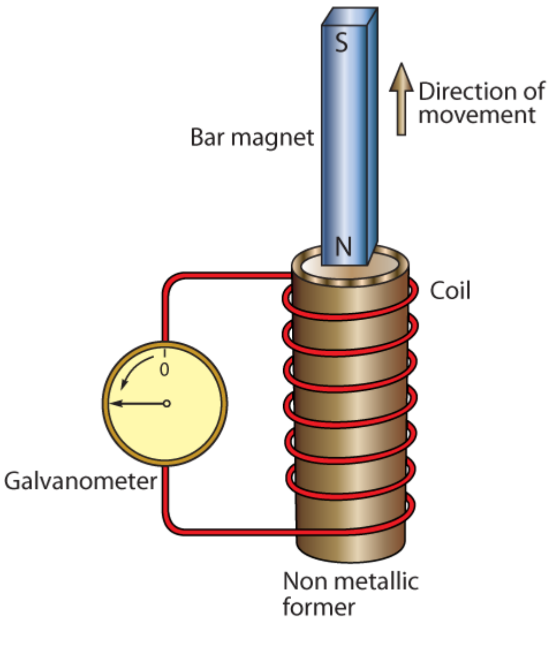
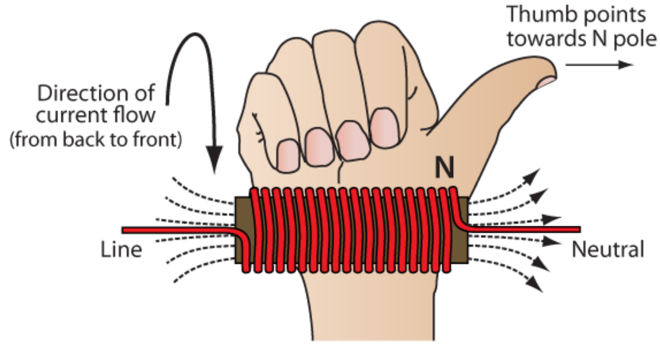
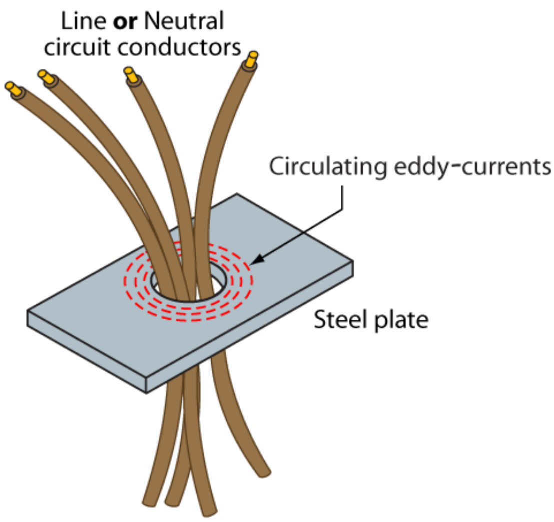
# Level 3 Diploma
# in
# Installing Electrotechnical Systems & Equipment

## C&G 2357

## Unit 309-5 Understand the fundamental principles which underpin the relationship between magnetism and electricity




B&B Training Associates Ltd
Learning Materials for the Electrical Industry

Produced by

B&B Training Associates Ltd

For further information contact:

Mrs A Bratley

23 St Paul's Drive,

Tickton, Nr Beverley,

East Yorkshire

HU17 9RN

Tel:-01964 – 543137

Fax:-01964 – 544109

Email:- sales@bbta.co.uk

timbenstead@bbta.co.uk

terry@bbta.co.uk

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# Aims and objectives

By the end of this study book you will have had:

- Describe the magnetic effects of electric current in terms of:
    - Production of a magnetic field.
    - Force on a current-carrying conductor.
    - Electromagnetism.
    - Electromotive force – emf.
    - Inductance:
        - Self
        - Mutual.
- Describe the basic principles of generating an a.c. supply in terms of:
    - a single loop generator
    - sine wave
    - frequency
    - emf
    - magnetic flux
- Explain how the characteristics of a sine wave affect the values of a.c. voltage and current.

# 1: Basic magnetism

In this session the student will:

- Gain an understanding of magnetic fields.
- Use terms such as magnetic flux and magnetic flux density.

Magnetism is often found to be one of the hardest subjects to come to grips with. It is essential however that you take your time and get a grasp of it. It is one of the most important subjects. Without a proper understanding of magnetism, electrical work will make no sense at all.

Without magnetism, we would have no motors or generators, no fluorescent or discharge lights. Just from these few examples you can see how important it is.

Magnetism and where it comes from is not fully understood, but at this level that doesn't really matter, as all we have to do is use some of the concepts.

No doubt at school or elsewhere, you will have come across the patterns that permanent magnets make when iron filings are scattered over them. These iron filings seem to follow a series of lines across the paper and look something like the drawings over the page.

You can see that when there is a north seeking pole and a south seeking pole that are close together, then the lines of flux would look something like the diagram below. The straightness of the lines of flux shows that the two poles are attracted to each other. The attraction of the north and south poles force the lines to 'shorten'.

In the diagram on the right of Figure 1, two north-seeking poles are close together. The lines of flux are 'pushed out' towards the sides. (The same would happen with two south seeking poles). This shows that the two poles are repelling each other. The lines don't shorten.

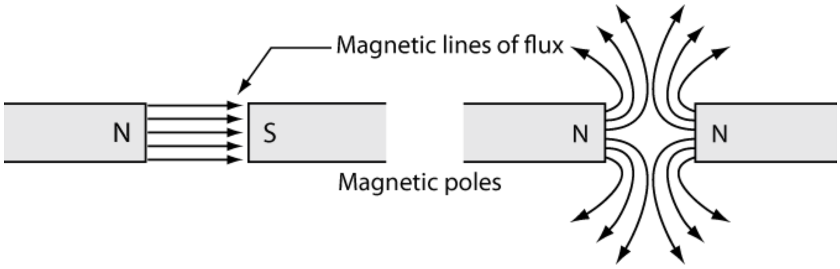



*Figure 1 Lines of magnetic flux when poles are opposing and attracting*

The general rules are; like poles repel, unlike poles attract.

Figure 2 is a very simple drawing showing the lines of ***magnetic flux*** of a bar magnet and a horseshoe magnet.

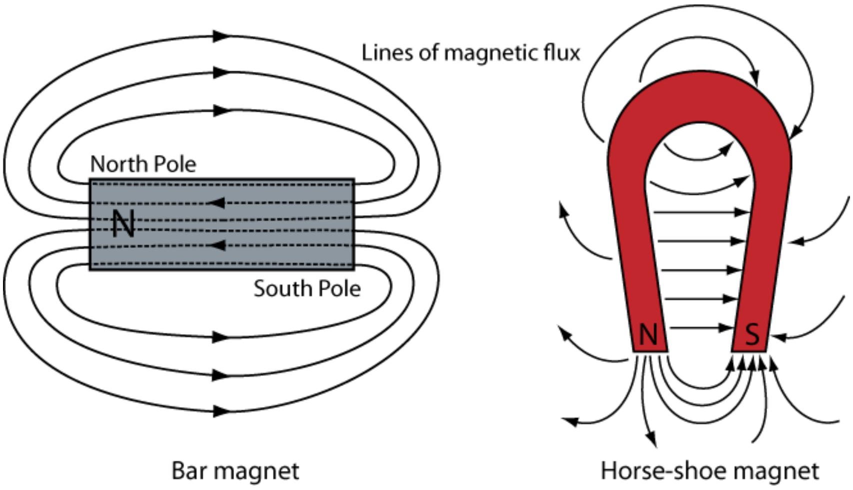



*Figure 2 Lines of magnetic flux in a bar magnet*

These lines of flux are said to pass from the '***north seeking***' pole of the magnet, and then go around and enter the magnet at the '***south seeking***' end. The idea that lines of flux 'flow' from one end to another is slightly false; in reality there is no 'flow'. The lines of flux do not really exist and are used as a means of understanding what is going on. Another way of thinking about them is as a type of force-field that emanates from the magnetic material.

Consider Figure 3, if the lines of flux were close together, you would have a strong magnetic field. If the lines of flux were not very close together then the magnetic field is weak. The amount of lines of flux in a particular area is called the ***magnetic flux density***.

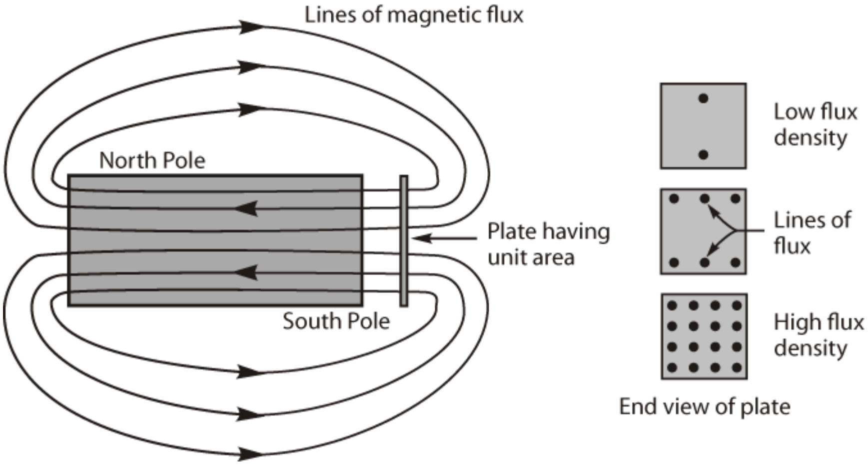



*Figure 3 Flux densities for different strengths of magnetic field*

Figure 3 and Figure 4 show the idea of flux density being based on area. If more lines passed through the unit area then the magnetic field would be much stronger.

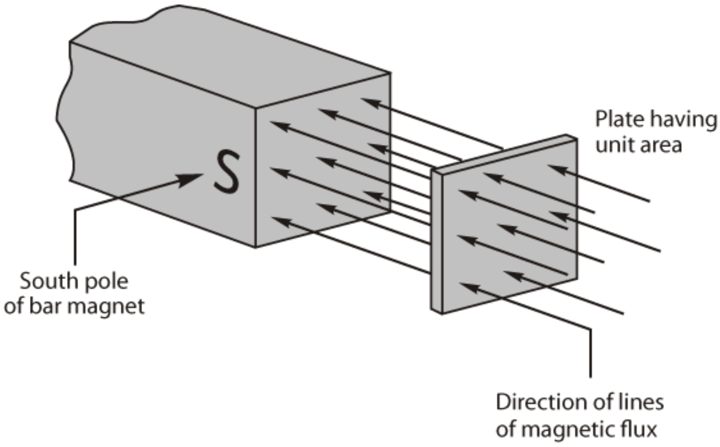



*Figure 4 Magnetic flux and flux density*

Two new concepts have now been introduced, ***flux*** and ***flux density***. By now you will be well aware that this is guaranteed to lead to a number of new names and probably some new formulae, and you may well be right. The symbol and unit of magnetic flux is given below.

| Unit | Symbol |
|---|---|
| Weber | $\phi$ |

## Magnetic flux

As with current, the definition of the '***weber***' is a little bit of a tongue twister. It does not need to be remembered, but here it is anyway. Just remember that magnetic flux is measured in Weber's.

**Either:**

**i) That magnetic flux which, when cut at a uniform rate by a conductor in 1 second, generates an emf of 1 volt, or**

**ii) That magnetic flux which, linking a circuit of 1 turn, induces in it an emf of 1 volt when the flux is reduced to zero at a uniform rate in 1 second**.

Do not worry about these two definitions, more will be made clear shortly.

## Magnetic flux density

Remember from earlier pages that magnetic flux is defined as the amount of lines of flux and that the amount of lines of flux in a particular area is called the ***magnetic flux density***.

