

If the voltmeter is incorrectly connected in series with the component to be measured, then the same current will flow through the voltmeter and the component. Since the voltmeter has a large resistance, this results in a small current through the component and it will not operate correctly.

12.9 Mixed circuit problems

$$1. \frac{1}{R_{23}} = \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{5} + \frac{1}{10}$$

$$R_{23} = 3.3 \Omega$$

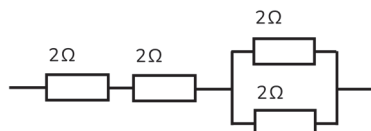
$$R_T = R_1 + R_{23} = 5 + 3.3 = 8.3 \Omega$$

$$2. R_{12} = R_1 + R_2 = 5 + 5 = 10 \Omega$$

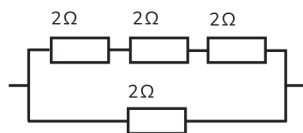
$$\frac{1}{R_T} = \frac{1}{R_{12}} + \frac{1}{R_3} = \frac{1}{10} + \frac{1}{10}$$

$$R_T = 5 \Omega$$

3. a)



b)



4. For R_3 : $V_3 = 48 \text{ V}$ (part (a))

$$V_3 = I_3 R_3$$

$$48 = I_3 \times 30$$

$$I_3 = 1.6 \text{ A (part (b))}$$

$$\text{For } R_1 \text{ and } R_2 \text{ combined: } V_{12} = I_{12} R_{12}$$

$$48 = I_{12} \times 30$$

$$I_{12} = I_1 = I_2 = 1.6 \text{ A (part (b))}$$

$$\text{Total current: } I_T = I_{12} + I_3 = 1.6 + 1.6 = 3.2 \text{ A (part (c))}$$

$$\text{For } R_1: V_1 = I_1 R_1 = 1.6 \times 20 = 32 \text{ V (part (a))}$$

$$\text{For } R_2: V_2 = I_2 R_2 = 1.6 \times 10 = 16 \text{ V (part (a))}$$

$$\text{For } R_1: P_1 = V_1 I_1 = 32 \times 1.6 = 51.2 \text{ W (part (d))}$$

$$\text{For } R_2: P_2 = V_2 I_2 = 16 \times 1.6 = 25.6 \text{ W (part (d))}$$

$$\text{For } R_3: P_3 = V_3 I_3 = 48 \times 1.6 = 76.8 \text{ W (part (d))}$$

$$W = VIt = 48 \times (1.6 + 1.6) \times 5 \times 60 = 46080 \text{ J (part (e))}$$

5. Voltage over 75Ω resistor is:

$$V = IR = 0.178 \times 75 = 13.35 \text{ V}$$

Current through the 300Ω and 100Ω resistors respectively is:

$$I = \frac{V}{R} = \frac{13.35}{300} = 0.0445 \text{ A}$$

$$I = \frac{V}{R} = \frac{13.35}{100} = 0.1335 \text{ A}$$

Ammeter A_2 measures the total current:

$$I_T = 0.178 + 0.0445 + 0.1335 = 0.356 \text{ A}$$

Total resistance of the circuit:

$$R_T = 30 + 1 \div \left(\frac{1}{300} + \frac{1}{100} + \frac{1}{75} \right) = 67.5 \Omega$$

Voltmeter measures total voltage across circuit:

$$V_T = I_T R_T = 0.356 \times 67.5 = 24.0 \text{ V}$$

$$6. R_T = 1 \div \left(\frac{1}{5} + \frac{1}{5} \right) + 5 = 2.5 + 5 = 7.5 \Omega$$

$$I_T = \frac{V_T}{R_T} = \frac{12}{7.5} = 1.6 \text{ A}$$

$$V_3 = I_3 R_3 = 1.6 \times 5 = 8 \text{ V}$$

$$P_3 = V_3 I_3 = 8 \times 1.6 = 12.8 \text{ W}$$

$$V_1 = V_2 = V_T - V_3 = 12 - 8 = 4 \text{ V}$$

$$I_1 = I_2 = \frac{V_1}{R_1} = \frac{4}{5} = 0.8 \text{ A}$$

$$P_1 = P_2 = V_1 I_1 = 4 \times 0.8 = 3.2 \text{ W}$$

Light bulb R_3 is 4 times brighter than light bulbs R_1 and R_2 .

