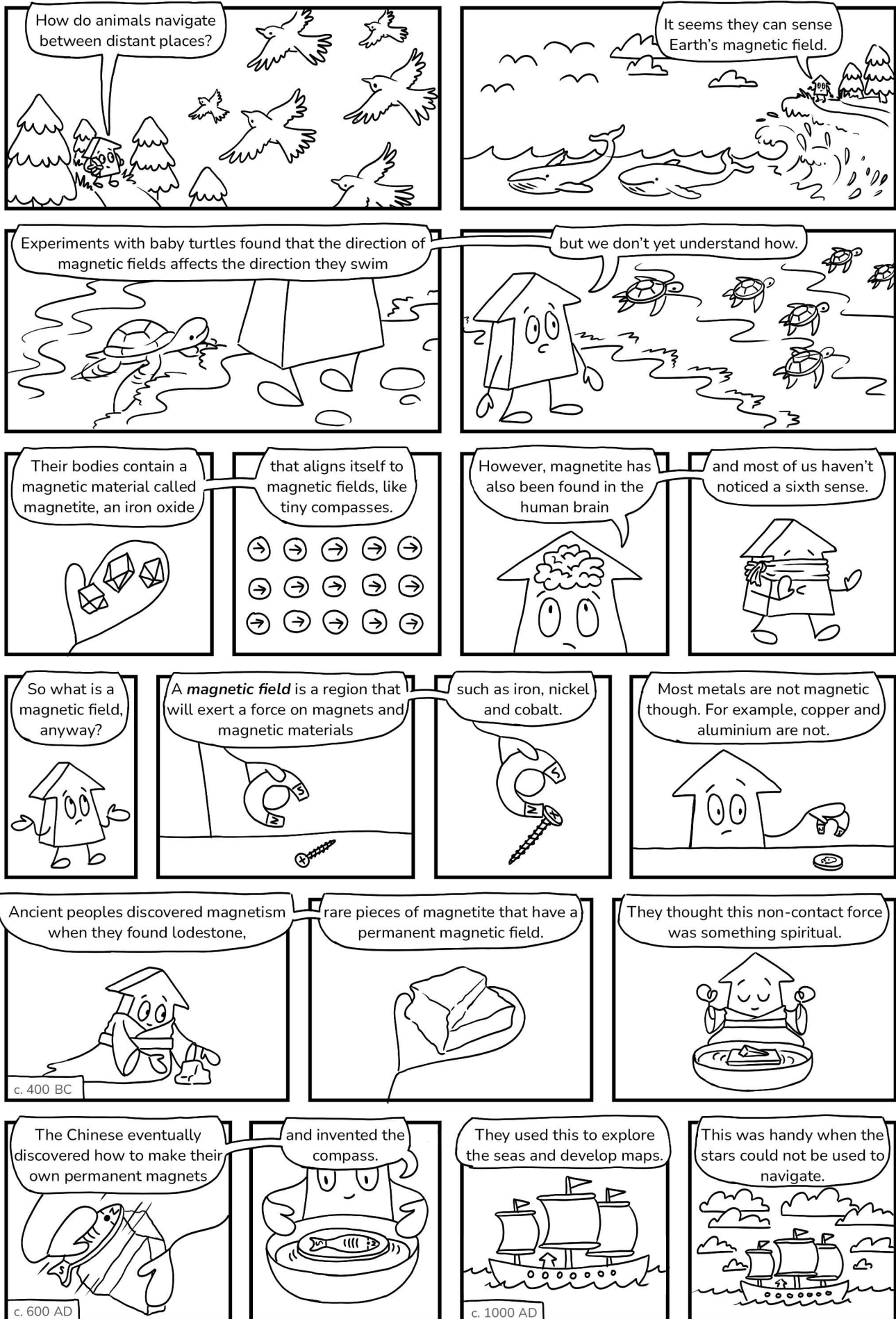
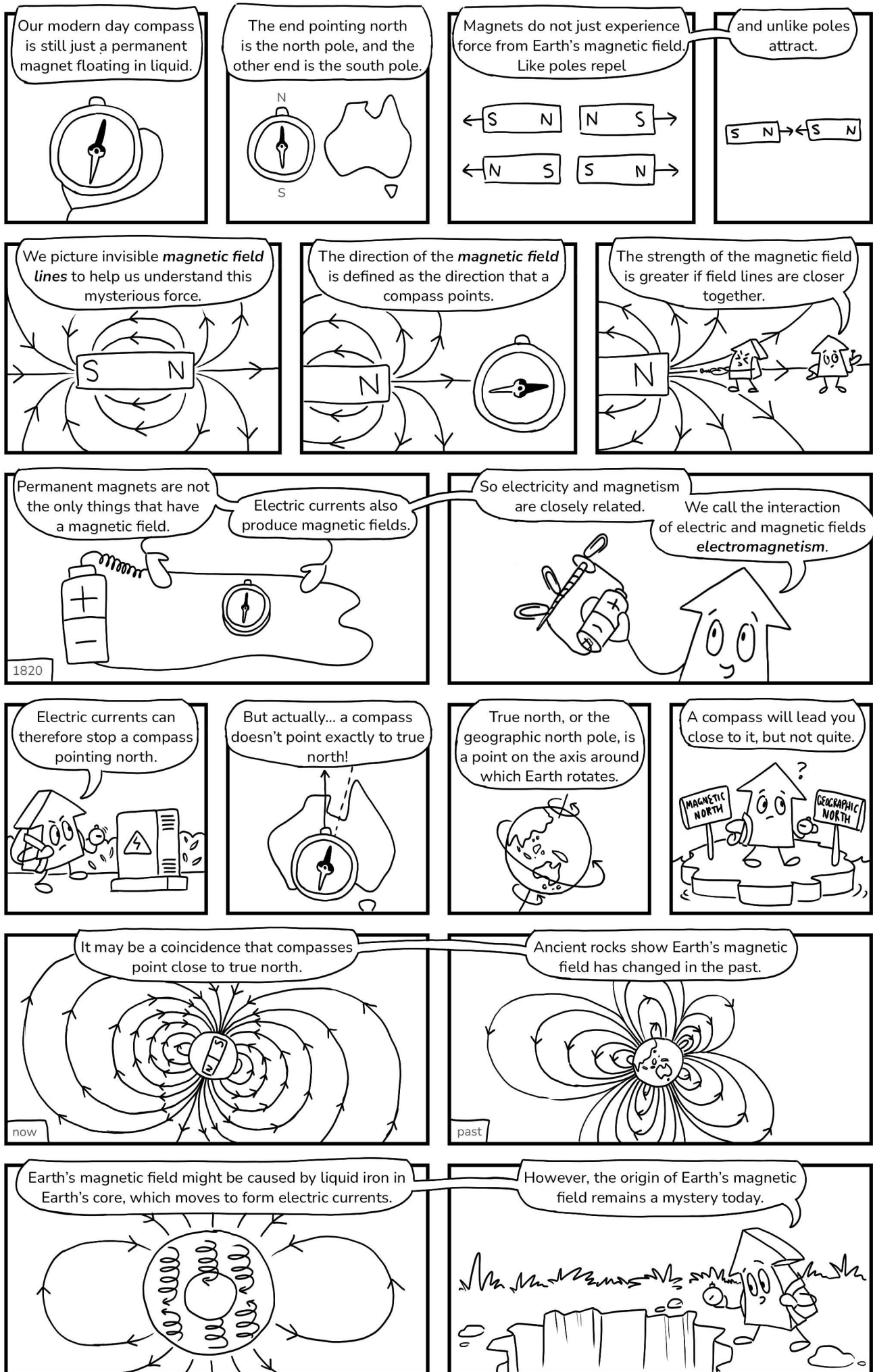


