Trade of Electrician

Standards Based Apprenticeship

Magnetism and Electromagnetism

Phase 2

Module No. 2.1

Unit No. 2.1.7

COURSE NOTES

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Introduction

Welcome to this section of your course, which is designed to assist you the learner, understand the very important effects and uses of magnetism in electrical work.

Objectives

By the end of this unit you will be able to:

- Explain the term magnetism
- List magnetic materials
- List non magnetic materials
- Understand the properties of magnetism
- Understand the laws of magnetism
- Magnetise a piece of soft iron
- Understand how a magnet can lose its magnetism
- Understand the term electromagnetism
- Use rules to determine the direction of magnetic fields and magnetic forces
- List applications of electromagnets
- Explain how a force is exerted on a current carrying conductor in a magnetic field
- Understand how a force is exerted on current carrying conductors in parallel
- Explain what is meant by electromagnetic induction
- State Faraday's Law of electromagnetic induction
- List the factors affecting the value of the induced EMF in a coil
- Calculate the induced EMF in a coil
- Differentiate between static induction and dynamic induction
- Recognise and use important symbols
- Understand the term inductance
- Define the unit of inductance
- List the factors affecting the inductance of a coil
- Differentiate between self inductance and mutual inductance
- Understand the effect of switching an inductive load

Reasons

Magnetism and electromagnetism play a very important part in electrical work and so must be understood.

Natural and Artificial Magnets

The Greeks discovered that a certain kind of rock had the power to attract pieces of iron. The rock was a type of iron ore called **magnetite.** These rocks are actually natural magnets. They were called **lodestones**, meaning **leading stones**. They were used as crude compasses for travelling across deserts and seas. The Earth itself is a huge natural magnet and the lodestones were attracted by its **magnetism.**

Artificial magnets can be made. Soft iron can be easily magnetised, but it may also lose its magnetism easily. These are called **temporary magnets**.
Steel alloys containing aluminium, cobalt or nickel are used to make good **permanent magnets**. A permanent magnet will retain its magnetism for long periods of time.

Permanent magnets are usually made of a bar of steel alloy, either straight or bent in the shape of a horseshoe. They will attract objects made of iron. If a magnet is suspended in free air, it will come to rest with one end pointing **North**. This is called the North-seeking Pole, and the opposite pole is the South-seeking Pole.

Figure 1

Magnetic and Non-Magnetic Materials

Listed below are some common magnetic and non-magnetic materials.

Magnetic Materials:

Magnetic materials are generally referred to as **ferro-magnetic** materials
Iron, steel, nickel, cobalt.

Non-Magnetic Materials:

Paper, plastics, wood, glass, brass.

Theory of Magnetism

Magnetism, like electricity, is an invisible force. Only its effects can be seen. The force around a magnet can be describes as "**invisible lines of force leaving the magnet at one point and entering it at another"**. These invisible lines of force are called **flux lines** and the shape of the area that they occupy, the **magnetic field**.

The magnetic field around a bar magnet can be shown by sprinkling iron filings around a magnet placed under a piece of paper. If the paper is tapped gently, the iron filings arrange themselves as shown in Figure 2. This arrangement of iron filings shows the pattern of the magnetic field around the magnet.

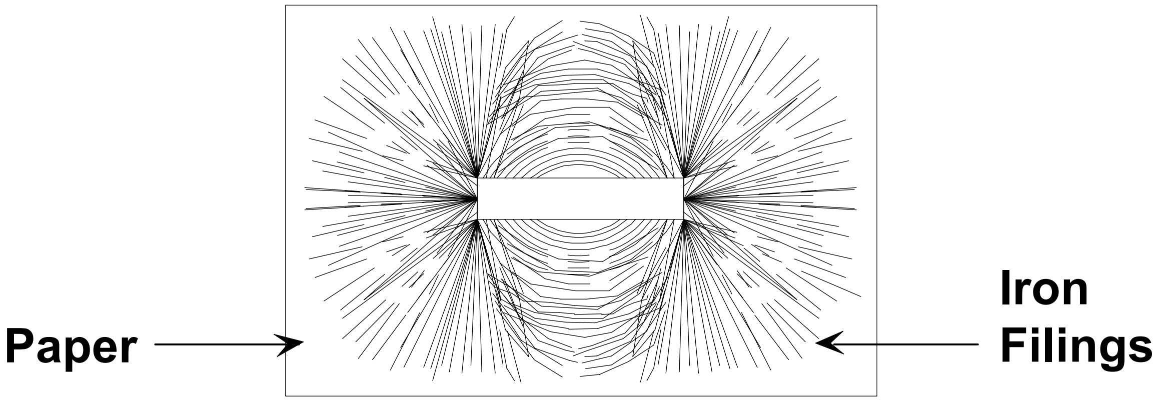


Figure 2

The magnetic field appears to be a series of curved lines, which conventionally are drawn running from the North Pole to the South Pole external to the magnet as illustrated in Figure 3.

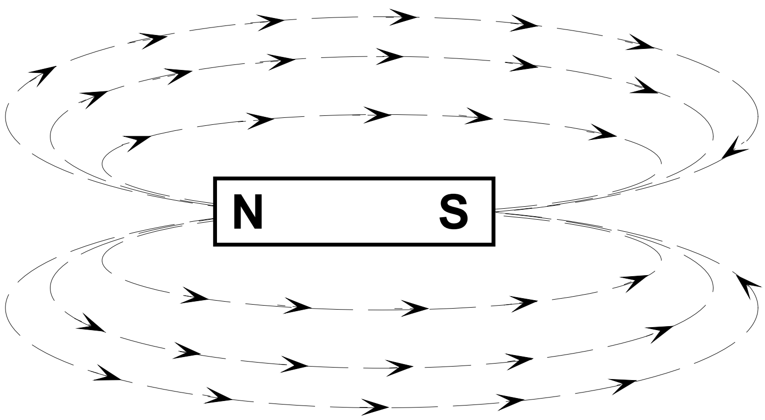


Figure 3

The arrows show the direction of the magnetic flux lines. A large number of lines may be drawn to represent a large number of flux lines (strong magnetic field).

A flux line has two proven characteristics:

- It acts in a definite direction.
- It appears endless.

Properties of Magnetic Fields

A magnetic field is made up of a large number of imaginary flux lines, which cannot be seen, felt or heard. These flux lines are more concentrated around the North and South poles of a magnet and have the following properties:

- They always form complete loops.
- They never cross one another.
- They have a definite direction, North to South external to the magnet.
- They try to contract as if they were stretched elastic threads.
- They repel one another when lying side-by-side in the same direction.

When two bar magnets are placed close together with the North Pole of one facing the South Pole of the other, the flux lines in the fields inter-act and their directions are altered and appear to be as shown in Figure 4. Flux lines attempt to **contract** and the magnets try to pull together.

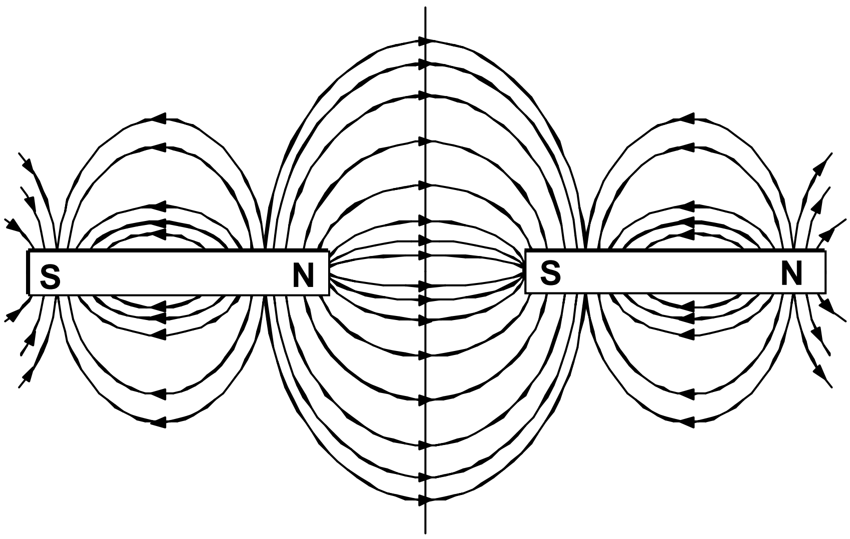


Figure 4

If two bar magnets are placed so that their North poles are very close to each other, then the flux lines will arrange themselves as shown in Figure 5.

