Stratton Products Ltd.

Electronics Tutorial, about ‘Magnetism’

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Magnetism

Electromagnetism is produced when an electrical current flows through a simple conductor such as a piece of wire or cable. A small magnetic field is created around the conductor with the direction of this magnetic field with regards to its "North" and "South" poles being determined by the direction of the current flowing through the conductor. Magnetism plays an important role in Electrical and Electronic Engineering because without it components such as relays, solenoids, inductors, chokes, coils, loudspeakers, motors, generators, transformers, and electricity meters etc, would not work if magnetism did not exist. Then every coil of wire uses the Effect of electromagnetism when an electrical current flows through it. But before we can look at **Magnetism** and especially **Electromagnetism** in more detail we need to remember back to our physics classes of how magnets and magnetism works.

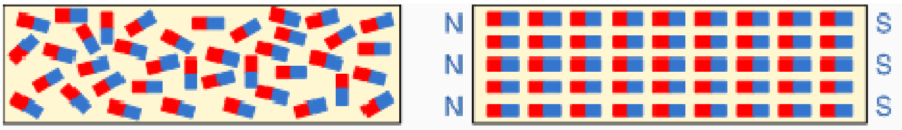
Magnetism

Magnets can be found in a natural state in the form of a magnetic ore, with the two main types being **Magnetite** also called "iron oxide", (FE_3O_4) and **Lodestone**, also called "leading stone". If these two natural magnets are suspended from a piece of string, they will take up a position in line with the earth's magnetic field always pointing north. A good example of this Effect is the needle of a compass. For most practical applications these natural occurring magnets can be disregarded as their magnetism is very low and because nowadays, manmade artificial magnets can be produced in many different shapes, sizes and magnetic strengths.

There are basically two forms of magnetism, "Permanent Magnets" and "Temporary Magnets", with the type being used dependent upon its application. There are many different types of materials available to make magnets such as iron, nickel, nickel alloys, chromium and cobalt and in their natural state some of these elements such as nickel and cobalt show very poor magnetic quantities on their own. However, when mixed or "alloyed" together with other materials such as iron or aluminium peroxide they become very strong magnets producing unusual names such as "alcomax", "hycomax", "alni" and "alnico".

Magnetic material in the non-magnetic state has its molecular structure in the form of loose magnetic chains or individual tiny magnets loosely arranged in a random pattern. The overall Effect of this type of arrangement results in zero or very weak magnetism as this haphazard arrangement of each molecular magnet tends to neutralise its neighbour. When the material is **magnetised** this random arrangement of the molecules changes and the tiny molecular magnets become "lined-up" in such a way that they produce a series magnet arrangement. This idea of the molecular alignment of ferromagnetic materials is known as **Weber's Theory** and is illustrated below.

Magnetic Molecule Alignment of a Piece of Iron and a Magnet



Loose and Individual
Magnetic Chain

Effect of Magnetization
Chains Lined-up in Series

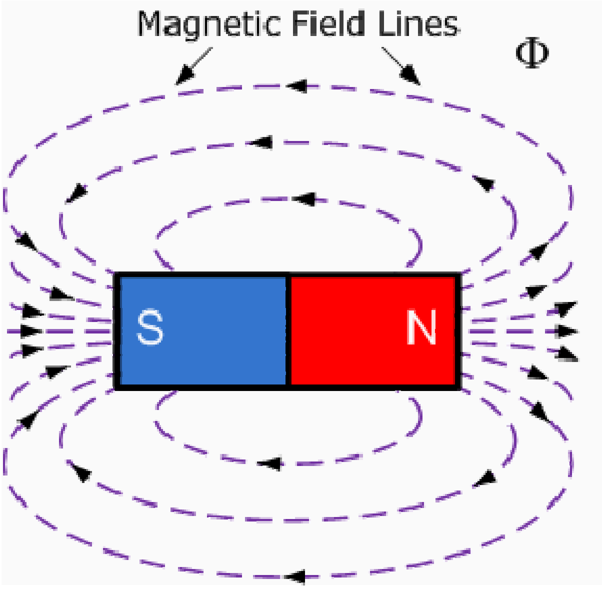
Weber's theory is based on the fact that all magnetic materials are composed of tiny magnets at a molecular level around the atoms, and a magnetised material will have most of its tiny magnets lined up in one direction only to produce a North Pole in one direction and a South Pole in the other direction. Likewise, a material that has its tiny molecular magnets pointing in all directions will have its molecular magnets neutralised by its neighbouring magnet, thereby neutralising any magnetic Effect.

Once the magnetising force has been removed, the magnetism within the material will either remain or decay away quiet quickly depending on the magnetic material being used. This ability of a material to retain its magnetism is called **Retentivity** and materials which are required to retain their magnetism will have a high retentivity and are used to make permanent magnets, while those materials required to loose their magnetism quickly such as soft iron cores for **relays** and **solenoids** will have a very low retentivity.

Magnetic Flux

The magnetism in and around a magnetic circuit will have a definite chain producing an organised and balanced pattern of invisible lines around it and which are referred to as the "magnetic field" of the magnet. The shape of this magnetic field is more intense in some parts than others with these areas being called "poles" and each end of a magnet is a pole. They can be seen visually (called a vector field) by using iron fillings sprinkled onto a sheet of paper or by using a small compass to trace them out. Magnetic poles are always present in pairs, there is always a North-pole and there is always a South-pole. Magnetic fields are always shown visually as lines of force that give a definite pole at each end of the material where the flux lines are more dense and concentrated. The lines which go to make up a magnetic field showing the direction and intensity are called **Lines of Force** or more commonly "Magnetic Flux" and are given the Greek symbol, Phi (Φ) as shown below.

Lines of Force from a Bar Magnets Magnetic Field



As shown above, the magnetic field is strongest at the poles of the magnet where the lines of flux are more dense and the general direction for the magnetic flux flow is from the North (N) to the South (S) pole. Magnetic poles are always in pairs. However, magnetic flux does not actually flow from the north to the South Pole or flow anywhere for that matter as magnetic flux is a static region around a magnet in which the magnetic force exists. In other words magnetic flux does not flow or move it is just there!. Some important facts emerge when plotting lines of force:

