11 Magnetic fields

- **investigate and analyse theoretically and practically the force on a current carrying conductor due to an external magnetic field, $F = nIlB$, where the directions of I and B are either perpendicular or parallel to each other**
- **analyse the use of a magnetic field to change the path of a charged particle, including:**

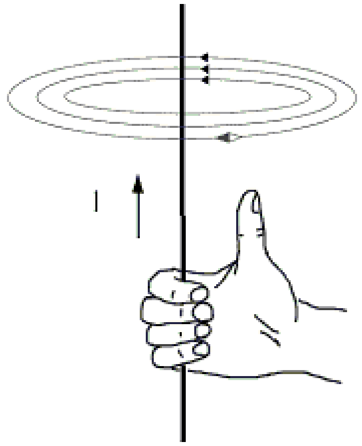
  – the magnitude and direction of the force applied to an electron beam by a magnetic field: $F = qvB$, in cases where the directions of v and B are perpendicular or parallel

  – the radius of the path followed by a low-velocity electron in a magnetic field:

  $$qvB = \frac{mv^2}{r}$$

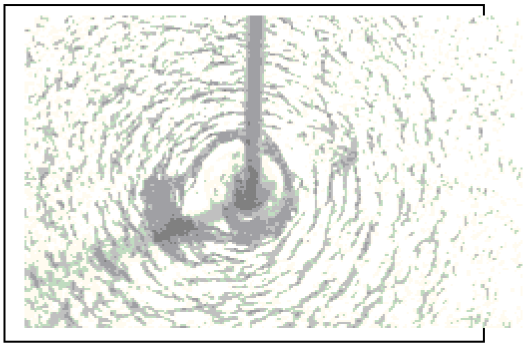
- **model the acceleration of particles in a particle accelerator (limited to linear acceleration by a uniform electric field and direction change by a uniform magnetic field).**

Magnetic Fields around Wires



A conductor carrying an electric current is always surrounded by a magnetic field.

That's right: every current-carrying wire becomes a <u>magnet</u>!



Electromagnetism is a temporary effect caused by the flow of electric current and it disappears when the current flow is stopped.

The magnetic field lines due to the current in a straight wire are concentric circles with the wire at the centre. The direction of the magnetic field can be found using the right-hand screw (grip) rule.

The wire is gripped with the **right** hand so that the thumb lines up with the direction of current flow. The direction of the magnetic field is given by the curl of the fingers.

The strength of the magnetic field caused by the flow of current is given by $\mathbf{B} = \frac{kI}{r}$ (k is a constant).

The current in the lightning stroke passes from ground to cloud. The result of this is to generate a magnetic field in the region of the stroke.

The force on a current carrying wire in a magnetic field

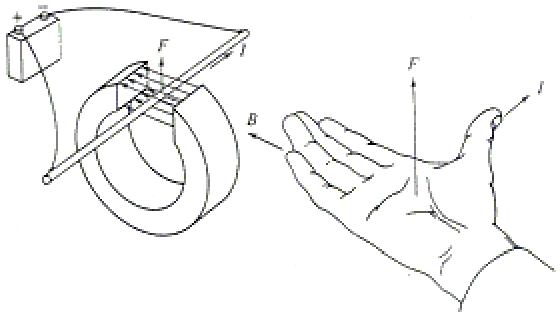
Remember that

- For a current-carrying conductor there is an associated magnetic field.

(The direction of the field is given by the right-hand grip rule)
A consequence of this is that

- For a current-carrying conductor <u>in a magnetic field</u> there is a force acting on it.

(The direction of the force can be determined by the right hand slap rule.)
In this rule, the hand is opened flat and the fingers are aligned with the magnetic field. The thumb is pointed in the direction of current flow and the palm is now facing the direction of the force.



Why is there a force on the wire?

The two magnetic fields will interact (as with two north poles repelling each other) and a force will be produced. So if we have two wires parallel to each other, each carrying a current, then both will be simultaneously creating its own magnetic field and under the influence of the other's magnetic field.

How strong is the force?

If the field is perpendicular to the flow of current, the force on a current-carrying wire in a magnetic field is proportional to the current, the length of wire in the field, and the strength of the field.

$$F = nBIL$$

n number of wires

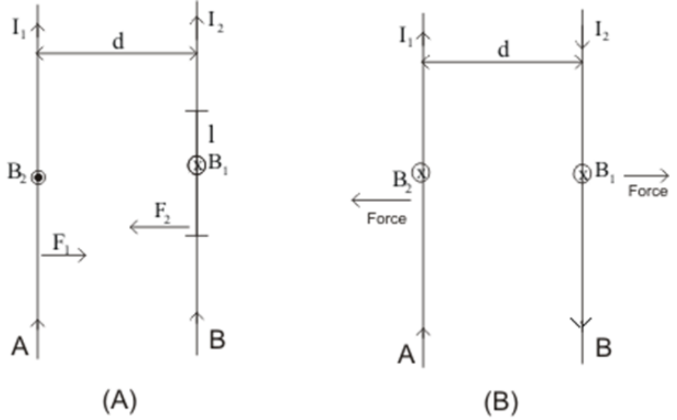
B strength of the field

I current

L length of the wire

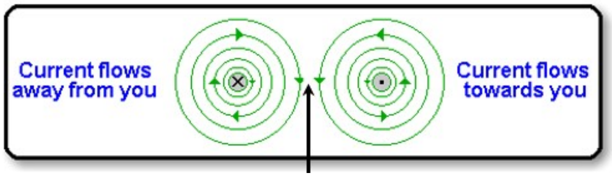
Forces between two parallel wires

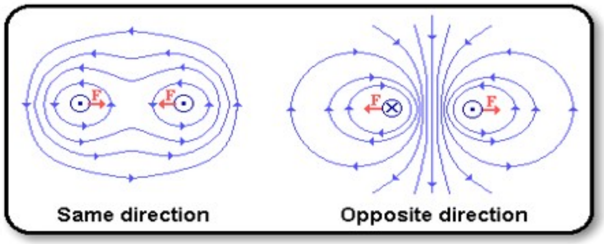
Below, two wires are viewed from above. They have current flowing in opposite directions.