7. Low heat: Close S_1 and S_3

$$R_T = R_1 + R_2 = 20 + 20 = 40 \Omega$$

$$I = \frac{V}{R_T} = \frac{12}{40} = 0.3 \text{ A}$$

$$P = VI = 12 \times 0.3 = 3.6 \text{ W}$$

Medium heat: Close S_1 and S_4 (S_2 and S_4 also work)

$$R_T = 20 \Omega$$

$$I = \frac{V}{R_T} = \frac{12}{20} = 0.6 \text{ A}$$

$$P = VI = 12 \times 0.6 = 7.2 \text{ W}$$

High heat: Close S_1 , S_2 and S_4

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{20} + \frac{1}{20}$$

$$R_T = 10 \Omega$$

$$I = \frac{V}{R_T} = \frac{12}{10} = 1.2 \text{ A}$$

$$P = VI = 12 \times 1.2 = 14.4 \text{ W}$$

8. a) A and C

b) B and D

c) The circuit shown effectively has the three light bulbs in parallel, since current splits into three paths at points A and C, then rejoins at points B and D. Removing the middle wires turns the circuit into a series circuit.

$$\text{In parallel, the total resistance is: } \frac{1}{R} = \frac{1}{2} + \frac{1}{2} + \frac{1}{2}$$

$$R = 0.67 \Omega$$

$$\text{Total power drawn: } P = VI = \frac{V^2}{R} = \frac{6^2}{0.67} = 54 \text{ W}$$

So each light bulb draws 18 W.

In series, the total resistance is: $R = 2 + 2 + 2 = 6 \Omega$

$$\text{Total power drawn: } P = VI = \frac{V^2}{R} = \frac{6^2}{6} = 6 \text{ W}$$

So each light bulb draws 2 W. The light bulbs are 9 times brighter with the wires in place.

9. a) $V = 10 \text{ V}$

$$I = \frac{V}{R} = \frac{10}{2} = 5 \text{ A}$$

b) The combined resistance of the resistor and voltmeter in parallel with it is:

$$\frac{1}{R} = \frac{1}{2} + \frac{1}{500 \times 10^3}$$

$$R = 2.0 \Omega$$

The combined resistance of this, the ammeter and switch in series is:

$$R = 0.1 + 2.0 + 0.05 = 2.15 \Omega$$

$$\text{Ammeter reading: } I = \frac{V}{R} = \frac{10}{2.15} = 4.7 \text{ A}$$

$$\text{Voltmeter reading: } V = IR = 4.7 \times 2 = 9.4 \text{ V}$$

Therefore the actual readings are slightly lower than the values in part (a).

13.2 Magnetic fields around permanent magnets

1. A field is a region where an object experiences a non-contact force. A magnetic field 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 iron, such as a paper clip. The fridge magnet only needs to be close enough to the paper clip, but does not need to touch it.

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

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

The strength of the magnetic field is represented by the density of the field lines. In other words, if field lines are

closer together, the magnetic field is stronger. Therefore, field lines around a bar magnet will be closer together near the poles than away from the poles.

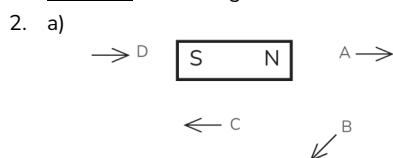
The direction of a magnetic field is defined as the direction that the north pole of a compass will point. Since a compass is actually a magnet, this means that the north pole of a compass will be repelled from the north pole of a bar magnet, and attracted towards the south pole of a bar magnet.

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

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

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

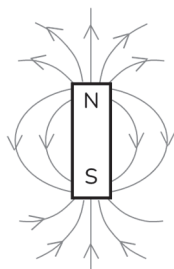
Because a magnetic field has both strength and direction, it is a vector quantity. So if there is a magnetic field exerted by two different magnets, the strength and direction of the magnetic field at one point is given by the resultant of the magnetic fields from each magnet.



b) The arrows show the direction of the magnetic field lines and are tangential to them.

c) D, because the magnetic field lines are closer together.