13.1 Magnetism and finding true north





13.2 Magnetic fields around permanent magnets

1. Describe magnetic fields by filling in the blanks.

attract	closer	compass	cross	density	field	invisible
iron	magnetic field	model	north	north	pole	repel
resultant	south	south	stronger	tangent	touch	vector

A _____ is a region where an object experiences a non-contact force. A _____ is a region that will exert a force on magnets and magnetic materials. For example, a fridge magnet will exert a magnetic force on objects containing _____, such as a paper clip. The fridge magnet only needs to be close enough to the paper clip, but does not need to _____ it.

Magnets have a north pole and a south _____. If the north pole of one magnet is brought close to the south pole of another, they will _____. If like poles of two magnets are brought close together, they will _____.

Magnetic fields are _____, but sprinkling iron filings in the region will reveal their shape. We can _____ the magnetic field by drawing field lines that follow this shape.

The strength of the magnetic field is represented by the _____ of the field lines. In other words, if field lines are closer together, the magnetic field is _____. Therefore, field lines around a bar magnet will be _____ together near the poles than away from the poles.

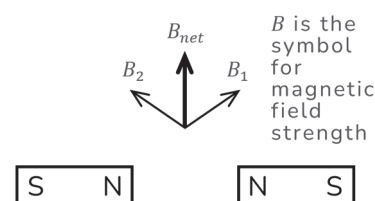
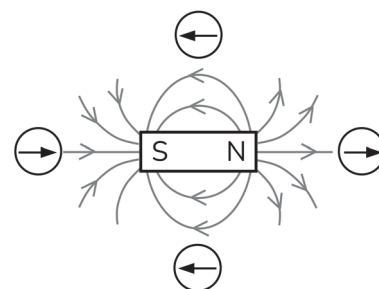
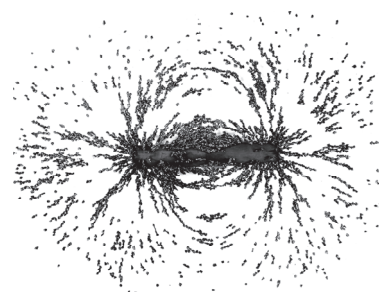
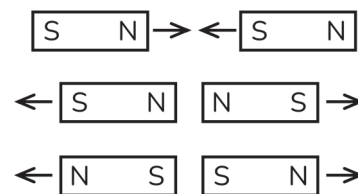
The direction of a magnetic field is defined as the direction that the north pole of a _____ will point. Since a compass is actually a magnet, this means that the north pole of a compass will be repelled from the _____ pole of a bar magnet, and attracted towards the _____ pole of a bar magnet.

This means that the direction of magnetic field lines around a bar magnet go from its _____ pole to its _____ pole.

Since the direction of the field lines shows the direction a compass will point, this means the compass direction is given by the _____ to the magnetic field line at each position.

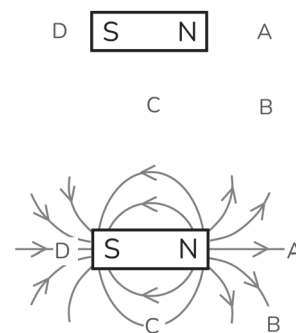
It also means that magnetic field lines cannot _____, because the compass will not point in two different directions.