(A) (B)

Figure 5. Current carrying wires exerts force on each other





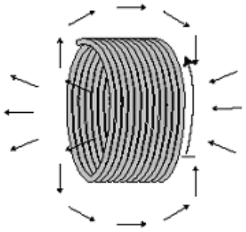
Left Wire
Using the right hand rule, the field direction is clockwise
Right Wire
Using the right hand rule, the field direction is anti-clockwise

If the current is in the same direction, there is an **attractive** force between the two wires
If the current is in the opposite direction, there is a **repulsive** force between the two wires

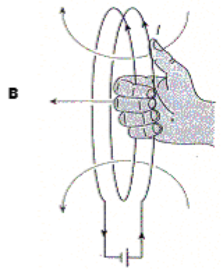
In between the two wires above, we can see that the field direction is the same for both wires: **down**. As “likes repel”, this means that these two wires will repel each other.

Loops of wire are called solenoids

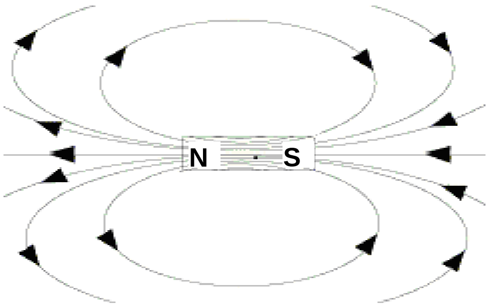
The electromagnetic effect of a current-carrying conductor can be magnified by using a conductor shaped into a loop or series of coils.



The shape of the magnetic field can be given by another right hand rule. The thumb is in the direction of the current and the fingers give the direction of the field.



A solenoid’s field lines are like a bar magnet. One end of the solenoid can be identified as the “north” end, and the other as the “south.”



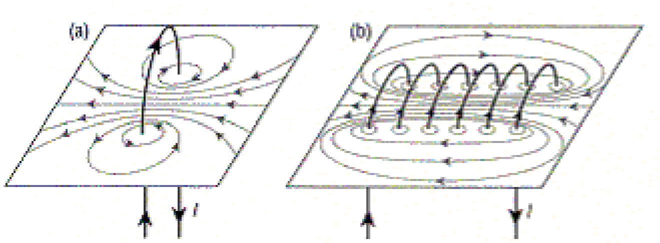
Note that on the inside of the solenoid, the field lines actually travel from south to north.

Thus, we can create a bar magnet using a solenoid with current flowing through it. This is called an electromagnet. The benefits of an electromagnet over a permanent bar magnet are that

- it can be turned on and off as required
- the field direction can be changed (ie. It’s poles can be reversed)

Alternative method to find direction: the Solenoid Rule

Grip the entire coil with the right hand with the fingers wrapped in the direction of the current flow, and the thumb will point to the North pole or in the direction of the magnetic field inside the coil. This is often called the right hand solenoid rule. Test the two methods on the loops of wire below.



Circular motion (revisited)

If a constant force is acting on an object perpendicular to its direction of motion, the object will travel in a circular path.

This force is given by F = $\frac{mv^2}{r}$.

Force on a moving charge

An electric current can be considered to be the movement of charge, therefore a moving charge can be considered to be an electric current

Current is defined as I = $\frac{q}{t}$.

The force on a current is given as F = Bil, which can be considered as F = $\frac{Bql}{t}$.

This can be rewritten as F = Bqv, where v is the speed of the charge given as $\frac{l}{t}$.

Using the right hand rule the direction of the force can be determined.

If an electron is moving to the left, it can be considered as a current to the right. The force will always be perpendicular to the direction of motion, so it will result in circular motion.

Therefore we can equate F = $\frac{mv^2}{r}$ with F = Bqv.

$$\therefore\ Bqv = \frac{mv^2}{r}.$$

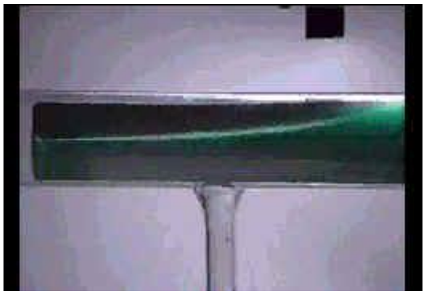
This applies when the velocity is low so that relativistic effects do not need to be taken into consideration.

The equation Bqv = $\frac{mv^2}{r}$ can also be simplified by cancelling v from both sides, this gives

$\therefore\ Bq = \frac{mv}{r}$, where mv is the momentum of the electron.

The force on a current

The force is on the wire is due to forces on the individual electrons moving in the wire. When the electrons are constrained to move within a conductor, then the force becomes the force acting on the wire.



The experiment on the left shows a cathode ray being bent by a magnetic field towards the top.

If the force on a charge remains perpendicular to its motion, the charge will move in a circular arc. (This is the same as an object attached to a string being swung in a horizontal plane – the motion will be circular.)

Generally, the magnitude of these forces is very small (in the order of 10^{-11}N) **but** they are not insignificant because the mass of an electron is 9.1×10^{-31} kg,

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