Electromagnetism

6.1 Permanent magnets.

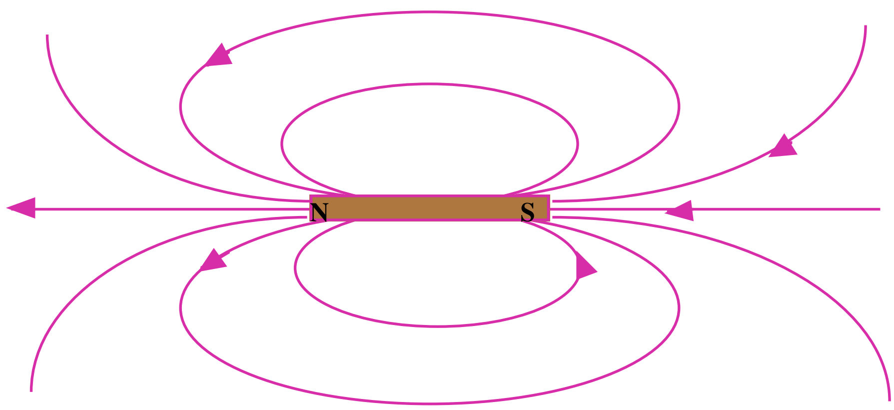
Iron, Cobalt, Nickel and some rocks containing them show the property of attracting and repelling each other. This is a new type of force as these objects are not electrically charged. These materials are called magnetic as they were first discovered in Magnesia near Greece. They also align themselves in a fixed manner in relation to geographic north. This suggests that the Earth is also magnetic. Iron exhibits these properties most strongly and is said to be, along with nickel and cobalt, ferromagnetic.

A Compass is a magnet shaped as a pointer is used as a compass. It is suspended or supported in some way so that it is free to turn and points to magnetic north. Small compasses can be used to investigate the region around a magnet. The end of a magnet that is attracted to the north pole of the earth is called the north seeking pole. This is shortened to just north pole and of course the other end is the south seeking pole.

6.2 Magnetic Fields.

A **region of space** in which magnetic forces act on magnets is called a magnetic field. **Lines of force** can be drawn using a small plotting compass which show the direction of these forces on a N pole.

Fig.6[i] The field of a bar magnet



Iron filings will also show the shape of the field of the magnet as they are acted on by the magnet. The field of a bar magnet is as shown below.The field strength [**H**] is greatest where the lines are closest together or densest Today most applications of magnetism are concerned with electromagnetic effects and a different quantity called **flux** is defined. The lines are the same shape but they are called lines of flux. The density of the lines is called **flux density** [**B**] . This is a measure of the force that the magnetic field exerts on electric currents or moving charges.

Fig.6[ii] Opposite poles attract.

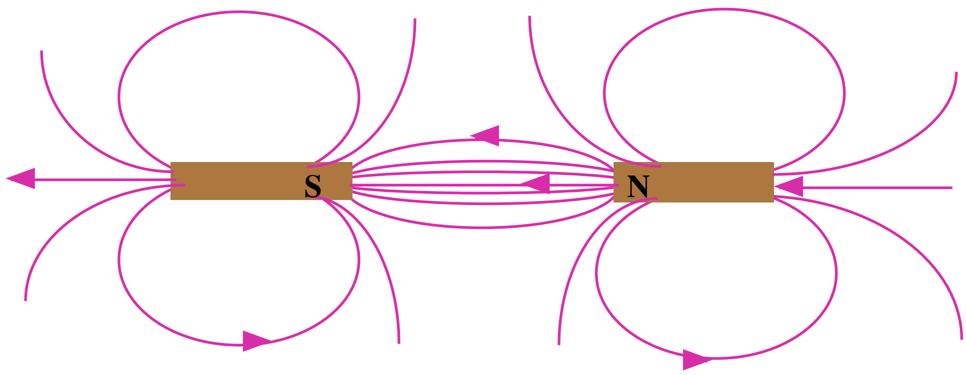
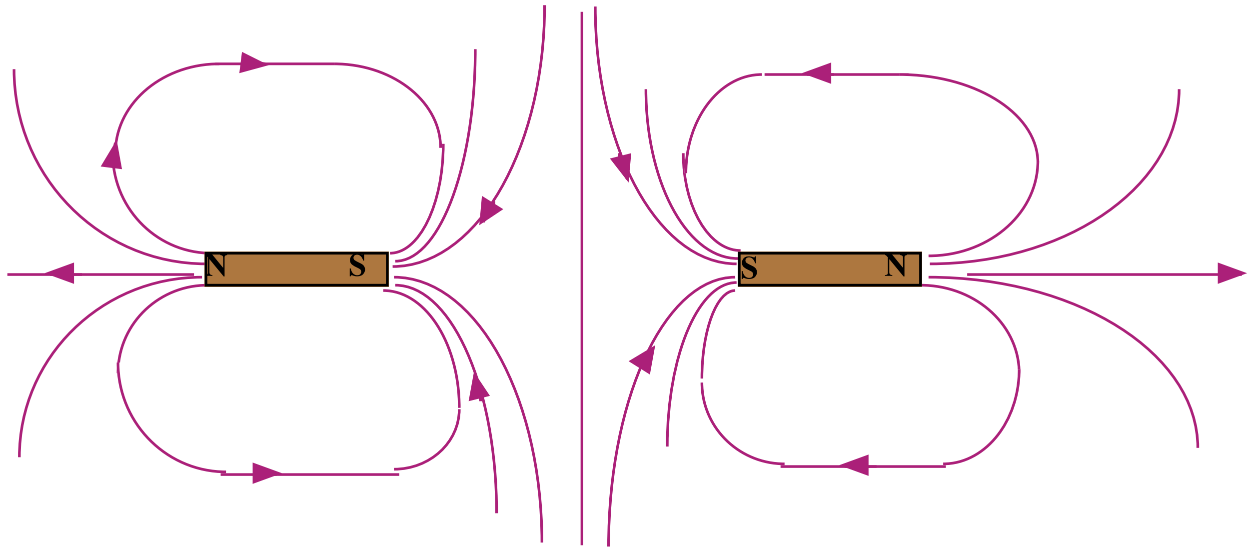


