

Region B because the field lines are further apart

Region B because the field lines are closer together
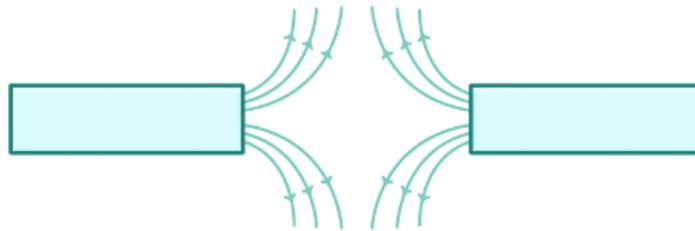
The above diagram shows two bar magnets which are:

Repelling each other

Attracting each other
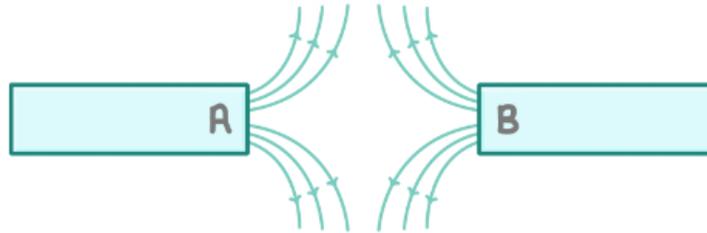
The above shows two bar magnets.

The poles of the two magnets are labelled A and B.

Which of the following is correct?

Pole A is north and pole B is south

Pole A is south and pole B is north

Pole A is north and pole B is north

Pole A is south and pole B is south

Perfect! You can tell both A and B must be the same pole, because the magnetic field lines are repelling each other. You can tell both A and B are north because the arrows on the lines are pointing out, rather than pointing in.

Electric Fields

This lesson covers:

1. What an electric field is
2. How to draw electrostatic field lines
3. Electrostatic attraction and repulsion
4. How air can be 'ionised' and how this can cause sparks

CHARGED

ELECTRIC FIELD

GRAVITATIONAL FIELDS

N S

MAGNETIC FIELDS

ARROWS ALWAYS GO FROM POSITIVE TO NEGATIVE

FIELD LINES

RIGHT ANGLES

FIELD LINES

RIGHT ANGLES

ARROWS ALWAYS GO FROM POSITIVE TO NEGATIVE

FIELD LINES   FIELD LINES

THE FIELD IS STRONGEST CLOSE TO THE PARTICLE
(GETS WEAKER THE FURTHER AWAY YOU GET)

←REPEL→   ←REPEL→   ELECTROSTATIC
                                                      ATTRACTION
                                                              Force
                                                              Force
                          FIELD LINES   'ELECTROSTATIC FORCE'

STRONGLY CHARGED   ELECTRIC FIELDS   ←→   AIR

(ELECTRICAL INSULATOR)   (ELECTRICAL INSULATOR)   (ELECTRICAL INSULATOR)
NO CHARGE   NO CHARGE   NO CHARGE

                                                         'IONISATION'
                                                         ↳ ABLE TO CONDUCT ELECTRICITY

Permanent & Induced Magnets

This lesson covers:

1 What a magnetic material is

2 The differences between 'permanent' magnets and 'induced' magnets

MAGNETIC MATERIAL

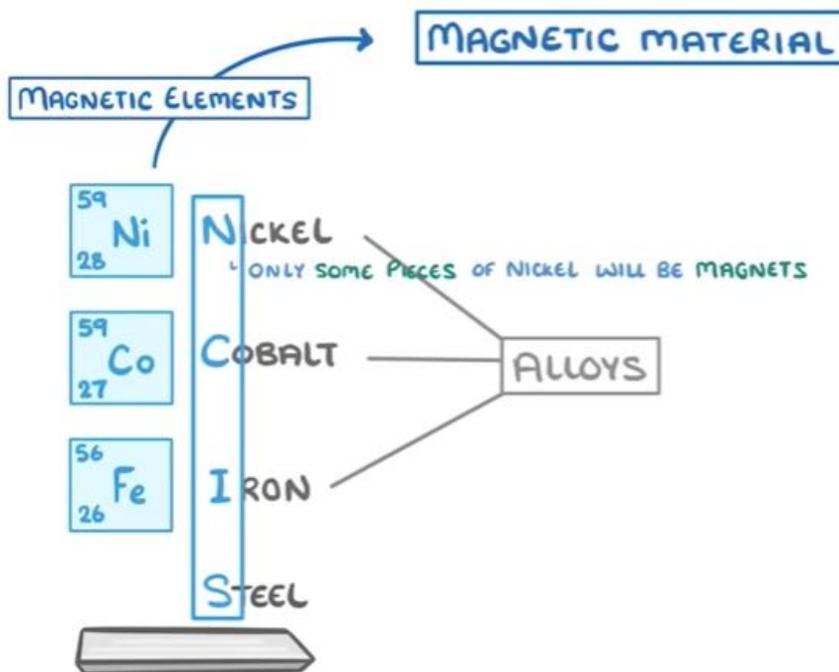ANY OBJECT THAT CAN BE INFLUENCED BY MAGNETIC FIELDS,
AND HAS THE POTENTIAL TO BECOME A MAGNET

PERMANENT MAGNETS   INDUCED MAGNETS

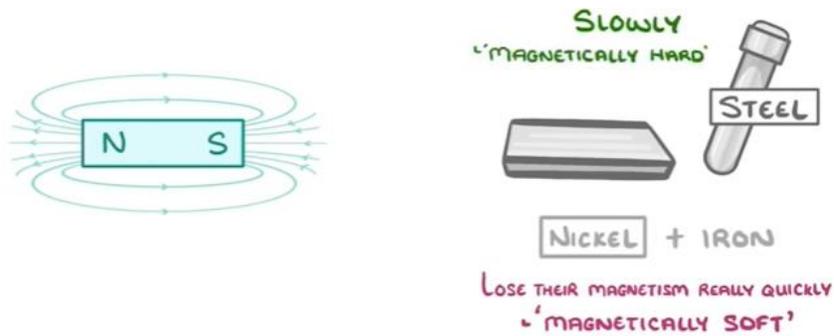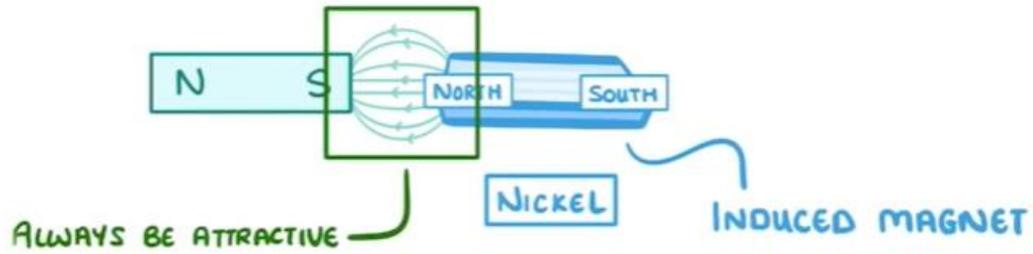AN ACTUAL MAGNET IS ANY OBJECT THAT PRODUCES A MAGNETIC FIELD

MAGNETIC MATERIAL

MAGNETIC ELEMENTS

| 59 |
| Ni |
| 28 |

NICKEL

↳ ONLY SOME PIECES OF NICKEL WILL BE MAGNETS

| 59 |
| Co |
| 27 |

COBALT ——— ALLOYS

| 56 |
| Fe |
| 26 |

IRON

STEEL

MAGNETIC MATERIAL

PERMANENT MAGNETS

└ PRODUCE THEIR OWN MAGNETIC FIELD ALL THE TIME

INDUCED / TEMPORARY MAGNETS

└ ONLY HAVE MAGNETIC FIELD TEMPORARILY

N S | NORTH SOUTH

ALWAYS BE ATTRACTIVE

NICKEL

INDUCED MAGNET

N S

SLOWLY
└ 'MAGNETICALLY HARD'

STEEL

NICKEL + IRON

LOSE THEIR MAGNETISM REALLY QUICKLY
└ 'MAGNETICALLY SOFT'

A magnetic material is any material or object that can be influenced by a **magnetic** field, and has the potential to become a magnet.

Which of the following elements are magnetic?
(Select all that apply)

- Nickel
- Copper
- Iron
- Cobalt

Which type of magnetism is it when a magnetic material temporarily becomes a magnet when it's placed close to a permanent magnet?

Induced

Which of the following are correct?

Permanent magnets only produce a magnetic field in the presence of another magnet
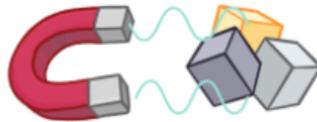
Permanent magnets always produce their own magnetic field

Temporary / induced magnets always produce their own magnetic field

Temporary / induced magnets only produce a magnetic field in the presence of another magnet

The force between a permanent and an induced magnet will:

Can be attractive or repulsive

Always be repulsive

Always be attractive

Magnetic materials that gain and lose magnetism quickly are called magnetically soft materials.

Magnetic materials that gain and lose magnetism slowly are called magnetically hard materials.

steel / iron

An example of a magnetically soft material is iron.

And example of a magnetically hard material is steel.

Static Electricity
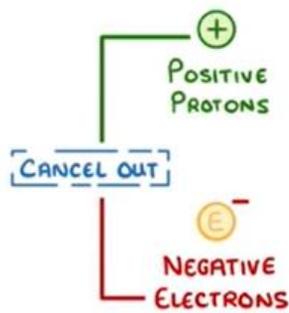
This lesson covers:

1. What 'static electricity' is
2. How static electricity builds up
3. How static electricity can cause a spark

STATIC ELECTRICITY

⌐ BUILD UP OF CHARGE ON INSULATING MATERIALS

SPARKS WHEN DISCHARGED

⊕ POSITIVE PROTONS

CANCEL OUT

Ⓔ⁻ NEGATIVE ELECTRONS

NEUTRAL OVERALL

CONTAIN CHARGE

STATIC ELECTRICITY

FRICTION BETWEEN OBJECTS

FRICTION BETWEEN OBJECTS

STATIC ELECTRICITY

CONDUCTING MATERIALS

CONDUCTING MATERIALS
ꜜ NO CHARGE EVER BUILDS UP

STATIC ELECTRICITY

INSULATING MATERIALS

LOST NEGATIVE CHARGE

ACETATE ROD

E^-

ELECTRONS CAN'T FLOW

CLOTH

ONLY NEGATIVE ELECTRONS THAT ARE BEING TRANSFERRED

NEGATIVE STATIC CHARGE

POLYTHENE ROD

E^-

LOST NEGATIVE CHARGE

CLOTH

POSITIVE STATIC CHARGE

WHICH WAY THE ELECTRONS GET TRANSFERRED DEPENDS ON THE SPECIFIC MATERIALS
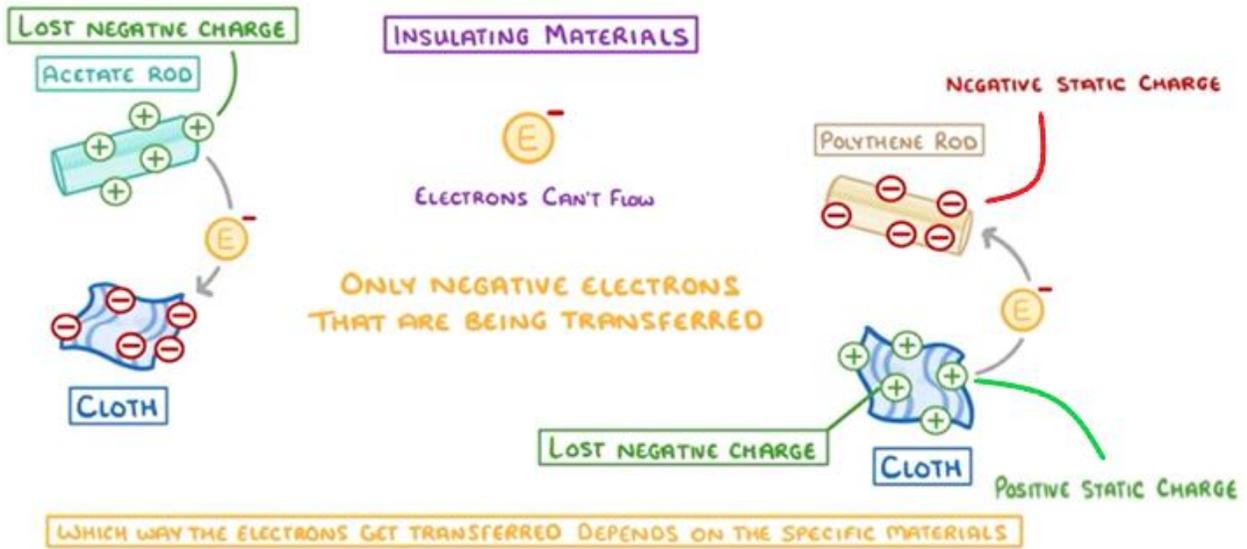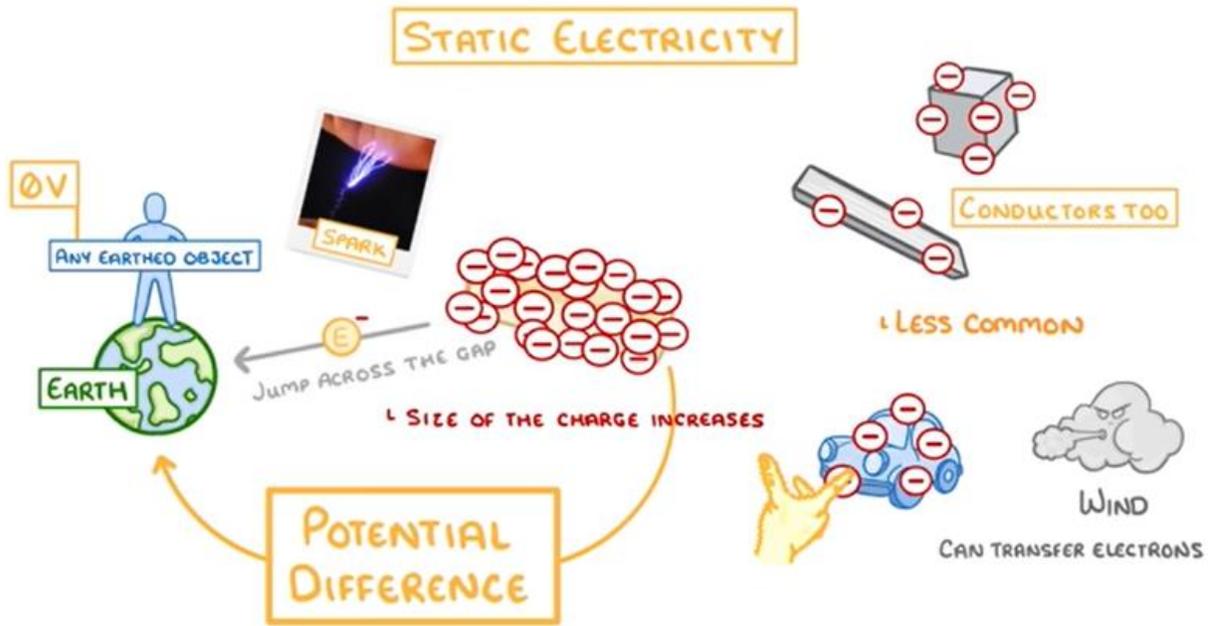
STATIC ELECTRICITY

Static electricity is the build up of charge on insulating materials

positive / negative / neutral / protons / electrons / neutrons

1 All objects have positively charged **protons** and negatively charged **electrons**.

2 Normally, the number of protons and electrons are the same which means the object is **neutral** overall.

⑦   3/3

charge / conducting / insulating / friction / positive

When two objects are rubbed together, the **friction** can cause electrons to move from one object onto the other. This can lead to a build up of **charge**.

However, this doesn't work for friction between two **conducting** materials as the electrons would just flow straight back again.

⑦   3/3

When two materials are rubbed together, which particles are transferred?

Neutrons

Protons

Electrons

⑦   1/1

A material which gains additional electrons will have a:

Positive charge

Negative charge

1/1

When two objects are rubbed together, electrons may be transferred. The object that becomes positive, must have _____ electrons.

gained	**lost**

Great! Electrons are negatively charged, so the object that becomes positive must have lost some of those negative electrons. It will now have more protons than electrons, and so has a positive charge overall.

1/1

potential difference / charge / protons / electrons

A large build up of **charge** on an object can cause a large **potential difference** between the object and the earth.

The large potential difference could allow **electrons** to jump through the air to earth, causing a spark.

3/3

True or False? The metal body of a car can build up charge from being in contact with the wind.
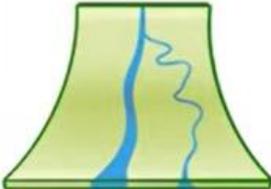
True	False

1/1

This lesson covers:

1 What charge is

2 The charge equation: $Q = It$

CHARGE

ᴸ A MEASURE OF THE TOTAL CURRENT THAT FLOWED WITHIN A CERTAIN PERIOD OF TIME

$$Q = I \times t$$

COULOMBS (C) (A) (S)

TOTAL AMOUNT OF WATER THAT HAS FLOWED DOWN THE HILL WITHIN A CERTAIN TIME

A KETTLE DRAWS 12 AMPS AND TAKES 50 SECONDS TO BOIL. HOW MUCH CHARGE PASSED THROUGH THE WIRE?

$$12 \times 50$$
$$= 600 \, C$$

CHARGE

ᴸ A MEASURE OF THE TOTAL CURRENT THAT FLOWED WITHIN A CERTAIN PERIOD OF TIME

CONVERT OUR UNITS $$Q = I \times t \quad \boxed{I = Q/t}$$

COULOMBS (C) (A) (S)

A PHONE CHARGER TRANSFERS A TOTAL CHARGE OF 43.2 kC OVER A PERIOD OF 2 HOURS. WHAT CURRENT FLOWED THROUGH THE WIRE?

$$\frac{43,200 \, C}{7,200 \, s}$$

$$= 6A$$

×60

120 MINS.

×60

7,200 S

×1,000

43,200 C

Charge / Voltage

Charge is a measure of the total current that flowed within a period of time

The formula for charge is:

$$\mathbf{charge = current \times time}$$

$$charge = \frac{current}{time}$$

$$charge = \frac{time}{current}$$

The units for charge are:

Amperes (A)

Volts (V)

Watts (W)

Coulombs (C)

The symbol formula for charge is:

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

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

$$Q = It$$

2 A of current flowed for 30 s.

How much charge flowed in that time period?

60 C

Well done! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

Hint

30 C of charge flowed through a wire in 10 s.

What is the current in the wire?

3 A

Well done! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

Hint   1/1

0.5 A of current flowed for 20 minutes.

How much charge flowed in that time period?

600 C

Great! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

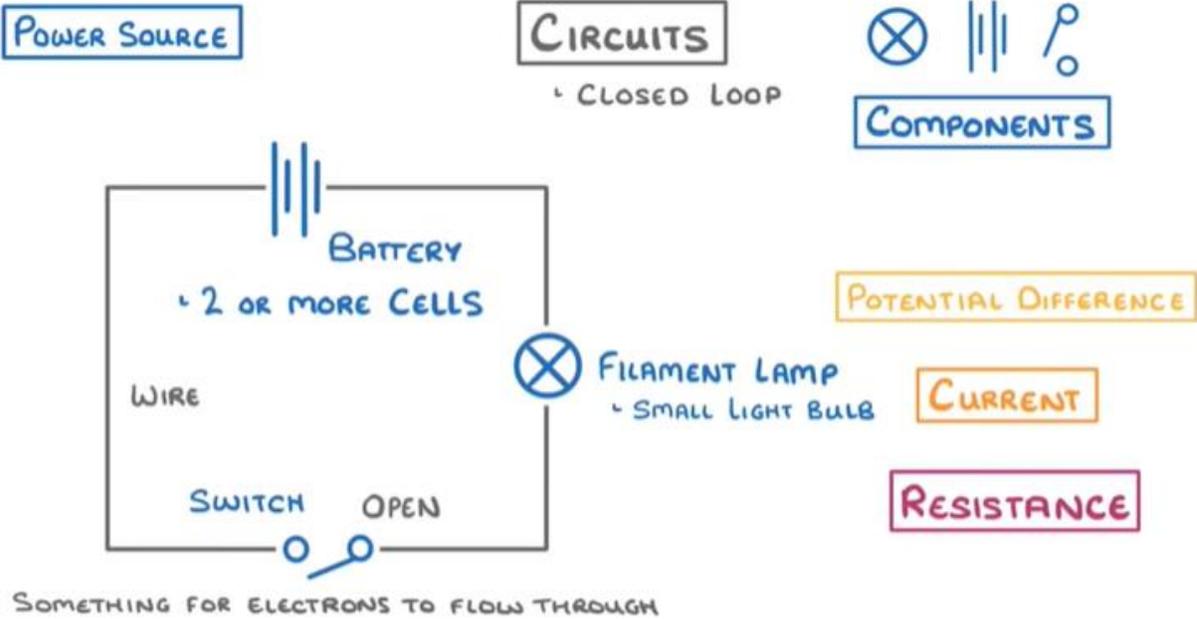Hint   1/1

Circuits Introduction

This lesson covers:

1 What an electric circuit is

2 The basic components of an electric circuit

3 An introduction to current, potential difference, and resistance

4 The direction of electron flow and current flow

POWER SOURCE

CIRCUITS
⌐ CLOSED LOOP

⊗ ||| ⌐₀ **COMPONENTS**

BATTERY
⌐ **2 OR MORE CELLS**

WIRE

⊗ **FILAMENT LAMP**
⌐ SMALL LIGHT BULB

POTENTIAL DIFFERENCE

CURRENT

RESISTANCE

SWITCH OPEN

⌐ SOMETHING FOR ELECTRONS TO FLOW THROUGH

POTENTIAL DIFFERENCE

V

FORCE DRIVING THE FLOW OF ELECTRONS

⌐ PROVIDED BY CELL / BATTERY

'VOLTAGE'
VOLTS (V)

CURRENT

I

A MEASURE OF THE FLOW OF ELECTRONS AROUND THE CIRCUIT
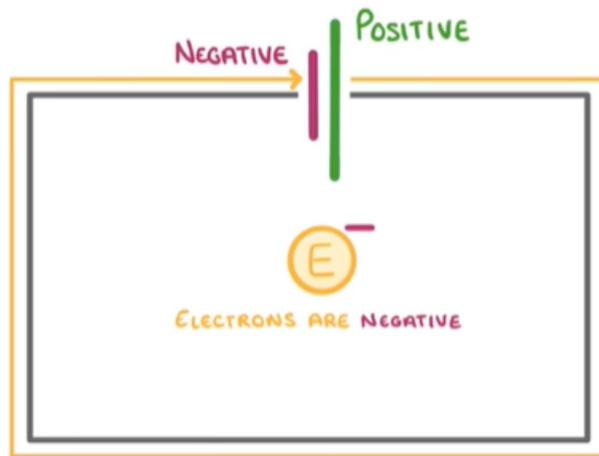
⌐ AMPERES
AMPS (A)

RESISTANCE

R

EVERYTHING THAT RESISTS OR OPPOSES THE FLOW OF ELECTRONS

OHMS (Ω)

WHICH WAY A CIRCUIT CURRENT FLOWS

NEGATIVE   POSITIVE

E⁻

ELECTRONS ARE NEGATIVE

FOR YOUR EXAM:
CURRENT ALWAYS FLOWS
FROM THE POSITIVE   TO THE NEGATIVE

A power source for an electric circuit could be a:
(Select all that apply)

Cell

Battery

Pump

Engine

2/2

This symbol is used to represent a **switch** on a circuit diagram.

1/1

voltage / current / resistance

Current is a measure of the flow of electrons around a circuit

1/1

This symbol is used to represent a **battery** on a circuit diagram.

Amperes, amps, or 'A' are the units of:

- Resistance
- **Current**
- Voltage

What does this symbol represent on a circuit diagram?

- Resistor
- Cell
- Battery
- **Filament Lamp**

current / potential difference / resistance

Potential difference is the force driving the flow of electrons around a circuit

In 'conventional current', we say that the electrons flow from:

- Negative terminal ➜ positive terminal
- **Positive terminal ➜ negative terminal**

current / potential difference / resistance

Resistance is everything that resists or opposes the flow of electrons in a circuit

⚡⚡⚡

Voltage, volts, and 'V', are all used to refer to:

Current

Potential difference

Resistance

1/1

Ohms (Ω) are the units of:

Current

Voltage

Resistance

1/1

Current (or 'conventional current') flows from:

Negative terminal ➜ positive terminal

Positive terminal ➜ negative terminal

Great! This is a bit confusing. Even though electrons travel from the negative terminal to the positive terminal, we say that current travels from the positive terminal to the negative terminal.
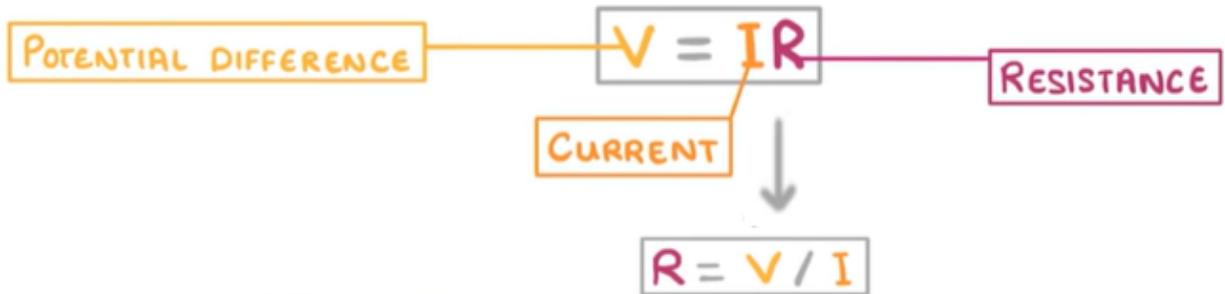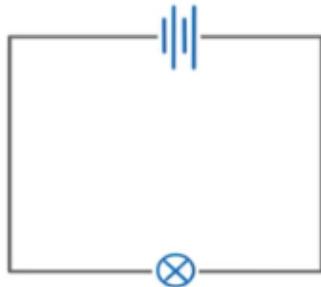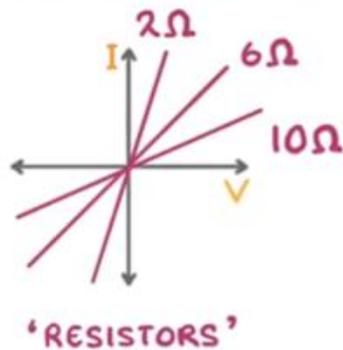
1/1

Ohm's Law & I-V Graphs

This lesson covers:
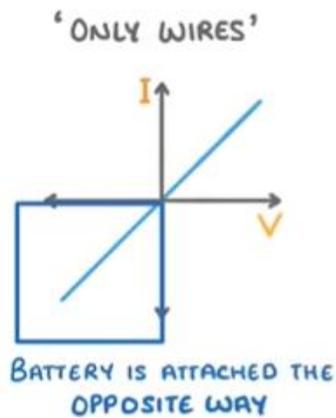
1. The relationship between voltage, current, and resistance: $V = IR$
2. The current / voltage graphs for resistors, filament lamps, and diodes

POTENTIAL DIFFERENCE — $V = IR$ — RESISTANCE

CURRENT

$R = V / I$

$24V$ / $8A$ = 3Ω

⎿ THE RELATIONSHIP BETWEEN

INCREASE — $V = IR$ — CONSTANT

INCREASE PROPORTIONALLY

'ONLY WIRES'

2Ω

6Ω

10Ω

⎿ ASSUMING TEMPERATURE STAYS CONSTANT

BATTERY IS ATTACHED THE OPPOSITE WAY

'RESISTORS'

TEMP. = RESISTANCE

'FILLAMENT LAMP'

$$V = IR$$

'DIODE'

WHEN THE P.D.
IS POSITIVE

REALLY HIGH RESISTANCE
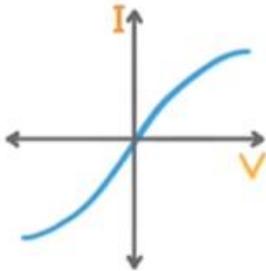
'HEATS UP
↓
INCREASES RESISTANCE
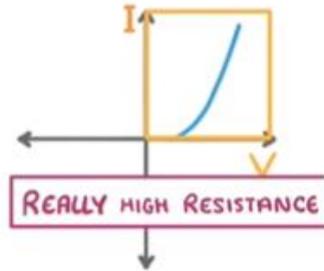
' ONLY ALLOW CURRENT
TO FLOW IN
ONE DIRECTION

The formula which relates voltage, current, and resistance is:

$V = \frac{R}{I}$

$V = IR$

$V = \frac{I}{R}$

1/1

A 12 Ω resistor has 2 A of current passing through it.
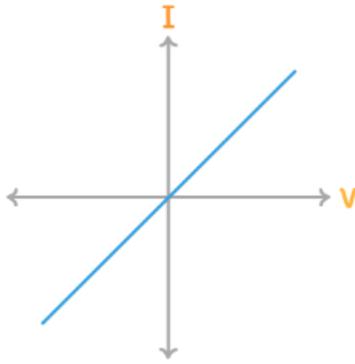
What is the potential difference across the resistor?

24 V

Great! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

Hint

1/1

The above diagram is a current / voltage graph for a:

Fixed Resistor

Diode

Filament lamp

1/1

16 V is supplied across a resistor that has 2 A of current flowing through it.

What is the resistance of the resistor?

8 Ω

Well done! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

Hint   1/1

For wires and resistors, increasing the temperature will _____ the resistance.
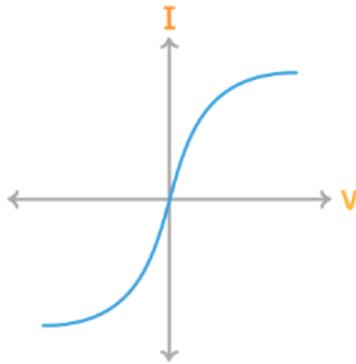
increase   decrease

Well done! As temperature increases, all of the ions in the metal vibrate faster, which makes it harder for electrons to pass along the wire (or in other words, the resistance increases).

1/1

The above diagram is a current / voltage graph for a:

Filament lamp

Resistor

Diode
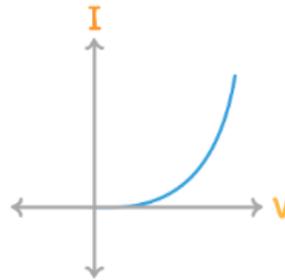
Diodes:

Switch circuits on and off

Supply power to a circuit

Only allow current to flow one way around a circuit

Measure the current in a circuit

The above diagram is a current / voltage graph for a:

Resistor

Filament lamp

Diode

Electrical Energy & Power

This lesson covers:

1. The equation E = Pt
2. The equation E = VIt
3. The equation E = QV
4. The equation P = IV
5. The equation P = I²R

There are 3 formulas for energy

Formula 1:

Energy (E) = Power (P) x Time (t)

E = Pt

Formula 2:

Energy (E) = Voltage (V) x Current (I) x Time (t)

E = VIt

Formula 3:

Energy (E) = Charge (Q) x Voltage (V)

E = QV

An **800 W** hairdryer is used for **30 seconds**.

How much energy is transferred in total? Give your answer in Joules.

24000 J

Great! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

Hint

1/1

A circuit with a **12 V** battery, and a **current of 6 A** is left on for **20 s**.

How much energy is transferred in total? Give your answer in Joules.

<div align="center">

1440 J

</div>

Well done! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

?   Hint   1/1

The **potential difference** between the two terminals on a battery is **6 volts**.

How much work (**energy**) is required to transfer **12 coulombs** of charge across the terminals?

<div align="center">

72 J

</div>

Perfect! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

?   Hint   1/1

There are 2 different formulas for power:

Formula 1:

Power (P) = Current (I) x Voltage (V)

P = IV

Formula 2:

Power = Current^2 x Resistance

P = I^2 × R

?

A circuit has a **potential difference of 12 V**, and a **current of 15 amps**.

Calculate the **power** of the circuit.

<div align="center">

180 W

</div>

Well done! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

?   Hint   1/1

A circuit with has a **current of 3 A**, and a total **resistance of 30 Ω**.

What is the power of the circuit?

270 W

Great! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

⑦   Hint   1/1

A handheld fan draws a current of 6 A. Over 20 seconds it transfers a 1200 J of energy.

What is the voltage of the battery that the fan uses?

10 V

Great! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

⑦   Hint   1/1

A circuit has a power of 20 W and a current of 4 A.

What is the resistance of the circuit? Give your answer to 3 s.f.

1.25 Ω

Well done! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

⑦   Hint   1/1

A component in a circuit has a potential difference of 5 V across it, and receives 30 J of energy.

How much charge passes through the component?

6 C

Well done! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

⑦   Hint   1/1

A circuit has a potential difference of 12 V, and produces 36 W of power.

Calculate the current of the circuit.

3 A

Perfect! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

⑦

Hint   1/1

A lamp with a power rating of 60 W transfers 2520 J of energy.

How long was the lamp on for?

42 s

Great! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

⑦

Hint   1/1

ELECTRIC POWER COMPONENTS ↗ LIGHT-EMITTING DIODE (LED)

CELL ⊗ FILAMENT LAMP ⊳⊲ DIODE
└ ONLY ALLOW CURRENT TO FLOW IN ONE DIRECTION

BATTERY FUSES
└ BREAK IF TOO MUCH CURRENT

CONTROL THE FLOW OF ELECTRICITY

OPEN SWITCH   CLOSED SWITCH

THERMISTOR COMPONENTS LIGHT-DEPENDENT RESISTORS
RESISTORS

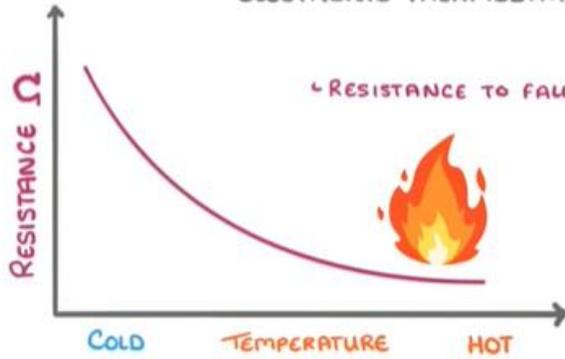VARIABLE RESISTOR   FIXED RESISTOR
└ MODIFY THE AMOUNT OF RESISTANCE
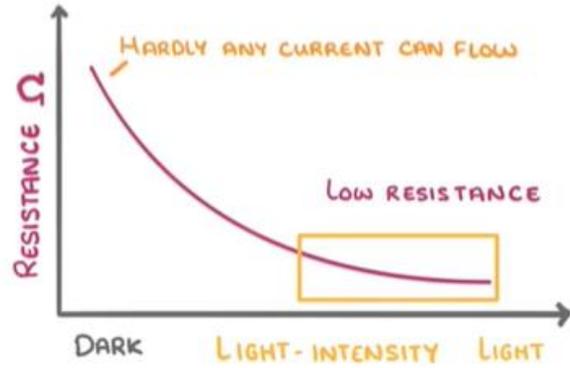
THERMISTOR

COMPONENTS

RESISTORS

- Temperature receptors:
  - Car Engines
  - Electronic Thermostats

- Resistance to fall

Graph: RESISTANCE Ω (y-axis) vs TEMPERATURE (x-axis), COLD → HOT

LIGHT-DEPENDENT RESISTORS

- Automatic night-lights
- Burglar alarms

Hardly any current can flow

Low resistance

Graph: RESISTANCE Ω (y-axis) vs LIGHT-INTENSITY (x-axis), DARK → LIGHT
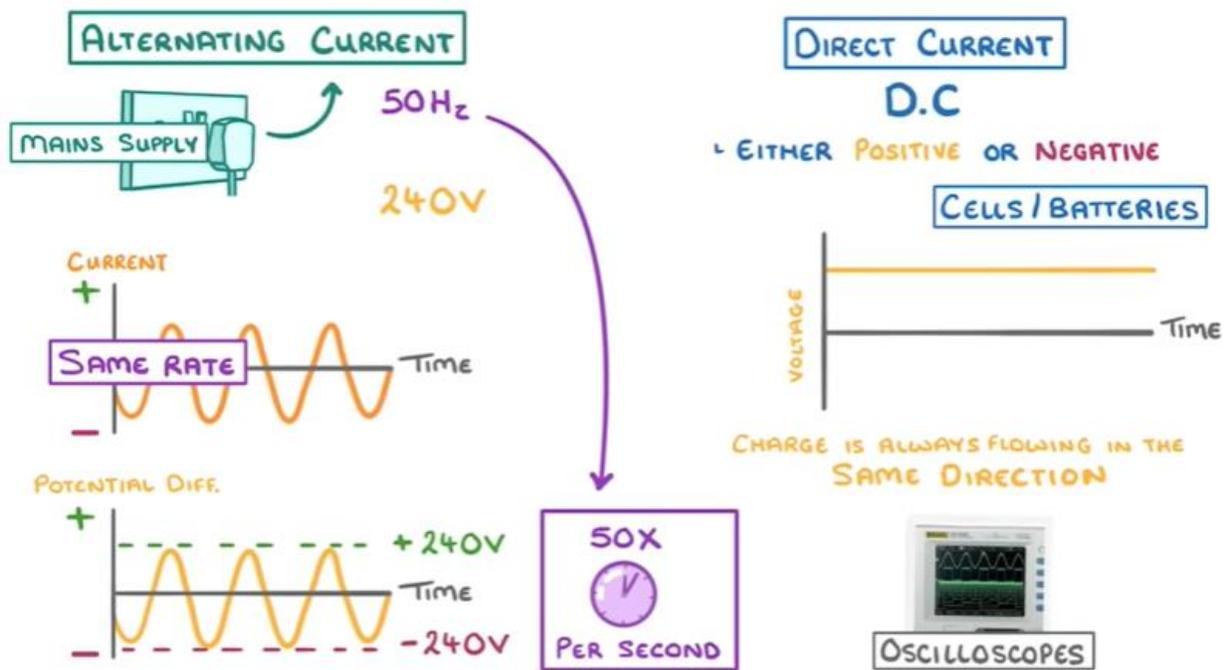
Alternating (AC) and Direct Current (DC)

This lesson covers:

1. The difference between alternating current and direct current
2. Voltage-time graphs
3. Oscilloscopes

ALTERNATING CURRENT

MAINS SUPPLY

50 Hz

240V

CURRENT

+

SAME RATE — Time

−

POTENTIAL DIFF.

+

+240V — Time

−240V

−

50X

V

PER SECOND

DIRECT CURRENT

D.C

∟ EITHER POSITIVE OR NEGATIVE

CELLS / BATTERIES

VOLTAGE

Time

CHARGE IS ALWAYS FLOWING IN THE
SAME DIRECTION

OSCILLOSCOPES

Series Circuits

This lesson covers:

1 What a 'series' circuit is

2 How series circuits affect potential difference, current, and resistance

VERY FEW THINGS ARE CONNECTED IN SERIES

THE POTENTIAL DIFFERENCE OF THE BATTERY
IS SHARED ACROSS ALL OF THE COMPONENTS

$$V_{total} = V_1 + V_2 + V_3 \ldots$$
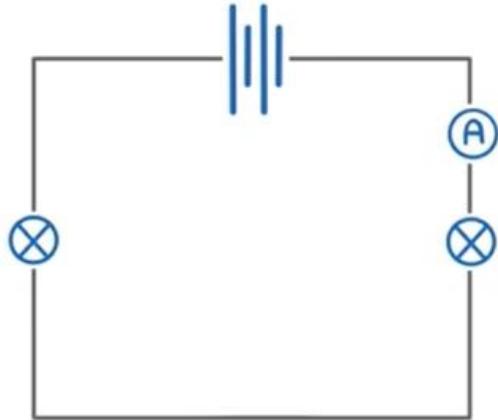
CURRENT

└ SAME EVERYWHERE IN THE CIRCUIT

(A)

AMMETER

└ PLACE IN SERIES

Ohm's Law

$V = IR$ $I = V/R$

RESISTANCE

TOTAL RESISTANCE $= \Sigma$ INDIVIDUAL RESISTANCES
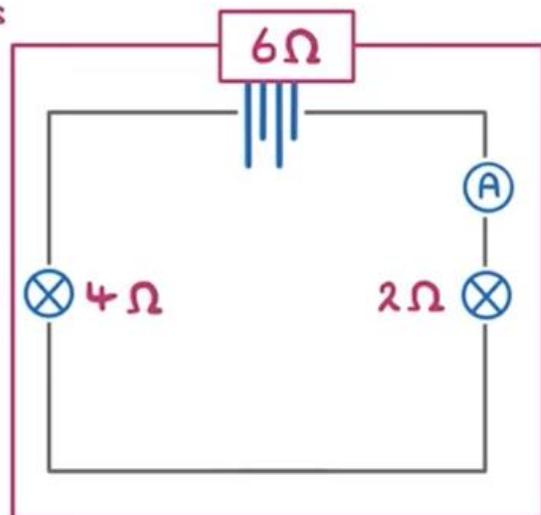OF EACH COMPONENT

Ohm's Law

$V = IR$

$$\frac{12V}{6\Omega} = 2A$$

(A)

AMMETERS

└ TINY RESISTANCES
  (IGNORE THEM)

SERIES

6Ω

(A)

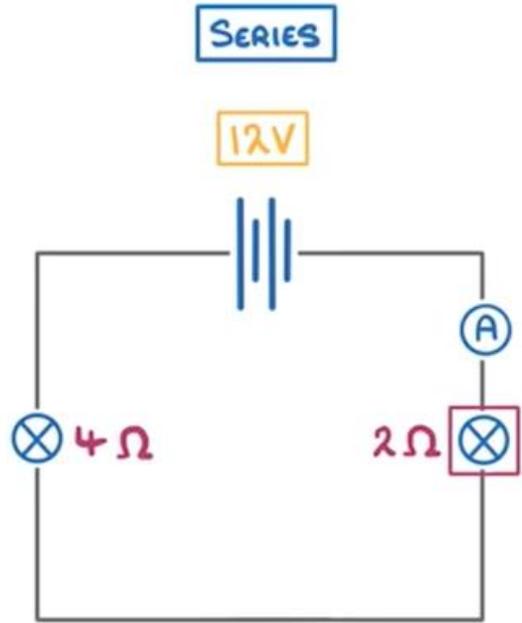⊗ 4Ω   2Ω ⊗

HOW TO CALCULATE THE VOLTAGE
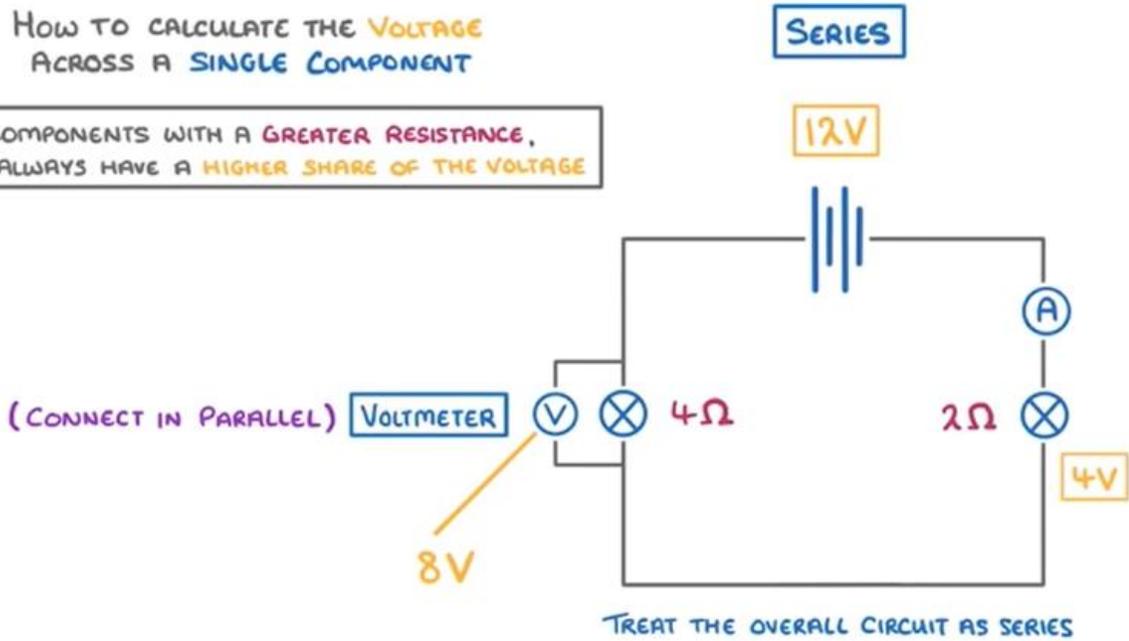ACROSS A SINGLE COMPONENT

SERIES

12V

Ohm's Law

$$V = IR$$

12V
$-$ 4V
$= 8V$

$2A \times 2\Omega$
$= 4V$

⊗ 4Ω   2Ω ⊗

Ⓐ

HOW TO CALCULATE THE VOLTAGE
ACROSS A SINGLE COMPONENT

SERIES

12V

COMPONENTS WITH A GREATER RESISTANCE,
WILL ALWAYS HAVE A HIGHER SHARE OF THE VOLTAGE

(CONNECT IN PARALLEL) VOLTMETER Ⓥ ⊗ 4Ω   2Ω ⊗

Ⓐ

4V

8V

TREAT THE OVERALL CIRCUIT AS SERIES

Parallel / Series

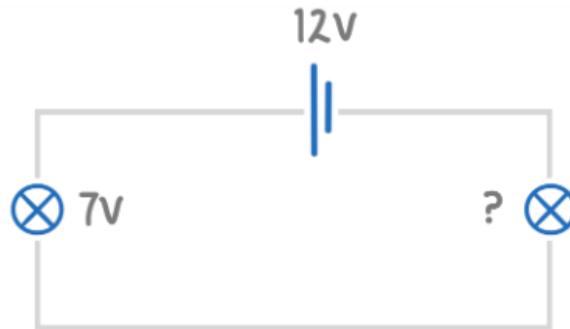Series circuits only have a single loop.

Parallel circuits have more than one loop.

In a series circuit, the potential difference of the battery is:

Shared across all of the components

The same everywhere in the circuit

12v

⊗ 7V   ? ⊗

The above series circuit shows a 12 V battery supply.

The left filament lamp has a voltage of 7 V measured across it.

What is the voltage across the right filament lamp?

5 V

Great! In a series circuit the voltage of the cell (or battery) is shared across the components. So if the cell is 12 V, and the filament lamp on the left gets 7 V, then the filament lamp on the right must get 12 - 7 = 5 V.
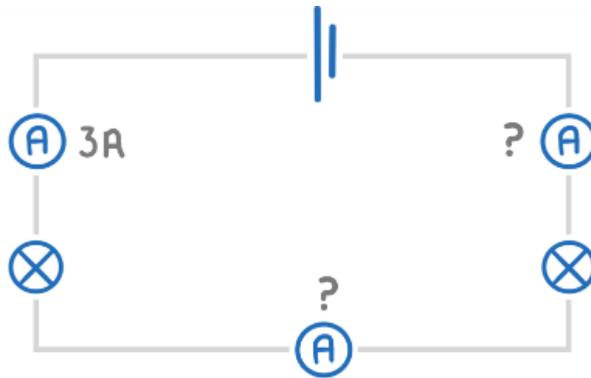
In a series circuit, the current is:

The same everywhere in the circuit

Shared across all of the components

The above series circuit has a battery, two filament lamps, and three ammeters.

The left ammeter shows 3 A.

What current would the other two ammeters show?

3 A

Great! In a series circuit, the current is the same everywhere in the circuit. So if the ammeter on the left reads 3 A, then the other ammeters would also read 3 A.

1 / 1

In a series circuit, the total resistance is _____ the sum of the individual resistances of each component.

more than
equal to
less than

1 / 1

The above series circuit has a battery and two filament lamps.