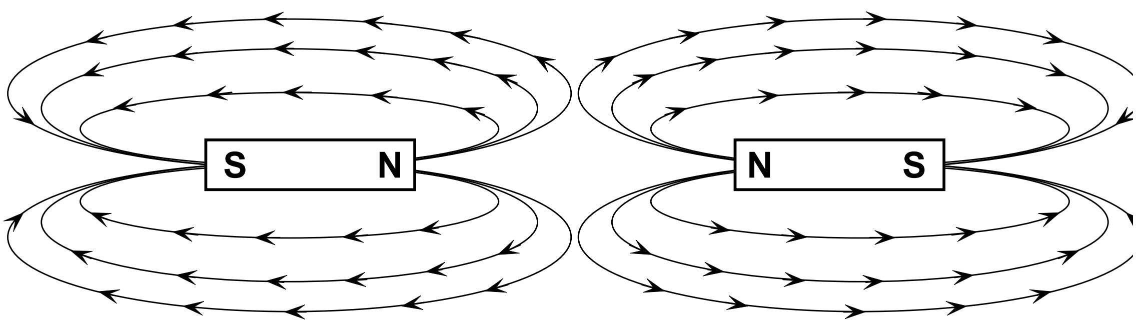


Figure 5

Since magnetic flux lines running side-by-side with the same direction **repel** each other, the two magnets try to push each other apart.

Laws of Magnetic Fields

1. Like Poles Repel

Two North Poles or two South Poles will try to push apart or repel. See Figure 6.

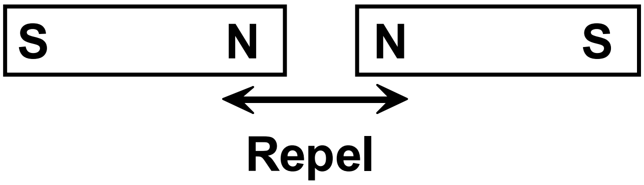


Figure 6

2. Unlike Poles Attract

A North Pole and a South Pole will try to come together or attract. See Figure 7.

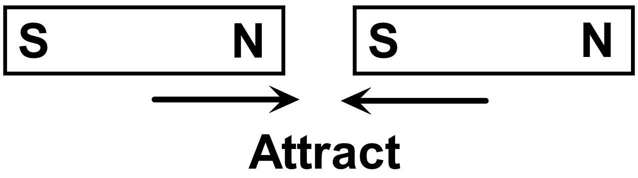


Figure 7

Method of Magnetising Soft Iron

Figure 8 illustrates how it is possible to magnetise a piece of soft iron by repeatedly rubbing it in the same direction with a bar magnet. Soft iron magnetised in this manner will lose its magnetism slowly as time goes by. Soft iron is easily magnetised and demagnetised.

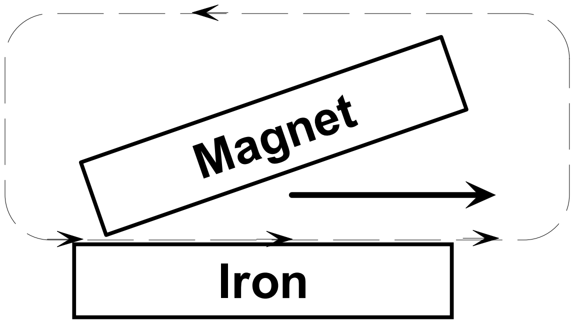


Figure 8

Loss of Magnetism

A magnet may lose its magnetism by two methods:

1. A sharp shock as a result of impact.
2. Heat.

Keepers

Magnets tend to lose their magnetism when stored for long periods. **Keepers** are pieces of soft iron, which are **placed** over the ends of the magnets to form a closed magnetic circuit. They should not be dragged or slid across the poles of the magnet.
See Figure 9.

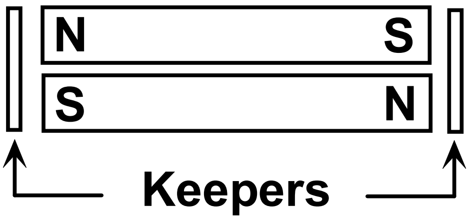


Figure 9

This helps prevent the loss of magnetism from the magnets.

Note the polarity of both magnets.

Magnets which do not deteriorate with time, and which resist demagnetisation by ill treatment are now available. Materials that make good permanent magnets are reluctant to change their magnetic direction. Such materials are said to be magnetically "HARD", e.g. **alnico and permalloy.**

Non-Magnetic Material in a Magnetic Field

When a non-magnetic material is placed into a magnetic field, the flux lines are unaffected. They behave as though the non-magnetic material was **not** there. See Figure 10.

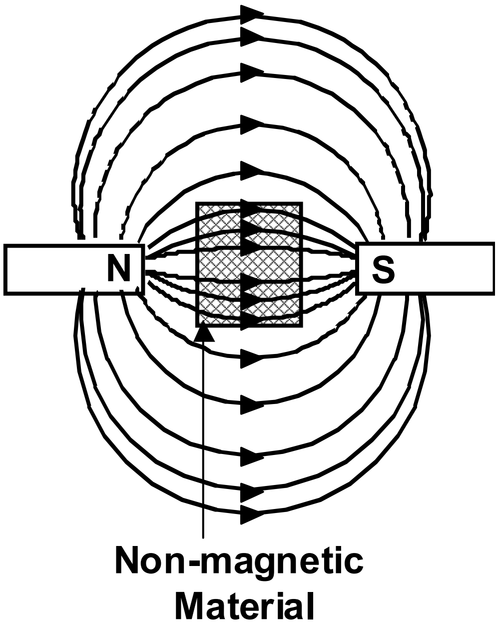


Figure 10

Ferro-Magnetic Material in a Magnetic Field

On the other hand, if a ferro-magnetic material, such as soft iron, is introduced into a magnetic field, the flux lines become more concentrated within the soft iron. See Figure 11.

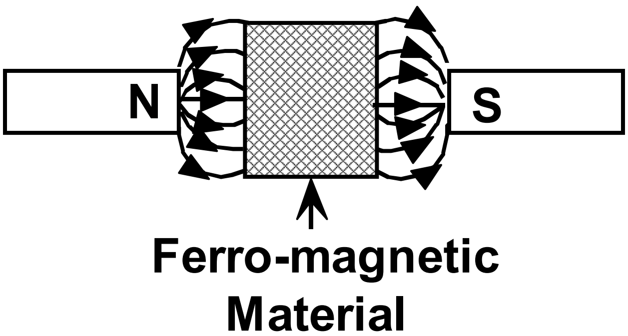


Figure 11

Electromagnetism

Direction of Magnetic Field

When a conductor carries a current, a magnetic field is produced around that conductor. This field is in the form of concentric circles along the whole length of the conductor. The direction of the field depends on the direction of the current - clockwise for a current flowing away from the observer, in the example illustrated in Figure 12.