Fig.6[iii] Repulsion of like poles.



The magnitude of the force between the magnets depends on several factors including the medium between the magnets. The property of the medium affecting the force is called it's relative permeability, μ_r. This is sometimes called just permeability.

6.3 The domain theory of magnetism.

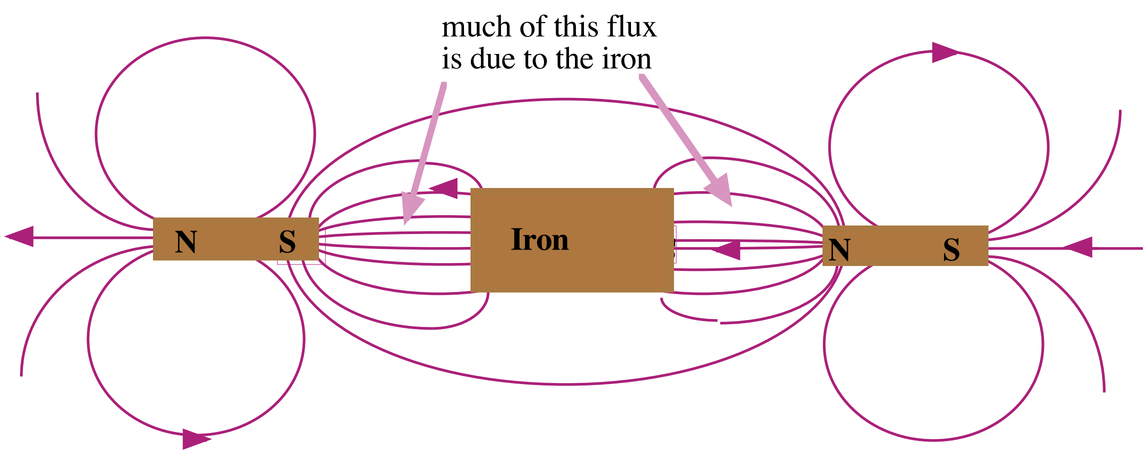
Ferromagnetic materials are transition elements that have atoms with unpaired electrons and also large numbers of atoms are arranged in groups all facing the same way. These number around tens of thousands and form a minute magnet. They are called domains. In a piece of unmagnetised iron the domains are arranged randomly but if the iron is put in a magnetic field then the domains begin to line up with the field, reinforcing it. More and more domains line up as the external field is increased. When the external field is removed the iron retains some of the domain arrangement. Pure iron does not retain much of this induced magnetism and it is said to be magnetically soft. Impurities in the iron increase the retention and steel retains most of the arrangement of the domains and it is said to be hard.

Permanent magnets must be made of magnetically hard materials and one of the hardest is **Alnico** an alloy of 54% iron, 28% nickel, 12% cobalt and 6% copper. Transformers and armatures in motors and generators must be able to lose their magnetism easily and a very soft alloy needs to be used. **Mumetal** an alloy of 76% nickel, 17% iron, 5% copper and 2% chromium is extremely soft. Energy is needed to reverse the polarity of the core every cycle. See Hysteresis losses in a later section and under transformers.

6.4 Induced magnetism.

The magnetic field will align the domains in a piece of iron such that it reinforces the field. This will make the attraction between say two magnets stronger.

Fig.6[iv] The iron bar is magnetised.