It sounds a bit of a mouthful but it is just a measure of the amount of flux in a particular area. Look at the diagrams on earlier pages again. The unit and symbol for magnetic flux density is given below.

| Unit | Symbol |
|---|---|
| Tesla | B |

There is no formula for flux but there is one for flux density.

$$B = \frac{\Phi}{A}$$

It is worthwhile doing one or two examples, just to get used to the terms.

1). A magnetic field of 7.5 mWb exists in an iron core, which has an area of $2 \times 10^{-3} \text{m}^2$. What is the flux density of the iron?

$$B = \frac{\Phi}{A} = \frac{7.5 \times \cancel{10^{-3}}}{2 \times \cancel{10^{-3}}} = \frac{7.5}{2} = \underline{\underline{3.75\text{T}}}$$

Remember that it is important to get everything into their base units. Try this next example.

2). The magnetic flux in a circuit is 0.12 mWb. If the flux density is 0.6 T what will be the area?

$$B = \frac{\Phi}{A} \quad \text{transpose for A gives}$$

$$A = \frac{\Phi}{B} = \frac{0.12 \times 10^{-3}}{0.6} = \frac{0.00012}{0.6} = \underline{\underline{0.0002\text{m}^2}}$$

$$\text{or} \quad A = 0.0002 \times 1 \times 10^{6} = \underline{\underline{200\text{mm}^2}}$$

Notice how I have converted the $m^2$ to $mm^2$ to make it a more usable figure.

There are magnetic fields other than those formed by the wide variety of permanent magnets that have to be considered, and are of more immediate use to us as electricians. These will be considered in the next section.

**Exercise 1.**

1) How might the magnetic field around a bar magnet be plotted using a small compass.

2) Draw a diagram showing the magnetic field for:

   a) One bar magnet on its own;

   b) Two similar bar magnets placed end to end but separated by 10 cm – opposing poles facing.

3) The flux density inside a solenoid is 0.075 T, and the cross-sectional are is 2 200 $mm^2$. Calculate the value of magnetic flux.

4) The flux in the pole of an electric motor is 13.4 mWb. The pole is circular and has a diameter of 105 mm. Determine the flux density.

5) A magnetic pole is rectangular and has sides of 12 mm×8 mm. The required magnetic flux density is 12 mT. What will be the magnetic flux?

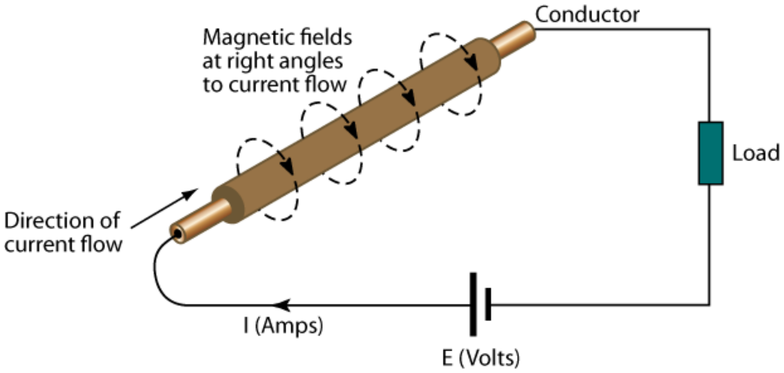
# 2: Magnetic fields and current-carrying conductors

In this session the student will:

- Understand how current is generated within a conductor in a magnetic field.
- Describe the rules that can be used to determine the direction of current flow and of magnetic field around or within conductors.

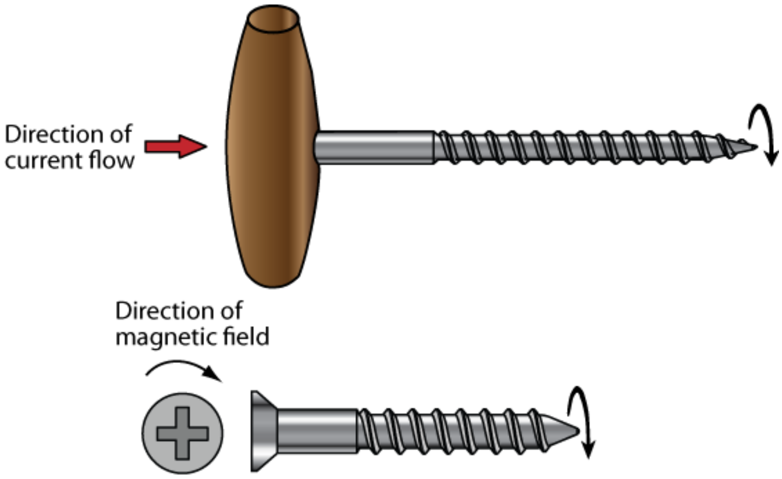
## Current-carrying conductors

When a conductor carries a current, a magnetic field forms around it. This cannot be avoided; it is a consequence of being a current carrying conductor.




From the diagram above we can see the shape of this magnetic field. Notice that it is circular and that it extends along the length of the conductor.

Notice that there are arrows showing the direction of the magnetic field around the conductor. For a current carrying conductor the direction of the magnetic field (north to south) can be determined using what is called the ***corkscrew*** rule or the ***right-hand thread*** rule. Again, this can best be described using a drawing.



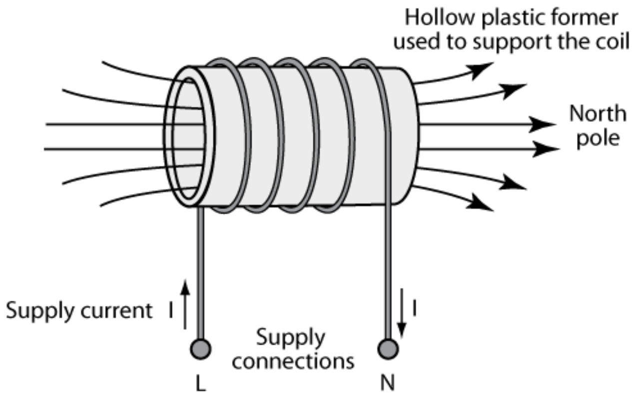

Notice from above that the direction of the current is into the cork. If I turn the corkscrew, as if I am screwing it into the bottle (clockwise), then the current is assumed to be flowing into the bottle and the magnetic field is said to be in a clockwise direction. If I turn the corkscrew as if I am removing it from a bottle, then the current and the magnetic field are in the opposite direction to that just stated.

There are some useful and some not so useful features of the magnetic effect produced when a conductor carries a current. On the '***down***' side, if these conductors carry a.c. (alternating current) and pass through an iron based material or a material that can become magnetised, an effect called '***eddy currents***' can be set up in the material. This can cause excess heating to occur. More of this will be mentioned when we come to look at conduit and trunking.

On the '***up***' side, when a number of conductors, whether it is a.c. or d.c., are brought close to each other, the strength of the magnetic field increases dramatically and this effect is used in motors, generators, relays, bells, chokes and transformers. We'll look at this effect next.

## Solenoids

A solenoid is simply a coil of wire wrapped around a former. If the turns of wire are formed around a different type of core, such as iron, then we usually talk of it in terms of being a coil.



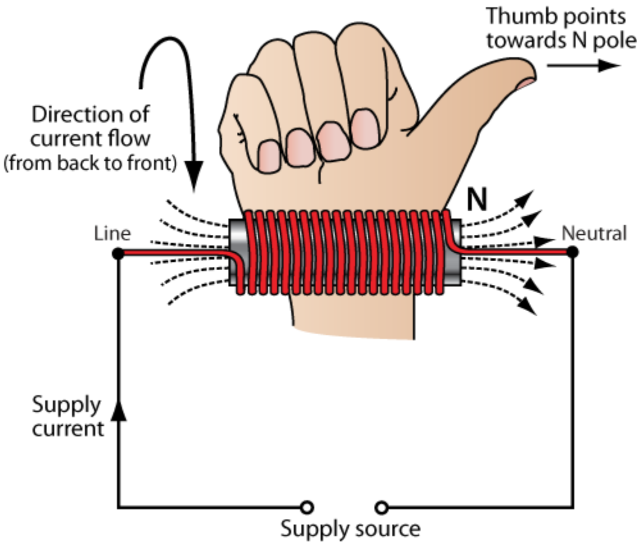

If we assume that each turn of the coil is a conductor, then increasing the number of turns increases the effective number of conductors and so we increase the strength of the magnetic field.

The increase in the strength of the magnetic field, which this effect produces, is dependent on the number of turns and the size of the current. Don't worry about the induced current yet; we'll look at it later in the outcome.

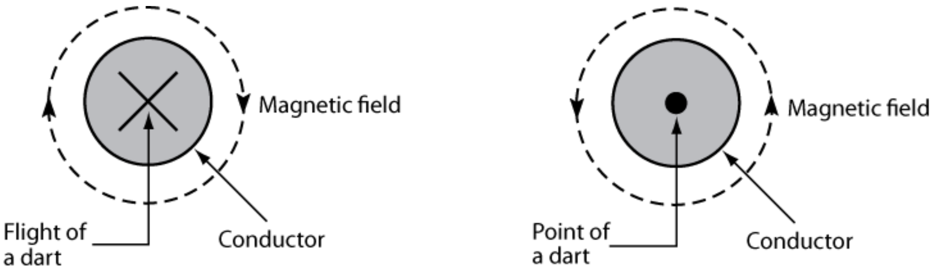
Notice how the magnetic field is strengthened and directed. The lines of flux get closer together. The solenoid has effectively become a magnet.

If an iron core were added instead of air then the strength of the magnetic field would increase dramatically.

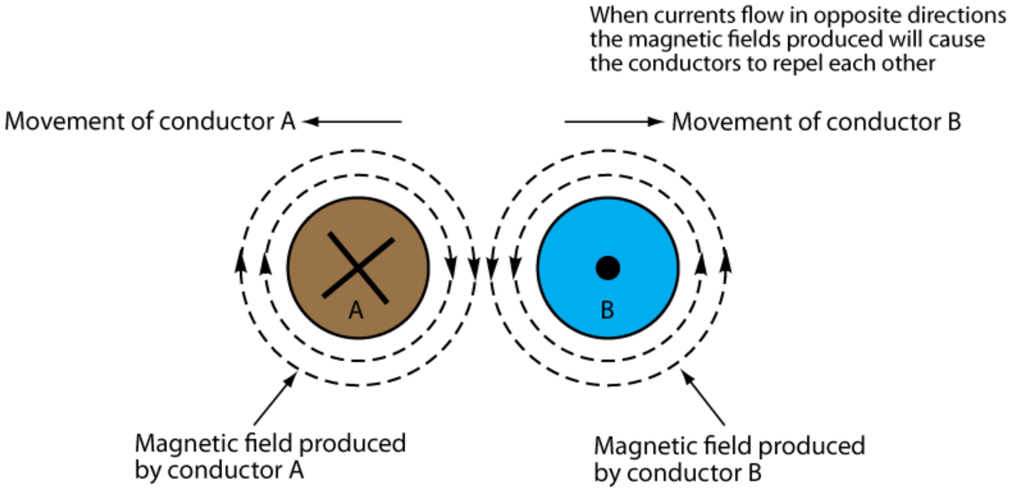
To determine the direction of the magnetic field assume that the fingers are showing the direction of the current in the coil or solenoid and that the thumb is always pointing north. This is called the ***right-hand grip rule***.




It would be useful if we now look at the general conventions that are used to describe the direction of current. When drawn on paper there is a convention, the cross shows that the current is flowing into the page. The dot shows that the current is flowing out of the paper. Think of it as a dart flying away from you or coming towards you, seeing either the feather or the point of the dart. Label the diagrams below.