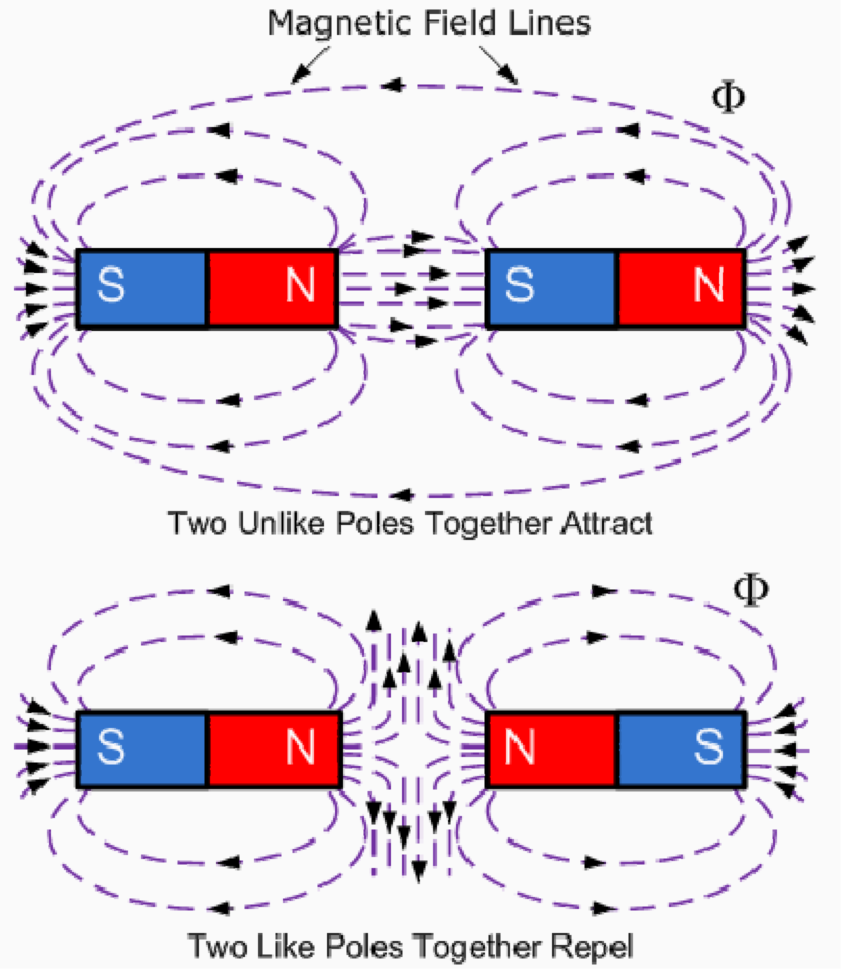
1. Lines of force NEVER cross.
2. Lines of force are CONTINUOUS.
3. Lines of force always form individual CLOSED LOOPS around the magnet.
4. Lines of force have a definite DIRECTION from North to South.
5. Lines of force that are close together indicate a STRONG magnetic field.
6. Lines of force that are farther apart indicate a WEAK magnetic field.

When two lines of force are brought close together the interaction between the two magnetic fields causes one of two things to occur:

1. When adjacent poles are the same they REPEL each other.
2. When adjacent poles are not the same they ATTRACT each other.

It can be remembered by the famous expression that "opposites attract" and this interaction of magnetic fields is easily demonstrated with iron fillings. The Effect upon the magnetic fields of the various combinations of poles as like poles repel and unlike poles attract can be seen below.

Magnetic Field of Like and Unlike Poles Together



When plotting magnetic field lines with a compass it will be seen that the lines of force are produced in such a way as to give a definite pole at each end of the magnet where the lines of force leave the N-pole and re-enter at the S-pole. Magnetism can be destroyed by heating or hammering the magnetic material, but cannot be destroyed by simply breaking the magnet into two as each half will become a separate magnet with its own north and South Poles. In order to make use of magnetism in electrical or electronic calculations, it is necessary to define the various aspects of magnetism.

Magnitude of Magnetism

We now know that the lines of force or more commonly the magnetic flux around a magnetic material is given the Greek symbol, Phi, (Φ) with the unit of flux being the Weber, (Wb) after Wilhelm Eduard Weber. But the number of lines of force within a given unit area is called the "Flux Density" and since flux (Φ) is measured in (Wb) and area (A) in metres squared, (m^2), flux density is therefore measured in $Webers/Metre^2$ or (Wb/m^2) and is given the symbol B.

However, when referring to flux density in magnetism, flux density is given the unit of the Tesla after Nikola Tesla so therefore one Wb/m^2 is equal to one Tesla, $1Wb/m^2 = 1T$. Flux density is proportional to the lines of force and inversely proportional to area so we can define **Flux Density** as:

Magnetic Flux Density

$$\text{Magnetic Flux Density, (tesla)} = \frac{\text{Magnetic Flux, (weber)}}{\text{Area, (m2)}}$$

The symbol for magnetic flux density is B and the unit of magnetic flux density is the Tesla, T.

$$\boxed{B = \frac{\Phi}{A} \quad \text{in Teslas}}$$

It is important to remember that all calculations for flux density are done in the same units, e.g., flux in Webers, area in m2 and flux density in Teslas.

Example No1

The amount of flux present in a round magnetic bar was measured at 0.013 Webers. If the material has a diameter of 12cm, calculate the flux density.

The cross sectional area of the magnetic material in m2 is given as:

$$\text{Diameter} = 12\text{cm}$$

$$\therefore \text{Area} = \pi r^2$$

$$A = 3.142 \times 0.06^2$$

$$\underline{A = 0.0113\,\text{m}^2}$$

The magnetic flux is given as 0.013 webers, therefore the flux density can be calculated as:

$$B = \frac{\Phi}{A} = \frac{0.013}{0.0113} = 1.15\text{T}$$

So the flux density is calculated as 1.15 Teslas.

When dealing with magnetism in electrical circuits it must be remembered that one tesla is the density of a magnetic field such that a conductor carrying 1 ampere at right angles to the magnetic field experiences a force of one newton-metre length on it and this will be demonstrated in the next tutorial about **Electromagnetism**.

Electromagnetism

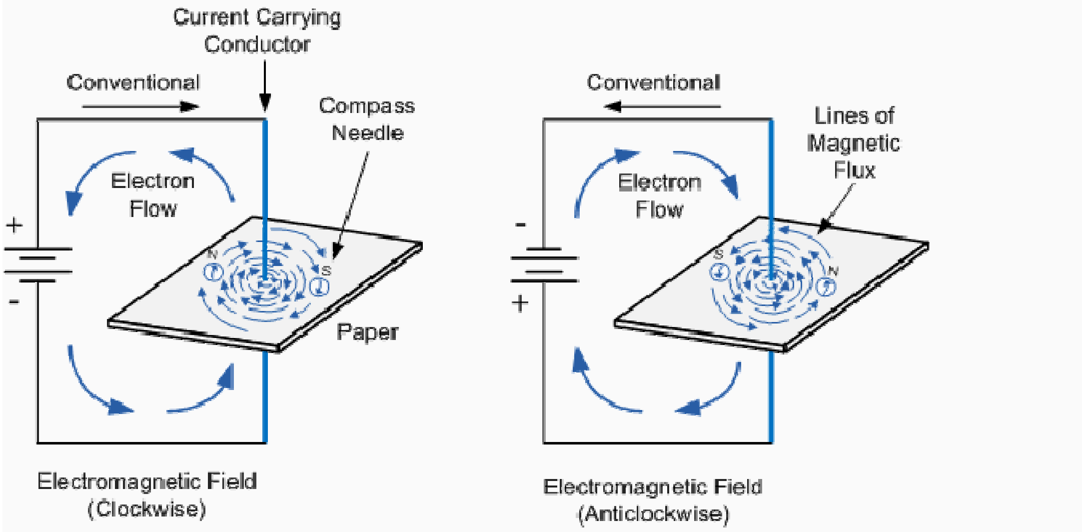
Electromagnetism

In the last tutorial about **Magnetism** we looked briefly at magnets and how they produce a magnetic field. While permanent magnets produce a good static magnetic field around themselves in some applications the strength of this field is still too weak or we need to control the amount of magnetic flux present. To obtain a stronger and more controllable magnetic field we need to use electricity, with coils of wire wrapped or wound around a soft magnetic material such as an iron core. This then gives us the basis of **Electromagnetism**.