The left filament lamp has a resistance of 5 Ω and the right filament lamp has a resistance of 4 Ω.

What is the total resistance of the circuit?

9 Ω

Well done! In a series circuit the total resistance is just the sum of the individual resistances. So if the left filament lamp has a resistance of 5 Ω and the right filament lamp has a resistance of 4 Ω, then the total resistance must be 5 + 4 = 9 Ω.

1/1

Ohm's law, which describes the relationship between **voltage**, **current**, and **resistance** is:

$V = \frac{I}{R}$

$V = IR$

$V = \frac{R}{I}$

1/1

In a series circuit, components with a greater resistance will always have a _____ share of the voltage.

equal

greater

lesser

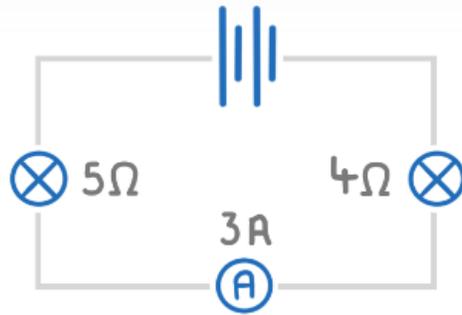**1/1**

The above series circuit has a battery, two filament lamps, and an ammeter.

The left filament lamp has a resistance of 5 Ω, the right filament lamp has a resistance of 4 Ω, and the ammeter shows 3 A.

What is the potential difference across the left filament lamp?

15 V

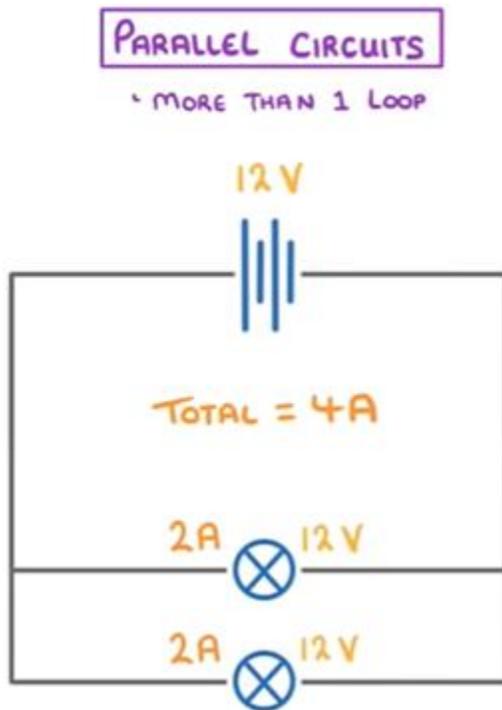Great! To see our step-by-step working use the hint button, or click here to reveal all steps at once.
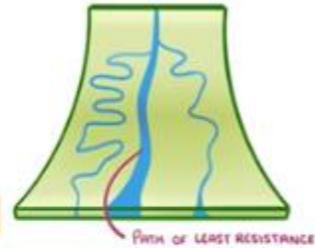
Hint

1/1

Parallel Circuits

This lesson covers:

1 What a parallel circuit is

2 How parallel circuits affect potential difference, current, and resistance

PARALLEL CIRCUITS

• MORE THAN 1 LOOP

12 V

TOTAL = 4A

2A 12 V

2A 12 V

RESISTANCE

• MORE COMPONENTS IN PARALLEL
= LOWER TOTAL RESISTANCE

PATH OF LEAST RESISTANCE

POTENTIAL DIFFERENCE

$$V_{total} = V_1 = V_2 = V_3 \cdots$$

CURRENT

$$I_{total} = I_1 + I_2 + I_3 \cdots$$

• LOOPS THAT HAVE GREATER RESISTANCE, TAKING A LOWER SHARE OF THE CURRENT
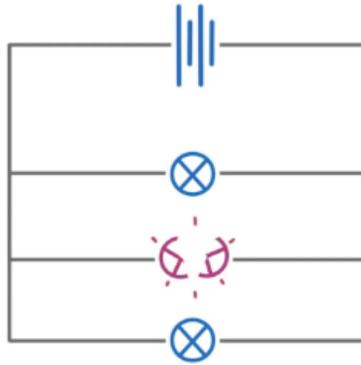
A

B

Which of these circuits is series, and which is parallel?

A is series and B is parallel

A is parallel and B is series

Great! Parallel circuits are those in which each component has its own loop, like in circuit A.

In the parallel circuit above, one of the filament lamps has blown and broken that part of the circuit.

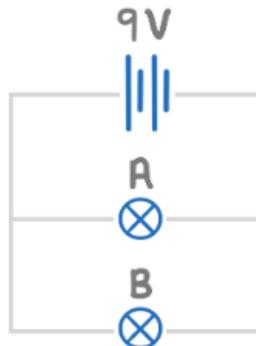In this scenario the other two lamps will:

| Turn off | Stay on |

Great! One of the main benefits of parallel circuits is that if one component breaks, the overall circuit will still work. This is because current can still flow through the other loops.

1/1

All the components in a parallel circuit have the same potential difference.

9V

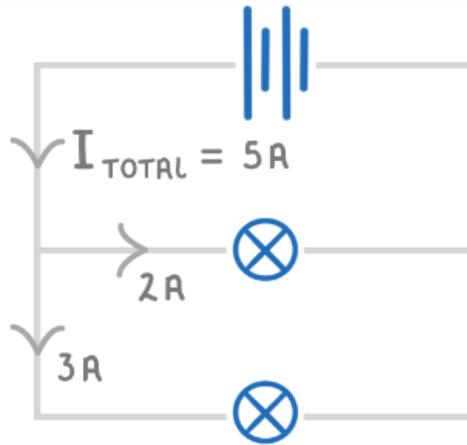The filament lamps A and B are in parallel.

The potential difference across filament lamp A is 9 V.

The potential difference across filament lamp B is 9 V.

Great! In parallel circuits, every component gets the source potential difference (which is just the technical way of saying that they get the same voltage as the cell/battery).

2/2

$I_{TOTAL} = 5A$

2 A

3 A

equal / shared / sum

The total current is _shared_ between all of the parallel loops.

The sum of the current in each loop is equal to the total current.

$I_{TOTAL} = 6A$

?

1 A
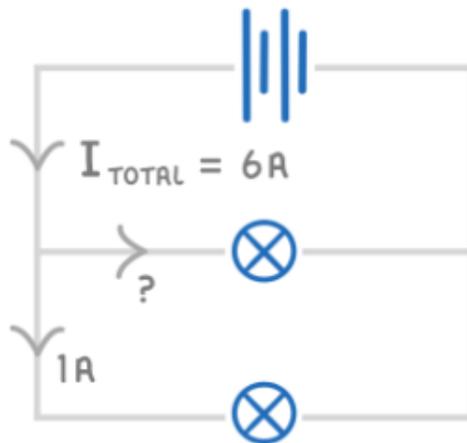
The above diagram shows a parallel circuit.

The total current is 6 A, and 1 A is flowing through the bottom filament lamp.

What is the current flowing through the top filament lamp?

5 A

Perfect! In parallel circuits, the total current is shared between the different loops. So if the total current is 6 A, and the bottom loop gets 1 A, then the top loop must get 6 - 1 = 5 A.

Adding a resistor in parallel with an existing resistor will _____ the overall resistance.

increase

decrease

Great! This might seem a bit counter-intuitive, but remember that adding another resistor will also add another loop, and so it introduces another possible pathway for the current to flow.
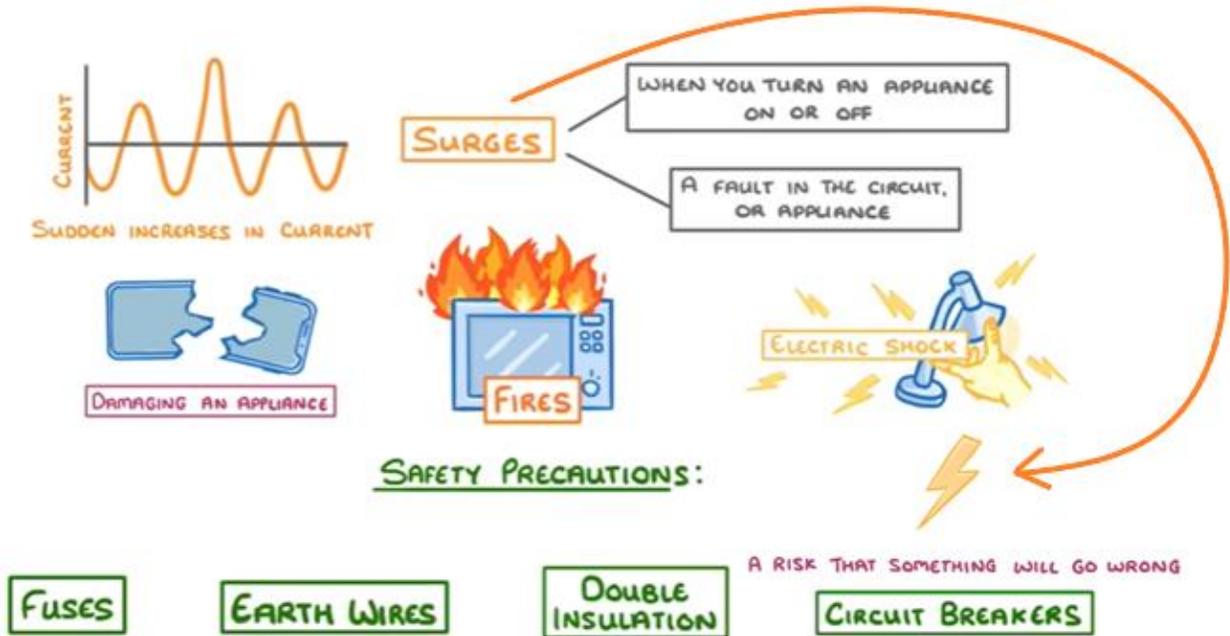
Fuses & Earthing

This lesson covers:

1 The 4 main safety mechanisms that are used in electrical circuits:

2 Fuses and circuit breakers, which prevent damage due to a surge in current

3 Earthing and double insulation, which minimise electric shocks

CURRENT

SUDDEN INCREASES IN CURRENT

SURGES

WHEN YOU TURN AN APPLIANCE ON OR OFF

A FAULT IN THE CIRCUIT, OR APPLIANCE

DAMAGING AN APPLIANCE

FIRES

ELECTRIC SHOCK

SAFETY PRECAUTIONS:

A RISK THAT SOMETHING WILL GO WRONG

FUSES

EARTH WIRES

DOUBLE INSULATION

CIRCUIT BREAKERS

FUSES

BREAKING THE CIRCUIT
WHENEVER THE CURRENT GETS TOO HIGH

CIRCUIT BREAKERS

∟ SIMPLE AND CHEAP

∟ PERMANENTLY BROKEN AFTER A SINGLE SURGE

LIVE WIRE — REPLACED EACH TIME — LIVE WIRE

VERY THIN PIECE OF WIRE

SURGE →

∟ HEAT UP

MELT

∟ BREAKS THE CIRCUIT
NO MORE CURRENT CAN FLOW

3A

5A

13A

WIRE INSIDE THE CASING

→ A RANGE OF DIFFERENT RATINGS
(WHAT CURRENT YOU WANT TO BREAK THE CIRCUIT)

10A

13A
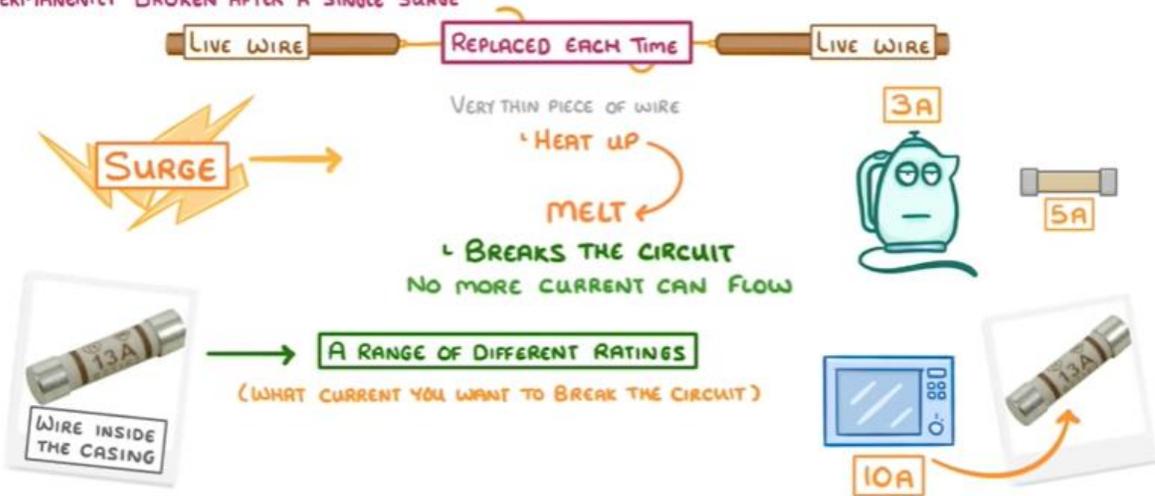
BREAK THE CIRCUIT WHENEVER THERE'S A SURGE   CIRCUIT BREAKERS

TRIPPED

CAN BE RESET   ←   TURN OFF THE CIRCUIT

PERMANENTLY DAMAGED

MORE EXPENSIVE THAN FUSES

MAIN WAYS SURGES CAN CAUSE HARM

TOUCH THE CASING

EARTHING

EARTH WIRE
(AN ALTERNATIVE PATHWAY)
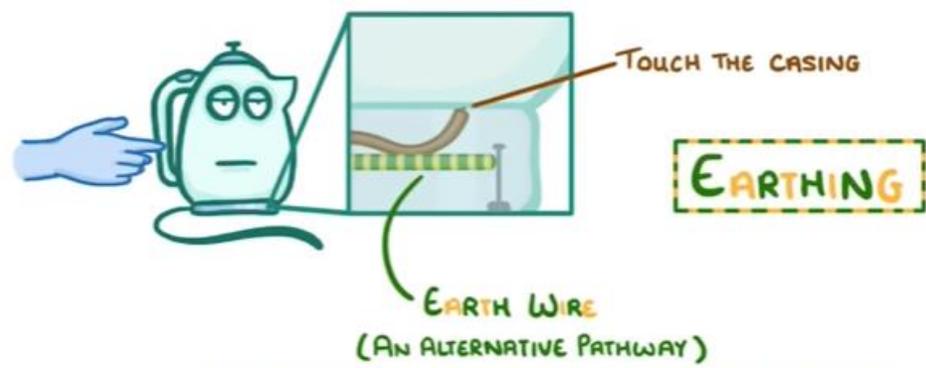
* ANY ELECTRICITY IS DIVERTED THROUGH THE EARTH WIRE

DOUBLE INSULATE

PLASTIC DOESN'T CONDUCT ELECTRICITY — CAN'T GET AN ELECTRIC SHOCK

COVERED IN A PLASTIC CASING

NEUTRAL

EARTH WIRE

NO EXPOSED METAL PARTS

LIVE WIRE
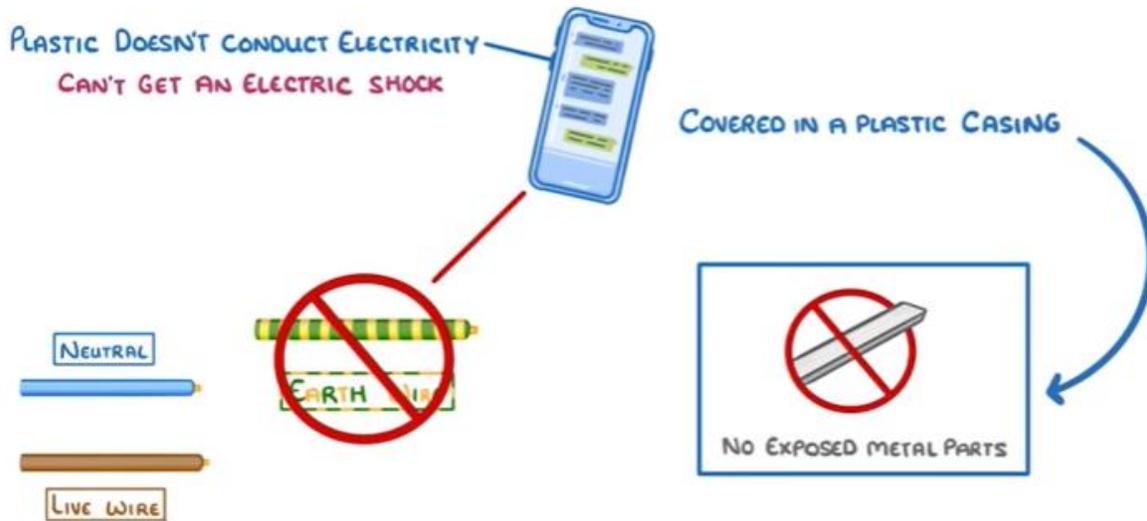
resistance / fire / voltage / current

One risk in electric circuits is a surge in current. The sudden increase in **current** can damage the appliance, cause a **fire**, or give an electric shock.

⑦

2 / 2

Which of the following safety features are used to protect against surges in current?
(Select all that apply)

| Double insulation |
| Earth wires |
| **Fuses** |
| **Circuit breakers** |

⑦

2 / 2

LIVE WIRE   LIVE WIRE

rating / high / low / description

Fuses have a thin wire which melts and breaks the circuit when the current is too **high**.

The **rating** of a fuse is the current that will cause the fuse to break the circuit.

⑦

2 / 2

above / below

Generally you should use a fuse with a rating a few amps **above** the recommended current for the appliance.

Great! Using a fuse with a rating a few amps above the recommended current means that it won't break under normal use. However, if there is a surge and the current rises significantly then it will surpass the rating and break the fuse.

Which of these fuse ratings would be appropriate for a kettle that is designed to operate at 5 A of current?

3 A
5 A
8 A
15 A

Well done! We always pick a fuse that has a rating a few amps above that of the appliance.

Circuit breakers are like a _____ that can be reset after they break the circuit.

lamp
cell
fuse

How earth wires protect us from electric shocks:

live / neutral / earth / battery / casing

1 The **earth** wire is connected to the casing of the appliance.

2 If the live wire touches the appliance **casing**, the earth wire provides an alternative pathway for electricity to flow.

3 This way, we don't get an electric shock from touching the live appliance casing.

An appliance has 'double insulation'. Therefore it most likely:

Has both plastic casing and an earth wire

Has neither plastic casing nor an earth wire

Has an earth wire, but no plastic casing

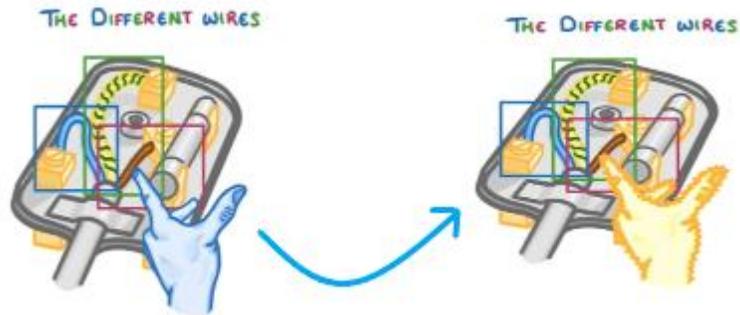**Has a plastic casing, but no earth wire**

Perfect! This may seem counter-intuitive because 'double' insulation makes it seem like it has both a casing and earth wire, but remember that 'double insulation' usually refers to just having a plastic casing.
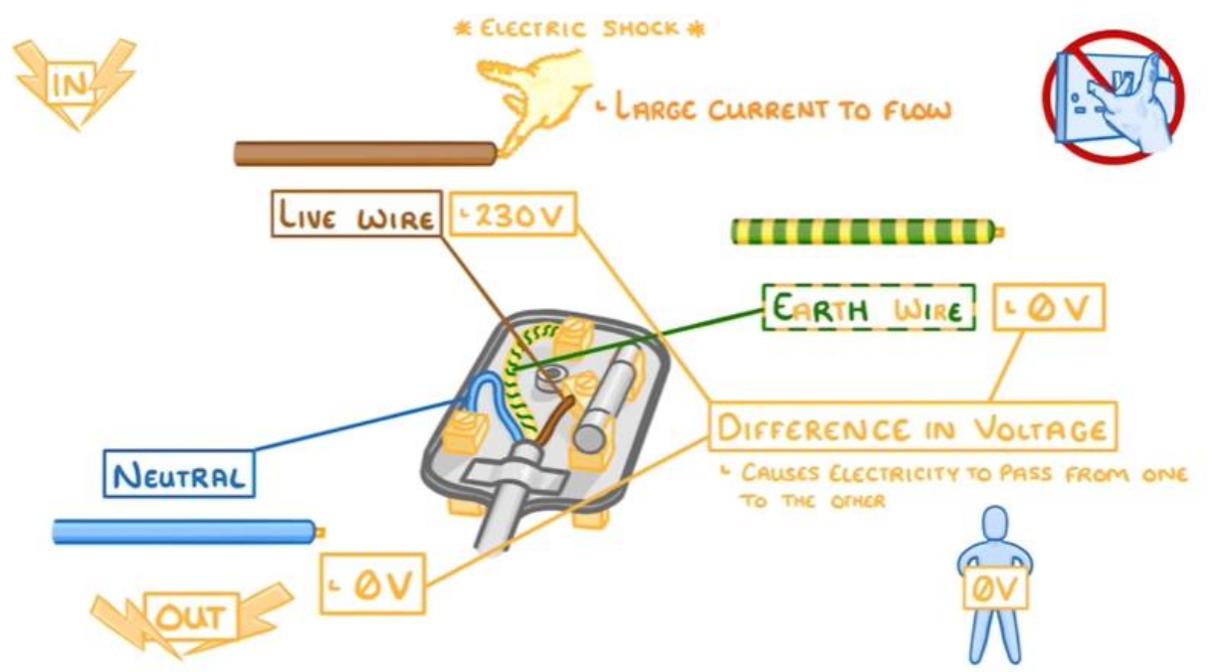
Plugs and Wires

This lesson covers:

1. What mains supply is
2. The roles and colours of the live, neutral and earth wires
3. Why plugs can give you an electric shock

NATIONAL GRID

MAINS SUPPLY

50 Hz

ALTERNATING CURRENT
230 VOLTS

LIVE WIRE

EARTH WIRE

NEUTRAL

COPPER

THREE-CORE CABLE
⌐ 3 WIRES INSIDE

INSULATING PLASTIC

* ELECTRIC SHOCK *

IN

⌐ LARGE CURRENT TO FLOW

LIVE WIRE   ⌐230V

EARTH WIRE   ⌐ ØV

NEUTRAL

DIFFERENCE IN VOLTAGE
⌐ CAUSES ELECTRICITY TO PASS FROM ONE
  TO THE OTHER

OUT   ⌐ ØV

ØV
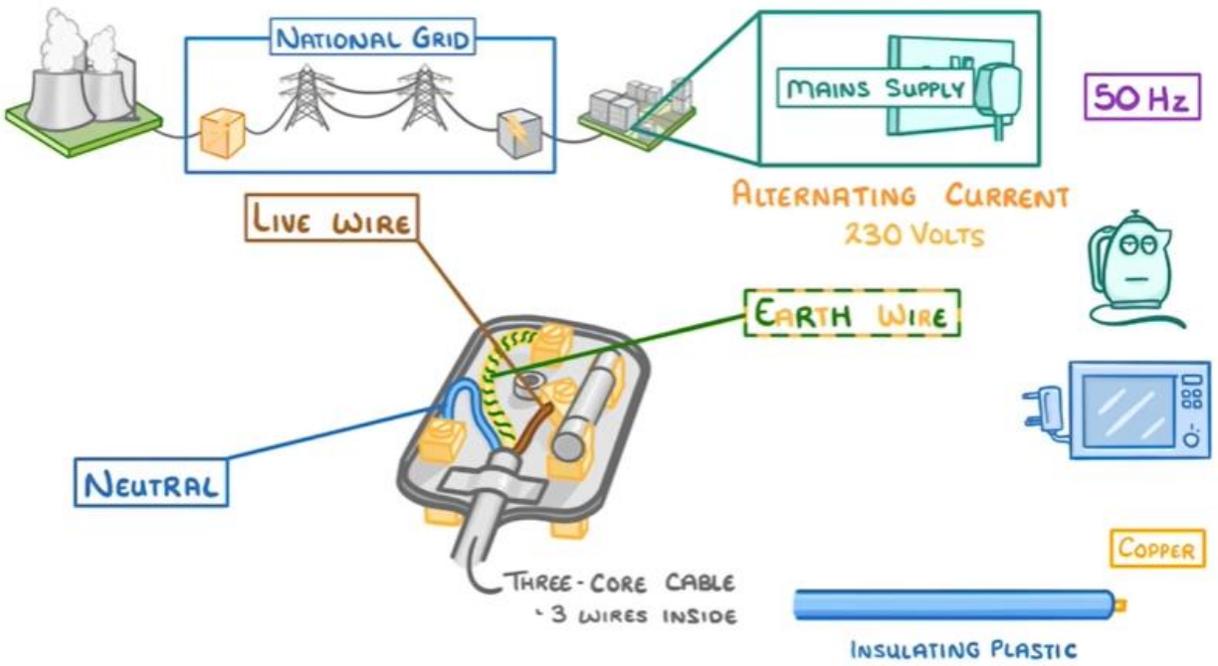
Name the three wires that are normally present in UK plugs.

1. Earth Wire
2. Neutral Wire
3. Live wire

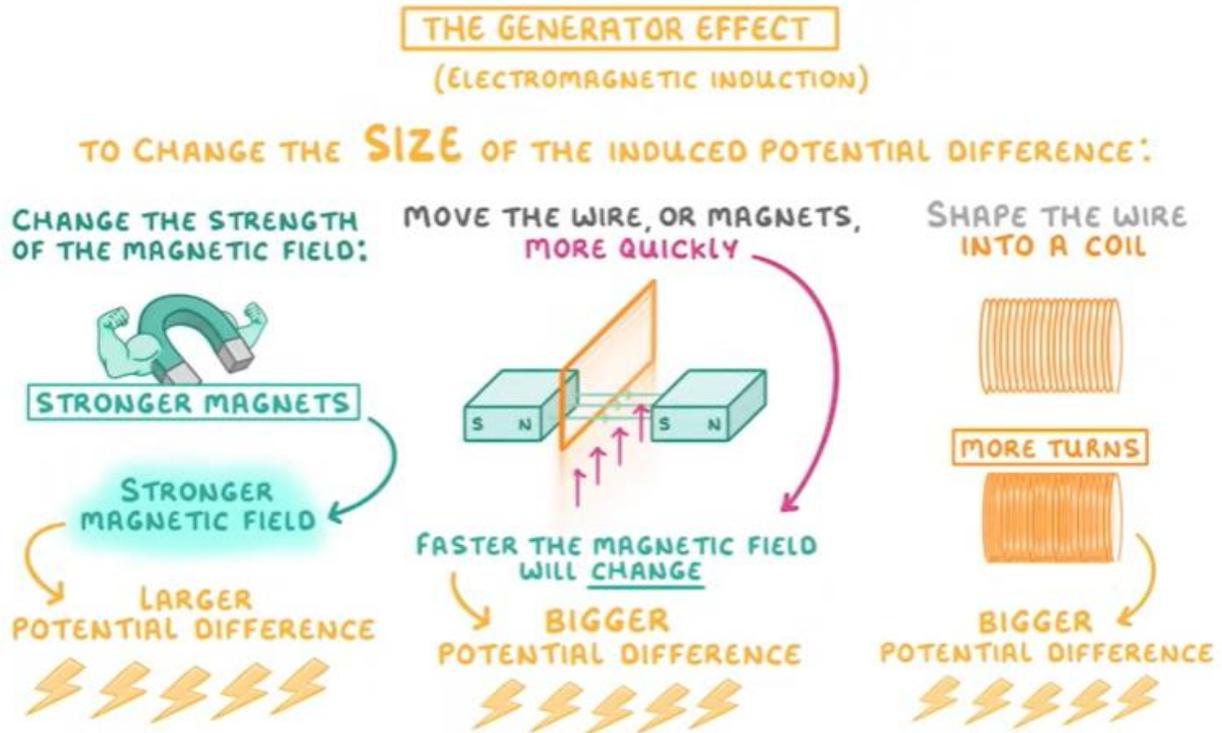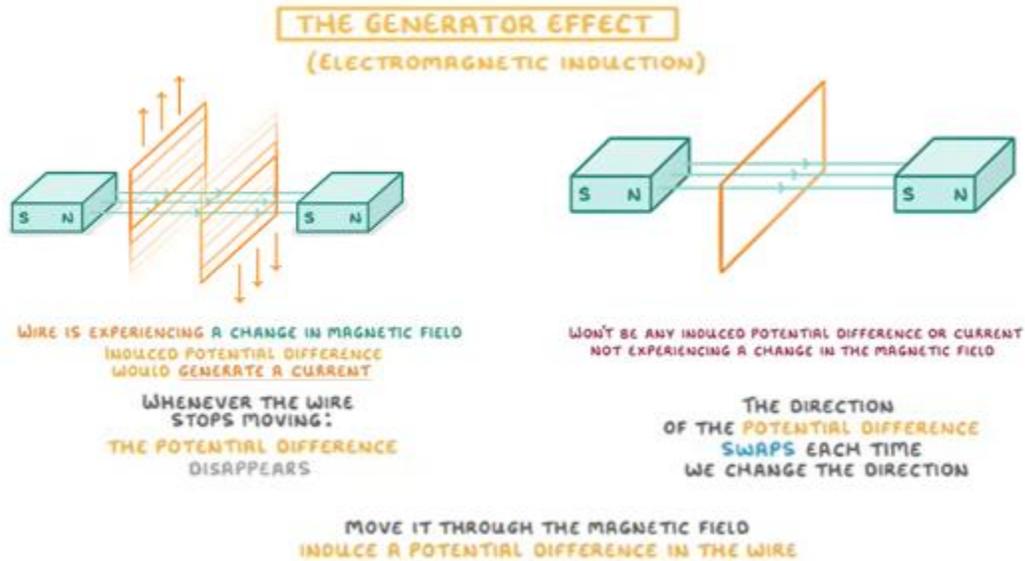*Tick off the marks that you got:*

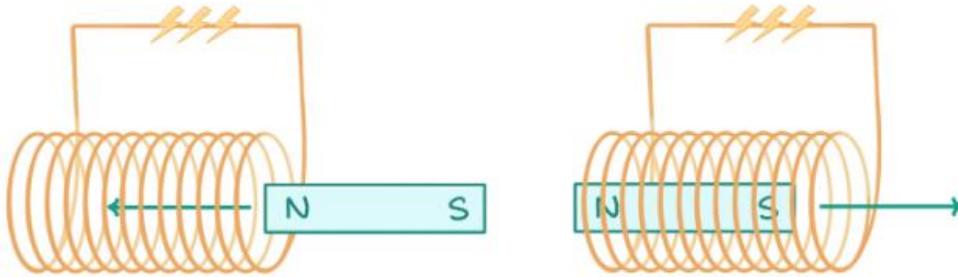☑ Live wire

☑ Neutral wire

☑ Earth wire

Electromagnetic Induction

This lesson covers:

1 How the generator effect / electromagnetic induction works

2 The three ways to increase the size of the induced potential difference

THE GENERATOR EFFECT
(ELECTROMAGNETIC INDUCTION)

WIRE IS EXPERIENCING A CHANGE IN MAGNETIC FIELD
INDUCED POTENTIAL DIFFERENCE
WOULD GENERATE A CURRENT

WHENEVER THE WIRE
STOPS MOVING:
THE POTENTIAL DIFFERENCE
DISAPPEARS

WON'T BE ANY INDUCED POTENTIAL DIFFERENCE OR CURRENT
NOT EXPERIENCING A CHANGE IN THE MAGNETIC FIELD

THE DIRECTION
OF THE POTENTIAL DIFFERENCE
SWAPS EACH TIME
WE CHANGE THE DIRECTION

MOVE IT THROUGH THE MAGNETIC FIELD
INDUCE A POTENTIAL DIFFERENCE IN THE WIRE

THE GENERATOR EFFECT
(ELECTROMAGNETIC INDUCTION)

TO CHANGE THE **SIZE** OF THE INDUCED POTENTIAL DIFFERENCE:

CHANGE THE STRENGTH OF THE MAGNETIC FIELD:

STRONGER MAGNETS

STRONGER MAGNETIC FIELD

LARGER POTENTIAL DIFFERENCE

MOVE THE WIRE, OR MAGNETS, MORE QUICKLY

FASTER THE MAGNETIC FIELD WILL CHANGE

BIGGER POTENTIAL DIFFERENCE

SHAPE THE WIRE INTO A COIL

MORE TURNS

BIGGER POTENTIAL DIFFERENCE

Moving a magnet into or out of a solenoid will induce a potential difference across the wire.

But a current will only flow if it's a closed circuit (which means that the wire forms a complete loop).

A potential difference is generated when a wire experiences a **change** in magnetic field.

Reset

Which of the following would generate a potential difference in a wire?
(the wire is within the magnetic field of a nearby magnet)
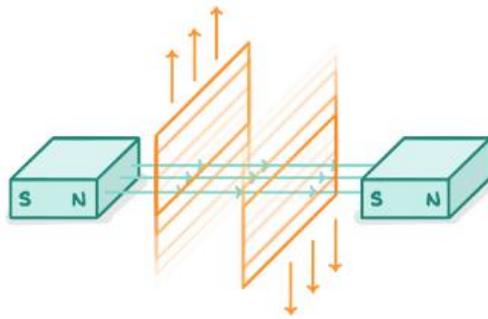
Moving either the wire or the magnet

Only moving the wire

Only moving the magnet

Reset

A wire moving up and down repeatedly perpendicular to a magnetic field will:

Generate an alternating potential difference

Generate a constant potential difference

Not generate a potential difference

Reset

A wire moving parallel to a magnetic field will:

Not generate a potential difference

Generate a constant potential difference

Generate an alternating potential difference

Reset

Name the three ways to increase the size of the potential difference generated in electromagnetic induction

Increase the magnetic field strength
Increasing the turns of the coil
Quickly Moving the coil through the magnetic field

Model answer

To increase the size of an induced potential difference you could use stronger magnets, move the coil or magnetic field faster, or add more turns to the coil.

Tick off the marks that you got:

☑ Increase the magnetic field strength / magnetic flux density

☑ Move the coil through the magnetic field faster

☑ Add more turns to the coil

Reset

3/3

---

constant / changing / voltage / current

1 When a wire experiences a **changing** magnetic field, a potential difference will be induced across the wire.

2 If the ends of the wire are connected to make a closed circuit, then a **current** will flow around the circuit.
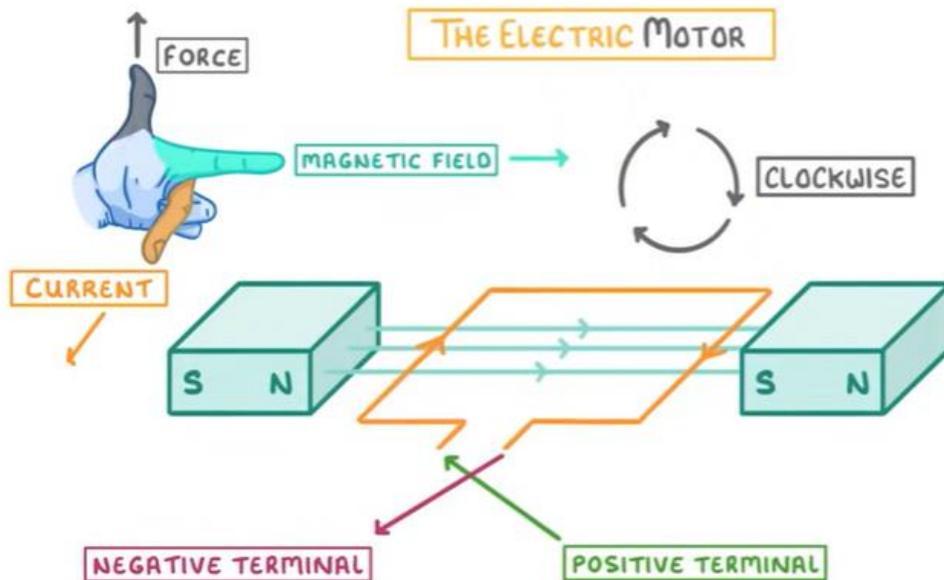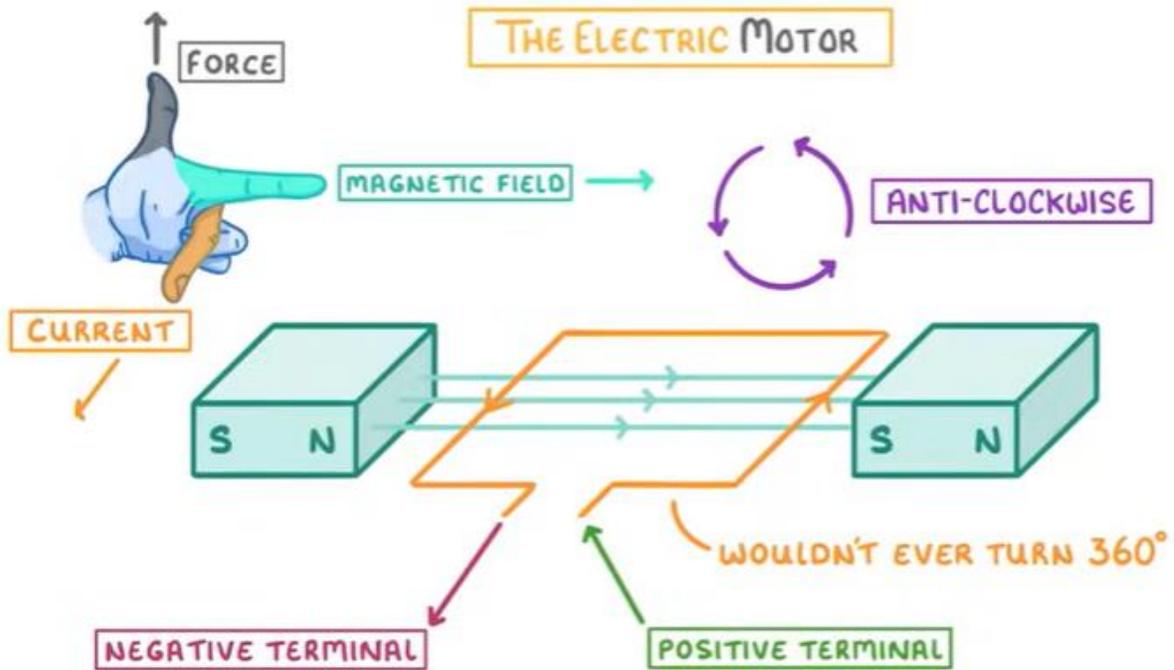
Reset

2/2

How D.C. Motors Work

This lesson covers:

1. How the motor effect can be used to generate a turning force from electricity
2. What a 'split-ring commutator' is, and why it's required
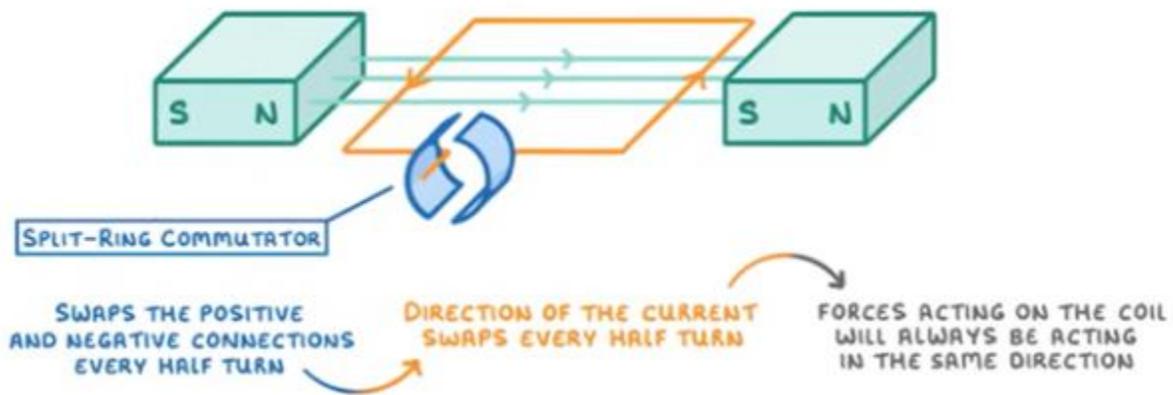3. Three ways to increase the speed of the rotation caused by the motor effect

THE ELECTRIC MOTOR

EXPERIENCE A FORCE
'THE MOTOR EFFECT'

THE ELECTRIC MOTOR

FORCE

MAGNETIC FIELD

CLOCKWISE

CURRENT

S   N

S   N

NEGATIVE TERMINAL

POSITIVE TERMINAL

THE ELECTRIC MOTOR

FORCE

MAGNETIC FIELD

ANTI-CLOCKWISE

CURRENT

S N

S N

WOULDN'T EVER TURN 360°

NEGATIVE TERMINAL

POSITIVE TERMINAL

THE ELECTRIC MOTOR

• CHANGE THE DIRECTION OF THE CURRENT EVERY HALF TURN
(COIL WILL THEN CONTINUE TO ROTATE IN THE SAME DIRECTION)

S N

S N

SPLIT-RING COMMUTATOR

SWAPS THE POSITIVE
AND NEGATIVE CONNECTIONS
EVERY HALF TURN

DIRECTION OF THE CURRENT
SWAPS EVERY HALF TURN

FORCES ACTING ON THE COIL
WILL ALWAYS BE ACTING
IN THE SAME DIRECTION

The Electric Motor

INCREASE THE SPEED OF THE ROTATIONS:

⌐ INCREASE THE CURRENT

INCREASE THE
MAGNETIC FLUX DENSITY:

⌐ ADD MORE TURNS TO THE COIL

STRONGER MAGNETS

The Electric Motor

THE DIRECTION OF THE CURRENT EVERY HAL
N CONTINUE TO ROTATE IN THE SAME

S N   S N

NEGATIVE TERMINAL   POSITIVE TERMINAL

WE CAN CREATE A SPINNING MOTION USING ELECTRICITY

Using Fleming's left hand rule, which way will the coil above rotate?

Clockwise   Anticlockwise

Reset

What do we call the blue device labelled A in the diagram above?

Split-ring commutator

Double disk

Double ring

Reset

How the split ring commutator ensure the coil rotates in one direction

current / half / full / same / opposite

1 The split-ring commutator swaps the positive and negative connections every **half** turn.

2 Therefore, the direction of the **current** through the coil reverses every half turn.

3 This means that the forces acting on the coil will always be acting in the **same** direction.

4 This causes the coil to rotate continuously in one direction.

Reset

heat / motion / electricity

Overall, electric motors use **electricity** to create a rotational **motion**.

Reset

Name the three ways to increase the speed of rotation in an electric motor

1) Adding more turns to the coil
2) Increasing the magnetic flux by using a stronger magnet
3) Increasing the current

Model answer

To increase the speed of an electric motor you can add more turns to the coil, use stronger magnets, or increase the current in the coil.