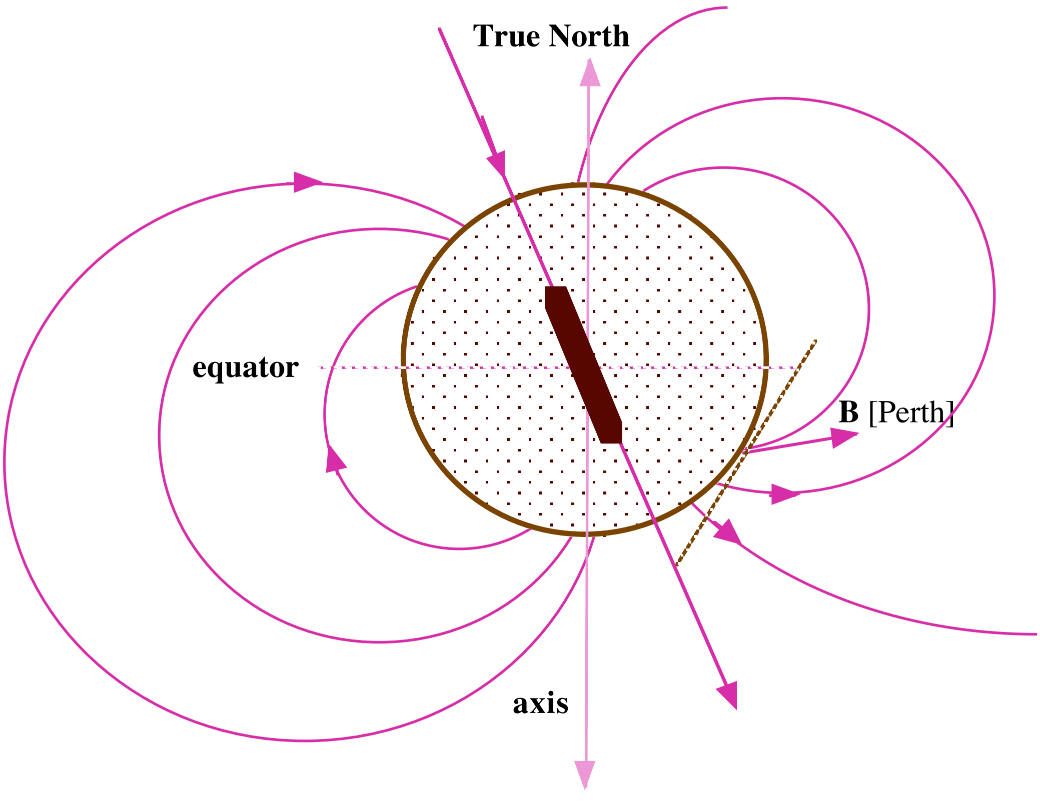


The relative permeability of iron is so large that the flux in a coil carrying a current can be increased nearly a thousand times.

6.5 The magnetic field of the Earth.

The Earth has a weak magnetic field that is similar in shape to that of a short bar magnet situated as shown. Of course the Earth's field is **not** due to ferromagnetism as the temperature of the core is much too high. Iron loses it's magnetism above a temperature of **770^{0}C** which is is called the **Curie** temperature, and other ferromagnetic materials also have a Curie temperature. The domain structure breaks down above this temperature. The sun and the huge gas giant planets like Jupiter have very strong magnetic fields and the field of the Earth, other planets and stars is probably due to circulating charges in the core. The field of the Earth has a South seeking pole at the geographic north pole. The angle that the lines leave the surface of the Earth at is called the angle of dip. In Perth it is about 66^0 above the horizontal. The direction of the Earth's field at any place on the surface can be affected by local deposits of iron ore for example L.Hancock's discovery in the Pilbara. These variations are shown on maps and the difference between true north and magnetic north is called the declination. Over long periods of time the magnetic field changes and in fact the poles have reversed several times.

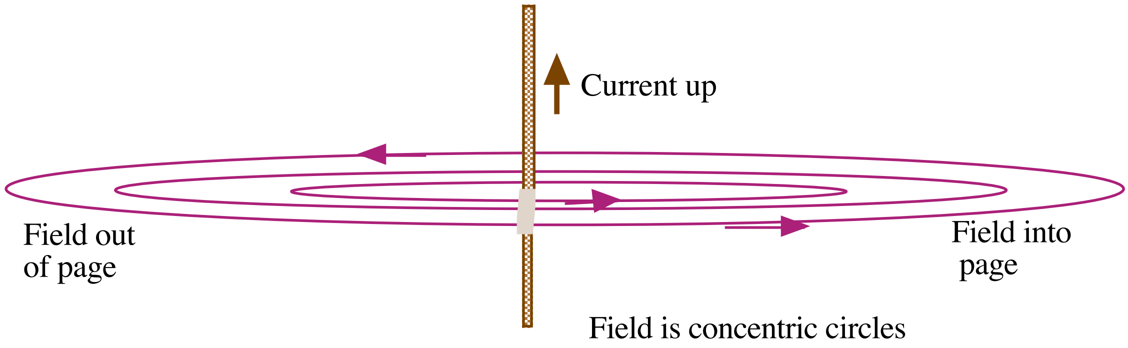
Fig.6[v] The magnetic field of the Earth.



6.6 Electromagnetism

In 1820 **Oersted** discovered that an electric current had an effect on a compass. In fact for a long time the unit of magnetic field strength was named after him in honour of the discovery. Today field strength is rarely used because most effects are electromagnetic and another quantity called Flux Density is more important. The lines of flux are in the same direction as the field lines. Oersted's discovery led to the widespread use of electricity today. **The S.I. unit for magnetic field strength [H] is, amp per metre [Am^{-1}]**. An electric current in a straight wire produces a magnetic field as shown below. This shows that magnetism is due to moving charges or electric currents. This is true for ferromagnetic materials as well, where the current is due to electrons circling atoms, which are aligned the same way in large numbers or blocks called **domains.**

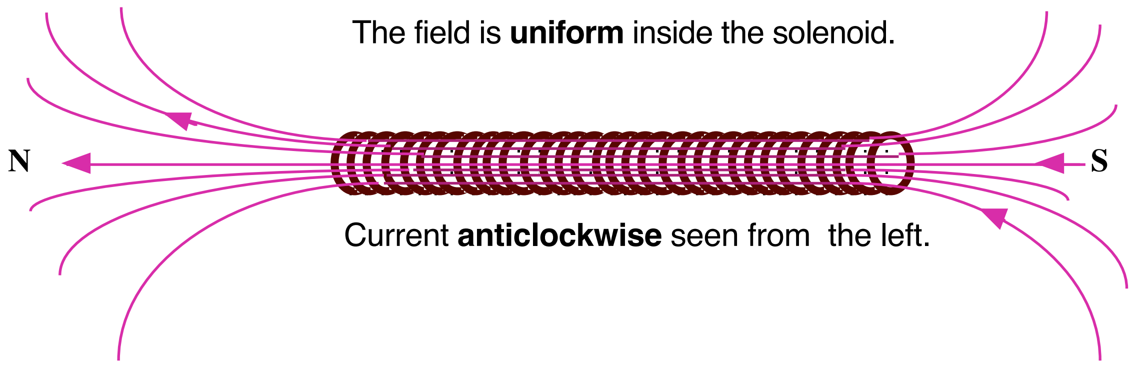
Fig.6[vi] Magnetic Field of a straight wire.