Because a magnetic field has both strength and direction, it is a _____ quantity. So if there is a magnetic field exerted by two different magnets, the strength and direction of the magnetic field at one point is given by the _____ of the magnetic fields from each magnet.



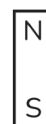
2. A bar magnet is shown to the right.

- Draw an arrow at each point A, B, C, and D, showing which way a compass would point if it were placed at that point.
- The magnetic field lines around the bar magnet are now shown. Describe the relationship between the arrows you drew in part (a) and the magnetic field lines shown.



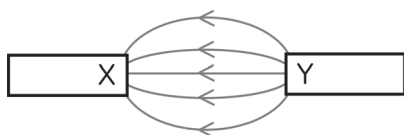
- Explain which point, A, B, C, or D, has a stronger magnetic field.

- The bar magnet is rotated by 90° as shown. Draw the magnetic field lines around it.

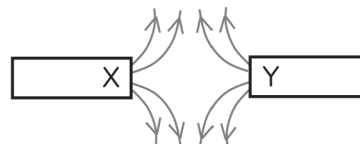


3. The magnetic field between pairs of bar magnets is shown. Identify whether X and Y are north or south poles on each.

a)



b)



4. For each pair of bar magnets below, draw the magnetic field between the pair of bar magnets and compare the strength of the magnetic field at points X and Y.

a)

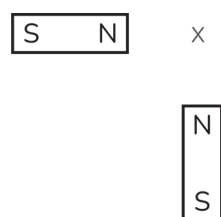


b)



5. Draw an arrow showing the direction of the magnetic field at point X. Show your working, by drawing the magnetic field from each individual magnet, then finding the resultant.

a)



b)



c)



6. Magnets come in a variety of shapes and sizes, but they all have a north pole and south pole. To model the magnetic field using field lines, the same rules apply. Draw the magnetic field lines around the following magnets, focusing on the area near or between the poles.

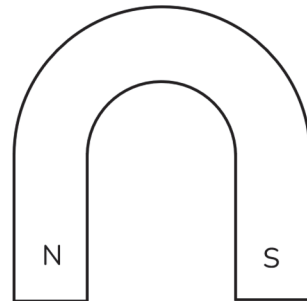
a) Disc magnet:

Often used for holding things, for example fridge magnets.



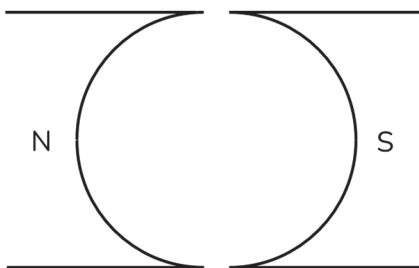
b) Horseshoe magnet:

Good for gripping heavy objects, looks good in cartoons.



c) Curved magnets:

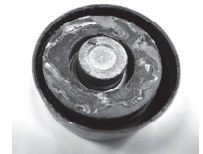
Used in motors, analog ammeters and voltmeters, so that electric current through a coil in the magnetic field makes the coil turn.



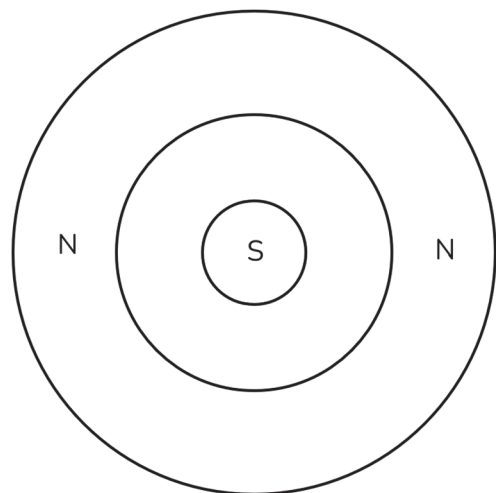
These are the poles of two curved magnets, which create a radial magnetic field between them. The other pole on each magnet is not shown.

d) Ring magnets:

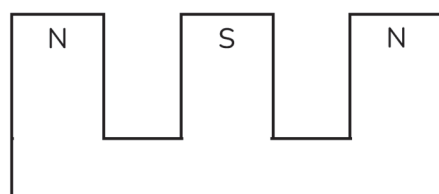
Used in loudspeakers. Current through a coil around the central pole makes the coil vibrate in the magnetic field, which makes the speaker cone vibrate.



Top view:



Side-on view:



13.3 Magnetic fields around currents

Long, straight current-carrying conductors

- Describe the magnetic field around straight conductors by filling in the blanks.

away	circle	clockwise	compass needle	cross
decreases	dot	Earth's	electromagnetism	electrons
fingers	further apart	left	positive	produce
right	straight conductor	thumb	two dimensional	

In 1820, Hans Christian Oersted showed that when a current flowed through a straight wire, it could make a _____ deflect, so that it pointed at right angles to the wire. When the current was switched off, the compass went back to pointing in the direction of the _____ magnetic field.

This implies that an electric current can _____ a magnetic field. It shows that electricity and magnetism are linked, opening up a new area of study in physics called _____.

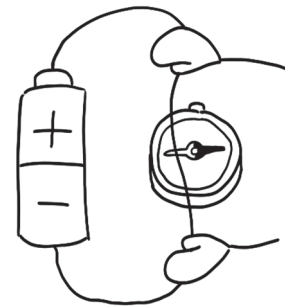
One way to remember the observed direction of the magnetic field around a _____ is the "**right hand grip rule**". Point your right _____ in the direction of the current. Then, the direction your _____ would close if you were gripping something gives the direction of the magnetic field. This direction goes in a _____ all the way around the current-carrying conductor. Recall that current direction is defined as the direction _____ charge flows, which is the opposite direction to the flow of _____.