Tick off the marks that you got:

☑ Add more turns to the coil

☑ Increase the magnetic field strength / magnetic flux density of the magnet
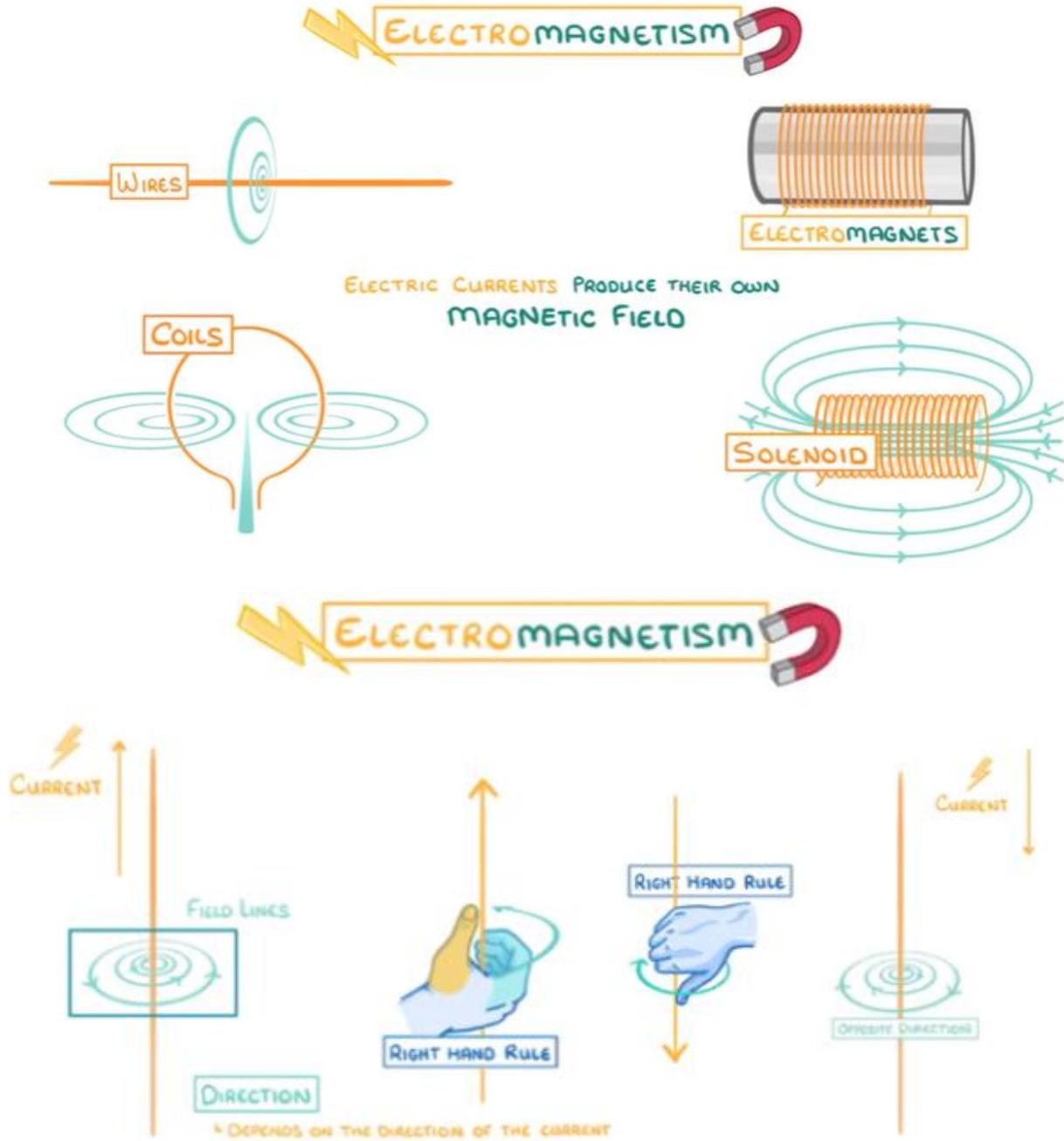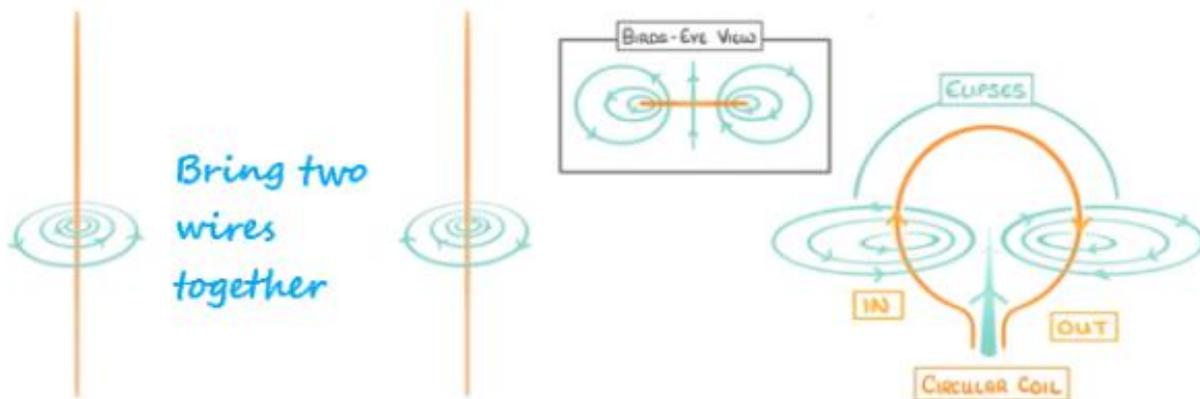
☑ Increase the current in the coil
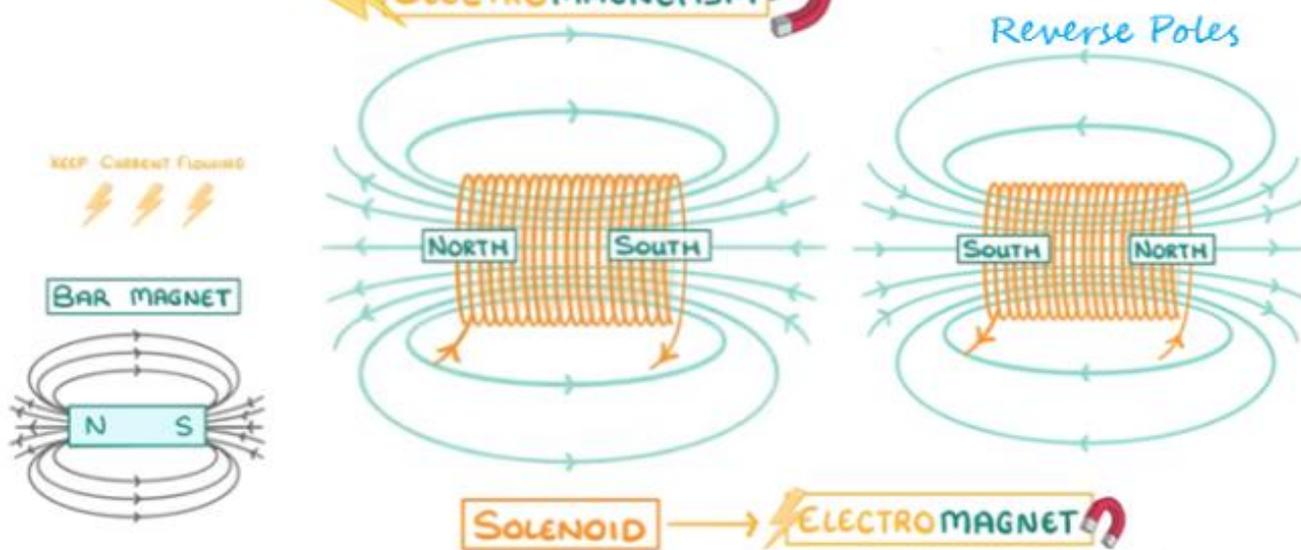
Reset

Electromagnetism

This lesson covers:

1. What 'electromagnetism' is, and how it works
2. How electromagnetism is created in wires, coils, solenoids, and electromagnets
3. The four ways to increase the strength of an electromagnet

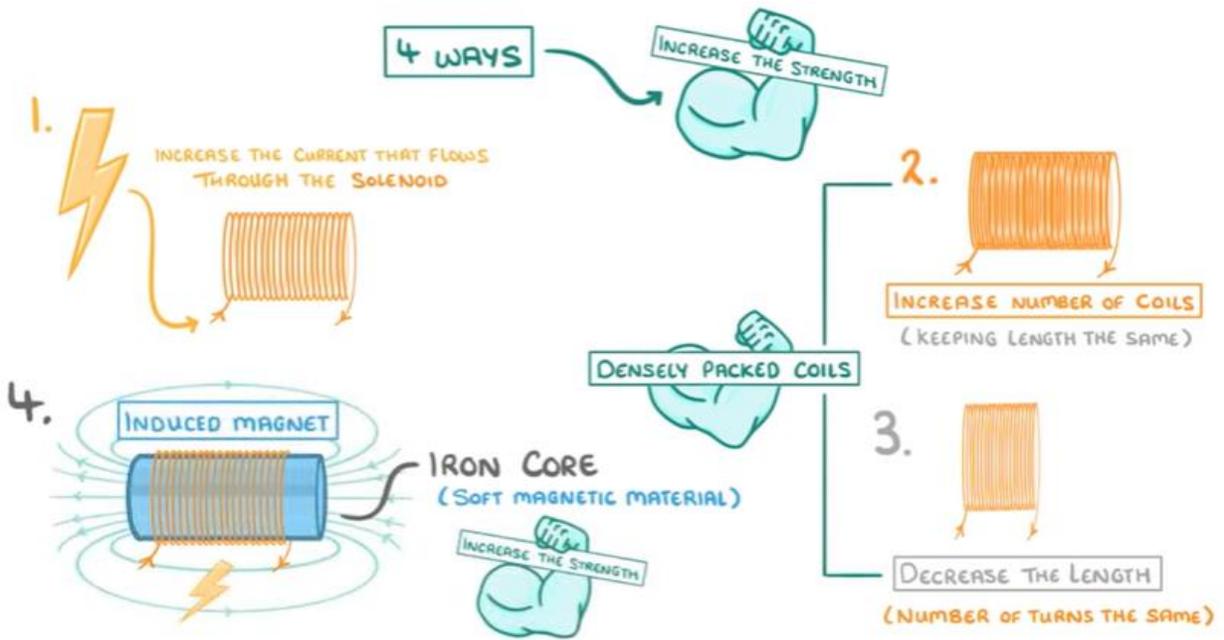# ELECTROMAGNETISM

Bring two
wires
together

BIRDS-EYE VIEW

ELIPSES

IN

OUT

CIRCULAR COIL

ELECTROMAGNETISM

Reverse Poles

KEEP CURRENT FLOWING

BAR MAGNET

N   S

NORTH   SOUTH

SOUTH   NORTH

SOLENOID → ELECTROMAGNET

4 WAYS

INCREASE THE STRENGTH

1. INCREASE THE CURRENT THAT FLOWS THROUGH THE SOLENOID

2. INCREASE NUMBER OF COILS (KEEPING LENGTH THE SAME)

3. DECREASE THE LENGTH (NUMBER OF TURNS THE SAME)

DENSELY PACKED COILS

INCREASE THE STRENGTH

4. INDUCED MAGNET

IRON CORE (SOFT MAGNETIC MATERIAL)

Which of the following is correct?

> When an electrical current flows through a material, a magnetic field is always produced

> When an electrical current flows through a material, a magnetic field is produced only if that material is a metal

Reset

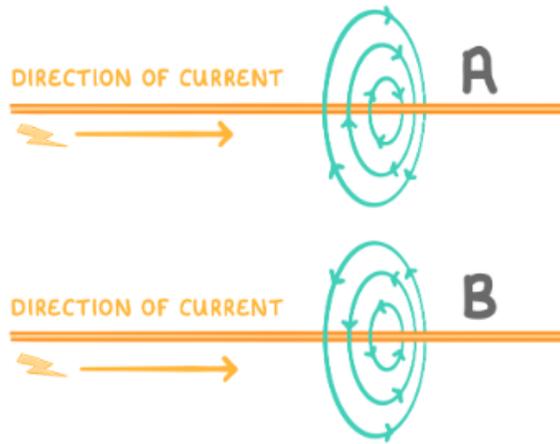## RIGHT HAND RULE

force / current / magnetic

The right hand rule can tell us the direction of the magnetic field induced by a flowing current.

In the right hand rule, the thumb is placed following the same direction as the **current** is travelling, and the fingers are the curled in the direction of the **magnetic** field lines.

Reset

DIRECTION OF CURRENT **A**

DIRECTION OF CURRENT **B**

The above diagram shows two wires with current flowing to the right.

Using the right hand grip rule, which of the two shows the correct direction of the magnetic field lines, A or B?
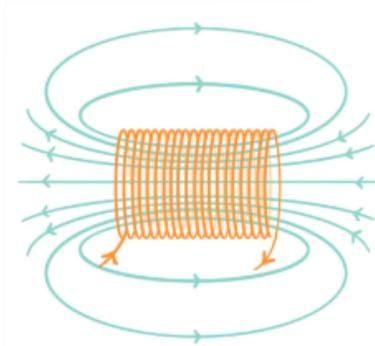
| A | **B** |

Reset

The above object can be called:
(Select all that apply)

A trapezoid

A solenoid

A cuboid

An electromagnet

Reset

In an electromagnet, a current is required to produce the magnetic field.

When the current is switched off, the magnetic field:

Remains the same

Disappears

Changes direction

Reset

Describe the four ways to increase the strength of an electromagnet.

1) Increase the number of coil
2) Use a soft iron core
3) Decrease the length of the coil
4) Increase the current through the selenoid

Model answer

You could increase the current, increase the number of turns of wire while keeping the length of the solenoid the same, reduce the length of the solenoid while keeping the number of turns of wire the same, or add a soft iron core.

Tick off the marks that you got:

☑ Increase the current

☑ Increase the number of turns in the solenoid, while keeping the length the same

☑ Reduce the length of the solenoid while keeping the number of turns the same
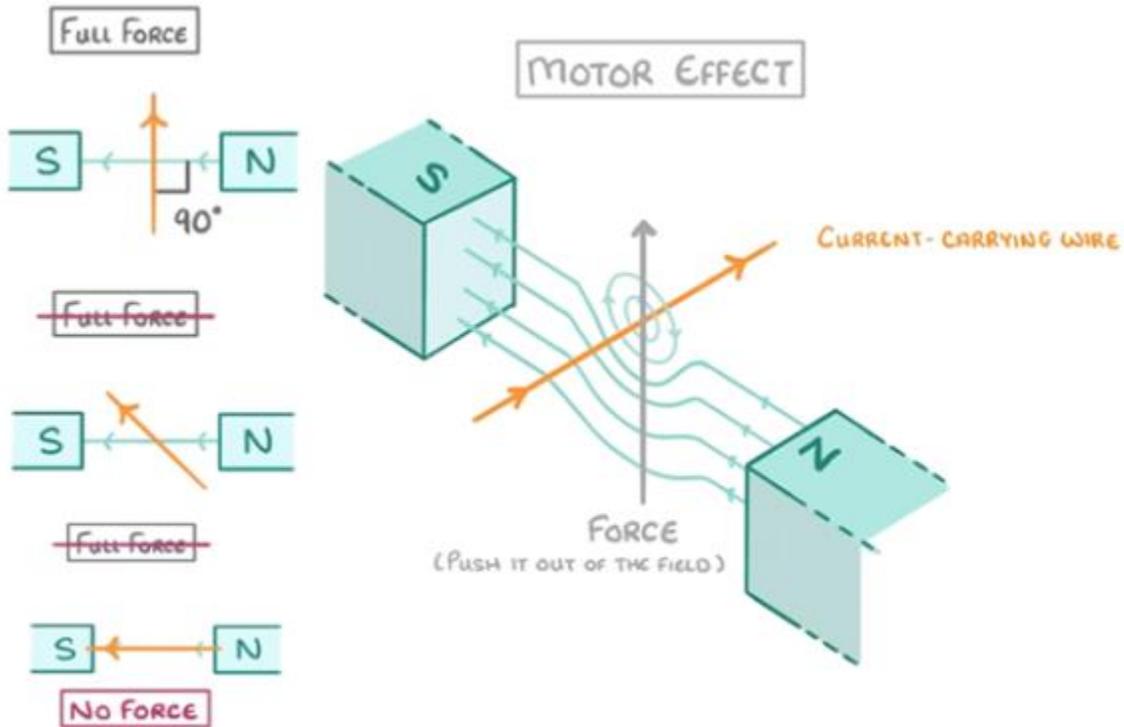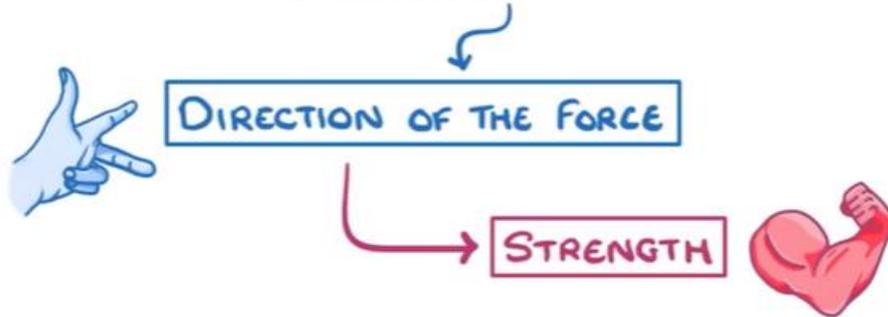
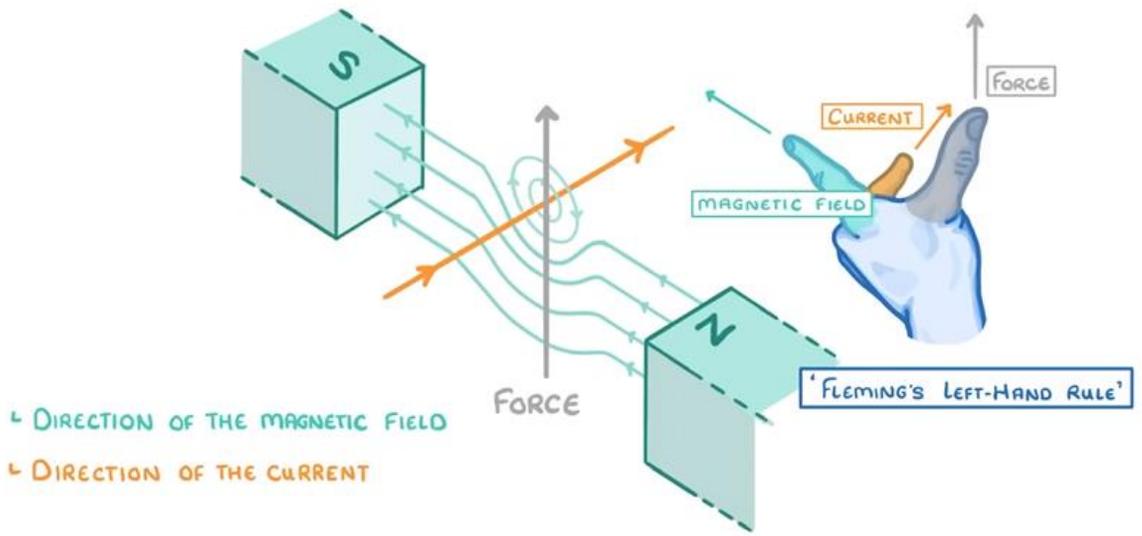☑ Add a soft iron core

Reset

Motor Effect

This lesson covers:

1. The idea that a current-carrying wire will experience a force if placed within a magnetic field
2. How to find the direction of the force using Fleming's left hand rule
3. How to find the strength of the force using the equation: $F = BIL$

MOTOR EFFECT

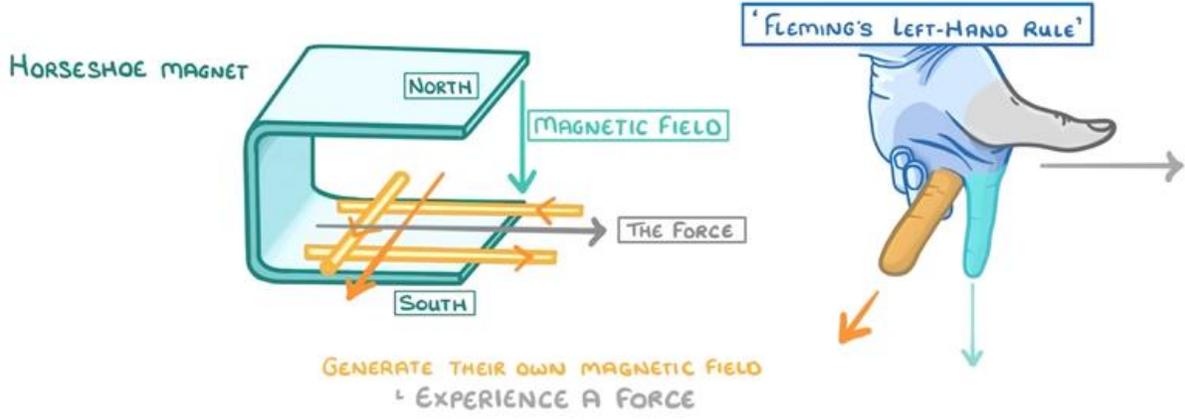A CURRENT CARRYING WIRE IN THE PRESENCE OF A MAGNETIC FIELD WILL EXPERIENCE A FORCE

DIRECTION OF THE FORCE

STRENGTH

FULL FORCE

S ← → N
90°

Full force

S ← N

Full force

S ← N
No FORCE

MOTOR EFFECT

S

N

CURRENT- CARRYING WIRE

FORCE
(PUSH IT OUT OF THE FIELD)

Find the Direction of the Force

S

Force

CURRENT

FORCE

MAGNETIC FIELD

N

FORCE

'FLEMING'S LEFT-HAND RULE'

└ DIRECTION OF THE MAGNETIC FIELD
└ DIRECTION OF THE CURRENT

Find the Direction of the Force

HORSESHOE MAGNET

NORTH

MAGNETIC FIELD

THE FORCE

SOUTH

'FLEMING'S LEFT-HAND RULE'

GENERATE THEIR OWN MAGNETIC FIELD
└ EXPERIENCE A FORCE

S ← N

RIGHT ANGLE
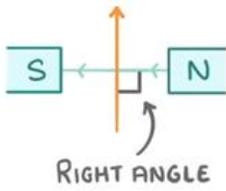
CALCULATE THE STRENGTH OF THE FORCE

$$F = B \times I \times L$$

FORCE (N)   MAGNETIC   CURRENT   LENGTH OF WIRE
             FLUX DENSITY   (A)   (m)
                (T)

10 cm / 100 = 0.1 m

S ← N   0.4T

5A
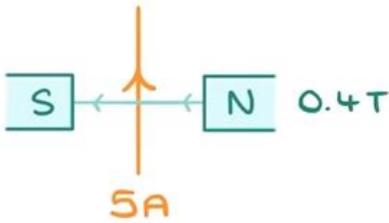
0.4T × 5A × 0.1m

= 0.2 N

motor / engine / current

A **current** carrying wire in the presence of a magnetic field will experience a force. This is called the **motor** effect.
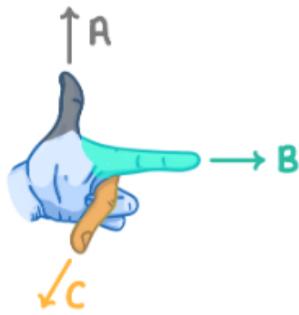
Reset

2/2

parallel / perpendicular

To experience the full force, a current carrying wire must be placed **perpendicular** to the magnetic field.
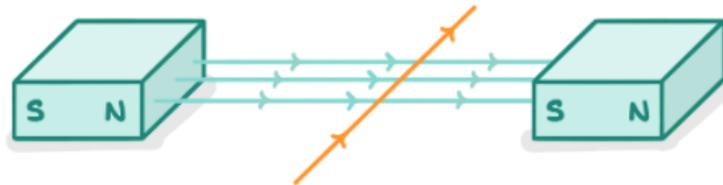
Reset

1/1

Fleming's left hand rule can be used to tell us the direction of the force experienced by a current carrying wire in a magnetic field.

In the diagram above, match the letters A to C with what they represent in Fleming's left hand rule:

Direction of the current: C
Direction of the force: A
Direction of the magnetic field: B

Reset

Use Fleming's left hand rule to find the direction of the force experienced by the wire.

The force is:

To the left

To the right

Upwards

Downwards

Reset

The force (F) experienced by the wire is determined by:

1. The current (I) in the wire
2. The magnetic field strength (B). This is also called magnetic flux density.
3. The length (L) of the wire that crosses the magnetic field.

The formula to calculate the force is:
(Note: this formula is given to you in the exam)

$$F = \frac{B}{IL}$$

$$F = BIL$$

$$F = \frac{BI}{L}$$

$$F = \frac{I}{BL}$$

Reset

1/1

The magnetic field strength (also known as magnetic flux density) is measured in:
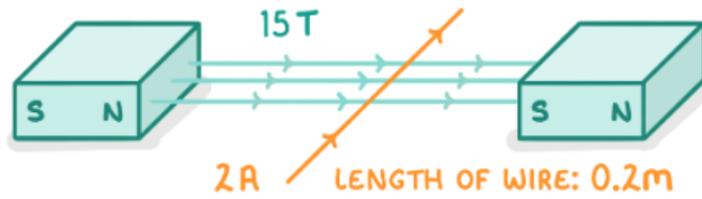
Volts (V)

Amperes (A)

Coulombs (C)

Teslas (T)

Reset

1/1

15 T

2 A   LENGTH OF WIRE: 0.2m

A wire carrying a current of 2 A is perpendicular to a magnetic field of 15 T.

The length of the wire in the field is 0.2 m.

What is the force experienced by the wire?

6 N

Great! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

Reset

Hint

1/1

30 T

6 A   LENGTH OF WIRE: 0.1 M

A wire carrying a current of 6 A is perpendicular to a magnetic field of 30 T.

The length of the wire in the field is 0.1 m.
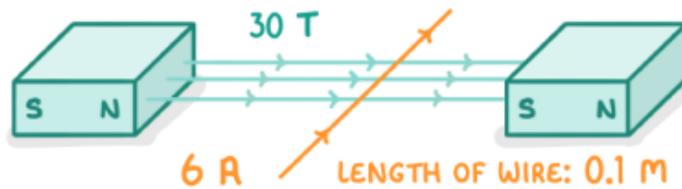
What is the force experienced by the wire?

18 N

Perfect! To see our step-by-step working use the hint button, or click here to reveal all steps at once.
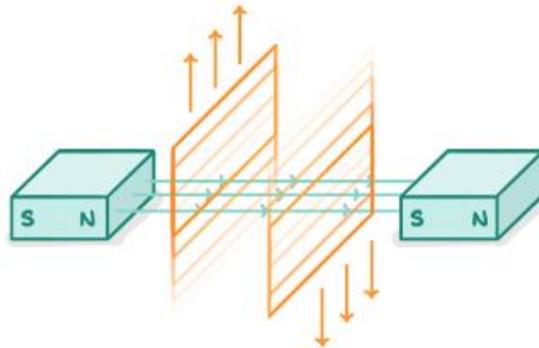
Reset

Hint

1/1

Alternators, Dynamos & Oscilloscopes

This lesson covers:

1. The two types of generators: alternators and dynamos
2. How alternators generate alternating current (a.c.)
3. How dynamos generate direct current (d.c.)
4. What a.c. and d.c. look like on an oscilloscope

Alternators and dynamos

If you remember from a previous lesson, electromagnetic induction (the 'generator effect') is the idea that we generate an electric current by moving a wire relative to a magnetic field.

Alternators and dynamos are generators

We use the generator effect in devices called 'generators'. These devices generate electricity from rotational motion (e.g. rotating a coil of wire).

'Alternators' and 'dynamos' are different types of generator.

A key difference
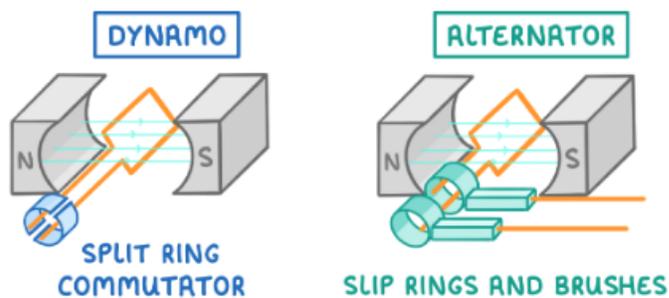
Alternators and dynamos look very similar - the key difference is that dynamos have a split ring commutator, whilst alternators have slip rings and brushes.

1. Due to the split ring commutator, dynamos produce direct current.

2. Due to the slip rings and brushes, alternators produce alternating current.

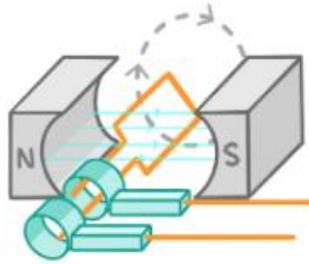# How alternators work

1   The coil of wire rotates relative to the magnets, this induces a magnetic field in the coil, which then induces a voltage and current in the coil.
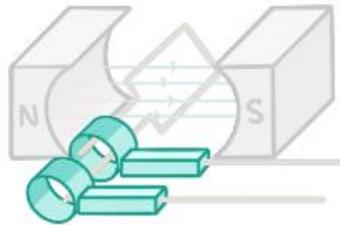
2   The slip rings and brushes mean that the contacts don't swap every half turn (like they do in a motor or dynamo).
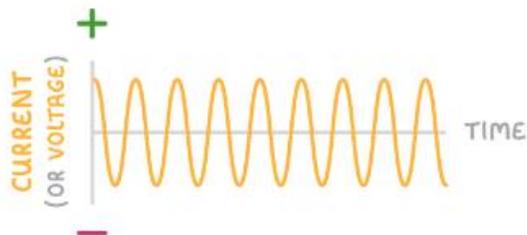
3   This means that they produce an alternating potential difference and an alternating current (a.c.). A visualisation of the current, like the image above, is produced by an oscilloscope.
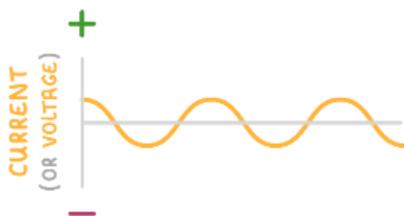
COIL ROTATING SLOWLY   COIL ROTATING QUICKLY
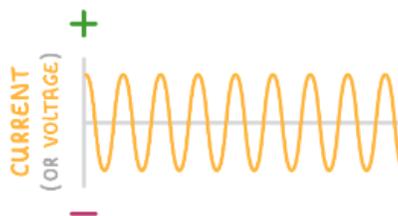
4   As the coil rotates faster, the peaks of the oscillations get larger, and more frequent.

How **dynamos** work
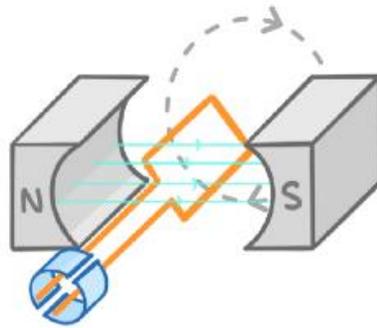
1 As the coil of wire spins relative to the magnet, a **magnetic field**, and hence a **voltage and current, is induced in the coil.**
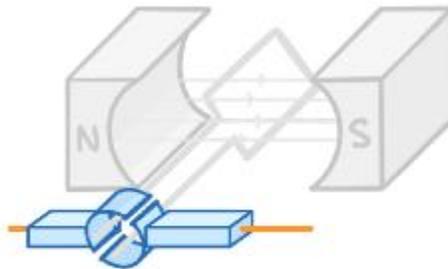
2 The **split ring commutator** means that the **contacts swap every half turn.**

+

CURRENT (OR VOLTAGE)

TIME

−

3 This means that they produce a **direct potential difference** and hence a **direct current (d.c.).** It's called **direct current** because the **current is always flowing in the same direction** (which is why it's always positive on the oscilloscope graph above).
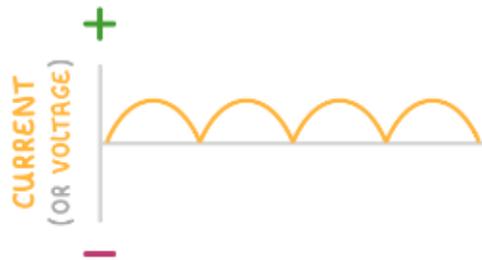
COIL ROTATING SLOWLY   COIL ROTATING QUICKLY

4 As the coil rotates faster, the peaks of the oscillations get larger and more frequent.

What does a.c. stand for?

Alternating current

Reset

1/1

What type of current is generated by a dynamo?

Alternating current   **Direct current**

Reset

1/1

What is the difference between the design of an alternator and the design of a dynamo?

1) It has split ring commutator as a result it produces direct current.
2) It has both slip rings and brushes so it produces alternating current.

Model answer

An alternator has slip rings and brushes whereas a dynamo has a split-ring commutator.

Tick off the marks that you got:

☑ An alternator has slip rings (and brushes)
☑ A dynamo has a split-ring commutator

Reset

2/2

Explain how an electromagnetic induction (generator effect) is used in dynamos.

When a coil spins inside a magnetic field, a current flows in the coil. A clever device called a commutator flips the connections halfway through each spin, making the current in the outside circuit flow in one direction, even though the coil's current changes.

Model answer

A coil of wire is turned inside a magnetic field, which induces a magnetic field, and hence current, in the coil of wire. The coil is connected to a commutator which switches the connections every half-turn. This causes the induced current in the external circuit to be in one direction (d.c.).

Tick off the marks that you got:
- ☑ A coil of wire is turned inside a magnetic field.
- ☑ This induces a (magnetic field and) current in the coil of wire.
- ☑ The commutator switches the connections every half-turn.
- ☑ This causes the current to be in one direction (d.c.).

Reset

What happens to the oscillations on an oscilloscope when you increase the speed at which a coil rotates in an alternator?

The amplitude and the frequency both increase.

The frequency increases, but the amplitude stays the same.

The amplitude and the frequency both stay the same.

The amplitude increases, but the frequency stays the same.

Reset

How Transformers Work

This lesson covers:

1. How transformers are used to minimise power loss when transmitting electricity across the national grid
2. How a transformer works

HOW TRANSFORMERS WORK

HOW THEY'RE USED IN THE NATIONAL GRID

POWER STATIONS

STEP UP TRANSFORMER

WIRES AND PYLONS

STEP DOWN TRANSFORMER

ᒪSAFE TO USE

INCREASES VOLTAGE: 400,000 V

ᒪ MINIMISE ENERGY LOSS

DECREASES VOLTAGE: ~230V

HOW TRANSFORMERS WORK

PRIMARY COIL

SECONDARY COIL

1. AN ALTERNATING POTENTIAL DIFFERENCE

2. CAUSES A CURRENT TO FLOW
ᒪ WILL ALSO ALTERNATE

3. A MAGNETIC FIELD AROUND THE COIL
ᒪ WILL ALSO ALTERNATE

IRON CORE

4. INDUCES AN ALTERNATING MAGNETIC FIELD IN THE IRON CORE

5. INDUCES A POTENTIAL DIFFERENCE

PART OF A COMPLETE CIRCUIT?

6. CAUSES A CURRENT TO FLOW

HOW TRANSFORMERS WORK

TRANSFERRING THE CURRENT →

PRIMARY COIL

SECONDARY COIL

INSULATED IN PLASTIC

CAN'T PASS TO THE IRON CORE

IRON CORE

USES THESE INDUCED MAGNETIC CURRENTS

HOW TRANSFORMERS WORK

CHANGE THE SIZE OF THE POTENTIAL DIFFERENCE BETWEEN THE TWO COILS:

STEP UP TRANSFORMER

10v →

20v →

TWICE AS MANY TURNS
↳ VOLTAGE GETS DOUBLED

FEWER TURNS

STEP THE VOLTAGE DOWN

Which type of transformer **increases the voltage**, and **decreases the current**, minimising energy loss whilst the electricity is transmitted across the national grid?

Step-up transformer

Step-down transformer
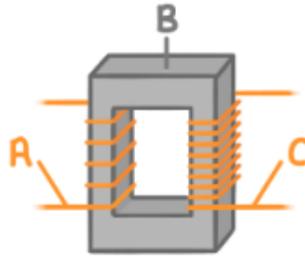
Reset

Match the letters A to C on the diagram above with the following parts of the step-up transformer:

Primary coil: A
Secondary coil: C
Iron core: B

Reset

Which type of transformer **decreases the voltage**, and **increases the current**, making the electricity safe to use in our homes?

Step-down transformer

Step-up transformer

Reset
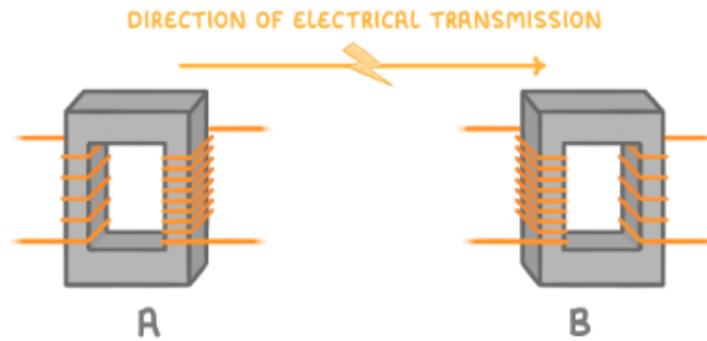
In this diagram the electricity is being transmitted from left to right.

Which transformer is the step-up transformer, and which is the step-down transformer?

A is the step-down transformer, and B is the step-up transformer

A is the step-up transformer, and B is the step-down transformer

Reset

1/1

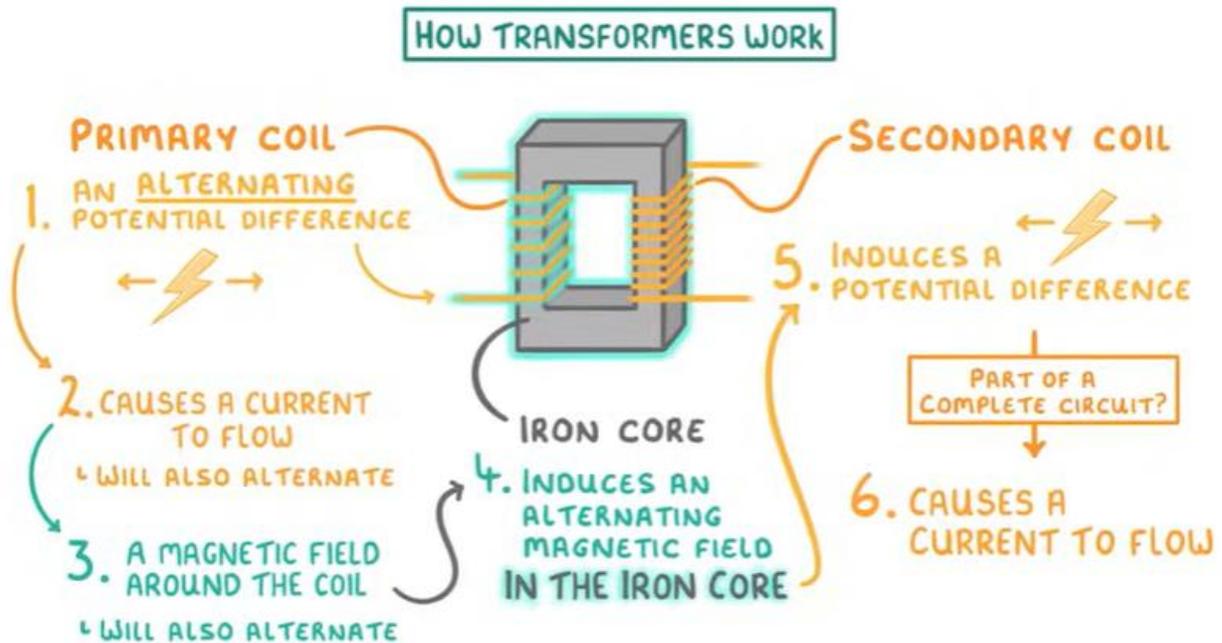For transformers to work, the current in the primary coil must be **alternating** current.

Reset

1/1

How transformers work

strength / electric / iron core / magnetic field / direct / alternating current

1. When supplied with an alternating current, the primary coil will generate an alternating **magnetic field**.
2. This then induces an alternating magnetic field in the **iron core**.
3. This in turn induces an alternating voltage in the secondary coil, which if the circuit is complete will lead to an **alternating current**.

Reset

3/3

The ratio of turns in the primary and secondary coil will affect:
(Select all that apply)

The voltage in the secondary coil

The current in the secondary coil

The resistance in the secondary coil

Reset

This lesson covers:

1. How to use the transformer equations: $\frac{V_p}{V_s} = \frac{n_p}{n_s}$ and $V_p\,I_p = V_s\,I_s$

CHANGE THE POTENTIAL DIFFERENCE
OF AN ELECTRICITY SUPPLY

STEP UP TRANSFORMERS
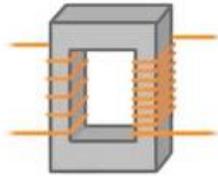
INCREASING THE POTENTIAL DIFFERENCE

STEP DOWN TRANSFORMERS
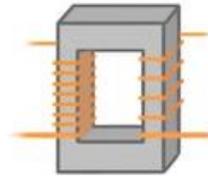
DECREASING THE POTENTIAL DIFFERENCE

$$\frac{V_P}{V_S} = \frac{n_P}{n_S}$$

$$V_P\,I_P = V_S\,I_S$$

'V' IS POTENTIAL DIFFERENCE

'n' IS NO. OF TURNS OF THE COIL

'I' IS CURRENT

'P' – PRIMARY

'S' – SECONDARY

HOW TO USE:

V_P

INPUT P.D

(PRIMARY COIL)

n_S

NO. OF TURNS
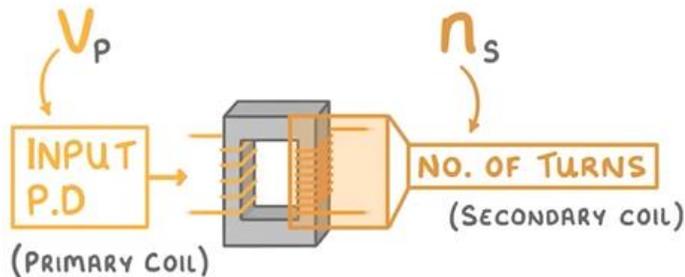
(SECONDARY COIL)

$$\boxed{\dfrac{V_P}{V_S} = \dfrac{n_P}{n_S}}$$

$$\overline{V_P I_P = V_S I_S}$$

'V' IS POTENTIAL DIFFERENCE
'n' IS NO. OF TURNS OF THE COIL
'I' IS CURRENT
'P' – PRIMARY
'S' – SECONDARY

HOW TO USE:

A TRANSFORMER HAS 18 TURNS ON ITS PRIMARY COIL, 54 TURNS ON ITS SECONDARY COIL, AND AN INPUT POTENTIAL DIFFERENCE OF 45V. CALCULATE ITS OUTPUT POTENTIAL DIFFERENCE.

$\boxed{135 \text{ VOLTS}}$

$n_P = 18$
$n_S = 54$
$V_P = 45$
$V_S = 135$

$\dfrac{45}{V_S} = 0.33$

REARRANGE

$135 = V_S$

$$\dfrac{V_P}{V_S} = \dfrac{n_P}{n_S}$$

$$\boxed{V_P I_P = V_S I_S}$$

'V' IS POTENTIAL DIFFERENCE
'n' IS NO. OF TURNS OF THE COIL
'I' IS CURRENT
'P' – PRIMARY
'S' – SECONDARY

HOW TO USE:

USING THE SAME TRANSFORMER, IF THE INPUT CURRENT WAS WHAT WOULD THE OUTPUT CURRENT BE?

$I_S = ?$
$I_P = 12$
$n_P = 18$
$n_S = 54$
$V_P = 45$
$V_S = 135$

$45 \times 12 = 135 \times I_S$

$\div 135$ $\div 135$

$\dfrac{(45 \times 12)}{135} = I_S$

$4 = I_S$

---

increase / decrease

Step-up transformers **increase** the potential difference.

Step-down transformers **decrease** the potential difference.

Reset
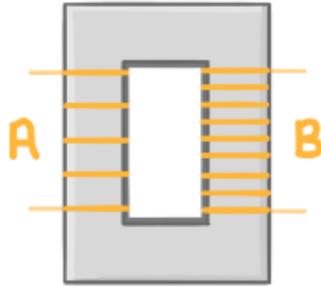
The number of turns on the primary coil A is: **5**
The number of turns on the secondary coil B is: **9**

Great! To find the number of turns in each coil, just count how many lines there are on each side of the transformer. In this diagram there are 5 lines on the left side (so 5 turns on the primary coil) and 9 lines on the right side (so 9 turns on the secondary coil).

Reset

In a transformer, the ratio of the voltage in the primary coil (V_p) and secondary coil (V_s) is equal to the ratio of the turns in the primary coil (n_p) and secondary coil (n_s).

The formula for this is:

$$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

$$V_p \, V_s = n_p \, n_s$$

Reset

1/1

A step-up transformer has 20 turns in its primary coil and 60 turns in its secondary coil.

The primary coil has a potential difference of 50 V.

What is the potential difference in the secondary coil?

150 V

Well done! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

Reset

Hint   1/1

A step-down transformer has 120 turns in its primary coil and 10 turns in its secondary coil.

The secondary coil has a potential difference of 30 V.

What is the potential difference in the primary coil?

360 V

Perfect! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

Reset

Hint

1/1

The power in the primary coil is equal to the power in the secondary coil.

Therefore, which formula is correct?
(Remember that $P = IV$)

$V_p \, I_p = V_s \, I_s$

$\frac{V_p}{I_p} = \frac{V_s}{I_s}$

Reset

1/1

A step-down transformer has 500 V in the primary coil and 100 V in the secondary coil.

The primary coil has a current of 0.4 A.

What is the current in the secondary coil?

2 A

Well done! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

Reset

Hint

1/1

A step-up transformer has 40 V in the primary coil and 600 V in the secondary coil.

The secondary coil has a current of 24 A.

What is the current in the primary coil?

360 A

Great! To see our step-by-step working use the hint button, or click here to reveal all steps at once.

Reset

Hint

1/1

National Grid

This lesson covers:

1. How electricity is formed and send across the country
2. Why we need to a low current and high voltage for electricity transmission
3. What step-up and step-down transformers do

$$P = V \times I$$

NATIONAL GRID
- HAS TO TRANSMIT HUGE AMOUNTS OF POWER

PYLONS

STEP-UP TRANSFORMER
- INCREASE THE VOLTAGE
400,000 V

TRANSMIT

STEP-DOWN TRANSFORMER
- VOLTAGE HAS TO BE REDUCED BACK DOWN
230V

TOWN

HIGH VOLTAGE

DANGEROUS

BLOW APPLIANCES

LOSE LOADS OF ENERGY

HIGH CURRENT = LOTS OF HEAT 🔥 (BECAUSE OF THE RESISTANCE)

NATIONAL GRID

PYLONS

- SAFE TO USE

POWER STATIONS

STEP-UP TRANSFORMER
INCREASING THE VOLTAGE

WIRES

STEP-DOWN TRANSFORMER
LOWERING THE VOLTAGE

SECTION 4

Electricity and magnetism

Topics

A familiar example of a magnet is a compass needle with one north-seeking pole. You will find that all magnets have two poles: like poles repel, unlike poles attract. A magnet can induce magnetism in certain materials such as iron and steel and is surrounded by a magnetic field which exerts a force on another magnet. The pattern of magnetic field lines can be made visible with the aid of iron filings. Electromagnets are formed from coils of wire through which an electrical current is passed that allows the strength of the magnet to be varied and turned on and off easily. They are used in many electrical devices from doorbells to motors. You will learn that permanent magnets and electromagnets have differing properties and uses.

In a magnetic field, the closer the field lines are at a point, the stronger is the magnetic field.

Properties of magnets

Magnetic materials
Some materials, known as ferromagnets, can be magnetised to form a magnet. In their unmagnetised form they are attracted to a magnet.

Magnetic poles
The *poles* are the places in a magnet to which magnetic materials, such as iron filings, are attracted. They are near the ends of a bar magnet and occur in pairs of equal strength.

North and south poles
A magnet has two poles; a north pole (N pole) and a south pole (S pole). If a magnet is supported so that it can swing in a horizontal plane it comes to rest with one pole, the N pole, always pointing roughly towards the Earth's north pole. A magnet can therefore be used as a *compass*.

Law of magnetic poles
If the N pole of a magnet is brought near the N pole of another magnet, repulsion occurs. Two S (south-seeking) poles also repel. By contrast, N and S poles always attract.
The law of magnetic poles summarises these facts and states:

Like poles repel, unlike poles attract.

The force between magnetic poles decreases as their separation increases.

Induced magnetism

When a piece of unmagnetised magnetic material touches or is brought near to the pole of a permanent magnet, it becomes a magnet itself. The material is said to have magnetism induced in it. Figure 4.1.1 shows that a N pole in the permanent magnet induces a N pole in the right-hand end of the magnetic material.
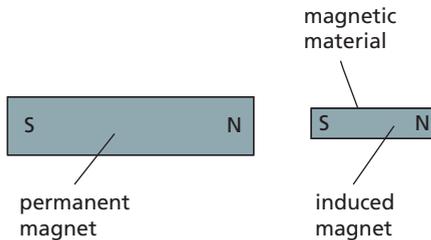
▲ **Figure 4.1.1** Induced magnetism

This can be checked by hanging two iron nails from the N pole of a magnet. Their lower ends repel each other (Figure 4.1.2a) and both are repelled further from each other when the N pole of another magnet is brought close (Figure 4.1.2b).
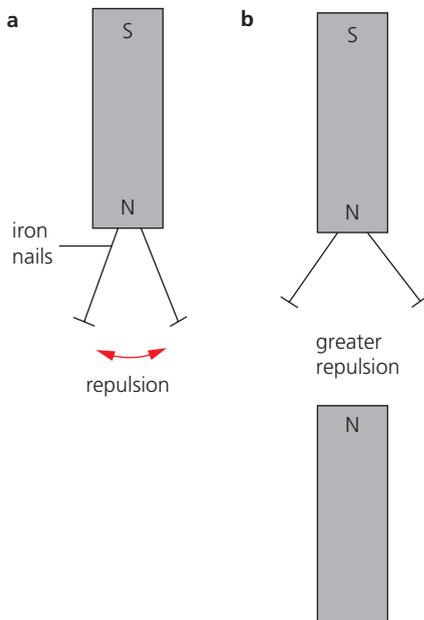
▲ **Figure 4.1.2** Magnetic repulsion

Magnetisation of iron and steel

Chains of small iron nails and steel paper clips can be hung from a magnet (Figure 4.1.3). Each nail or clip magnetises the one below it and the unlike poles so formed attract.

If the iron chain is removed by pulling the top nail away from the magnet, the chain collapses, showing that magnetism induced in iron is **temporary**. When the same is done with the steel chain, it does not collapse; magnetism induced in steel is **permanent**.

> **Key definitions**
>
> **Temporary magnets** made of soft iron, lose their magnetism easily
>
> **Permanent magnets** made of steel, retain their magnetism
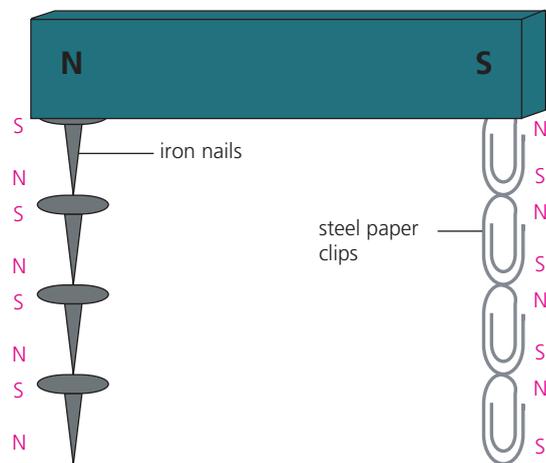
▲ **Figure 4.1.3** Investigating the magnetisation of iron and steel

Magnetic materials such as iron that magnetise easily but readily lose their magnetism (are easily demagnetised) are said to be **soft**. Those such as steel that are harder to magnetise than iron but stay magnetised are **hard**. Both types have their uses; very hard ones are used to make permanent magnets.

Magnetic and non-magnetic materials

Magnetic materials such as iron, steel, nickel and cobalt are attracted by a magnet and can be magnetised temporarily or permanently. **Non-magnetic materials** such as aluminium and wood are not attracted by a magnet and cannot be magnetised.