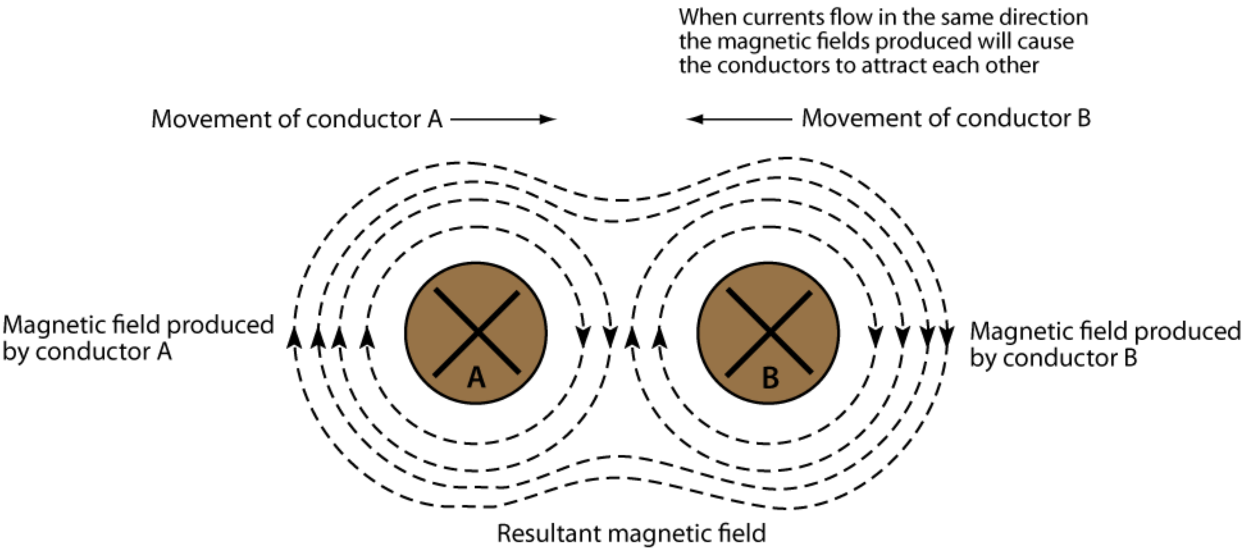



Taking this idea a step further, in the diagram over the page there are two conductors, and as you can see, they are carrying current in opposite directions.




You can see that between the two conductors, the lines of magnetic flux are closer together, or there are more lines of flux between the conductors. Although this may not be that obvious, the effect is that it reduces the ***overall*** magnetic field to zero.

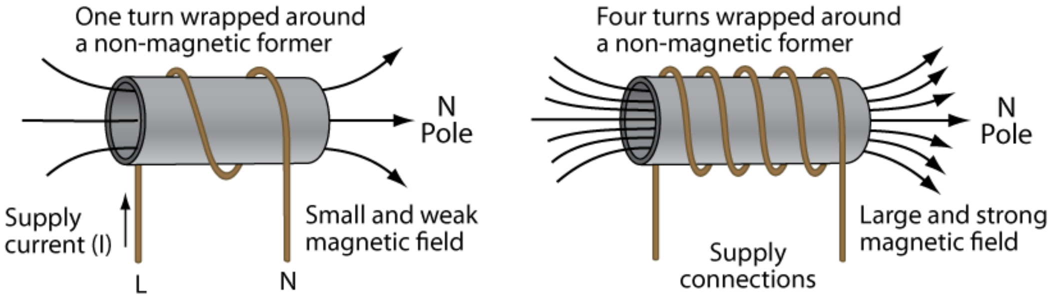
Below, the conductors have a current passing in the same direction. You can see that the lines of magnetic flux between the conductors decrease, that is they seem to be going in the opposite directions. Again, although it may not be that obvious, the ***overall*** magnetic field increases.




These two effects are both helpful and unhelpful depending on what we want.

## Increasing the number of turns on the coil

We have already seen that running parallel current-carrying conductors next to each other can increase the overall magnetic field, as long as the current is flowing in the same direction.




This particular method of increasing the strength of the magnetic field is dependent on the relationship between the number of turns and the increase in current.

## Increase the current

There is a direct link between the level of current that a conductor carries and the strength of the magnetic field surrounding it.

When we combine the increase in the number of turns on the coil and the increase in current, we are dealing with the magnetising force. This is called the ***magnetomotive force***.

If you remember your work with potential and voltage, you will remember that an electromotive force is applied to a load or conductor and current flows. The electromotive force is the 'driving' force behind the flow of the current. With magnetism, the magnetomotive force (or mmf) can be said to provide a similar function.

The mmf is not solely dependent therefore on the current but also on the number of turns of the conductor.

The best definition would be:-

| |
|---|
| The magnetomotive force is the force that causes a magnetic field to be built up or established. |

There are, as you would expect, units and symbols attached to this particular quantity.

$$\text{mmf } (F) = \text{current } (I) \times \text{number of turns } (N)$$
$$F = IN(\text{At or A})$$

You can see that the symbol is ***F*** and the units are ***amps*** or ***amp-turns***. This means that for a single turn of the conductor the mmf is exactly the same as the current in value.

We'll work through a couple of examples covering flux, flux density and mmf. Some of this work should be familiar to you however.

1). A coil has 150 turns and a current of 5 mA flowing in it. What is the mmf?

$$F = IN$$
$$F = 5 \times 10^{-3} \times 150 = \underline{\underline{0.75At}}$$

2). If an mmf of 350 At is required, how much current would need to flow in a coil that had 250 turns?

$$F = IN$$
$$I = \frac{F}{N} = \frac{350}{250} = \underline{\underline{1.4A}}$$

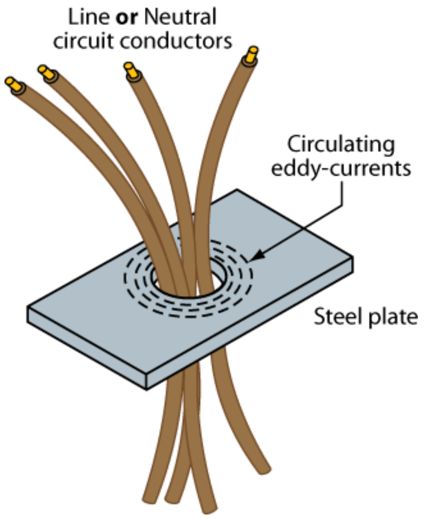
3). What is the mmf of a circuit when the coil has 350 turns and the current is 0.6 A.

$$F = IN$$
$$F = 0.6 \times 350 = \underline{\underline{210At}}$$

There are only so many ways of looking at this type of problem. The key feature is for you to recognise that current and number of turns create the force that sets up the magnetic field.

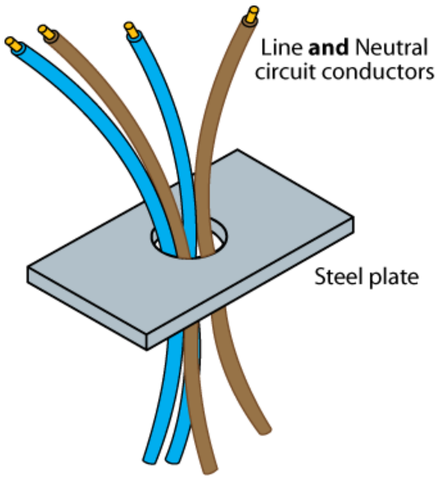
## Problems associated with magnetic fields

If the cables are all line conductors of one type (all neutral or all line conductors-a.c. supply), so that all the currents are passing in the same direction then, what are called ***eddy currents*** build up in the steelwork. This causes overheating along with other unwanted side effects.




You can see here that there are a number of current carrying conductors passing through a metal plate. In this case the conductors are of one type, either line **or** neutral. This metal plate could be the panel of a consumer unit, or the edge of some metal trunking, anything based on iron or steel in fact.

As current passes through the conductors, a magnetic circuit is built in the steelwork. This current (eddy current) circulates continually unless we do something about it.

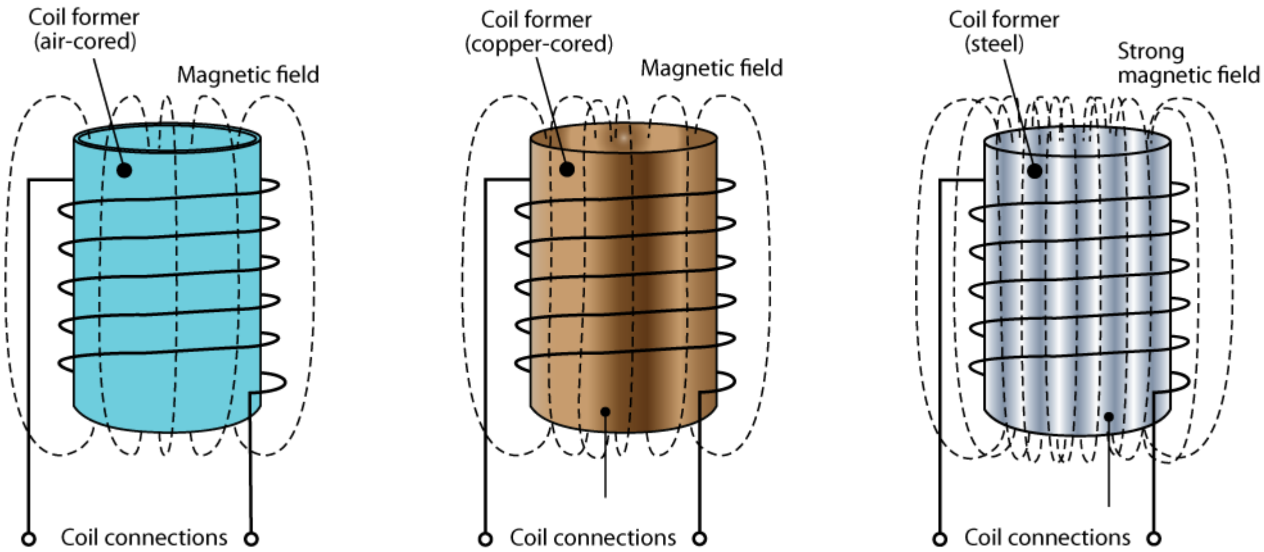



Regulation 521.5.1 requires us to make sure that the cables all pass through the same hole. By this we mean that the line **and** neutral conductors of a circuit must pass through the same hole.

This reduces the likelihood of the eddy currents being produced. This reduction in eddy currents is brought about because the magnetic fields surrounding the conductors is cancelled out by the current in the line and neutral conductors flowing in opposite directions.

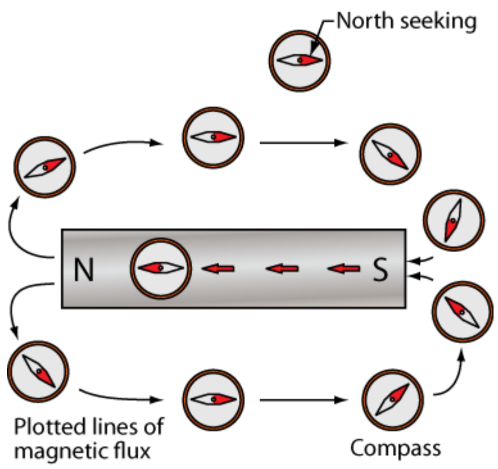
However, if we want a useful coil we need the extra magnetism that comes from currents passing in the same direction around a core.

The solenoid is more often called a ***coil***, although strictly speaking a coil has a core other than air. In the figures below, the first has a former of air, the middle has a former made from copper and the last one has a former made of steel. It can be seen that the lines of flux is dependent upon what the former is made from. The weakest magnetic field has a former of air whilst the strongest magnetic field has a former made of steel.




As we have already looked at, the direction of all these magnetic fields can be determined in a variety of ways, such as the right-hand grip rule and the corkscrew rule.

For a permanent magnet, you can determine the direction of the magnetic fields by placing a compass near to the end of the magnet and plotting the direction of the line as you move the compass. As you can see, the compass needle moves as the compass is moved around.



