UK Atomic Energy Authority

Magnificent Magnets & Cool Currents

Teachers' Pack

Magnificent Magnets & Cool Currents contains a series of activities which explore how magnets and electricity interact and how these interactions can be utilised to address some of the challenges faced when trying to create a fusion machine. The activities in this pack are best suited for secondary school pupils and can be run as one approximately 90-minute workshop or used as the basis for a series of workshops. The activities below can also be run individually or in combination to suit particular groups.

All the activities in this pack are fun, not especially complex to set up and have fairly short kit lists. Activities 2 and 4 have underlying science which can be gone into in considerable depth if desired, meaning that this teachers' pack can be used with pupils of different ages and levels. Please visit the appendices, the risk assessment and the accompanying PowerPoint slides to make the most of the information available in this teachers' pack.

Contents

Curriculum links

ENGLAND KS3 CURRICULUM LINKS

FORCES

- forces as pushes or pulls, arising from the interaction between two objects
- using force arrows in diagrams, adding forces in one dimension, balanced and unbalanced forces
- non-contact forces: gravity forces acting at a distance on Earth and in space, forces between magnets and forces due to static electricity

FORCES AND MOTION

- forces being needed to cause objects to stop or start moving, or to change their speed or direction of motion (qualitative only)

MAGNETISM

- magnetic poles, attraction and repulsion
- magnetic fields by plotting with compass, representation by field lines
- Earth's magnetism, compass and navigation
- the magnetic effect of a current, electromagnets, D.C. motors (principles only)

ENGLAND KS4 CURRICULUM LINKS

MAGNETISM AND ELECTROMAGNETISM

- exploring the magnetic fields of permanent and induced magnets, and the Earth's magnetic field, using a compass
- magnetic effects of currents, how solenoids enhance the effect