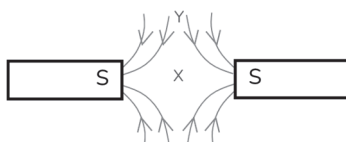
d)



3. a) X – south, Y – north

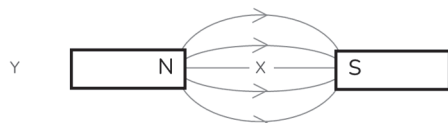
b) X – north, Y – north

4. a)



X has zero magnetic field, as the magnetic field from both magnets cancel each other out. Y therefore has a stronger magnetic field, since the net magnetic field will be downwards.

b)



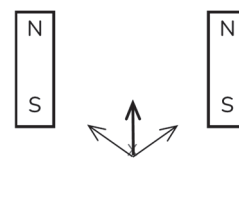
X has a stronger magnetic field than Y, since both magnets give a magnetic field to the right at X and the net magnetic field is the vector sum of these. Y is much further than the magnet on the right so the field from it is much weaker.

5.

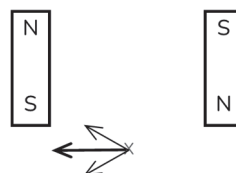
a)



b)

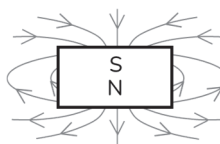


c)



6.

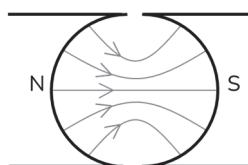
a)



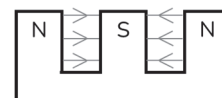
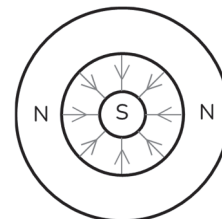
b)



c)



d)



13.3 Magnetic fields around currents

1. In 1820, Hans Christian Oersted showed that when a current flowed through a straight wire, it could make a compass needle 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 Earth's magnetic field.

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

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

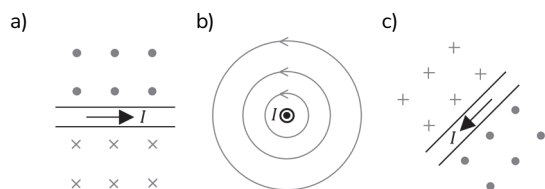
As fields extend in all three dimensions, we need new symbols to represent them on a two dimensional page. We can represent the direction out of the page with a dot – imagine an arrow is coming towards you and what you see closest to you is the arrow tip. We can represent the direction that is into the page with a cross – 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 left of it, to show the magnetic field is out of the page, and crosses on the right 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 away 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 clockwise.

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

2.



3. a) into page
b) into page
c) into page
d) into page
e) out of page
f) out of page
4. a) X: zero; Y: up
b) X: into page; Y: out of page
5. a) left
b) into page
c) out of page

6. When the current travels to the right, the magnetic field at X is into the page, as given by the "right hand grip rule". As the current changes to travel to the left, the magnetic field at X is out of the page. This continues periodically.

7. When current flows along a conductor that is not straight, it still produces a magnetic field. The magnetic field at a point will be the vector sum 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 into the page. This is because if we use the "right hand grip rule" and stick our thumb on each point on the circular coil in the current direction, our fingers 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 thumb represents the direction of the magnetic field inside the coil.

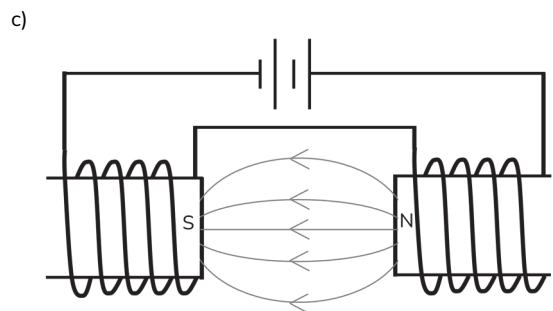
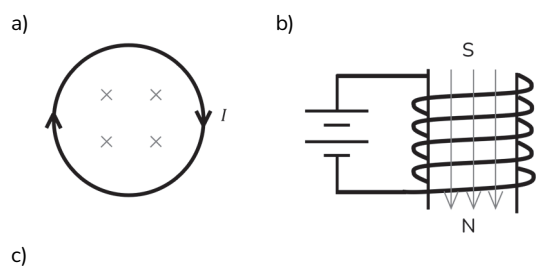
A **solenoid** consists of a long wire looped around many turns around a cylinder. Each turn contributes a magnetic field inside the solenoid the same way a single coil does. Therefore, the more turns, the stronger the magnetic field inside the solenoid will be, with the direction given by the

right hand coil rule. Solenoids can often have hundreds of turns.