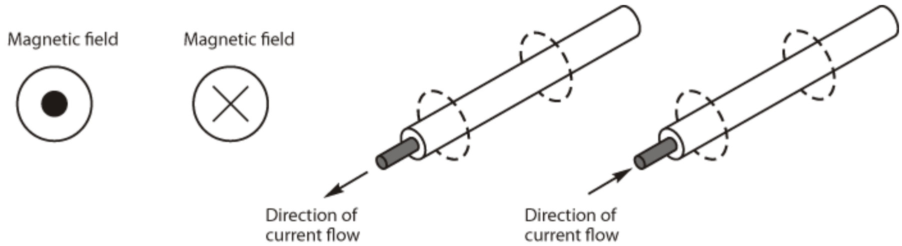

If you have access to a lab, try out an experiment and see if you can plot the lines of flux.

**Exercise 2.**

1) State six places where you expect to find an electrical coil.

2) What do you think would happen to a magnetic field if a.c. were supplied to a coil, rather than d.c.?

3) Show on the following diagrams which way the magnetic field is 'flowing'.




4) Calculate the mmf of a 350-turn coil when a current of 0.5 A is flowing through it.

5) Determine the current flowing in a 24 V coil that has a resistance of 470 Ω. If the coil has 400 turns, what will be the mmf?

# 3: Production of an emf

In this session the student will:

- Understand the nature of electromagnetic induction.
- Understand the difference between self inductance and mutual inductance.

We are now going to look at how we determine what is happening to these current carrying conductors in more detail.

We will look at the force on a current carrying conductor, the emf induced in a current carrying conductor, the direction of this induced emf and we'll also take a look at self and mutual induction.

Most of this is material that you have covered before, but to have a quick recap is no bad thing and if you are anything like a normal student, you will have found magnetism difficult the first time around.

One new term is introduced in this session:

***Magnetomotive force*** ***mmf***

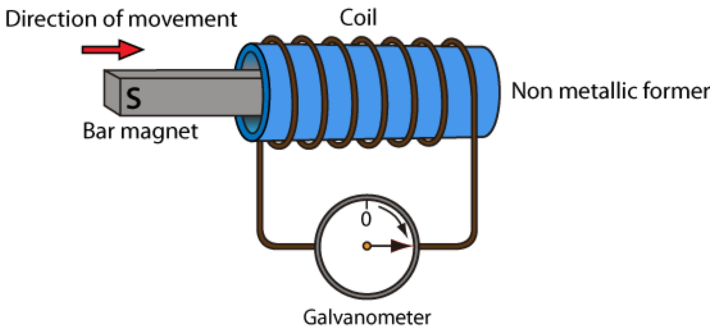
Although the concept of the magnetomotive force is quite difficult to understand, we can think of it as the force required to magnetise a magnetic circuit. It can be thought of in a similar way to the emf of a circuit. As the emf 'drives' current around a circuit, so the mmf 'creates the magnetic flux' within a circuit.

When current flows in a conductor, a magnetic field appears around that conductor.

- When there is an a.c. supply there is an alternating (changing) current.
- When there is an alternating (changing) current then the magnetic field changes.

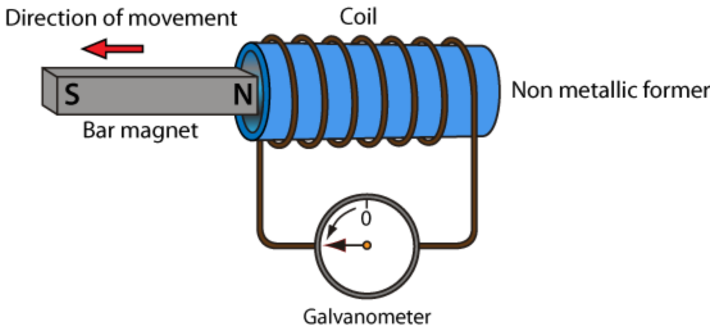
Remember that the magnetomotive force (mmf) is that which causes a magnetic circuit to be created. The mmf depends on the current flowing in the conductors and the number of turns of wire in the coil.

When a magnetic field varies and a conductor moves near to it an emf (electromotive force) is '***induced***'' in the conductor. This is called ***Faraday's law of electromagnetic induction***.




Above, you can see that the magnet moves towards the coil, which is the current carrying conductor. Because the magnetic flux is moving across the conductors, an emf is induced in the conductors of the coil and the galvanometer (current sensitive meter) moves.

If the magnet were to move in the opposite direction, the needle would deflect in the opposite direction.




It is always the case that an induced emf is generated whenever there is some form of relative movement between the magnetic field and the conductor. If the conductor moves near a magnetic field then there will be an induced emf generated within the conductor.

Additionally, if the magnetic field is constantly changing, then there will be an induced emf generated within the conductor.

The strength of this induced emf depends on three things:

- the strength of the magnetic field
- the number of turns
- the speed of the movement between the magnetic field and the conductor.

The induced emf is affected by the magnetic flux density, the length of the conductor and the speed or velocity with which the magnetic field or the conductor moves.

$$e = Blv$$

Where $e =$ Induced emf (V)

$B =$ Magnetic flux density (T)

$l =$ Length (m)

$v =$ Velocity ($ms^{-1}$)

Try some examples before you move on.

1). A conductor having a length of 5.5 m has a velocity of 31.4 $ms^{-1}$. If the magnetic flux density is 1 T what will be the induced emf?

$$e = Blv = 1 \times 5.5 \times 31.4 = \underline{\underline{172.7V}}$$

2). A conductor has an emf of 25 V induced in it when it moves through a magnetic field of flux density 0.85 T. If the length of conductor is 3 m what will be the speed that it has to move through the field?

$$e = Blv$$

$$v = \frac{e}{Bl} = \frac{25}{0.85 \times 3} = \underline{\underline{9.8ms^{-1}}}$$

3). An aircraft flies through the air at 1 150 km/h. It cuts the earth's magnetic field, which has a flux density of 40 µT. If the wingspan is 50 m, what will be the emf induced in it?

$$e = Blv$$

convert velocity to $ms^{-1}$

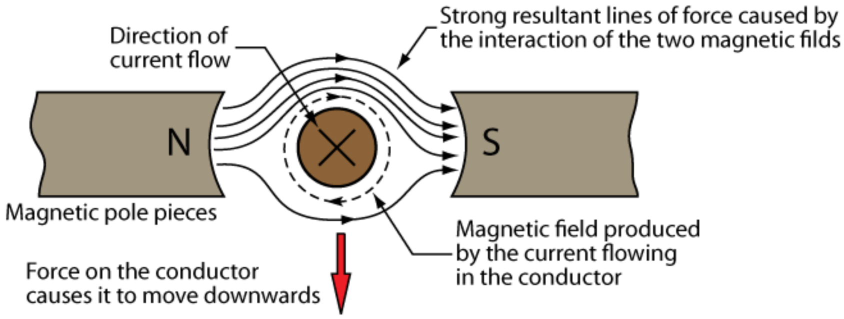
$$v = \frac{1150 \times 1000}{60 \times 60} = \underline{\underline{319.44ms^{-1}}}$$

$$e = 40 \times 10^{-6} \times 50 \times 319.44 = \underline{\underline{0.64V}}$$

These types of equations relate to motors and the voltages that are induced in their windings. It affects the way that you view what is happening in a motor or generator.

## Force on a conductor within a magnetic field

When we see a current-carrying conductor within a magnetic field then there will be a force acting on that conductor (measured in Newton's). The reason is that the conductor will have created a magnetic field and this magnetic field reacts with the second one.




The strength of this reaction depends on three main factors:

- the strength of the magnetic field – the one provided either by the coil or a permanent magnet
- the current flowing in the coil – it is this current that produces the magnetic field around the conductor
- the length of the conductor within the magnetic field – the longer the conductor in the magnetic field the more the effect.

This is all put together into one formula.

$$F = BIl$$

where: $F =$ Force on a conductor (N)

$B =$ Magnetic flux density (T)

$I =$ Current (A)

$l =$ Length of conductor within the magnetic field (m)

We'll look at a couple of examples before we go any further.

1). A conductor 1.5 m long carries a current of 35 A. It is moving straight across a magnetic field, which has a magnetic flux density of 0.4 T. What is the force acting on the conductor?

$$F = BIl$$
$$F = 0.4 \times 35 \times 1.5 = \underline{\underline{21N}}$$

2). What current is required to flow in a conductor to produce a force of 12 N? Assume that the length of the conductor is 8 m and the magnetic flux density is 0.25 T.

$$F = BIl$$
$$I = \frac{F}{Bl}$$
$$I = \frac{12}{0.25 \times 8} = \underline{\underline{6A}}$$

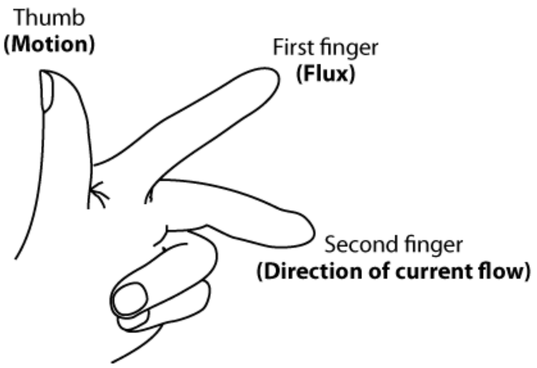
3). A straight conductor 500 mm long carries a current of 32 A. If the magnetic flux density is 0.5 T, what will be the force applied to the conductor?

$$F = BIl$$
$$F = 0.5 \times 32 \times 0.5 = \underline{\underline{8N}}$$

Be aware that these types of equation relate to motors and the voltages that are induced in their windings. It affects the way that you view what is happening in a motor or generator.

## Fleming's left hand rule

We can determine the direction of motion of a current carrying conductor in a magnetic field by the application of Fleming's left hand rule. This rule is applied to motors where we have a current carrying conductor in a magnetic field. The rule will tell us which direction the induced current is flowing.




Have a look at the fingers.

- The first finger always points in the direction of the magnetic field, i.e. from north to south.
- The second finger points in the direction of the current flow in the conductor.
- The thumb points in the direction of the motion of the conductor relative to the magnetic field.

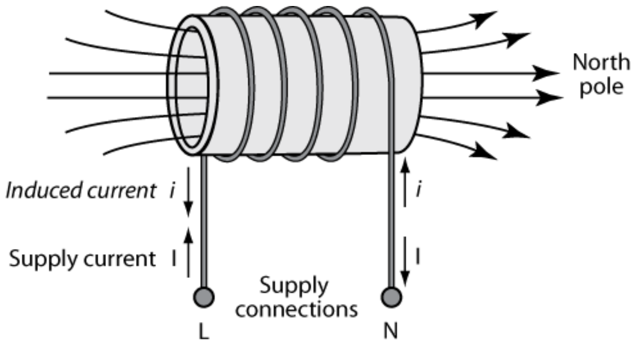
# Inductance

We'll now take a more detailed look at what happens when we have a changing magnetic field around a conductor.

Assume that we have a conductor with an a.c. supply connected to it. An a.c. supply has, as you know, both a positive and a negative half cycle. ***Because the supply is changing, the current is changing, and because the current is changing then so is the magnetic field around the conductor.***

Do try to remember the text in bold, it is important.

