

*Physics*

## Big idea (age 11-14)

# PEM: Electricity and magnetism

### What's the big idea?

The familiar everyday world we live in is largely a consequence of the properties and behaviour of electric charge. Matter is held together by electrostatic forces, and these influence chemical changes. Electricity and magnetism initially seem to be distinct phenomena, but are later found to be closely interrelated. Understanding electricity and magnetism helps us to develop our technology and find applications that can transform our everyday lives.

### Key concepts

The big idea is developed through a series of key concepts at age 11-14, which have been organised into teaching topics as follows:

*Topic PEM1***Simple electric circuits**

Key concepts:

- PEM1.1 Making circuits
- PEM1.2 Electric current
- PEM1.3 Voltage
- PEM1.4 Static electricity

*Topic PEM2***More electric circuits**

Key concepts:

- PEM2.1 Resistance
- PEM2.2 Parallel circuits

*Topic PEM3***Magnets and electromagnets**

Key concepts:

- PEM3.1 Magnetic fields
- PEM3.2 Electromagnets

The numbering gives some guidance about teaching order based on research into effective sequencing of key concepts. However, the teaching order can be tailored for different classes as appropriate.

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## Guidance notes

All three of these teaching topics can be quite challenging and you could consider teaching them reasonably late on in the 11-14 teaching sequence.

In these topics the following terms are used to describe electric circuits:

- a simple circuit is one which consists of a single device connected to the two terminals of a battery (or power supply).
- a series circuit is one in which two or more devices are connected, one after the other, between the battery terminals in a single loop.
- a simple parallel circuit is one in which two or more devices are each connected directly to the two terminals of the battery.

Wires and switches are not counted as 'devices'; so any of these types of circuit may also include one or more switches, in series with a device or with the battery.

'Voltage' has been used to mean 'potential difference'.

'Battery' has been used throughout and not 'cell'. Strictly speaking a 4.5V battery is made up from three 1.5V cells; a cell being the unit that uses a chemical reaction to generate electricity – such as a standard 1.5V battery! Switching between 'battery' and 'cell' can be somewhat confusing, contradicts everyday use of the word 'battery', and is not necessary to develop understanding.

### *Energy in electricity and magnetism*

Energy is an important idea in all of the sciences because it provides a way of looking at events and processes across a very wide range of contexts. Energy ideas can enable us to say whether something can happen, though not to predict it will happen, and to calculate specific outcomes of events. Energy ideas do not, however, help to explain how or why an event happens.

In the big idea of 'Electricity and magnetism' ideas about energy are developed in the contexts of: electric circuits; electromagnets; and generating electricity.

## Learning progression

The science story associated with the big idea develops from age 5 to age 16, and could be summarised as follows:

### **Science story at age 5-11**

From learning before age 11, and from informal everyday situations, students are expected to have already met the following ideas:

#### *Magnets*

Some materials are magnets. A magnet attracts some materials (which are called magnetic materials). These include certain metals, notably iron. The attraction between a magnet and a magnetic material can be felt across an air gap, and through other materials (such as paint, paper, card).

Two magnets may also repel each other, depending on which parts of the magnets are brought together.

The Earth is a large magnet. A bar magnet that is free to turn will point roughly north-south. So a magnet can be used as a compass, for navigation.

### *Electric circuits*

Many common electrical devices (e.g. a bulb, motor, buzzer) have two connection points, or terminals. To operate such a device, its two terminals need to be connected by wires (or other conducting material) to the two terminals of a battery (or other power supply). Several devices can be operated from a single battery by connecting them with wires in a closed loop from one battery terminal to the other (a series circuit). The order of the devices round the loop makes no difference to how they operate.

A switch is a device that completes or breaks a circuit. A switch anywhere in a series circuit switches everything in the circuit on and off together.

A material that can be used successfully to complete an electric circuit is called an electrical conductor. A material that cannot is called an electrical insulator. Metals are conductors, as are a few other materials (e.g. graphite, salt solutions). Plastics, ceramics and air are insulators.