Outside the solenoid, there is still a magnetic field, which gets weaker away from the ends of the solenoid. The shape of the magnetic field outside the solenoid is similar to the magnetic field around a bar magnet. Unlike a bar magnet, we can turn the magnetic field from the solenoid on and off, by switching the current 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 north pole to the south 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 compass inside the solenoid would point.

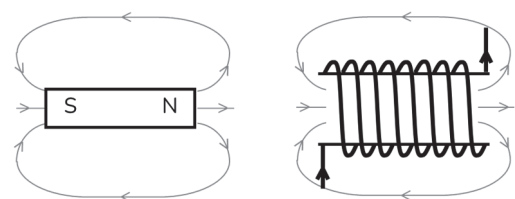
8. a) Anti-clockwise
b) From Y to X
c) From Y to X

9.



10. A big coil of wire underground, carrying a current running clockwise around the laboratory, would produce a south pole at the surface of the ground, which would attract the north pole of the compass.

11.



12. A solenoid has many turns, with the total magnetic field inside it being the sum of the magnetic fields from each single turn, whereas a straight conductor would only produce a magnetic field around the size of each single turn at most.
13. When the switch is closed, current flows through the solenoid, creating a magnetic field upwards. This turns the top of the solenoid into a north pole, which will attract the south pole of the bar magnet, so the bar magnet moves down towards the solenoid.

13.4 Magnetic field strength

- Magnetic field strength is related to how much force 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 vector sum of the magnetic field strength contributed by each bit of the conductor. If you change the shape 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 = current through the conductor (A)

r = perpendicular distance from the conductor (m)

μ_0 is a constant 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 vacuum. For a magnetic material such as iron, the permeability would be much higher. This formula assumes that r is small compared to conductor length.

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

- Toaster in use 5×10^{-7} T

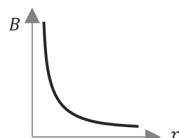
Earth's magnetic field at equator 3.1×10^{-5} T

Fridge magnet 5×10^{-3} T

- $\vec{B} = \frac{\mu_0 I}{2\pi r} = \frac{\text{N A}^{-2} \times \text{A}}{\text{m}} = \frac{\text{kg} \times \text{m} \times \text{s}^{-2}}{\text{A} \times \text{m}} = \text{kg s}^{-2} \text{ A}^{-1}$

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

b)



- At X from left wire: $\vec{B} = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \times 2}{2\pi \times 1 \times 10^{-2}} = 4 \times 10^{-5}$ T up
 - At X from right wire: $\vec{B} = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \times 3}{2\pi \times 1 \times 10^{-2}} = 6 \times 10^{-5}$ T up
 - Total at X: $\vec{B} = 4 \times 10^{-5} + 6 \times 10^{-5} = 1 \times 10^{-4}$ T up
 - At Y from left wire: $\vec{B} = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \times 2}{2\pi \times 3 \times 10^{-2}} = 1.3 \times 10^{-5}$ T up
 - At Y from right wire: $\vec{B} = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \times 3}{2\pi \times 1 \times 10^{-2}} = 6 \times 10^{-5}$ T down
 - Total at Y: $\vec{B} = 6 \times 10^{-5} - 1.3 \times 10^{-5} = 4.7 \times 10^{-5}$ T down
- Magnetic field from the current must be east, so current must run from north to south through the wire.

$$\tan 45^\circ = \frac{B}{50 \times 10^{-6}}$$

$$B = 50 \times 10^{-6} \text{ T}$$

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

$$50 \times 10^{-6} = \frac{4\pi \times 10^{-7} \times I}{2\pi \times 1.5 \times 10^{-2}}$$

$$I = 3.75 \text{ A}$$

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

The magnetic field strength inside a solenoid is given by:

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

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

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

I = current through the conductor (A)

N = number of turns (m)

L = length of solenoid (m)

The formula tells us that the magnetic field strength is proportional 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 turns or decreasing the length of the solenoid. This means that packing the coils tightly together, so there are more turns per length, will increase the magnetic field.