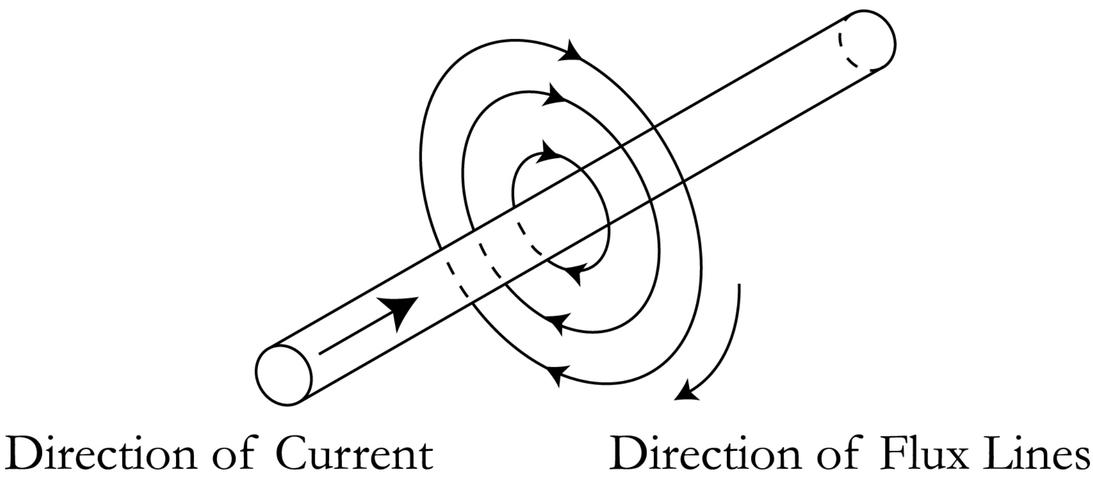


Figure 12

Figure 13A shows how a **plus sign** is used to illustrate current flowing in a direction, which is **away** from the observer.

Figure 13B shows how a **point or dot** is used to illustrate current flowing in a direction, which is **towards** the observer.

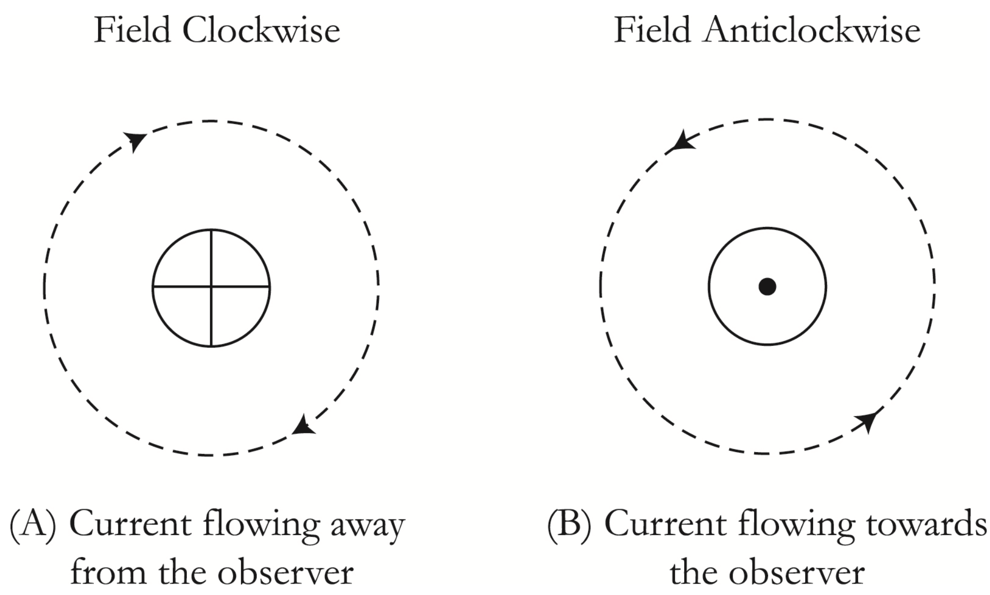


Figure 13A **Figure 13B**

Hand Rules

There is a definite relationship between the direction of current flow in a conductor and the direction of the magnetic field around that conductor. The direction can be determined by the use of either the Right Hand Grip Rule or the Corkscrew Rule.

Right Hand Grip Rule

In a current carrying conductor which is a straight wire, the direction of the magnetic field lines may be found quite simply by using the method shown in Figure 14.

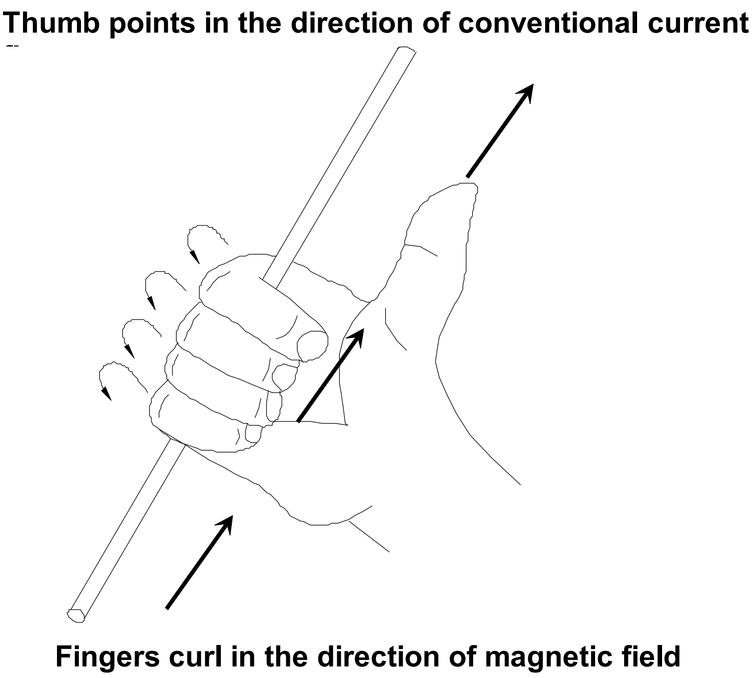


Figure 14

Corkscrew Rule

Refer to Figure 15, visualise a screw being twisted into or out of the end of a conductor in the same direction as the current flow. The direction of rotation of the screw will indicate the direction of the magnetic field.

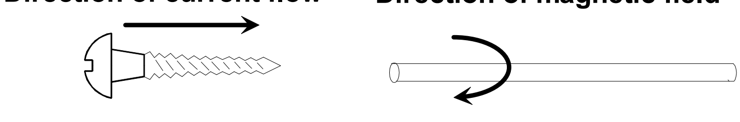


Figure 15

Magnetic Field of a Straight Conductor

Figure 16 illustrates how the magnetic field of a straight conductor is in the form of concentric circles along the whole length of the conductor.

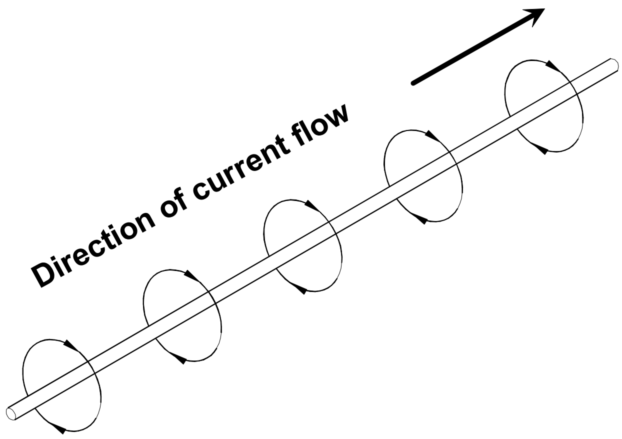


Figure 16

Magnetic Field of a Coil

Figure 17 illustrates a current passing up through a sheet of paper on the left hand side and down through the sheet on the right hand side.

The direction of the magnetic field on the left is anti-clockwise and the direction of the magnetic field on the right is clockwise.

Note that the resulting magnetic field is strongest between the two conductors.

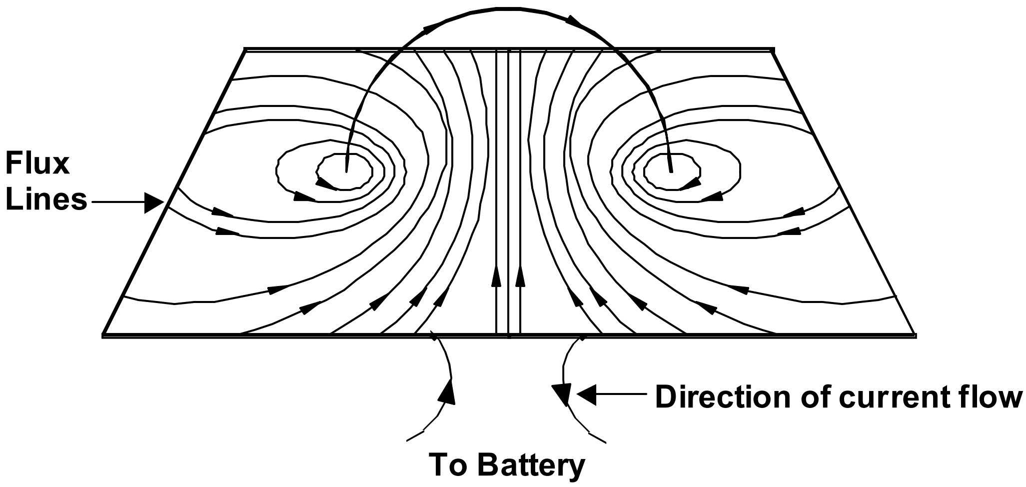


Figure 17

Experiment

Refer to Figure 18. Assemble the circuit shown. Position a number of plotting compasses on the sheet of paper.

