A2 Level Physics

Chapter 7 – Electric and Magnetic Fields

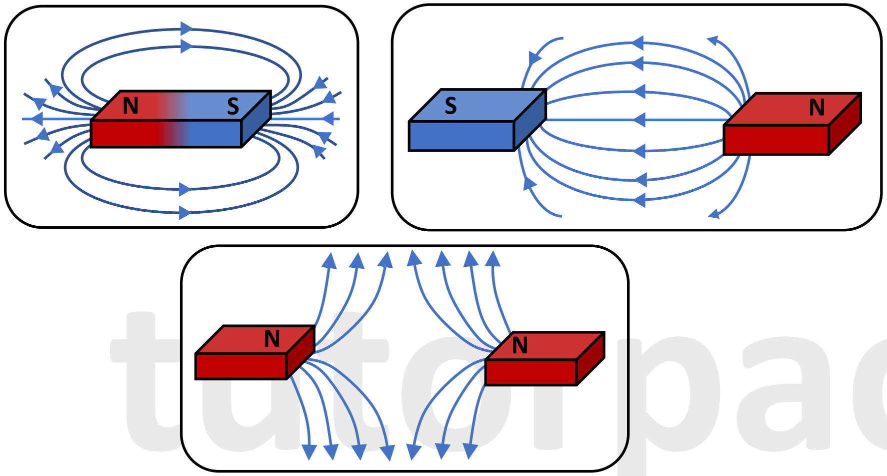
7.3.1 Magnetic Fields

Notes

Magnetic Fields

A magnetic field is similar to a gravitational and electric fields in that it is a region in which a force acts.

A permanent magnet, current carrying conductor, magnetically susceptible materials (e.g. iron), or a moving electric charge will all experience a force when they go through a magnetic field.



Magnetic fields are represented by magnetic field lines (also known as flux lines), which show field lines running from a magnet's north pole to its south pole.

The magnetic field strength in a given region can be measured by the relative density of the field lines (i.e. number of field lines per unit area).

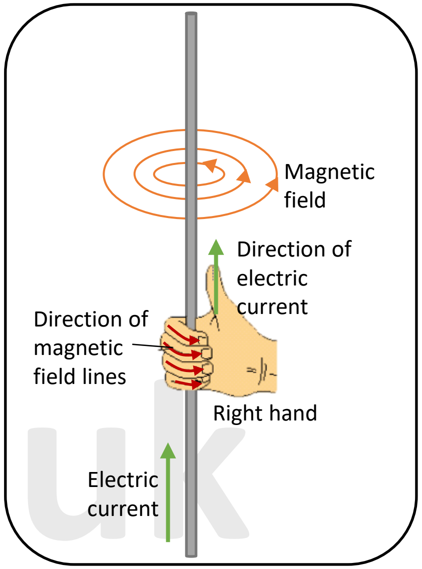
- The stronger the field, the closer the field lines are.
- A constant field strength, or a uniform magnetic field, is indicated by parallel field lines.
- Field lines that converge imply a strengthening magnetic field, while field lines that diverge suggest a weakening magnetic field.

Magnetic field patterns around a long straight current-carrying wire

A circular magnetic field is created around a wire when current flows through it.

The size of the current, the arrangement of the conductor, and the medium in which it is situated all affect the shape and magnitude of the field.

The simplest setup for creating a magnetic field from an electric current is shown below. A magnetic field is induced around a wire or any other straight conductor when current passes through it. The field lines are concentric circles centred on the wire.



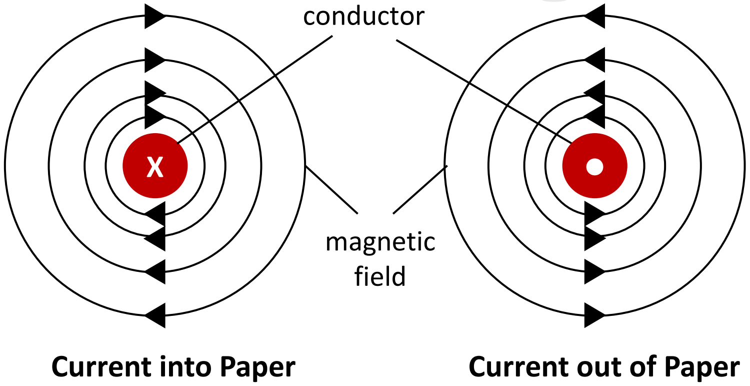
The direction of the magnetic field and current can be predicted using the: Right-Hand Grip Rule

- Imagine holding the wire in your right hand and pointing your thumb up.
- The direction of the current across the wire is indicated by the thumb. Therefore, if you know which way the current is flowing, you should point your thumb in that direction.
- The direction of the field is indicated by your curled fingers.