As fields extend in all three dimensions, we need new symbols to represent them on a _____ page. We can represent the direction out of the page with a _____ – imagine an arrow is coming towards you and what you see closest to you is the arrow tip. We can represent the direction that is into the page with a _____ – imagine the arrow is going away from you and what you see closest to you is the tail feathers.

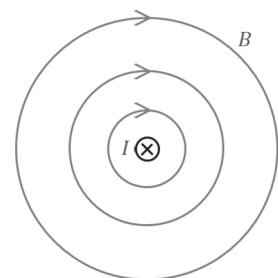
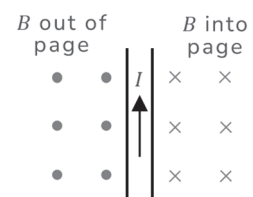
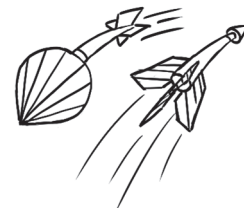
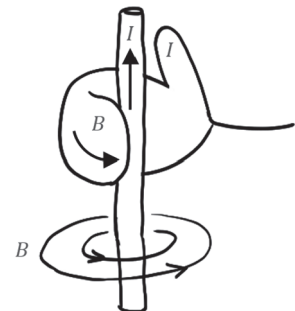
Therefore, to represent the magnetic field around a current going up the page through a straight conductor, we can use dots on the _____ of it, to show the magnetic field is out of the page, and crosses on the _____ of it, to show the magnetic field is into the page.

We can also use dots and crosses to represent current direction, so if the current in the conductor is travelling _____ from you, into the page, you use a cross. The right hand grip rule would tell you that the magnetic field around this current is _____.

The strength of the magnetic field as you move away from the conductor _____. Therefore, you need to draw the magnetic field lines _____.



Right hand grip rule



2. Draw the magnetic field around the following current-carrying conductors.

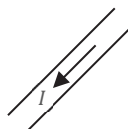
a)



b)



c)

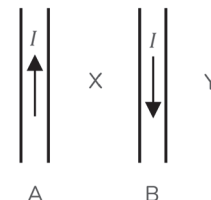


Use your right hand!

To represent fields in 2D on a page, you can draw dots, crosses or circles.

3. Two wires, A and B, carry a current of the same magnitude, as shown. In what direction is:

- the magnetic field at point X due to wire A? _____
- the magnetic field at point X due to wire B? _____
- the resultant magnetic field at point X? _____
- the magnetic field at point Y due to wire A? _____
- the magnetic field at point Y due to wire B? _____
- the resultant magnetic field at point Y? _____



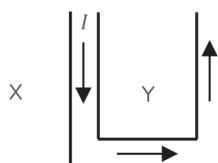
Recall that magnetic field strength gets weaker as distance from the wire increases.

4. Circle the option that identifies the direction of the magnetic field at points X and Y in the following scenarios.

- a) The two currents have the same magnitude. Point X is halfway between them.



- b) Point Y is the same distance from each side.



Recall the resultant magnetic field is the vector sum of the magnetic fields from each object producing one.

X: left / right / up / down / into page / out of page / zero

X: left / right / up / down / into page / out of page / zero

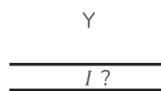
Y: left / right / up / down / into page / out of page / zero

Y: left / right / up / down / into page / out of page / zero

If you feel like you're twisting your arm, try rotating the page instead.

5. The direction of the magnetic field at a point, near a straight current-carrying conductor, is either stated or shown by a compass. State the direction of the current.

a)



Magnetic field at Y is into page

b)



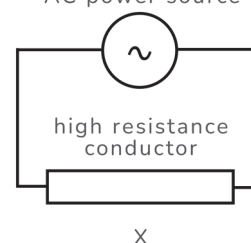
c)



Current direction: _____ Current direction: _____ Current direction: _____

6. Alternating current (AC) means current that switches direction periodically. A power source of alternating current is connected to a high resistance conductor, as shown. Explain what happens to the magnetic field at point X.

AC power source



Current-carrying coils

7. Describe the magnetic field around a current-carrying coil by filling in the blanks.

bar magnet	compass	current	fingers
into the page	magnetic field	north	right hand coil
right hand grip	single coil	south	stronger
thumb	turns	vector sum	weaker

When current flows along a conductor that is not straight, it still produces a _____. The magnetic field at a point will be the _____ of the magnetic field from each bit of the conductor.

The magnetic field inside a circular coil with a current travelling clockwise in it will therefore be _____. This is because if we use the “_____ rule” and stick our thumb on each point on the circular coil in the current direction, our _____ always point into the page in the middle of the coil.

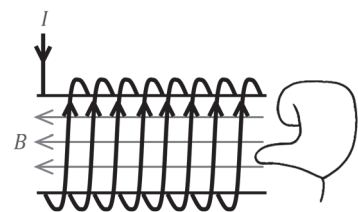
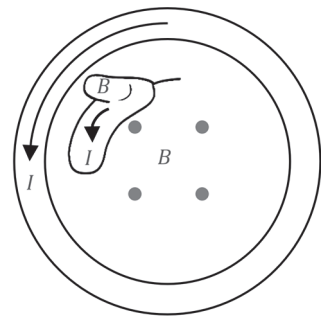
To work out the direction of the magnetic field in a coil faster, we can use the “**right hand coil rule**”. This time, your fingers wrap in the direction of the current in the coil and your _____ represents the direction of the magnetic field inside the coil.