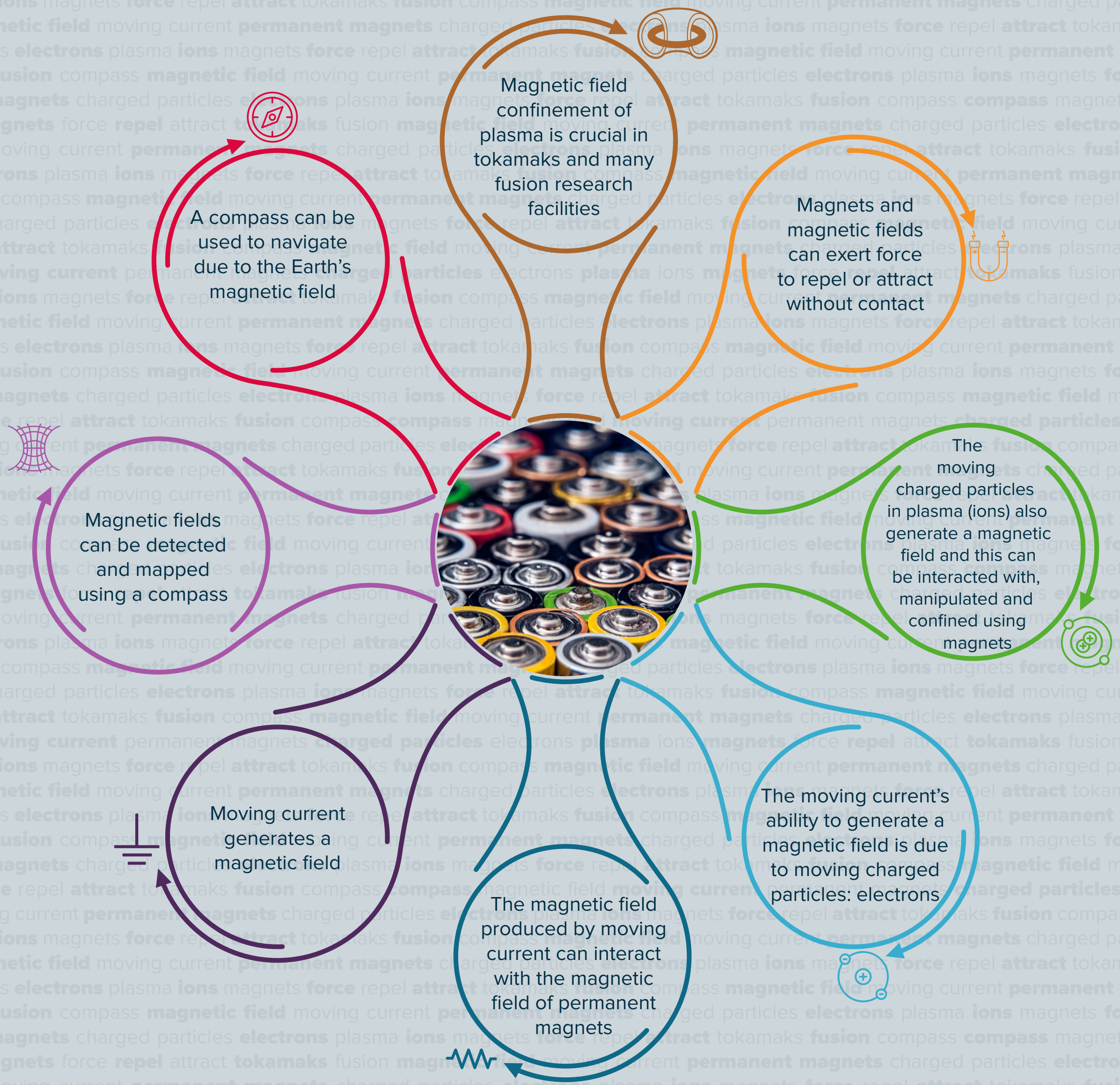
ATOMIC STRUCTURE

- nuclear fission, nuclear fusion and our Sun's energy
- ionisation; absorption or emission of radiation related to changes in electron orbits

FORCES

- forces and fields: electrostatic, magnetic, gravity

Learning objectives



Kit list

ACTIVITY 1: MAGNETIC FIELDS

PER PAIR:

- **Two bar magnets**, preferably labelled North and South
- **A compass**

DEMO:

- **One circuit**, such as one or two AA batteries, a light and wires[1].
- **Handful of compasses**, these can be the compasses listed above.
- A visualiser or repeat the exercise to ensure all pupils have seen it.

[1] See Appendix A for more information

ACTIVITY 2: HOMOPOLAR MOTOR OR SPINNING WIRES

PER PUPIL (OR PAIR):

- **A battery**[2].
- One or more lengths of **uninsulated wire**[2], each approximately 15cm in length.
- 1-3 small strong **neodymium magnets**[2].

[2] See Appendix B and Risk Assessment for more information

ACTIVITY 3: LEVITATING PENCIL

PER GROUP (OR PAIR):

- 6-10 **ring magnets**.
- **Supporting material** – this can be erasers, cardboard or a foam board[3].
- **A pencil** or similar shaped item that will fit through the ring magnets.

[3] See Appendix C for set-up which will clarify the supporting material item.

ACTIVITY 4: ELECTRIC TRAIN

PER GROUP (OR ONE SET AS A DEMO):

- A long length of **uninsulated wire**.
- **Something to wind the wire around**, such as a whiteboard pen or broom handle
- **A battery**[4] – AAA recommended
- 2-4 small strong **neodymium magnets**[4].

[4] See Appendix D and Risk Assessment for more information

Introduction

Our solar system's star, the Sun (pictured on slide 2), emits huge amounts of light and heat. Light and heat are two forms of energy. But where does this energy come from?

Inside the sun, a reaction called fusion takes place. Scientists and engineers are very interested in fusion as it releases huge amounts of energy. They want to recreate this kind of reaction, essentially building our very own star on earth, and capture the energy to power our homes, industries and transport. Fusion energy production is a carbon-free process at the point of generation and does not create greenhouse gases such as methane, CO_2 or NO_x gases.

The three states of matter, solid, liquid and gas, are represented on slide 3. In a solid, the particles (atoms or molecules) are close together and have very little energy. In a liquid, the atoms or molecules are better able to move around, allowing the liquid to flow. Liquids will take the shape of their container. In a gas, the particles have a lot of kinetic energy and are able to move freely, filling the available space. These three states of matter are the most familiar to us here on Earth.

The Sun is a rather different environment, with the centre of the sun being around 15 million°C. Consequently, the behaviour of the particles in the Sun does not correspond to that of a solid, liquid or gas. The Sun is a different state of matter, called a plasma (also shown on slide 3).

There are some plasmas that you may have encountered before: lightning, neon lights, the northern lights/auroras, electric sparks and plasma balls.

How do the particles behave in stars and in other plasmas? Firstly, plasmas are hotter or higher energy than solids, liquids and gases. This means that the particles move around more and they move faster. In a plasma, the tiny electrons are stripped away from the nucleus of the atoms, where the much larger protons and neutrons are (see slide 4 for illustration of this). This results in negatively charged ions – electrons – and positively charged ions – nuclei.

Similar to a gas, this plasma wants to spread out and take up as much space as possible. However, due to the ions' charges, plasma has an additional dimension to its behaviour. In a gas, the atoms or molecules move around randomly. In a plasma, the ions interact with each other when they come close. This behaviour can be explored if we imagine our plasma ions as magnets.

When two similar poles (two electrons or two nuclei) come close, they will repel. If two opposing poles (a nucleus and an electron) come close, they will attract each other. These repulsions and attractions create bursts of speed that are not present in the behaviours of other states mentioned.

BONUS FACT

In plasma, the particles are in such a high energy state that the nuclei and electrons do not stay recombined into atoms as they would do if the plasma was cooler, i.e. a gas.

These bursts of speed give plasma a less "placid" and consistent pattern of movement than the pattern seen in a gas. If plasma is magnets, a gas would be small bars of metal. A room full of randomly moving bars of metal and a room full of initially randomly moving magnets would have rather different resulting patterns of movement.