> **Key definitions**
>
> **Magnetic materials** materials that can be magnetised by a magnet; in their unmagnetised state they are attracted by a magnet
>
> **Non-magnetic materials** materials that cannot be magnetised and are not attracted by a magnet

Magnetic fields

The space surrounding a magnet where it produces a magnetic force is called a **magnetic field**. The force around a bar magnet can be detected and shown to vary in direction, using the apparatus in Figure 4.1.4. If the floating magnet is released near the N pole of the bar magnet, it is repelled to the S pole and moves along a curved path known as a **line of force** or a **field line**. It moves in the opposite direction if its south pole is uppermost.
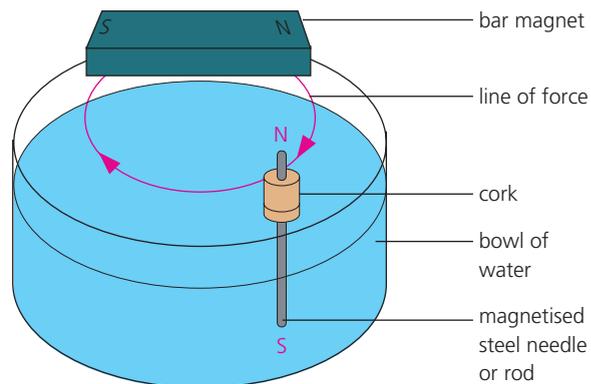
▲ **Figure 4.1.4** Detecting magnetic force

It is useful to consider that a magnetic field has a direction and to represent the field by lines of force. It has been decided that the **direction of a magnetic field at a point** should be the direction of the force on a N pole. To show the direction, arrows are put on the lines of force and point away from a N pole towards a S pole.

> **Key definition**
>
> **Direction of a magnetic field at a point** the direction of the force on the N pole of a magnet at that point

Strength of magnetic fields

A magnetic field is stronger in regions where the field lines are close together than where they are further apart.

> **Test yourself**
>
> 1 Which one of these statements is true?
> A magnet attracts
>   **A** plastics
>   **B** any metal
>   **C** iron and steel
>   **D** aluminium.
> 2 Two bar magnets are positioned side by side as shown in Figure 4.1.5. The north pole is marked on one of the magnets.
>
>
>
> ▲ **Figure 4.1.5**
>
> Copy the diagram and mark on the position of all the poles if the magnets
>   **a** attract each other
>   **b** repel each other.
> 3 In Figure 4.1.8a on the next page, is the magnetic field stronger or weaker at X than at a point closer to one of the magnets? Explain your answer.

Practical work

Plotting lines of force

Plotting compass method

A plotting compass is a small pivoted magnet in a glass case with non-magnetic metal walls (Figure 4.1.6a).

a

compass needle

b
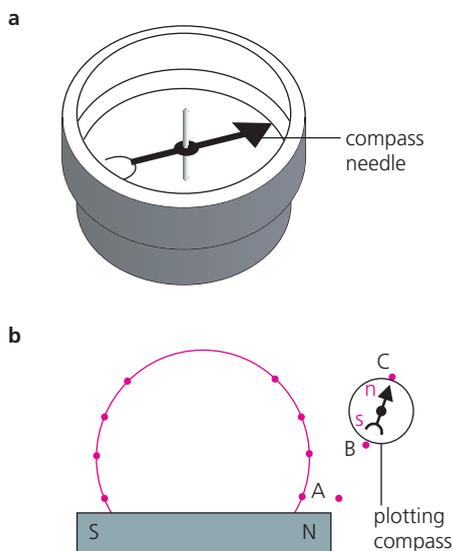
plotting compass

▲ **Figure 4.1.6**

Lay a bar magnet on a sheet of paper. Place the plotting compass at a point such as A (Figure 4.1.6b), near one pole of the magnet. In Figure 4.1.6b it is the N pole. Mark the position of the poles (n, s) of the compass by pencil dots B, A. Move the compass so that pole s is exactly over B, mark the new position of n by dot C.

Continue this process until the other pole of the bar magnet is reached (in Figure 4.1.6b it is the S pole). Join the dots to give one line of force and show its direction by putting an arrow on it. Plot other lines by starting at different points round the magnet.

A typical field pattern is shown in Figure 4.1.7.
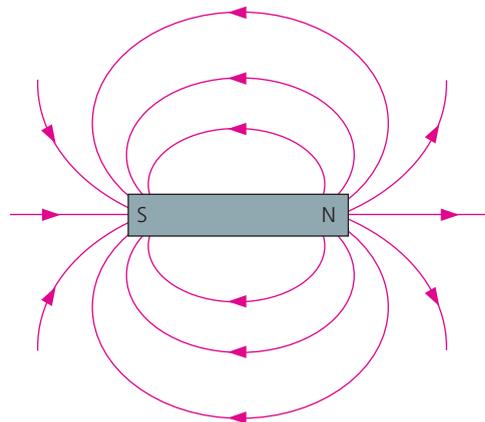
▲ **Figure 4.1.7** Magnetic field lines around a bar magnet

The combined field due to two neighbouring magnets can also be plotted to give patterns like those in Figure 4.1.8. In part a, where two like poles are facing each other, the point X is called a **neutral point**. At X, the field due to one magnet cancels out that due to the other and there are no lines of force.

a

b
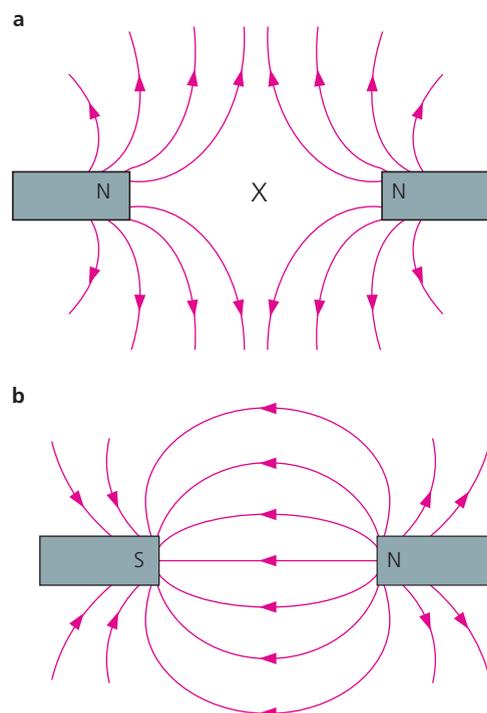
▲ **Figure 4.1.8** Field lines due to two neighbouring magnets

Iron filings method

Place a sheet of paper *on top of* a bar magnet and sprinkle iron filings *thinly and evenly* onto the paper from a 'pepper pot'.

Tap the paper gently with a pencil and the filings should form patterns showing the lines of force. Each filing turns in the direction of the field when the paper is tapped.

This method is quick but no use for weak fields.

1   Sketch the field lines around a bar magnet marking on the N and S poles and the direction of the field lines.
2   Figure 4.1.9 shows typical iron filings patterns obtained with two magnets. Why are the patterns different?
3   What combination of poles would give the observed patterns in Figure 4.1.9 a and b?
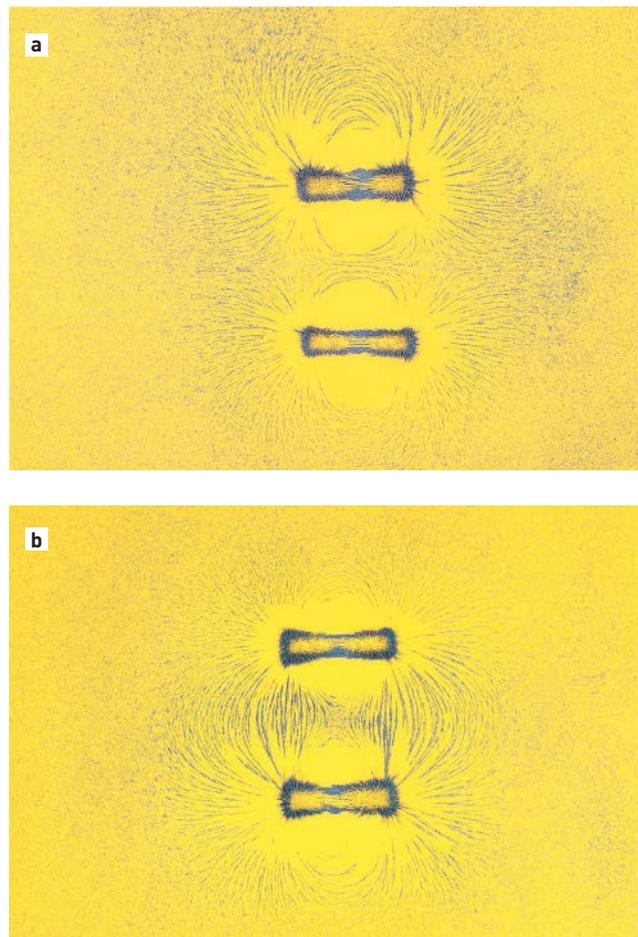
▲ **Figure 4.1.9** Field lines round two bar magnets shown by iron filings

---

➡ Going further

Magnetisation and demagnetisation

A ferromagnetic material can be magnetised by placing it inside a solenoid and gradually increasing the direct current (d.c.). This increases the magnetic field strength in the solenoid (the density of the field lines increases), and the material becomes magnetised. Reversing the direction of current flow reverses the direction of the magnetic field and reverses the polarity of the magnetisation. A magnet can be demagnetised by placing it inside a solenoid through which an alternating current (a.c.) is passed and gradually reduced.

Solenoids (see Topic 4.5) can be used to magnetise and demagnetise magnetic materials (Topic 4.5.4); dropping or heating a magnet also causes demagnetisation. Hammering a magnetic material in a magnetic field causes magnetisation but in the absence of a field it causes demagnetisation. 'Stroking' a magnetic material several times in the same direction with one pole of a magnet will also cause it to become magnetised.

Practical work

Simple electromagnet

An **electromagnet** is a coil of wire wound on a soft iron core. A 5 cm iron nail and 3 m of PVC-covered copper wire (SWG 26) are needed.

a Leave about 25 cm at one end of the wire (for connecting to the circuit) and then wind about 50 cm as a single layer on the nail. *Keep the turns close together and always wind in the same direction.* Connect the circuit of Figure 4.1.10, setting the rheostat (variable resistor, see p. 199) at its maximum resistance.
Find the number of paper clips the electromagnet can support when the current is varied between 0.2 A and 2.0 A. Record the results in a table.
Deduce how the strength of the electromagnet changes when the current is increased.

b Add another two layers of wire to the nail, winding in the *same direction* as the first layer. Repeat the experiment.
Deduce how the strength of the electromagnet has been changed by increasing the number of turns of wire.
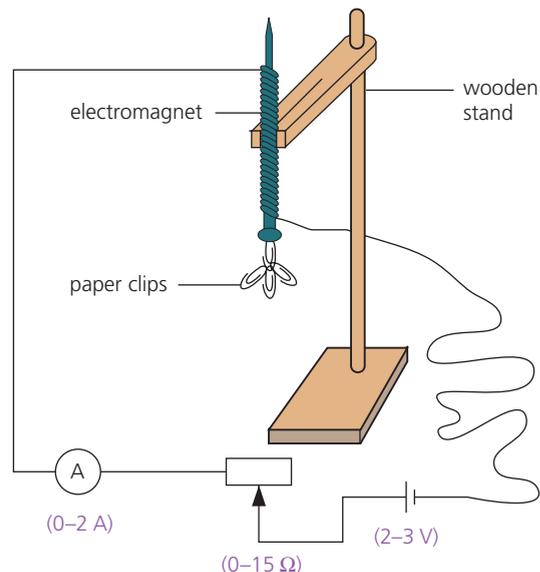
▲ **Figure 4.1.10**

c Place the electromagnet on the bench and under a sheet of paper. Sprinkle iron filings on the paper, tap it gently and observe the field pattern. Compare the pattern with that given by a bar magnet.

d Use a plotting compass to find which end of the electromagnet is a N pole.

4 Name two variables which you might think could affect the strength of an electromagnet.

5 How could you use a compass to determine which end of the current-carrying coil is a north pole?

Electromagnets

An electromagnet is formed from a coil of wire through which an electrical current is passed that allows the strength of the magnet to be varied. The magnetism of an electromagnet is *temporary* and can be switched on and off, unlike that of a permanent magnet. It has a core of soft iron which is magnetised only when there is current in the surrounding coil.

The strength of an electromagnet increases if
(i) the *current* in the coil increases
(ii) the *number of turns* on the coil increases
(iii) the poles are moved *closer together*.
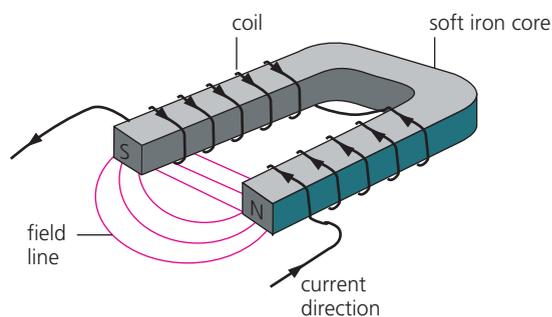
▲ **Figure 4.1.11** C-core or horseshoe electromagnet

In C-core (or horseshoe) electromagnets, condition (iii) is achieved (Figure 4.1.11). Note that the coil on each limb of the core is wound in *opposite* directions.

Uses of permanent magnets and electromagnets

Permanent magnets made from magnetic materials such as steel retain their magnetism, so can be used in applications where the magnetic field does not need to be varied. These include a compass, computer hard disk, electric motor (see Topic 4.5.5) electricity generator (see Topic 4.5.2), microphone, loudspeaker and many more everyday devices such as credit and debit cards.

An advantage over an electromagnet is that it does not require a current to maintain its magnetism.

Electromagnets are temporary and are used where one wants to be able to vary the strength of the magnetic field (by varying the current) and switch it on and off. As well as being used in cranes to lift iron objects, scrap iron, etc. (Figure 4.1.12), electromagnets are an essential part of many electrical devices such as electric bells, magnetic locks, relays and practical motors and generators (see Topic 4.5.3).

▲ **Figure 4.1.12** Electromagnet being used to lift scrap metal.

Going further

Magnetic shielding

Any ferromagnetic material can be used for magnetic screening of sensitive electronic equipment. Steel is often used as it is cheap, readily available and works well in strong magnetic fields. Mu-metal, a nickel-iron soft ferromagnetic material, is more effective for weaker magnetic fields but is more expensive.

Earth's magnetic field

If lines of force are plotted on a sheet of paper with no magnets nearby, a set of parallel straight lines is obtained. They run roughly from S to N geographically (Figure 4.1.13), and represent a small part of the Earth's magnetic field in a horizontal plane.
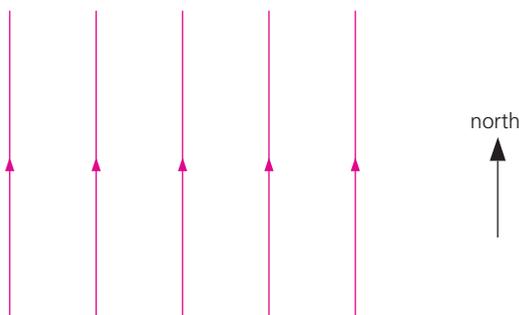
▲ **Figure 4.1.13** Lines of force due to the Earth's field

At most places on the Earth's surface a magnetic compass points slightly east or west of true north, i.e. the Earth's geographical and magnetic north poles do not coincide. The angle between magnetic north and true north is called the declination (Figure 4.1.14). In Hong Kong in 2020 it was about 3º W of N and changing slowly.
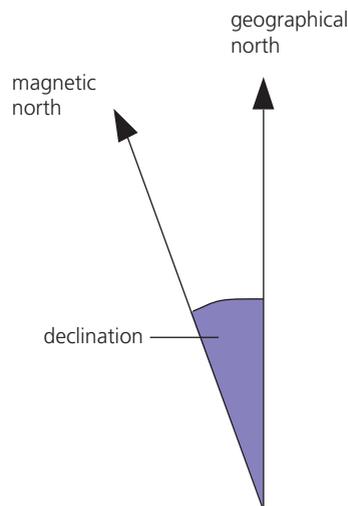
▲ **Figure 4.1.14** The Earth's geographical and magnetic poles do not coincide.

Revision checklist

After studying Topic 4.1 you should know and understand:
✔ like magnetic poles repel, unlike magnetic poles attract
✔ the difference between magnetic and non-magnetic materials, and permanent and electromagnets
✔ how to map the magnetic field around a bar magnet, by the plotting compass and iron filings methods.

After studying Topic 4.1 you should be able to:
✔ state the properties of magnets, describe induced magnetism and distinguish between the magnetic properties of iron and steel
✔ recall that a magnetic field is the region round a magnet where a magnetic force is exerted and is represented by lines of force whose direction at any point is the direction of the force on a N pole
✔ recall that the magnetic field is strongest in regions where the field lines are closest together.

Exam-style questions

1 Copy Figure 4.1.15 which shows a plotting compass and a magnet.
  a Label the N pole of the magnet. [1]
  b Sketch the magnetic field line on which the compass lies. [2]
  c State the direction of the magnetic field line. [1]

▲ **Figure 4.1.15**

[Total: 4]

2 a Describe an experiment using a plotting compass to map the magnetic field lines around a bar magnet. [4]
  b Explain why permanent magnets are used in some applications and electromagnets in others. [4]
  c Give two uses of a permanent magnet. [2]
  [Total: 10]

3 a Explain how magnetic forces arise. [2]
  b Where are the magnetic field lines strongest around a bar magnet? [2]
  c State how you would recognise from a pattern of magnetic field lines where the field is
    i strongest
    ii weakest. [2]
  [Total: 6]

Electrical quantities

4.2.1 Electric charge

FOCUS POINTS

★ Understand that there are positive and negative charges and that opposite charges attract and like charges repel.
★ Explain the charging of solids by friction.
★ Describe an experiment to determine whether a material is an electrical conductor or an insulator.
★ Explain the difference between electrical conductors and insulators using a simple electron model, and give examples of each.
★ Know that charge is measured in coulombs.
★ Describe an electric field, explain its direction and describe simple electric field patterns.

Electrostatic charges arise when electrons are transferred between objects by rubbing. Sparks can fly after you comb your hair or walk across a synthetic carpet when you touch an earthed object, through which the charge can be neutralised; the discharge can lead you to feel a small electric shock. A flash of lightning is nature's most spectacular static electricity effect. There are two types of electrostatic charge. Like charges repel while opposite charges attract. Charges build up on an insulator such as plastic and remain static, but for conductors like metals, charges flow away to try to neutralise charge. Both electrical conductors and insulators have their uses.

Electric charges are surrounded by an electric field which exerts a force on a nearby charge. This effect is made use of in applications from ink-jet printers to crop sprayers. As with a magnetic field, an electric field exerts an action-at-a-distance force.

▲ **Figure 4.2.1** A flash of lightning

Clothes containing nylon often crackle when they are taken off. We say they are charged with static electricity; the crackles are caused by tiny electric sparks which can be seen in the dark. Pens and combs made of certain plastics become charged when rubbed on your sleeve and can then attract scraps of paper.

Positive and negative charges

When a strip of polythene is rubbed with a cloth it becomes charged. If it is hung up and another rubbed polythene strip is brought near, repulsion occurs (Figure 4.2.2). Attraction occurs when a rubbed strip of cellulose acetate is brought near.
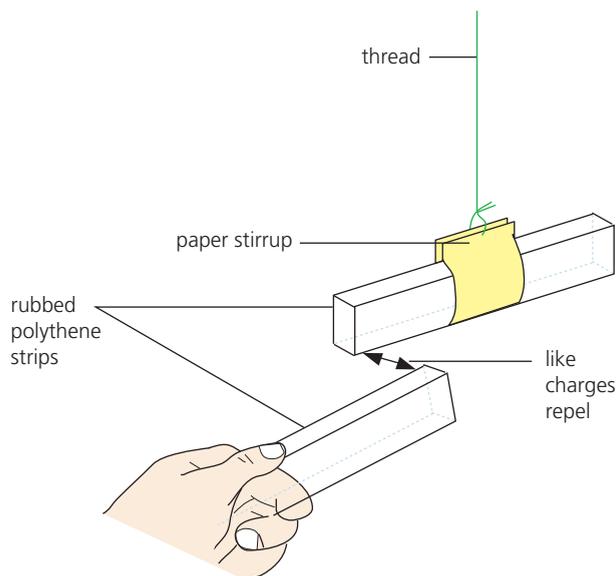
▲ **Figure 4.2.2** Investigating charges

This shows there are two kinds of electric charge. That on cellulose acetate is taken as **positive** (+) and that on polythene is **negative** (–). It also shows that:

Like charges (+ and +, or – and –) repel, while unlike charges (+ and –) attract.

The force between electric charges decreases as their separation increases.

Key definitions

Positive charges repel other positive charges, but positive charges attract negative charges

Negative charges repel other negative charges, but negative charges attract positive charges

Charges, atoms and electrons

There is evidence (Topic 5.1) that we can picture an atom as being made up of a small central nucleus containing positively charged particles called **protons**, surrounded by an equal number of negatively charged **electrons**. The charges on a proton and an electron are equal and opposite so an atom as a whole is normally electrically neutral, i.e. has no net charge.

Hydrogen is the simplest atom with one proton and one electron (Figure 4.2.3). A copper atom has 29 protons in the nucleus and 29 surrounding electrons. Every nucleus except hydrogen also contains uncharged particles called **neutrons**.

▲ **Figure 4.2.3** Hydrogen atom

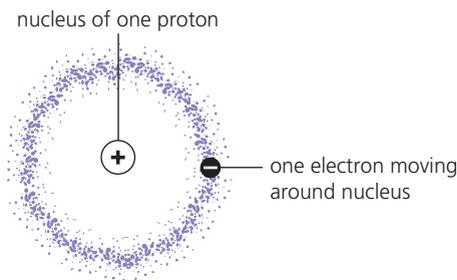The production of charges by rubbing can be explained by supposing that friction causes electrons to be transferred from one material to the other. For example, when cellulose acetate is rubbed with a cloth, electrons go from the acetate to the cloth, leaving the acetate short of electrons, i.e. positively charged. The cloth now has more electrons than protons and becomes negatively charged. Note that it is only electrons which move; the protons remain fixed in the nucleus.

Test yourself

1 Two identical conducting balls, suspended on nylon threads, come to rest with the threads making equal angles with the vertical, as shown in Figure 4.2.4.
 Which of these statements is true?
 This shows that
 A the balls are equally and oppositely charged
 B the balls are oppositely charged but not necessarily equally charged
 C one ball is charged and the other is uncharged
 D the balls both carry the same type of charge.
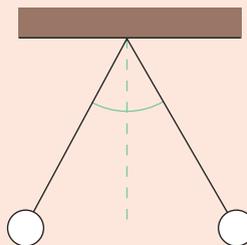
▲ **Figure 4.2.4**

2 Explain in terms of electron movement what happens when a polythene rod becomes charged negatively by being rubbed with a cloth.

3 Two electrostatic charges are brought close together.
 a When one charge is positive and the other is negative, are they attracted or repelled from each other?
 b When both charges are negative, are they attracted or repelled?

Units of charge

Charge is measured in **coulombs** (C) and is defined in terms of the ampere (see Topic 4.2.2).

The charge on an electron e = 1.6×10^{-19} C.

> **Key definition**
> **Coulomb** (C) unit of charge

➡ Going further

⚡ Practical work

Gold-leaf electroscope

- metal cap
- metal rod
- insulating plug
- metal plate
- gold leaf
- glass window
- wooden or metal case earthed by resting on bench

▲ **Figure 4.2.5** Gold-leaf electroscope

A gold-leaf electroscope consists of a metal cap on a metal rod at the foot of which is a metal plate with a leaf of gold foil attached (Figure 4.2.5). The rod is held by an insulating plastic plug in a case with glass sides to protect the leaf from draughts.

Detecting a charge

Bring a charged polythene strip towards the cap: the leaf rises away from the plate. When you remove the charged strip, the leaf falls again. Repeat with a charged acetate strip.

Charging by contact

Draw a charged polythene strip *firmly across the edge of the cap*. The leaf should rise and stay up when the strip is removed. If it does not, repeat the 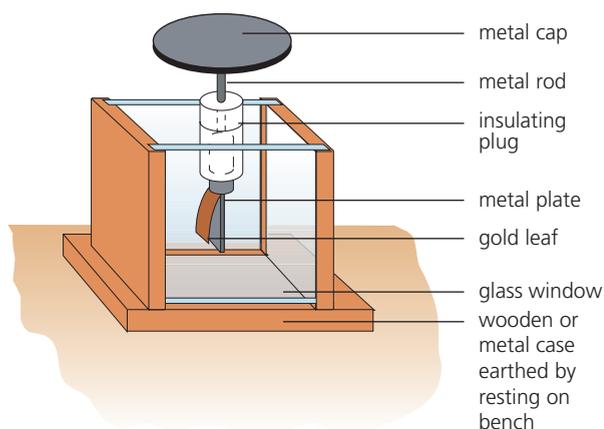process but press harder. The electroscope has now become negatively charged by contact with the polythene strip, from which electrons have been transferred.

Insulators and conductors

Touch the cap of the charged electroscope with different things, such as a piece of paper, a wire, your finger, a comb, a cotton handkerchief, a piece of wood, a glass rod, a plastic pen, rubber tubing. Record your results.

When the leaf falls, charge is passing to or from the ground through you and the material touching the cap. If the fall is rapid the material is a *good conductor*; if the leaf falls slowly, the material is a poor conductor. If the leaf does not alter, the material is a *good insulator*.

The gold-leaf electroscope used in this experiment could be replaced by an electronic instrument capable of measuring electric charge – an electrometer.

1 How could you charge a polythene rod?
2 How could you transfer charge from a polythene rod to a gold-leaf electroscope?
3 Why does the leaf of the electroscope rise when it gains charge?
4 How can you discharge the electroscope?

Electrons, insulators and conductors

In an insulator all electrons are bound firmly to their atoms; in a conductor some electrons can move freely from atom to atom. An insulator can be charged by rubbing because the charge produced cannot move from where the rubbing occurs, i.e. the electric charge is *static*. A conductor will become charged only if it is held with an insulating handle; otherwise electrons are transferred between the conductor and the ground via the person's body.

Good insulators include plastics such as polythene, cellulose acetate, Perspex and nylon. All metals and carbon are good conductors. In between are materials that are both poor conductors and (because they conduct to some extent) poor insulators. Examples are wood, paper, cotton, the human body and the Earth. Water conducts and if it were not present in materials such as wood and on the surface of, for example, glass, these would be good insulators. Dry air insulates well.

Electric fields

When an electric charge is placed near to another electric charge it experiences a force. The electric force does not require contact between the two charges so we call it an 'action-at-a-distance force' – it acts through space. The region of space where an electric charge experiences a force due to other charges is called an **electric field**. If the electric force felt by a charge is the same everywhere in a region, the field is uniform; a uniform electric field is produced between two oppositely charged parallel metal plates (Figure 4.2.6). It can be represented by evenly spaced parallel lines drawn perpendicular to the metal surfaces. The **direction of an electric field at a point**, denoted by arrows, is the direction of the force on a small *positive* charge placed in the field (negative charges experience a force in the opposite direction to the field). An electric field is a vector quantity as it has both magnitude (strength) and direction.

> **Key definition**
>
> **Direction of an electric field at a point** the direction of the force on a positive charge at that point
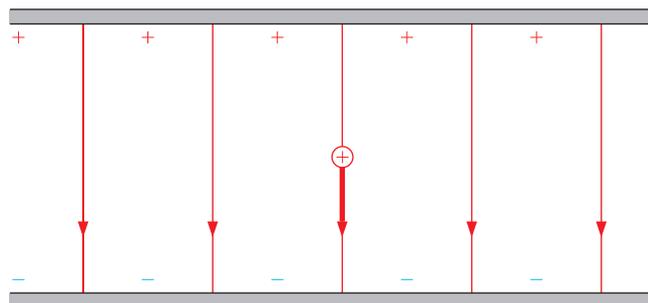
▲ **Figure 4.2.6** Uniform electric field

Moving charges are deflected by an electric field due to the electric force exerted on them.

The electric field lines radiating from an isolated positively charged conducting sphere and a point charge are shown in Figures 4.2.7a and b: the field lines again emerge at right angles to the conducting surface.
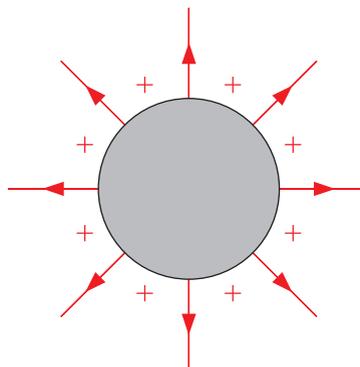
▲ **Figure 4.2.7a** Electric field around a charged conducting sphere
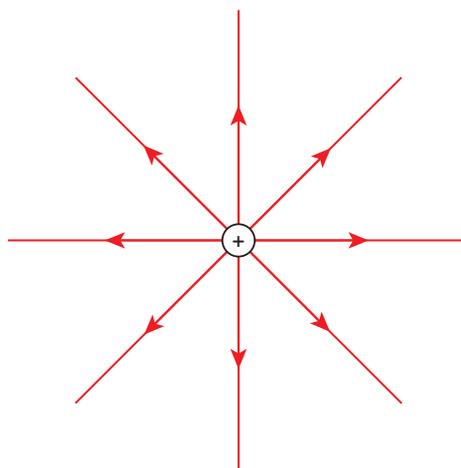
▲ **Figure 4.2.7b** Electric field around a point charge

→ Going further

Dangers of static electricity

Sparks occur between electrostatic charges when the electric field is strong enough. Damage can be reduced by providing an easy path for electrons to flow safely to and from the earth. For example, a tall building is protected by a lightning conductor consisting of a thick copper strip fixed on the outside of the building connecting metal spikes at the top to a metal plate in the ground (Figure 4.2.8).

Thunderclouds carry charges: a negatively charged cloud passing overhead repels electrons from the spikes to the Earth. The points of the spikes are left with a large positive charge (charge concentrates on sharp points) which removes electrons from nearby air molecules, so charging them positively and causing them to be repelled from the spike. This effect, called action at points, results in an 'electric wind' of positive air molecules streaming upwards which can neutralise electrons discharging from the thundercloud in a lightning flash. If a flash occurs it is now less violent and the conductor gives it an easy path to ground.

▲ **Figure 4.2.8** Lightning conductor

Sparks from static electricity can be particularly dangerous when flammable vapour is present. Fuel flowing in a pipeline (particularly a plastic pipe) experiences friction, which may lead to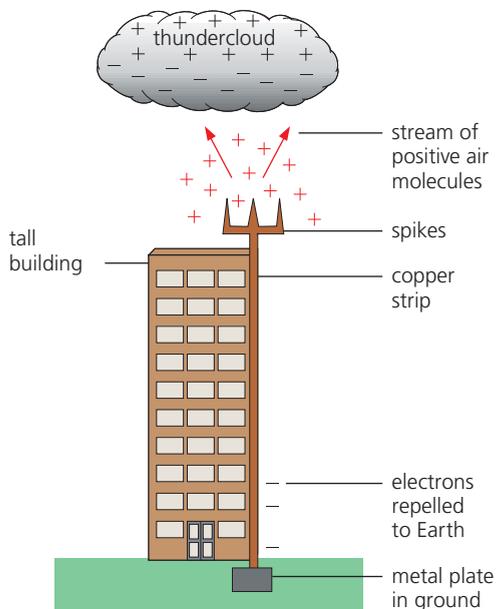 a build-up of static charge. During refuelling, aircraft, fuel tanker and pipeline hoses are all earthed to avoid sparks which could ignite the fuel and cause an explosion.

Computers and sensitive electronic equipment should also be earthed to avoid electrostatic damage.

Uses of static electricity

There are many uses of static electricity in applications from flue-ash precipitation in coal-burning power stations, paint and crop spraying to photocopiers and ink-jet printers.

In an ink-jet printer tiny drops of ink are forced out of a fine nozzle, charged electrostatically and then passed between two oppositely charged plates; a negatively charged drop will be attracted towards the positive plate causing it to be deflected as shown in Figure 4.2.9. The amount of deflection and hence the position at which the ink strikes the page is determined by the charge on the drop and the p.d. between the plates; both of these are controlled by a computer. About 100 precisely located drops are needed to make up an individual letter but very fast printing speeds can be achieved.
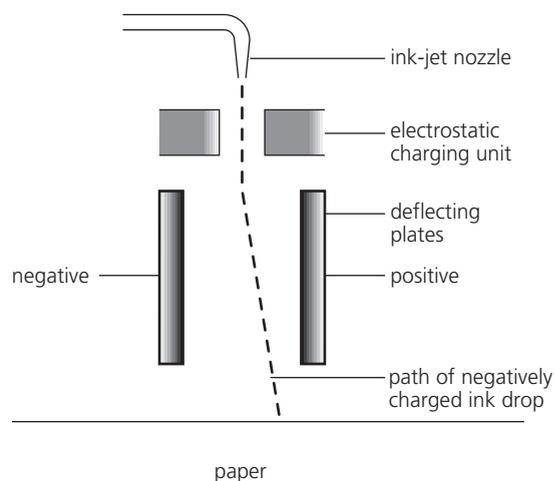
▲ **Figure 4.2.9** Ink-jet printer

Test yourself

4 Describe the electric field around a negatively charged conducting sphere.

Test yourself

5 Name
   a two applications
   b two dangers
   of static electricity.

4.2.2 Electric current

FOCUS POINTS

★ Understand that an electric current consists of moving electric charges.
★ Define electric current and use the correct equation in calculations.
★ Describe the use of analogue and digital ammeters and the difference between alternating current (a.c.) and direct current (d.c.).
★ Describe the role of free electrons in electrical conduction in metals.
★ Know that the flow of electrons in a circuit is in the opposite direction to that of the conventional current flow.

In the previous topic you learnt about positive and negative static charges and how they were produced on conductors and insulators. In this topic you will discover that moving charges in a conductor produce an electric current which is proportional to the rate of flow of charge. Every electrical appliance you use, from hair dryer to computer, relies on the flow of an electric current. In a metal the current is produced by the movement of electrons. By convention, electric current is linked to the flow of positive charge, which is in the opposite direction to the way electrons move. You will find out how to connect an ammeter to a circuit to measure the size of an electric current and learn about the different types of current.

An **electric current** consists of moving electric charges. In Figure 4.2.10, when the van de Graaff machine is working, it produces a continuous supply of charge which produces an electric field between the metal plates to which it is connected. The table-tennis ball shuttles rapidly backwards and forwards between the plates and the very sensitive meter records a small current. As the ball touches each plate it becomes charged and is repelled to the other plate. In this way charge is carried across the gap. This also shows that static charges, produced by friction in the van de Graaff machine, cause a deflection on a meter just as current electricity produced by a battery does.

In a metal, each atom has one or more loosely held electrons that are free to move. When a van de Graaff or a battery is connected across the ends of such a conductor, the free electrons drift slowly along it in the direction from the negative to the positive terminal of a battery. There is then a current of negative charge. This is how electrical conduction occurs in a metal.
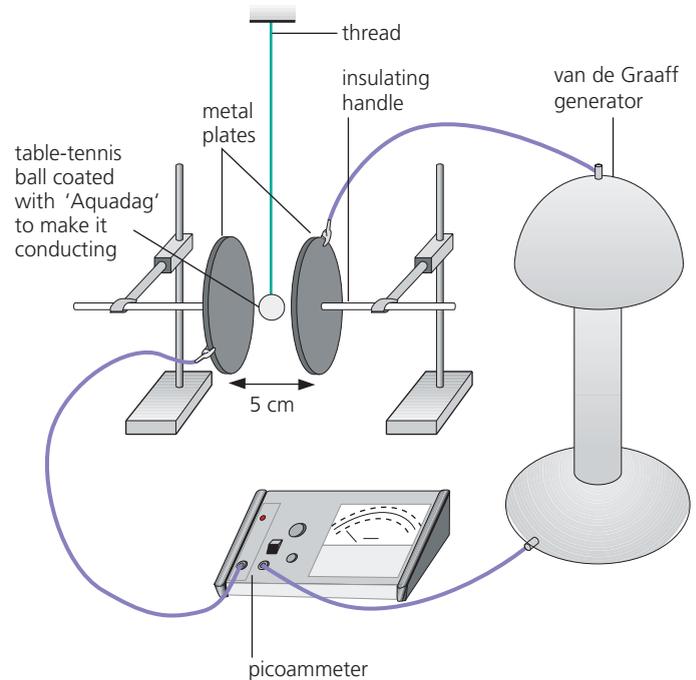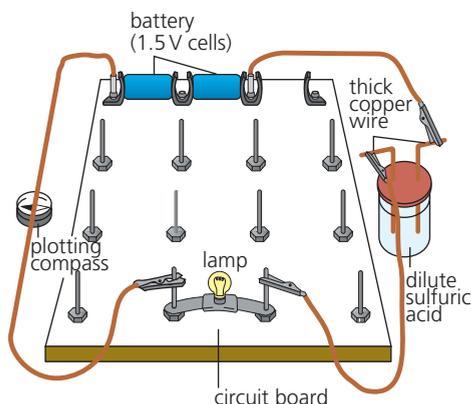

▲ **Figure 4.2.10** Demonstrating that an electric current consists of moving charges

Effects of a current

An electric current has three effects that reveal its existence and which can be shown with the circuit of Figure 4.2.11.

▲ **Figure 4.2.11** Investigating the effects of a current

Heating and lighting
The lamp lights because the small wire inside (the filament) is made white hot by the current.

Magnetic
The plotting compass is deflected when it is placed near the wire because a magnetic field is produced around any wire carrying a current.

Chemical
Bubbles of gas are given off at the wires in the acid because of the chemical action of the current.

The ampere and the coulomb

An **electric current** is defined as the charge passing a point per unit time and can be written in symbols as

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

where I is the current when charge Q passes any point in a circuit in time t.

It shows that current is the rate of flow of charge in a circuit.

The unit of current is the **ampere** (A). One milliampere (mA) is one-thousandth of an ampere. Current is measured by an **ammeter**.

> **Key definition**
>
> **Electric current** the charge passing a point per unit time
>
> electric current $I = \dfrac{\text{charge}}{\text{time}}$ or $\dfrac{Q}{t}$ where Q is the charge flowing past a particular point in time t.

The unit of charge, the **coulomb** (C), is defined in terms of the ampere.

One coulomb is the charge passing any point in a circuit when a steady current of 1 ampere flows for 1 second. That is, $1\,C = 1\,A\,s$.

> **Key definition**
>
> **Ampere (A)** unit of current given by the coulomb per second (C/s)

In general, if a steady current I (amperes) flows for time t (seconds) the charge Q (coulombs) passing any point is given by

$$Q = I \times t$$

Current must have a complete path (a circuit) of conductors if it is to flow. When drawing circuit diagrams, components are represented by symbols. Some commonly used symbols are represented in Topic 4.3.1.

> **? Worked example**
>
> Current flows in an electrical circuit.
>
> a   A charge of 2 C passes a point in the circuit in 5 s, calculate the current flowing past that point.
>
> $I = Q/t = 2\,C/5\,s = 0.4\,A$
>
> b   A current of 3 A flows past another point in the circuit in 10 seconds. How much charge passes the point in this time?
>
> $Q = I \times t = 3\,A \times 10\,s = 30\,C$
>
> ### Now put this into practice
>
> 1   A current of 2 A flows past a point in an electrical circuit in 20 s. How much charge passes the point in this time?
> 2   A charge of 2 C passes a point in an electrical circuit in 7 s. Calculate the current flowing past that point.

Conventional current

Before the electron was discovered scientists agreed to think of current as positive charges moving round a circuit in the direction from positive to negative of a battery. This agreement still stands. Arrows on circuit diagrams show the direction of what we call the **conventional current**, i.e. the direction in which *positive* charges would flow. Electrons flow in the opposite direction to the conventional current.

> **Key definition**
>
> **Conventional current** flows from positive to negative; the flow of free electrons is from negative to positive
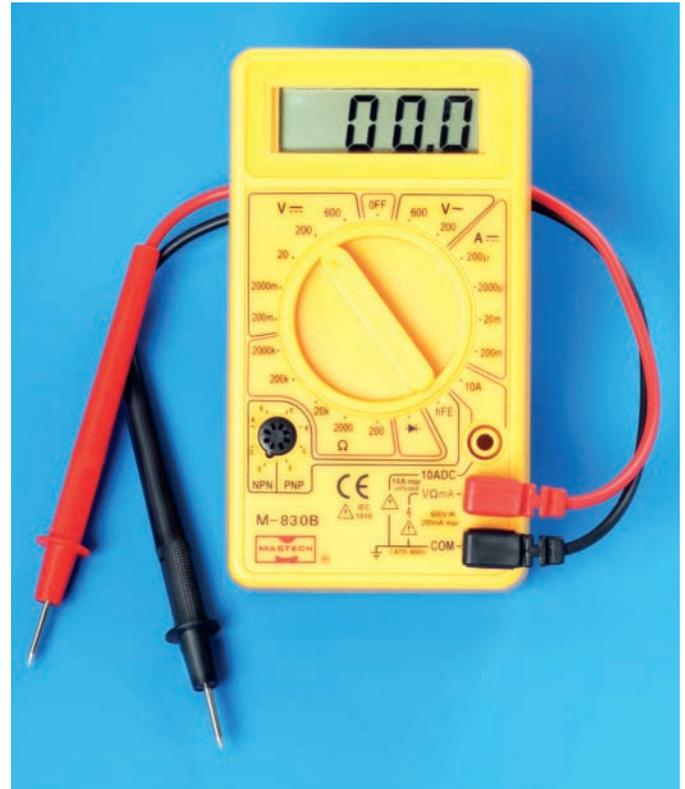
Ammeters

An ammeter is used to measure currents. It should always be placed in series in a circuit with the positive terminal on the ammeter connected to the positive terminal of the supply, as described in the practical work below (see Figure 4.2.13 overleaf). A simple moving coil ammeter will read d.c. currents only on an analogue display. It may have two ranges and two scales in the display.

A **multimeter** can have either a digital or analogue display (see Figure 4.1.12a and b) and be used to measure a.c. and d.c. currents (or voltages and also resistance). The required function is first selected, say d.c. current.

When making a measurement on either type of ammeter a suitable range must be chosen. For example, if a current of a few milliamps is expected, the 10 mA range might be selected and the value of the current (in mA) read from the display; if the reading is off-scale, the **sensitivity** should be reduced by changing to the higher, perhaps 100 mA, range.

▲ **Figure 4.2.12b** Digital multimeter

▲ **Figure 4.2.12a** Analogue multimeter

Test yourself

6 Explain how electrical conduction occurs in a metal.
7 Explain how you would connect an ammeter into a circuit.
8 What is the current in a circuit if the charge passing each point is
   a 10 C in 2 s
   b 20 C in 40 s
   c 240 C in 2 minutes?
9 How long does it take a charge of 5 C to pass a point in an electrical circuit where the current flowing is 2 A?

Practical work

Measuring current

a Connect the circuit of Figure 4.2.13a (on a circuit board if possible), ensuring that the + of the cell (the metal stud) goes to the + of the ammeter (marked red). Note the current.

b Connect the circuit of Figure 4.2.13b. The cells are in *series* (+ of one to – of the other), as are the lamps. Record the current. Measure the current at B, C and D by disconnecting the circuit at each point in turn and inserting the ammeter. Record the values of the current in each position.

c Connect the circuit of Figure 4.2.13c. The lamps are in *parallel*. Read the ammeter. Also measure and record the currents at P, Q and R. Comment on your results.

5 In Figure 4.2.13a how could you tell when current flows?
6 In Figure 4.2.13b
   a how many paths are there for current to flow?
   b would you expect the current to be different in different parts of the circuit?
7 In Figure 4.2.13c
   a how many paths are there for current to flow?
   b would you expect the current to be different in different parts of the circuit?
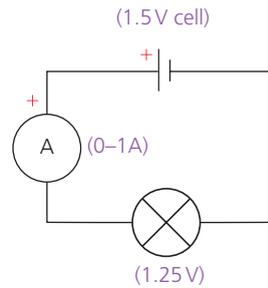
▲ **Figure 4.2.13a**
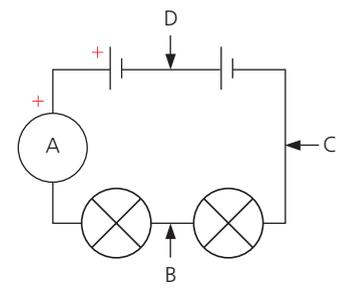
▲ **Figure 4.2.13b**
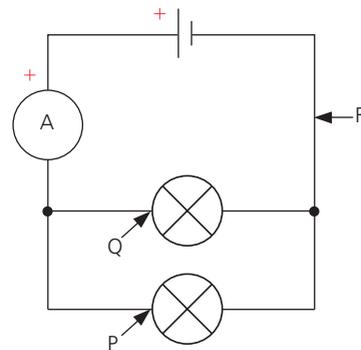
▲ **Figure 4.2.13c**

Direct and alternating current

Difference

In a **direct current** (d.c.) the electrons flow in one direction only. Graphs for steady and varying d.c. are shown in Figure 4.2.14.
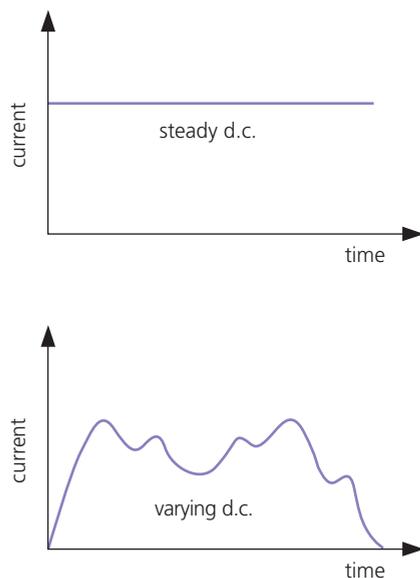
▲ **Figure 4.2.14** Direct current (d.c.)

In an **alternating current** (a.c.) the direction of flow reverses regularly, as shown in the graph in Figure 4.2.15. The circuit sign for a.c. is given in Figure 4.2.16.
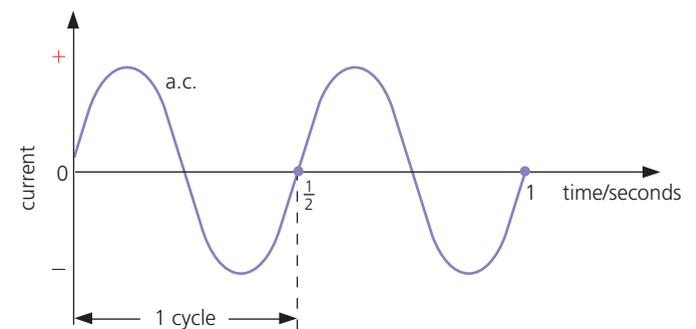
▲ **Figure 4.2.15** Alternating current (a.c.)

▲ **Figure 4.2.16** Symbol for alternating current

The pointer of an ammeter for measuring d.c. is deflected one way by the direct current. Alternating current makes the pointer move back and forth about the zero if the changes are slow enough; otherwise no deflection can be seen.

Batteries give d.c.; generators can produce either d.c. or a.c.

Frequency of a.c.

The number of complete alternations or cycles in 1 second is the *frequency* of the alternating current. The unit of frequency is the *hertz* (Hz). The frequency of the a.c. in Figure 4.2.15 is 2 Hz, which means there are two cycles per second, or one cycle lasts 1/2 = 0.5 s. The mains supply in many countries is a.c. of frequency 50 Hz; each cycle lasts 1/50th of a second. This regularity was used in the tickertape timer (Topic 1.2) and is relied upon in mains-operated clocks.

See Topic 4.6 for how an oscilloscope can be used to measure the frequency of an a.c. signal.