The direction of a magnetic field is the way a small compass points. The direction of the field around a current carrying conductor can be remembered by the **Right Hand Rule**. That is, if the right hand makes a loose fist then the thumb is current, and the fingers are in the direction of the field lines.

Since the wire has a magnetic field it will experience a force if it is in another field. This means that two wires each carrying currents will exert forces on each other. If the wires are parallel and the currents are the same way then the wires will attract each other. Similarly currents in opposite directions will repel. This phenomenon is used to define the Ampere. Check the rule for attraction or repulsion by the rules you have learned.

Fig.6[vii] The magnetic field of a solenoid.

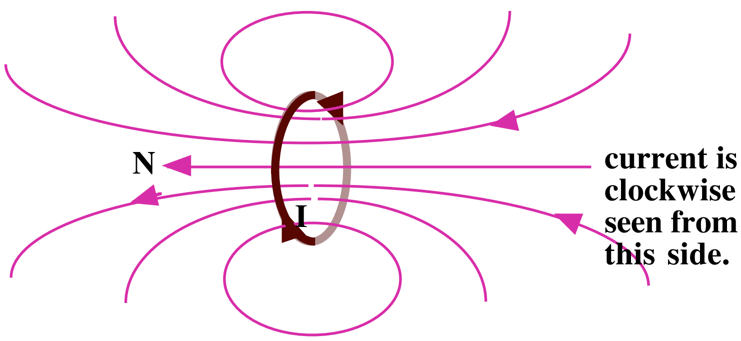


There are several rules for remembering the direction of the field inside a solenoid.

[i] Using your right hand, wrap your fingers around the solenoid in the direction of the current. Your **thumb** will show the direction of flux **inside** the coils.

[ii] A simple **rule** is that the polarity of a coil or end of a solenoid is South if it appears clockwise seen from that side and North if moving anticlockwise seen from that side. This can be learned by remembering that **anti** has an **'N'** in it.

Fig.6[viii] The magnetic field of a plane coil.



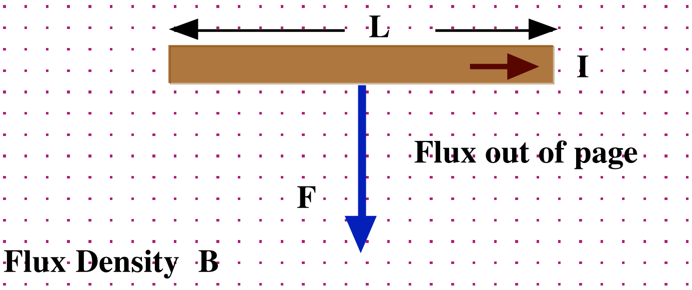
n.b. You should also draw the field around the following

[i] two wires with opposite currents
[ii] a straight wire in a uniform field
[iii] two wires with unequal currents
[iv] the field of a coil in a motor with a radial field.

6.7 Flux Density. Symbol [**B**]. unit tesla [**T**] **vector**

Flux density is a measure of the magnetic field defined in terms of the force acting on an element of current at a point in the field. It is not to be confused with magnetic field strength **[H]**.

Fig.6[ix] Force on a conductor in a magnetic field.



Flux Density at a point, in the uniform field above, is defined as being a vector out of the page, equal in magnitude to the **force per unit current-length** acting on a current carrying conductor at that point in the field and perpendicular to the flux.

Therefore for a uniform field flux density $\mathbf{B} = {}^{\mathbf{F}}/_{\mathbf{IL}}$ and **F** is perpendicular to **I** [and **L**].

The units of **B** are called **tesla** [**T**] [$NA^{-1}m^{-1}$] This definition of flux density should be compared to

[i]	a gravitational field	$\mathbf{g} = {}^{\mathbf{F}}/_{\mathbf{m}}$	[units Nkg^{-1}]
[ii]	an electric field	$\mathbf{E} = {}^{\mathbf{F}}/_{\mathbf{q}}$	[units NC^{-1}]
[iii]	a magnetic field	$\mathbf{B} = {}^{\mathbf{F}}/_{\mathbf{IL}}$	[units $NA^{-1}m^{-1}$]

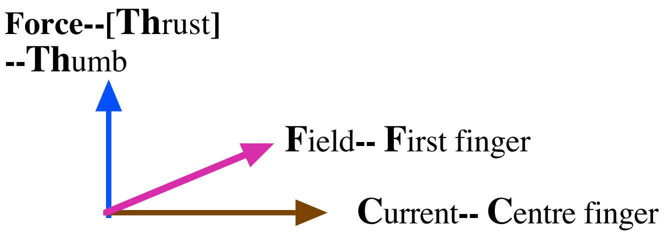
The value of the flux density **B** is equal to the force that would act on a 1.0m long wire carrying a current of 1.0A perpendicular to the uniform field shown in Fig.6[ix]. For a non uniform field the current element is taken to be infinitesimally short **dL**, the force is **dF** and if θ is the angle between the flux and the current element then the flux density at a point is:

$$\mathbf{B} = {}^{\mathbf{dF}}/_{\mathbf{I}\ \mathbf{dL}\sin\theta}\ .$$

The direction of the force, **F** is as shown above. It is always mutually perpendicular to the current **I** and the field **B**. It can be remembered by several methods one of the simplest being the **left hand rule**, in which the thumb and first two fingers are held mutually perpendicular [comfortably] and they then represent the quantities shown below.