Electromagnetism is produced when an electrical current flows through a simple conductor such as a piece of wire or cable. A small magnetic field is created around the conductor with the direction of this magnetic field with regards to its "North" and "South" poles being determined by the direction of the current flowing through the conductor. Therefore, it is necessary to establish a relationship between current flowing in the conductor and the resultant magnetic field produced by this current flow and thereby defining the definite relationship that exists between **Electricity** and **Magnetism** in the form of **Electromagnetism**.

When an electrical current flows through a conductor a circular electromagnetic field is generated around it. The direction of rotation of this magnetic field is governed by the direction of the current flowing through the conductor with the corresponding magnetic field produced being stronger near to the centre of the current carrying conductor and weaker farther away from it as shown below.

Magnetic Field around a Conductor



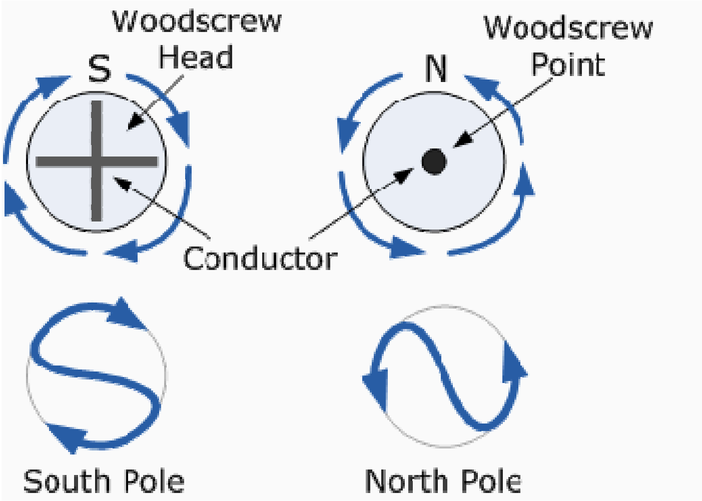
A simple way to determine the direction of the magnetic field around the conductor is to consider screwing an ordinary wood screw into a sheet of paper. As the screw enters the paper the rotational action is CLOCKWISE and the only part of the screw that is visible above the paper is the screw head.

If the wood screw is of the Pozidriv or Philips type head design, the cross on the head will be visible and it is this cross that is used to indicate current flowing "into" the paper and away from the observer. Likewise, the action of removing the screw is the reverse, anti-clockwise. As the current enters from the top it therefore leaves the underside of the paper and the only part of the wood screw that is visible from below is the tip or point of the screw and it is this point which is used to indicate current flowing "out of" the paper and towards the observer.

Then the physical action of screwing into and out of the paper indicates the direction of the current in the conductor and therefore, the direction of rotation of the electromagnetic field around it as shown on the following page.

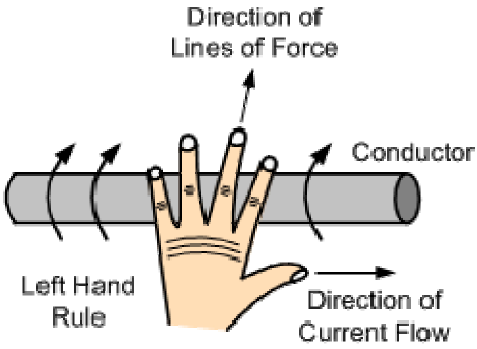
This concept is known generally as the Right Hand Screw Action.

The Right Hand Screw Action



A magnetic field implies the existence of poles and the polarity of a current carrying conductor can be established by drawing the capital letters S and N and then adding arrow heads to the free end of the letters as shown above giving a visual representation of the magnetic field direction.

Another more familiar concept which determines the direction of current flow and the resulting direction of the magnetic flux around the conductor is called the "Left Hand Rule".



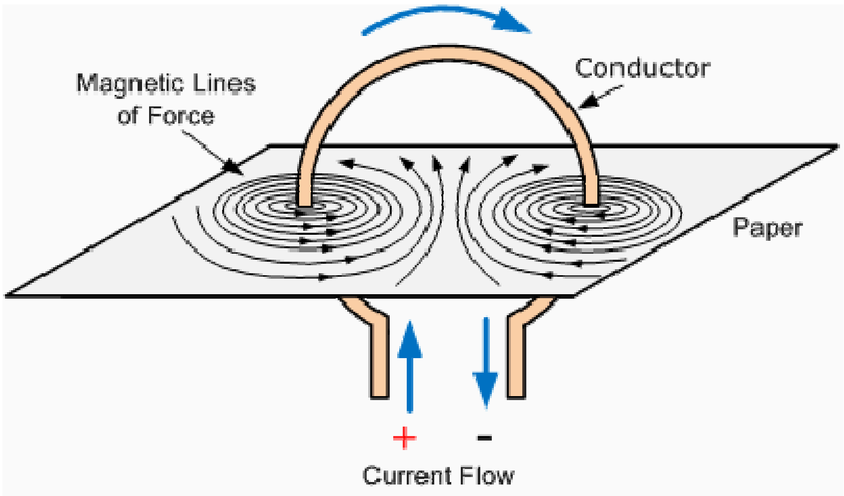
Left Hand Rule of Electromagnetism

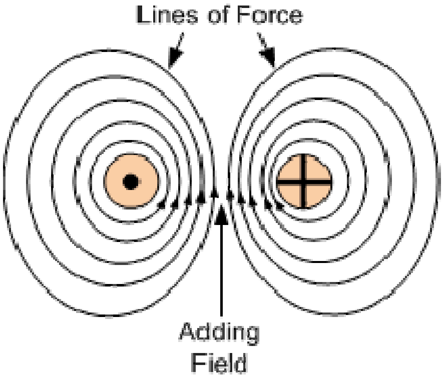
By holding the current carrying conductor in your left hand with the thumb extended it will be pointing in the direction of the *electron flow* from negative to positive. The position of the fingers laid across the conductor will now point in the direction of the magnetic lines of force as shown.

If the direction of the electron flowing through the conductor is reversed, the left hand will need to be placed onto the other side of the conductor with the thumb pointing in the new direction of the electron current flow. Also as the current is reversed the direction of the magnetic field produced around the conductor will also be reversed. This "Left Hand Rule" can also be used to determine the magnetic direction of the poles in an electromagnetic coil. This time, the fingers point in the direction of the electron flow from negative to positive while the extended thumb indicating the direction of the North Pole. There is a variation on this rule called the "right hand rule" which is based on so-called conventional current flow, (positive to negative).