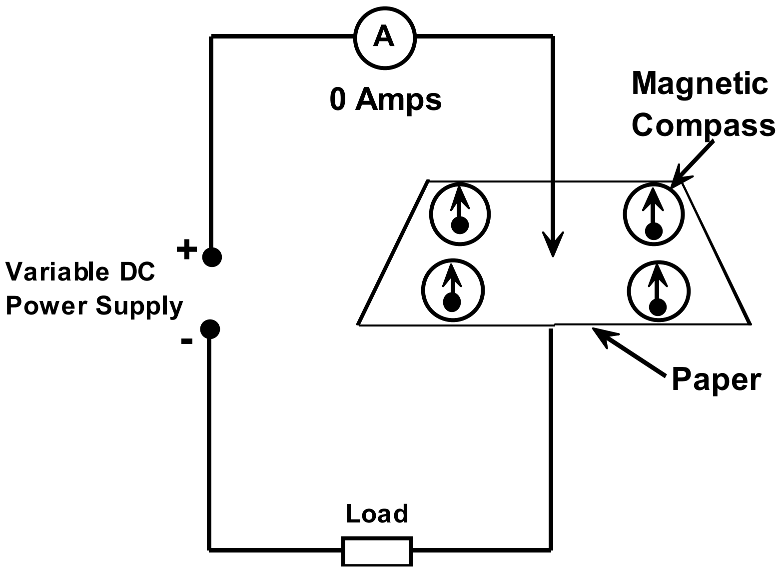


Figure 18

Refer to Figure 19. Switch on the power supply and increase the current to about 4 Amps. Notice that the plotting compasses line up in the direction of the magnetic field. The greater the current the more effective it will be.

Reverse the polarity of the supply and notice the difference in direction of the plotting compasses.

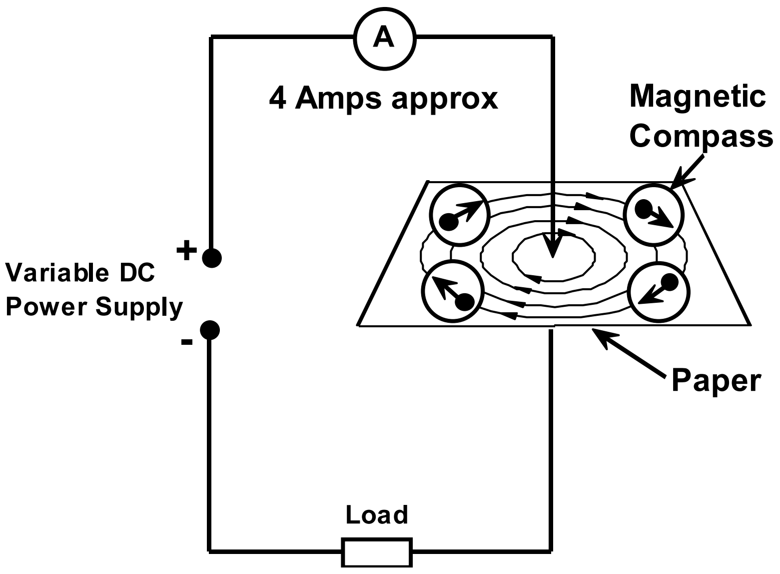


Figure 19

Magnetic Force between Current Carrying Conductors

Figure 20 shows the magnetic fields between two conductors through which current is flowing in opposite directions. There will be a force of repulsion exerted between the conductors. This represents what is occurring in a twin cable for instance.

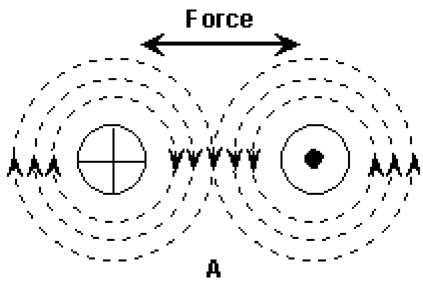


Figure 20

Figure 21 shows the magnetic fields between two conductors in which current is flowing in the same direction. There will be a force of attraction exerted between the conductors. This represents what is occurring when two cables are operating in parallel for instance.

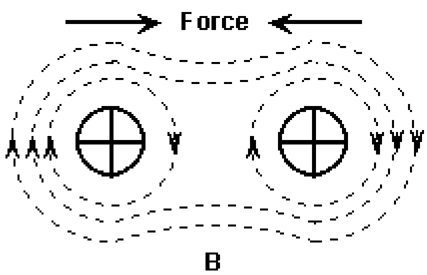


Figure 21

The Solenoid

If an insulated conductor is wound so that it forms many circular coils or **turns** it is called a **solenoid**. The strength of the magnetic field of a solenoid, depends on the value of the current flowing through the conductor and on the number of turns used in forming the solenoid. The magnetic field will be more concentrated in the centre of the solenoid.
See Figure 22.

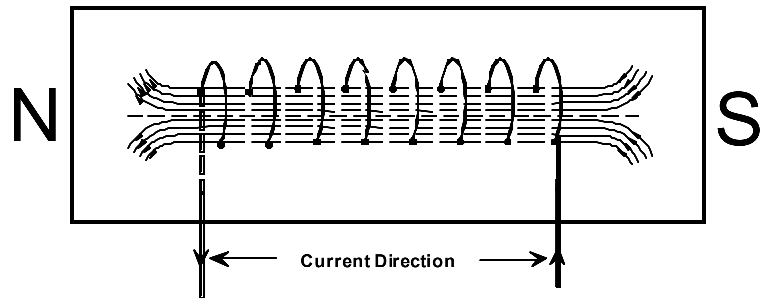


Figure 22

The magnetic field of a solenoid is the same as that of a bar magnet.
See Figure 23.

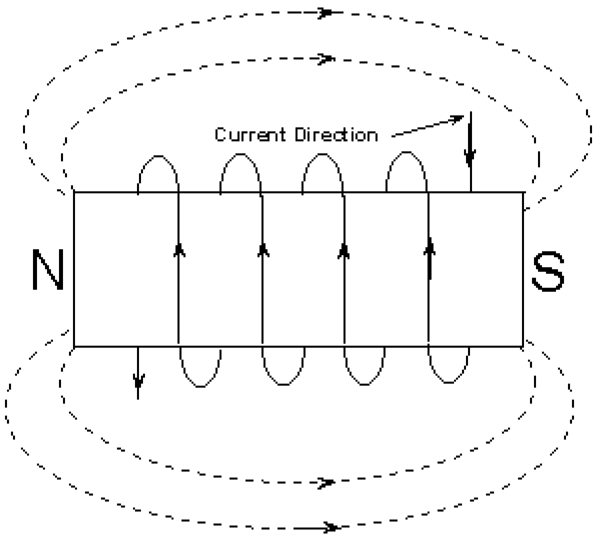


Figure 23

The solenoid is the electrical equivalent of the permanent magnet, but is often more versatile. For instance, the magnetic field can be altered by a variation of solenoid current, or reduced to zero by switching off the current. Since a solenoid is simply a coil of conducting wire, its size and shape can be varied to suit almost any requirement.

The Electromagnet

The electromagnet, based on the solenoid, is used in many items of electrical equipment. Some examples are as follows:

- Bell
- Contactor
- Relay
- MCB
- RCD

If the turns of a solenoid are wound around a soft iron core, the magnetic field is more concentrated and the magnetic flux produced for the same current will be increased many times. This effect may be used in various ways. One example is a chime bell shown in Figure 24.