Fig.6[x] Diagrams for the L.H.R.

[a] mutually perpendicular



The definition of flux density is usually rearranged for a uniform field to

$$\boxed{F = I\,L\,B}$$

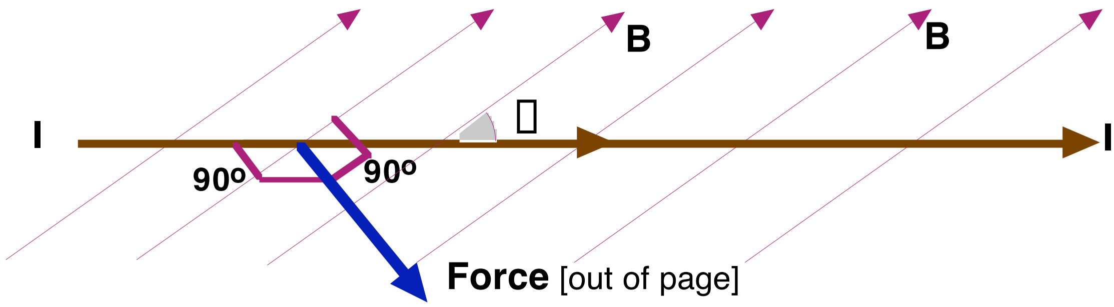
where **B** and **I** are perpendicular.

If the field and current are not perpendicular then the force is still in the same direction but it is less. The component of the field perpendicular to the direction of the current must be used and the equation becomes

$$F = ILB\sin\theta$$ where θ is the angle between the field and the current.

If the wire and the field are parallel the force is zero. The product **IL x B** is a vector product and the order must **not** be changed to **F = BIL.**

[b] any angle



6.8 Lines of Flux.

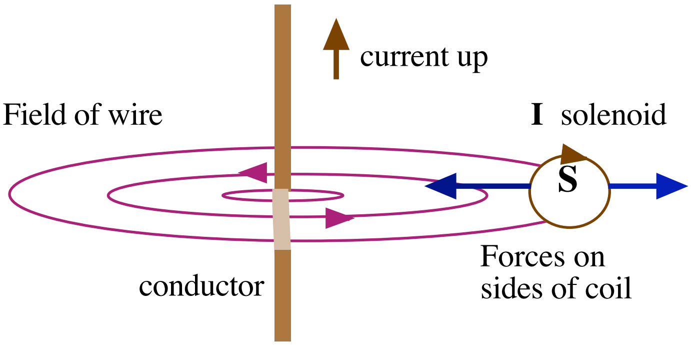
Lines showing the direction of the flux **B** are called lines of flux as distinct from lines of force. It is the closeness together of these lines of flux that indicates the magnitude of the flux density. The density of the lines or number of lines per unit area is proportional to **B**, hence the term flux density.

This distinction between flux density and field strength is not in the syllabus and the use of the term magnetic field strength or just field strength may occur when flux density is intended. If this happens assume that flux density is intended.

6.9 Compasses and Magnetic Fields.

So why does a compass point the way it does ? A compass is a magnet, which is similar to a current carrying solenoid. The forces on the sides of the coils **turn** the solenoid to face as shown. The direction of the forces is found by the LH rule or the slap rule.

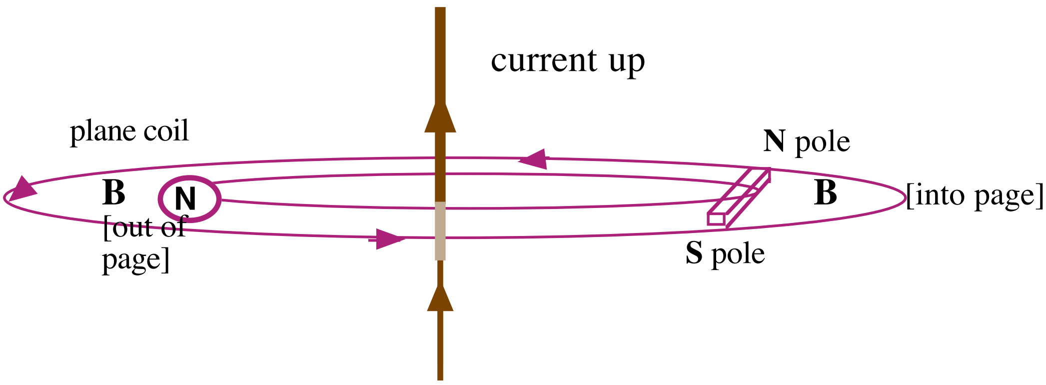
Fig.6[xi] Forces on a current in a solenoid.



The current **clockwise** as seen from this side in coil. Forces on the coil turn it until there is zero torque.