When a single straight piece of wire is bent into the form of a single loop as shown below, the current will be flowing in opposite directions through the paper such that a clockwise field and an anticlockwise field are produced next to each other. The resulting space between these two conductors becomes an "intensified" magnetic field with the lines of force spreading out in such a way that they assume the form of a bar magnet generating a distinctive north and South Pole at the point of intersection.

Electromagnetism around a Loop





Lines of Force around the Loop

The current flowing through the two parallel conductors of the loop are in opposite directions as the current exits the left hand side and returns on the right hand side. This results in the magnetic field around each conductor inside the loop being in the "SAME" direction to each other. The resulting lines of force generated by the current flowing through the loop oppose each other in the space between the two conductors were the two like poles meet thereby deforming the lines of force around each conductor as shown.

However, the distortion of the magnetic flux in between the two conductors results in an intensity of the magnetic field at the middle junction as the lines of force become closer together. The resulting interaction between the two like fields produces a mechanical force between the two conductors as they try to repel away from each other. As the conductors cannot move, the two magnetic fields therefore help each other generating a north and South Pole along the line of interaction. This results in the magnetic field being strongest in the middle between the two conductors. The intensity of the magnetic field around the conductor is proportional to the distance away from it and the amount of current flowing through it.

If several loops of wire are wound together along the same axis producing a coil, the resultant magnetic field will become even stronger than the single loop producing an electromagnetic coil more commonly called a **Solenoid**. Then every coil of wire uses the Effect of electromagnetism when an electrical current flows through it and we will look at this Effect in more detail in the next tutorial.

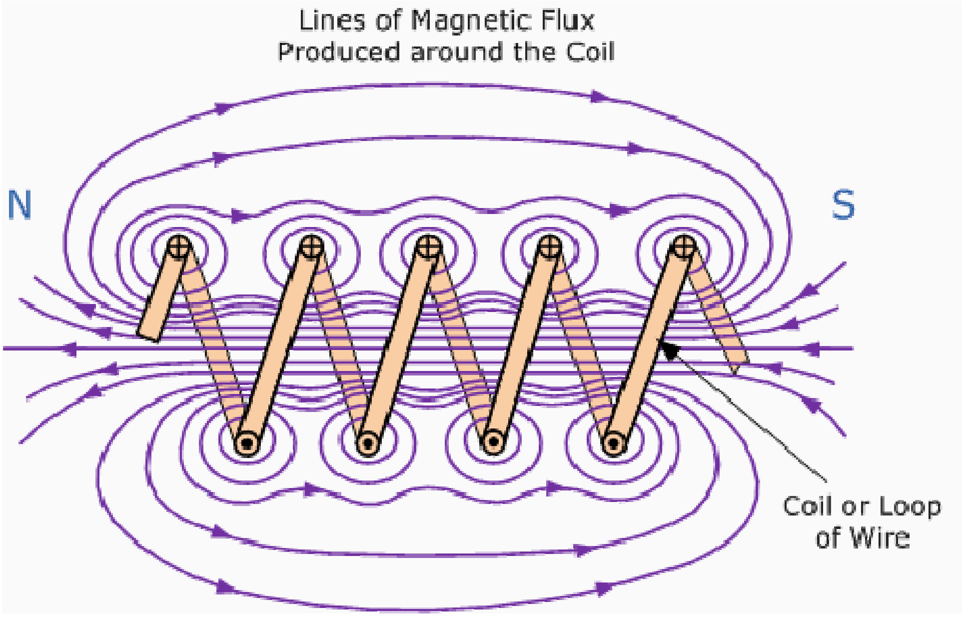
Electromagnets

Electromagnets

We now know that a straight current carrying conductor produces a circular magnetic field around itself at all points along its length and that the direction of rotation of this magnetic field depends upon the direction of current flow through the conductor. In the last tutorial about **Electromagnetism** we saw that if we bend the conductor into a single loop the current will flow in opposite directions through the loop producing a clockwise field and an anticlockwise field next to each other. **Electromagnets** use this principal by having several individual loops magnetically joined together to produce a coil.

Electromagnets are basically coils of wire which behave like bar magnets with a distinct north and South Pole when current passes through them. The static magnetic field produced by each individual coil loop is summed with its neighbour with the combined magnetic field concentrated like the single wire loop we looked at in the last tutorial in the centre of the coil. The resultant static magnetic field with a North Pole at one end and a South Pole at the other is uniform and a lot stronger in the centre of the coil than around the exterior.

Lines of Force around Electromagnets



The magnetic field that this produces is stretched out in a form of a bar magnet giving a distinctive north and South Pole with the flux being proportional to the amount of current flowing in the coil. If additional layers of wire are wound upon the same coil with the same current flowing, the magnetic field strength will be increased. It can be seen from this therefore that the amount of flux available in any given magnetic circuit is directly proportional to the current flowing through it and the number of turns of wire within the coil. This relationship is called Magneto Motive Force or m.m.f., and is given as

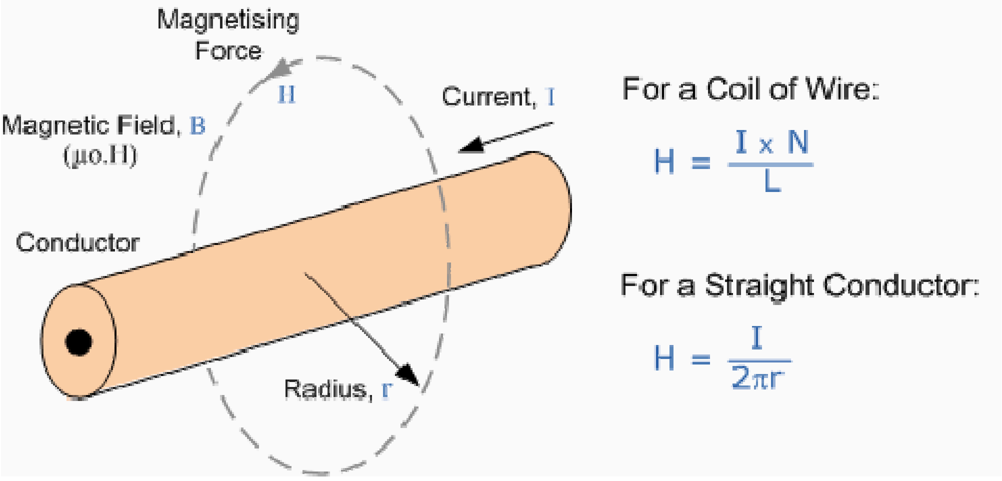
$$\text{Magneto Motive Force, (m.m.f.)} = I \times N \quad \text{ampere turns}$$

Magneto Motive Force is expressed as a current, I flowing through a coil of N turns. The magnetic field strength of an electromagnet is therefore determined by the *ampere turns* of the coil with the more turns of wire in the coil the greater will be the strength of the magnetic field.