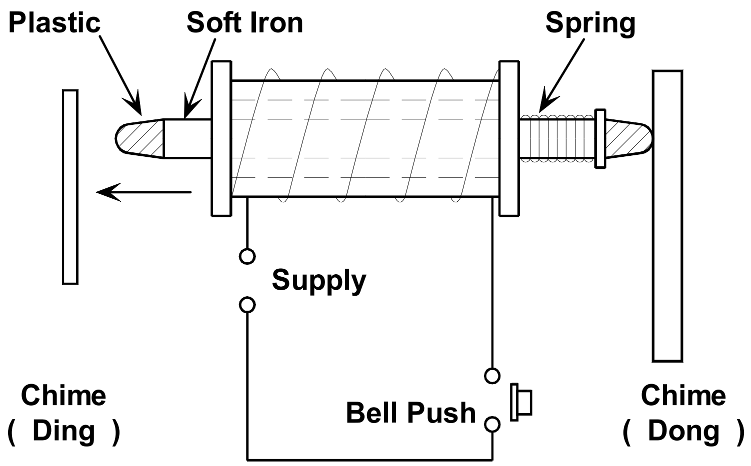


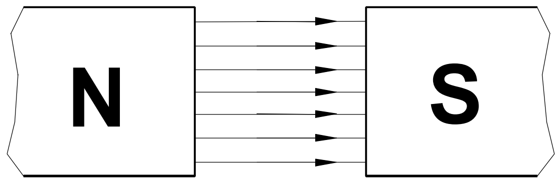
Figure 24

When the bell push is depressed, the solenoid is energised, and the soft iron rod, with plastic end inserts, is attracted by the magnetic field in the direction shown, and the "ding" chime will sound. When the bell push is released the spring will return the rod with enough force to sound the "dong" chime again.

Electric Motor Principle

The electric motor principle is based on the interaction of two magnetic fields. A basic motor consists of a permanent magnet and an arrangement of current carrying conductors. The permanent magnet is fixed in position. The arrangement of current carrying conductors is mounted on the shaft of the motor and is therefore free to rotate.

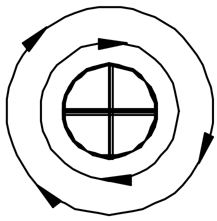
Figure 25 shows the magnetic field associated with a permanent magnet. The arrows indicate the direction of the flux lines.



Permanent magnet with associated magnetic field

Figure 25

Figure 26 shows the magnetic field associated with a current carrying conductor. The arrows indicate the direction of the flux lines.



Current carrying conductor with associated magnetic field

Figure 26

When these two magnetic fields are brought together, they interact with each other. The current carrying conductors experience a magnetic force. This force causes the conductors to move. The only way they can move is clockwise or anti-clockwise. The combination of magnetic fields, determines the direction in which they move.

Figure 27 shows the combined flux of the permanent magnet and the current carrying conductor. At point A the flux lines of the magnet and the conductor are acting in the same direction. They reinforce one and other, producing a strong magnetic field.

At point B the flux lines of the permanent magnet and the current carrying conductor are in opposite directions. They tend to cancel one and other, producing a weak magnetic field. The result is a sort of "catapult" effect, which propels the conductor in the direction indicated.

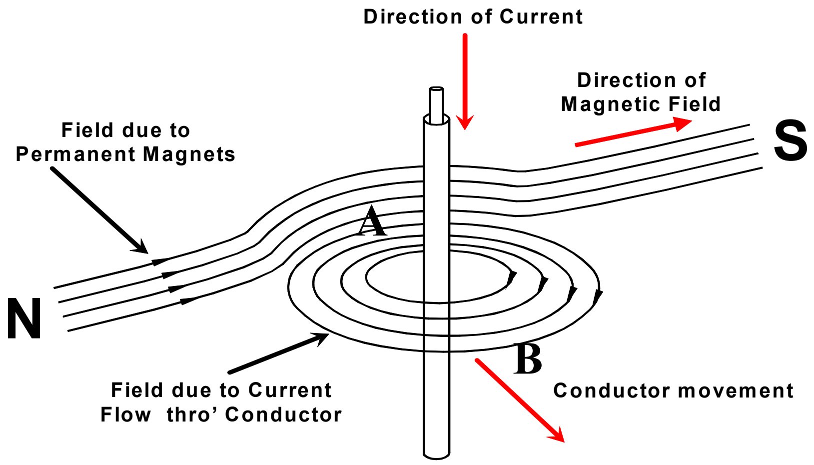


Figure 27.

There are two methods of determining the direction of this force. One method is to draw out the magnetic fields as shown above, and reason it out. The other is Fleming's Left Hand Rule.

Fleming's Left Hand Rule

This rule links the direction of current flow in the conductor, the direction of the fixed magnetic field and the direction of the movement of the conductor. Given any two of these directions, it enables us to find the third. **John Fleming** (1849-1945): See Figure 28.

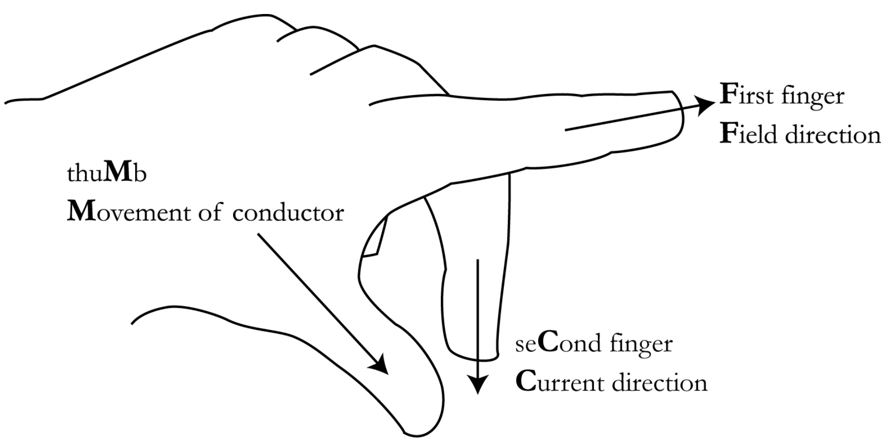


Figure 28

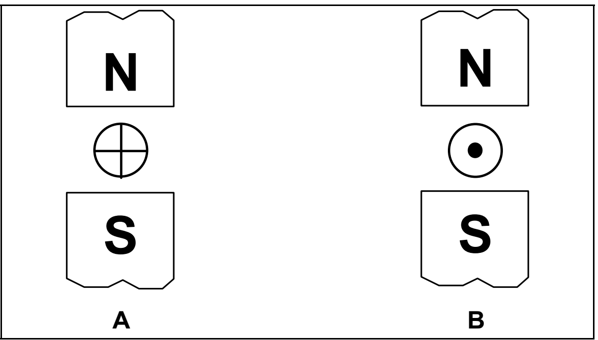
A little practice is required to become familiar with this rule. Remember, it must be carried out using the **left hand**, and applies only to the **motor effect**.

Exercise

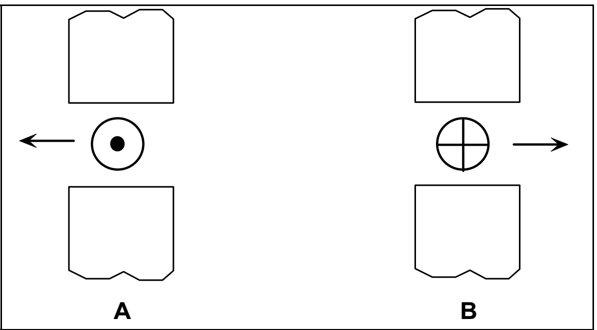
Using Fleming's Left Hand Rule for Motors

Examine the diagrams below and determine the following:

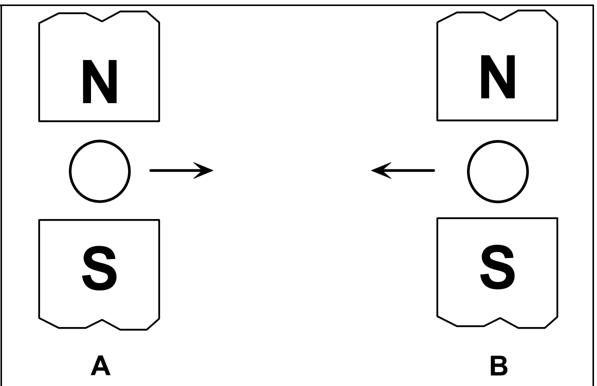
1 The direction in which the conductor is moved by the magnetic forces



2 The polarity of the magnet system



3 The direction of the current flow in the conductor



Electromagnetic Induction

It was shown that when a current flows in a conductor there is a magnetic field set up around the conductor. Under certain conditions a magnetic field can be responsible for the flow of an electric current. This is known as electromagnetic induction.