Thus the coil aligns itself this way. A south pole as shown , a north pole into the page. This is how a magnet would align itself which is shown below.

Fig.6[xii] Diagram to show the alignment of a magnet in a field.



The magnet or compass turns to point in the direction of the field because of the turning effect of the forces on the orbiting electrons. The electrons all orbit in the same direction, since the domains have lined up. The actual forces acting on the moving charges are towards and away from the wires as shown on the solenoid.

6.10 Relative permeability, μ_r.

In any medium other than a vacuum the forces are different and the value of the flux density around a magnet or a current carrying coil is different. Relative permeability is simply the **ratio** of the flux density in the medium to what it would be in a vacuum. Iron has a relative permeability of up to a thousand, since the domains add their own flux to that of the applied field. The word relative is often dropped and just permeability used. It is certain that permeability will only be examined qualitatively.

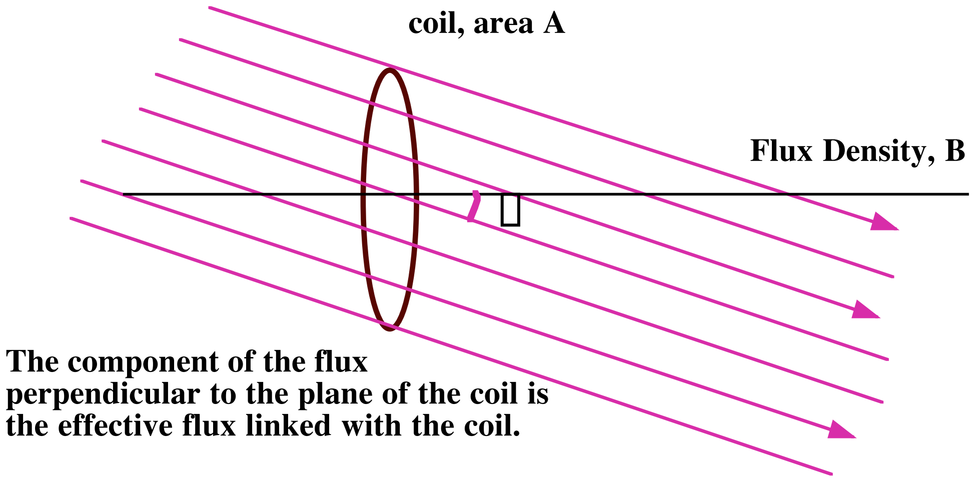
6.11 Flux. symbol [Φ]. unit weber [**Wb**]. scalar

Flux can be thought of as the 'total amount of the magnetic field' passing through an area. It is a concept very useful in electromagnetic induction, it can be thought of as the 'stuff' of the field. If **B** is proportional to the density of the lines then flux Φ is proportional to the total number of lines through an area. For a uniform field and an area perpendicular to the flux then :-

$$\Phi = \mathbf{B}\, A$$

If the flux lines are not perpendicular to the area then the component of the flux that is must be taken.

Fig.6[xiii] Flux through an area.



$\Phi = \mathbf{B\, A} \cos\theta$ where θ is the angle between the axis of the coil and **B**

Flux density, **B** is therefore also in $\mathrm{Wbm^{-2}}$; but of course it is flux density that is defined first and it is not possible to define flux density as flux per unit area.

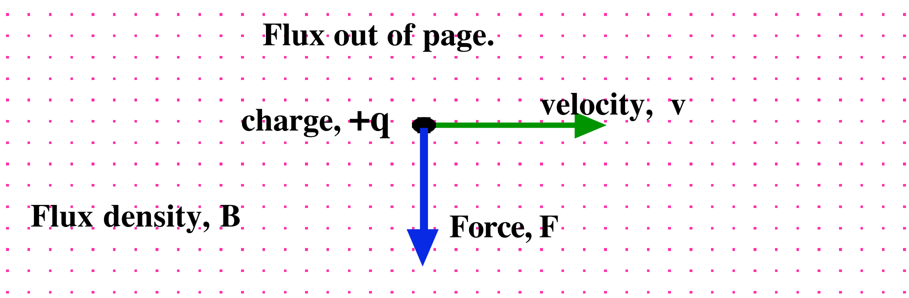
6.12 The force on a charged particle moving in a magnetic field.

A moving charge constitutes a current and therefore it experiences a force. The direction of the current is that of the flow of positive charge and if a negative charge is moving in the field then the conventional current is in the opposite direction to the velocity. The magnitude of the force is given by

F = q v B where velocity, flux and force are **mutually perpendicular .**

The direction of the force is remembered by the same rule as for the force on a current for example the left hand rule. The product **v** x **B** is a vector [cross] product and this gives the direction automatically, if the rules for vectors are known. The path followed by the particle is a circle if the initial direction was perpendicular to the field. This is because the force is always at right angles to the velocity and of constant magnitude [see topic on circular motion]. If the particle is moving parallel to the field then the force is zero.

Fig.6[xiv]



If there is an angle θ between the velocity and the flux lines the force is less than given by the formula but is still in the same direction.