The Magnetic Strength of Electromagnets

We now know that were two adjacent conductors are carrying current, magnetic fields are set up according to the direction of the current flow. The resulting interaction of the two fields is such that a mechanical force is experienced by the two conductors. When the current is flowing in the same direction (the same side of the coil) the field between the two conductors is weak causing a force of attraction as shown above. When the current is flowing in opposite directions the field between them becomes intensified and the conductors are repelled. The intensity of this field around the conductor is proportional to the distance from it with the strongest point being next to the conductor and progressively getting weaker further away from the conductor. In the case of a single straight conductor, the current flowing and the distance from it are factors which govern the intensity of the field. The formula therefore for calculating the "Magnetic Field Strength", H sometimes called "Magnetising Force" of a long straight current carrying conductor is derived from the current flowing through it and the distance from it.

Magnetic Field Strength for Electromagnets



- Where:
- H - is the strength of the magnetic field in ampere-turns/metre, At/m
- N - is the number of turns of the coil
- I - is the current flowing through the coil in amps, A
- L - is the length of the coil in metres, m

Then to summarise, the strength or intensity of a coils magnetic field depends on the following factors.

1. The number of turns of wire within the coil.
2. The amount of current flowing in the coil.
3. The type of core material.

Magnetic Permeability of Electromagnets

The magnetic field strength of the electromagnet also depends upon the type of core material being used as the main purpose of the core is to concentrate the magnetic flux in a well-defined and predictable path. So far only air cored coils have been considered but the introduction of other materials into the core (the centre of the coil) has a controlling Effect on the magnetic field. If the material is non-magnetic for example wood, for calculation purposes it can be regarded as free space as they have very low permeability. If however, the core material is **Ferromagnetic** such as iron, nickel, cobalt or a mixture of their alloys, a considerable difference in the flux density around the coil will be observed.

Ferromagnetic materials are those which can be magnetised. Ferromagnetic cores are usually made from soft iron, steel or various nickel alloys with the introduction of this type of material into a magnetic circuit has the Effect of concentrating the magnetic flux making it more concentrated and dense. This degree of intensity of the magnetic field either by air or by introducing ferromagnetic materials into the core is called **Magnetic Permeability** and it is a measure of the ease by which the core can be magnetised.

The numerical constant given for the permeability of a vacuum is given as: $\mu_o = 4.\pi.10^{-7}$ H/m with the relative permeability of free space (a vacuum) generally given a value of 1. It is this value that is used as a reference in all calculations dealing with permeability and all materials have their own specific values of permeability. The problem with using just the permeability of different iron, steel or alloy cores is that the calculations involved can become very large so it is more convenient to define the materials by their relative permeability.

Relative Permeability, symbol μ_r is the product of μ (absolute permeability) and μ_o the permeability of free space and is given as.

Relative Permeability

$$\mu_r = \frac{\mu}{\mu_o} = \frac{\text{Flux Density in the Material}}{\text{Flux Density in a Vacuum}}$$

Example No1

The absolute permeability of a soft iron core is given as 80 milli-henrys/m (80.10^{-3}). Calculate the equivalent relative permeability value.

$$\mu_r = \frac{\mu}{\mu_o} = \frac{80\times10^{-3}}{4\times\pi\times10^{-7}} = 64$$

When ferromagnetic materials are used in the core the use of relative permeability to define the field strength gives a better idea of the strength of the magnetic field for the different types of materials used. For example, a vacuum and air have a relative permeability of 1 and iron around 500, so the field strength of an iron core is 500 times stronger than an equivalent coil in air and this is much easier to understand than $0.628\text{x}10^{-3}$ H/m.

While, air may have a permeability of just one, some ferrite and perm-alloy materials can have a permeability of 10,000 or more. However, there are limits to the amount of magnetic field strength that can be obtained from a single coil as the core becomes heavily saturated as the magnetic flux increases and this is looked at in the next tutorial about **B-H curves** and **Hysteresis**.

Magnetic Hysteresis

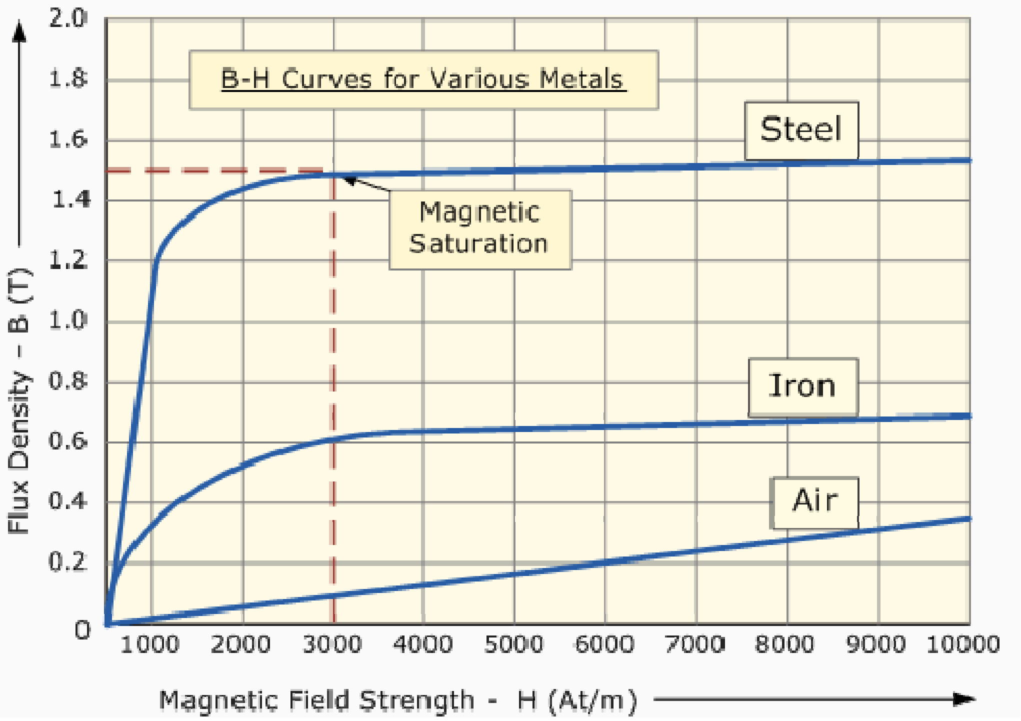
Magnetic Hysteresis

Magnetic Hysteresis relates to the magnetisation properties of a material in which it becomes magnetised and then de-magnetised. We know that the magnetic flux generated by an electromagnetic coil is the amount of magnetic field or lines of force produced within a given area and that it is more commonly called "Flux Density". Given the symbol B with the unit of flux density being the Tesla, T. We also know from the previous tutorials that the magnetic strength of an electromagnet depends upon the number of turns of the coil, the current flowing through the coil or the type of core material being used, and if we increase either the current or the number of turns we can increase the magnetic field strength, symbol H.