Test yourself

10 Sketch
  a a d.c. current
  b an a.c. current
  c the circuit symbol used for a.c.
11 An a.c. current has a frequency of 1000 Hz. How long does each cycle last?

4.2.3 Electromotive force and potential difference

FOCUS POINTS

★ Define electromotive force.
★ Describe the use of analogue and digital voltmeters.
★ Define potential difference and know that it is measured in volts.
★ Use the correct equations for electromagnetic force and potential difference.

As you will have seen in the previous topic, a complete circuit of conductors is needed for a current to flow. In this topic you will learn that it is the electromotive force of a supply which provides the energy needed to move charge around a complete circuit. The supply may vary from a simple torch battery to your mains electricity supply. There are usually several components in a circuit, for example lamps, motors or other electrical devices, from which energy is transferred to the surroundings. The energy transferred from a device can be calculated by introducing the concept of potential difference. Previously you used an ammeter to measure the current in an electrical circuit; now you will learn how to use a voltmeter to measure potential difference.

The chemical action inside a battery produces a surplus of electrons at one of its terminals (the negative) and creates a shortage at the other (the positive). It is then able to maintain a flow of electrons, i.e. an *electric current*, in any circuit connected across its terminals for as long as the chemical action lasts. Work is done by the battery in moving charge around the circuit.

Electromotive force (e.m.f.), symbol E, is defined as the electrical work, w, done by a source in moving a unit charge around a complete circuit:

$$\text{e.m.f.} = \frac{\text{work done (by a source)}}{\text{charge}}$$

or

$$E = \frac{W}{Q}$$

Key definitions

Electromotive force e.m.f. the electrical work done by a source in moving unit charge around a complete circuit

Potential difference p.d. the work done by a unit charge passing through a component

Electromotive force is measured in **volts** (V). The e.m.f. of a car battery is 12 V and the domestic mains supply in many countries is 240 V.

There are usually a number of components in an electrical circuit through which charge flows. **Potential difference** (p.d.) is defined as the work done by a unit of charge passing through a component:

$$\text{p.d.} = \frac{\text{work done (on a component)}}{\text{charge}}$$

or

$$V = \frac{W}{Q}$$

Like e.m.f., potential difference between two points is measured in volts (V). The term **voltage** is sometimes used instead of p.d.

Energy transfers and p.d.

In an electric circuit, an electric current transfers energy from an energy store, such as a battery, to components in the circuit which then transfer energy into the surroundings. In the case of a lamp, energy is transferred to the surroundings by light and by heating.

When each of the circuits shown in Figure 4.2.17 is connected up, it will be found from the ammeter readings that the current is about the same (0.4 A) in each lamp. However, the mains lamp with a potential difference of 230 V applied across it gives much more light and heat than the car lamp with 12 V across it.
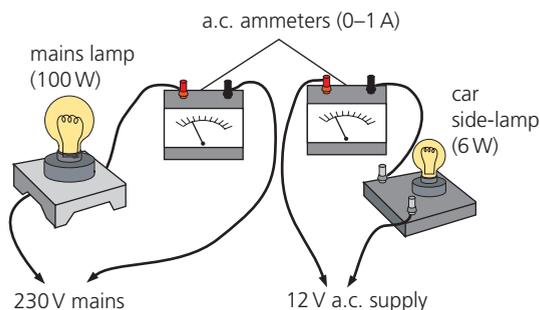
▲ **Figure 4.2.17** Investigating the effect of p.d. (potential difference) on energy transfer

Evidently the p.d. across a device affects the rate at which it transfers energy. This gives us a way of defining the unit of potential difference: the volt.

Model of a circuit

It may help you to understand the definition of the volt, i.e. what a volt is, if you *imagine* that the current in a circuit is formed by 'drops' of electricity, each having a charge of 1 coulomb and carrying equal-sized bundles of electrical energy. In Figure 4.2.18, Mr Coulomb represents one such drop. As a drop moves around the circuit it gives up all its energy which is transferred to other energy stores. Note that *electrical energy, not charge or current, is used up.*
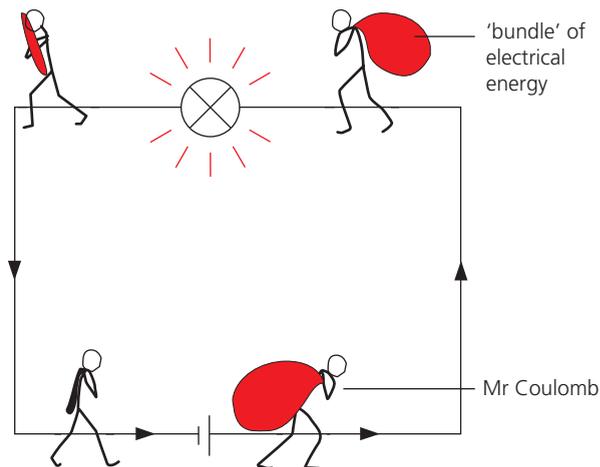
▲ **Figure 4.2.18** Model of a circuit

In our imaginary representation, Mr Coulomb travels round the circuit and unloads energy as he goes, most of it in the lamp. We think of him receiving a fresh bundle every time he passes through the battery, which suggests he must be travelling very fast. In fact, as we found earlier (Topic 4.2.2), the electrons drift along quite slowly. As soon as the circuit is complete, energy is delivered at once to the lamp, not by electrons directly from the battery but from electrons that were in the connecting wires. The model is helpful but is not an exact representation.

The volt

The demonstrations of Figure 4.2.17 show that the greater the e.m.f. of a supply, the larger is the bundle of energy given to each coulomb and the greater is the rate at which energy is transferred from a lamp.

In general, if W (joules) is the energy transferred (i.e. the work done) when charge Q (coulombs) moves around a complete circuit, the e.m.f. E (volts) of the supply is given by

$$E = W/Q$$

or

$$W = Q \times E$$

The p.d. between two points in a circuit is 1 volt if 1 joule of energy is transferred when 1 coulomb passes from one point to the other.

That is, 1 volt = 1 joule per coulomb (1 V = 1 J/C). If 2 J is transferred by each coulomb, the p.d. is 2 V.

In general, if W (joules) is the work done when charge Q (coulombs) passes between two points, the p.d. V (volts) between the points is given by

$$V = W/Q$$

or

$$W = Q \times V$$

If Q is in the form of a steady current I (amperes) flowing for time t (seconds) then $Q = I \times t$ (Topic 4.2.2) and

$$W = I \times t \times V$$

? Worked example

A lamp is connected to a battery in a circuit and a current flows.

a Calculate the p.d. across the lamp if 6 J of work are done when 2 C of charge pass through the lamp.
From the equation $V = W/Q$

the p.d. across the lamp = $W/Q = 6 J/2 C = 3 V$

b If the p.d. across the lamp is increased to 5 V calculate the energy transferred to the lamp when a current of 2 A flows in the lamp for 5 seconds.

$Q = I \times t = 2 A \times 5 s = 10 C$

Rearranging the equation $V = W/Q$ gives

$W = Q \times V = 10 C \times 5 V = 50 J$

Now put this into practice

1 Calculate the p.d. across a lamp in an electric circuit when 8 J of work are done when a charge of 4 C passes through the lamp.
2 The p.d. across a lamp is 6 V.
How many joules of energy are transferred when a charge of 2 C passes through it?
3 The p.d. across a lamp is 6 V. Find the work done when a current of 3 A flows in the lamp for 10 s.

Voltmeters

A **voltmeter** is used to measure potential differences; it should always be placed *in parallel* with the component across which the p.d. is to be measured. The positive terminal on the voltmeter should be connected to the side of the component into which current flows as is shown in the practical work and Figure 4.2.21 overleaf. A simple moving-coil voltmeter will read d.c. voltages only on an analogue display.

The face of an analogue voltmeter is represented in Figure 4.2.19. The voltmeter has two scales. The 0–5 scale has a full-scale deflection of 5.0 V. Each small division on the 0–5 scale represents 0.1 V. This voltmeter scale can be read to the nearest 0.1 V. The human eye is very good at judging a half division, so we are able to estimate the voltmeter reading to the nearest 0.05 V with considerable precision. The 0–10 scale has a full-scale deflection of 10.0 V; each small division on this scale represents 0.2 V so the precision of a reading is less than on the 0–5 V scale.
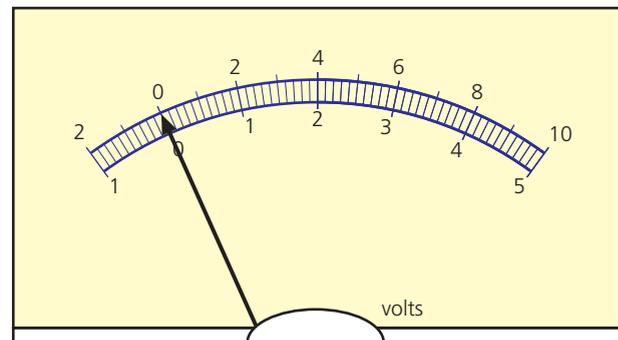
▲ **Figure 4.2.19** An analogue voltmeter scale

Analogue voltmeters or multimeters are adapted moving-coil **galvanometers** (Topic 4.5.5). Digital multimeters are constructed from integrated circuits. On the voltage setting they have a very high input resistance (10 MΩ); this means they affect most circuits very little and so give very accurate readings.

When making a measurement on either an analogue or digital voltmeter a suitable range must first be chosen. For example, if a voltage of a few millivolts is expected, the 10 mV range might be selected and the value of the voltage (in mV) read from the display; if the reading is off-scale, the sensitivity should be reduced by changing to the higher, perhaps 100 mV, range.

Every measuring instrument has a calibrated scale. When you write an account of an experiment (see p. viii, *Using scientific skills*) you should include details about each scale that you use.

? Worked example

The scales of an analogue voltmeter are shown in Figure 4.2.20.
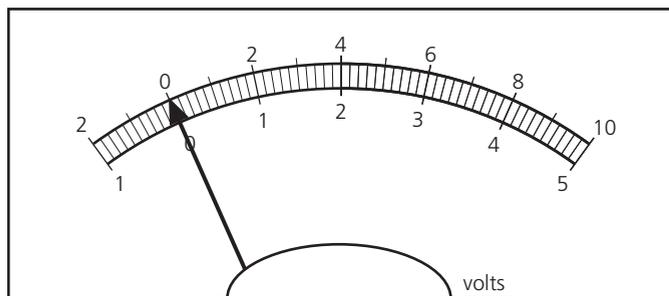
▲ **Figure 4.2.20**

a What are the two ranges available when using the voltmeter?
The lower scale reads 0–5 V and the upper scale reads 0–10 V.
b What do the small divisions between the numbers 3 and 4 represent?
0.1 V
c Which scale would you use to measure a voltage of 4.6 V?
The lower scale 0–5 V will give a more accurate reading.
d When the voltmeter reads 4.0 V where should you position your eye to make the reading?
Above the 4 to reduce parallax error.

Now put this into practice

1 Use the scales of the voltmeter shown in Figure 4.2.20.
a What do the small divisions between the numbers 6 and 8 represent?
b Which scale would you use to measure a voltage of 5.4 V?
c When making the reading for 4.0 V an observer's eye is over the 0 V mark. Explain why the value obtained by this observer is higher than 4.0 V.

⚡ Practical work

Measuring voltage

A voltmeter is an instrument for measuring voltage or p.d. It looks like an ammeter but has a scale marked in volts. Whereas an ammeter is inserted in *series* in a circuit to measure the current, a voltmeter is connected across that part of the circuit where the voltage is required, i.e. in *parallel*.

To prevent damage to the voltmeter make sure that the + terminal (marked red) is connected to the point nearest the + of the battery.

a Connect the circuit of Figure 4.2.21a. The voltmeter gives the p.d across the lamp. Read it.
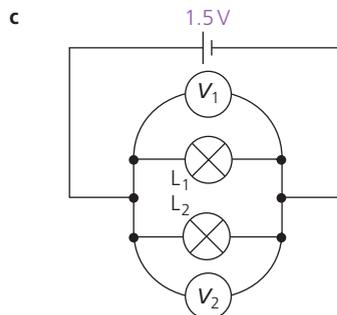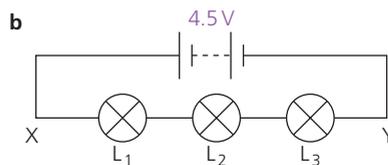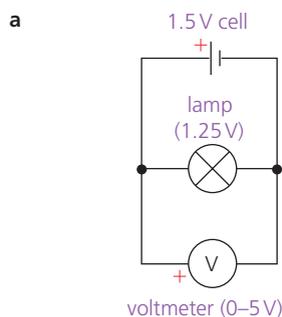
▲ **Figure 4.2.21**

b Connect the circuit of Figure 4.2.21b. Measure:
   i the p.d V between X and Y
   ii the p.d V_1 across lamp L_1
   iii the p.d V_2 across lamp L_2
   iv the p.d V_3 across lamp L_3.

c Connect the circuit of Figure 4.2.21c, so that two lamps L_1 and L_2 are in parallel across one 1.5 V cell. Measure the p.d.s, V_1 and V_2 across each lamp in turn.

8 For step **b** above, calculate the value of $V_1 + V_2 + V_3$ and compare with the value of V.

9 For step **c** above, compare the values of V_1 and V_2.

10 If all the lamps shown in Figure 4.2.21b are identical, what would you expect the p.d. across each to be?

11 a Explain where you would connect and how you would use a voltmeter to measure the p.d. across a device.
   b In the circuit shown in Figure 4.2.21c, if V_1 measures 1.5 V, what would you expect the value of V_2 to be?

> ### Test yourself
>
> **12 a** Define electromotive force.
>   **b** Define potential difference.
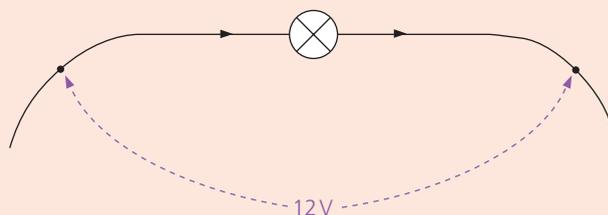> **13** The p.d. across the lamp in Figure 4.2.22 is 12 V. How many joules of electrical energy are transferred into light and heat when
>   **a** a charge of 1 C passes through it
>   **b** a charge of 5 C passes through it
>   **c** a current of 2 A flows in it for 10 s?
>
>
>
> ▲ **Figure 4.2.22**

4.2.4 Resistance

FOCUS POINTS

★ Know the correct equation for resistance and use it correctly to determine resistance using a voltmeter and an ammeter.
★ Draw and interpret current–voltage graphs.
★ Understand the dependence of the resistance of a metal wire on its length and cross-sectional area.
★ Know that resistance is directly proportional to length and inversely proportional to cross-sectional area in a metallic electrical conductor.

In this topic you will learn that the ease of passage of electrons depends on the nature of the material. This effect is measured by resistance. More work has to be done to drive a current through a high resistance than a low resistance. For the element in an electric fire, a high-resistance wire is needed so that a large amount of energy is transferred. The opposite is required for the connecting wires in a circuit, where low-resistance wires are used to reduce energy losses. Current flow is easier in a wire with a large cross-sectional area so thick wires are used where large currents are needed, for example in the starter motor in a car or a kitchen oven. The longer a wire, the harder it is for current to flow; energy loss is reduced by using short connecting wires.

Electrons move more easily through some conductors than others when a p.d. is applied. The opposition of a conductor to current is called its **resistance**. A good conductor has a low resistance and a poor conductor has a high resistance.

The ohm

If the current in a conductor is I when the voltage across it is V, as shown in Figure 4.2.23a, its resistance R is defined by

$$\text{resistance} = \frac{\text{p.d.}}{\text{current}}$$

or

$$R = \frac{V}{I}$$

This is a reasonable way to measure resistance since the smaller I is for a given V, the greater is R. If V is in volts and I in amperes, then R is in **ohms** (symbol Ω, the Greek letter omega). For example, if $I = 2\,A$ when $V = 12\,V$, then $R = 12\,V/2\,A$, that is, $R = 6\,\Omega$.

The ohm is the resistance of a conductor in which the current is 1 ampere when a voltage of 1 volt is applied across it.
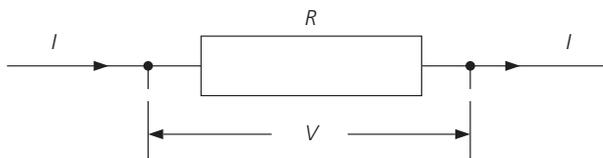
▲ **Figure 4.2.23a**
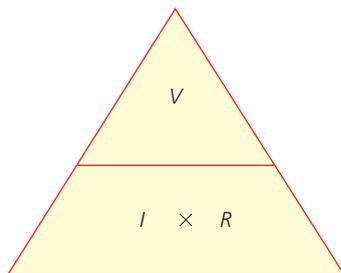
▲ **Figure 4.2.23b**

Alternatively, if R and I are known, V can be found from

$$V = IR$$

Also, when V and R are known, I can be calculated from

$$I = \frac{V}{R}$$

The triangle in Figure 4.2.23b is an aid to remembering the three equations. It is used in the same way as the 'density triangle' in Topic 1.4.

? Worked example

a   If a p.d. of 4.5V is applied across a lamp, the current flowing through the lamp is 1.5A. Calculate the resistance of the lamp.

$$R = \frac{V}{I}$$

so $R = \dfrac{4.5\,V}{1.5\,A} = 3\,\Omega$

b   A current of 0.5A flows through a resistance of $5\,\Omega$. Calculate the p.d. across the lamp.

$$V = IR = 0.5\,A \times 5\,\Omega = 2.5\,V$$

Now put this into practice

1   The current flowing through a resistor is 0.30A when a p.d. of 4.5V is applied across it. Calculate the value of the resistor.
2   A current of 0.2A flows through a resistor of $10\,\Omega$. Calculate the p.d. across the resistor.
3   A p.d. of 12.0V is applied across a lamp of $24\,\Omega$ and the lamp lights up. Calculate the current passing through the lamp.

Resistors

Conductors intended to have resistance are called **resistors** (Figure 4.2.24a) and are made either from wires of special alloys or from carbon. Those used in radio and television sets have values from a few ohms up to millions of ohms (Figure 4.2.24b).

▲ **Figure 4.2.24a** Circuit symbol for a resistor
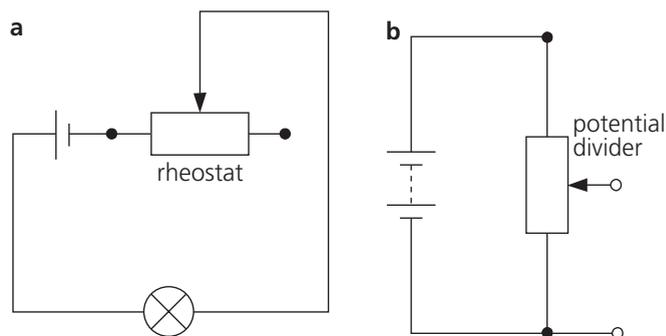

▲ **Figure 4.2.24b** Resistor

▲ **Figure 4.2.24c** Variable resistor (potentiometer)

Variable resistors are used in electronics (and are then called **potentiometers**) as volume and other controls (Figure 4.2.24c). Variable resistors that take larger currents, like the one shown in Figure 4.2.25, are useful in laboratory experiments. These consist of a coil of constantan wire (an alloy of 60% copper, 40% nickel) wound on a tube with a sliding contact on a metal bar above the tube.
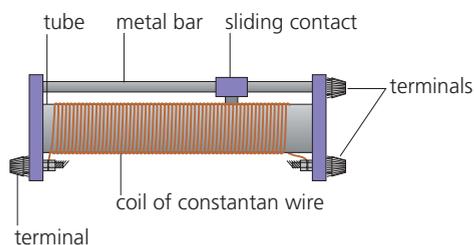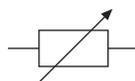

▲ **Figure 4.2.25** Large variable resistor

There are two ways of using such a variable resistor. It may be used as a **rheostat** for changing the current in a circuit; only one end connection and the sliding contact are then required. In Figure 4.2.26a moving the sliding contact to the left reduces the resistance and increases the current. This variable resistor can also act as a **potential divider** for changing the p.d. applied to a device; all three connections are then used. In Figure 4.2.26b any fraction from the total p.d. of the battery to zero can be 'tapped off' by moving the sliding contact down. Figure 4.2.27 shows the circuit diagram symbol for a variable resistor being used in rheostat mode.

▲ **Figure 4.2.26** A variable resistor can be used as a rheostat or as a potential divider.

▲ **Figure 4.2.27** Circuit symbol for a variable resistor used as a rheostat

Test yourself

14 What is the resistance of a lamp when a voltage of 12 V across it causes a current of 4 A?
15 Calculate the p.d. across a 10 Ω resistor carrying a current of 2 A.
16 The p.d. across a 3 Ω resistor is 6 V. Calculate the current flowing (in ampere).
17 Calculate the number of coulombs per second passing through a 4 Ω resistor connected across the terminals of a 12 V battery.

Practical work

Measuring resistance

Safety

● Avoid touching the wire when current is flowing as it may become hot.

The resistance R of a conductor can be found by measuring the current I in it when a p.d. V is applied across it and then using $R = V/I$. This is called the *ammeter–voltmeter* method.

Set up the circuit of Figure 4.2.28 in which the unknown resistance R is 1 metre of SWG 34 constantan wire. Altering the rheostat changes both the p.d. V and the current I. Record in a table, with three columns, five values of I (e.g. 0.10, 0.15, 0.20, 0.25 and 0.3 A) and the corresponding values of V (in the range 1.0 V to 4.0 V).

Repeat the experiment, but instead of the wire use (i) a lamp (e.g. 2.5 V, 0.3 A), (ii) a **semiconductor diode** (e.g. 1 N4001) connected first one way then the other way around and (iii) a thermistor (e.g. TH 7). (Semiconductor diodes and thermistors are considered in Topic 4.3 in more detail.)

to three 1.5 V (4.5 V) cells in series

R

crocodile clip

A

ammeter (0–1 A)

rheostat (0–25 Ω)

circuit board

V

voltmeter (0–5 V)
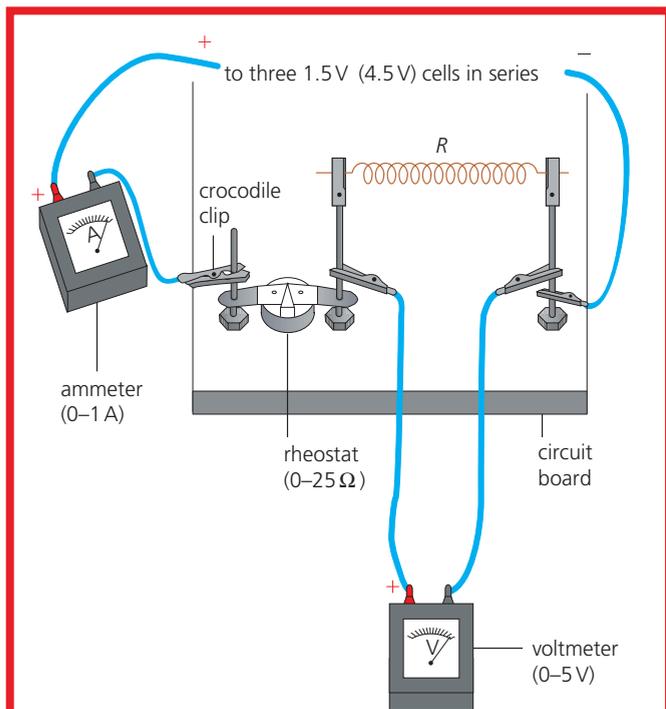
▲ **Figure 4.2.28**

12 Work out R for each pair of readings from the equation $R = V/I$.

13 Draw the symbols for **a** a resistor and **b** a variable resistor.

14 List the equipment you would need to measure the resistance of a wire.

15 Calculate the resistance of a wire that has a current of 0.15 A passing through it when the p.d. across it is 4.5 V.

Resistance of a metal wire

The **resistance of a metallic wire**
(i) increases as its length increases
(ii) increases as its cross-sectional area decreases
(iii) depends on the material.

A long thin wire has more resistance than a short thick one of the same material. Silver is the best conductor, but copper, the next best, is cheaper and is used for connecting wires and for domestic electric cables.

Key definition

Resistance of a metallic wire directly proportional to its length and inversely proportional to its cross-sectional area

Experiments show that the resistance R of a wire of a given material is

(i) directly proportional to its length l, i.e. $R \propto l$
(ii) inversely proportional to its cross-sectional area A, i.e. $R \propto 1/A$ (doubling A halves R).

? Worked example

A copper wire has a diameter of 0.50 mm, a length of 1 km and a resistance of 84 Ω.

a Calculate the resistance of a wire of the same material and diameter with a length of 500 m.
Let $R_1 = 84\,\Omega$, length $l_1 = 1.0\,\text{km} = 1000\,\text{m}$, length $l_2 = 500\,\text{m}$ and R_2 the required resistance.
Then since $R \propto 1/A$ and A is constant

$$\frac{R_2}{R_1} = \frac{l_2}{l_1}$$

and $R_2 = R_1 \times \dfrac{l_2}{l_1} = 84\,\Omega \times \dfrac{500\,\text{m}}{1000\,\text{m}} = 42\,\Omega$

The resistance is halved when the length of the wire is halved.

b Calculate the resistance of a wire of the same material with a diameter of 1.0 mm and a length of 1 km.
Let $R_1 = 84\,\Omega$, diameter $d_1 = 0.50\,\text{mm}$, diameter $d_2 = 1.0\,\text{mm}$ and R_2 the required resistance.
If r is the radius of the wire, the cross-sectional area $A = \pi r^2 = \pi(d/2)^2 = (\pi/4)\,d^2$, so

$$\frac{A_1}{A_2} = \frac{(d_1)^2}{(d_2)^2} = \frac{(0.50\,\text{mm})^2}{(1.0\,\text{mm})^2} = 0.25$$

Then since $R \propto \dfrac{l}{A}$ and l is constant

$$\frac{R_2}{R_1} = \frac{A_1}{A_2}$$

and $R_2 = R_1 \times \dfrac{A_1}{A_2} = 84\,\Omega \times 0.25 = 21\,\Omega$

Now put this into practice

1 A certain wire has a length of 10 m and a resistance of 60 Ω. Calculate the resistance of 20 m of the wire.

2 A certain wire has diameter of 0.20 mm and a resistance of 60 Ω. Calculate the resistance of a wire of the same material with a diameter of 0.40 mm.

I–V graphs: Ohm's law

The variation of current with voltage is shown for various conductors in Figure 4.2.29.

a Ohmic conductor

b Semiconductor diode

c Filament lamp

d Thermistor
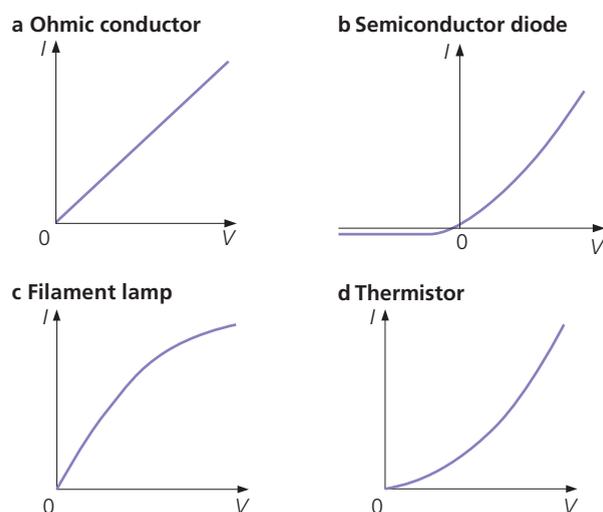
▲ **Figure 4.2.29** *I–V* graphs

Metallic conductors

Metals and some alloys give *I–V* graphs that are a straight line through the origin, as in Figure 4.2.29a, provided that their temperature is constant. *I* is directly proportional to *V*, i.e. $I \propto V$. Doubling *V* doubles *I*, etc. Such conductors obey **Ohm's law**, stated as follows.

The current in a metallic conductor is directly proportional to the p.d. across its ends if the temperature and other conditions are constant.

They are called **ohmic** or **linear conductors** and since $I \propto V$, it follows that $V/I =$ a constant (obtained from the slope of the *I–V* graph). The resistance of an ohmic conductor therefore does not change when the p.d. does.

Semiconductor diode

The typical *I–V* graph in Figure 4.2.29b shows that current passes when the p.d. is applied in one direction but is almost zero when the p.d. is applied in the opposite direction. A diode has a small resistance when connected one way round but a very large resistance when the p.d. is reversed. It conducts in one direction only and is a **non-ohmic** conductor.

Filament lamp

A filament lamp is a non-ohmic conductor at high temperatures. For a filament lamp the *I–V* graph curve flattens as *V* and *I* increase (Figure 4.2.29c). That is, the resistance (*V/I*) increases as *I* increases and makes the filament hotter.

Variation of resistance with temperature

In a metal, the current in a circuit is carried by free electrons. When the temperature of the metal increases, the atoms vibrate faster and it becomes more difficult for the electrons to move through the material. This means that the resistance of the metal increases. From Ohm's law $V = IR$, so that if *R* increases, the p.d. *V* across the conductor also increases if a constant current *I* is to be maintained.

The effect of increasing resistance can be seen in the *I–V* curve for a filament lamp (Figure 4.2.29c). When the current increases, the metal filament heats up and its resistance increases as is indicated by the curvature of the graph. The resistance of semiconductor **thermistors** decreases if their temperature rises, i.e. their *I–V* graph bends upwards, as in Figure 4.2.29d.

Variation of resistance with light intensity

The resistance of some semiconducting materials decreases when the intensity of light falling on them increases. This property is made use of in **light-dependent resistors** (LDRs) (see Topic 4.3.3). The *I–V* graph for an LDR is similar to that shown in Figure 4.2.29d for a thermistor. Both thermistors and LDRs are non-ohmic conductors.

> ### ▶ Test yourself
>
> **18 a** Sketch the *I–V* graph for a resistor of constant resistance.
>   **b** How could you obtain a value of the resistance from the graph?
> **19 a** Sketch the *I–V* graph for a filament lamp.
>   **b** Explain the shape of the graph.

4.2.5 Electric power

FOCUS POINTS

★ Know and use the correct equations for electrical power and electrical energy.
★ Define the kilowatt-hour (kWh) and use this unit to calculate the cost of using some electrical appliances.

The e.m.f. applied to a circuit drives current around the circuit. In the process, energy is transferred from the electrical cell or mains supply to the wires and components of the circuit. The total energy transferred to a device depends on its power consumption and the time span over which it is used. In this section you will learn how to measure power consumption, the typical power consumption of some everyday household appliances and how to calculate the cost of electricity usage.

Power in electric circuits

In many circuits it is important to know the rate at which the electric current transfers energy from the source to the circuit components.

Earlier (Topic 1.7.4) we said that *energy transfers were measured by the work done* and power was defined by the equation

$$\text{power} = \frac{\text{work done}}{\text{time taken}} = \frac{\text{energy transferred}}{\text{time taken}}$$

In symbols

$$P = \frac{W}{t} \quad (1)$$

where W is in joules (J), t in seconds (s) and P is in J/s or watts (W).

From the definition of p.d. (Topic 4.2.3) we saw that if W is the work done when there is a steady current I (in amperes) for time t (in seconds) in a device (e.g. a lamp) with a p.d. V (in volts) across it, as in Figure 4.2.30, then

$$W = I \times t \times V$$

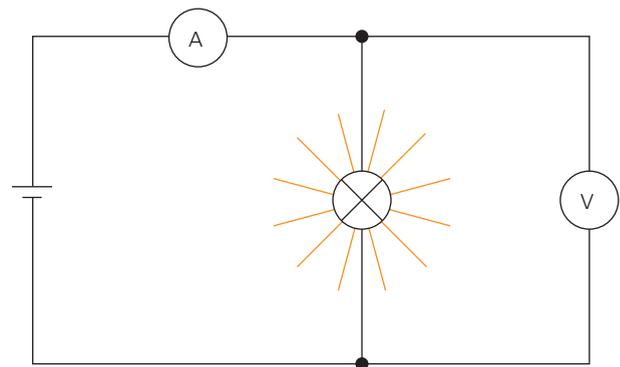Substituting for W in (1) gives $P = \dfrac{I \times t \times V}{t}$

so $P = IV$

or   power = current × voltage

and in time t the electrical energy transferred is $E = Pt$

so $E = IVt \quad (2)$

or   energy = current × voltage × time

To calculate the power P of an electrical appliance we multiply the current I in it by the p.d. V across it.

▲ **Figure 4.2.30**

For example if a lamp on a 240 V supply has a current of 0.25 A in it, its power

$$P = IV = 240\,\text{V} \times 0.25\,\text{A} = 60\,\text{W}$$

This means that 60 J of energy are transferred to the lamp each second. Larger units of power are the *kilowatt* (kW) and the *megawatt* (MW) where

$$1\,\text{kW} = 1000\,\text{W} \text{ and } 1\,\text{MW} = 1\,000\,000\,\text{W}$$

In units

$$\text{watts} = \text{amperes} \times \text{volts} \quad (3)$$

It follows from (3) that since

$$\text{volts} = \frac{\text{watts}}{\text{amperes}} \quad (4)$$

the volt can be defined as a *watt per ampere* and p.d. calculated from (4).

If all the energy is transferred to thermal energy in a resistor of resistance R, then $V = IR$ and the rate of transfer to thermal energy is given by

$$P = V \times I = IR \times I = I^2 R$$

That is, if the current is doubled, four times as much thermal energy is produced per second. Also, $P = V^2/R$. The thermal energy can be transferred to the surroundings by light and by heating.

? Worked example

A lamp of resistance $12\,\Omega$ has a current of $0.5\,A$ flowing through it.
a   Calculate the p.d. across the lamp.

   p.d. $V = IR = 0.5\,A \times 12\,\Omega = 6\,V$

b   What is the power of the lamp?

   $P = IV = 0.5\,A \times 6\,V = 3\,W = 3\,J/s$

c   How much energy is transferred to the lamp in $6\,s$?

   $P = E/t$ so $E = Pt = 3\,J/s \times 6\,s = 18\,J$

Now put this into practice

1   A lamp has a resistance of $12\,\Omega$ and a current of $1.0\,A$ passing through it.
   a   Calculate the p.d. across the lamp.
   b   Calculate the power of the lamp.
   c   How much energy is transferred to the lamp in $10\,s$?
2   A small electric motor attached to a $12\,V$ supply has a current of $0.3\,A$ passing through it.
   a   Calculate the power of the motor in watts.
   b   Give the power of the motor in joules/second.
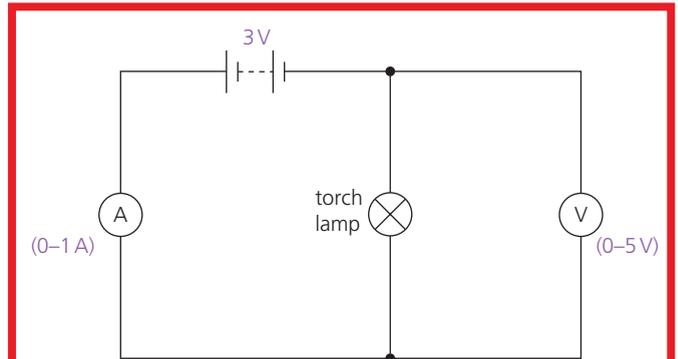   c   How much energy is transferred to the motor in 1 minute?

⚡ Practical work

Measuring electric power

Lamp
Connect the circuit of Figure 4.2.31. Note the ammeter and voltmeter readings and work out the electric power supplied to the lamp in watts.

▲ **Figure 4.2.31**

Motor
Replace the lamp in Figure 4.2.31 by a small electric motor. Attach a known mass m (in kg) to the axle of the motor with a length of thin string and find the time t (in s) required to raise the mass through a known height h (in m) at a steady speed. Then the power output P_o (in W) of the motor is given by

$$P_o = \frac{\text{work done in raising mass}}{\text{time taken}} = \frac{mgh}{t}$$

If the ammeter and voltmeter readings I and V are noted while the mass is being raised, the power input P_i (in W) can be found from

$$P_i = IV$$

The efficiency of the motor is given by

$$\text{efficiency} = \frac{P_o}{P_i} \times 100\%$$

Also investigate the effect of a greater mass on: (i) the speed, (ii) the power output and (iii) the efficiency of the motor at its rated p.d.

16 When a p.d. of $30\,V$ is applied across an electric motor, a current of $0.5\,A$ flows through it. Calculate the power supplied to the motor.
17 An electric motor raises a mass of $500\,g$ through $80\,cm$ in $4\,s$. Calculate the output power of the motor.

Going further

Joulemeter

Instead of using an ammeter and a voltmeter to measure the electrical energy transferred to an appliance, a joulemeter can be used to measure it directly in joules. The circuit connections are shown in Figure 4.2.32.

electrical supply		joulemeter		appliance
input		output		
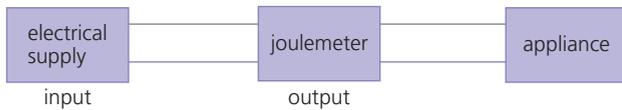
▲ **Figure 4.2.32** Connections to a joulemeter

Paying for electricity

Electricity supply companies charge for the amount of energy they supply. A joule is a very small amount of energy and a larger unit, the **kilowatt-hour** (kWh), is used.

A kilowatt-hour is the energy used by a 1 kW appliance in 1 hour.

$$1\,\text{kWh} = 1000\,\text{J/s} \times 3600\,\text{s}$$

$$= 3\,600\,000\,\text{J} = 3.6\,\text{MJ}$$

A 3 kW electric fire working for 2 hours uses 6 kWh of energy – usually called 6 'units'. Electricity meters, which are joulemeters, are marked in kWh: the latest have digital readouts like the one in Figure 4.2.33.

Key definition

Kilowatt-hour (kWh) the energy used by a 1 kW appliance in 1 hour

$1\,\text{kWh} = 1000\,\text{J/s} \times 3600\,\text{s}$

$= 3\,600\,000\,\text{J} = 3.6\,\text{MJ}$

▲ **Figure 4.2.33** Electricity meter with digital display

Typical powers of some appliances are given in Table 4.2.1.

▼ **Table 4.2.1** Power of some appliances

DVD player	20 W	Iron	1 kW
Laptop computer	50 W	Fire	1, 2, 3 kW
Light bulbs	60, 100 W	Kettle	2 kW
Television	100 W	Immersion heater	3 kW
Refrigerator	150 W	Cooker	6.4 kW

Note that the current required by a 6.4 kW cooker is given by

$$I = \frac{P}{V} = \frac{6400\,\text{W}}{230\,\text{V}} = 28\,\text{A}$$

This is too large a current to draw from the ring main of a house and so a separate circuit must be used.

? Worked example

If the price of 1 kWh (1 unit) of electricity is 10 cents, how much will it cost to use a 3000 W electric heater for 3 hours?

Convert watts to kilowatts: $3000\,W = 3\,kW$

Electrical energy $E = Pt = 3\,kW \times 3\,h = 9\,kWh$

Cost of using the heater $= 9\,kWh \times 10\,cents = 90\,cents$

Now put this into practice

1 If the price of 1 kWh (1 unit) of electricity is 10 cents, how much will it cost to use a 6.4 kW oven for 2 hours?

2 If the cost of 1 kWh (1 unit) of electricity is 10 cents, how much will it cost to use a 150 W refrigerator for 12 hours?

▶ Test yourself

20 How much energy in joules is transferred to a 100 watt lamp in
   a 1 second
   b 5 seconds
   c 1 minute?
21 a What is the power of a lamp rated at 12 V 2 A?
   b How many joules of energy are transferred per second to a 6 V 0.5 A lamp?

Revision checklist

After studying Topic 4.2 you should know and understand:
✔ that positive and negative charges are produced by rubbing and like charges repel while unlike charges attract
✔ what is meant by an electric field and that the direction of an electric field at a point is the direction of the force on a positive charge at that point
✔ that an electric current in a metal is a flow of free electrons from the negative to the positive terminal of the battery around a circuit
✔ the difference between d.c. and a.c.
✔ the meaning of the terms electromotive force and potential difference
✔ how to use ammeters and voltmeters, both analogue and digital
✔ how to solve simple problems using the equation resistance = p.d./current $(R = V/I)$

After studying Topic 4.2 you should be able to:
✔ explain the charging of objects in terms of the motion of negatively charged electrons and describe simple experiments to show how electrostatic charges are produced and detected
✔ give examples of conductors and insulators and explain the differences between them using a simple electron model

✔ state the units of charge and current
✔ recall the relation electric current = charge/time $(I = Q/t)$ and use it to solve problems
✔ distinguish between electron flow and conventional current
✔ state that e.m.f. and p.d. are measured in volts and that the volt is given by a joule per coulomb
✔ recall and use the equations e.m.f. = work done (by a source)/charge $(E = W/Q)$ and p.d. = work done (on a component)/charge $(V = W/Q)$
✔ describe an experiment to measure resistance and relate the resistance of a wire to its length and diameter
✔ state Ohm's law
✔ plot and explain I–V graphs for different conductors
✔ describe the effect of temperature increase on the resistance of a resistor
✔ recall the equations power = current × voltage $(P = IV)$ and energy = current × voltage × time $(E = IVt)$ and use them to solve simple problems on energy transfers
✔ define the kilowatt-hour and calculate the cost of using electrical appliances.

Exam-style questions

1 a Explain in terms of electron movement what happens when a piece of cellulose acetate becomes positively charged by being rubbed with a cloth. [3]

b Two positive electrostatic charges are brought close together. Will they be repelled or attracted to each other? [1]

c A positive and a negative electric charge are brought close to each other. Will they be attracted or repelled from each other? [1]

d How many types of electric charge are there? [1]

[Total: 6]

2 a Describe an experiment to distinguish between electrical conductors and insulators. [4]

b Identify two good electrical conductors. [2]

c Identify one electrical insulator. [1]

d Explain the difference between electrical conductors and insulators in terms of electrons. [3]

[Total: 10]

3 a Explain what is meant by an electric field. [2]

b Sketch the electric field lines (including their direction) between two oppositely charged conducting parallel plates. Indicate the direction in which a positive charge would move if placed between the plates. [4]

c State the units of charge. [1]

[Total: 7]

4 a State the direction of an electric field. [3]

b Draw the field lines around a positively charged conducting sphere. [4]

[Total: 7]

5 Study the circuits in Figure 4.2.34. The switch S is open (there is a break in the circuit at this point). In which circuit would lamps Q and R light but not lamp P?
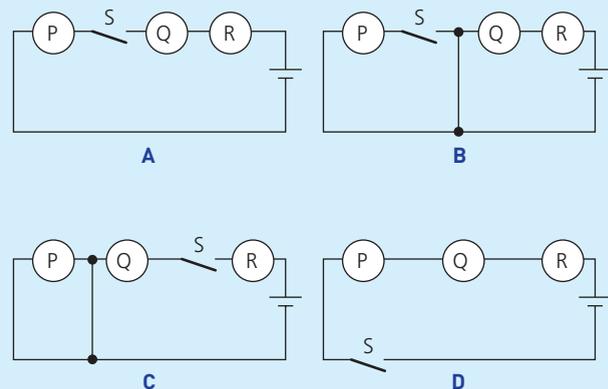
▲ **Figure 4.2.34** [Total: 1]

6 Using the circuit in Figure 4.2.35, which of the following statements is correct?

A When S_1 and S_2 are closed, lamps A and B are lit.

B With S_1 open and S_2 closed, A is lit and B is not lit.

C With S_2 open and S_1 closed, A and B are lit.

D With S_1 open and S_2 open, A is lit and B is not lit.
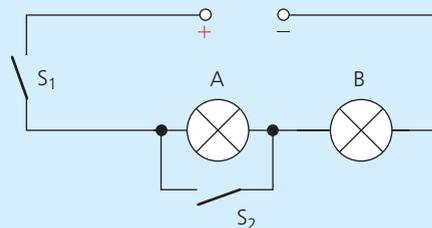
▲ **Figure 4.2.35** [Total: 1]

7 a Identify the particles which carry a current in a metal. [1]

b Explain the difference between direct current (d.c.) and alternating current (a.c.). [2]

c Explain where you would connect and how you would use an ammeter to measure the d.c. current in a circuit. [3]
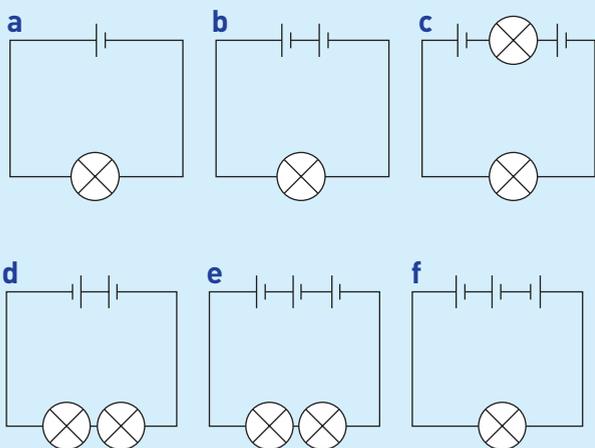
[Total: 6]

8 a Define electric current. [2]
  b An electric current passes through a device.
    i Calculate the current at a point in the circuit where 180 C of charge passes in 1 minute. [2]
    ii If the current in the device is 2 A, what charge passes through it in 1 minute? [3]
      [Total: 7]

9 a If the current in a floodlamp is 5 A, what charge passes in
    i 10 s [2]
    ii 5 minutes? [2]
 b Calculate how long it will take 300 C to pass through the floodlight. [3]
      [Total: 7]

10 The lamps and the cells in all the circuits of Figure 4.2.36 are the same. If the lamp in **a** has its full, normal brightness, what can you say about the brightness of the lamps in **b**, **c**, **d**, **e** and **f**?
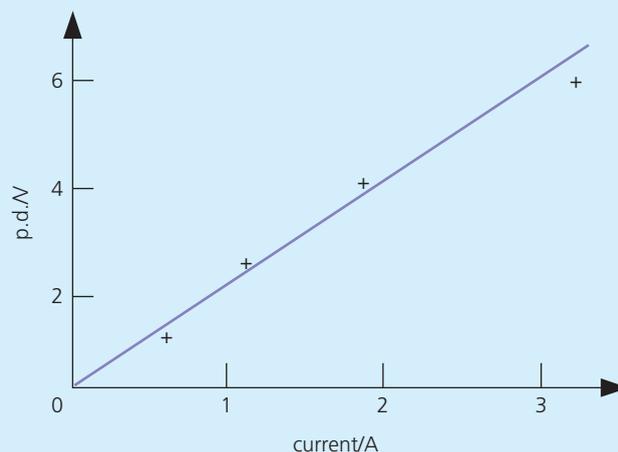

▲ **Figure 4.2.36** [Total: 5]

11 Three voltmeters V, V_1 and V_2 are connected as in Figure 4.2.37.
  a If V reads 18 V and V_1 reads 12 V, what does V_2 read? [2]
  b If the ammeter A reads 0.5 A, how much electrical energy is changed to heat and light in lamp L_1 in one minute? [4]
  c Copy Figure 4.2.37 and mark with a + the positive terminals of the ammeter and voltmeters for correct connection. [4]
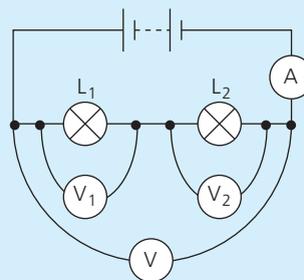
▲ **Figure 4.2.37** [Total: 10]

12 The graph in Figure 4.2.38 illustrates how the p.d. across the ends of a conductor is related to the current in it.
  a State the relationship between V and I that can be deduced from the graph, giving reasons. [4]
  b Calculate the resistance of the conductor. [3]

▲ **Figure 4.2.38** [Total: 7]

13 a Describe how the resistance of a wire depends on its length and cross-sectional area. [3]
  b The resistance of a wire of length 1 m is 70 Ω. Calculate the resistance of a 20 cm length of the wire. [3]
  c If the 1 m length of wire is replaced with a wire of the same material and length but of half the diameter calculate its resistance. [4]
      [Total: 10]

14 Sketch a current–voltage graph of
  a a resistor of constant resistance [3]
  b a semiconductor diode [3]
  c a filament lamp. [3]
      [Total: 9]

15 a Calculate the energy transferred to a 6.4 kW cooker in 30 minutes. [3]

b Calculate the cost of heating a tank of water with a 3000 W immersion heater for 80 minutes if electricity costs 10 cents per kWh. [3]

[Total: 6]

16 a Below is a list of wattages of various appliances. State which is most likely to be the correct one for each of the appliances named.