Stars are made of plasma. Stars are also incredibly massive – they are made of a large amount of matter and are very heavy. Although plasma will naturally spread out to take up as much space as possible, in a star, the plasma stays contained. This is due to the massive nature of the stars. The force of gravity pulling the plasma towards the centre balances out the plasma's attempts to expand.

If scientists and engineers are to create a sun on earth, one of their challenges is to find a way to prevent the plasma from expanding and cooling down. Given that the Sun is 15 million°C, there are significant challenges in attempting to contain something of this temperature. There are no know materials that can survive temperatures anywhere near 15 million°C.

Instead of attempting to create a material that can survive contact with the centre of the sun, scientists and engineers created the tokamak, shown on slide 5. A tokamak is a doughnut-shaped machine, a doughnut shape in geometry being called a torus. This design of machine uses electromagnets to induce a magnetic field. The plasma, made of ions, swirls around in this torus shape, and is pushed away from the walls of the machine by the electromagnetic field.

Oxfordshire is home to JET and MAST-U, two tokamaks. At the end of 2023, JET ran its last experiments. Now a new round of experiments begins – how to take apart and best process a fusion machine. MAST-U is a different shape to JET and many other tokamaks in that it has a cored apple shape. A huge new machine is being built in France, called ITER. Finally, the UKAEA is planning the world's first fusion machine combined with a power station, called STEP, to be built in Nottinghamshire.

FUN FACT

The electromagnets in JET are strong enough to pick up a small aircraft. The electromagnets in ITER will be strong enough to lift an aircraft carrier.

The activities in this pack explore how magnets behave, how electricity, charged particles and magnetic fields interact, and how these interactions play a huge role in fusion research today.

Activity 1: Magnetic fields

Compasses can be used for navigation. This is possible because the Earth has a magnetic field – there is a giant molten iron and nickel deposit in the outer core of the planet.

When a compass is brought near a magnet, the magnet has a stronger effect on the compass than the Earth's magnetic field, and so the compass will point based on the magnetic field of the magnet rather than of the Earth.

FUN FACTS

The North Pole of the planet in the Arctic Circle is actually the South pole of Earth's internal magnet.

The magnetic North and South poles on Earth "wander" up to tens of kilometres per year. Some creatures can sense the Earth's magnetic field, such as homing pigeons and honeybees. The consequences of magnetic polar wandering on creatures that use magnetoreception in migration are not well known.

WITH THE CLASS IN PAIRS:

- Get the pupils to position magnets with the North poles together, then South poles together, then opposite poles together. Note the attraction and repulsive forces. What happens if you put a pole to the centre of the other magnet?
- Get the pupils to move the compass around the magnet and vice versa. Watch the compass needle closely.

The direction that a compass needle points is based on magnetic fields. We can consider a compass to be a magnetic field detector. The compass needle is attracted towards the North and repelled by the South pole of the magnet. As you move the compass around the magnet, the needle points in different directions – this is the direction of the magnetic field lines. If you were to draw out all the directions that the compass needle points in all positions around the magnet, you would get a magnetic field line diagram. See slide 6 for an illustration of this.

FUN FACT

The alignment of the Earth's iron and nickel deposit, with the poles in the Arctic and Antarctica, is the reason the northern lights and southern lights are most visible at the poles. Near the poles, the magnetic field lines are closer together and therefore the effect is strongest. These lights are created when charged particles from solar wind interact with the Earth's magnetic field to form plasma.

DEMONSTRATION:

- Make a simple circuit, for example with batteries and a light. Hold one of the wires over a handful of plotting compasses. Close and open the circuit while the pupils watch the compass needles carefully. The needles should move when the circuit is complete. Switch the arrangement around so that the current flows in the opposite direction over the compasses. The compass needles should now move in the opposite direction. See Appendix A for set-up diagram and further information.

Considering compasses as magnetic field detectors, the movement of the needles when the wire from the complete circuit is nearby means that there is a magnetic field present when the circuit is complete. Reversing the direction of the flow of current reverses the magnetic field and so the compass needles move in the opposite direction.

Electricity or current is the flow of electrons. When we have moving electrons, we have a magnetic field. This applies to any charged particles, including the ions in a plasma.

KEY LEARNING POINT

Movement of charged particles generates a magnetic field. See slide 8 for an illustration.

Activity 2: Homopolar motor or spinning wires

See Appendix B for set-up. Information on suitable equipment and safety information can be found in Appendix B and the Risk Assessment. Further explanation on the science behind this activity can be found in Appendix E.

Demonstrate the following and then get the pupils to create their own:

- Take a strong magnet or pair of magnets.
- Place a battery on top.
- Bend a pre-cut length of wire to form a pinch in the centre.
- Continue to shape wire into rectangular shape.
- Balance the "pinch" on the battery and allow it to spin.

Have a couple of different shapes already bent and tested in different designs to demonstrate or to let pupils try, especially if they are having trouble.

It does not matter which way up the battery is, nor which way up the magnet(s) are relative to it. This means you can try inverting the battery or the magnets to see if it works better – it can make a big difference to the spinning speed.