Magnetic field patterns around a long straight current-carrying wire

Although magnetic fields are three-dimensional (3D), it is more common in diagrams to represent the directions of current and field in two dimensions (2D), as seen below.

The current direction is represented by a dot (current direction coming out of the paper) or a cross (current direction going into the paper) in the centre of the conductor. Consider the appearance of a dart: when facing away from you, all you see is the rear flight, resulting in the cross; when facing you, all you see is the point, resulting in the dot.



Magnetic field patterns around a long straight current-carrying wire

As we move away from the wire, the field lines become further apart, indicating that the field weakens with distance.

We model the magnetic field by assuming it to be filled with magnetic flux, which is shown in diagram by field lines. Magnetic flux is a useful concept for determining field strength in terms of flux concentration.

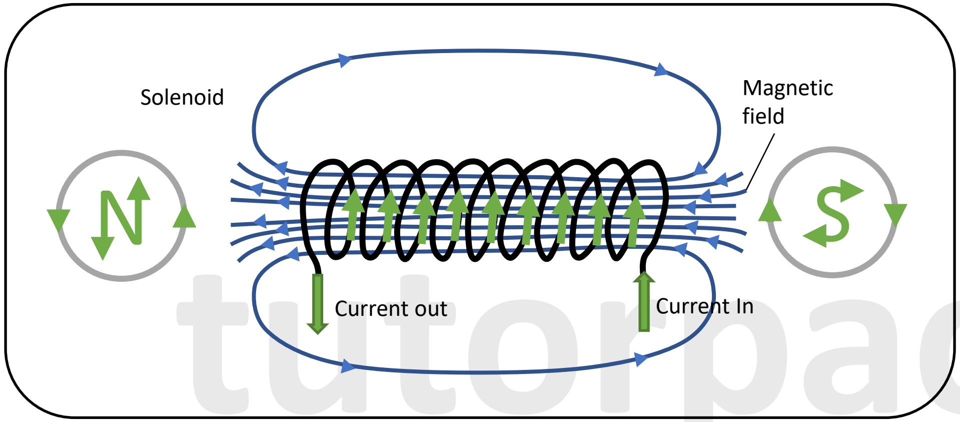
Flux density (flux per unit area) measurements around a current-carrying wire show that it is:

- Directly proportional to the current in the wire.
- Inversely proportional to the distance from the centre of the wire.

Long Solenoid

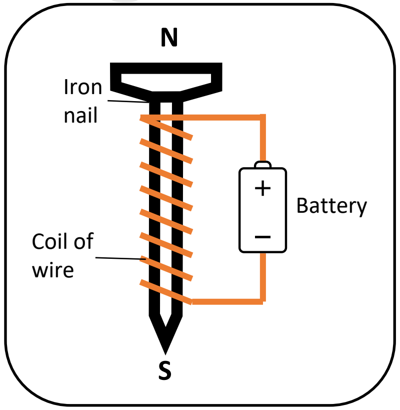
A solenoid is a long thin spiral of insulated wire used to generate a magnetic field. The majority of solenoids are cylindrical, although they can also be square or flat rectangular prism solenoids.

The magnetic field pattern created when there is a current in the windings is very similar to that of a bar magnet, as seen in the diagram below.



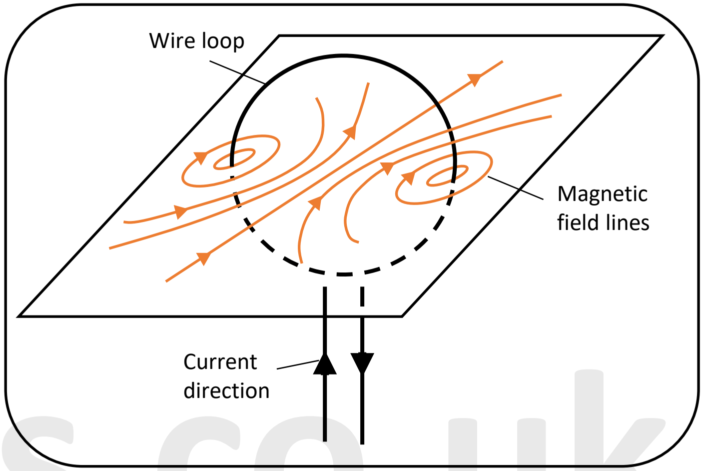
The field lines inside the solenoid are close together, parallel, and evenly spaced. This indicates that the field is strong and uniform.