### *Static electricity*

If you rub objects of certain kinds (such as plastics) with a cloth, they will attract light objects (such as scraps of paper, hair, specks of dust). The rubbed object is said to be (electrically) charged. This is called static electricity. Sparks when you take off a jumper or get out of a car, and lightning, are caused by static electricity.

Note: here an introduction to charge has been included, as it seems likely that students will have encountered this phenomenon before age 11. Charge is not included in the National Curriculum for Key Stages 1 and 2 in England, but it is included in (for example) the Next Generation Science Standards for the corresponding age group in the United States.

### **Science story at age 11-14**

#### *Magnetic poles*

A magnet has two specific places (called poles) at which its magnetic effect is strongest. There are two types of magnetic pole, called north-seeking (N) and south-seeking (S). Like poles repel each other; unlike poles attract.

The Earth behaves like a large magnet, with its poles near the geographic north and south. The N-pole of a bar magnet that is free to turn will point towards the magnetic north pole. So a magnet can be used as a compass, for navigation.

#### *Electric charge*

If you use a cloth to charge (by rubbing) two objects made of the same material, they repel each other. However, two charged objects made of different materials may attract each other. There seem to be two types of charge, which are called positive and negative. Two objects with the same type of charge repel each other; two with different types of charge attract.

If a charged object touches another object, they can share the charge. If a small amount of charge is shared with a large object, the charge can become so spread out that it is not noticeable. So a charged object can discharge (lose its charge) if it is connected to Earth (e.g., by a wire, or through a person's body). It can also discharge by gradually sharing its charge with its surroundings, including the air.

### *Fields*

Around any magnet there is a region in which another magnet experiences a force. Similarly, around an electrically charged object there is a region in which another charge experiences a force. This region is called a field. There is a magnetic field around a magnet and an electric field around an electrically charged object. The field gets gradually weaker with distance from the magnet or charged object that is causing it.

The shape and strength of a magnetic field can be represented by field lines. These show the direction of the force that would be experienced by the N pole of a small magnet placed at each point in the field. The lines are closer together where the field is stronger.

Gravity is another common field force. There is a gravitational field in the region around an object (a mass). Any other object in this region will experience an attractive force. The force is very small between objects of an everyday size. It only becomes easy to detect when one of the objects is extremely large, such as the Earth.

### *The electron model of charging*

A model to explain electric charging is that all materials are made up of tiny particles, some of which have a permanent positive electric charge whilst others have a permanent negative electric charge. These particles are called positive charges and negative charges. Most objects contain equal amounts of positive and negative charge, and so are electrically neutral (uncharged). A charged object has more of one type of charge than the other.

The negative charges in materials are called electrons. They can be moved more easily than the positive charges. When an object is charged by rubbing against another object, some electrons are transferred from one to the other. If an object loses electrons, it becomes positively charged. If it gains electrons, it becomes negatively charged.

Electrons can move around freely throughout metals and some other materials. These are called (electrical) conductors. If an object made from a conductor is charged (e.g., by rubbing, or by touching another charged object), electrons move around within it so that all parts of the object become charged.

In many other materials, electrons can only move a very short distance. These materials are called (electrical) insulators. Most non-metals are insulators. It is possible to charge just part of an object made of an insulating material (e.g., rubbing a balloon with a cloth – only the rubbed part becomes charged).

A charged object may suddenly discharge as electrons move rapidly to or from it. If the movement is across an air gap, it can cause a spark.

### *A simple electric circuit*

A simple electric circuit consists of a single device connected by wires to the two terminals of a battery (or power supply), perhaps with a switch somewhere in the loop. When it is switched on, there is an electric current everywhere in the circuit instantly.

An electric current is a movement of charged particles. The wires and other devices in a circuit are full of charges (electrons) that are free to move. These charges all move together (like a continuous belt, or chain). As they are negatively charged, electrons move away from the negative terminal of the battery and towards the positive terminal.

The size of the electric current at a particular point in a circuit is a measure of the amount of electric charge passing that point every second. An ammeter is a device that measures the size of the electric current going through it. The unit of electric current is the ampere (or amp, A).