TROUBLESHOOTING

- Check the contact points. The wire must touch the metal at the top of the battery. There must also be contact between the wire and the magnet.

  Bend the wire slightly to improve contact. Try placing the pinch point off the central bump or invert the battery.
- Check the balance. Is spinning impeded or impossible due to an uneven shape or unwanted contact?

  If this is proving difficult to resolve, try inverting the battery.

The electricity from the battery travels out and down through the wire, then travels up through the magnets back to the battery. This is a circuit, which means electrons are flowing. Movement of charged particles generates a magnetic field. As we saw earlier with the pairs of magnets, when two magnetic fields are close, they interact to generate a force – either attraction (pull) or repulsion (push). The magnetic field from the magnets interacts with the magnetic field from the circuit to produce a force. This force causes the wire to spin. Further information and diagrams illustrating this can be found in Appendix E.

FURTHER ACTIVITIES:

- Get the pupils to try out different wire shapes. More suggestions can be found in Appendix B.
- Challenge pupils to get the wire to spin the other way. This can be achieved by inverting the battery or the magnets. If you invert both, it cancels out so it stays the same.
- Challenge pupils to see if they can get the wire to spin faster. Adding more magnets should make it spin faster. This may be prevented by friction or an unbalanced wire.

Activity 3: Levitating pencil

See Appendix C for experimental set up and more information.

Magnets can attract magnetic items and repel or attract other magnets. Here we are going to use magnetic repulsion to make a pencil or similar item levitate.

- Hold magnets near each other to establish which sides attract and repel each other
- Place four magnet pairs onto the board and fix them in place (we used tape) – they should repel those beside them
- Place two more magnets on the pencil and fix them in place (we used tape)
- Place the pencil on top of the board, magnets above the magnets
- Use an object at one end of the floating pencil to keep the pencil's magnets positioned over the lower magnets

TROUBLESHOOTING

- Test the repulsion and attraction of the magnet pairs. Reverse the direction of the magnets until you can feel the pencil's magnets being pushed upwards by the lower magnets.
- Ensure all ring magnets are vertical and not slightly angled. If they are angled, the pencil will be pushed diagonally. This will move it out of the magnetic field. The pencil should be pushed directly upwards by vertically-oriented magnets otherwise levitation will not be achieved.

A simpler version of this activity can be performed with ring magnets and a pencil. Hold the pencil vertically and stack the ring magnets on the pencil. Invert some of the magnets. The upper magnets will be pushed up.

You can press down gently on the levitating magnets and feel the resistance. The magnets will then bob back up.

Unlike most types of forces, magnets do not have to make contact with something to exert a force upon it. Here we use magnetic repulsion to push magnets upwards. Using this method of magnetic repulsion, scientists and engineers can use the magnetic fields of electromagnets to push against the magnetic field created by the moving charged particles, ions, in plasma.

In our fusion machines at the UKAEA, we use electromagnets to create repulsive forces to push our plasma inwards. This keeps the plasma from expanding, stops it from cooling down, and also keeps it away from the walls of the machine. This reduces the temperatures the walls are exposed to, which means the materials lining the machine will last longer.

KEY LEARNING POINT

This kind of fusion machine is called a tokamak, and this method of using magnetic fields to hold and manipulate the plasma is called magnetic confinement.

A tokamak is shaped like a doughnut and the plasma spins around inside the doughnut shape. See slide 5 for a diagram of a tokamak machine.

FUN FACT

UKAEA's plasma is pink. The colour of the plasma is determined by the chemicals inside it, in the same way as a flame test or fireworks have different colours. Our machines usually use different isotopes of hydrogen, which gives a pink colour. Helium, a waste product, gives a blue or yellow colour.

Activity 4: Electric train

See Appendix D for set-up and additional information. Further explanation on the underlying science can be found in Appendix E.

- Coil a long length of wire. A broom handle or whiteboard pen might be a good starting point. The coil should be slightly larger in diameter than the batteries and magnets. Place the coiled wire on the table. This is your "train track".
- Take two or three strong magnets. Turn one so that it repels and place the battery in between. This is your "train".
- Place the train inside the coiled wire.

TROUBLESHOOTING

- Ensure the magnets are arranged correctly – they should repel each other.
- Push the train completely into the tunnel so that the rear magnet is also touching the wire.

This activity works in the same way as the homopolar motor or spinning wires activity. The electricity travels from the battery through the magnet, then through the wire to the magnet at the opposite end and back into the battery. As before, the force pushes the wire away from the magnet. In this case this does not result in the wire spinning. Instead, the train spins and also travels along inside the tunnel.

More things for you to try with your train:

- Join the ends of the tunnel together and allow the train to whizz round in a loop.
- Cross the tunnel over itself or on top of an object and challenge the train to climb uphill.
- Try compressing and stretching the tunnel along its length. Does this make a difference?
- Add another magnet to your train. It should go faster.
- If your tunnel loop is long enough, add a second train.