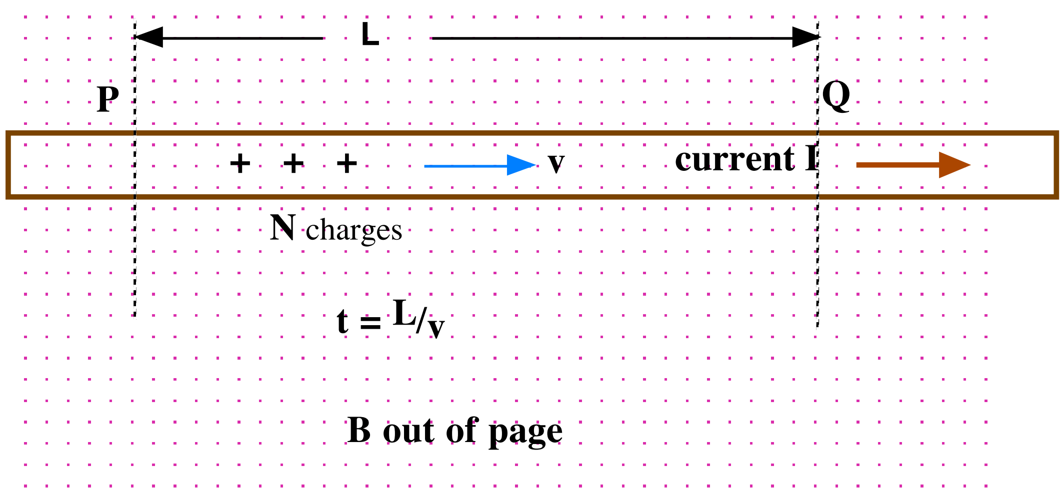
$$F = q\,v\,B\,\sin\theta \qquad \text{i.e. max. when } \theta = 90^0$$

The path is then a helix as the component of the velocity parallel to the field is not altered and the perpendicular component results in a circle. The combined path is a **helix**.

6.13 The derivation of F = q v B

In the conductor shown below there are N charge carriers between P and Q each of charge q moving with velocity v. The current is I and the dimensions as shown.

Fig.6[xv]



The number of charges passing point **Q** in time **t** is **N**

The time to move from P to Q is $\mathbf{t = {}^{L}/_{v}}$

thus the current $\mathbf{I = {}^{Nq}/_{t} = {}^{Nqv}/_{L}}$

The force on a length L of the conductor is

$$\mathbf{F = ILB = {}^{Nqv\,LB}/_{L} = qvB\ N}$$

This force is actually on **all** the moving charges in the length L.

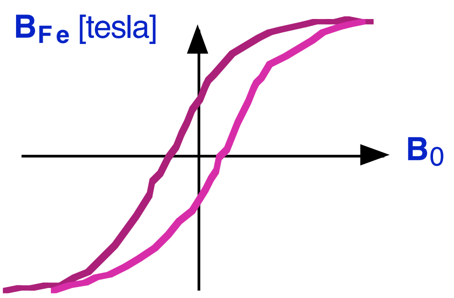
The force on a **single** charge must be $\mathbf{F = qvB}$

n.b. Remember that if the charge is **negative** then the force is in the opposite direction. When using your rule to find the direction treat the negative charges as a conventional current in the opposite direction.

6.14 Hysteresis.

It requires energy to magnetise a mass of iron or steel and it also requires energy to demagnetise it. The continuous reversing of the polarity of the iron cores in transformers, motors and generators uses a great deal of energy which the process converts to thermal energy and the cores get hot. Large transformers need cooling systems to dissipate this thermal energy. The cycle is called a hysteresis cycle and the thermal energy losses are called hysteresis losses. The word hysteresis comes from the Greek for delay. This is because when the external field is removed and the iron retains it's field the external field must be reversed to demagnetise the iron. As the external field and the induced magnetic field in the iron go through the cycle the iron lags behind or is delayed.

Fig. [xvi] The graph shows flux in the iron against flux in vacuo.



The larger the area enclosed in the loop the more energy is needed to complete the cycle. Soft iron has the smallest area whilst still giving a strong magnetic field.

6.15 Other forms of magnetism.

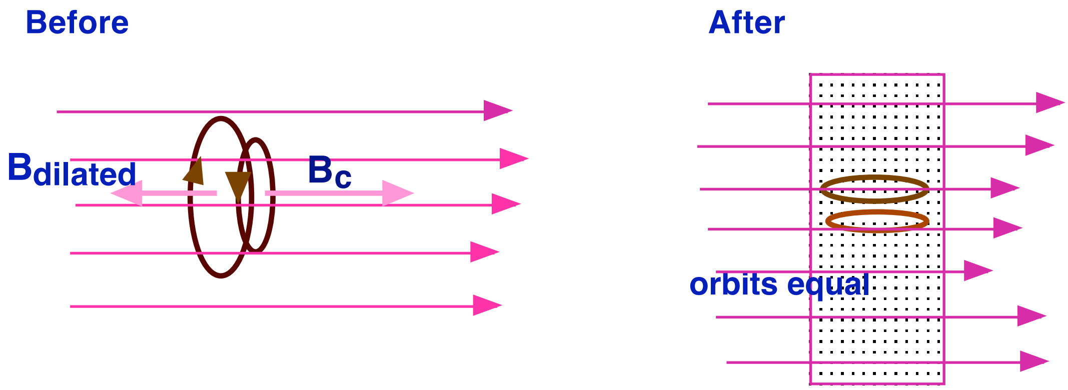
[i] Paramagnetism.

This is due to unpaired electrons spinning around the nucleus forming a very weak magnet. The external field lines the atoms up in the same way as domains. Many substances show paramagnetism. There is no retention of the rearrangement of the atoms when the external field is removed and the induced field is extremely weak. The relative permeability of say Aluminium is 1.000022. Above the Curie temperature ferromagnetic materials become paramagnetic.