It was **Michael Faraday** (1791 - 1867) who discovered the principles of **electromagnetic induction.** He found that when a bar magnet was moved towards a stationary coil, the magnetic field created electricity in the coil. By moving the bar magnet away from the coil he could make the electricity flow in the opposite direction. This principle is the same if the coil is moved instead of the magnet.

Faraday's Law states that if a coil is placed in the region of a changing magnetic flux, an EMF will be induced in that coil.

Dynamic Induction

Figure 29 shows a short piece of copper conductor being moved relative to a stationary permanent magnet. The copper wire is connected to a sensitive galvanometer. The galvanometer needle will deflect in one direction when the wire is passed in through the magnetic field. It will move in the opposite direction when the wire is passed out through the magnetic field. The faster this is done, the greater will be deflection of the needle.

This effect is known as **dynamic induction** as the word "**dynamic**" suggests **force** and **movement**.

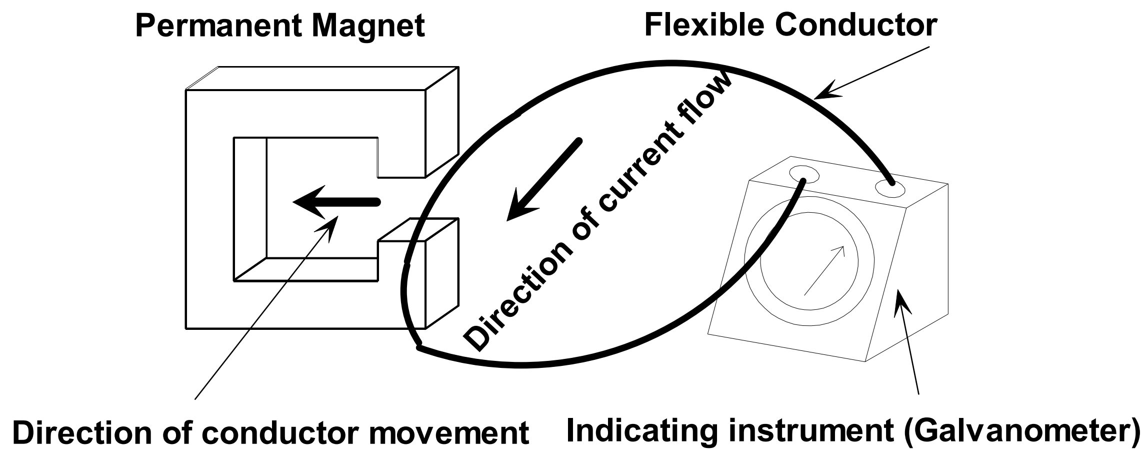


Figure 29

Factors Affecting the Value of EMF (e) Induced in a Coil.

1. The field strength or the magnetic flux density (B) between the magnetic poles.
2. The length (l) of conductor under the influence of the magnetic field.
3. The velocity (v) or speed of the conductor passing through the magnetic field.

Therefore it follows that $e = B \times l \times v$

$$e = B \times l \times v$$

Where:
e = Induced EMF measured in Volts
B = Magnetic flux density measured in **Teslas** symbol (T)
l = Length of conductor in the magnetic field in **Metres**
v = Velocity of the conductor measured metres per second (m/s)

Worked Examples

1 A 400 mm length of conductor is moved at the rate of 2 metres per second through a uniform magnetic field having a flux density of 3 Tesla. Calculate the induced EMF.

Solution:

$e = B \times l \times v$

$B = 3$ Tesla

$l = 400$ mm $= 400 \times 10^{-3}$ Metres

$v = 2$ m/s

$e = 3 \times 400 \times 10^{-3} \times 2$

$e = 2400 \times 10^{-3}$

$e =$ **2.4 Volts**

2. When a 0.5 Metre length of conductor is moved at the rate of 1 m/s through a uniform magnetic field, an EMF of 2 Volts is induced in it. Calculate the magnetic flux density.

Solution:

$e = B \times l \times v$

$$B = \frac{e}{l \times v}$$

$e = 2$ Volts

$l = 0.5$ Metres

$v = 1$ m/s

$$B = \frac{2}{0.5 \times 1}$$

$$B = \frac{2}{0.5}$$

$B =$ **4 T (Tesla)**

3. A length of conductor is moved at the rate of 1.25 m/s through a uniform magnetic field having a flux density of 2 Tesla, an EMF of 4 Volts is induced in it. Calculate the length of the conductor.

Solution:

$$e = B \times l \times v$$

$$l = \frac{e}{B \times v}$$

$$e = 4 \text{ Volts}$$

$$B = 2 \text{ Tesla}$$

$$v = 1.25 \text{ m/s}$$

$$l = \frac{4}{2 \times 1.25}$$

$$l = \frac{4}{2.5}$$

$$l = \underline{\textbf{1.6 Metres}}$$

4. When a 600 mm length of conductor is moved through a uniform magnetic field having a flux density of 2.5 Tesla, an EMF of 3 Volts is induced in it. Calculate the velocity of the conductor.

Solution:

$$e \quad B \times l \times v$$

$$v = \frac{e}{B \times l}$$

$$e = 3 \text{ Volts}$$

$$B = 2.5 \text{ Tesla}$$

$$l = 600 \text{ mm} = 0.6 \text{ Metres}$$

$$v = \frac{3}{2.5 \times 0.6}$$

$$v = \frac{3}{1.5}$$

$$v = \underline{2 \text{ m/s}}$$

Fleming's Right Hand Rule

This rule links the direction of induced current flow in the conductor, the direction of the fixed magnetic field and the direction of the movement of the conductor. Given any two of these directions, it enables us to find the third.
See Figure 30.

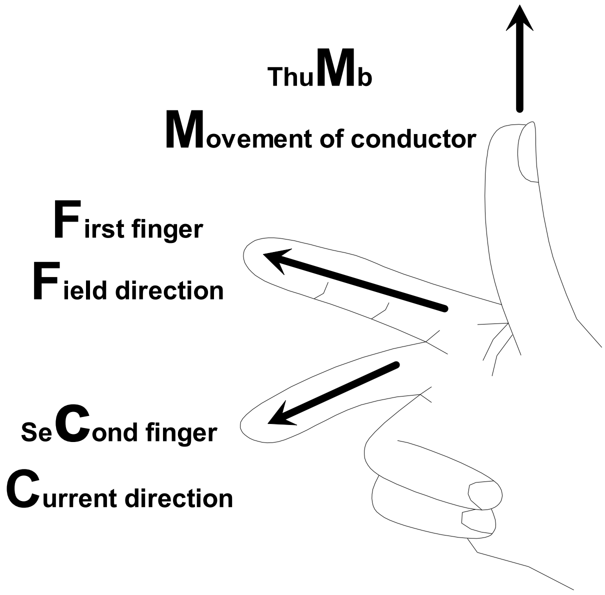


Figure 30

A little practice is required to become familiar with this rule. Remember, it must be carried out using the **right hand**, and applies only to the **generator effect**.