A **solenoid** consists of a long wire looped around many turns around a cylinder. Each turn contributes a magnetic field inside the solenoid the same way a _____ does. Therefore, the more turns, the _____ the magnetic field inside the solenoid will be, with the direction given by the _____ rule. Solenoids can often have hundreds of _____.

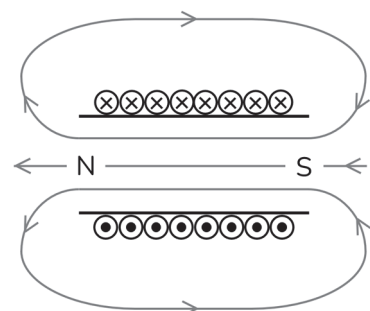
Outside the solenoid, there is still a magnetic field, which gets _____ away from the ends of the solenoid. The shape of the magnetic field outside the solenoid is similar to the magnetic field around a _____. Unlike a bar magnet, we can turn the magnetic field from the solenoid on and off, by switching the _____ on and off. This is how an **electromagnet** works, and these are found in automated locking systems.

The magnetic field lines outside the solenoid go from the _____ pole to the _____ pole of the electromagnet. However, inside the solenoid, they go from the south pole to the north pole, since this is the direction that a _____ inside the solenoid would point.

Right hand coil rule

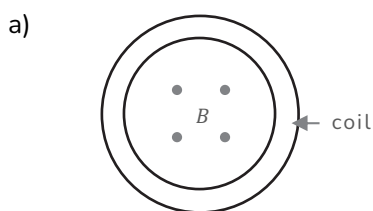


This solenoid has 8 turns

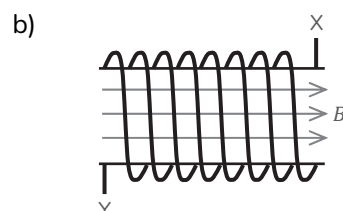


Same solenoid as above, cross section shown

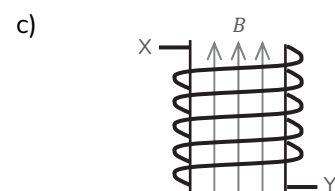
8. Which way must the current travel to produce the magnetic field shown? Circle the correct answer.



Clockwise / anti-clockwise



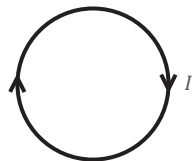
From X to Y / From Y to X



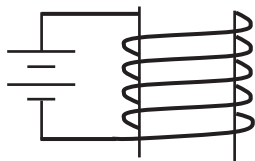
From X to Y / From Y to X

9. A magnetic field is produced by a current in the following scenarios.

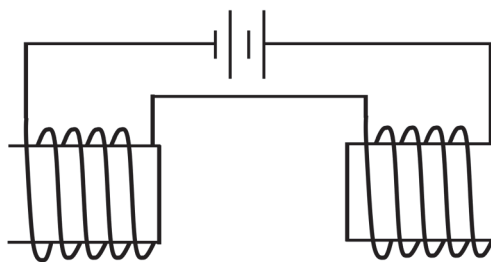
a) Draw the magnetic field inside the coil.



b) Draw the magnetic field in the solenoid and identify the poles.

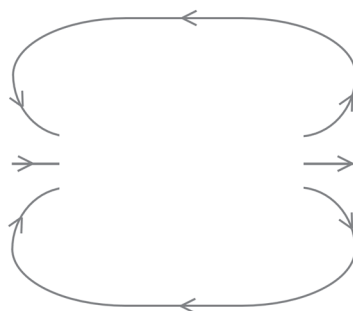
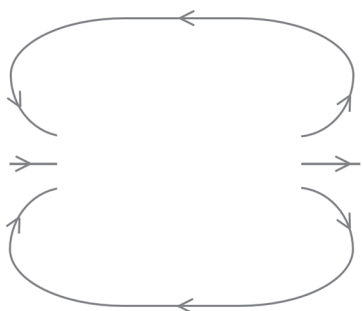


c) Draw the magnetic field between the solenoids and identify the poles.



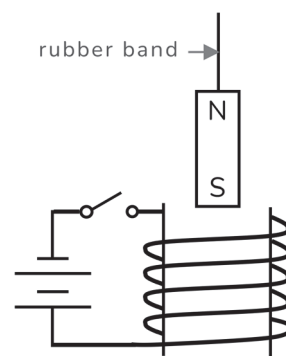
10. In the TV series *Stranger Things*, a curious group of kids notice that their compass points to a laboratory as they walk around it, instead of pointing north. Propose and explain what could be underground at the laboratory if this happened in real life.

11. A similar magnetic field is produced by two different objects, shown below. Add a drawing of each of the objects that could create the magnetic field.



12. Explain why the magnetic field inside a solenoid is stronger than the magnetic field produced by a straight conductor, carrying the same current.

13. A bar magnet hangs from a rubber band, above a solenoid attached to a power source. Explain what happens to the magnet when the switch is closed.



13.4 Magnetic field strength

Long, straight current-carrying conductors

- Describe magnetic field strength around a straight conductor, by filling in the blanks.

constant	current	distance	force	iron	right hand grip
shape	small	vacuum	vector	vector sum	

Magnetic field strength is related to how much _____ is exerted on magnetic objects by an external magnetic field, and is measured in **tesla** (T).