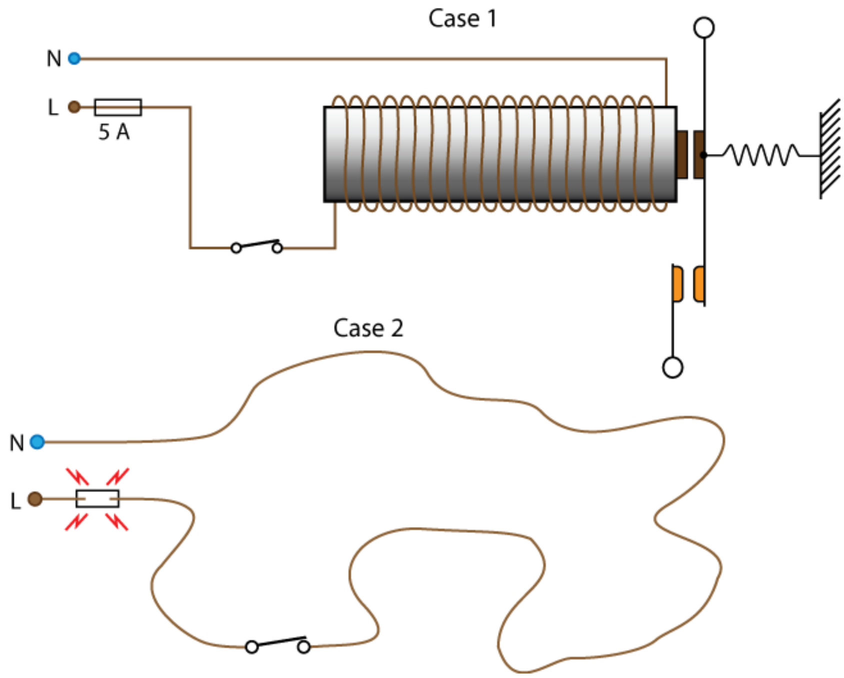
We have a magnetic field produced by the supply current, which is constantly changing. This changing magnetic field, because it is moving relative to the first magnetic field, produces, or induces, a second emf in the conductor. This second, induced emf is said to oppose the supply. It is often given the name of a '***back emf***'.




Because there is an induced emf there must also be an induced current, and this induced current flows in the opposite direction to the supply current.

This is called '***self induction***'. It is called this because the varying magnetic field produced by the supply current itself also induces an emf back into the current carrying conductor. Think about this in a practical setting.

When a coil is fed from a supply, why does the fuse protecting that coil not '***blow***'? After all we know that a coil is just a length of wire and therefore should have a relatively small resistance. If there is a small resistance then the current flow will depend on Ohm's law and therefore any fuse or circuit breaker should operate. What is happening to stop that fuse operating?




You can see that a coil, when unwound, is just a length of thin wire connected between line and neutral if it is an a.c. supply, or positive and negative if it is a d.c. supply.

- **The coil when wound creates a large magnetic field around itself.**
- **This magnetic field is changing and so an emf is induced into it.**
- **This emf creates an induced current.**
- **This current opposes the supply current and so reduces the overall current to a value that cannot cause the fuse to operate.**

There are two conflicting thoughts that you may have, based on what we have covered so far:

1). With an increase in current flow we assume that there will be a large increase in the magnetic field surrounding the conductor. This is true.

2). With an increased current flow and an increased magnetic field there will also be an increase in the size of the induced emf and induced current. This is also true.

We will look at some of the formulae for inductance shortly. However, you need to realise that there are a whole series of forces at work in any one particular problem.

Consider that the coil on the previous page is now unwound. We will assume that there are 200 turns of copper wire with a diameter of 0.2 mm making up the coil.

$$A = \frac{\pi d^2}{4} = \frac{\pi \times 0.2^2}{4} = \underline{\underline{0.0314 mm^2}}$$

The cross-sectional area (csa) of the conductor is only 0.0314 mm$^2$.

We will also assume that the diameter of each turn of wire is 20 mm.

$$C = \pi d = \pi \times 20 = 62.83 mm$$
$$l = C \times turns = 62.83 \times 200 = 12566 mm = \underline{\underline{12.57 m}}$$

If we were to unwind the coil, as in the diagram above, the length of wire would be approximately 12.57 m. If we now do a brief calculation, we will see what the resistance is.

I have assumed that the resistivity of copper is $17.2 \mu\Omega\text{mm}$. Notice that I have determined the area of the conductor first. It is no use using the diameter.

$$R = \frac{\rho l}{a} = \frac{17.2 \times 10^{-6} \times 12566}{0.0314} = \underline{\underline{6.88\Omega}}$$

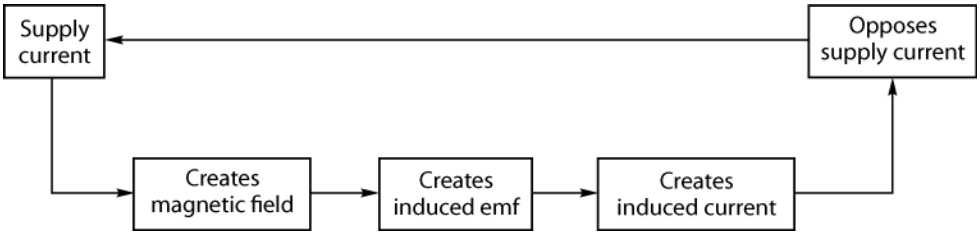
We can now move on and look at what sort of current we should get with a resistance of approximately 7 Ω.

$$I = \frac{U}{R}$$
$$I = \frac{230}{7} = \underline{\underline{33A}}$$
$$I = \frac{110}{7} = \underline{\underline{16A}}$$
$$I = \frac{24}{7} = \underline{\underline{3.5A}}$$

Here we have three different supply voltages (230 V; 110 V and 24 V) and the currents that would be produced from our length of copper wire. In our example, the 24 V supply would not cause our 5 A fuse to operate. This is fine, but we very rarely use such a low voltage, and commonly our coils are rated at 230 V and even 400 V!

So why does the protective device not operate when the current begins to flow? By rights, we are here looking at a short circuit, but the coil doesn't act like that.

What has happened is that the current when it first begins to flow creates a magnetic field around the conductor: this we have seen in the last session. This created magnetic field is a changing field and so it creates a second emf. We call this the ***induced emf*** or ***back emf***. This induced emf creates an induced current. It is this induced current that opposes the supply current, and hence the supply current is reduced.




This reduction in the supply current is enough to stop the protective device operating. Everything settles down when there is sufficient supply current to maintain the magnetic field in the coil.

The strength of this effect varies depending on a number of things.

- The number of turns on the coil.
  - More turns means more inductance.
- The magnetic flux.
  - This will vary depending what the coil is wrapped around. If it is wound on to an iron former then the inductance will be large.
- The current in the current carrying conductor (coil).
  - You already know that to increase the current is to increase the magnetic field from your work on magnetomotive force.
- The time taken for the current to change.
  - If the current varies in a very short time then the induced emf can be very large. This effect is a particular problem when large inductors are switched off, such as motors and discharge lighting circuits. Because the circuits are opened very quickly, due to the switch, the induced emf due to the change in the current is very large and the switch can be damaged by arcing. When switches are chosen, this effect has to be taken into account.

Let's look at this in a little more detail.

You need to realise that the induced emf is not induction, it is merely related to the '***property of induction***'. The unit of inductance is called the '***Henry***' (***H***) and is named after an American. Its symbol is '***L***'. For a definition look below;

> A circuit has a self inductance of one henry if an emf of one volt is induced in the circuit when the current in the circuit changes at the rate of one ampere per second.

This sounds like a mouthful, and it is! You don't have to memorise it, but you should know how it works out.

It can be simplified into two mathematical statements.

- The first one looks at the induced emf being dependent on the change in the magnetic flux, and although this is related to inductance, it doesn't have inductance in the equation.
- The second one relates the level of inductance and the current.

## For a coil:

$$\text{Average induced e.m.f.} = \text{Average rate of change of flux}$$

or,

$$e = -\frac{\Phi_2 - \Phi_1}{t_2 - t_1}$$

$$e = -\frac{\Delta\Phi}{\Delta t}$$ or where ther are turns;

$$e = -N\frac{\Delta\Phi}{\Delta t}$$

Where $\Delta\Phi = \text{Change of flux (Wb)}$
$\Delta t = \text{Change of time (s)}$
$N = \text{Number of turns of coil}$
$(-) = \text{Direction of induced e.m.f.}$

This may appear a bit frightening; however all we are looking at is the **change in flux over a period of time**. The number of turns of the coil would affect the value because that increases the strength of the flux.

## Self inductance:

$$\text{Self induced e.m.f.} = -L \times \text{Rate of change of current}$$

or,

$$e = -L \times \frac{I_2 - I_1}{t_2 - t_1}$$

$$e = -L\frac{\Delta I}{\Delta t}$$

Where $L = \text{Inductance (H)}$
$\Delta I = \text{Average change in current (A)}$
$\Delta t = \text{Average change in time (s)}$

Both of these formulae can be used to determine the induced emf, and the induced emf would still be the same value.

This makes sense because we already know that the flux depends on the current flowing. We also know that the level of inductance depends on the number of turns of the conductor and the material that those turns are wrapped around.

We'll try a couple of examples to see what happens.

1). Calculate the emf induced in a circuit of inductance of 0.5 H when the current changes from 25 mA to 75 mA in 10 µs.

In this example, we are looking at the inductance equation. You should remember that the final current value comes first in the calculation. In this example, the final value is 75 mA.

$$e = -L\frac{\Delta I}{\Delta t}$$

$$e = -0.5 \times \frac{(75\times10^{-3})-(25\times10^{-3})}{10\times10^{-6}}$$

$$e = -0.5 \times \frac{50\times10^{-3}}{10\times10^{-6}}$$

$$e = -0.5 \times 5000 = \underline{\underline{-2500\text{V}}}$$

The first thing that you should notice here is just how large this induced emf can be; the faster the change in current, the larger the induced emf. The negative sign tells us that the direction of the induced emf is opposing the change. The supply is being opposed by the induced emf. This is an application of Lenz's law.

Lenz's Law states:

> The emf induced in a conductor or coil acts to circulate a current in a direction that opposes the change in the magnetic flux that gave rise to the induced emf.

Lenz's Law sounds a little bit difficult, but in effect Lenz's law states that whatever causes the change is to be opposed.

The changing magnetic field caused by the change in the current flow produces the induced emf. This is itself affected by the second magnetic field that the induced emf produces. This second magnetic field causes a second induced emf to be created in the coil and this induced emf opposes the first.

It is because of this effect that switches that control inductive circuits have to be rated at a higher level than you might expect. In addition, this effect is used to start discharge lighting circuits such as fluorescent fittings.

Consider this last statement a little more closely.

You may already be aware of how a low-pressure mercury vapour fitting works (fluorescent fitting). A large magnetic field is built up around the choke and when the starter switch opens, a large voltage appears across the tube and an arc is struck.

Why should the voltage be so high?

The voltage is large because the starter switch opens rapidly; it is the induced emf that appears across the tube.

2). A current of 5 A flows in a coil of 1000 turns. The flux created is 8 mWb. Calculate the average induced emf when the current is reduced to 0 A in 7 ms.

$$e = -N\frac{\Delta\Phi}{\Delta t}$$

$$e = -1000 \times \frac{0-\left(8\times10^{-3}\right)}{7\times10^{-6}}$$

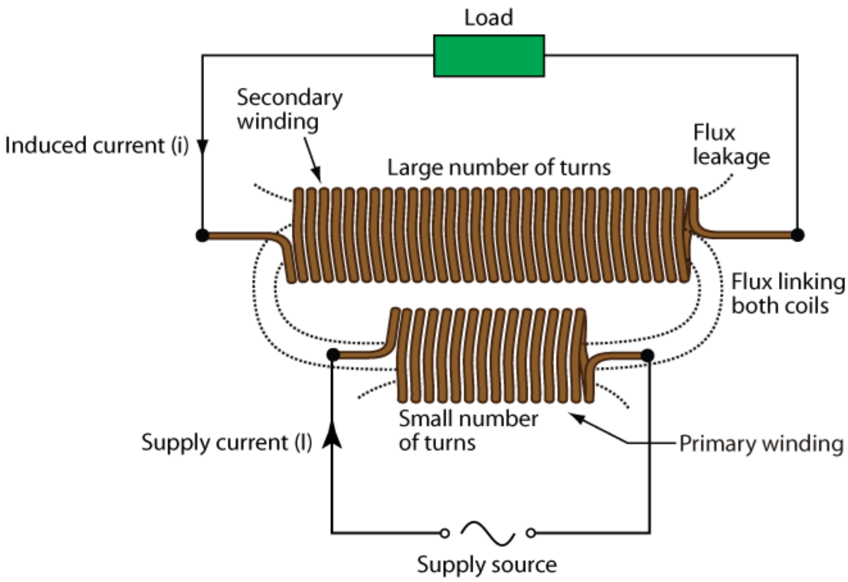
$$e = -1000 \times \left(-1.143\right) = \underline{\underline{1142.86\text{V}}}$$

You will see from the example, that the direction of the voltage is positive. This means that the induced emf is trying to supply the coil. This is again a classic example of Lenz's law at work.