A solenoid coiled on a soft iron core makes up an electromagnet. The soft iron core dramatically increases the strength of the magnetic field. A basic electromagnet is shown below::

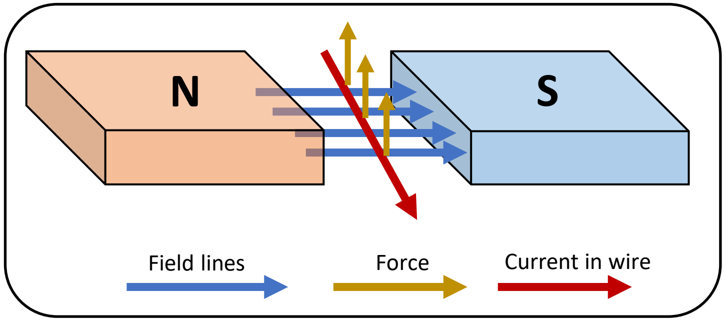


A flat coil

When a current-carrying wire is looped into a coil in one plane, the surrounding magnetic field is doughnut shaped.



Force on a current – carrying conductor in a magnetic field



As indicated in the diagram above, a current-carrying wire placed in the magnetic field between two magnet poles experiences a force. The direction of current, magnetic field, and force are all perpendicular to one another.

You can increase the size of the force (F) acting on the wire by increasing:

- The magnetic field strength or magnetic flux density (B).
- The size of the current (I) in the wire.
- The length (L) of wire which is in the field.

Force on a current – carrying conductor in a magnetic field

The force (F) acting on a wire of length (L) carrying a current (I) at right angles to a magnetic field of magnetic field strength or magnetic flux density (B) is equal to:

$$F = BIL$$

Where:

F = force on a current carrying wire in N

B = magnetic flux density in tesla, T

I = current through the wire in A

L = length of the wire in m

The magnetic flux density is a vector quantity with a magnitude and a direction. The unit of magnetic field strength or magnetic flux density (B) is the tesla, T.

$$1\,Tesla = 1\,weber\ per\ metre\ squared$$

$$1\,T = Wb\,m^{-2}$$

Or:

$$1\,Tesla = 1\,newton\ per\ amp\ per\ metre$$

$$1\,T = 1\frac{N}{Am}$$

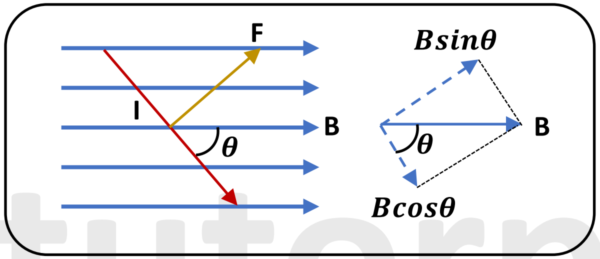
Since $B = \frac{F}{IL}$

Magnetic Flux density or magnetic field strength (B) is defined as the force acting per unit current in a wire of unit length which is at right angles to the field.

Force on a current – carrying conductor in a magnetic field

The maximum force that the wire could experience is given by the equation $F = BIL$. However, if the wire is not at right angles to the magnetic field, a force will act on it, but it will be smaller (as long as the wire is not parallel to the magnetic field).

The force on a wire that is at an angle (θ) to the magnetic field lines is calculated using the component of the field at 90° to the wire $(B\sin\theta)$:



As a result, the force (F) acting on a wire of length (L) carrying a current (I) at an angle (θ) to a uniform magnetic field of flux density (B) can be calculated using:

$$F = BIL\ sin\theta$$

When the wire is at 90° to the magnetic field:

$\theta = 90^\circ$, so $sin\theta = sin90^\circ = 1$ and $F = BIL$

When the wire is parallel to the magnetic field:

$\theta = 0^\circ$, so $sin\theta = sin0^\circ = 0$ and $F = 0$

Fleming's Left-Hand Rule

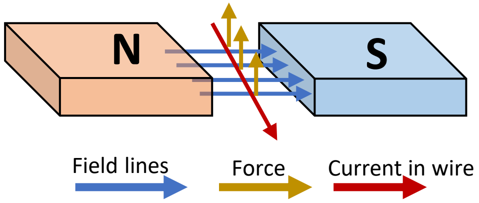
The direction of the force exerted on a current carrying wire at right angles to a magnetic field cab be found using the Fleming's left-hand rule.