The magnetic field strength at a point due to a current-carrying conductor is given by the _____ of the magnetic field strength contributed by each bit of the conductor. If you change the _____ and size of the conductor, you change the magnetic field strength. For a long, straight current-carrying conductor, the magnetic field strength is given by:

$$\vec{B} = \frac{\mu_0 I}{2\pi r}$$

where: $\vec{B}$ = magnetic field strength (T)

$\mu_0 = 4\pi \times 10^{-7}$ (N A⁻²) (permeability of free space)

I = _____ through the conductor (A)

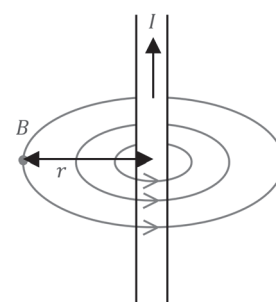
r = perpendicular _____ from the conductor (m)

μ_0 is a _____ called the **permeability of free space**.

Magnetic permeability means how much a material affects the strength of a magnetic field passing through it. The permeability of free space is defined for a magnetic field passing through a _____. For a magnetic material such as _____, the permeability would be much higher.

This formula assumes that r is _____ compared to conductor length.

Magnetic field strength is a _____, so it has a magnitude and a direction, given by the _____ rule for a straight conductor.



Free smartphone apps allow it to be used as a compass, to measure magnetic field direction, or a magnetometer, that measures magnetic field strength. The reason why smartphones have a magnetometer built in is so navigation using maps works.

Example: Two long wires are shown, one carrying a current of 1.5 A and the other 1.0 A. Determine the magnetic field at points X and Y.

Answer:

At X from left wire: $\vec{B} = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \times 1.5}{2\pi \times 2.5 \times 10^{-3}} = 1.2 \times 10^{-4}$ T out of page

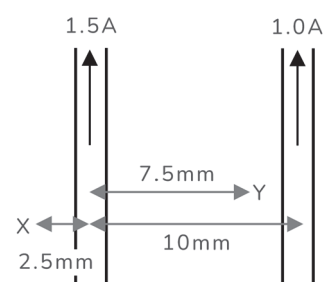
At X from right wire: $\vec{B} = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \times 1}{2\pi \times 12.5 \times 10^{-3}} = 1.6 \times 10^{-5}$ T out of page

Total at X: $\vec{B} = 1.2 \times 10^{-4} + 1.6 \times 10^{-5} = 1.36 \times 10^{-4}$ T out of page

At Y from left wire: $\vec{B} = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \times 1.5}{2\pi \times 7.5 \times 10^{-3}} = 4 \times 10^{-5}$ T into page

At Y from right wire: $\vec{B} = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \times 1}{2\pi \times 2.5 \times 10^{-3}} = 8 \times 10^{-5}$ T out of page

Total at Y: $\vec{B} = 8 \times 10^{-5} - 4 \times 10^{-5} = 4 \times 10^{-5}$ T out of page



2. The table below gives a rough idea of the size of some magnetic fields. Write each in scientific notation. Some of the table is done for you as an example.

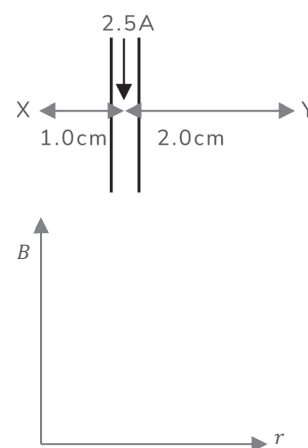
Object	Magnetic field	Magnetic field in scientific notation
Human brain	1 pT	$1 \times 10^{-12} \text{ T}$
Toaster in use	500 nT	
Earth's magnetic field at equator	31 μT	
Fridge magnet	5 mT	
Neodymium magnet	1.25 T	1.25 T
Strongest continuous magnetic field produced in a laboratory	45.22 T	$4.522 \times 10^1 \text{ T}$

3. The unit for magnetic field strength, tesla (T), is not an SI unit. Use the formula for magnetic field strength to deduce the equivalent unit for a tesla in SI units, comprising kg, A and s.

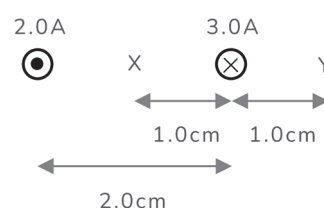
4. A long wire is shown, which carries a current of 2.5 A.

- a) Determine the magnetic field at each of points X and Y.

- b) Sketch a graph of the magnetic field strength vs distance from the wire.



5. The cross sections of two long wires are shown, one carrying a current of 2.0 A and the other 3.0 A. Determine the magnetic field at points X and Y.



Draw vectors on the diagram to represent the magnetic field from each wire, to help with working out the resultant.

6. In a Sydney laboratory, the horizontal component of Earth's magnetic field is measured to be $50 \mu\text{T}$ and makes a compass sitting horizontally on a bench point north. A long, straight wire is positioned 1.5 cm above the compass, parallel to the bench top, running in a north-south direction. What current would be required to make this compass point north east, and which way must it flow through the wire?

Use pens as visual aids to represent the compass, magnetic fields and the wire.

Solenoids

7. Describe magnetic field strength due to a solenoid, by filling in the blanks. Use the diagrams to help you.

coil	current	length	length	magnetic field	permeability
proportional	solenoid	tightly	turns	turns	uniform

A coil with many turns is called a _____. If a solenoid is much longer than its diameter, and the coils are very close together, the magnetic field inside the solenoid is _____. Its direction is given by the right hand _____ rule.