[ii] Diamagnetism.

Atoms with even numbers of electrons which spin in opposite senses exhibit a different form of magnetism. Bismuth is an example. A thin rod of Bismuth aligns itself perpendicular to the external field. Their weak magnetic fields due to electrons spinning cancel but in an external field the orbits are dilated if their field opposes the external field and contracted if their field reinforces the external field. This is shown in diagram [i]. The permeability of these substances is less than unity.

Fig.6[xvi] Electron orbits and diamagnetism



The induced magnetism opposes the field and the atoms turn away, but when they are spinning on an axis perpendicular to the field as in diagram [ii] the orbits are unaltered and the turning effect disappears. All substances are diamagnetic but this is swamped by paramagnetism in other substances. At high temperatures diamagnetism predominates.

6.16 The definition of the ampere.

A straight wire carrying a current has a magnetic field that is symmetrical in two dimensions. The field spreads out like ripples on a pond and this means that the effect of the current will diminish inversely with distance from the wire. The lines of flux are circles and you can think of them loosing strength as their length increases, which is the circumference of a circle centred on the wire.

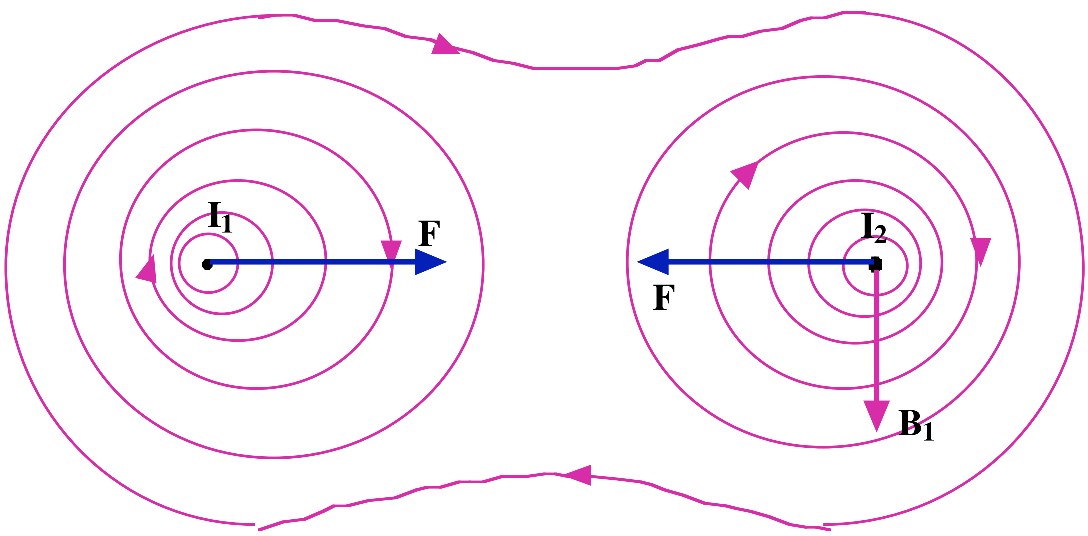
Thus $\mathbf{B \propto {}^{1}/_{2\pi d}}$ where **d** is the distance from the wire.

It should be obvious that the flux density is directly proportional to the magnitude of the current. The reason is that flux density itself is defined in terms of the force on a current. Since action and reaction are equal and opposite, then B must be directly dependent on I. Thus B a I and combining the two relations we have:-

$$\mathbf{B \propto {}^{I}/_{2\pi d}}$$

There is a force between two long parallel conductors. The wires attract if the currents are the same way. The combined field appears as shown in the diagram. The currents $\mathbf{I_1}$ on the left and $\mathbf{I_2}$ on the right are both into the page. Considering the force **F** on a length **L** of the wire carrying the current $\mathbf{I_2}$ which is in the magnetic field $\mathbf{B_1}$ of the current $\mathbf{I_1}$ then :

Fig.6[xvii] The field of parallel conductors.



$$F = I_2 L B_1 \;\square\; I_2 L \left[I_1 / 2\pi d \right]$$

Thus $F/L = \mu_0 I_1 I_2 / 2\pi d$ where μ_o is a constant

The constant μ_0 is called the **permeability of free space.** The value of the permeability of free space is **defined** to be equal to **4π x 10^{-7}** exactly. This fixes the magnitude of the ampere in the relationship above. The choice of this value for μ_0 is historical. It gives a value for the ampere very close to the older definition in terms of charge and Coulomb's law. Thus the ampere can be defined as follows.

"One amp is that current which, when flowing in each of two infinitely long parallel wires of negligible cross section, one metre apart in vacuo, causes a force between them of exactly 2 x 10^{-7} Nm^{-1} ."

6.17 Special relativity and the origin of magnetism.

Einstein's special theory of relativity shows that the observed force between two objects is altered if they are moving relative to each other and/or the observer. Relativity explains magnetic forces as a relativistic effect due to the movement of the charges. There is really only one force which changes with the frame of reference. This is called the electromagnetic force and it is more complicated than just the coulomb force.

The theory is well beyond the scope of this secondary courses but it does not require any really difficult mathematics and is very interesting. Chapters 21 to 24 cover enough of the theory to derive some of the electromagnetic formulae used here from the effects of motion on the electric field.