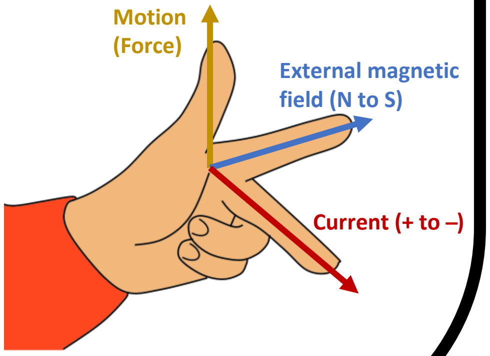
Fleming's left-hand rule can also be used to determine the direction of the current going through the wire or the direction of the external magnetic field.

However, the direction of at least two of the properties must be known before you can find out the direction of the third (i.e. you need to know the direction of the force and current to find the direction of the magnetic field).

Remember to use your left hand and stretch your thumb, forefinger, and middle finger out as indicated below when using the Fleming's left-hand rule, and follow the rules:

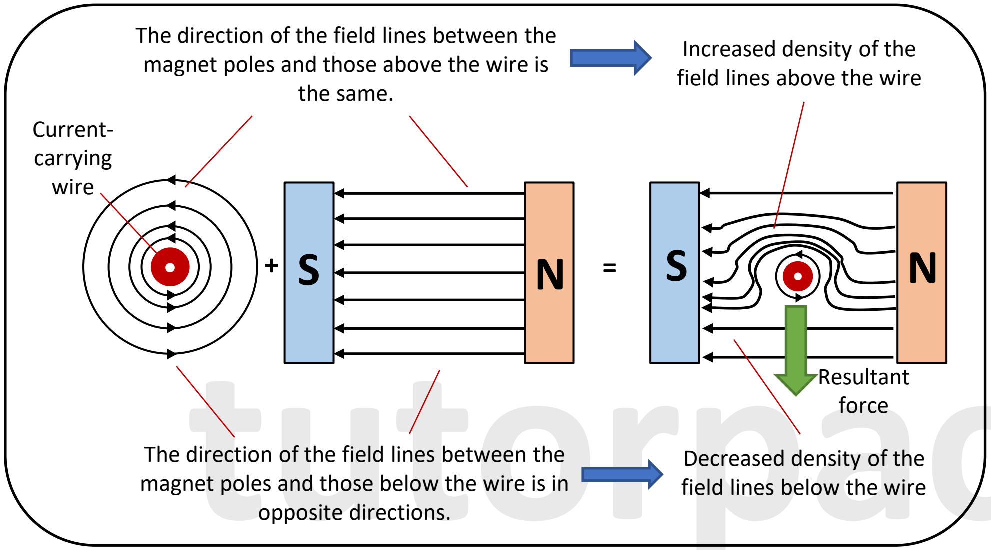
- The First finger points in the direction of the uniform magnetic field lines pointing from North to South.
- The second finger points in the direction of the conventional current flow pointing from positive to negative.
- The thumb points in the direction of the force (the direction of Motion).





Force on a current-carrying wire - Explained

When a current-carrying wire is placed in an external magnetic field (for example, between two magnets), the field around the wire and the field from the magnets are added together.



As a result when a current-carrying wire is placed in a uniform magnetic field between two magnet poles it will experience a resultant force.

The interaction of the field around the wire with the field between the poles produces a resultant magnetic field with a higher flux density above the wire. This is because in the region above the wire, the field due to the current is in the **same direction** as that between the poles and therefore they reinforce each other resulting in a higher **flux density.** The fields are oppositely directed below the wire, resulting in a lower flux density.

The distorted field has the overall effect of exerting a force on the wire, which will then move if it is free to do so.