In the previous tutorial about **Electromagnets** the relative permeability, symbol μ_r was defined as the product of μ (absolute permeability) and μ_o the permeability of free space and was given as a constant. However, the relationship between B and H can be defined by the fact that the relative permeability, μ_r is not a constant but a function of the magnetic field intensity thereby giving magnetic flux density as: $B = \mu H$.

So for ferromagnetic materials the ratio of flux density to field strength (B/H) is not constant but varies with flux density. However, for air cored coils or any non-magnetic medium core such as woods or plastics, this ratio can be considered as a constant and this constant is known as μ_o, the permeability of free space. By plotting values of flux density, (B) against field strength, (H) we can produce a set of curves called **Magnetisation Curves**, **Magnetic Hysteresis Curves** or more commonly **B-H Curves** for individual types of core materials as shown below.

Magnetisation or B-H Curve



The set of curves above represents an example of the relationship between B and H for soft-iron and steel cores but every type of core material will have its own set of curves. You may notice that the flux density increases in proportion to the field strength until it reaches a point were it can not increase any more becoming almost level and constant as the field strength continues to increase. This is because there is a limit to the amount of flux density that can be generated by the core. The condition were the flux density reaches its limit is called **Magnetic Saturation** also known as **Saturation of the Core** and in our simple example above the saturation point of the steel curve begins at about 3000 ampere-turns per metre.

Saturation occurs because as we remember from the previous **Magnetism** tutorial which included Weber's theory, the random haphazard arrangement of the molecule structure within the core material changes as the tiny molecular magnets within the material become "lined-up". As the magnetic field strength, (H) increases these molecular magnets become more and more aligned until they reach perfect alignment producing maximum flux density and any increase in the magnetic field strength due to an increase in the electrical current flowing through the coil will have little or no Effect.

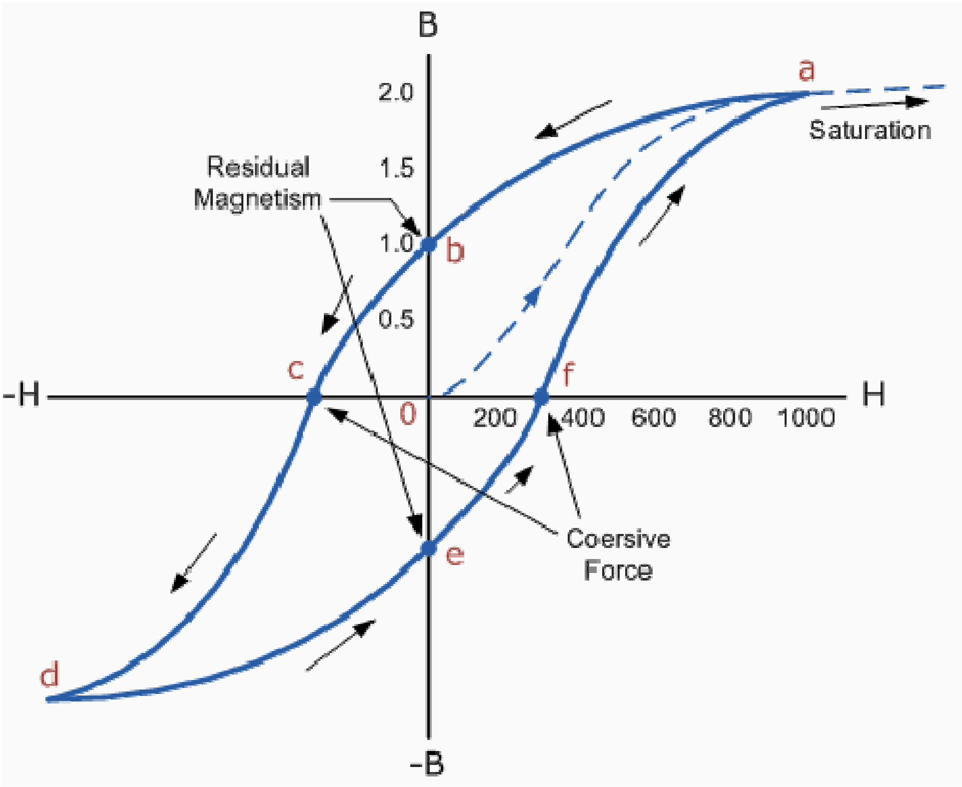
Retentivity

Let's assume that we have an electromagnetic coil with a high field strength due to the current flowing through it, and that the ferromagnetic core material has reached its saturation point, maximum flux density. If we now open a switch and remove the magnetising current flowing through the coil we would expect the magnetic field around the coil to disappear as the magnetic flux reduced to zero. However, the magnetic flux does not completely disappear as the electromagnetic core material still retains some of its magnetism even when the current has stopped flowing in the coil. This ability to retain some magnetism in the core after magnetisation has stopped is called **Retentivity** or **Remanence** while the amount of flux density still present in the core is called **Residual Magnetism**, B_r.

The reason for this that some of the tiny molecular magnets do not return to a completely random pattern and still point in the direction of the original magnetising field giving them a sort of "memory". Some ferromagnetic materials have a high retentivity (magnetically hard) making them excellent for producing permanent magnets. While other ferromagnetic materials have low retentivity (magnetically soft) making them ideal for use in electromagnets, solenoids or relays. One way to reduce the this residual flux density to zero is to reverse the direction of current flow through the coil making the value of H, the magnetic field strength negative and this is called a **Coersive Force**.

If this reverse current is increased further the flux density will also increase in the reverse direction until the ferromagnetic core reaches saturation again but in the reverse direction from before. Reducing the magnetising current once again to zero will produce a similar amount of residual magnetism but in the reverse direction. Then by constantly changing the direction of the magnetising current through the coil from a positive direction to a negative direction, as would be the case in an AC supply, a **Magnetic Hysteresis** loop of the ferromagnetic core can be produced.