There is another type of induction other than self-induction and that is '***mutual induction***'.

## Mutual induction

Mutual induction takes place when two coils are brought close together, one of which has a current flowing through it. Because the coil has current flowing through it then there must be a magnetic field surrounding it. This magnetic field interacts with the second coil and induces an emf into it.




The effect is more obvious when an a.c. supply is connected to the coil because with an a.c. supply the current is constantly changing and therefore, so is the magnetic field. It is also used in car ignition coils however, where the d.c. from the battery is fed to a coil located within a second coil. The coil from the battery has a few turns of wire and the second coil has many turns of wire.

The supply to the first coil is interrupted by a contact, which 'breaks' the d.c., effectively producing a '***varying d.c.***'. This varying d.c. produces a magnetic field around the first coil. This magnetic field then links with the second coil, and because it is a changing magnetic field, it induces an emf in it. This induced emf produces a very high voltage.

The induced emf produced via mutual induction again depends on a number of things:

- the number of turns on the secondary winding (that is the coil not directly supplied with current)
- the current in the coil that is connected to the supply
- the time taken for the current to change from one value to another.

Mutual induction is made use of when we use transformers and motors. It is more an a.c. effect than a d.c. one. We will consider transformers in another outcome.

For a definition of mutual induction, look below.

> An emf is mutually induced in one coil only when the current is changing in the other coil.

If two coils (C1 and C2), have a mutual inductance of M (Henry's), and if the current in coil C1 changes within a certain time, then the average mutual inductance can be determined using:

$$e = -M\frac{i_2 - i_1}{t_2 - t_1}\,Volts \qquad so\ e = -M\frac{\Delta I}{\Delta t}Volts$$

This shows that the average induced emf is the mutual inductance multiplied by the average rate of change of the current in the first coil, C1. We can calculate the mutual inductance by equating current change, flux change, emf and the number of turns on the coils, and come up with:

$$M = N_2 \times \frac{\Delta\Phi}{\Delta I}\ Henry's$$

Let's consider a couple of examples.

1). Two coils have a mutual inductance of 250 mH. If the current in one coil changes from 5.1 A to 1.85 A in 0.35 s, calculate the average induced emf in the other coil.

$$e = -M\frac{\Delta I}{\Delta t} \quad = -250\times10^{-3}\times\frac{(1.85-5.1)}{0.35} = 2.32V$$

2) Based on the above, what would be the change in flux if there were 200 turns on the secondary?

$$M = N_2 \times \frac{\Delta\Phi}{\Delta I} \qquad so\ \Delta\Phi = \frac{M}{N_2}\times\Delta I = \frac{250\times10^{3}}{200}\times(5.1-1.85) = 4.06\,mWb$$

There is quite a bit more to look at with mutual inductance but we will look at this in more detail when we come to look at transformers.

We now need to know in which sense, or in which direction, that the induced emf operates as it is this induced emf that produces a current.

In the diagrams that you have already seen in this, and no doubt other books, the direction of the induced current is shown as being opposite to the supply current.

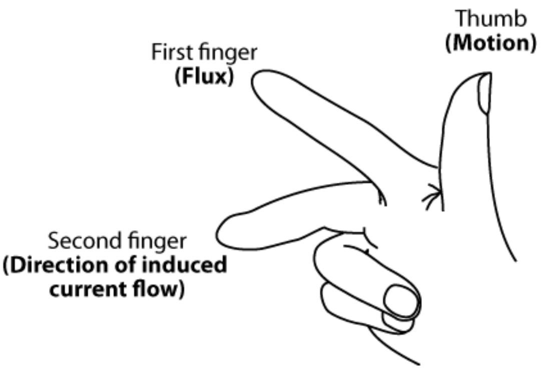
There are two methods of determining in which direction that this current flows. The first method is called '***Fleming's Right-hand Rule***'; the second method is called '***Lenz's Law***'.

Fleming's right-hand rule is the easier rule to apply when the conductor is moving relative to the magnetic field, but it is not so easy to see when we look at a coil similar to the type found on transformers etc.

Let's have a look at what Fleming's rule is and when it can be applied best.

## Fleming's right hand rule

This rule is applied to generators where we will have a prime mover (engine of some sought), moving a conductor in a magnetic field. The rule will tell use which direction the induced current is flowing.



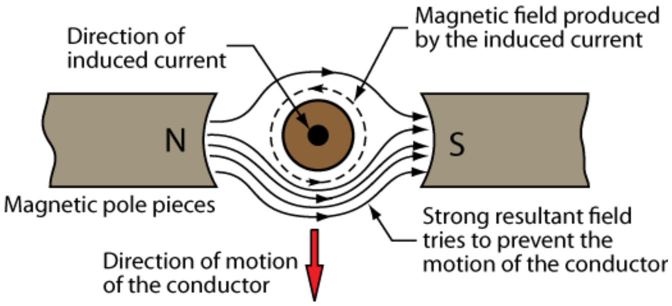

Have a look at the fingers.

- The first finger always points in the direction of the magnetic field. This means that this finger points from north to south.
- The second finger points in the direction of the induced current flow.
- The thumb points in the direction of the motion of the conductor relative to the magnetic field.

Try to remember this as we work on an example.

Example 1

Below, the conductor is moving from top to bottom.

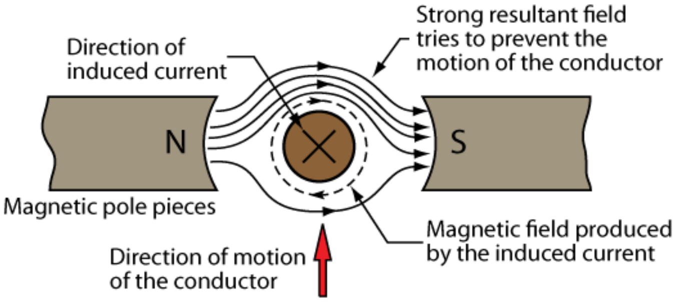



As the conductor moves through the magnetic field, the flux is said to 'flow' from north to south; that is your first finger.

You already know the direction of the conductor, and so your thumb is taken care of. The second finger is left pointing away from the page, and points in the direction of the induced current.

Example 2

In this second example, the motion of the conductor is upwards.




The first finger points from north to south, the thumb points in the direction of the conductors' movement and the second finger is left pointing in the direction of the induced current.

You can see that the direction of the induced current can be found quite readily.

Try the end of exercise questions on the next page.

**Exercise 3.**

1) Name three factors that affect the size of the induced emf?

2) If the induced emf in a coil is 220 V, its length per turn is 75 mm and it has 700 turns, what will be its velocity within the magnetic field if its magnetic flux density is 0.35 T?

3) What two rules can be used to determine the direction of the induced emf?

4) A conductor is moved through a magnetic field of strength 380 mT. If there are 850 turns and the diameter of the former that the coil is wound on is 150 mm. What will be the force applied to the conductor when it has a current of 0.25 A flowing in it?

5) Determine the induced emf in a coil containing 200 turns wrapped around a former of 200 mm diameter. The speed of rotation is 25 $ms^{-1}$ and the magnetic flux density is 0.071 T.

6) How quickly will a coil need to pass through a magnetic field of flux density 0.35 T to generate an emf of 120 V if its length is 45 m?

7) The force on a current-carrying conductor is to be limited to 1 N. What will the maximum current be if the magnetic flux density is 0.56 T and the length of the conductor is 4.75 m?

8) How long will a conductor need to be to create a force of 12.5 N if the current in the conductor is 3.2 A and the external magnetic field has a flux density of 100 mT?

9) What is the difference between self and mutual induction, and give an example of each?

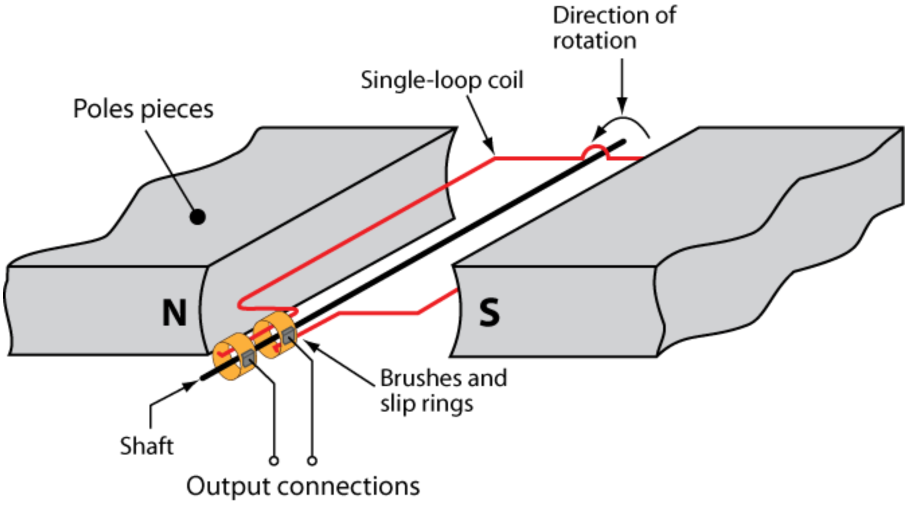
10) An electromagnet has an inductance of 14 H. If the current in the coil falls from 2.5 A to 1.1 A in 10 ms, what will be the average induced emf?

# 4: Production of an a.c. supply

In this session the student will:

- Describe the waveform that is generated from an a.c. generator.
- Draw a sinusoidal waveform and label its parts.
- Understand what is meant by rms.

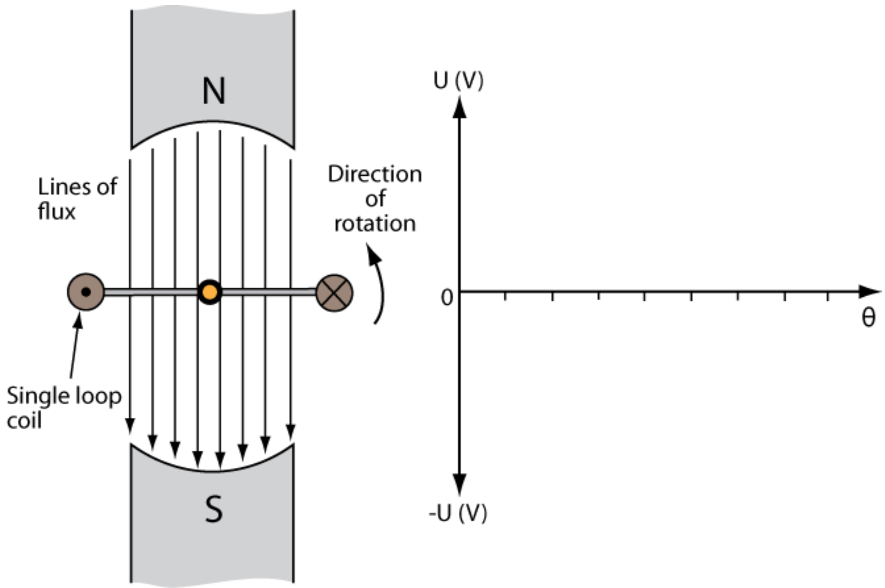
Alternating current or a.c. is the supply most common in the UK; this is due to a large number of economic and electrical factors. An alternating current is produced when a coil is placed within a magnetic field and allowed to rotate




The diagram above shows a pair of magnets which have to be north and south in order to get a magnetic field to flow between them. There is a centre shaft upon which a single loop conductor is mounted and is connected to two slip rings. There are two brushes which sit on the slip rings and these are used to take off the power generated.