60 W   250 W   850 W   2 kW   3.5 kW

i kettle [1]
ii table lamp [1]
iii iron [1]

b Calculate the current in a 920 W appliance if the supply voltage is 230 V. [4]

[Total: 7]

Alternative to Practical

17 a Give an expression relating the resistance of a metal wire to the p.d. across it and the current flowing through it. [1]

b Describe how you could measure the resistance of a wire; include the equipment you would need. [4]

c In an experiment to determine the resistance of a wire the following values were obtained for the current through the wire and the p.d. across it.

Current/A	p.d./V
0.04	2.0
0.08	4.0
0.12	6.0
0.16	8.0
0.20	10.0
0.24	12.0

i Plot a graph of p.d. versus current. [3]
ii Determine the value of the resistor. [2]

[Total: 10]

18 Plan an experiment to find how the resistance of a wire varies with its length. You are provided with a battery, ammeter, voltmeter, connecting wires (attached to crocodile clips) and different lengths of wires of varying material.

You should:

– draw a diagram of the circuit you would use to determine the resistance of a wire being tested
– explain briefly how you would carry out the investigation, including the measurements you would take
– state the key variables that you would control
– give a suitable table, with column headings, to show how you would display your readings.

[Total: 6]

4.3 Electric circuits

4.3.1 Circuit diagrams and components

FOCUS POINTS

★ Draw and interpret circuit diagrams containing a variety of different components and understand how these components behave in the circuit.

You will find that electrical circuits can contain many different types of components. The circuit configuration is expressed by circuit diagrams. Conventional symbols represent the different types of components. Such diagrams are used in the design of circuits and the analysis of their behaviour.

Some of the symbols used for the various parts of an electric circuit are shown in Figure 4.3.1. So far you have encountered cells, batteries, lamps, resistors, ammeters and voltmeters. In this section you will be introduced to some more of the components frequently used in electric circuits including thermistors, light-dependent resistors (LDRs), relays, **light-emitting diodes** (LEDs) and semiconductor diodes.
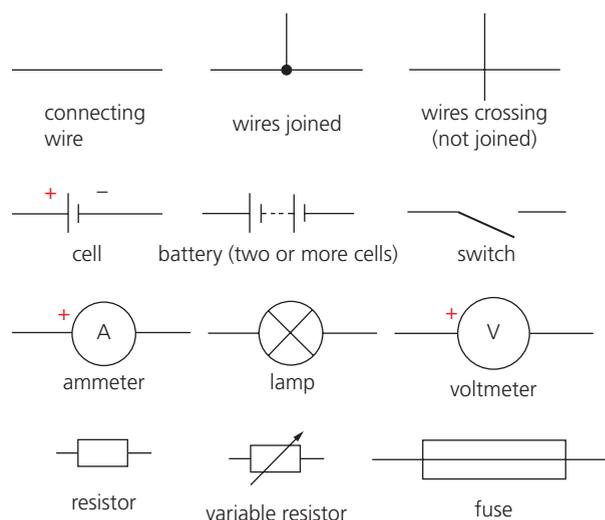
▲ **Figure 4.3.1** Circuit symbols

4.3.2 Series and parallel circuits

FOCUS POINTS

★ Understand that current in a series circuit is the same at any point.
★ Calculate the currents and p.d.s in series and parallel circuits.
★ Understand how to construct and use series and parallel circuits.
★ Calculate the combined e.m.f. of two or more sources in series and of two identical sources in parallel.
★ Understand that the sum of the currents into a junction equals the sum of the currents out of the junction.
★ Calculate the effective resistance of two resistors in parallel and the combined resistance of two or more resistors in series.
★ Know that in a lighting circuit there are advantages to connecting lamps in parallel.

In the preceding topic you learned about the concepts of current, p.d. and resistance and how they are related to each other in simple circuits. Electrical circuits can branch and reconnect. The net effect depends on the way the components are connected. The sum of the currents into a junction equals the sum of the currents out of the junction. This means that there are different effects when resistors follow each other (in series) from those when they lie on parallel wires. There are significant advantages in connecting lamps in parallel in a lighting circuit.

A circuit usually contains several components and the effect of connecting components together in series and parallel configurations will be now be considered.

Current in a series circuit

In a **series circuit**, such as the one shown in Figure 4.3.2, the different parts follow one after the other and there is just one path for the current to follow. The reading on an ammeter will be the same whether it is placed in the position shown or at B, C or D. That is, current is not used up as it goes around the circuit.

The current at every point in a series circuit is the same.
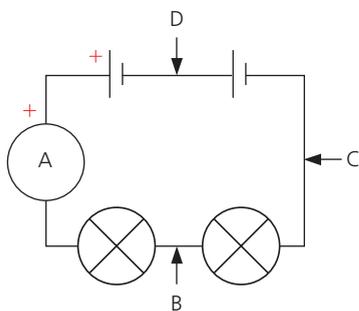
▲ **Figure 4.3.2** Current in a series circuit

Current in a parallel circuit

In a **parallel circuit**, such as the one shown in Figure 4.3.3, the lamps are side by side and there are alternative paths for the current. The current splits: some goes through one lamp and the rest through the other. The current from the source is larger than the current in each branch. For example, if the ammeter reading was 0.4 A in the position shown, then if the lamps are identical, the reading at P would be 0.2 A, and so would the reading at Q, giving a total of 0.4 A. Whether the current splits equally or not depends on the lamps; for example, if the lamps are not identical, the current might divide so that 0.3 A goes one way and 0.1 A by the other branch.
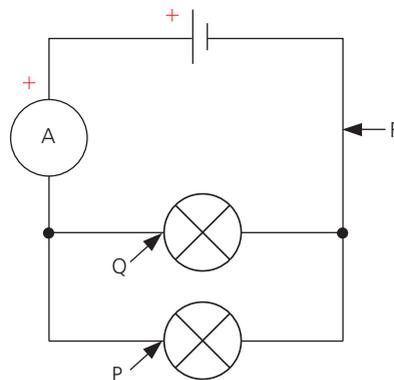
▲ **Figure 4.3.3** Currents in a parallel circuit

Practical work associated with currents in series and parallel circuits can be found in Topic 4.2.2.

> **Key definitions**
>
> **Series circuit** components connected one after another; current is the same in each component
>
> **Parallel circuit** components are connected side by side and the current splits into alternative paths and then recombines.

Current at a junction

Electric current in a circuit cannot be stored. This means that when circuits join or divide, the total current going into a junction must be equal to the total current leaving the junction. A simple example of this is provided by the splitting and re-joining of the current when it goes into and comes out of a parallel circuit.

Potential difference in a series circuit

The total p.d. across the components in a series circuit is equal to the sum of the individual p.d.s across each component. In Figure 4.3.4

$$V = V_1 + V_2 + V_3$$

where V_1 is the p.d. across L_1, V_2 is the p.d. across L_2 and V_3 is the p.d. across L_3.
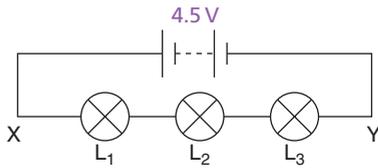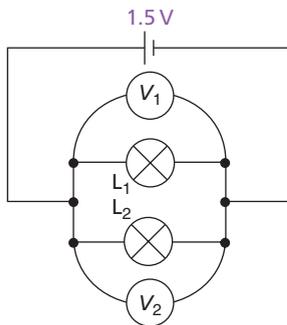
▲ **Figure 4.3.4** p.d. in a series circuit

For example, if $V_1 = 1.4\,V$, $V_2 = 1.5\,V$ and

$V_3 = 1.6\,V$, then V will be $(1.4 + 1.5 + 1.6)\,V = 4.5\,V$.

Potential difference in a parallel circuit

In the circuit of Figure 4.3.5

$$V_1 = V_2$$

The p.d. across devices in parallel in a circuit are equal.

▲ **Figure 4.3.5** p.d.s in a parallel circuit

The p.d. across an arrangement of parallel resistance is the same as the p.d. across one branch.

Practical work associated with voltage in series and parallel circuits can be found in Topic 4.2.3.

Cells, batteries and e.m.f.

A battery (Figure 4.3.6) consists of two or more **electric cells**. Greater e.m.f.s are obtained when cells are joined in series, i.e. + of one to − of next; the e.m.f.s of each are added together to give the combined e.m.f. In Figure 4.3.7a the two 1.5 V cells give an e.m.f. of 3 V at the terminals A, B.

▲ **Figure 4.3.6** Compact batteries

The cells in Figure 4.3.7b are in opposition and the e.m.f. at X, Y is zero.

If two 1.5 V cells are connected in parallel, as in Figure 4.3.7c, the e.m.f. at terminals P, Q is still 1.5 V but the arrangement behaves like a larger cell and will last longer.
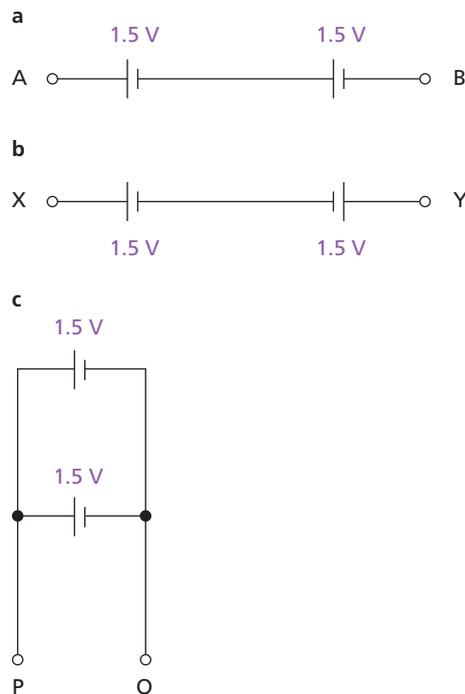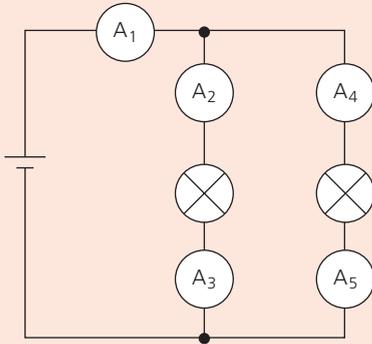

▲ **Figure 4.3.7**

The p.d. at the terminals of a battery decreases slightly when current is drawn from it. This effect is due to the internal resistance of the battery which causes heating as current flows through it.

When no current is drawn from a battery it is said to be an 'open circuit' and its terminal p.d. is a maximum and equal to the e.m.f. of the battery.

▶ Test yourself

1 If the lamps are both the same in Figure 4.3.8 and if ammeter A_1 reads 0.50 A, what do ammeters A_2, A_3, A_4 and A_5 read?
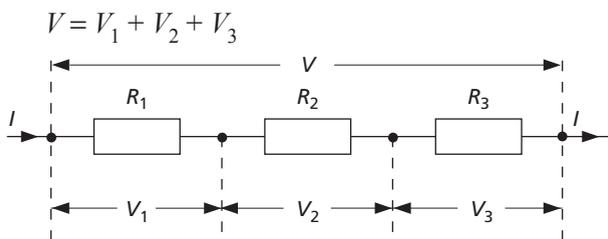

▲ **Figure 4.3.8**

2 Three 2 V cells are connected in series and used as the supply for a circuit.
   What is the p.d. at the terminals of the supply?
3 How many joules of energy does 1 C gain on passing through
   a a 2 V cell
   b three 2 V cells connected in series?

Resistors in series

The resistors in Figure 4.3.9 are in series. The same current I flows through each and the total voltage V across all three is the sum of the separate voltages across them, i.e.

$$V = V_1 + V_2 + V_3$$

▲ **Figure 4.3.9** Resistors in series

But $V_1 = IR_1$, $V_2 = IR_2$ and $V_3 = IR_3$. Also, if R is the combined resistance, $V = IR$, and so

$$IR = IR_1 + IR_2 + IR_3$$

Dividing both sides by I,

$$R = R_1 + R_2 + R_3$$

? Worked example

A 4.5 V battery is connected across three resistors of values $3\,\Omega$, $4\,\Omega$ and $5\,\Omega$ connected in series.

a Calculate the current flowing through the resistors.
   Combined resistance of resistors in series

$$R = R_1 + R_2 + R_3 = 3\,\Omega + 4\,\Omega + 5\,\Omega = 12\,\Omega$$

Rearrange equation $V = IR$ to give $I = V/R$ then the current flowing through the three resistors

$$I = \frac{4.5\,\text{V}}{12\,\Omega} = 0.38\,\text{A}$$

b Calculate the p.d. across the $4\,\Omega$ resistor.
   p.d. across R_2 is given by

$$V_2 = IR_2 = 0.38\,\text{A} \times 4\,\Omega = 1.5\,\text{V}$$

Now put this into practice

1 Three resistors of value $4\,\Omega$, $6\,\Omega$ and $8\,\Omega$ are connected in series. Calculate their combined resistance.
2 A 4.5 V battery is connected across two resistors of value $3\,\Omega + 6\,\Omega$. Calculate
   a the current flowing through the resistors
   b the p.d. across each.

Resistors in parallel

The resistors in Figure 4.3.10 are in parallel. The *voltage V between the ends of each is the same* and the total current I equals the sum of the currents in the separate branches, i.e.

$$I = I_1 + I_2 + I_3$$
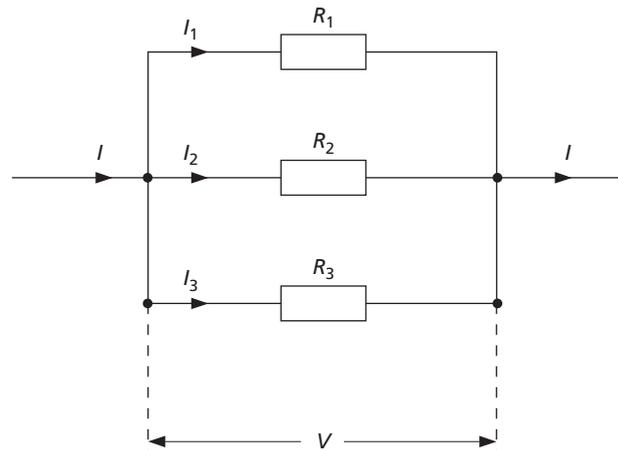
▲ **Figure 4.3.10** Resistors in parallel

But $I_1 = V/R_1$, $I_2 = V/R_2$ and $I_3 = V/R_3$.

Also, if R is the combined resistance, $I = V/R$,

$$\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

Dividing both sides by V,

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

For the simpler case of *two* resistors in parallel

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{R_2}{R_1 R_2} + \frac{R_1}{R_1 R_2}$$

$$\therefore \frac{1}{R} = \frac{R_2 + R_1}{R_1 R_2}$$

Inverting both sides,

$$R = \frac{R_1 R_2}{R_1 + R_2} = \frac{\text{product of resistances}}{\text{sum of resistances}}$$

Properties of parallel circuits

We can summarise the results for parallel circuits as follows:

(i) the sum of the currents in the branches of a parallel circuit equals the current entering or leaving the parallel section

(ii) the combined resistance, R, of two resistors in parallel is less than that of either resistor R_1 or R_2 alone and is calculated from

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

You can check these statements are true in the Worked example below.

Lamps are connected in parallel (Figure 4.3.5) rather than in series in a lighting circuit.

The advantages are as follows:

(i) The p.d. across each lamp is fixed (at the supply p.d.), so the lamp shines with the same brightness irrespective of how many other lamps are switched on.

(ii) Each lamp can be turned on and off independently; if one lamp fails, the others can still be operated.

Practical work associated with measuring resistance can be found in Topic 4.2.4.

? Worked example

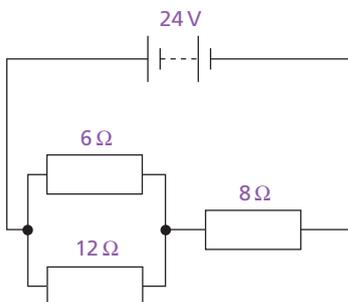A p.d. of 24 V from a battery is applied to the network of resistors in Figure 4.3.11a.

a What is the combined resistance of the 6 Ω and 12 Ω resistors in parallel?

Let R_1 = resistance of 6 Ω and 12 Ω in parallel.
Then

$$\frac{1}{R_1} = \frac{1}{6} + \frac{1}{12} = \frac{2}{12} + \frac{1}{12} = \frac{3}{12}$$

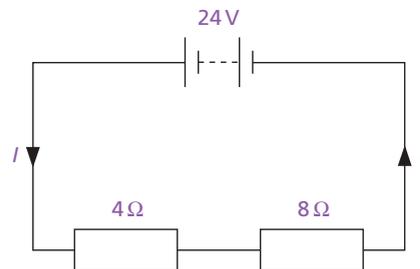$$\therefore R_1 = \frac{12}{3} = 4\,\Omega$$

▲ **Figure 4.3.11a**

b What is the current in the 8 Ω resistor?

Let R = total resistance of circuit = 4 Ω + 8 Ω, that is, $R = 12\,\Omega$. The equivalent circuit is shown in Figure 4.3.11b, and if I is the current in it then, since $V = 24$ V

$$I = \frac{V}{R} = \frac{24\,\text{V}}{12\,\Omega} = 2\,\text{A}$$

$\therefore$ current in 8 Ω resistor = 2 A

▲ **Figure 4.3.11b**

c What is the voltage across the parallel network?
Let V_1 = voltage across parallel network in
Figure 4.3.11a. Then

$$V_1 = I \times R_1 = 2\,\text{A} \times 4\,\Omega = 8\,\text{V}$$

d What is the current in the $6\,\Omega$ resistor?
Let I_1 = current in $6\,\Omega$ resistor, then since $V_1 = 8\,\text{V}$

$$I_1 = \frac{V_1}{6\,\Omega} = \frac{8\,\text{V}}{6\,\Omega} = \frac{4}{3}\,\text{A}$$

Now put this into practice

1 a Calculate the combined resistance R of a $1\,\Omega$, $2\,\Omega$ and $3\,\Omega$ resistor connected in series.
b A 12 V battery is connected across the resistors. Calculate the current I flowing through each resistor.
c What is the p.d. across each resistor?
2 a Calculate the combined resistance R_a of $2\,\Omega$ and $3\,\Omega$ resistors connected in parallel.
b A 12 V battery is connected across the resistors. What is the p.d. across each resistor?
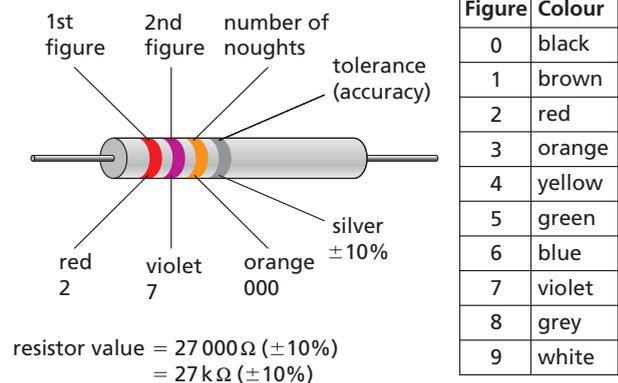**c** Calculate the current I flowing through
   i the $2\,\Omega$ resistor
   ii the $3\,\Omega$ resistor.

➡ Going further

Resistor colour code

Resistors have colour-coded bands as shown in Figure 4.3.12. In the orientation shown the first two bands on the left give digits 2 and 7; the third band gives the number of noughts (3) and the fourth band gives the resistor's 'tolerance' (or accuracy, here ±10%). So the resistor has a value of 27 000 Ω (±10%).

resistor value = 27 000 Ω (±10%)
= 27 kΩ (±10%)

Figure	Colour
0	black
1	brown
2	red
3	orange
4	yellow
5	green
6	blue
7	violet
8	grey
9	white

Tolerance	
±5%	gold
±10%	silver
±20%	no band

▲ **Figure 4.3.12** Colour code for resistors

▶ Test yourself

4 a Write down the equation for calculating the combined resistance R of resistors R_1, R_2 and R_3 connected in series.
b Is the current in R_1 larger, the same or smaller than in R_3?

5 a Write down the equation for calculating the combined resistance R of resistors R_1 and R_2 connected in parallel.
b Is the current in R_1 larger, the same or smaller than in R_2 if R_1 is smaller than R_2?

# 4.3.3 Action and use of circuit components

FOCUS POINTS
★ Describe how a variable potential divider works and use the correct equation for two resistors used as a potential divider.
★ Describe how thermistors and LDRs can be used as input sensors.

The action of potential dividers and a range of other components, including thermistors, LDRs, relays, light-emitting diodes and semiconductor diodes, will be considered in this section. These components are widely used in electrical circuits in applications ranging from intruder and temperature alarms to indicator lamps and switching circuits.

Variable potential divider

The resistance of materials other than metals does not necessarily rise when their temperature increases. For example, in a semiconductor thermistor, the resistance decreases when its temperature increases.

If a thermistor is part of a potential divider circuit (see Figure 4.3.13) then its resistance decreases when the external temperature rises. The combined resistance of the two resistors then decreases, so if the supply voltage remains constant, the current in the circuit will increase. This means that the p.d. across the fixed resistor increases relative to that across the thermistor. The p.d. across the fixed resistor could then be used to monitor temperature.
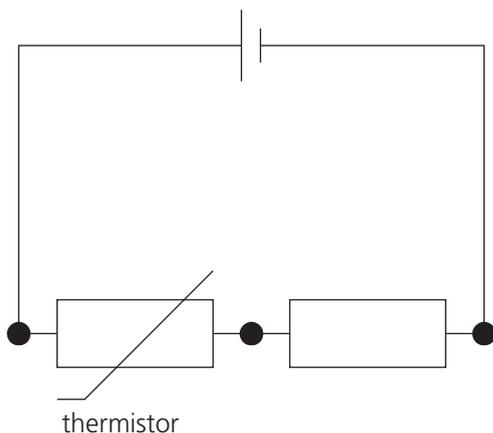
▲ **Figure 4.3.13** Potential divider circuit for monitoring temperature

A variable resistor can also be used as a potential divider (see Figure 4.2.26b, p. 199). Moving the contact on the resistor changes the output p.d.

Potential divider

In the circuit shown in Figure 4.3.14, two resistors R_1 and R_2 are in series with a supply of voltage V. The current in the circuit is

$$I = \frac{\text{supply voltage}}{\text{total resistance}} = \frac{V}{(R_1 + R_2)}$$

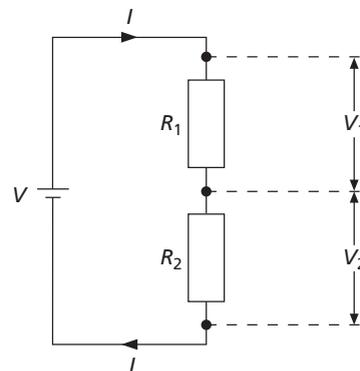So the voltage across R_1 is

$$V_1 = I \times R_1 = \frac{V \times R_1}{(R_1 + R_2)} = V \times \frac{R_1}{(R_1 + R_2)}$$

and the voltage across R_2 is

$$V_2 = I \times R_2 = \frac{V \times R_2}{(R_1 + R_2)} = V \times \frac{R_2}{(R_1 + R_2)}$$

Also the ratio of the voltages across the two resistors is

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

▲ **Figure 4.3.14** Potential divider circuit

? Worked example

Resistors $R_1 = 80\,\Omega$ and $R_2 = 40\,\Omega$ are connected in series and used as a potential divider.

a Calculate the ratio of the p.d.s across the resistors.
From the potential divider equation

$$V_1/V_2 = R_1/R_2 = 80\,\Omega\,/40\,\Omega = 2$$

Ratio of voltages is 2:1

b If the supply voltage is 24 V, what is the p.d. across each resistor?
Dividing the supply voltage in the ratio 2:1 gives

$$V_1 = 2 \times \frac{24\,\mathrm{V}}{3} = 16\,\mathrm{V}$$

and

$$V_2 = 1 \times \frac{24\,\mathrm{V}}{3} = 8\,\mathrm{V}$$

Now put this into practice

1 Write down the equation relating p.d.s and resistances in a potential divider circuit.

2 Resistors $R_1 = 9\,\Omega$ and $R_2 = 6\,\Omega$ are connected in series and used as a potential divider.
  a Calculate the ratio of the p.d.s across the resistors.
  b If the supply voltage is 30 V, what is the p.d. across each resistor?

Input sensors

Thermistors and light-dependent resistors can be used as input sensors in a circuit to detect changes in the environment.

Light-dependent resistor (LDR)

The action of an LDR depends on the fact that the resistance of the semiconductor cadmium sulfide decreases as the intensity of the light falling on it increases.

An LDR and a circuit showing its action are shown in Figures 4.3.15a and b. Note the circuit symbol for an LDR, sometimes seen with a circle. When light from a lamp falls on the window of the LDR, its resistance decreases and the increased current lights the lamp.

LDRs are used in photographic exposure meters and in series with a resistor to provide an input signal in switching circuits such as a light-operated intruder alarm.
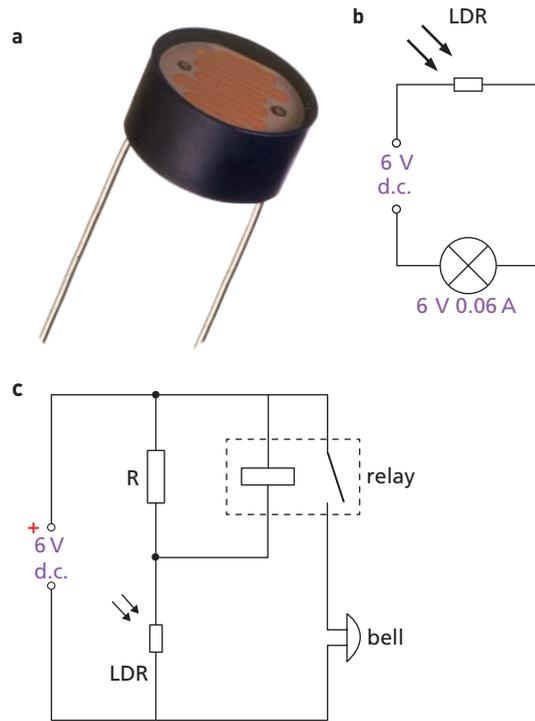
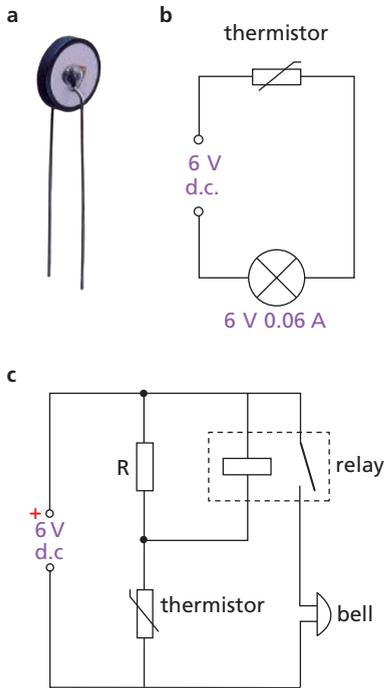▲ **Figure 4.3.15 a** LDR; **b** LDR demonstration circuit; **c** light-operated intruder alarm

Figure 4.3.15c shows how an LDR can be used to switch a relay (Topic 4.5.3). The LDR forms part of a potential divider across the 6 V supply. When light falls on the LDR, the resistance of the LDR, and hence the voltage across it, decreases. There is a corresponding increase in the voltage across resistor R and the relay; when the voltage across the relay coil reaches a high enough p.d. (its operating p.d.) it acts as a switch and the normally open contacts close, allowing current to flow to the bell, which rings. If the light is removed, the p.d. across resistor R and the relay drops below the operating p.d. of the relay so that the relay contacts open again; power to the bell is cut and it stops ringing.

Thermistor

A negative temperature coefficient (NTC) thermistor contains semiconducting metallic oxides whose resistance decreases markedly when the temperature rises. The temperature may rise either because the thermistor is directly heated or because a current is in it.

Figure 4.3.16a shows one type of thermistor. Figure 4.3.16b shows the symbol for a thermistor in a circuit to demonstrate how the thermistor works. When the thermistor is heated with a match, the lamp lights.

A thermistor in series with a meter marked in °C can measure temperatures. Used in series with a resistor it can also provide an input signal to switching circuits.


▲ **Figure 4.3.16 a** Thermistor; **b** thermistor demonstration circuit; **c** high-temperature alarm

Figure 4.3.16c shows how a thermistor can be used to switch a relay. The thermistor forms part of a potential divider across the d.c. source. When the temperature rises, the resistance of the thermistor falls, and so does the p.d. across it. The voltage across resistor R and the relay increases. When the voltage across the relay reaches its operating p.d. the normally open contacts close, so that the circuit to the bell is completed and it rings. If a variable resistor is used in the circuit, the temperature at which the alarm sounds can be varied.

Relays

A switching circuit cannot supply much power to an appliance so a relay is often included; this allows the small current provided by the switching circuit to control the larger current needed to operate a buzzer as in a temperature-operated switch or other device. Relays controlled by a switching circuit can also be used to switch on the mains supply for electrical appliances in the home. In Figure 4.3.17 if the output of the switching circuit is 'high' (5 V), a small current flows to the relay which closes the mains switch; the relay also isolates the low voltage circuit from the high voltage mains supply.
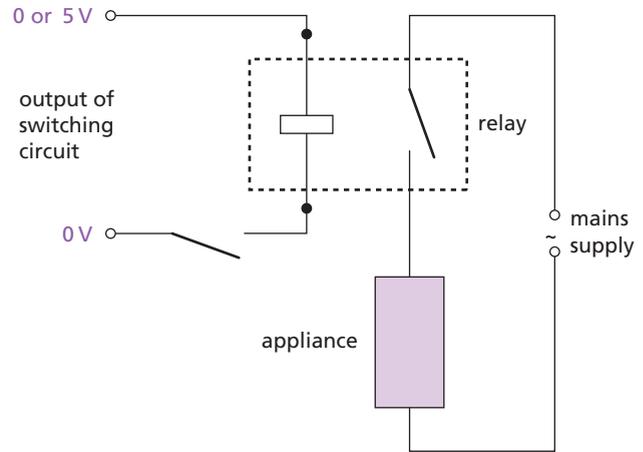

▲ **Figure 4.3.17** Use of a relay to switch mains supply

Light-emitting diode (LED)

An LED, shown in Figure 4.3.18a, is a diode made from the semiconductor gallium arsenide phosphide. When forward biased (with the cathode C connected to the negative terminal of the voltage supply, as shown in Figure 4.3.18b), the current in it makes it emit red, yellow or green light. No light is emitted on reverse bias (when the anode A is connected to the negative terminal of the voltage supply). If the reverse bias voltage exceeds 5 V, it may cause damage.

In use, an LED must have a suitable resistor R in series with it (e.g. $300\,\Omega$ on a 5 V supply) to limit the current (typically 10 mA). Figure 4.3.18b shows the symbol for an LED in a demonstration circuit.
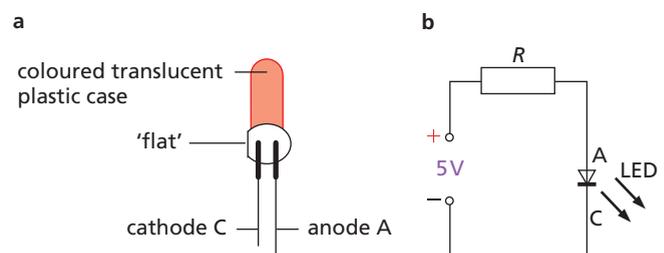

▲ **Figure 4.3.18 a** LED and **b** demonstration circuit

LEDs are used as indicator lamps on computers, radios and other electronic equipment. Many clocks, calculators, video recorders and measuring instruments have seven-segment red or green numerical displays (Figure 4.3.19a). Each segment is an LED and, depending on which have a voltage across them, the display lights up the numbers 0 to 9, as in Figure 4.3.19b.

LEDs are small, reliable and have a long life; their operating speed is high and their current requirements are very low.

Diode lasers operate in a similar way to LEDs but emit coherent laser light; they are used in optical fibre communications as transmitters.
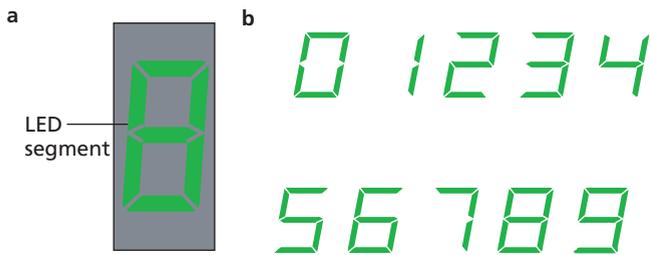
▲ **Figure 4.3.19** LED numerical display

Semiconductor diode

A diode is a device that lets current pass in one direction only. One is shown in Figure 4.3.20 with its symbol. (You will also come across the symbol with an outer circle.) The wire nearest the band is the **cathode** and the one at the other end is the **anode**.
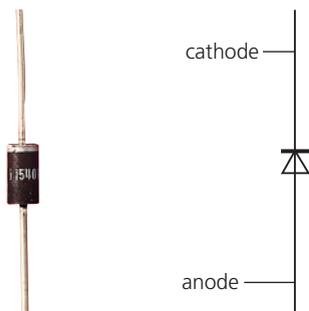

▲ **Figure 4.3.20** A diode and its symbol

The typical I–V graph is shown in Figure 4.2.29b (Topic 4.2.4). The diode conducts when the anode goes to the + terminal of the voltage supply and the cathode to the − terminal (Figure 4.3.21a). It is then **forward-biased**; its resistance is small and conventional current passes in the direction of the arrow on its symbol. If the connections are the other

way around, it does not conduct; its resistance is large and it is **reverse-biased** (Figure 4.3.21b).

The lamp in the circuit shows when the diode is conducting, as the lamp lights up. It also acts as a resistor to limit the current when the diode is forward-biased. Otherwise the diode might overheat and be damaged.
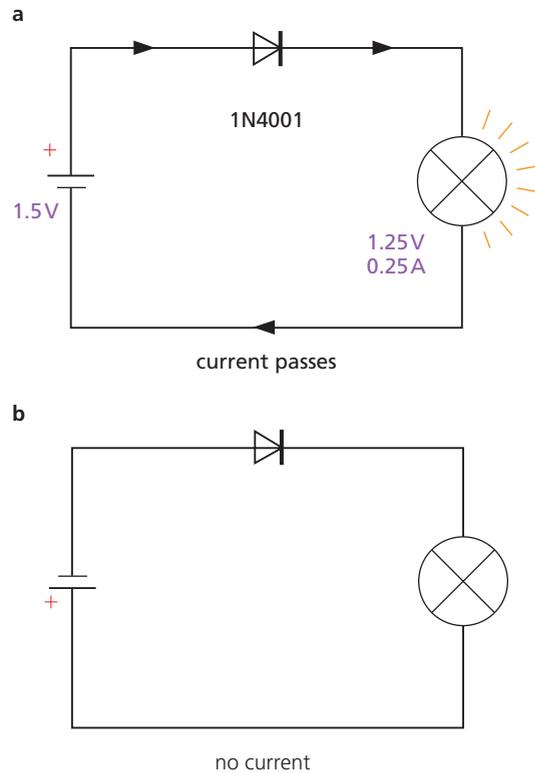
▲ **Figure 4.3.21** Demonstrating the action of a diode

A diode is a **non-ohmic** conductor. It is useful as a **rectifier** for changing alternating current (a.c.) to direct current (d.c.). Figure 4.3.22 shows the rectified output voltage obtained from a diode when it is connected to an a.c. supply.
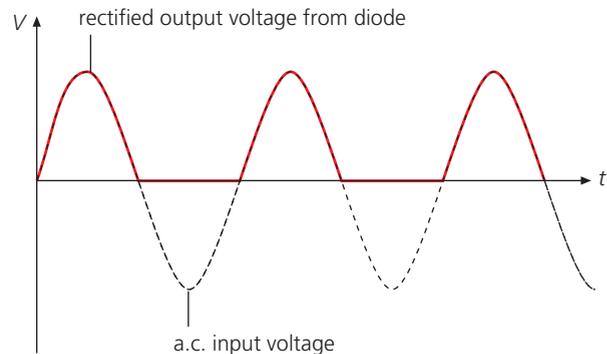

▲ **Figure 4.3.22** Rectification by a diode

Test yourself

6 Resistors $R_1 = 12\,\Omega$ and $R_2 = 36\,\Omega$ are connected in series and used as a potential divider.
  a Draw a potential divider circuit containing a battery and resistors R_1 and R_2 in series.
  b Calculate the ratio of the p.d.s across the resistors.
  c If the supply voltage is 20 V, what is the p.d. across each resistor?

7 Identify the following components from their symbols:
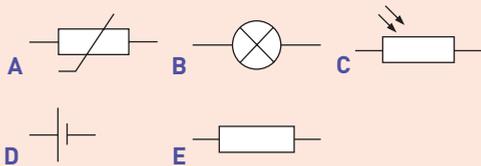
▲ **Figure 4.3.23**

8 Identify the following components from their symbols:
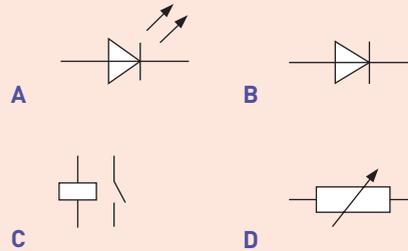
▲ **Figure 4.3.24**

9 A circuit is required to demonstrate that the resistance of a thermistor decreases when its temperature rises. Draw a circuit diagram that could be used containing a battery, a lamp and a thermistor.

Revision checklist

After studying Topic 4.3 you should know and understand:
✔ how to connect simple series and parallel circuits
✔ that the current in a series circuit is the same everywhere in the circuit and that for a parallel circuit, the sum of the currents into a junction is equal to the sum of the currents that leave the junction
✔ the effect on p.d. of a change in the resistance of a conductor
✔ the advantages of having lamps connected in parallel in lighting circuits.

After studying Topic 4.3 you should be able to:
✔ use the equations for resistors in series, and for two resistors in parallel
✔ calculate current, p.d. and resistance in series and parallel circuits
✔ calculate p.d. in potential divider circuits
✔ recognise and draw symbols for a variety of components in electric circuits and be able to draw and interpret circuit diagrams incorporating those components, and explain their behaviours in a circuit.

Exam-style questions

1 Three voltmeters are connected as in Figure 4.3.25.
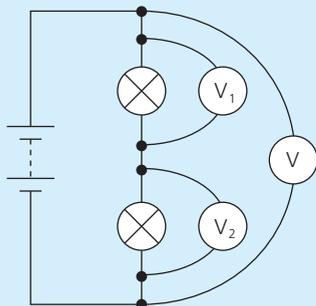
▲ **Figure 4.3.25**

What are the voltmeter readings x, y and z in the table below (which were obtained with three different batteries)?

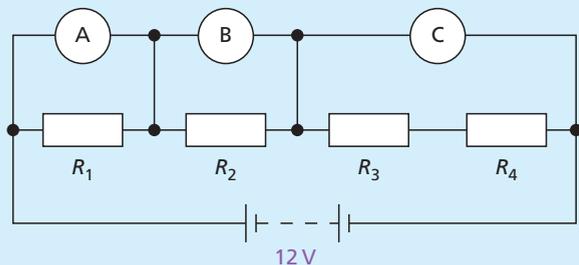| V/V	V_1/V	V_2/V
x	12	6
6	4	y
12	z	4

x [2]

y [2]

z [2]

[Total: 6]

2 The resistors R_1, R_2, R_3 and R_4 in Figure 4.3.26 are all equal in value.
What would you expect each of the voltmeters A, B and C to read, assuming that the connecting wires in the circuit have negligible resistance?
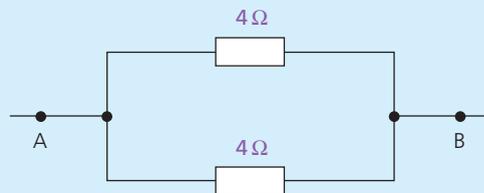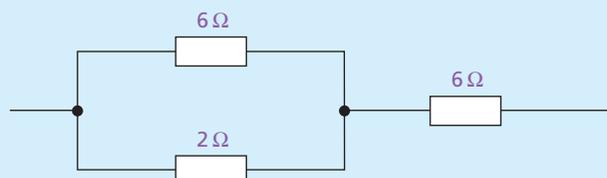
A [4]

B [2]

C [2]

▲ **Figure 4.3.26**

[Total: 8]

3 a Calculate the effective resistance between A and B in Figure 4.3.27. [4]

▲ **Figure 4.3.27**

b Figure 4.3.28 shows three resistors. Calculate their combined resistance in ohms. [6]

▲ **Figure 4.3.28**

[Total: 10]

4 a Resistors of value $6\,\Omega$, $7\,\Omega$ and $8\,\Omega$ are connected in series.
  i Calculate the combined resistance of the resistors. [2]
  ii The resistance of one of the resistors increases. If the current through the combination must remain unchanged does the supply voltage need to be increased or decreased? [1]

b Give two advantages of connecting lamps in parallel. [4]

c Two resistors of the same size are connected in parallel. Is the resistance of the combination greater or less than that of one of the resistors? [1]
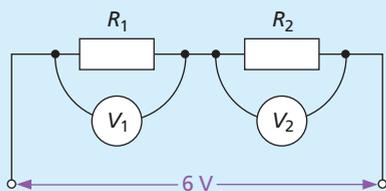
[Total: 8]

5 What are the readings V_1 and V_2 on the high-resistance voltmeters in the potential divider circuit of Figure 4.3.29 if

a $R_1 = R_2 = 10\,\text{k}\Omega$ [2]

b $R_1 = 10\,\text{k}\Omega$, $R_2 = 50\,\text{k}\Omega$ [4]

c $R_1 = 20\,\text{k}\Omega$, $R_2 = 10\,\text{k}\Omega$? [4]

▲ **Figure 4.3.29**

[Total: 10]

6 A battery of 12 V is connected across a light-dependent resistor (LDR) in series with a resistor R.

a Draw the circuit diagram. [2]

b The value of the resistor R is $20\,\Omega$ and the resistance of the LDR is $28\,\Omega$. Calculate

  i the value of the current in the circuit [2]

  ii the p.d. across the resistor [2]

  iii the p.d. across the LDR. [2]

c The intensity of the light falling on the LDR increases. State what happens to

  i the resistance of the LDR [1]

  ii the current in the circuit [1]
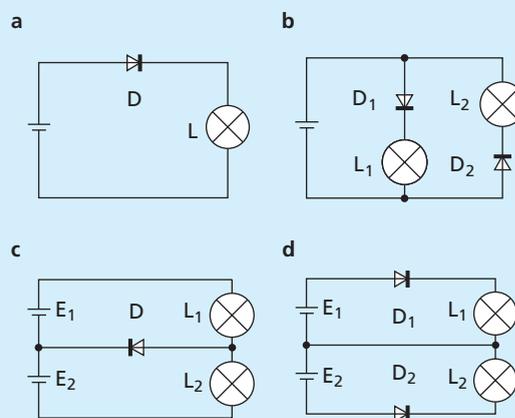
  iii the p.d. across R. [1]

[Total: 11]

7 Figure 4.3.30a shows a lamp, a semiconductor diode and a cell connected in series. The lamp lights when the diode is connected in this direction. Say what happens to each of the lamps in **b**, **c** and **d**. Give reasons for your answers.

b [3]

c [4]

d [3]

▲ **Figure 4.3.30**

[Total: 10]

4.4 Practical electricity

FOCUS POINTS

★ State some common uses of electricity, from heating and lighting to battery charging, powering motors and electronic systems.
★ State various potential hazards when using a mains supply.
★ Know the three wires that make up a mains circuit and where switches should be placed to enable the mains supply to be switched off safely.
★ Understand how trip switches and fuses work and choose appropriate settings and values for each.
★ Know that electrical appliances are made safer by having the outer casing non-conducting or earthed.

In the twenty-first century we would be lost without all the benefits electricity supplies bring us. Because electric circuits transfer substantial amounts of energy, use of the mains supply requires caution and electrical safety is important. You will learn that overheated wires and damaged insulation pose fire risks. Damp or wet conditions increase the risk of electric shock from faulty wiring in appliances since water reduces the electrical resistance of a person's skin. If too many appliances are connected to a circuit, the current flowing in the circuit increases and can cause cables to overheat. To prevent problems, devices such as fuses and trip switches (circuit breakers) are installed to break the circuit before the safe current level is exceeded. Safety features incorporated into appliances include double insulation and earthing of metal casing via the mains plug.

Electric lighting

LED lights

LEDs (Topic 4.3) are increasingly being used in the lighting of our homes. These semiconductor devices are 40–50% efficient in transferring the energy carried by an electrical current to light. The efficiency of the filament lamps used in the past was only about 10%.

Fluorescent lamps

Fluorescent strip lamps (Figure 4.4.1a) are long lasting and efficient. When one is switched on, the mercury vapour emits invisible ultraviolet radiation which makes the powder on the inside of the tube fluoresce (glow), i.e. visible light is emitted. Different powders give different colours.

Compact energy-saving fluorescent lamps (Figure 4.4.1b) are available to fit straight into normal light sockets.
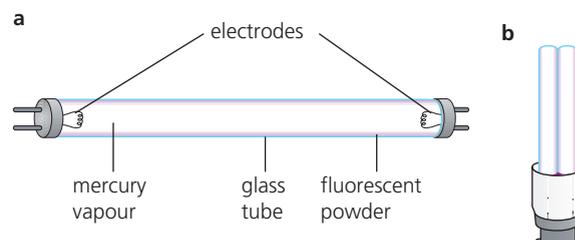
▲ **Figure 4.4.1** Fluorescent lamps

Electric heating

Heating elements

In domestic appliances such as electric fires, cookers, kettles and irons the 'elements' (Figure 4.4.2) are made from Nichrome wire. This is an alloy of nickel and chromium which does not oxidise (and so become brittle) when the current makes it red hot.

The elements in **radiant** electric fires are at red heat (about 900°C) and the radiation they emit is directed into the room by polished reflectors. In **convector** types the element is below red heat (about 450°C) and is designed to warm air which

is drawn through the heater by natural or forced convection. In **storage heaters** the elements heat fire-clay bricks during the night using 'off-peak' electricity. On the following day these cool down, giving off the stored heat to warm the room.
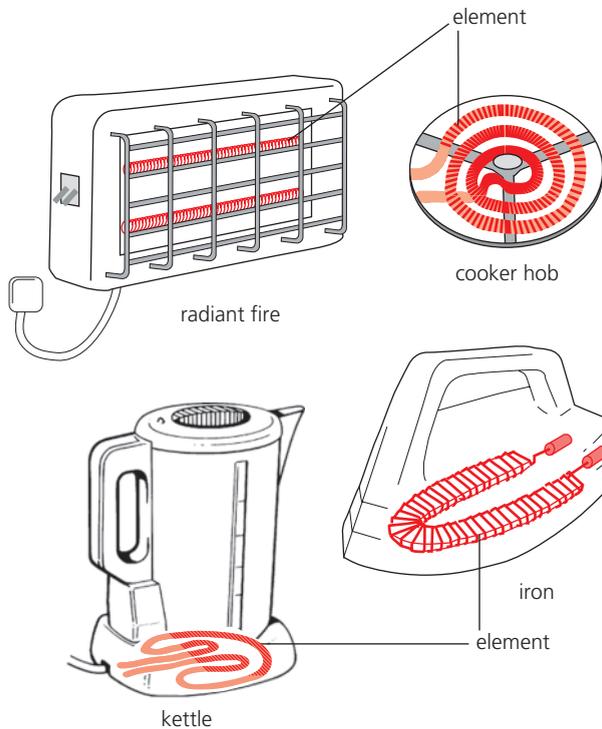
▲ **Figure 4.4.2** Heating elements

Battery chargers

A battery charger transfers energy to a secondary cell (or rechargeable battery) by forcing an electric current to flow in the opposite direction to the normal current flow from the cell.