Summary

We have learned that the matter inside the sun is not a solid, liquid or gas but a plasma. Solids, liquids and gases are made of atoms or molecules. Plasmas are made of ions – positively charged nuclei and negatively charged electrons. Plasmas are a higher energy state than solids, liquids and gases, so they are hotter and their particles move around faster.

Magnets can attract and repel other magnets and can produce forces without the need for contact. A compass can be used as a "magnetic field detector" and we can use this to see that wires with current running through them have a magnetic field. This is due to the movement of charged particles, in this case electrons, inducing a magnetic field.

If we combine the magnetic field due to the moving electrons with the magnetic field due to the magnets, we see the interaction between the two magnetic fields produces a force which makes the wire spin. This is despite the fact that the force produced is perpendicular to the wire.

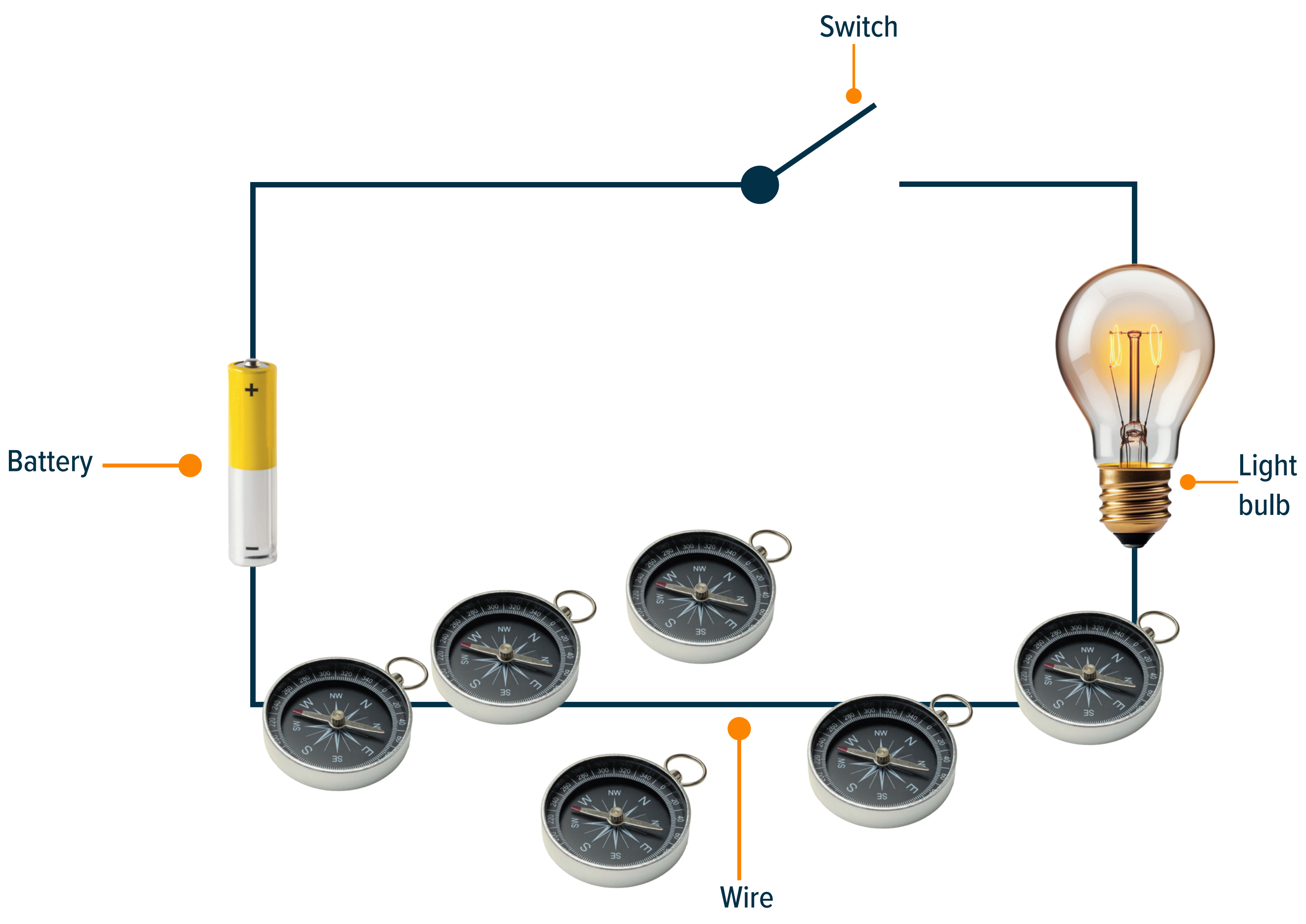
The electric train activity uses the same interactions to produce the effect of the train simultaneously spinning around and travelling through the coiled wire tunnel.

Tokamak style fusion machines use magnetic confinement, which means large electromagnets use magnetic forces to contain and control hot plasma.