Magnetic Hysteresis Loop



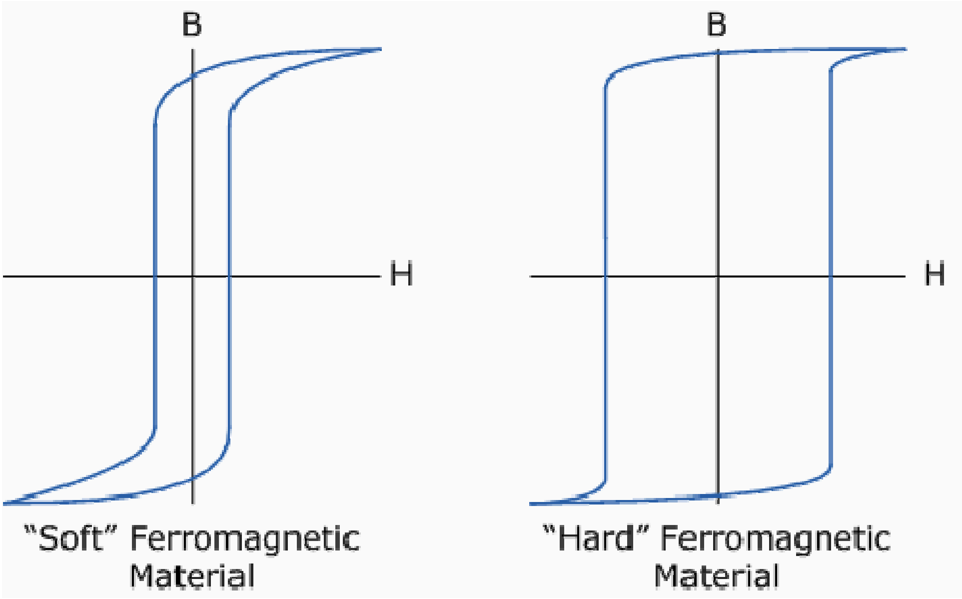
The **Magnetic Hysteresis** loop above, shows the behaviour of a ferromagnetic core graphically as the relationship between B and H is non-linear. Starting with an unmagnetised core both B and H will be at zero, point 0 on the magnetisation curve. If the magnetisation current is increased in a positive direction to some value, I the magnetic field strength H increases linearly with I and the flux density B will also increase as shown by the curve from point

0 to point a as it heads towards saturation. Now if the magnetising current in the coil is reduced to zero the magnetic field around the core reduces to zero but the magnetic flux does not reach zero due to the residual magnetism present within the core and this is shown on the curve from point a to point b.

To reduce the flux density at point b to zero we need to reverse the current flowing through the coil. The magnetising force which must be applied to null the residual flux density is called a Coersive Force. This coersive force reverses the magnetic field re-arranging the molecular magnets until the core becomes unmagnetised at point c. An increase in the reverse current causes the core to be magnetised in the opposite direction and increasing this magnetisation current will cause the core to reach saturation but in the opposite direction, point d on the cure which is symmetrical to point b. If the magnetising current is reduced again to zero the residual magnetism present in the core will be equal to the previous value but in reverse at point e. Again reversing the magnetising current flowing through the coil this time into a positive direction will cause the magnetic flux to reach zero, point f on the curve and as before increasing the magnetisation current further in a positive direction will cause the core to reach saturation at point a. Then the B-H curve follows the path of a-b-c-d-e-f-a as the magnetising current flowing through the coil alternates between a positive and negative value such as the cycle of an AC voltage. This path is called a **Magnetic Hysteresis Loop**.

The Effect of magnetic hysteresis shows that the magnetisation process of a ferromagnetic core and therefore the flux density depends on which part of the curve the ferromagnetic core is magnetised on as this depends upon the circuits past history giving the core a form of memory. Then ferromagnetic materials have memory because they remain magnetised after the external magnetic field has been removed. However, soft ferromagnetic materials such as iron or silicon steel have very narrow magnetic hysteresis loops resulting in very small amounts of residual magnetism making them ideal for use in relays and solenoids as they can be easily magnetised and demagnetised.

Magnetic Hysteresis Loops for Soft and Hard Materials



Hysteresis results in the dissipation of energy in the form of heat with the energy wasted being in proportion to the area of the magnetic hysteresis loop. As said previously, the shape of the hysteresis loop depends upon the nature of the iron or steel used and in the case of iron which is subjected to massive reversals of magnetism, for example transformer cores, it is important that the B-H hysteresis loop is as small as possible.

Electromagnetic Induction

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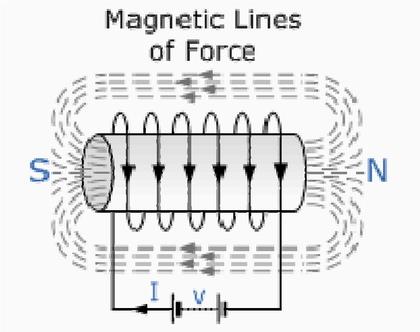
We have seen previously that when a DC current pass through a long straight conductor a magnetising force, H and a static magnetic field, B is developed around the wire. If the wire is then wound into a coil, the magnetic field is greatly intensified producing a static magnetic field around itself in the shape of a bar magnet giving a distinct North and South Pole. The magnetic flux around the coil being proportional to the amount of current flowing in the coils windings as shown. If additional layers of wire are wound upon the same coil with the same current flowing, the static magnetic field strength will be increased and therefore, the magnetic field strength of a coil is determined by the *ampere turns* of the coil with the more turns of wire within the coil the greater will be the strength of the static magnetic field around it.



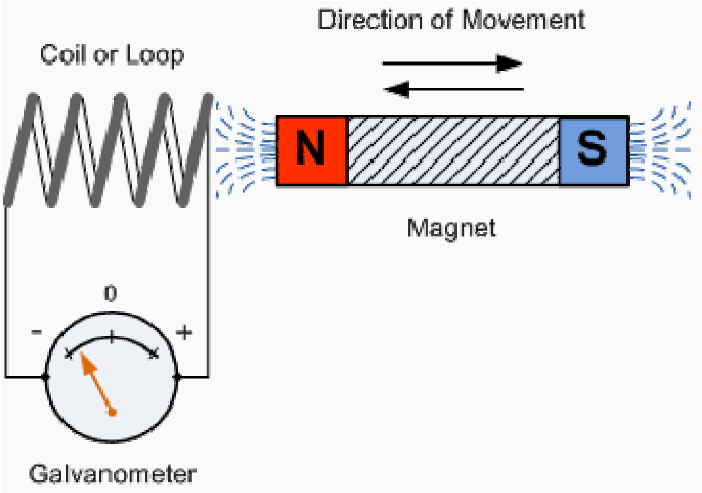
Air-core Coil

But what if we reversed this idea by disconnecting the electrical current from the coil and instead of free-air placing a bar magnet inside the open core of the coil of wire. By moving the magnet "in" and "out" of the coil a voltage would be induced into the coil by the physical movement of the magnetic flux inside it. This then is known as **Electromagnetic Induction** and is the basic principal of operation of transformers, motors and generators.

Electromagnetic Induction was first discovered way back in the 1830's by **Michael Faraday**. Faraday noticed that when he moved a permanent magnet in and out of a coil or a single loop of wire it induced an ElectroMotive Force or EMF, in other words a Voltage, and therefore a current was produced. So what Michael Faraday discovered was a way of producing an electrical current in a circuit by using only the force of a magnetic field and not batteries. This then lead to a very important law linking electricity with magnetism, **Faraday's Law of Electromagnetic Induction**. So how does this work?

When the magnet shown below is moved "towards" the coil, the pointer or needle of the Galvanometer, which is basically a very sensitive centre zeroed moving-coil ammeter, will deflect away from its centre position in one direction only. When the magnet stops moving and is held stationary with regards to the coil the needle of the galvanometer returns back to zero as there is no physical movement of the magnetic field. When the magnet is moved "away" from the coil in the other direction, the needle of the galvanometer deflects in the opposite direction with regards to the first indicating a change in polarity. Then by moving the magnet back and forth towards the coil the needle of the galvanometer will deflect left or right, positive or negative, relative to the directional motion of the magnet.