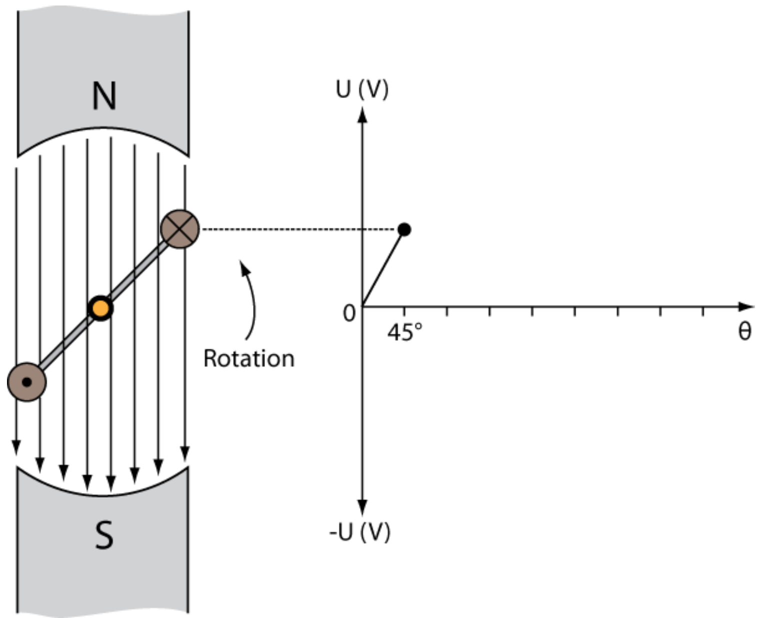
Let us assume that there is something attached to the shaft that is going to turn the coil in the magnetic field. Let us also re-draw the arrangement so that we can look at it end on.

Let us start with the coils horizontal or at 0°.



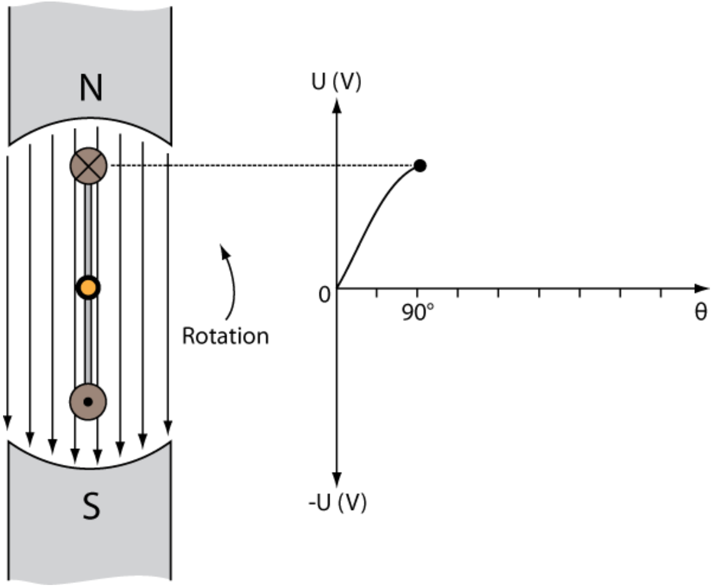

At this instant of time, the coil is parallel to the magnetic field. No flux is being cut which means there is no voltage being generated. Remember, whenever a conductor is cut by a magnetic field an emf is induced. At this point, that is not happening.

Let us rotate the conductor by 45°.



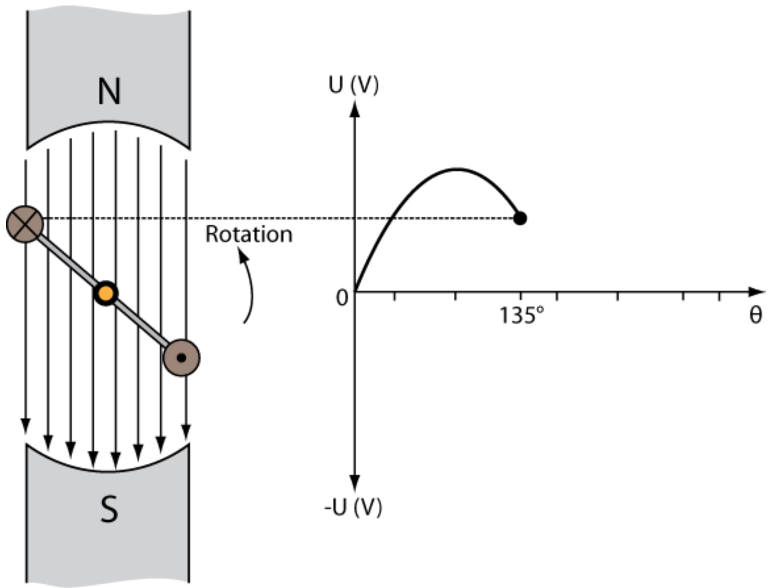

The coil has moved in the field and is therefore being cut by the magnetic field which flows from north to south. Not a lot of flux has been cut so the emf induced is fairly small.

Let us rotate the conductor by another 45° which brings the single-loop coil to 90°.



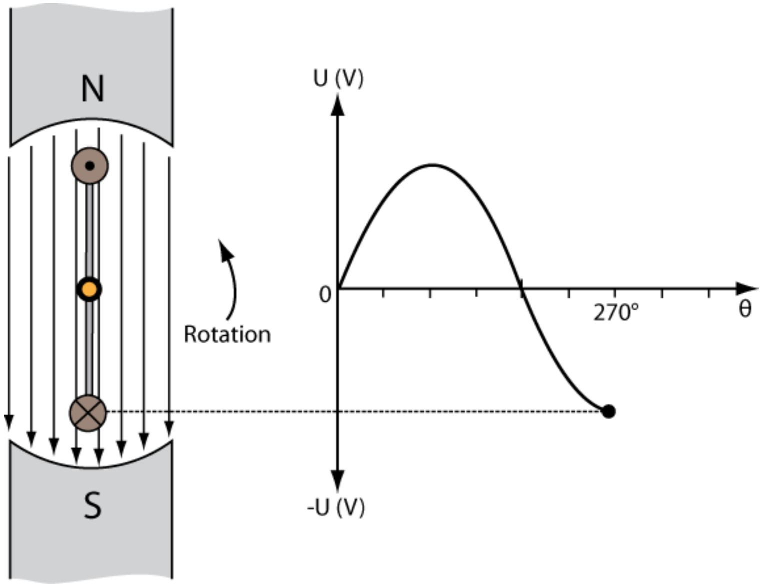

At this position the coil is being cut by the maximum amount of flux. Maximum flux cutting occurs when the coil is directly under the poles; this is true if the coil was under the South Pole. At this instant in time, maximum emf is induced into the single-loop coil and the output is taken off by the slip rings.

Let us move the conductor by yet another 45° so we are now at 135° around our cycle.



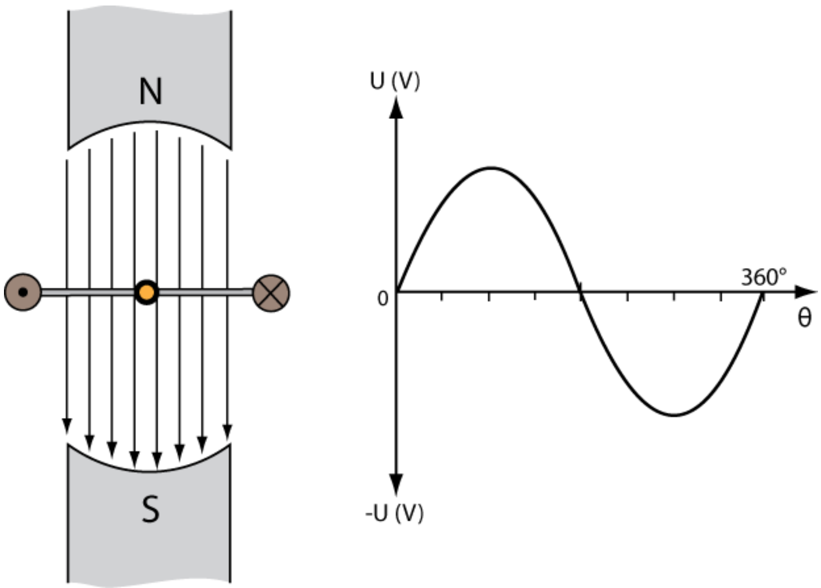

The coil has moved away from the maximum flux cutting position and is now heading towards zero. From the waveform diagram we can see that the voltage has moved from a peak position to a lower value.

Now let us rotate the conductor by 135° which places it two thirds around our cycle at 270°.



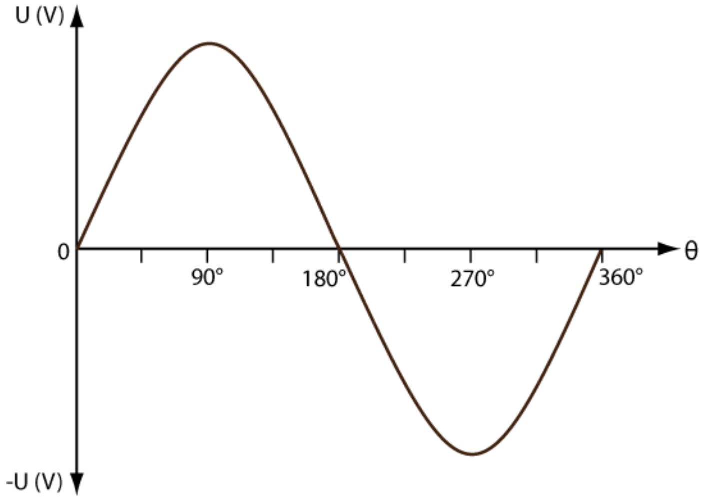

I think you can see a pattern emerging here. The sine waveform is now at a maximum in the negative half cycle. The part of the coil that was under the North Pole is now under the South Pole, maximum flux cutting is taking place but at opposite polarity.

To finish off, let us rotate the coil by 90° to complete the 360° cycle.




What follows is merely a repetition of what has occurred shown in each of the stages above. The waveform takes its customary sinusoidal shape.

To recap, the diagram below is a standard sine wave. It moves from zero up to a maximum in one direction. It then moves from the maximum, back through zero and then on to a maximum in the opposite direction, and then to zero. When a sine wave has completed one of these sequences, it is then ready to begin another the same.




Each complete wave is called a '***cycle***' or '***period***'. The quantity of cycles in one second is called the '***frequency***'.

A simple formula is attached to this idea.

$$T = \frac{1}{f}$$

$$f = \frac{1}{T}$$

where:- T = time (s)

f = frequency (Hz)

Each cycle or period lasts for a certain amount of time. This is usually measured in seconds or milli-seconds.

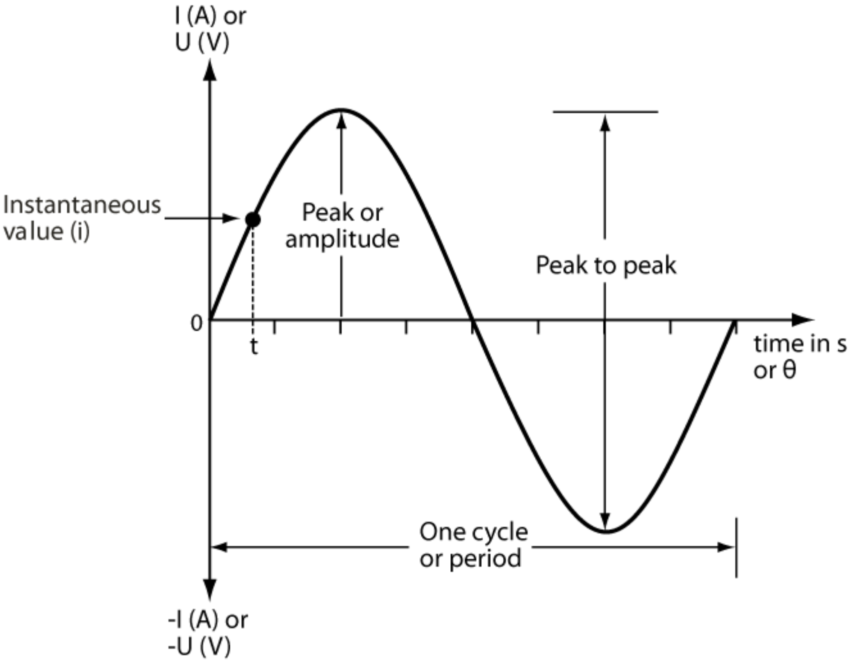
Follow these examples.