Appendices

Appendix A

EXPERIMENTAL SET-UP FOR ACTIVITY 1



ADDITIONAL INFORMATION

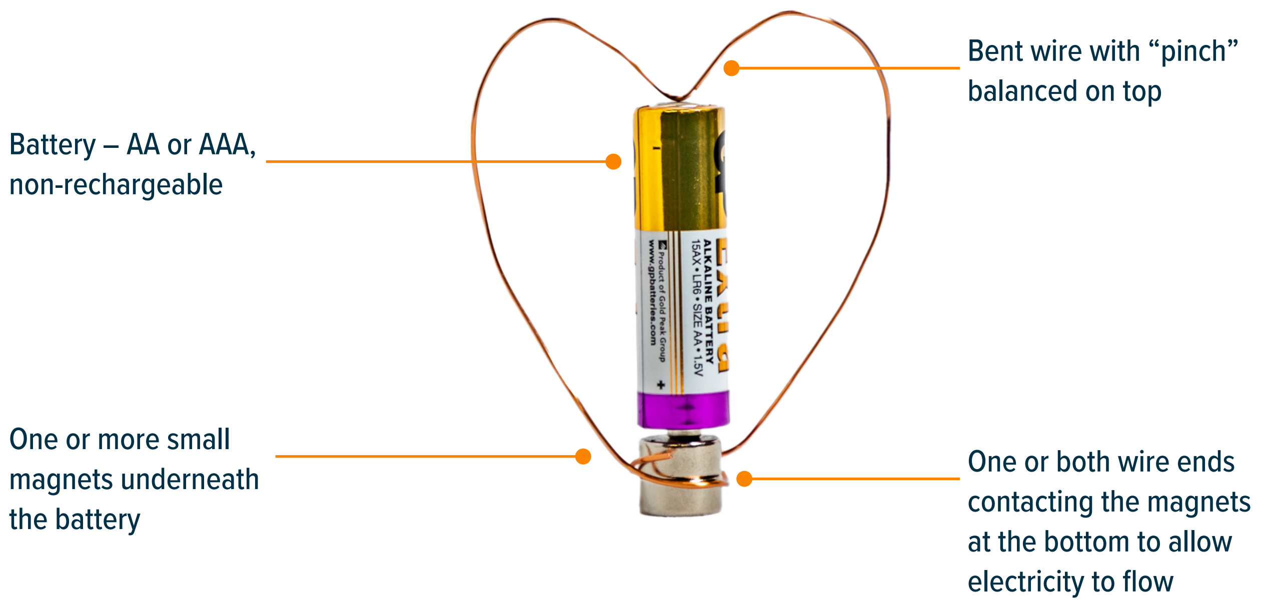
Although most household appliance cables will not cause the compass needles to deflect, a deflection was seen when a hair dryer cable was very close to the compass. A phone charger cable with a fabric sheath (rather than plastic) also caused visible movement.

Using classroom circuit components to build a circuit is recommended, but an additional experiment or a low-kit version could be done using this information.

Additional experiments could also be done on whether insulated or stripped wire make a difference to how much the compass needle deflects. In all cases, ensure the wire used is not too thin and that the circuits are safe for the pupils and setting.

Appendix B

EXPERIMENTAL SET-UP FOR ACTIVITY 2



Additional design ideas: heart, asymmetrical, spiral, wide, narrow, cage.

ADDITIONAL INFORMATION

For this activity, you will need uninsulated wire. Coated or enamelled wire is also no good. These coatings or insulation will prevent the wire from making contact with the battery and magnet and the wire will therefore not spin.

Wire cutters are recommended for making the pre-cut lengths. The ideal length depends on the desired shape and also on the size of battery and magnets. 15cm should provide plenty of scope to work with without being cumbersome.

AA and AAA batteries are suitable for this experiment. AA batteries were slightly easier to work with.

We used 12mm diameter neodymium magnets and found that it was the perfect size for AA or AAA batteries.

Adding additional magnets will increase the strength of the magnetic field. This will increase the force on the wire, resulting in a greater spin speed.

The battery can be inverted. Its orientation is not important for the experiment to work. Inverting it can however resolve issues with balancing the wire on top.

Sometimes inverting the battery or the magnets can get a reluctant wire to spin.

Appendix C

EXPERIMENTAL SET-UP FOR ACTIVITY 3

When balanced correctly, this pencil floats above the magnets at the bottom. Feel the magnetic forces as you assemble this experiment.

N-S
N-SN-S
N-SN-S

S-N
S-NS-N
S-NS-N

This object prevents the pencil from moving sideways out of the magnetic field of the lower magnets.

Here we used a small cardboard box, pencils and tape to stabilise and secure the lower magnets.

ADDITIONAL INFORMATION

This experiment can be tricky to set up and may take a little time and patience to see success.

To stabilise the lower magnets, we put pencils through a small cardboard box. We found this easier than using tape alone, as the pencils helped to keep the magnet pairs vertical.

Appendix D

EXPERIMENTAL SET-UP FOR ACTIVITY 4

Uninsulated uncoated copper wire to allow the electricity to flow and make a circuit on contact.

Form the tunnel using something slightly larger in diameter than the battery and magnets. We used a whiteboard pen.