The battery (or power supply) is the cause of the current in an electric circuit. If the battery in a simple circuit is replaced by one with a larger potential difference (voltage), the effects observed are larger, e.g. bulbs are brighter, motors run faster, etc. This is because the electric current is larger. The potential difference of a battery is a measure of its 'strength'. Its size depends on the chemicals used to make the battery. It is measured in volts (V).

If several batteries are connected in line (in series), the potential difference of the combination is the sum of the potential differences of the individual batteries, taking account of their directions.

Many devices are designed to be used with a battery (or power supply) that has a particular potential difference; often this is marked on the device. If a device is connected to a battery of smaller potential difference, it will either operate more weakly or not at all. A device can be damaged if it is connected to a battery whose potential difference is higher than it is designed for (because it causes a current that is larger than the device is designed to take).

Standard symbols are widely used to represent electric circuits. These show the connections in the circuit, but not its physical shape or appearance. Circuits are normally shown as rectangular, with 90° corners and straight connecting wires.

### *Energy in electric circuits*

In any event where two or more objects interact, if some objects lose energy, others gain energy. The total amount of energy stored in all of the objects involved is the same at the end as it was at the beginning.

We can identify objects, or groups of objects, that have gained (or lost) energy by noticing that they:

- are moving faster (or slower) than they were
- have reacted chemically
- are hotter (or cooler) than they were
- have been raised (or lowered)
- are magnets/electric charges which have been moved apart/together in a magnetic/electric field
- are springy and have been distorted (stretched, compressed, bent, twisted), or allowed to spring back from a distorted state

Convenient labels for these different ways in which energy can be stored are (respectively): kinetic, chemical, thermal, gravitational, magnetic, electrostatic, and elastic

During an event, energy can be transferred from the initial energy store(s) to the final energy store(s) in different ways. These energy transfer pathways are:

- mechanical (by a force)
- electrical (by an electric current)
- by heating
- by radiation

Many devices change the way in which energy is being transferred, without storing any themselves. For example, energy is often transferred to a motor electrically and from it mechanically.

At the end of many events, some energy is often stored in the surroundings, which have become hotter. This is a consequence of friction or drag (air or fluid resistance).

Although energy is always conserved in any event or process, it also gets more spread out amongst the objects involved: it is **dissipated**.

### *Resistance*

The size of the electric current in a simple circuit also depends on the resistance of the circuit. It is easier for electrons to move through some materials than others. For example, electrons can move very freely through metals such as copper, and a few non-metallic substances (like graphite). These materials are very good conductors and offer very low resistance (almost zero) to the movement of electrons. So they are used for connecting wires. Some other metals, and some non-metallic substances, are also conductors but have a higher resistance. Electrons can move through them, but not as easily as through connecting wires. They get hotter when there is an electric current through them, and are used for heating elements and bulb filaments. Some non-metallic substances, such as plastics and ceramics, offer extremely high resistance to the movement of electrons. These substances are called electrical insulators; electrons cannot flow through them. In general, the larger the resistance of a simple electric circuit, the smaller the current.

The resistance of an object can be found by connecting it to a battery or power supply of known potential difference and measuring the electric current through it. Resistance is then calculated as potential difference (in V)/current (in A). The resistance of an object is measured in ohms ( $\Omega$ ).

In situations involving static and current electricity, a potential difference causes electric charges to move. A key difference is that the potential differences involved in static electrical phenomena are very much bigger than those involved in electric circuits.

One consequence of this is that objects and materials can appear to be insulators when used to complete a circuit with a battery and a bulb, but conductors when they provide a path from a charged object to Earth. The human body is an example. Its resistance is quite high so a battery can push only a very small current through it, and this is not enough to light a bulb. A charged object, however, is at a very high voltage, and can push a current through and discharge itself. (The amount of charge involved is tiny, however, so this is not hazardous.)

Similarly, an air gap has a very high resistance and stops a series battery-and-bulb circuit working. But a high voltage can make electrons move across an air gap and create a spark. Lightning is an extreme and spectacular example of this.

The potential difference of the mains is higher than a battery and can push an appreciable current through a human body, so it is hazardous.