- $I = \frac{V}{R} = \frac{12}{131} = 0.0916 \text{ A}$

$$\vec{B} = \frac{\mu_0 NI}{L} = \frac{4\pi \times 10^{-7} \times 2160 \times 0.0916}{0.06} = 4.14 \times 10^{-3} \text{ T}$$

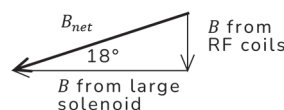
- Since $\vec{B} = \frac{\mu_0 NI}{L}$ the gradient of the graph is $\frac{\mu_0 N}{L}$.

$$\frac{\mu_0 N}{L} = \frac{4\pi \times 10^{-7} \times N}{L} = \frac{15 \times 10^{-3}}{3}$$

$$\frac{N}{L} = 4000 \text{ turns per m} = 40 \text{ turns per cm}$$

- The magnetic field increases if the number of turns per length, $\frac{N}{L}$, increases. For a given number of turns, this increases if the turns are closer together, reducing L .

- a)



- $b) B = \frac{0.5}{\tan 18^\circ} = 1.54 \text{ T}$

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

$$1.54 = \frac{4\pi \times 10^{-7} \times 9550 \times I}{1}$$

$$I = 128 \text{ A}$$

13.5 Magnetic materials and electromagnet cores

- Atoms have negatively charged electrons that orbit around a nucleus and spin on their axes. Moving charges 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 align itself with an external magnetic field.

In many atoms, the magnetic moments of all the electrons cancel out, so overall the atom has no magnetic moment. Elements with atoms like this, such as copper, are not attracted to magnets.

However, **paramagnetic** materials, such as aluminium and oxygen, have atoms with a permanent magnetic moment. The magnetic moments of all the atoms in the material are in random directions, so they cancel each other out, leaving no magnetic field overall.

Magnetic moments in paramagnetic materials will align themselves in the same direction as an external magnetic field though. So paramagnetic materials are weakly attracted to magnets.

Ferromagnetic materials, such as iron, nickel and cobalt, also have atoms with a permanent magnetic moment. Unlike 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 magnetic fields of the domains are in different random directions.

However, the magnetic fields of the domains will align themselves in the same direction as an external magnetic field. This causes ferromagnetic materials to be strongly attracted to magnets. The total magnetic field is increased, because the magnetic field from the ferromagnetic material is added to the external magnetic field.

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

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

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

2. a) The magnetic field of an electromagnet can be turned on and off, whereas a bar magnet has a permanent magnetic field.
b) X is a north pole.
c) $I = \frac{V}{R} = \frac{120}{50} = 2.4 \text{ A}$
 $\vec{B} = \frac{\mu_0 NI}{L} = \frac{4\pi \times 10^{-7} \times 1000 \times 2.4}{0.25} = 0.012 \text{ T}$
d) A soft iron core would increase the total magnetic field inside the coil, as the magnetic field produced by the current would make the domains in the soft iron core align in the same direction, adding their magnetic field to the one from the coil. This would create a stronger total magnetic field than that calculated in part (c). In a hard iron core, the domains are not free to rotate, so it has a fixed magnetic field, which could either increase or decrease the total magnetic field, depending which way the core was aligned.
e) The strength of the electromagnet can be increased by lowering the resistance of the variable resistor to increase the current, according to $\vec{B} = \frac{\mu_0 NI}{L}$. Choosing a solenoid with more turns that are tightly packed together also increases the magnetic field.
3. The magnetic field direction can be determined using the right hand coil rule, where the fingers represent the movement of positive charge and the thumb represents the magnetic field produced. If the electron were a positive charge, this would give a magnetic field pointing down, but this is flipped upwards because the electron is negative.
4. Copper will not be attracted to the magnet.
This is because the magnetic moments of its electrons cancel each other out, leaving copper atoms with no overall magnetic moment.
Soft iron will be attracted to the magnet.
This is because the magnetic moments of its atoms are grouped into domains, which align with the external magnetic field of the bar magnet and are therefore attracted to it.

A compass will rotate so that its north pole points away from the north pole of the bar magnet.

This is because it is made of hard iron, with its domains permanently aligned in the same direction, so the whole compass will rotate so its magnetic field is aligned with the bar magnet's field.

5. a) False – most metals are not, for example copper.
b) True – the magnetic moments of the domains in each are still aligned in the same direction.
c) False – soft or hard here refers to whether the iron is permanently magnetised, not its strength.
d) False – copper is not ferromagnetic.
6. a) Ferromagnetic materials such as iron.
b) Since the direction of the magnetic field is defined by the direction a compass points, the field lines go from the geographic south pole towards the geographic north pole, making X a magnetic south pole.