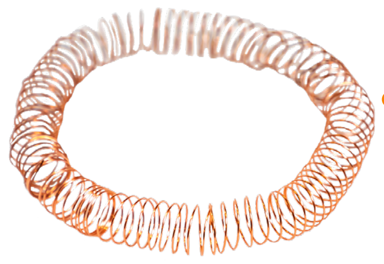
This is the train. Note the orientation of the magnets.

See below.

S N
or
N S

N S
or
S N

The magnets must be marginally larger in diameter than your battery.



Try out the additional ideas, like creating a loop. Which one is your favourite?

ADDITIONAL INFORMATION

The magnets should be the same diameter or marginally larger than the battery so that the magnets at both ends can touch the wire simultaneously. We found AAA batteries work with 12mm diameter neodymium magnets. Slightly larger magnets would be needed to work with AA batteries.

The wire coil should be large enough in diameter for the train to fit in easily. The larger in diameter the coil, the greater the length you will need to make a reasonable length of tunnel, hence a smaller diameter is better. Try a broom handle or thick pen for starting points for coil forms.

Appendix E

ADDITIONAL EXPLANATION FOR ACTIVITY 2 AND ACTIVITY 4

Current flows around the circuit from the protruding positive terminal, through the wires, down to the magnets, then returns to the battery through the flat negative terminal. Due to convention, electrons flow in the opposite direction to current. This is shown in the first diagram.

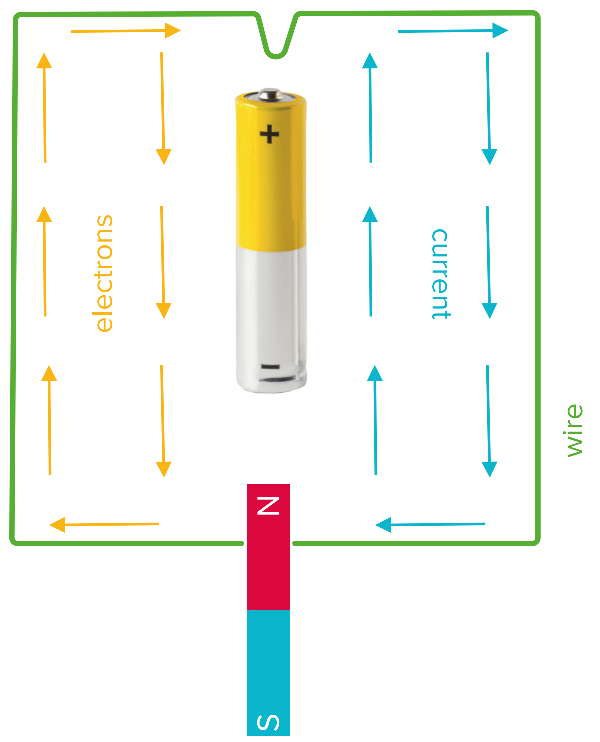
The right hand rule states that if the direction of force is up (thumb), the direction of current is pointing out in front of you (pointer finger) and the direction of the magnetic field is left (middle finger) this is shown on the diagram on the right.

Combining our circuit and the right hand rule, both wires show current (pointer finger, blue) travelling downwards. The magnetic field in both cases is pointing out away from the base of the battery. On the right side, the magnetic field (red arrow, middle finger) is pointing right, and on the left side, pointing left. That leaves the direction of force (purple arrow, thumb). On the right hand side, this comes towards us out of the page, on the left side it runs into the page.

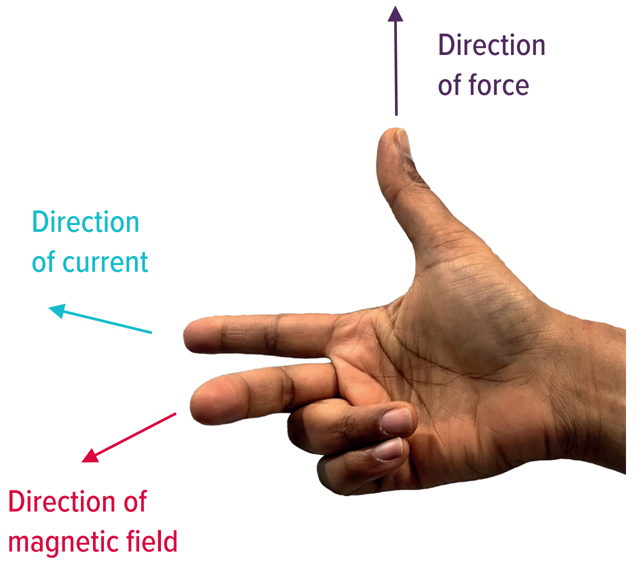
The same principles apply in Activity 4. In this case, the direction of current moves around the battery, along the lines of the coils of wire. Consider this (initially) to be a line flat on the table. The direction of magnetic field comes straight up from the table top. That leaves the direction of force to be along the coil, in the direction the battery lies.