### *Series and parallel circuits*

In a series circuit, the size of the electric current is the same everywhere round the loop.

The size of the current in a series circuit depends on the potential difference of the battery (or power supply) and the resistance of the components in the circuit. Increasing the battery voltage increases the current. Increasing the resistance of any component decreases the current.

In a circuit with branches, a device will operate only if there is a closed conducting loop from one terminal of the battery, through the device, and back to the other terminal of the battery.

In any circuit with branches, the size of the current is the same everywhere within a branch. At a junction, the sum of the currents arriving is equal to the sum of the currents leaving.

A simple parallel circuit works as a set of simple circuits sharing a battery, but otherwise working independently of each other. Increasing the battery voltage increases the current in every branch.

Increasing the resistance of a branch decreases the current in that branch (but has no effect on the current in the other branches).

### *Magnetic effects of an electric current*

Close to any wire carrying an electric current, there is a magnetic field. A current in a coil of wire produces a magnetic field similar in shape to that of a bar magnet. The strength of this field can be greatly increased (over 1000 times) by placing a piece of iron in the centre of the coil. The iron core behaves as a magnet (an electromagnet) while there is a current in the coil.

If a current-carrying wire is placed in the magnetic field of a magnet, it experiences a force. The two sides of a square coil, lying parallel with the lines of a magnetic field, experience forces in opposite directions making the coil turn. By changing the direction of the electric current in the coil (or of the magnetic field) in time with each half-turn of the coil, it can be made to rotate continuously. This is how a d.c. electric motor works.

### **Science story at age 14-16**

When students progress on to learning about science at ages 14-16 it is expected that they will meet the following ideas:

#### *Electric charge*

When two objects are rubbed together they become charged, because electrons are transferred from one object to the other. Electrons are negatively charged. Objects with similar charges repel, and objects with opposite charges attract.

Around every electric charge there is an electric field; in this region of space the effects of charge can be felt; when another charge enters the field there is an interaction between them and both charges experience a force.

The shape and strength of an electric field can be represented by field lines. These show the direction of the force that would be experienced by a small positively charged object placed at each point in the field. The lines are closer together where the field is stronger

#### *Electric circuits*

An electric current is the rate of flow of charge; in an electric circuit the metal conductors (the components and wires) contain many charges that are free to move. When a circuit is made, the battery causes these free charges to move, and these charges are not used up but flow in a continuous loop.

In a given circuit, the larger the potential difference across the power supply the bigger the current. Components (for example, resistors, lamps, motors) resist the flow of charge through them; the resistance of connecting wires is usually so small that it can be ignored. The larger the resistance in a given circuit, the smaller the current will be.

When electric charge flows through a component (or device), work is done by the power supply and energy is transferred from it to the component and/or its surroundings. Potential difference measures the work done per unit charge.

In a series circuit the charge passes through all the components, so the current through each component is the same and the work done on each unit of charge by the battery must equal the total work done by the unit of charge on the components. The potential difference (p.d.) is largest across the component with the greatest resistance and a change in the resistance of one component will result in a change in the potential differences across all the components.

In a parallel circuit each charge passes through only one branch of the circuit, so the current through each branch is the same as if it were the only branch present and the work done by each unit of charge is the same for each branch and equal to the work done by the battery on each charge. The current is largest through the component with the smallest resistance, because the same battery p.d. causes a larger current to flow through a smaller resistance than through a bigger one.

When two or more resistors are placed in series the effective resistance of the combination (equivalent resistance) is equal to the sum of their resistances, because the battery has to move charges through all of them. Two (or more) resistors in parallel provide more paths for charges to move along than either resistor on its own, so the effective resistance is less.

The resistance of some components stays the same when the potential difference across them increases (ohmic conductors) and the resistance of other (non-ohmic conductors) changes, e.g. the resistance of a filament bulb increases with the size of the p.d. and the resistance of a diode changes in a different way.

Some components are designed to change resistance in response to changes in the environment e.g. the resistance of an LDR varies with light intensity, the resistance of a thermistor varies with temperature; these properties used in sensing systems to monitor changes in the environment.