Some rechargeable batteries, such as those used for an electric car, require a fast rate of charging (large current); others, such as the batteries used for electric lawn mowers or mobile phones, use a slower rate. A battery charger should be switched off after charging batteries that can be damaged by overcharging; the life of a battery can be prolonged if the correct charging method is used.

As well as mains-operated battery chargers, the p.d. from solar cells can be used directly to charge a battery. A smart battery charger can adjust its rate of charging according to the state of charge of the battery; this is useful for making cost-effective use of energy supplies, for example from a rooftop solar system.

Powering motors

Electric motors are found in many electrical appliances, from sewing machines and vacuum cleaners to electric cars and trains. An electric motor transfers the energy carried by an electric current to kinetic energy. The action of a d.c. electric motor is explained fully in Topic 4.5.5. The power (P) required by a motor is given by $P = IV$ and is measured in watts (W) (see Topic 4.2.5).

The power needed for the motor in an electric car is around 100 kW; for a DVD player only about 20 W are required.
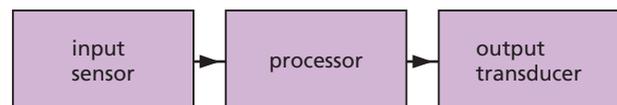
Electronic systems

The use of electronics in our homes, factories, offices, banks and hospitals is growing all the time. The development of semiconductor devices such as integrated circuits has given us, among other things, computers, programmable control devices, robots, home entertainment systems, digital cameras and heart pacemakers. Electric circuits enable electrical signals to be processed.

▲ **Figure 4.4.3 Heart pacemaker**

An electronic system can be considered to consist of three main parts: an input sensor, a processor and a device called an output transducer as shown in Figure 4.4.4.

▲ **Figure 4.4.4 Electronic system**

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The input sensor detects changes in the environment and transfers energy from its present form to an electric current. Input sensors include LDRs (light-dependent resistors) and thermistors (see Topic 4.3.3), and also microphones and pressure switches.

The processor decides on what action to perform on the electrical signal it receives from the input sensor. It may involve an operation such as counting, amplifying, timing or storing.

The output device transfers the energy carried by the electric current in the processor to the environment. These devices include lamps, LEDs (light-emitting diodes) loudspeakers, motors, heaters, relays and oscilloscopes.

In a radio, the input sensor is the aerial that sends an electrical signal to processors in the radio. One of the functions of the processors is to amplify the signal so that a loudspeaker can produce sound waves.

Dangers of electricity

There are a number of **hazards associated with using the mains electricity supply**.

> **Key definition**
>
> **Hazards associated with using mains electricity supply** include damaged insulation, overheated cables, damp conditions, excess current from overloaded plugs, extension leads, single and multiple sockets

Electric shock

Electric shock occurs if current flows from an electric circuit through a person's body to earth. This can happen if there is *damaged insulation* or *faulty wiring*. The typical resistance of dry skin is about $10\,000\,\Omega$, so if a person touches a wire carrying electricity at $240\,V$, an estimate of the current flowing through them to earth would be $I = V/R = 240/10\,000 = 0.024\,A = 24\,mA$. For wet skin, the resistance is lowered to about $1000\,\Omega$ (since water is a good conductor of electricity) so the current would increase to around $240\,mA$; a lethal current.

It is the *size of the current* (not the voltage) and the *length of time* for which it acts which determine the strength of an electric shock. The path the current takes influences the effect of the shock; some parts of the body are more vulnerable than others. A current of $100\,mA$ through the heart is likely to be fatal.

Damp conditions increase the severity of an electric shock because water lowers the resistance of the path to earth; wearing shoes with insulating rubber soles or standing on a dry insulating floor increases the resistance between a person and earth and will reduce the severity of an electric shock.

To avoid the risk of getting an electric shock:
(i) switch off the electrical supply to an appliance before starting repairs
(ii) use plugs that have an earth pin and a cord grip; a rubber or plastic case is preferred
(iii) do not allow appliances or cables to come into contact with water, for example holding a hairdryer with wet hands in a bathroom can be dangerous; keep electrical appliances well away from baths and swimming pools
(iv) do not have long cables trailing across a room, under a carpet that is walked over regularly or in other situations where the insulation can become damaged. Take particular care when using electrical cutting devices (such as hedge cutters) not to cut the supply cable.

In case of an electric shock, take the following actions.
1 *Switch off the supply* if the shocked person is still touching the equipment.
2 *Send for qualified medical assistance.*
3 *If breathing or heartbeat has stopped, start CPR* (cardiopulmonary resuscitation) by applying chest compressions at the rate of about 100 a minute until there are signs of chest movement or medical assistance arrives.

Fire risks

If flammable material is placed too close to a hot appliance such as an electric heater, it may catch fire. Similarly, if the electrical wiring in the walls of a house becomes overheated, a fire may start. Wires become hot when they carry electrical currents – the larger the current carried, the hotter a particular wire will become.

To reduce the risk of fire through *overheated cables*, the maximum current in a circuit should be limited by taking the following precautions.
(i) Use the correct fuse in an appliance or plug (see p. 226).

(ii) Do not attach too many appliances to a circuit via extension leads or single and multiple sockets.

(iii) Do not overload circuits by using too many adapters.

(iv) Appliances such as heaters use large amounts of power (and hence current), so do not connect them to a lighting circuit designed for low current use. (Thick wires have a lower resistance than thin wires so are used in circuits expected to carry high currents.)
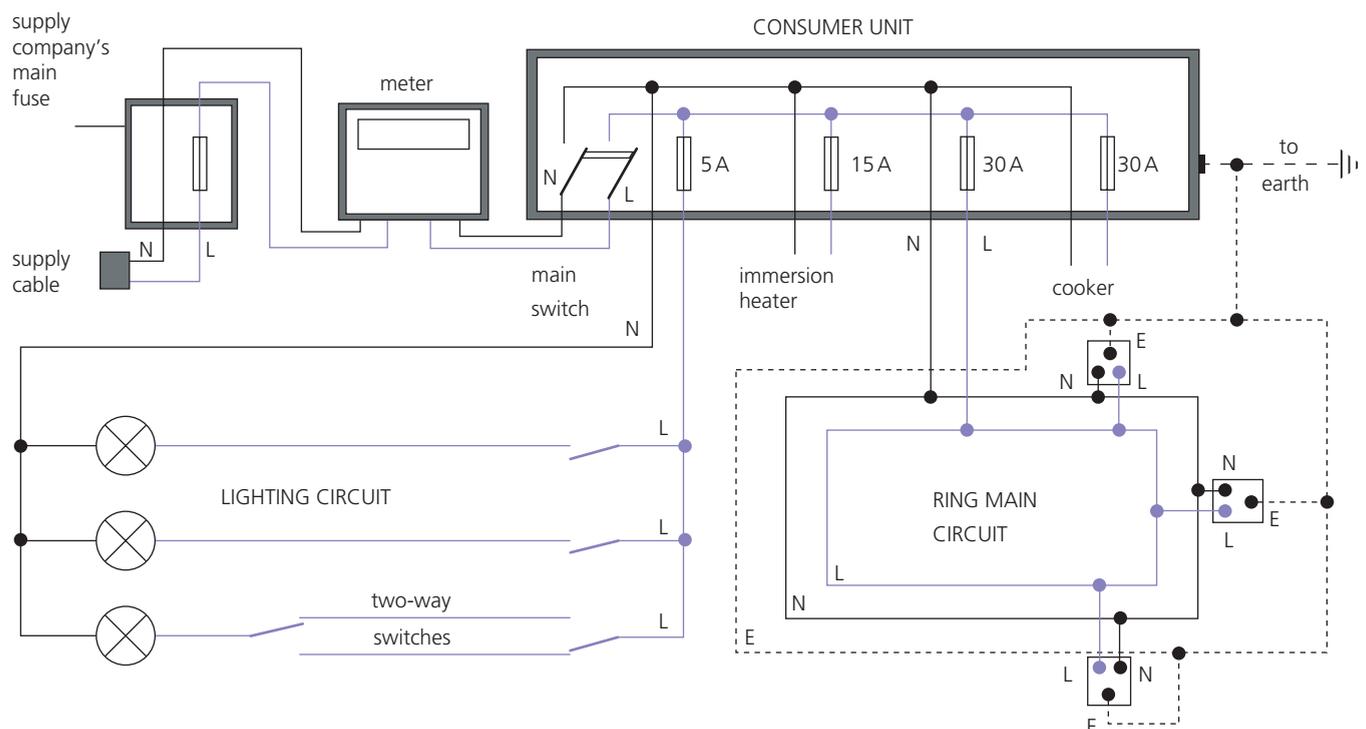
Damaged insulation or faulty wiring which leads to a large current flowing to earth through flammable material can also start a fire.

The factors leading to fire or electric shock can be summarised as follows:

damaged insulation	→ electric shock and fire risk
overheated cables	→ fire risk
damp conditions	→ increased severity of electric shocks
overloading – plugs, extension leads or sockets	→ fire risk and electric shock

House circuits

Electricity usually comes to our homes by an underground cable containing two wires, the **live** (L) and the **neutral** (N). The neutral is earthed at the local sub-station and so there is no p.d. between it and earth. A third wire, the *earth* (E) also connects the top socket on the power points in the home to earth. The supply in many countries is a.c. (Topic 4.2) and the live wire is alternately positive and negative. Study the typical house circuits shown in Figure 4.4.5.

Circuits in parallel

Every circuit is connected in parallel with the supply, i.e. across the live and neutral, and receives the full mains p.d. (for example 230 V).

The advantages of having appliances connected in parallel, rather than in series, can be seen by studying the lighting circuit in Figure 4.4.5.

(i) The p.d. across each lamp is fixed (at the mains p.d.), so the lamp shines with the same brightness irrespective of how many other lamps are switched on.

(ii) Each lamp can be turned on and off independently; if one lamp fails, the others can still be operated.

In a staircase circuit, the light is controlled from two places by the two two-way switches.

▲ **Figure 4.4.5** Electric circuits in a house

Switches

Switches and fuses are always in the live wire. If they were in the neutral, light switches and power sockets would be 'live' when switches were 'off' or fuses 'blown' or melted (see below). A fatal shock could then be obtained by, for example, touching the element of an electric fire when it was switched off.

Ring main circuit

The live and neutral wires each run in two complete rings round the house and the power sockets, each rated at 13 A, are tapped off from them. Thinner wires can be used since the current to each socket flows by two paths, i.e. from both directions in the ring. The ring has a 30 A fuse and if it has, say, ten sockets, then all can be used so long as the total current does not exceed 30 A, otherwise the wires overheat. A house may have several ring circuits, each serving a different area.

Fuses

A **fuse** protects a circuit; it is always placed in the live wire. It is a short length of wire of material with a low melting temperature, often 'tinned copper', which melts and breaks the circuit when the current in it exceeds a certain value. Two reasons for excessive currents are 'short circuits' due to worn insulation on connecting wires and overloaded circuits. Without a fuse the wiring would become hot in these cases and could cause a fire. *A fuse should ensure that the current-carrying capacity of the wiring is not exceeded.* In general, the thicker a cable is, the more current it can carry, but each size has a limit.

Two types of fuse are shown in Figure 4.4.6. *Always switch off before replacing a fuse,* and always replace with one of the same value as recommended by the manufacturer of the appliance. A 3 A (red) fuse will be needed for appliances with powers up to 720 W, or 13 A (brown) for those between 720 W and 3 kW.
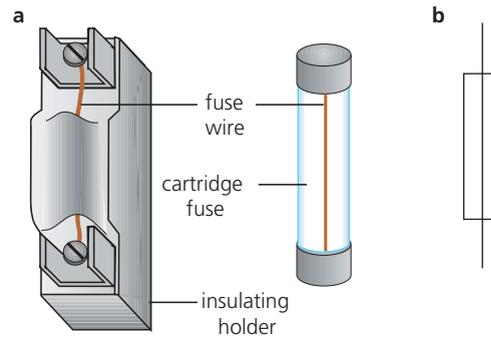
▲ **Figure 4.4.6 a** Two types of fuse; **b** the circuit symbol for a fuse

Typical power ratings for various appliances are shown in Table 4.2.1, p. 204. Calculation of the current in a device allows the correct size of fuse to be chosen.

Trip switches (circuit breakers)

Trip switches (also known as **circuit breakers**) (Figure 4.4.7) are now used instead of fuses in consumer units. They contain an electromagnet (Topic 4.1) which, when the current exceeds the rated value of the circuit breaker, becomes strong enough to separate a pair of contacts and break the circuit Like fuses, circuit breakers are always placed in the live wire.

In the design shown in Figure 4.4.7, when the current is large enough in an electromagnet, an adjacent iron bolt is attracted far enough for a plunger to be released, which allows a push switch to open and contact to the rest of the circuit to be broken.

Circuit breakers operate much faster than fuses and have the advantage that they can be reset by pressing a button. As for a fuse, the trip switch setting should be chosen to be a little higher than the value of the current in the device being protected.

▲ **Figure 4.4.7** Circuit breakers

The *residual current circuit breaker* (RCCB), also called a residual current device (RCD), is an adapted circuit breaker which is used when the resistance of the earth path between the consumer and the substation is not small enough for a fault-current to blow the fuse or trip the circuit breaker. It works by detecting any difference between the currents in the live and neutral wires; when these become unequal due to an earth fault (i.e. some of the current returns to the substation via the case of the appliance and earth) it breaks the circuit before there is any danger. They have high sensitivity and a quick response.

An RCD should be plugged into a socket supplying power to a portable appliance such as an electric lawnmower or hedge trimmer. In these cases, the risk of electrocution is greater because the user is generally making a good earth connection through their feet.

? Worked example

An electric heater has a power rating of 2 kW.

a If the supply voltage is 240 V, calculate the current in the heater.

Power $P = IV$

Rearrange the equation to give

$$I = \frac{P}{V} = \frac{2000\,\text{W}}{240\,\text{V}} = 8.3\,\text{A}$$

b Should a 3 A or 13 A fuse or trip switch setting be chosen to protect the heater?

The fuse/trip switch setting should have a higher rating than the current in the heater, so a 13 A fuse/trip switch setting should be chosen.

Now put this into practice

1 An electric heater has a power rating of 1.5 kW.
   a If the supply voltage is 240 V, calculate the current in the heater.
   b Should a 3 A, 13 A or 30 A fuse be used to protect the heater?

2 A television has a power rating of 100 W.
   a If the supply voltage is 240 V, calculate the current in the television.
   b Should a 3 A, 13 A or 30 A fuse be chosen to protect the television?

3 An electric cooker has a power rating of 6.4 kW.
   a If the supply voltage is 240 V, calculate the current in the cooker.
   b Should a 3 A, 13 A or 30 A trip switch setting be chosen to protect the oven?

Earthing

A ring main has a third wire which goes to the top socket on all power points and is earthed by being connected either to a *metal* water pipe entering the house or to an earth connection on the supply cable. This third wire is a safety precaution to prevent electric shock should an appliance develop a fault.

The earth pin on a three-pin plug is connected to the metal case of the appliance which is thus joined to earth by a path of almost zero resistance. If then, for example, the element of an electric fire breaks or sags and touches the case, a large current flows to earth and 'blows' the fuse. Otherwise the case would become 'live' and anyone touching it would receive a shock which might be fatal, especially if they were 'earthed' by, say, standing in a damp environment, such as on a wet concrete floor.

Double insulation

Appliances such as vacuum cleaners, hairdryers and food mixers are usually double insulated. Connection to the supply is by a two-core insulated cable, with no earth wire, and the appliance is enclosed in a *non-conducting* plastic case. Any metal attachments that the user might touch are fitted into this case so that they do not make a direct connection with the internal electrical parts, such as a motor. There is then no risk of a shock should a fault develop.

Test yourself

1 The largest number of 100 W lamps connected in parallel which can safely be run from a 230 V supply with a 5 A fuse is

   A 2   **B** 5   **C** 11   **D** 12

2 What is the maximum power in kilowatts of the appliance(s) that can be connected safely to a 13 A 230 V mains socket?

3 a To what part of an appliance is the earth pin on a three-pin plug attached?

   b How can a two-pin appliance be designed to reduce the risk of the user receiving an electric shock if a fault develops?

Revision checklist

After studying Topic 4.4 you should know and understand
✔ why switches, fuses and circuit breakers are wired into the live wire in house circuits
✔ the benefits of earthing metal cases and double insulation.

After studying Topic 4.4 you should be able to:
✔ recall the hazards of damaged insulation, damp conditions, overheated cables and excess current from overloaded circuits
✔ state the function of a fuse and choose the appropriate fuse rating for an appliance; explain the use, choice and operation of a trip switch.

Exam-style questions

1 There are hazards in using the mains electricity supply.
   a Identify two factors which can increase the risk of fire in circuits connected to the mains supply. [2]
   b Identify two factors which can increase the risk of electric shock. [2]
   c Describe the steps you would take before replacing a blown fuse in an appliance. [3]
   d Explain why an electrical appliance is double insulated or the outer casing is earthed. [3]
   [Total: 10]

2 Fuses are widely used in electrical circuits connected to the mains supply.
   a Explain the function of a fuse in a circuit. [2]
   b The circuits of Figures 4.4.8a and b show 'short circuits' between the live (L) and neutral (N) wires. In both, the fuse has blown but whereas circuit a is now safe, b is still dangerous even though the lamp is out which suggests the circuit is safe. Explain. [4]
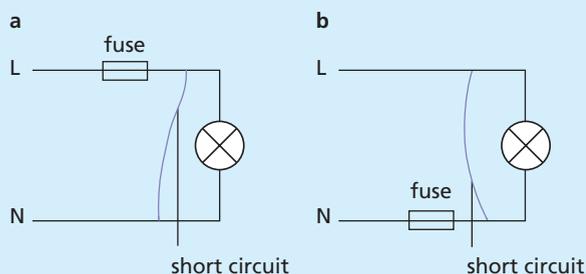
▲ Figure 4.4.8   [Total: 6]

3 a A child whose hands are damp touches a wire carrying electricity at 240 V. The resistance of the child's skin between hand and earth is 800 Ω.
   i Calculate the current which would flow through the child. [2]
   ii State whether the current you calculated in i is likely to be lethal. [1]
   iii State how the current could be reduced. [2]
   b Work out the size of fuse (3 A or 13 A) which should be used in the following appliances if the supply is 230 V:
   i a 150 W television [2]
   ii a 900 W iron [2]
   iii a 2 kW kettle. [2]
   [Total: 11]

4.5 Electromagnetic effects

4.5.1 Electromagnetic induction

> **FOCUS POINTS**
> ★ Know that an electromotive force (e.m.f.) is induced in a conductor when it moves across a magnetic field or a changing magnetic field links with the conductor.
> ★ Describe how electromagnetic induction can be demonstrated and state the factors which affect the size of an induced e.m.f.
> ★ Know that the direction of an induced e.m.f. is such as to oppose the change causing it.
> ★ Determine the relative directions of force, field and induced current.

Electricity and magnetism are closely linked. You will learn that an electrical conductor moving through a magnetic field can induce a current. Similarly, an electrical conductor in a changing magnetic field acquires an electromotive force (e.m.f.). You will find out about the factors which determine the size of the induced e.m.f. Electromagnetic induction plays an important role in many electrical applications from induction cookers and motors to electricity generators.

The effect of producing electricity from magnetism was discovered in 1831 by Faraday and is called **electromagnetic induction**. It led to the construction of generators for producing electrical energy in power stations.

Electromagnetic induction experiments

Two ways of investigating electromagnetic induction follow.

Straight wire and U-shaped magnet

First the wire is held at rest between the poles of the magnet. It is then moved in each of the six directions shown in Figure 4.5.1 and the meter observed. Only *when it is moving upwards* (direction 1) or *downwards* (direction 2) is there a deflection on the meter, indicating an induced current in the wire. The deflection is in opposite directions in these two cases and only lasts while the wire is in motion.

Bar magnet and coil

The magnet is pushed into the coil, one pole first (Figure 4.5.2 overleaf), then held still inside it. It is then withdrawn. The meter shows that current
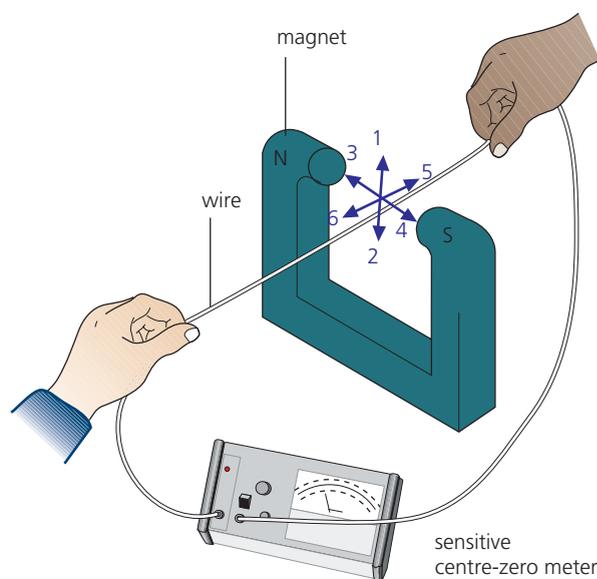
▲ **Figure 4.5.1** A current is induced in the wire when it is moved up or down between the magnet poles.

is induced in the coil in one direction as the magnet is *moved in* and in the opposite direction as it is *moved out*. There is no deflection when the magnet is at rest. The results are the same if the coil is moved instead of the magnet, i.e. only **relative motion** is needed.
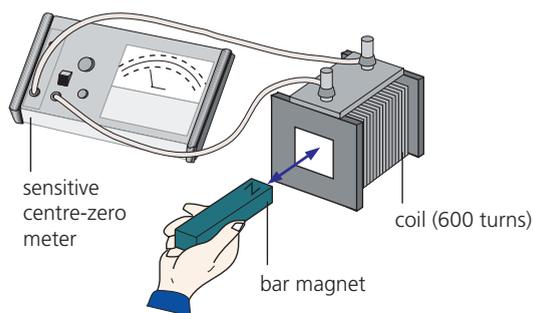
▲ **Figure 4.5.2** A current is induced in the coil when the magnet is moved in or out.

This experiment indicates that an e.m.f. is induced in a conductor when it is linked by a changing magnetic field or when it moves across a magnetic field.

Practical work

Induced currents

Connect a sensitive centre-zero meter to a 600 turn coil as shown in Figure 4.5.2.

Record the values and the direction of the current detected by the meter when you move the magnet first towards the coil and then away from the coil. Try moving the magnet faster; record your results again. Repeat the procedure by moving the coil instead of the magnet.

1   When is a current produced in the circuit?
2   How is the induced e.m.f. related to the current in the circuit?

Factors affecting the size of an induced e.m.f.

To explain electromagnetic induction Faraday suggested that an e.m.f. is induced in a conductor whenever it 'cuts' magnetic field lines, i.e. moves *across* them, but not when it moves along them or is at rest. If the conductor forms part of a complete circuit, an induced current is also produced.

Faraday identified three **factors affecting the magnitude of an induced e.m.f.** and it can be shown with apparatus like that in Figure 4.5.2, that the induced e.m.f. increases with increases of
(i) the *speed of motion* of the magnet or coil
(ii) the *number of turns* on the coil
(iii) the *strength of the magnet*.

These facts led him to state that:

The size of the induced e.m.f. is directly proportional to the rate at which the conductor cuts magnetic field lines.

> **Key definition**
> **Magnitude of an induced e.m.f.** e.m.f. increases with increases of:
> (i) the rate of change of the magnetic field or the rate of cutting of magnetic field lines
> (ii) the *number of turns* on the coil

Direction of induced e.m.f.

The direction of an induced e.m.f. opposes the change causing it.

In Figure 4.5.3a the magnet approaches the coil, north pole first. According to **Lenz's law**, the induced e.m.f. and resulting current flow should be in a direction that makes the coil behave like a magnet with its top a north pole. The downward motion of the magnet will then be opposed since like poles repel.

> **Key definition**
> **Lenz's law** the effect of the current produced by an induced e.m.f. is to oppose the change producing it

When the magnet is withdrawn, the top of the coil should become a south pole (Figure 4.5.3b) and attract the north pole of the magnet, so hindering its removal. The induced e.m.f. and current are thus in the opposite direction to that when the magnet approaches.

▲ **Figure 4.5.3** The induced current opposes the motion of the magnet.

This behaviour is an example of the principle of conservation of energy. If the currents produced a magnetic field of opposite polarity to those shown

in Figure 4.5.3 in each coil, energy would be created from nothing. As it is, work is done, by whoever moves the magnet, to overcome the forces that arise.

➡ Going further

For a straight wire moving at right angles to a magnetic field, the direction of the induced current can be found from **Fleming's right-hand rule** (the 'dynamo rule') (Figure 4.5.4).

Hold the thumb and first two fingers of the right hand at right angles to each other with the **F**irst finger pointing in the direction of the **F**ield and the thu**M**b in the direction of **M**otion of the wire, then the se**C**ond finger points in the direction of the induced **C**urrent. Note that the direction of motion represents the direction in which the force acts on the conductor.
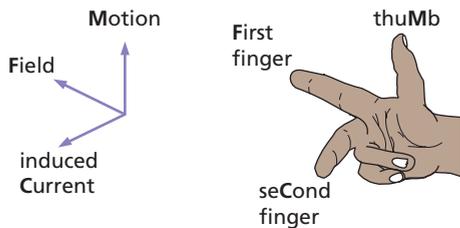
▲ **Figure 4.5.4** Fleming's right-hand (dynamo) rule

Key definition

Fleming's right-hand (dynamo) rule used to show the relative directions of force, field and induced current. When the thumb and first two fingers of the right hand are held at right angles to each other with the first finger pointing in the direction of the magnetic field and the thumb in the direction of the motion of the wire, then the second finger points in the direction of the induced current.

▶ Test yourself

1   A magnet is pushed, N pole first, into a coil as in Figure 4.5.5. Which one of the following statements **A** to **D** is *not* true?
   A   An e.m.f. is induced in the coil and causes a current through the sensitive centre-zero meter.
   B   The induced e.m.f. increases if the magnet is pushed in faster and/or the coil has more turns.
   C   Energy is transferred by an electric current.
   D   The effect produced is called electrostatic induction.
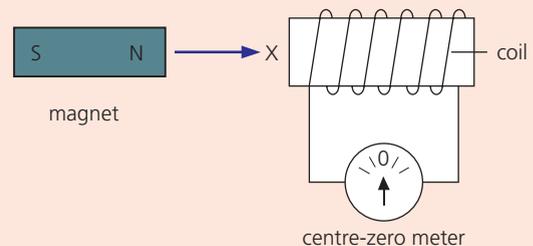
▲ **Figure 4.5.5**

2   A straight wire moves vertically upwards at right angles to a magnetic field acting horizontally from right to left. Make a sketch to represent the directions of the magnetic field, the motion of the wire and the induced current in the wire if it is connected to a complete circuit.

4.5.2 The a.c. generator

FOCUS POINTS

★   Describe the construction and action of a simple a.c. generator.
★   Sketch and interpret a graph of e.m.f against time for an a.c. generator.

When a coil is rotated between the poles of a magnet, the conductor cuts the magnetic field lines and an e.m.f. is induced. The size of the e.m.f. generated changes with the orientation of the coil and alternates in sign during the course of each rotation. This process is used in the large generators in power stations to produce an alternating (a.c.) electricity supply.
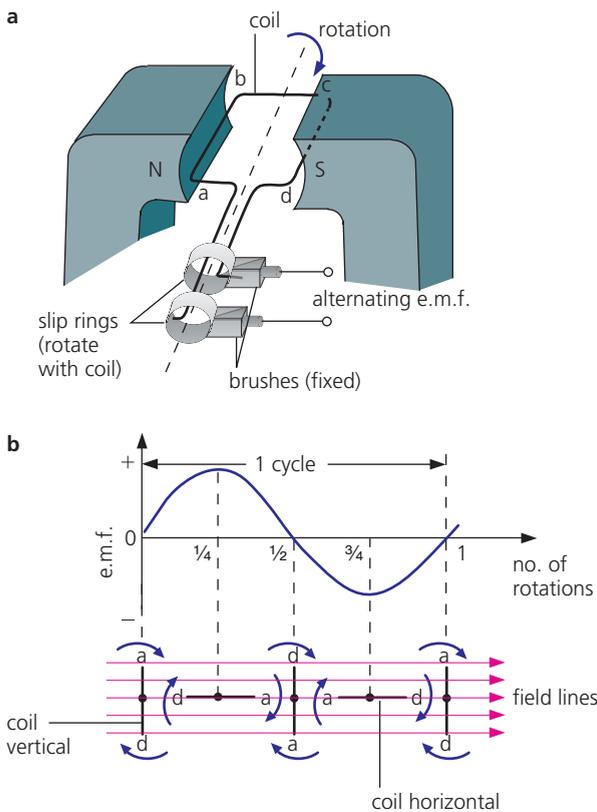
Simple a.c. generator

The simplest alternating current (a.c.) generator (**alternator**) consists of a rectangular coil between the poles of a C-shaped magnet (Figure 4.5.6a). The ends of the coil are joined to two **slip rings** on the axle and against which *carbon brushes* press.

When the coil is rotated it cuts the field lines and an e.m.f. is induced in it. Figure 4.5.6b shows how the e.m.f. varies over one complete rotation.

As the coil moves through the vertical position with **ab** uppermost, **ab** and **cd** are moving along the lines (**bc** and **da** do so always) and no cutting occurs. The induced e.m.f. is zero.

▲ **Figure 4.5.6** A simple a.c. generator and its output

During the first quarter rotation the e.m.f. increases to a maximum when the coil is horizontal. Sides **ab** and **dc** are then cutting the lines at the greatest rate.

In the second quarter rotation the e.m.f. decreases again and is zero when the coil is vertical with **dc** uppermost. After this, the direction of the e.m.f. reverses because, during the next half rotation, the motion of **ab** is directed upwards and **dc** downwards.

An alternating e.m.f. is generated which acts first in one direction and then the other; it causes a.c. to flow in a circuit connected to the brushes. The frequency of an a.c. is the number of complete cycles it makes each second and is measured in hertz (Hz), i.e. 1 cycle per second = 1 Hz. If the coil rotates twice per second, the a.c. has frequency 2 Hz. The mains supply is a.c. of frequency 50 Hz.

➡ Going further

Practical generators

In power stations several coils are wound in evenly spaced slots in a soft iron cylinder and electromagnets usually replace permanent magnets. The electromagnets rotate (the rotor, Figure 4.5.7a) while the coils and their iron core are at rest (the stator, Figure 4.5.7b). The large e.m.f. and currents (e.g. 25 kV at several thousand amps) induced in the stator are led away through stationary cables, otherwise they would quickly destroy the slip rings by sparking. Instead the relatively small power required by the rotor is fed via the slip rings from a small generator (the exciter) which is driven by the same turbine as the rotor.

▲ **Figure 4.5.7** The rotor and stator of a power station alternator

In a thermal power station (Topic 1.7), the turbine is rotated by high-pressure steam obtained by heating water in a coal- or oil-fired boiler or in a nuclear reactor (or by hot gas in a gas-fired power station). A block diagram of a thermal power station is shown in Figure 4.5.8. The Sankey diagram showing energy transfer was given in Figure 1.7.5, p. 62.
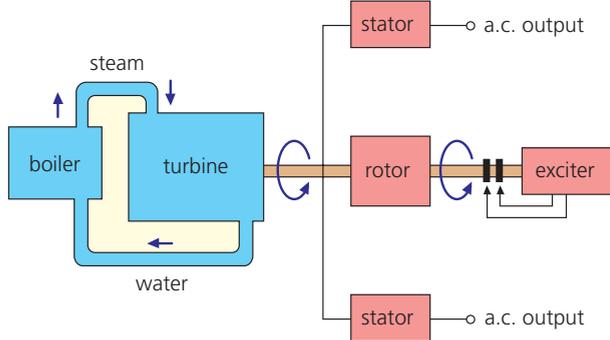
▲ **Figure 4.5.8** Block diagram of a thermal power station

4.5.3 Magnetic effect of a current

FOCUS POINTS
★ Describe the pattern and direction of the magnetic field around a current-carrying straight wire and a solenoid.
★ Use the examples of relays and loudspeakers to describe the application of the magnetic effect of a current.
★ Describe the variation of the magnetic field strength around a current-carrying straight wire and a solenoid and recall the effect on the magnetic field of changing the current's direction and size.

A further link between electricity and magnetism comes from the presence of a magnetic field around a conductor carrying a current. In this topic you will learn that the magnetic field can be concentrated by the geometry of the conductor. A long cylindrical coil (a solenoid) will act like a bar magnet when current is switched on. As you have seen in Topic 4.1, electromagnets have many applications. In this topic you can discover how they are also used in switches, relays, bells and loudspeakers.

Magnetic field lines are used to represent the variation in magnetic field strength around a current-carrying conductor and its dependence on the size and direction of the current.

Oersted's discovery

In 1819 Hans Oersted accidentally discovered the magnetic effect of an electric current. His experiment can be repeated by holding a wire over and parallel to a compass needle that is pointing N and S (Figure 4.5.9). The needle moves when the current is switched on. Reversing the current causes the needle to move in the opposite direction.

Evidently around a wire carrying a current there is a magnetic field. As with the field due to a permanent magnet, we represent the field due to a current by *field lines* or *lines of force*. Arrows on the lines show the direction of the field, i.e. the direction in which a N pole points.

Different field patterns are given by differently shaped conductors.
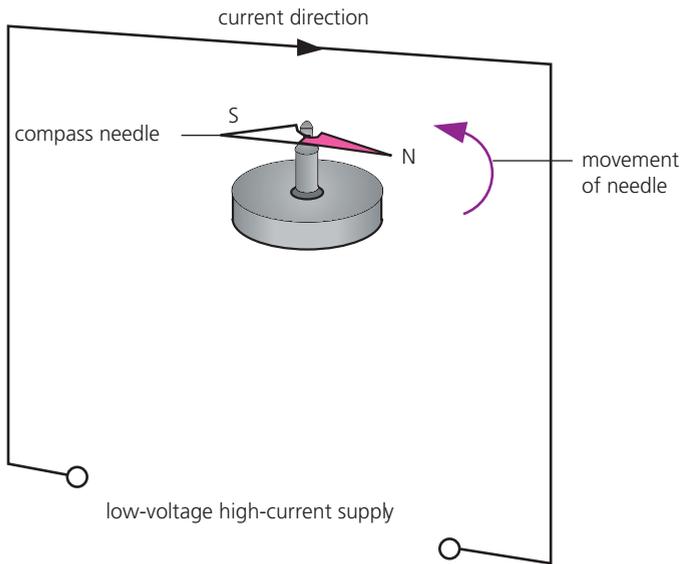
▲ **Figure 4.5.9** An electric current produces a magnetic effect.

Field due to a straight wire

If a straight vertical wire passes through the centre of a piece of card held horizontally and there is a current in the wire (Figure 4.5.10), iron filings sprinkled on the card settle in concentric circles when the card is gently tapped.
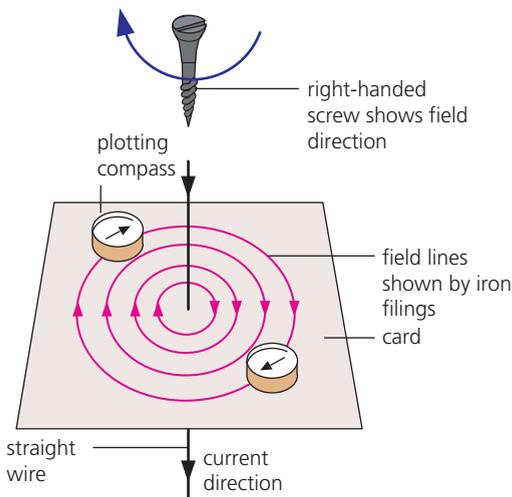
▲ **Figure 4.5.10** Field due to a straight wire

Plotting compasses placed on the card settle along the field lines and show the direction of the field at different points. When the current direction is reversed, the compasses point in the opposite direction showing that the direction of the field reverses when the current reverses.

If the current direction is known, the direction of the field can be predicted by the **right-hand screw rule**:

> If a right-handed screw moves forwards in the direction of the current (conventional), the direction of rotation of the screw gives the direction of the magnetic field.

Field due to a circular coil

The field pattern is shown in Figure 4.5.11. At the centre of the coil the field lines are straight and at right angles to the plane of the coil. The right-hand screw rule again gives the direction of the field at any point.
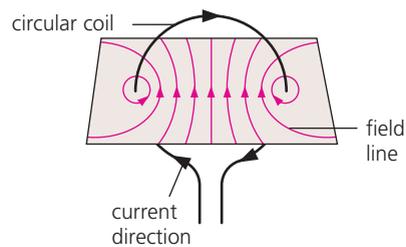

▲ **Figure 4.5.11** Field due to a circular coil

Field due to a solenoid

A **solenoid** is a long cylindrical coil. It produces a field similar to that of a bar magnet; in Figure 4.5.12a, end A behaves like a N pole and end B like a S pole. The polarity can be found as before by applying the right-hand screw rule to a short length of one turn of the solenoid. Alternatively, the **right-hand grip rule** can be used. This states that if the fingers of the right hand grip the solenoid in the direction of the current (conventional), the thumb points to the N pole (Figure 4.5.12b). Figure 4.5.12c shows how to link the end-on view of the current direction in the solenoid to the polarity. A compass could be used to plot the magnetic field lines around the solenoid (see Topic 4.1).
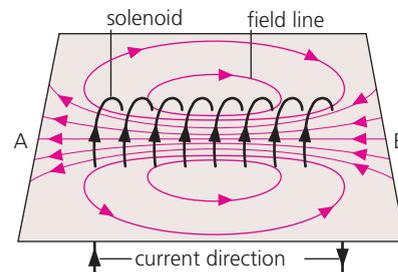
▲ **Figure 4.5.12a** Field due to a solenoid
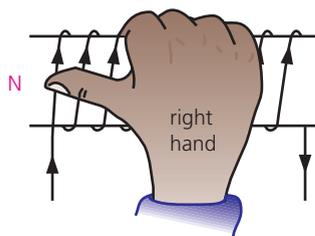
▲ **Figure 4.5.12b** The right-hand grip rule

(i) View from A   (ii) View from B
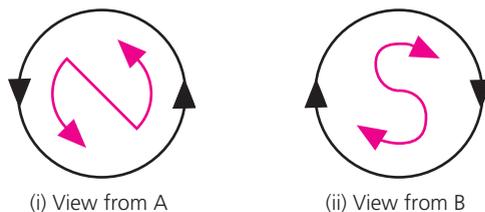
▲ **Figure 4.5.12c** End-on views

Variation of magnetic field strength

There is **variation of magnetic field strength** around a current-carrying straight wire (Figure 4.5.10) – it becomes less as the distance from the wire increases. This is shown by the magnetic field lines becoming further apart. When the current through the wire is increased, the strength of the magnetic field around the wire increases and the field lines become closer together. When the direction of the current changes, the magnetic field acts in the opposite direction.

Inside the solenoid in Figure 4.5.12a, the field lines are closer together than they are outside the solenoid. This indicates that the magnetic field is stronger inside a solenoid than outside it. When the direction of the current changes in the solenoid, the magnetic field acts in the opposite direction. The field inside a solenoid can be made very strong if it has a large number of turns or a large current. Permanent magnets can be made by allowing molten ferromagnetic metal to solidify in such fields.
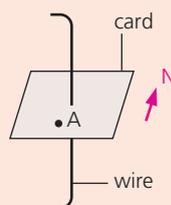
> **Key definition**
>
> **Variation of magnetic field strength** the magnetic field decreases with distance from a current-carrying wire and varies around a solenoid
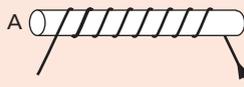
> ## Test yourself
>
> 5 The vertical wire in Figure 4.5.13 is at right angles to the card. In what direction will a plotting compass at A point when
>   a there is no current in the wire
>   b the current direction is upwards?
>
>
>
> ▲ **Figure 4.5.13**
>
> 6 Figure 4.5.14 shows a solenoid wound on a core of soft iron. Will the end A be a N pole or S pole when the current is in the direction shown?
>
>
>
> ▲ **Figure 4.5.14**
>
> 7 a State where the magnetic field is strongest in a current-carrying solenoid.
>   b Name two factors which affect the strength of a magnetic field around a current-carrying solenoid.

# Applications of the magnetic effect of a current

Relay

A **relay** is a switch based on the principle of an electromagnet. It is useful if we want one circuit to control another, especially if the current and power are larger in the second circuit. Figure 4.5.15 shows a typical relay. When a current is in the coil from the circuit connected to AB, the soft iron core is magnetised and attracts the L-shaped iron armature. This rocks on its pivot and closes the contacts at C in the circuit connected to DE. The relay is then 'energised' or 'on'.
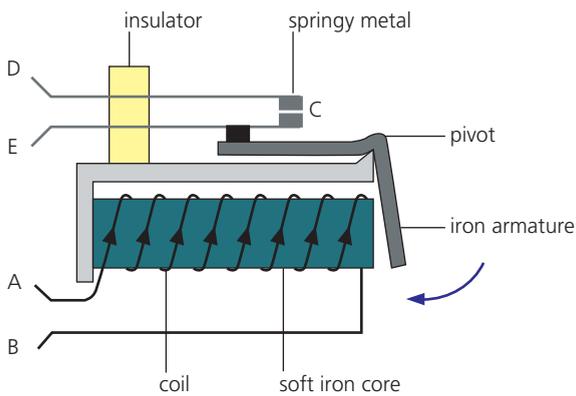
▲ **Figure 4.5.15** Relay

The current needed to operate a relay is called the *pull-on* current and the *drop-off* current is the smaller current in the coil when the relay just stops working.

If the coil resistance, R, of a relay is $185\,\Omega$ and its operating p.d. V is $12\,V$, then the pull-on current $I = V/R = 12/185 = 0.065\,A = 65\,mA$. The symbols for relays with normally open and normally closed contacts are given in Figure 4.5.16.
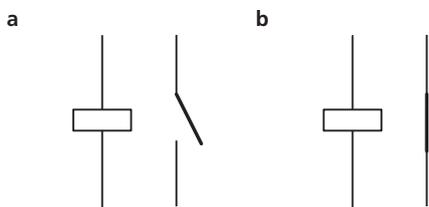

▲ **Figure 4.5.16** Symbols for a relay: **a** open; **b** closed

Loudspeaker

Varying currents from a radio, CD player, etc. pass through a short cylindrical coil whose turns are at right angles to the magnetic field of a magnet with a central pole and a surrounding ring pole (Figure 4.5.17a).

The magnetic fields around the coil and the magnet interact and the coil vibrates with the same frequency as the a.c. of the electrical signal it receives. A paper cone attached to the coil moves with it and sets up sound waves in the surrounding air (Figure 4.5.17b).
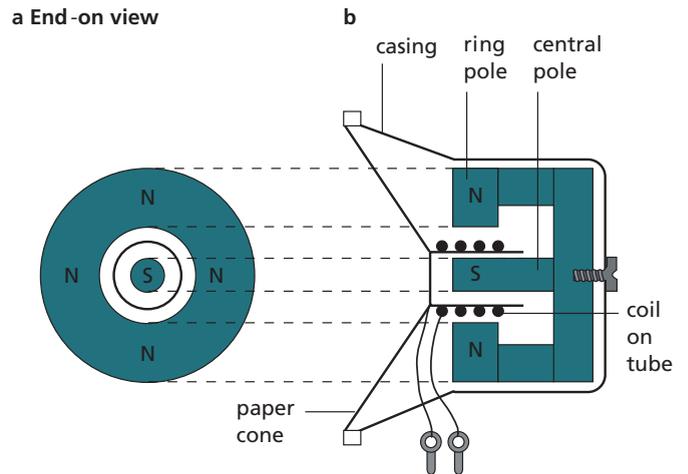
▲ **Figure 4.5.17** Moving-coil loudspeaker

> ## Test yourself
>
> 8 Explain when a relay would be used in a circuit.
> 9 The resistance, R, of the coil in a relay is $300\,\Omega$ and its operating p.d. V is $15\,V$. Calculate the pull-on current.
> 10 The pull-on current in a relay is $60\,mA$ and it operates at $12\,V$. Calculate the resistance of the coil.
> 11 Explain how an a.c. signal is converted into sound by a loudspeaker.

Going further

Electric bell

When the circuit in Figure 4.5.18 is completed, by someone pressing the bell push, current flows in the coils of the electromagnet which becomes magnetised and attracts the soft iron bar (the armature).

The hammer hits the gong but the circuit is now broken at the point C of the contact screw.

The electromagnet loses its magnetism (becomes demagnetised) and no longer attracts the armature. The springy metal strip is then able to pull the armature back, remaking contact at C and so completing the circuit again. This cycle is repeated so long as the bell push is depressed, and continuous ringing occurs.
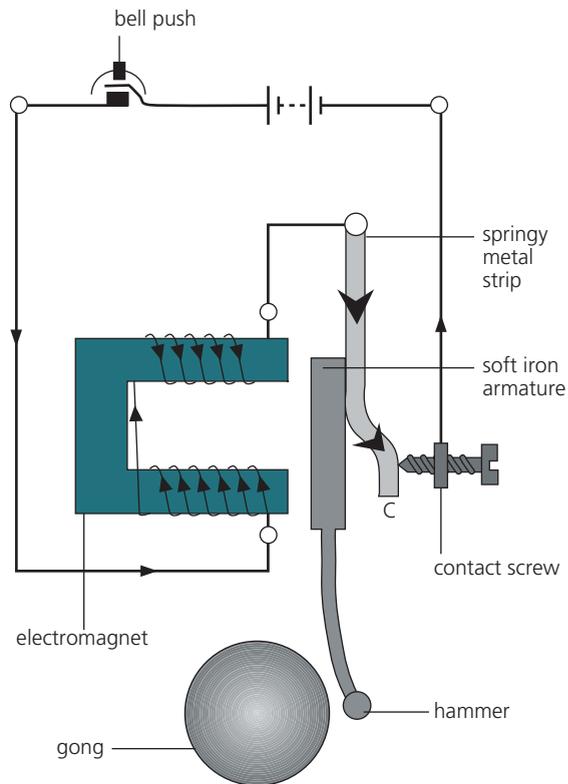
▲ **Figure 4.5.18** Electric bell

4.5.4 Force on a current-carrying conductor

FOCUS POINTS

★ Describe an experiment that demonstrates that a force acts on a conductor in a magnetic field when it carries a current.
★ Know how the directions of force, magnetic field and current relate to each other.
★ Describe the magnetic field pattern and the resultant force between two parallel current-carrying conductors.

Electric motors form the heart of many electrical devices ranging from domestic appliances such as vacuum cleaners and washing machines to electric trains and lifts. In a car, the windscreen wipers are usually driven by one and the engine is started by another. All these devices rely on the fact that a current flowing in a magnetic field experiences a force. The force will cause a current-carrying conductor to move or be deflected, and cause two parallel current-carrying wires to be attracted or repelled.

The motor effect

A wire carrying a current in a magnetic field experiences a force. If the wire can move, it does so.

Demonstration

In Figure 4.5.19, the flexible wire is loosely supported in the strong magnetic field of a C-shaped magnet (permanent or electromagnet).