Additional time can be spent discussing why the movement is rotational when the force applied is perpendicular. Additional time can also be spent drawing out diagrams like those in Appendix E for Activity 4.

The current flows from the positive terminal (with the bump), through the wires down to the magnets, then back into the negative terminal. Due to convention, electrons move in the opposite direction to current flow.



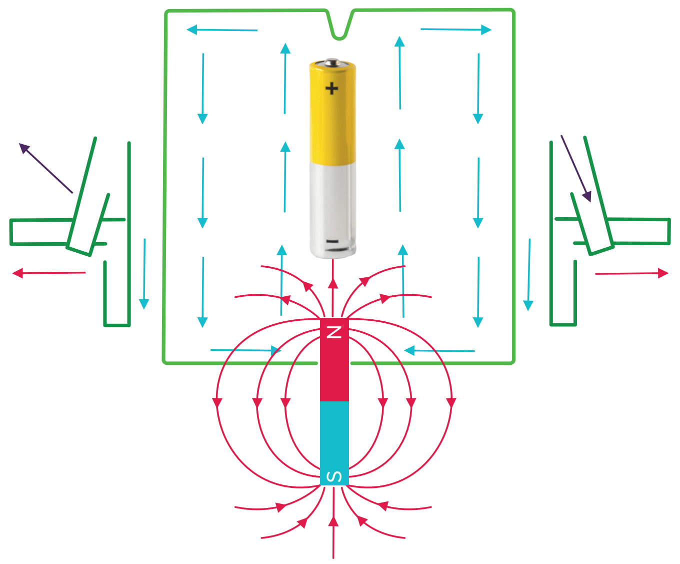
The right hand rule:



When you add the right hand rule on to the diagram, the current is flowing down the wires on the outsides (blue arrow on hands). The magnetic field is going away from the magnet (i.e. left on the left side and right on the right side, red arrows on hands) and the force is therefore the thumb (purple arrow on hands, running into the page on the left and out of the page on the right). Therefore, if viewed from the top, this setup would spin clockwise.

If the magnet were to be inverted, the magnetic field would be reversed, making the red arrows on the hands point towards the centre rather than away from each other. I.e. the hands would switch places and the setup would spin counter clockwise.

Likewise, if the battery is inverted, the current will flow in the opposite direction, changing the direction of the blue arrows, and also switching the direction of spin. You can use the right hand rule to show or calculate these as well.



Risk assessment

DESCRIPTION OF TASKS	POTENTIAL HAZARDS	WHAT COULD GO WRONG?	WHAT WILL BE DONE TO CONTROL THESE RISKS?
Activity 1 – magnetic fields. Using magnets and compasses to investigate magnetic forces and magnetic fields.	Small parts	Injury could result from swallowing magnets or compasses.	Ensure magnets and compasses are not given to small children or those who may attempt to swallow them.
Using a circuit to make a compass needle deflect.	Using electricity		Ensure the circuit used is safe.
Activity 2 – homopolar motor. Using magnets, batteries and wires to make a wire spin.	Wire could get hot	Burns or mild discomfort	Use appropriately thick wire. Motor not to be left running for long periods of time especially if there is no movement – remove the wire and try again. Disposable batteries to be used, not rechargeable batteries.
	Strong magnets	Pinch injuries	Verbally warn participants that magnets are strong, that they could potentially cause pinch injuries and to use appropriate caution.
	Ends of cut wire may be sharp.	Scratches	Ensure supervision and or gloves available if appropriate.
Activity 3 – levitating pencil. Using magnets to make a pencil levitate.	Strong magnets	Pinch injuries	Verbally warn participants as above.
Activity 4 – electric train. Using a battery, magnets and wire to create a moving “train” through a tunnel	Strong magnets	Pinch injuries	Verbally warn participants as above.
	Wire could get hot	Burns or mild discomfort	Use appropriately thick wire. Do not allow the train to sit in the coil of wire unmoving for long periods of time.
	Ends of cut wire may be sharp	Scratches	Ensure supervision and or gloves available if appropriate
Wire cutters (may be used to set up activities 2 and 4).	Wire cutters have sharp edges. Finger traps.	Nicks, finger traps, minor injuries	Wire cutters to be used by responsible adults only.

Please note that classroom related risks, pupil related risks and others are not included on this risk assessment.

UK Atomic Energy Authority

The UK Atomic Energy Authority's mission is to lead the delivery of sustainable fusion energy and maximise scientific and economic benefit

Find out more
www.gov.uk/ukaea

UKAEA is one of the world's leading fusion research laboratories, where our scientists and engineers are working with partners around the globe to develop fusion as a new source of cleaner energy for tomorrow's power stations. We are at the forefront of delivering fusion energy – a sustainable low carbon energy source that could change the world.

Fusion is based on the same processes that powers the stars. In the face of a changing climate and dwindling fossil fuel reserves, fusion offers the potential for a safe, abundant, low carbon, reliable baseload energy supply.

With our partners from industry and academia we will all support UKAEA's mission through:

- **Commitment**
- **Performance**
- **Openness & transparency**

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