The energy transferred when electric charge flows through a component (or device), depends on the amount of charge that passes and the potential difference across the component. The power rating (in watts, W) of an electrical device is a measure of the rate at which work is done by an electrical power supply transfers energy to the device and/or its surroundings. The rate of energy transfer depends on both the potential difference and the current. The greater the potential difference, the faster the charges move through the circuit, and the more energy each charge transfers.

The National Grid uses transformers to step down the current for power transmission. The power output from a transformer cannot be greater than the power input, therefore if the current increases, the potential difference must decrease. Transmitting power with a lower current through the cables results in less power being dissipated during transmission.

Mains electricity in the home works when there is a complete circuit through an appliance between the live wire and the neutral wire. Fuses or circuit breakers are added to the live wire, before an appliance, to break the circuit if too much current is flowing. This helps prevent damage to the appliance and fire. Earth wires are connected to appliances with metal cases and will complete a circuit with the live wire if there is a fault and the metal case becomes live. Current flowing in this circuit causes the fuse or circuit breaker to break the circuit and helps to prevent electric shocks. Appliances with non-conducting cases are often double insulated and do not need an earth wire.

### *Electromagnetism*

Around any magnet there is a region, called the magnetic field, in which another magnet experiences a force. The magnetic effect is strongest at the poles. The field gets gradually weaker with distance from the magnet. The direction and strength of a magnetic field can be represented by field lines. These show the direction of the force that would be experienced by the N pole of a small magnet, placed in the field. Where the field lines are closer together, the field is stronger. The magnetic field around the Earth, with poles near the geographic north and south, provides evidence that the core of the Earth is magnetic. The N-pole of a magnetic compass will point towards the magnetic north pole.

Magnetic materials (such as iron, nickel and cobalt) can be induced to become magnets by placing them in a magnetic field. When the field is removed permanent magnets retain their magnetisation whilst other materials lose their magnetisation.

When there is an electric current in a wire, there is a magnetic field around the wire; the field lines form concentric circles around the wire. Winding the wire into a coil (solenoid) makes the magnetic field stronger, as the fields of each turn add together. Winding the coil around an iron core makes a stronger magnetic field and an electromagnet that can be switched on and off.

In loudspeakers and headphones the magnetic field produced due to a current through a coil interacts with the field of a permanent magnet.

The magnetic fields of a current-carrying wire and a nearby permanent magnet will interact and the wire and magnet exert a force on each other. This is called the 'motor effect'. If the current-carrying wire is placed at right angles to the magnetic field lines, the force will be at right angles to both the current direction and the lines of force of the field. The direction of the force can be inferred using Fleming's left-hand rule. The size of the force is proportional to the length of wire in the field, the current and the strength of the field. The motor effect can result in a turning force on a rectangular current-carrying coil placed in a uniform magnetic field; this is the principle behind all electric motors.

Mains electricity is produced using the process of electromagnetic induction. When a magnet is moving into a coil of wire a potential difference is induced across the ends of the coil; if the magnet is moving out of the coil, or the other pole of the magnet is moving into it, there is a potential difference induced in the opposite direction. If the ends of the coil are connected to make a closed circuit, a current will flow round the circuit.

In a moving coil microphone sound waves cause a diaphragm to vibrate. The diaphragm is attached to a coil which is in the field of a permanent magnet. Sounds make the coil vibrate, inducing a changing potential difference across the ends of the coil. This potential difference drives a changing current in an electric circuit.

In a generator, a magnet or electromagnet is rotated within a coil of wire to induce a voltage across the ends of the coil. The induced voltage across the coil of an alternating current (a.c.) generator (and hence the current in an external circuit) changes during each revolution of the magnet or electromagnet. To generate d.c., a split-ring commutator is used so that the current always flows in the same direction to or from each side of the generator.

A changing magnetic field caused by changes in the current in one coil of wire can induce a voltage in a neighbouring coil. A simple transformer has two coils of wire wound on an iron core; a changing current in one coil of a transformer will cause a changing magnetic field in the iron core, which in turn will induce a changing potential difference across the other transformer coil.