When the switch is closed, current flows in the wire, which jumps upwards as shown. If either the direction of the current or the direction of the field is reversed, the wire moves downwards. *The force increases if the strength of the field increases and if the current increases.*
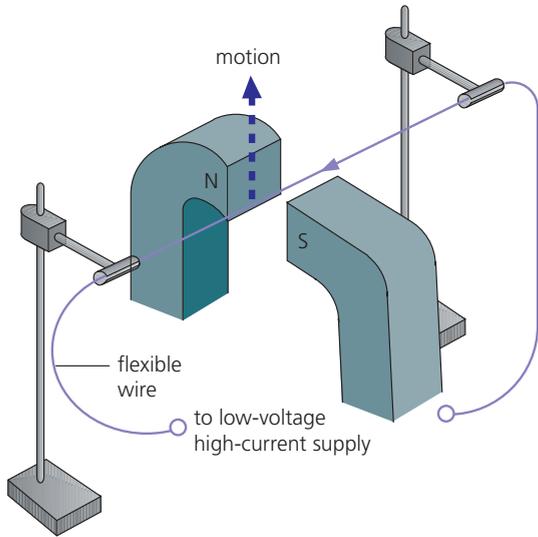

▲ **Figure 4.5.19** A wire carrying a current in a magnetic field experiences a force.

Explanation

Figure 4.5.20a is a side view of the magnetic field lines due to the wire and the magnet. Those due to the wire are circles and we will assume their direction is as shown. The dotted lines represent the field lines of the magnet and their direction is towards the right.

The resultant field obtained by combining both fields is shown in Figure 4.5.20b. There are more lines below than above the wire since both fields act in the same direction below but they are in opposition above. If we *suppose* the lines are like stretched elastic, those below will try to straighten out and in so doing will exert an upward force on the wire.
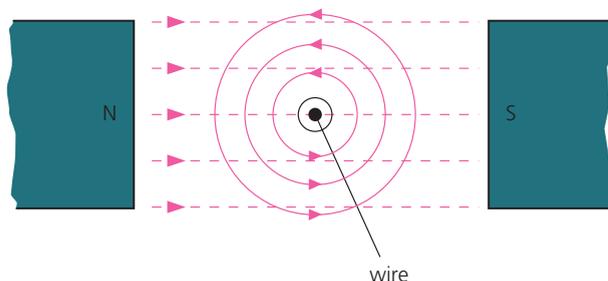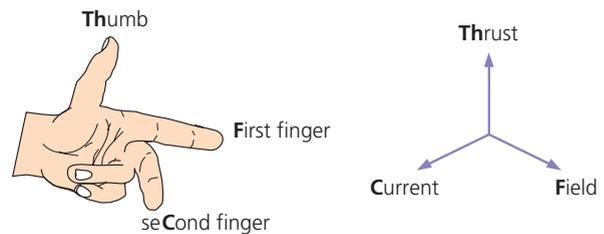

▲ **Figure 4.5.20a**
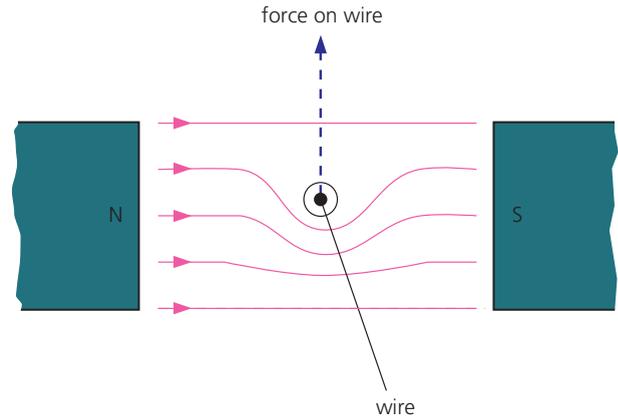
▲ **Figure 4.5.20b**

Fleming's left-hand rule

The direction of the force or thrust on the wire can be found by **Fleming's left-hand rule**, which is also called the **motor rule** (Figure 4.5.21).

Hold the thumb and first two fingers of the left hand at right angles to each other with the **F**irst finger pointing in the direction of the **F**ield and the se**C**ond finger in the direction of the **C**urrent, then the **Th**umb points in the direction of the **Th**rust (or force).

If the wire is not at right angles to the field, the force is smaller and is zero if the wire is parallel to the field.


▲ **Figure 4.5.21** Fleming's left-hand (motor) rule

Force on beams of charged particles in a magnetic field

In Figure 4.5.22 the evenly spaced crosses represent a uniform magnetic field (i.e. one of the same strength throughout the area shown) acting into and perpendicular to the paper. A beam of electrons entering the field at right angles to the field experiences a force due to the motor effect whose direction is given by Fleming's left-hand rule. This indicates that the force acts at right angles to the direction of the beam and makes it follow a *circular* path as shown. The beam of negatively charged electrons is treated as being in the opposite direction

to conventional current. A beam of positively charged particles would be deflected in the opposite direction to that shown (see Topic 5.2, p. 267).
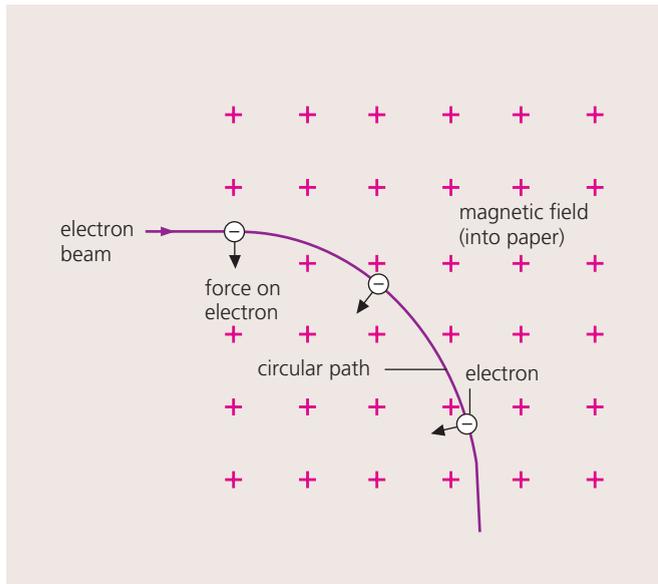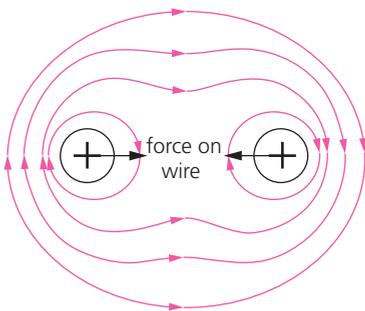

▲ **Figure 4.5.22** Path of an electron beam at right angles to a magnetic field
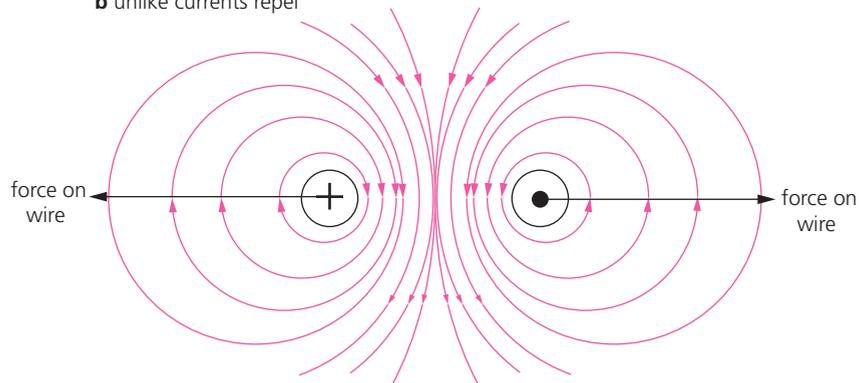
Magnetic field between two parallel current-carrying wires

When two long parallel wires are near each other and carry currents in the same direction, their magnetic fields interact to give the resultant field pattern shown in cross-section in Figure 4.5.24a; there are fewer lines between the wires (where the fields are in opposite directions) than on their outer sides (where they are in the same direction.)

As a result the wires experience equal and opposite forces towards each other. When the currents in the parallel wires are in opposite directions, their magnetic fields interact to give the resultant field pattern shown in Figure 4.5.24b; the density of field lines is now greatest between the wires and a repulsive force between the wires results. Current direction into the page is represented by + and out of the page by ●.

a like currents attract
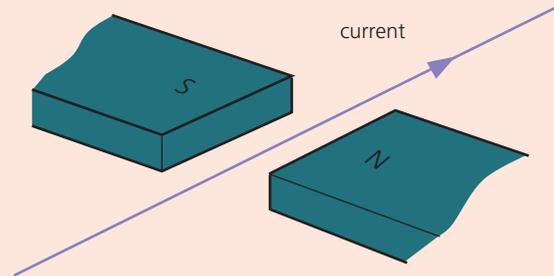
b unlike currents repel

▲ **Figure 4.5.24** Magnetic field between two parallel current-carrying wires

The direction of the force experienced by one wire due to the current in the other can be found from Fleming's left-hand rule, after using the right-hand screw rule to find the direction of the field around each wire.

In summary: like currents attract, unlike currents repel.

4.5.5 The d.c. motor

FOCUS POINTS

★ Know the factors that may increase the turning effect on a current-carrying coil in a magnetic field.
★ Describe how an electric motor works.

In the previous topic you learnt that a current flowing in a magnetic field experiences a force. The force may lead to a turning effect on a current-carrying coil in a magnetic field because of the forces acting on the two sides of the coil. The magnitude of the turning effect is increased by increasing the number of turns on the coil, increasing the current or increasing the strength of the magnetic field. This turning effect is the basis of all electric motors from electric toothbrushes to ship propulsion.

The motor effect shows that a straight current-carrying wire in a magnetic field experiences a force. If the wire is wound into a coil, forces act on both sides of the coil and a turning effect results when the coil carries current in a magnetic field.

Turning effect on a coil

A rectangular coil of wire mounted on an axle which can rotate between the poles of a magnet may experience a turning effect when a direct current (d.c.) is passed through it.
The turning effect increases if:
(i) the number of turns on the coil increases
(ii) the current flowing in the coil increases
(iii) the strength of the magnetic field increases.

The larger the turning effect on the coil, the faster it will turn.

Simple d.c. electric motor

A simple motor to work from direct current (d.c.) consists of a rectangular coil of wire mounted on an axle which can rotate between the poles of a C-shaped magnet (Figure 4.5.25).

Each end of the coil is connected to half of a split ring of copper, called a **split-ring commutator**, which rotates with the coil. Two carbon blocks, the **brushes**, are pressed lightly against the commutator by springs. The brushes are connected to an electrical supply.

If Fleming's left-hand rule is applied to the coil in the position shown, we find that side **ab** experiences

an upward force and side **cd** a downward force. (No forces act on **ad** and **bc** since they are parallel to the field.) These two forces rotate the coil in a clockwise direction until it is vertical.
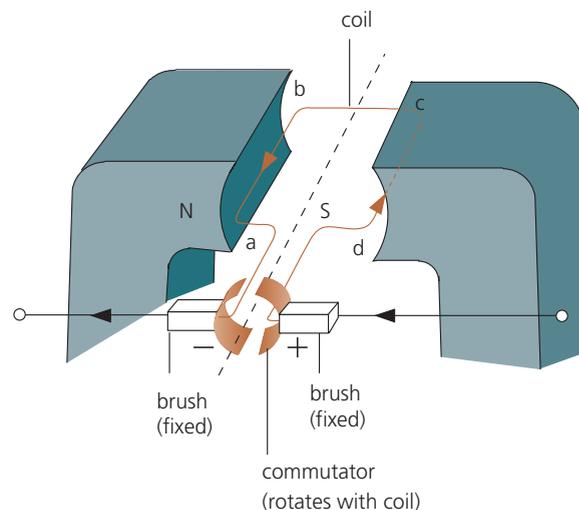

▲ **Figure 4.5.25** Simple d.c. motor

The brushes are then in line with the gaps in the commutator and the current stops. However, because of its inertia, the coil overshoots the vertical and the commutator halves change contact from one brush to the other. This reverses the current through the coil and so also the directions of the forces on its sides. Side **ab** is on the right now, acted on by a downward force, while **cd** is on the left with an upward force. The coil thus carries on rotating clockwise.

Practical motors

Practical motors have the following features:

(i) *A coil of many turns wound on a soft iron cylinder or core* which rotates with the coil. This makes it more powerful. The coil and core together are called the **armature**.

(ii) *Several coils* each in a slot in the core and each having a pair of commutator segments. This gives increased power and smoother running. The motor of an electric drill is shown in Figure 4.5.26.

(iii) *An electromagnet* (usually) to produce the field in which the armature rotates.

Most electric motors used in industry are **induction motors**. They work off a.c. (alternating current) on a different principle from the d.c. motor.
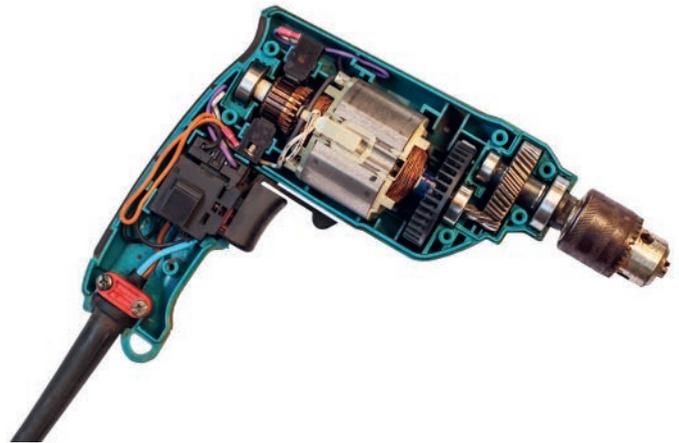
▲ **Figure 4.5.26** Motor inside an electric drill

---

Practical work

A model motor

The motor shown in Figure 4.5.27 is made from a kit.

a Wrap Sellotape round one end of the metal tube which passes through the wooden block.

b Cut two rings off a piece of narrow rubber tubing; slip them on to the taped end of the metal tube.

c Remove the insulation from one end of a 1.5-metre length of SWG 26 PVC-covered copper wire and fix it under both rubber rings so that it is held tight against the Sellotape. This forms one end of the coil.

d Wind 10 turns of the wire in the slot in the wooden block and finish off the second end of the coil by removing the PVC and fixing this too under the rings but on the opposite side of the tube from the first end. The bare ends act as the commutator.

e Push the axle through the metal tube of the wooden base so that the block spins freely.

f Arrange two 0.5 metre lengths of wire to act as brushes and leads to the supply, as shown. Adjust the brushes so that they are vertical and each touches one bare end of the coil when the plane of the coil is horizontal. *The motor will not work if this is not so.*

g Slide the base into the magnet with *opposite poles facing*. Connect to a 3 V battery (or other low-voltage d.c. supply) and a slight push of the coil should set it spinning at high speed.

3 List the variables in the construction of a simple d.c. motor.

**4** How would the motion of the coil change if you reversed the current direction?
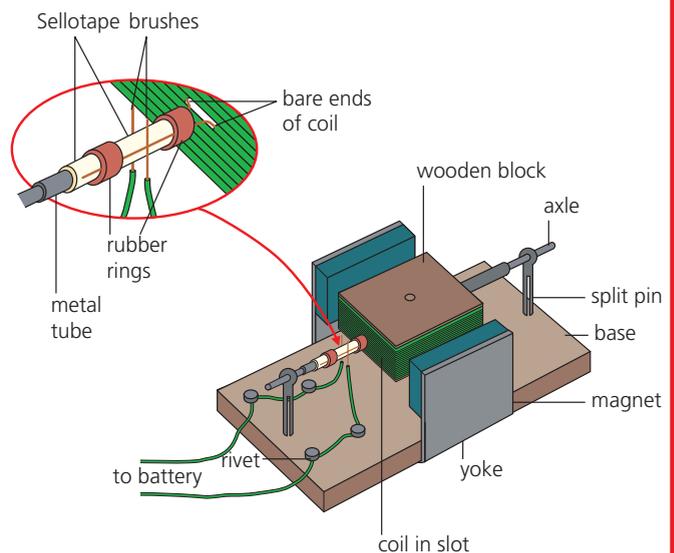

▲ **Figure 4.5.27** A model motor

➡️ **Going further**

Moving-coil galvanometer

A galvanometer detects small currents or small p.d.s, often of the order of milliamperes (mA) or millivolts (mV). In the moving-coil pointer-type meter, a coil is pivoted between the poles of a permanent magnet (Figure 4.5.28a). Current enters and leaves the coil by hair springs above and below it. When there is a current, a pair of forces act on the sides of the coil (as in an electric motor), causing it to rotate until stopped by the springs. The greater the current, the greater the deflection which is shown by a pointer attached to the coil.

a
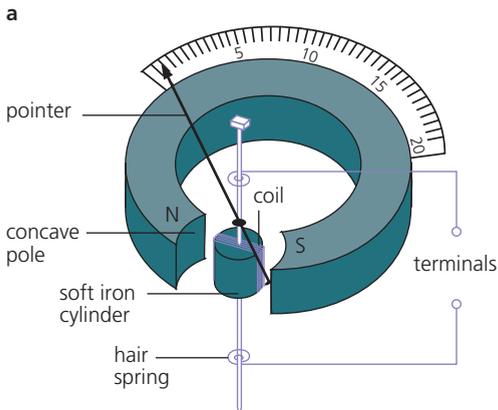
b view from above
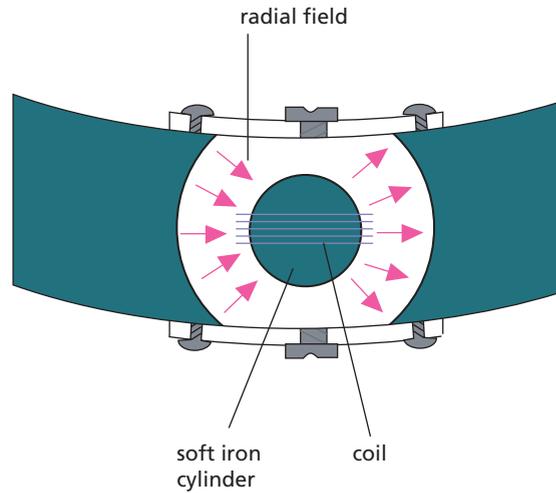
▲ **Figure 4.5.28** Moving-coil pointer-type galvanometer

The soft iron cylinder at the centre of the coil is fixed and along with the concave poles of the magnet it produces a radial field (Figure 4.5.28b), i.e. the field lines are directed to and from the centre of the cylinder. The scale on the meter is then even or linear, i.e. all divisions are the same size.

Test yourself

14 How would the turning effect on a current-carrying coil in a magnetic field change if
   a the size of the magnetic field is increased
   b the direction of the magnetic field is reversed?
15 In the simple d.c. electric motor of Figure 4.5.29, the coil rotates anticlockwise as seen by the eye from the position X when current flows in the coil. Is the current flowing clockwise or anticlockwise around the coil when viewed from above?
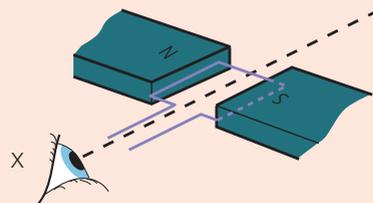
▲ **Figure 4.5.29**

16 Explain the function of the split-ring commutator and brushes in a d.c. motor.

4.5.6 The transformer

FOCUS POINTS

★ Describe the construction of a simple transformer.
★ Explain how a simple iron-cored transformer works.
★ Understand the terms primary, secondary, step-up and step-down and correctly use the transformer equation.
★ Describe how high-voltage transformers are used in the transmission of electricity and why high voltages are preferred.

Many household devices such as electronic keyboards, toys, lights and telephones require a lower voltage than is provided by the mains supply and a transformer is needed to reduce the mains voltage. When two coils lie in a magnetic field, variations in the current in one coil induce a current change in the other. In this section you will learn that this effect is used in a transformer to raise or lower alternating voltages. The voltage transformation depends on the ratio of the number of turns of wire in each coil. Alternating current generated in a power station is transformed into a very high voltage for long-distance electrical transmission. This reduces the size of the current flowing in the transmission cables and minimises the energy lost to thermal energy due to the resistance of the cables.

Transformers

A **transformer** transforms (changes) an *alternating* voltage from one value to another of greater or smaller value. It has a primary coil and a secondary coil consisting of insulation-coated wires wound on a complete soft iron core, either one on top of the other (Figure 4.5.30a) or on separate limbs of the core (Figure 4.5.30b).

a

b
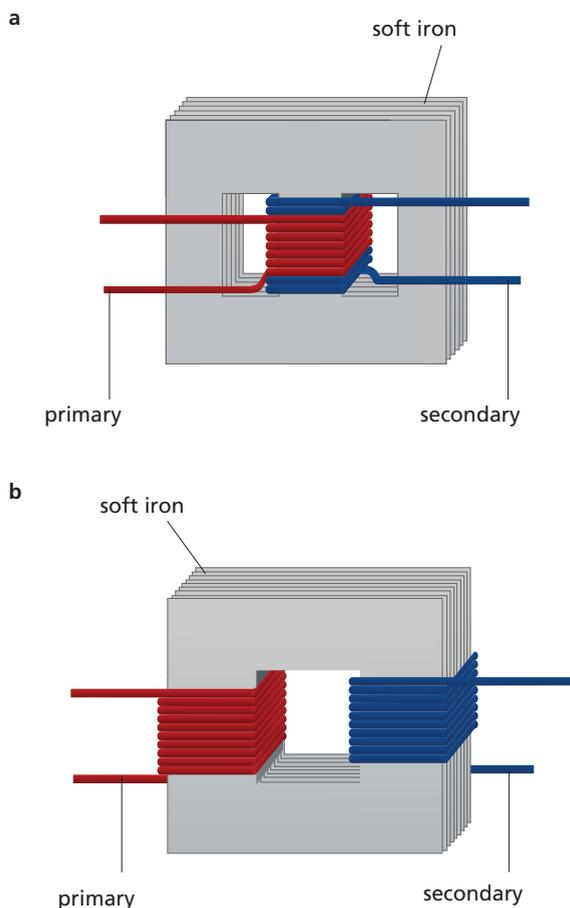
▲ **Figure 4.5.30** Primary and secondary coils of a transformer

Mutual induction

When the current in a coil is switched on or off or changed in a simple iron-cored transformer, a voltage is induced in a neighbouring coil. The effect, called **mutual induction**, is an example of electromagnetic induction and can be shown with the arrangement of Figure 4.5.31. Coil A is the *primary* and coil B the *secondary*.
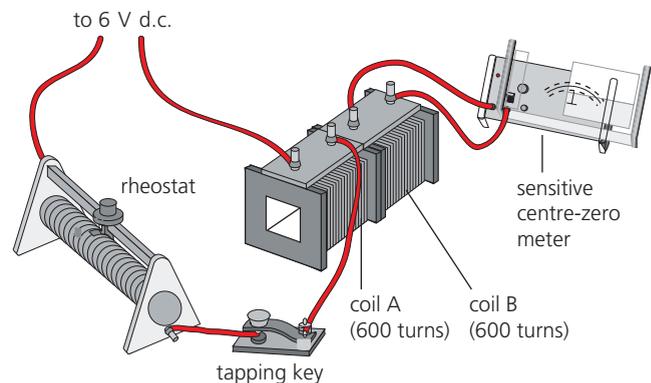
▲ **Figure 4.5.31** A changing current in a primary coil (A) induces a current in a secondary coil (B).

Switching on the current in the primary sets up a magnetic field and as its field lines grow outwards from the primary, they cut the secondary. A p.d. is induced in the secondary until the current in the primary reaches its steady value. When the current is switched off in the primary, the magnetic field dies away and we can imagine the field lines cutting the secondary as they collapse, again inducing a p.d. in it. Changing the primary current by *quickly* altering the rheostat has the same effect.

The induced p.d. is increased by having a soft iron rod in the coils or, better still, by using coils wound on a complete iron ring. More field lines then cut the secondary due to the magnetisation of the iron.

Practical work

Mutual induction with a.c.

An a.c. is changing all the time and if it flows in a primary coil, an alternating voltage and current are induced in a secondary coil.

Connect the circuit of Figure 4.5.32. All wires used should be insulated. The 1 V high current power unit supplies a.c. to the primary and the lamp detects the secondary current. Insulated wires should be used for the primary and secondary coils.

Find the effect on the brightness of the lamp of

(i) pulling the C-cores apart slightly
(ii) increasing the secondary turns to 15
(iii) decreasing the secondary turns to 5.

high current power unit iron C-cores

lamp (2.5 V 0.3 A)

1 V a.c.

spare wire

primary (10 turns) secondary (10 turns)
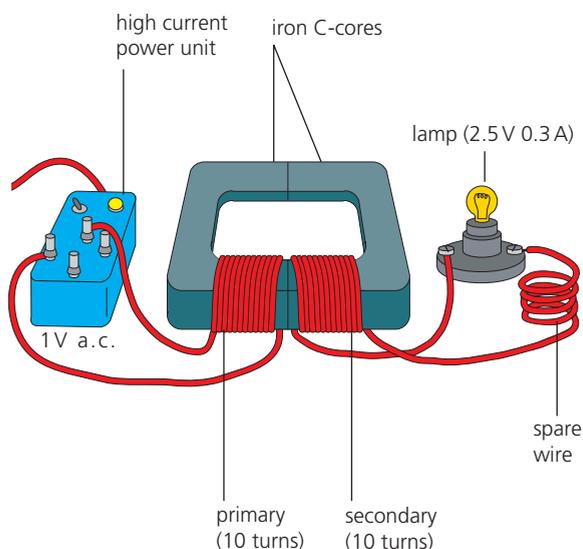
▲ **Figure 4.5.32**

5 In the circuit of Figure 4.5.32, if a d.c. supply were used instead of an a.c. supply, would you expect the lamp to light? Explain your answer.

6 In the circuit of Figure 4.5.33 would you expect the brightness of the lamp to increase or decrease if you lowered the voltage to the primary coil?

Transformer equation

An alternating voltage applied to the primary induces an alternating voltage in the secondary. The value of the secondary voltage can be shown, for a transformer in which all the field lines cut the secondary, to be given by

$$\frac{\text{primary voltage}}{\text{secondary voltage}} = \frac{\text{primary turns}}{\text{secondary turns}}$$

In symbols

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

A *step-up* transformer has more turns on the secondary than the primary and V_S is greater than V_P (Figure 4.5.33a). For example, if the secondary has twice as many turns as the primary, V_S is about twice V_P. In a *step-down* transformer there are fewer turns on the secondary than the primary and V_S is less than V_P (Figure 4.5.33b).

a   b
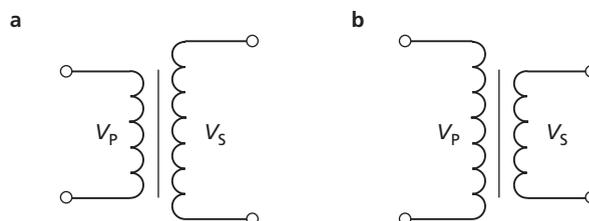
V_P V_S V_P V_S

▲ **Figure 4.5.33** Symbols for a transformer:
a step-up ($V_S > V_P$); **b** step-down ($V_P > V_S$)

▶ Test yourself

17 The main function of a step-down transformer is to
   A decrease current
   B decrease voltage
   C change a.c. to d.c.
   D change d.c. to a.c.
18 A transformer has 1000 turns on the primary coil. The voltage applied to the primary coil is 230 V a.c. How many turns are on the secondary coil if the output voltage is 46 V a.c.?
   A 20
   C 2000
   B 200
   D 4000

Going further

Energy losses in a transformer

If the p.d. is stepped up in a transformer, the current is stepped down in proportion. This must be so, if we assume that all the energy transferred by the current to the primary appears in the secondary, i.e. that energy is conserved and the transformer is 100% efficient or 'ideal' (many approach this efficiency). Then

$$\text{power in primary} = \text{power in secondary}$$

$$I_P V_P = I_S V_S$$

where I_P and I_S are the primary and secondary currents, respectively.

$$\therefore \quad \frac{I_S}{I_P} = \frac{V_P}{V_S}$$

So, for the ideal transformer, if the p.d. is doubled the current is halved. In practice, it is more than halved, because of small energy losses in the transformer arising from the following causes.

Resistance of windings

The windings of copper wire have some resistance and heat is produced by the current in them. Large transformers like those in Figure 4.5.34 have to be oil-cooled to prevent overheating.

▲ **Figure 4.5.34** Step-up transformers at a power station

Eddy currents

The iron core is in the changing magnetic field of the primary and currents, called eddy currents, are induced in it which cause heating. These are reduced by using a laminated core made of sheets, insulated from one another to have a high resistance.

? Worked example

A transformer steps down the mains supply from 230 V to 10 V to operate an answering machine.

a What is the turns ratio, $\frac{N_P}{N_S}$, of the transformer windings?

primary voltage, $V_P = 230\,\text{V}$

secondary voltage, $V_S = 10\,\text{V}$

turns ratio $= \dfrac{N_P}{N_S} = \dfrac{V_P}{V_S} = \dfrac{230\,\text{V}}{10\,\text{V}} = \dfrac{23}{1}$

b How many turns are on the primary if the secondary has 100 turns?

secondary turns, $N_S = 100$

From **a**,

$$\frac{N_P}{N_S} = \frac{23}{1}$$

$$\therefore \quad N_P = 23 \times N_S = 23 \times 100$$
$$= 2300 \text{ turns}$$

Now put this into practice

1 A transformer steps down the mains supply from 240 V to 12 V to operate a doorbell.

   a What is the turns ratio $\frac{N_P}{N_S}$ of the transformer windings?

   b How many turns are on the primary if the secondary has 80 turns?

2 A transformer steps up an a.c. voltage of 240 V to 960 V.

   a Calculate the turns ratio of the transformer windings.

   b How many turns are on the secondary if the primary has 500 turns?

Transmission of electrical power

Grid system

The **National Grid** is a network of cables, mostly supported on pylons, that connects all the power stations in a country to consumers. In the largest modern stations, electricity is generated at 25 000 V (25 kilovolts = 25 kV) and stepped up in a transformer to a higher p.d. to be sent over long distances. Later, the p.d. is reduced by substation transformers for distribution to local users (Figure 4.5.35).

At the National Control Centre, engineers direct the flow of electricity and re-route it when breakdown occurs. This makes the supply more reliable and cuts costs by enabling smaller, less efficient stations to be shut down at off-peak periods.

Advantages of high-voltage transmission

The efficiency with which transformers step alternating p.d.s up and down accounts for the use of a.c. rather than d.c. in power transmission.

Power cables have resistance and so the electric current causes heating of the cable during the transmission of electricity from the power station to the user. In order to reduce energy losses, the current in the cables should be kept low.

Higher voltages are used in the transmission of electric power so that smaller currents can be used to transfer the energy. **Advantages of high-voltage transmission of electricity** include:

(i) reducing the amount of energy lost as thermal energy in the transmission cables

(ii) allowing wires with small cross-sectional areas to be used; these are cheaper and easier to handle than the thicker wires required to carry large currents.

High p.d.s require good insulation but are readily produced by a.c. generators.

> **Key definition**
> **Advantages of high-voltage transmission of electricity**
> (i) lower power loss in transmission cables
> (ii) lower currents in cables so thinner/cheaper cables can be used
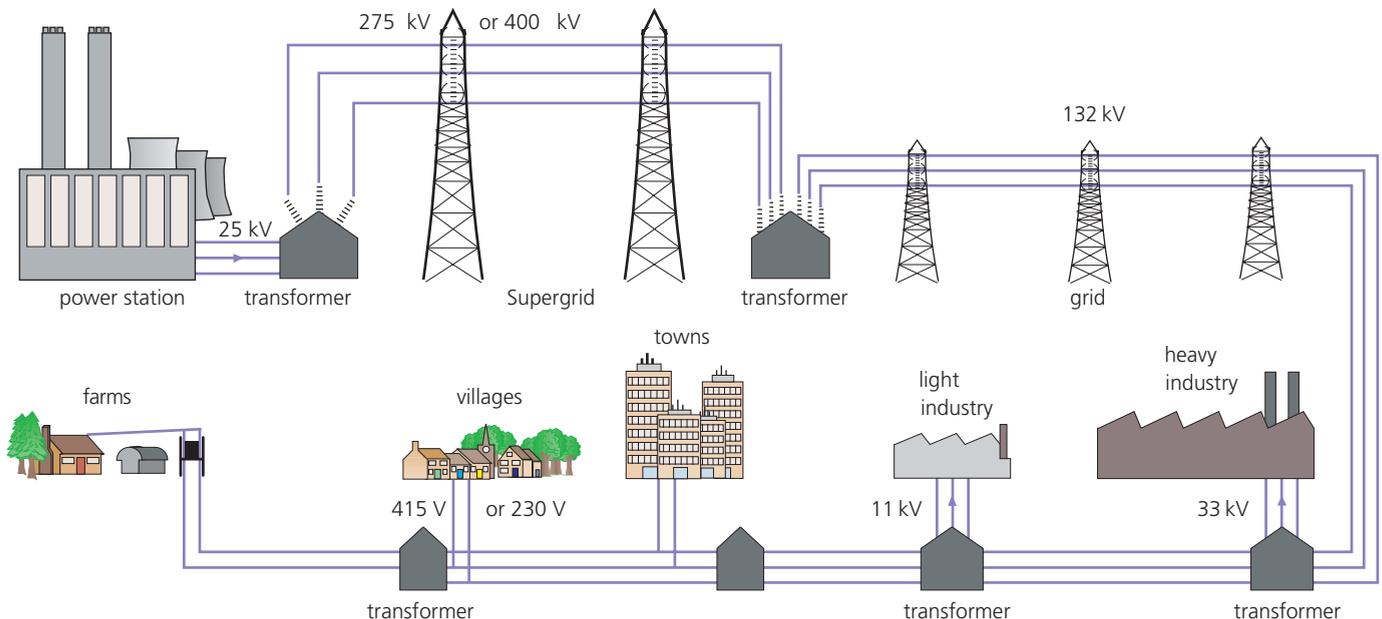
▲ **Figure 4.5.35** The National Grid transmission system in Britain

Revision checklist

After studying Topic 4.5 you should know and understand:
✔ Faraday's explanation of electromagnetic induction
✔ the right-hand screw and right-hand grip rules for relating current direction and magnetic field direction
✔ the action and applications of a relay and a loudspeaker
✔ that a rectangular current-carrying coil experiences a turning effect in a magnetic field and that the effect is increased by increasing the number of turns on the coil, the current in the coil or the strength of the magnetic field
✔ how to use Fleming's left-hand rule for relating directions of force, field and current
✔ the terms primary, secondary, step-up and step-down in relation to a transformer
✔ the use of transformers in the high voltage transmission of electrical power
✔ the reasons why greater voltage a.c. is preferred

After studying Topic 4.5 you should be able to:
✔ describe experiments to show electromagnetic induction
✔ predict the direction of induced e.m.f.s and currents and describe and explain the operation of a simple a.c. generator
✔ draw sketches to identify the pattern of magnetic field lines arising from currents in straight wires and solenoids
✔ identify regions of different magnetic field strength around a solenoid and straight wire and describe the effect on their magnetic fields of changing the magnitude and direction of the current
✔ describe an experiment that demonstrates a force acts on a current-carrying conductor in a magnetic field, and recall the factors which influence the size and direction of the force
✔ describe how the magnetic field patterns due to the current in two parallel wires causes the wires to be attracted or repelled
✔ explain the action of a simple d.c. electric motor
✔ describe the construction of a transformer and use the transformer equation $V_S/V_P = N_S/N_P$
✔ explain the action of a transformer.

Exam-style questions

1 a Describe an experiment to demonstrate electromagnetic induction. [4]
  b State the factors affecting the magnitude of an induced e.m.f. [3]
  [Total: 7]

2 a Describe the deflections observed on the sensitive, centre-zero meter G (Figure 4.5.36) when the copper rod XY is connected to its terminals and is made to vibrate up and down (as shown by the arrows), between the poles of a U-shaped magnet, at right angles to the magnetic field. [2]
 **b** Explain the behaviour of the meter in part **a**. [4]
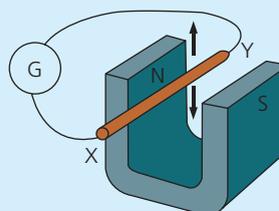
▲ **Figure 4.5.36**

[Total: 6]

3 A simple a.c. generator is shown in Figure 4.5.37.
  a Identify A and B and describe their purpose. [3]
  b Describe changes that could be made to increase the e.m.f. generated. [3]
  c Sketch a graph of e.m.f. against time for the generator and relate the position of the generator coil to the peaks, troughs and zeros of the e.m.f. [4]
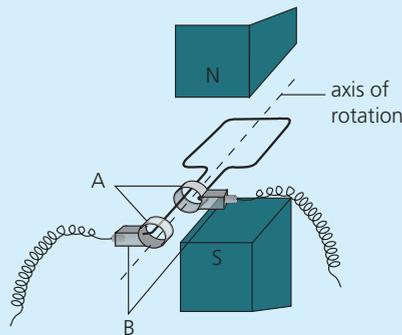
▲ **Figure 4.5.37**

[Total: 10]

4 a Sketch the magnetic field lines (including their direction) around a current-carrying solenoid. [4]
b What happens if the direction of the current in the wire is reversed? [1]
[Total: 5]

5 Part of the electrical system of a car is shown in Figure 4.5.38. Explain why
a connections are made to the car body [2]
b there are *two* circuits in parallel with the battery [2]
c wire A is thicker than wire B [1]
d a relay is used. [2]
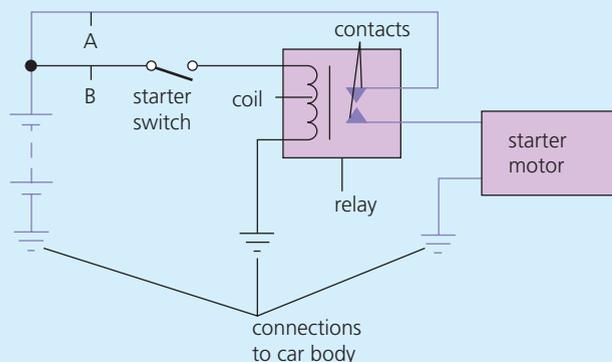
▲ **Figure 4.5.38**

[Total: 7]

6 Explain how a loudspeaker works.
[Total: 6]

7 a Describe an experiment to show that a force acts on a current-carrying conductor in a magnetic field, including the effect of reversing the current or the direction of the magnetic field. [5]

b A current-carrying coil experiences a turning effect in a magnetic field. State the effect on the magnitude of the turning effect of:
i increasing the current in the coil [1]
ii reducing the number of turns on the coil [1]
iii increasing the strength of the magnetic field. [1]
[Total: 8]

8 An electric motor is used to raise a weight attached to a string. Select which of the following is used to transfer energy in the process.
A Mechanical working
B Heating
C Electrical working
D Electromagnetic waves
[Total: 1]

9 a Draw a labelled diagram of the essential components of a simple d.c. motor. [3]
b Explain how continuous rotation is produced in a d.c. motor and show how the direction of rotation is related to the direction of the current. [4]
c State what would happen to the direction of rotation of the motor you have described if
i the current direction was reversed [1]
ii the magnetic field was reversed [1]
iii both current and field were reversed simultaneously. [1]
[Total: 10]

10 a Describe the construction of a simple transformer with a soft iron core. [4]
b Explain the function of a step-up transformer. [2]
c A step-up transformer is used to obtain a p.d. of 720 V from a mains supply of 240 V. Calculate the number of turns that will be needed on the secondary if there are 120 turns on the primary. [4]
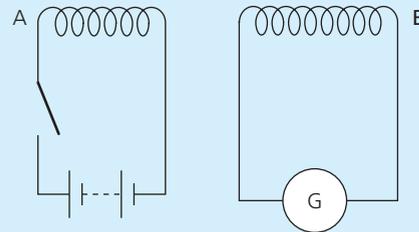[Total: 10]

11 a Explain what is meant by the following terms in connection with a transformer:
    i primary
    ii secondary
    iii step-up
    iv step-down. [4]
  b Calculate the number of turns on the secondary of a step-down transformer which would enable a 12 V lamp to be used with a 230 V a.c. mains power, if there are 460 turns on the primary. [4]
                                       [Total: 8]

12 Two coils of wire, A and B, are placed near one another (Figure 4.5.39). Coil A is connected to a switch and battery. Coil B is connected to a centre-reading meter, G.
  a If the switch connected to coil A were closed for a few seconds and then opened, the meter connected to coil B would be affected. Explain and describe, step by step, what would actually happen. [7]

b What changes would you expect if a bundle of soft iron wires was placed through the centre of the coils? Give a reason for your answer. [3]
c What would happen if more turns of wire were wound on the coil B? [1]

▲ **Figure 4.5.39**

                                       [Total: 11]

13 a Explain the use of transformers in the transmission of electrical power. [3]
  b Give two reasons for the use of high voltages in the transmission of electricity. [2]
   [Total: 5]

FOCUS POINTS

★ Explain how an oscilloscope can be used to display waveforms and measure p.d. and intervals of time.

The discovery of the electron led to great technological advances in electronics. Electrons moving at high speed in a vacuum are called cathode rays, and twentieth century televisions and computer screens all contained a cathode ray tube. The cathode ray oscilloscope (CRO) is an important scientific instrument that works in a similar way. The oscilloscope allows rapidly changing electrical signals to be analysed by plotting a voltage–time graph on a screen. When a microphone is used to convert a sound wave into an electrical signal, the waveform can be viewed directly on the oscilloscope screen. An oscilloscope can be used as a voltmeter, to measure varying p.d.s, and also to measure intervals of time, enabling the frequency of a signal to be found.

Oscilloscope settings

A small **cathode ray oscilloscope (CRO)** is shown in Figure 4.6.1a. The circuit symbol for an oscilloscope is shown in Figure 4.6.1b.

a

b
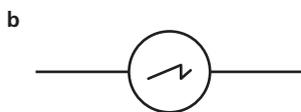
▲ **Figure 4.6.1 a Oscilloscope; b circuit symbol for an oscilloscope**

The vertical axis on an oscilloscope screen provides a measurement of p.d. and the horizontal axis is a measure of time. The signal to be displayed or measured is connected to the Y-input terminal of the oscilloscope. The **Y-gain** control amplifies the input p.d. to make it large enough to appear a suitable size on the screen. The Y-gain setting in volts per division or V/div allows the size of the input p.d. to be measured.

The **timebase** controls how fast the bright spot (the input signal) moves from left to right. The distance moved by the spot is directly proportional to time and so the horizontal axis becomes a time axis. The timebase setting in milliseconds per division or ms/div allows time intervals in a varying p.d. to be measured.

When preparing the oscilloscope for use, set the X-shift and Y-shift controls (which allow the spot to be moved 'manually' over the screen in the X and Y directions, respectively) to their mid-positions. The timebase and Y-gain controls can then be adjusted to suit the input.

Key definitions

**Y-gain** controls the amplification of the input p.d.

Timebase controls the time interval displayed on the horizontal axis of the screen

With the timebase switched on, Figure 4.6.2 shows the display on an oscilloscope screen (called traces) for three different input p.d.s. In Figure 4.6.2a, the p.d. applied to the Y-input is zero, and there is a straight line across the centre of the screen. In Figure 4.6.2b, the Y-input is a constant d.c. signal and the trace is a horizontal line displaced upwards by an amount determined by the Y-gain setting. In Figure 4.6.2c, the Y-input is an a.c. signal, so the p.d. is alternately positive and negative.
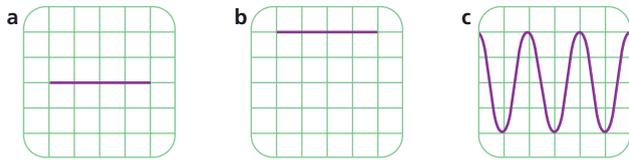
▲ **Figure 4.6.2 Oscilloscope traces with timebase on**

When the timebase is switched off, the trace is concentrated to a spot that does not move from left to right. Figure 4.6.3 shows how the display appears for different inputs. In Figure 4.6.3a, the input p.d. is zero and the spot remains at the centre of the screen. In Figure 4.6.3b, the input p.d. is a constant d.c. signal and the spot is displaced upwards.In Figure 4.6.3c, the Y-input is an a.c. signal, so the p.d. is alternately positive and negative and the trace appears as a continuous vertical line whose length increases when the Y-gain is increased.
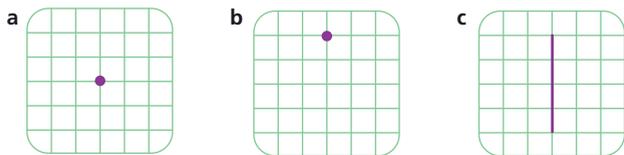
▲ **Figure 4.6.3 Oscilloscope traces with timebase off**

A concentrated spot can damage the screen so the timebase should be set to produce an extended line when possible.

Uses of an oscilloscope

Measuring p.d.s

An oscilloscope can be used as a d.c./a.c. voltmeter by connecting the p.d. to be measured to the Y-input terminals; the displacement of the trace in the vertical direction is proportional to the p.d.

For example, if the Y-amp gain control is set on 1 V/div, a vertical displacement of one whole division on the screen would be given by a 1 V d.c. input. A vertical line one division long (timebase off) would be produced by an a.c. input of 1 V peak to trough (i.e. amplitude 0.5 V).

The vertical displacement can be measured with the timebase either on or off. To find the value of a d.c voltage, count the number of whole divisions the trace (horizontal line or spot) is displaced vertically and multiply that number by the V/div setting. For an a.c. input, count the number of divisions occupied by the vertical line (timebase off) or vertical peak-to-trough distance (timebase on). The amplitude of the a.c. voltage can then be found by multiplying the V/div setting by half the number of vertical divisions counted.

Displaying waveforms

When the timebase is on, the oscilloscope acts as a 'graph-plotter' to show the waveform, i.e. the variation with time, of the p.d. applied to its Y-input. The displays in Figure 4.6.4 are of alternating p.d.s with sine waveforms. For the trace in Figure 4.6.4a, the timebase frequency *equals* that of the input and one complete wave is obtained. For the trace in Figure 4.6.4b, it is *half* that of the input and two waves are formed. If the traces are obtained with the Y-amp gain control on, say, 0.5 V/div, the vertical peak-to-trough voltage of the a.c. = 3.0 divs × 0.5 V/div, that is, 1.5 V, and the amplitude of the signal = 0.75 V.

Sound waveforms can be displayed if a microphone is connected to the Y-input terminals (see Topic 3.4).

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a   **b**
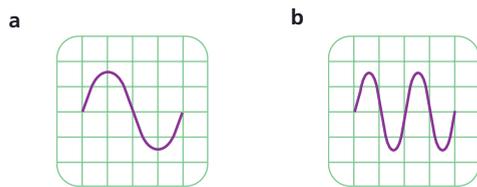
▲ **Figure 4.6.4 Alternating p.d. waveforms on the CRO**

Measuring time intervals and frequency

These can be measured if the oscilloscope has a calibrated timebase. For example, when the timebase is set on 10 ms/div, the spot takes 10 milliseconds to move one division horizontally across the screen. If this is the timebase setting for the waveform in Figure 4.6.4b then, since one complete wave occupies two horizontal divisions, we can say

$$\text{time for one complete wave} = 2.0\,\text{divs} \times 10\,\text{ms/div}$$

$$= 20\,\text{ms}$$

$$= \frac{20}{1000} = \frac{1}{50}\,\text{s}$$

∴ number of complete waves per second = 50
∴ frequency of a.c. applied to Y-input = 50 Hz

Exam-style questions

1 **a** Describe the function on an oscilloscope of
  i the timebase control
  ii the Y-gain control.
                                  [4]

  b You are asked to use an oscilloscope to display a waveform. If you want to make two wavelengths occupy the screen rather than one wavelength, which setting would you change on the oscilloscope?
                                    [1]

  c An oscilloscope is used to measure a d.c. voltage. Calculate the value of the voltage if the trace on the oscilloscope is displaced (from zero) by 2.8 divisions when the Y-gain is set at 0.1 V/div.
                                    [2]
                                   [Total: 7]