The magnetic field strength inside a solenoid is given by:

$$\vec{B} = \frac{\mu_0 NI}{L}$$

where: $\vec{B}$ = _____ strength (T)

$\mu_0 = 4\pi \times 10^{-7} \text{ (N A}^{-2}\text{)}$ (_____ of free space)

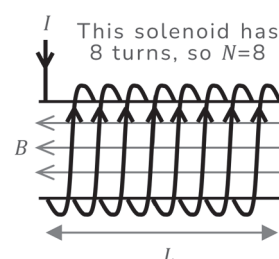
I = _____ through the conductor (A)

N = number of _____

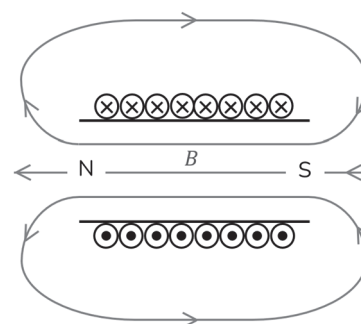
L = _____ of solenoid (m)

The formula tells us that the magnetic field strength is _____ to the current, which means that the strength of an electromagnet made using a solenoid can be varied by changing the current.

The magnetic field strength can also be increased by increasing the number of _____ or decreasing the _____ of the solenoid. This means that packing the coils _____ together, so there are more turns per length, will increase the magnetic field.



Same solenoid as above, cross section shown



Example: A solenoid has a 13 cm coil length. When a current of 5.0 A flows through the solenoid, a magnetic field of 27 mT is produced inside the coil. How many turns does the solenoid have?

Answer: $\vec{B} = \frac{\mu_0 NI}{L}$

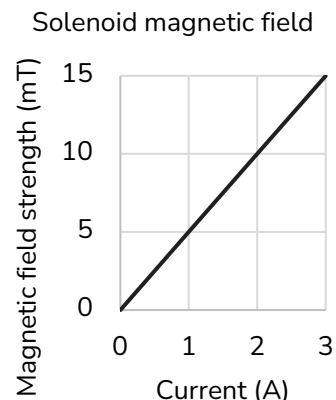
$$0.027 = \frac{4\pi \times 10^{-7} \times N \times 5}{0.13}$$

$$N = 560 \text{ turns}$$

8. A small solenoid has a length of 6.00 cm and 2160 turns, with a resistance of 131 Ω . When connected to a 12.0 V power supply, what would be the magnetic field inside the solenoid?

9. The graph shows the magnetic field strength inside a solenoid as the current is varied. Calculate the number of turns per centimetre in the solenoid.

$\frac{N}{L}$ gives turns per metre



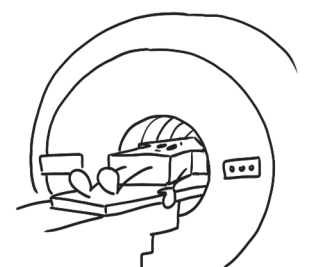
10. Explain why an effective solenoid needs to have a tightly wound coil.

11. Magnetic resonance imaging (MRI) uses magnetic fields to detect causes of injuries and tumours from cancer. MRI works by detecting hydrogen nuclei in us, which each have a small magnetic field. A patient undergoing MRI is put inside a large solenoid, which produces a strong magnetic field that makes the magnetic fields of the hydrogen nuclei align in the same direction. Also, a pair of coils, called RF coils, sit on each side of the large solenoid. A current through the RF coils is turned on for a short time, to add a second magnetic field. Once the current in the RF coils is turned off, the time taken for the hydrogen nuclei to re-align with the original magnetic field gives information about the patient's tissues.

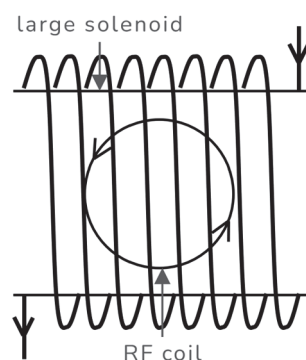
The diagrams show a simplified model of the large solenoid and RF coils, when they are both carrying a current.

- a) Sketch a vector diagram showing the direction of the resultant magnetic field, in the top down view.

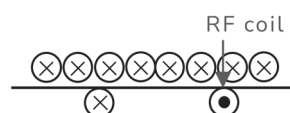
- b) When the current in the RF coil is on, the resultant magnetic field direction changes by 18.0° from the magnetic field due to the large solenoid alone. The RF coil alone produces a magnetic field of 0.500 T. The large solenoid is 1.00 m long and has 9550 turns. What is the current in the large solenoid?



Side view



Top down view
cross section



13.5 Magnetic materials and electromagnet cores

- Describe magnetic materials, by filling in the blanks.

added to	agitated	align	cancel	different	direction
domains	ferromagnetic	iron	magnetic field	moving charges	nucleus
neodymium	unlike	not	negatively charged	oxygen	permanent
same	short time	strongly	no magnetic moment	weakly	

Atoms have _____ electrons that orbit around a _____ and spin on their axes. _____ create currents, and currents create magnetic fields. So a moving electron creates a tiny magnetic field, called a **magnetic moment**, meaning it will rotate to _____ itself with an external magnetic field.

In many atoms, the magnetic moments of all the electrons cancel out, so overall the atom has _____. Elements with atoms like this, such as copper, are _____ attracted to magnets.

However, **paramagnetic** materials, such as aluminium and _____, have atoms with a permanent magnetic moment. The magnetic moments of all the atoms in the material are in random directions, so they _____ each other out, leaving no magnetic field overall. Magnetic moments in paramagnetic materials will align themselves in the _____ direction as an external magnetic field though. So paramagnetic materials are _____ attracted to magnets.