Electromagnetic Induction



Likewise, if the magnet is now held stationary and ONLY the coil is moved towards or away from the magnet the needle of the galvanometer will also deflect in either direction. Then the action of moving a coil or loop of wire through a magnetic field induces a voltage in the coil with the magnitude of this induced voltage being proportional to the speed or velocity of the movement. In other words the faster the movement of the magnetic field the greater will be the induced EMF or voltage in the coil, so for Faraday's law to hold true there must be "relative motion" or movement between the coil and the magnetic field and either the magnetic field, the coil or both can move.

Faraday's Law of Induction

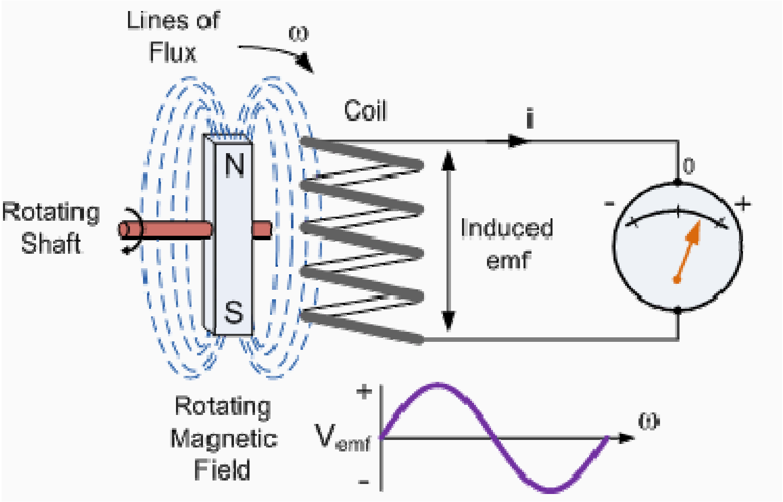
From the above description we can say that a relationship exists between an electrical voltage and a changing magnetic field to which Michael Faraday's famous law of electromagnetic induction states "that a voltage is induced in a circuit whenever relative motion exists between a conductor and a magnetic field and that the magnitude of this voltage is proportional to the rate of change of the flux".

So how much voltage (EMF) can be induced into the coil using just magnetism. Well this is determined by the following 3 different factors.

1. Increasing the number of turns of wire in the coil. - By increasing the amount of individual conductors cutting through the magnetic field, the amount of induced EMF produced will be the sum of all the individual loops of the coil, so if there are 20 turns in the coil there will be 20 times more induced EMF than in one piece of wire.
2. Increasing the speed of the relative motion between the coil and the magnet. - If the same coil of wire passed through the same magnetic field but its speed or velocity is increased, the wire will cut the lines of flux at a faster rate so more induced EMF would be produced.
3. Increasing the strength of the magnetic field. - If the same coil of wire is moved at the same speed through a stronger magnetic field, there will be more EMF produced because there are more lines of force to cut.

If we were able to move the magnet in the diagram above in and out of the coil at a constant speed and distance without stopping we would generate a continuously induced voltage that would alternate between one polarity and another producing an alternating or AC output voltage and this is the basic principal of how a Generator works similar to those used in dynamos and car alternators. In small generators such as a bicycle dynamo, a small permanent magnet is rotated by the action of the bicycle wheel inside a fixed coil. Alternatively, an electromagnet powered by a fixed DC voltage can be made to rotate inside a fixed coil, such as in large power generators producing in both cases an alternating current.

Simple Generator



The simple dynamo type generator above consists of a permanent magnet that rotates around a shaft and next to a coil of wire. As the magnet spins, the magnetic field around the top and bottom of the coil constantly changes between a north and a South Pole. This rotational movement of the magnetic field results in an alternating EMF being induced into the coil as defined by Faraday's law of electromagnetic induction.

The magnitude of the motional EMF is directly proportional to the flux density, β the total length of the conductor, l in meters and the velocity, v of the conductor in meters/second or m/s and is giving by the expression:

$$\varepsilon = -\beta.\ell.\upsilon \quad \text{volts}$$

If the conductor does not move at right angles (90°) to the magnetic field then the angle θ° will be added to the above expression giving a reduced output as the angle increases:

$$\varepsilon = -\beta.\ell.\upsilon \sin\theta \quad \text{volts}$$

Lenz's Law of Electromagnetic Induction

Faraday's Law tells us that inducing a voltage into a conductor can be done by moving it through a magnetic field, or moving the magnetic field past the conductor and if this conductor is part of a complete circuit, a current will flow. This voltage is called an **induced EMF** as it has been induced into the conductor by a changing magnetic field due to electromagnetic induction.

But a changing magnetic flux produces a varying current through the coil which itself will produce its own magnetic field as we saw in the **Electromagnets** tutorial. This self-induced EMF opposes the change that is causing it and the faster the rate of change of current the greater is the opposing EMF. This self-induced EMF will, by Lenz's law oppose the change in current in the coil and because of its direction this self-induced EMF is generally called a **back-EMF**.

Lenz's Law states that: "the direction of an induced EMF is such that it will always oppose the change that is causing it". In other words, an induced current will always OPPOSE the motion or change which started the induced current in the first place. Likewise, if the magnetic flux is decreased then the induced EMF will oppose this decrease by generating and induced magnetic flux that adds to the original flux.

Lenz's law is one of the basic laws in electromagnetic induction for determining the direction of flow of induced currents and is related to the law of conservation of energy. According to the law of conservation of energy which states that the total amount of energy in the universe will always remain constant as energy cannot be created nor destroyed. Lenz's law is derived from Michael Faraday's law of induction.

One final comment about Lenz's Law regarding electromagnetic induction. We now know that when a relative motion exists between a conductor and a magnetic field, an EMF is induced within the conductor. But the conductor may not actually be part of the coils electrical circuit, but may be the coils iron core or some other metallic part of the system. The induced EMF within this metallic part of the system causes a circulating current to flow around it and this type of core current is known as an **Eddy Current**.

Eddy currents generated by electromagnetic induction circulate around the coils core or any connecting metallic components inside the magnetic field because for the magnetic flux they are acting like a single loop of wire. Eddy currents do not contribute anything towards the usefulness of the system but instead they oppose the flow of the induced current by acting like a negative force generating heat and power loss within the system. However, there are electromagnetic induction furnace applications in which only eddy currents are used to heat and melt ferromagnetic metals.

Eddy current losses cannot be eliminated but can be greatly reduced by laminating the magnetic core material of the system into very thin strips thereby increasing the overall resistance of the eddy current path and it is for this reason why the magnetic iron circuit of transformers and electrical machines are all laminated and it is something we will discuss in another tutorial.