Investigating Force on a current-carrying wire in a magnetic field

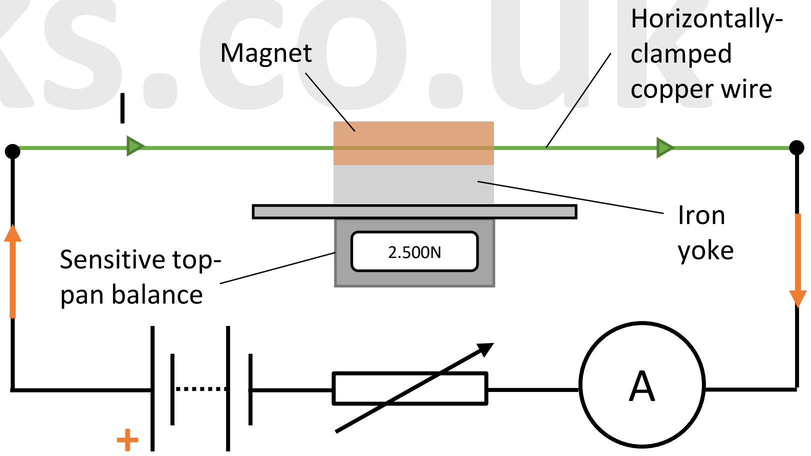
Apparatus:

Iron yoke, 2x magnets, copper wire, clamp or wooden support blocks, crocodile clips, leads, power supply (low-voltage), ammeter, resistor, sensitive top-pan balance.

Method:

You can use a top pan balance and the set-up shown below to investigate the force exerted on a current-carrying wire placed perpendicularly in a magnetic field.

Step 1: Attach magnets to a soft-iron yoke with their opposite poles facing each other, creating a strong magnetic field between them.



Investigating Force on a current-carrying wire in a magnetic field

Step 2: When the yoke and magnets are placed on the pan, make sure the top-pan balance must is set to zero. As a result, the mass measurement is solely due to the force caused by the current in the magnetic field (and not due to the mass of the equipment).

When a current (I) flows through the clamped wire, it experiences an upward force inside the magnetic field (Flemings LH rule). According to Newtons 3rd law, there is then an equal and opposite force (F) exerted on the yoke + magnet which pushes down on the pan to give a reading on the balance.

Step 3: Record the mass displayed on the digital balance as well as the current. Then change the current with the variable resistor and record the new mass reading. Repeat this process until you've tested a wide range of currents, then repeat it three times more to get three mass readings for each current.

Step 4: Calculate the mean for each mass reading.

Step 5: Multiply the mean balance reading in kg by $g = 9.81\ N\ kg^{-1}$ to get the size of the force exerted $(F = ma)$.

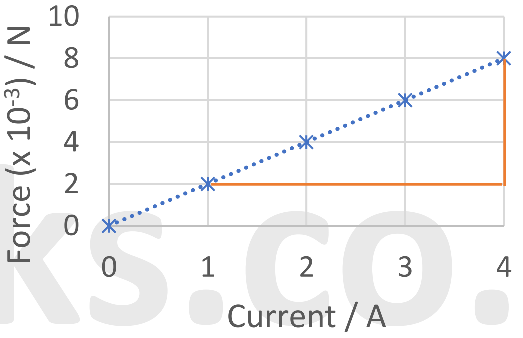
Step 6: In a table like the one below, record your findings:

Current / A	Mean mass recorded on top pan balance / g				Force acting on current-carrying wire/ N
	1	2	3	Mean	
1.0				0.20	0.0020
2.0				0.41	0.0040
3.0				0.61	0.0060
4.0				0.82	0.0080

Investigating Force on a current-carrying wire in a magnetic field

Step 7: Plot your data on a force F against current I graph. Then draw a best-fit line. You should have a straight line that goes through the origin and shows that force is proportional to current. The gradient of the line of best fit is equal to BL since $F = BIL$. By keeping the length constant, you can calculate the magnetic flux density by dividing the gradient by your value for L.

You will get a graph similar to the one below:



Force is directly proportional to current since the graph is a straight line through the origin.

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

To calculate the magnetic flux density you do:

$$B = \frac{gradient}{L}$$

Note:

If the mass reading is negative, turn off the dc power supply and reverse the crocodile clips to make the mass positive.

A dc supply is required to keep the force's direction constant; if an ac supply were used, the force's direction would keep changing.

If the reading is in grams don’t forget to convert it to kg.

Please see '7.3.2 Magnetic Fields worked examples' pack for exam style questions.

For more revision notes, tutorials and worked examples please visit www.tutorpacks.co.uk.