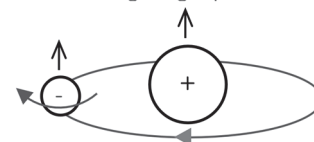
Ferromagnetic materials such as _____, nickel and cobalt, also have atoms with a permanent magnetic moment. _____ paramagnetic materials, in ferromagnetic materials, the atoms group into regions called **domains**, in which neighbouring atoms have their magnetic moments aligned in the same direction. Normally, the domains' magnetic fields are in _____ random directions. However, the domains' magnetic fields will align themselves in the same direction as an external _____. This causes ferromagnetic materials to be _____ attracted to magnets. The total magnetic field is increased, because the magnetic field from the ferromagnetic material is _____ the external magnetic field.

When the external magnetic field is removed, the domains retain the same alignment for a _____. This is why stroking an iron nail many times with the same pole of a magnet will temporarily magnetise the nail too, because the domains' magnetic fields are now in the same _____. The nail is demagnetised when the domains return to random directions by being _____, for example by hitting or heating the nail. This type of iron is called **soft iron**, where the overall magnetic field is not _____.

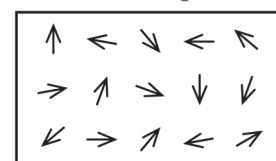
Permanent magnets are made of **hard iron**, with added impurities that stop _____ returning to random alignments.

Alloys containing iron are often also _____. For example, strong neodymium magnets contain a mixture of the elements iron, _____ and boron.

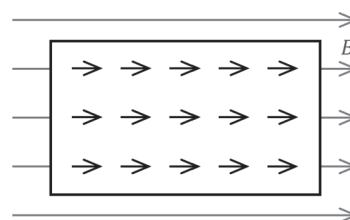
In this diagram, the magnetic moments are represented by the arrows going up.



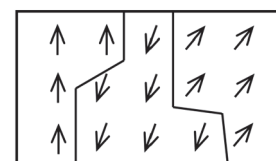
Paramagnetism: magnetic moments of atoms when there is no external magnetic field



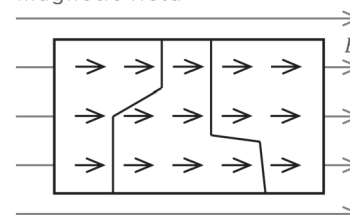
Paramagnetism in external magnetic field



Ferromagnetism: magnetic moments within each domain are aligned, even when there is no external magnetic field



Ferromagnetism in external magnetic field



Electromagnets

2. An **electromagnet** consists of a solenoid, or long coil of wire, wrapped around a soft iron core, as shown in the diagram.

Electromagnets are often used to pick up objects containing iron in real life, such as scrap metal, or in automated door locks, and may be connected in a circuit as shown.

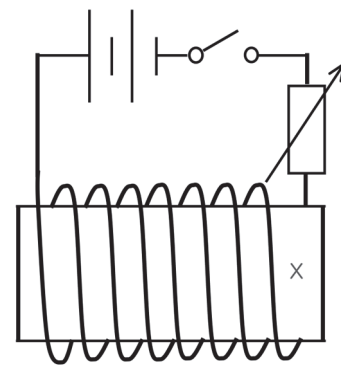
- a) Why does the switch in the circuit provide electromagnets with an advantage over bar magnets?

- b) Identify whether X would be a north or south pole in the diagram, when the switch is closed.

- c) The voltage of the power source is 120 V and the total resistance of the circuit is $50\ \Omega$. The solenoid has 1000 turns and a length of 25 cm. The soft iron core is removed so there is just air in the core. Calculate the magnetic field inside the solenoid when the switch is on.

- d) Justify the use of a soft iron core in the electromagnet, instead of an air core or a hard iron core.

- e) Explain how the magnetic field strength due to an electromagnet can be increased.



Identify the direction of current in the coil first.

Which two equations are needed?

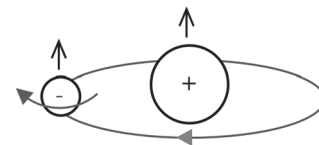
Compare the magnetic fields in each case, to explain why it is an advantage to use a soft iron core.

The diagram gives hints about what can be changed in an electromagnet.

Refer to relevant equations in explanations.

More on magnetic materials

3. The model shows an electron spinning on its axis and orbiting around a nucleus. Explain why this creates a magnetic field pointing upwards.



4. Compare the behaviour of a piece of copper, a piece of soft iron and a compass, when a bar magnet is brought close to each.

Copper will _____

This is because _____

Soft iron will _____

This is because _____

A compass will _____

This is because _____

5. True or false? Explain your reasoning.

a) All metals are magnetic.

b) If a bar magnet is cut in half, each piece will still have a north pole and south pole.

c) Soft iron is not as strong as hard iron, so it cannot be used for construction.

d) The copper used in the coil of an electromagnet is ferromagnetic.

6. A compass actually does not point north exactly... thinking this way is a simplification! The geographic north pole is defined as a point on Earth's axis of rotation. However, the Earth rotating has no direct link to creating a magnetic field around Earth and it may be by coincidence that a compass points roughly towards geographic north.

a) What materials inside Earth might be responsible for its magnetic field?

b) The diagram shows a simplified model of the magnetic field lines around Earth. In this model, the Earth behaves like there is a giant bar magnet in its core, as shown. Explain whether X is the north pole or south pole of this imaginary magnet.