Summary

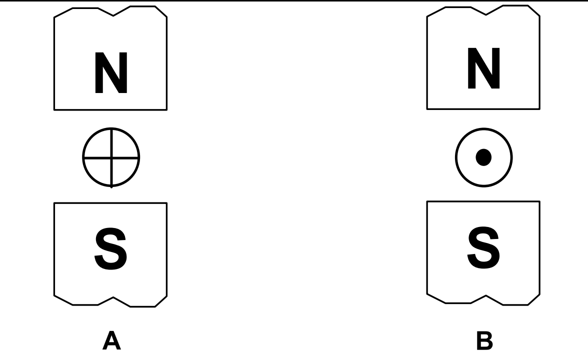
- When a conductor moves across a magnetic field an EMF is induced in it.
- When a conductor moves parallel to the flux lines, no EMF is induced in it.
- Where a magnetic field is strongest, the maximum EMF is induced in the conductor.
- The direction of the current flow in a conductor will depend on:
  - The direction of the magnetic field;
  - The direction of the conductor movement

Exercise

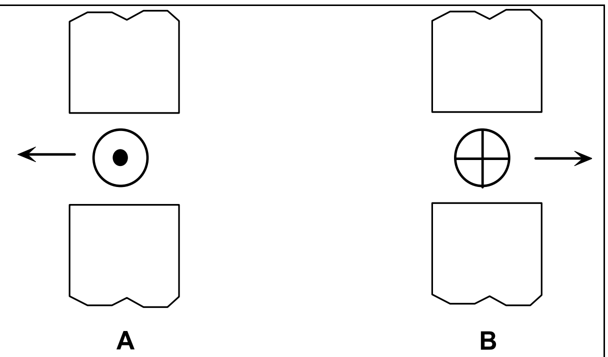
Using Fleming's Right Hand Rule for Generators

Examine the three diagrams below and determine the following:

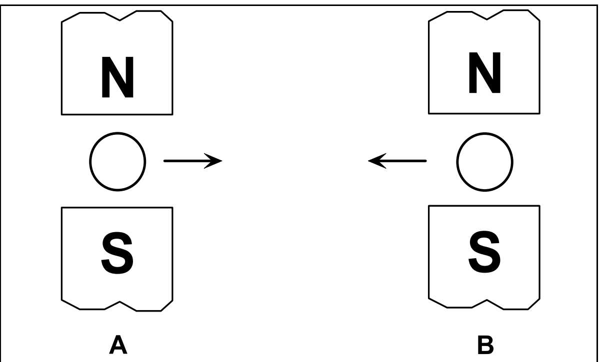
1. The direction in which the conductor is moved through the magnetic field.



2. The polarity of the magnetic field



3. The direction of the induced current in the conductor



Lenz's Law

Lenz's Law states that the direction of the induced EMF is always such that it opposes the motion producing it.

Consider a conductor being moved by an external source of energy at right angles to a magnetic field as illustrated in Figure 31A. Fleming's Right Hand Rule shows that the direction of induced current in the conductor is towards the observer. See Figure 31B.

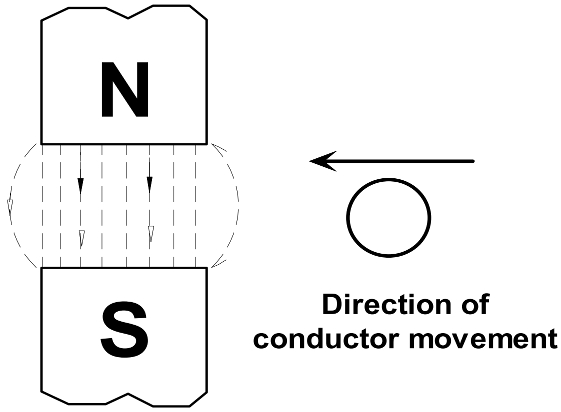


Figure 31A

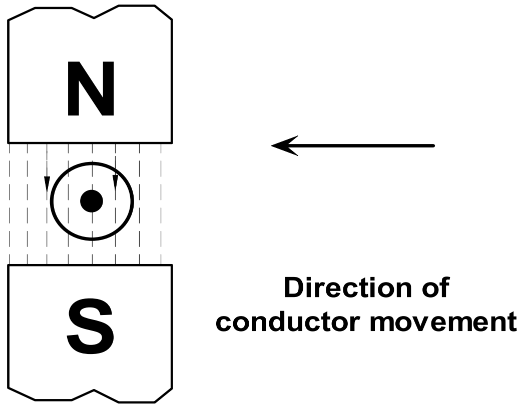


Figure 31B

We now have a current carrying conductor, which sets up its own magnetic field, as illustrated in Figure 32. We now have two magnetic fields – one due to the permanent magnet and the other due to the induced current in the conductor.

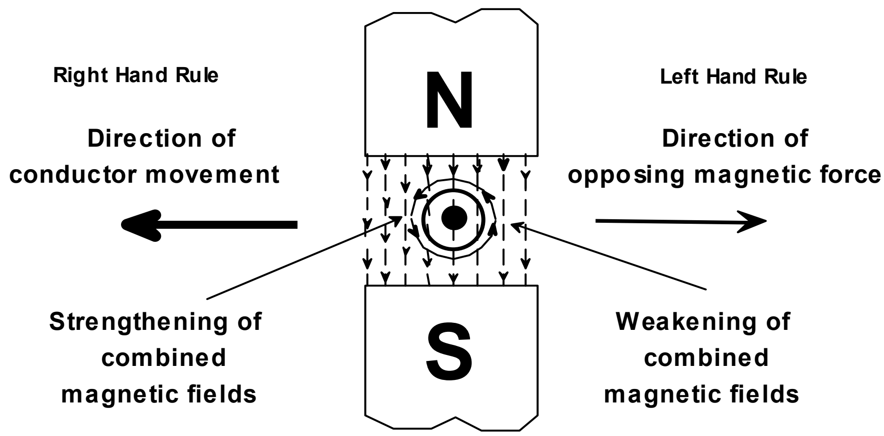


Figure 32

There will be a strengthening of the combined magnetic fields on the left hand side of the conductor, and a weakening of the combined magnetic fields on the right hand side. This will result in the conductor experiencing a force, which is in opposition to its direction of movement. The more current that is induced in the conductor the stronger the magnetic field and so more energy is required to move the conductor through the magnetic field. The opposing force will not stop the movement of the conductor. If it did, the induced EMF and current flow in the conductor would cease. There would be no magnetic field around the conductor hence no force produced.

Inductance

When the current in an inductive circuit changes, the circuit opposes the change. The property of that circuit, which opposes the change, is called **inductance**.

A circuit in which, a change of current is accompanied by a change of **magnetic flux**, and therefore, also by an induced EMF, is an **inductive circuit**. It is impossible to have a perfectly non-inductive circuit, i.e. a circuit in which no flux is set up by a current; but for most purposes a circuit which is not in the form of a coil may be regarded as being practically non-inductive.

The **Henry** (**H**) is the unit of inductance (symbol **L**).

"A circuit has an inductance of 1 Henry, when the EMF induced in it is 1 Volt as a result of the current changing at the rate of 1 Amp per Second".

Factors, which Determine the Inductance of a Coil

1. The number of turns forming the coil
2. The diameter of the coil
3. The core material.

Static Induction

We have already seen that an induced EMF due to movement of a conductor in a stationary magnetic field is known as **dynamic induction**.

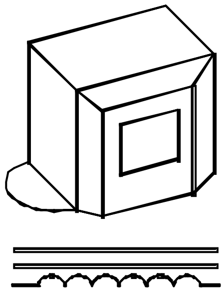
Magnetic flux lines can move without any physical movement, which we can see. Every time a current flow changes in value or direction, magnetic flux lines move. If these flux lines cut across any conductor, an EMF will be induced in that conductor.

This effect is known as **static induction** as the word "static" suggests **stationary**.

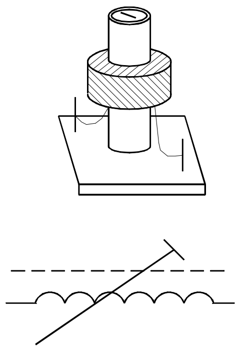
Common Inductors and Associated Symbols

Iron Cored Inductor

1Henry to 10Henry

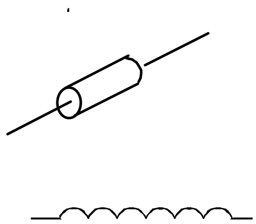


Ferrite Cored Inductor
(Preset)
1milliHenry to 100milliHenry



Air Cored Inductor

10microHenry to 100microHenry



Relay or Contactor Coil Symbol

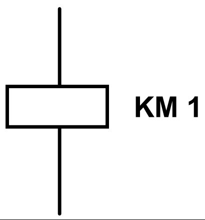


Figure 33

Self-Inductance

"The Self-Inductance of a coil is 1 Henry when the EMF induced in it is 1 Volt as a result of the current changing at the rate of 1 Amp per second."

Let us consider the effect of forming a coil from a length of wire, and connecting it to a DC source of supply.
Refer to Figure 34. Consider then, what happens when the switch S is first closed.

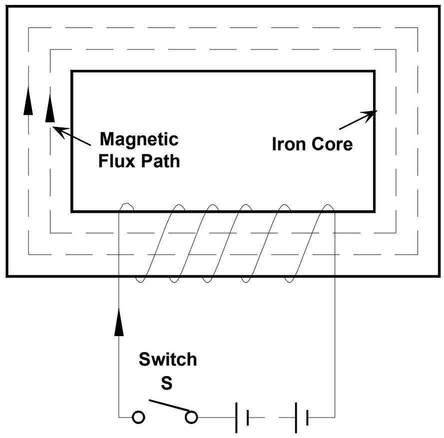


Figure 34.

As the current increases from zero to a maximum, the flux in the core also increases, and this growing magnetic field cuts across the conductors of the coil, inducing an EMF in them. This EMF, called the **back EMF** operates in the reverse direction to the supply voltage and opposes the change in the circuit current that is producing it. The effect of this opposition is to slow down the rate of change of current in the circuit. When the current reaches a steady value the magnetic field is stationary therefore no EMF is induced in the coil.

When the switch S is opened, the current falls to zero and the magnetic field collapses. Again, lines of force cut across the conductors of the coil inducing an EMF in them. The polarity of this induced EMF (back EMF) is the same as the supply voltage and tries to maintain current flow in the circuit. In this case, the back EMF appears across the switch contacts in the form of an arc. The switch should be designed for the purpose or it should be de-rated.

Any circuit, which has the property of inducing such an EMF in itself, is said to be self-inductive. All circuits are, to some extent, self-inductive, but some conductor arrangements give rise to a much greater self-inductance than others.

Factors Affecting the Self induced EMF in a Coil

1. The total magnetic flux change.
2. The time it takes to complete the change.
   (the shorter the time the greater the induced EMF).

Mutual Inductance

The Mutual Inductance between two coils is One Henry when the current changing in the first coil at one Ampere per second induces an EMF of one Volt in the second coil.

Figure 35 shows two coils of wire placed side by side, but not touching or in electrical contact with each other. The first coil is connected in series with a battery and a switch, so that current can be made to flow through it and can then be switched off. The second coil has a measuring instrument connected to its ends.

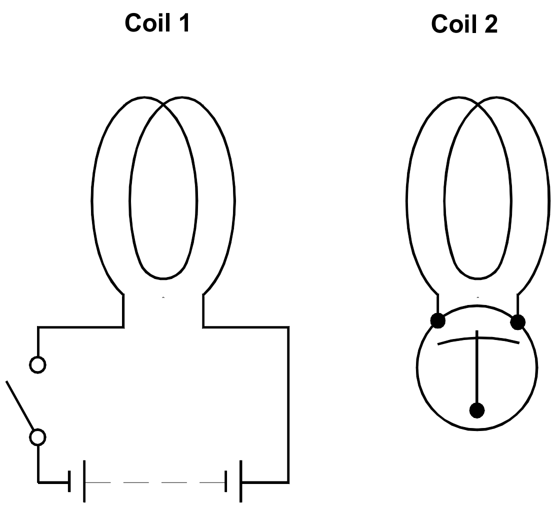


Figure 35.

If the switch in the circuit of coil 1 is closed, the instrument needle will move and then return to zero. This will occur each time the switch is turned on or off, the needle moving in a different direction at each operation. See Figure 36.

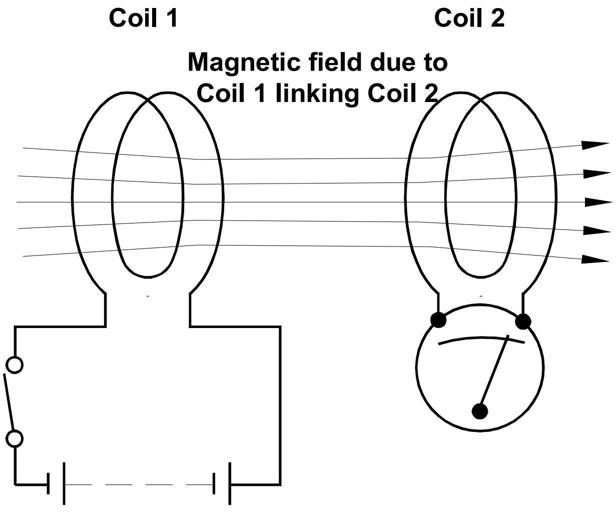


Figure 36.

When the switch is off, coil 1 has no magnetic field around it. When the switch is turned on, coil 1 sets up an expanding magnetic field, some of which passes through, or links with coil 2. This expanding magnetic field cuts the turns of coil 2 and induces an EMF in it. This will cause the instrument needle to move. The EMF will only be induced while the magnetic field is changing. When the current reaches a steady value, the magnetic field is no longer moving. Therefore there will be no EMF induced in coil 2 and the meter needle returns to zero.

When the switch is turned off, the magnetic field will collapse. This collapsing magnetic field cuts the turns of coil 2 and induces an EMF in it. The collapsing magnetic field cuts the turns of coil 2 in the opposite direction to that of the expanding magnetic field. This will cause the instrument needle to move in the opposite direction. When the current reaches a steady value, the magnetic field is no longer moving. Therefore there will be no EMF induced in coil 2 and the meter needle returns to zero again.

The unit of mutual inductance is also called the Henry (symbol H).

This is the basic principle of the operation of the transformer, which will be covered later in this course.

Switching Inductive Circuits

Energy is stored in an inductor in the form of a magnetic field. If the current is switched off, the magnetic field will collapse. The energy stored, will be returned to the circuit in the form of current, driven by the induced EMF.

If an attempt is made to switch off the DC supply to a highly inductive circuit a very large back EMF will be induced which will either cause an arc across the switch contacts or damage to the coil insulation.

Experiment

The back EMF generated by the coil of a relay can be shown very effectively using the circuit illustrated in Figure 37.

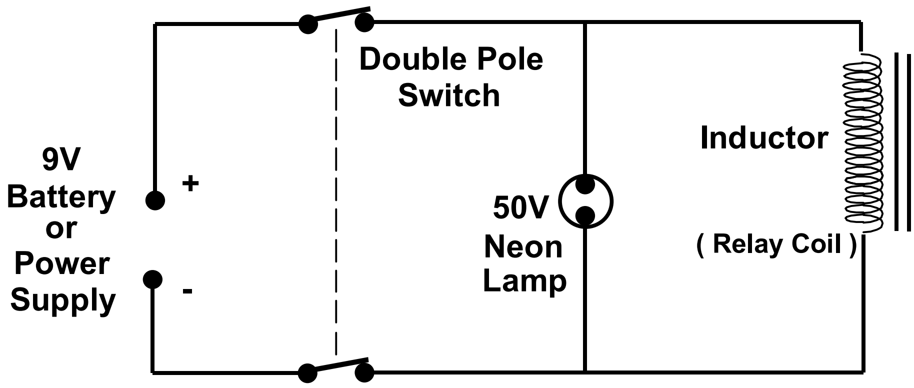


Figure 37

Switch on the circuit and suddenly switch it off. The back EMF will cause the neon lamp to glow for a short period of time. The duration of the glow will depend on the self-inductance of the coil.

The back EMF will be higher than the applied voltage. This is evident because the neon lamp will **not** glow if placed across the battery terminals but will glow when the switch contacts are opened indicating the presence of a higher voltage (back EMF).

When switching inductive loads, for example fluorescent lamps, the switches may have to be de-rated to prevent damage to the switch contacts.