1). T=20 ms. Calculate the frequency; $f = \frac{1}{T} = \frac{1}{20 \times 10^{-3}} = \underline{\underline{50\text{Hz}}}$

2). f=1 kHz. What is the period? $T = \frac{1}{f} = \frac{1}{1000} = \underline{\underline{1\text{ms}}}$

3). f=1 MHz. What is the period? $T = \frac{1}{f} = \frac{1}{1000000} = \underline{\underline{1\mu\text{s}}}$

Each part of the cycle above the zero line is called the positive half-cycle, and each part under the zero line is called the negative half-cycle.

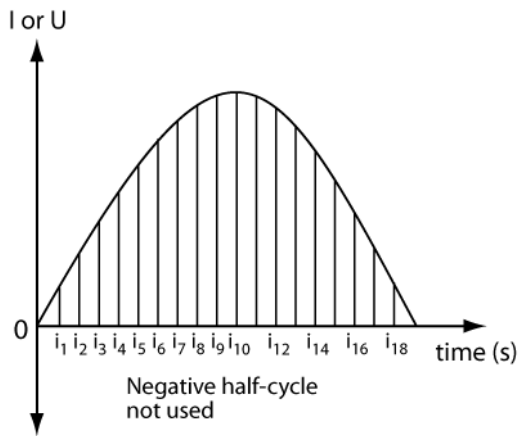



A number of labels are attached to the sine wave.

From the centre or zero line to the peak of one of the half-cycles is called appropriately, the '***peak***' value. From the peak of the positive half-cycle to the peak of the negative half-cycle we have the '***peak-to-peak***' value.

We can see from the shape of the wave that it is not semi-circular, so the area under the wave is more complex to work out. Problems arise from that.

The maximum or peak value cannot be the total useful current, power or voltage, as so much of the wave is less than the maximum. This being the case another figure, something less than the peak, needs to be used.




One of these worth looking at is the ***average*** value. This cannot be done over both positive and negative half cycles, as this would produce an average value of zero. So to look at the average value of current or voltage we must only look at one of the half-cycles.

In this instance, a series of readings are taken at different points on the half-cycle and then they are averaged. See above drawing.

$$\text{Average value } U = \frac{u_1 + u_2 + u_3 + u_4 + \ldots + u_n}{n}$$

What has been found is that it does not matter what the size of the current or voltage is, the average value is always **0.637** times the maximum value available. Therefore, the average value of a maximum voltage of 100 V would be 63.7 V. The average value of 230 V maximum would be 146.5 V. It is the same for current as for voltage.

For this example, we will assume that the maximum value is 100 V and readings are taken every 10° starting at 0° and ending at 170°. The reason we won't go to 180° is because that is where the waveform passes through zero again, giving us the negative values we don't consider.
The average value is found from the following formula.

In our particular example, the equation would read as follows:-

$$U = \frac{u_1 + u_2 + u_3 + u_4 + u_5 + u_6 + u_7 + u_8 + u_9 + u_{10} + u_{11} + u_{12} + u_{13} + u_{14} + u_{15} + u_{16} + u_{17} + u_{18}}{18}$$

If we took more readings, the equation would be longer! Don't forget this is true for current as well as voltage.

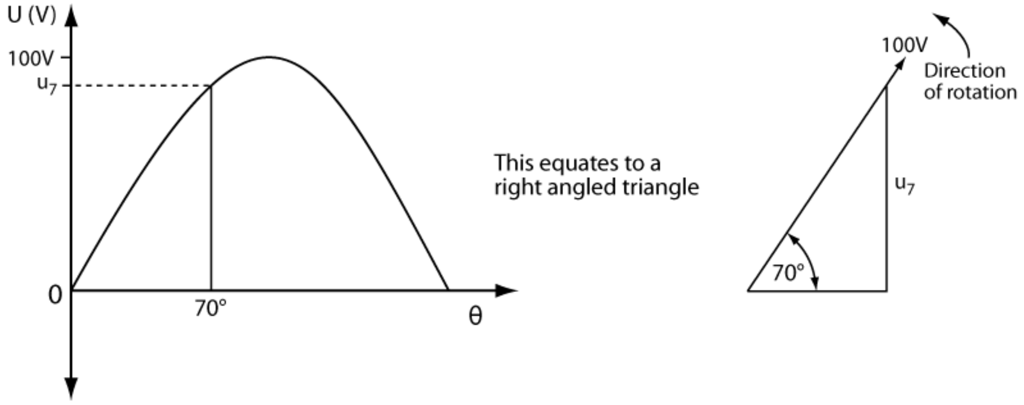
Each of these individual instantaneous voltages relates to the point at which we measure their value. For example $\boldsymbol{u_1}$, relates to the voltage when the sine wave is at 0°. In our example, a reading is taken every 10°.

How are the readings taken?
There are two options:

1. Draw the sine wave to scale using a protractor and measure each and every instantaneous value.
2. Use the trigonometry you learned in the maths module, this is much easier and less time consuming!

We shall use option 2.

Let us consider the instantaneous value at 70°. Assume the maximum value of voltage is 100V




The height of the line $u_7$ corresponding to its position within the positive half cycle:

$$u_7 = U \times \sin\theta = 100 \times 0.9397 = 93.97V$$

If you work through all the eighteen readings using the process above, we would get the set of readings below. Actually, you only need to do from 0° up to 90°, after that the values repeat themselves as the sine wave works its way back to zero!

| Angle° | Voltage (U) |
|---|---|
| 0 | 0 |
| 10 | 17.36 |
| 20 | 34.20 |
| 30 | 50.00 |
| 40 | 64.28 |
| 50 | 76.60 |
| 60 | 86.60 |
| 70 | 93.97 |
| 80 | 98.48 |
| 90 | 100 |
| 100 | 98.48 |
| 110 | 93.97 |
| 120 | 86.60 |
| 130 | 76.60 |
| 140 | 64.28 |
| 150 | 50.00 |
| 160 | 34.20 |
| 170 | 17.36 |

You should notice that as the angle moves closer to 90° then the value of voltage doesn't rise so fast. With a sine wave, the maximum figure always occurs at 90°.

We now need to take all the values we have just calculated and add them together.

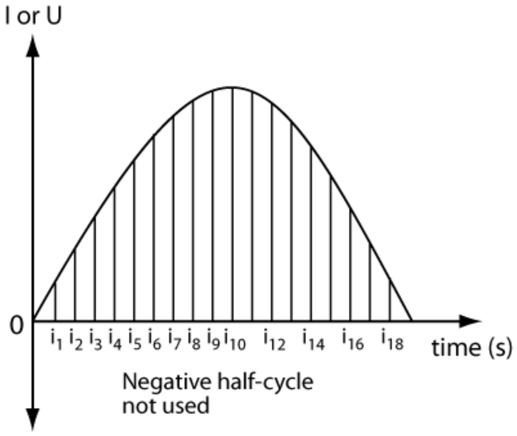
$$U_{Ave.} = \frac{1142.98}{18} = \underline{\underline{63.5V}}$$

We should get 63.7 V, which is 63.7% of our maximum 100 V. The reason we are a little out is that we need to take more readings. The more readings we get the more accurate we will become. We are however within 0.2 V of the right answer, which isn't bad!

In modern day electrical work, the average value doesn't give us a figure that allows us to compare it to anything else. It was used for moving coil instruments, but with the ability of modern day digital meters to measure rms values directly, the average value of current or voltage is losing its importance.

For example, what is a d.c. voltage of 100 V equivalent to in a.c. terms. This is where the rms value comes in. We will now look at the ***rms*** or ***root mean square*** value in a little more detail.

As with the average value only one half-cycle is considered. The relationship we look at is the ***equivalent d.c. heating effect***. The term used to describe this effect is called the ***root mean square*** or ***rms***.




As you can see the diagram is exactly the same, however the formula is not.

$$\text{rms value } U = \sqrt{\frac{u_1^2 + u_2^2 + u_3^2 + u_4^2 + \ldots + u_n^2}{n}}$$

For a maximum voltage of 100 V with eighteen readings again taken, our formula would look like this:

$$\text{rms value } U = \sqrt{\frac{u_1^2 + u_2^2 + u_3^2 + u_4^2 + u_5^2 + u_6^2 + u_7^2 + u_8^2 + u_9^2 + u_{10}^2 + u_{11}^2 + u_{12}^2 + u_{13}^2 + u_{14}^2 + u_{15}^2 + u_{16}^2 + u_{17}^2 + u_{18}^2}{18}}$$

We begin in exactly the same way as with the average values. We need to produce a table with all of our known values and then we can square them.

| Angle° | Voltage (U) | Voltage squared ($U^2$) |
|---|---|---|
| 0 | 0 | 0 |
| 10 | 17.36 | 301.34 |
| 20 | 34.20 | 1169.64 |
| 30 | 50.00 | 2500 |
| 40 | 64.28 | 4131.92 |
| 50 | 76.60 | 5867.56 |
| 60 | 86.60 | 7499.56 |
| 70 | 93.97 | 8830.36 |
| 80 | 98.48 | 9698.31 |
| 90 | 100 | 10000 |
| 100 | 98.48 | 9698.31 |
| 110 | 93.97 | 8830.36 |
| 120 | 86.60 | 7499.56 |
| 130 | 76.60 | 5867.56 |
| 140 | 64.28 | 4131.92 |
| 150 | 50.00 | 2500 |
| 160 | 34.20 | 1169.64 |
| 170 | 17.36 | 301.34 |

The total figure for the squared value is 89997.38, but only for this example. We need to put the figures into our formula. This has now become something a whole lot shorter and easier to handle.

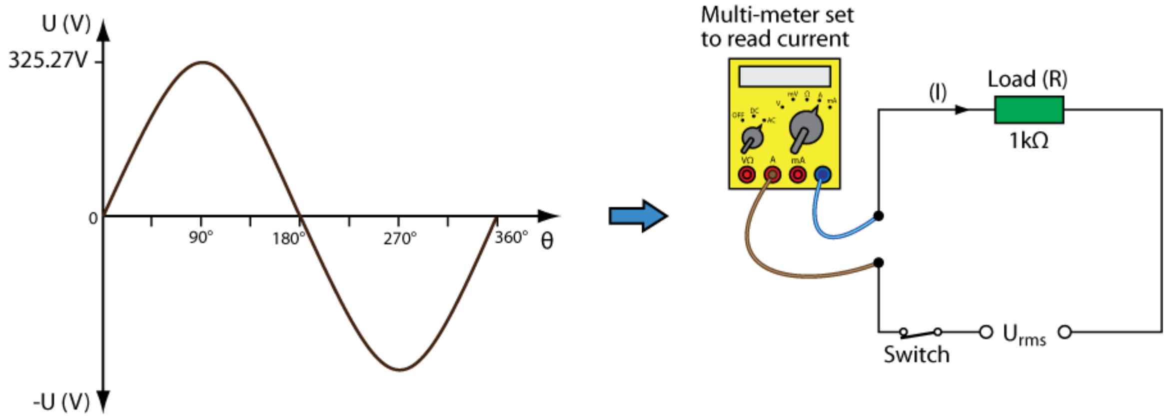
$$U_{rms} = \sqrt{\frac{89997.38}{18}} = \sqrt{4999.85} = \underline{\underline{70.71\text{V}}}$$

Therefore, you can see that the rms value works out very close to the stated figure.

It still may seem to be complex, but you will not be expected to use it at this level of course. For our purposes it is sufficient to know that the ***rms*** value is always ***0.7071 times*** the maximum value of current, voltage or power.

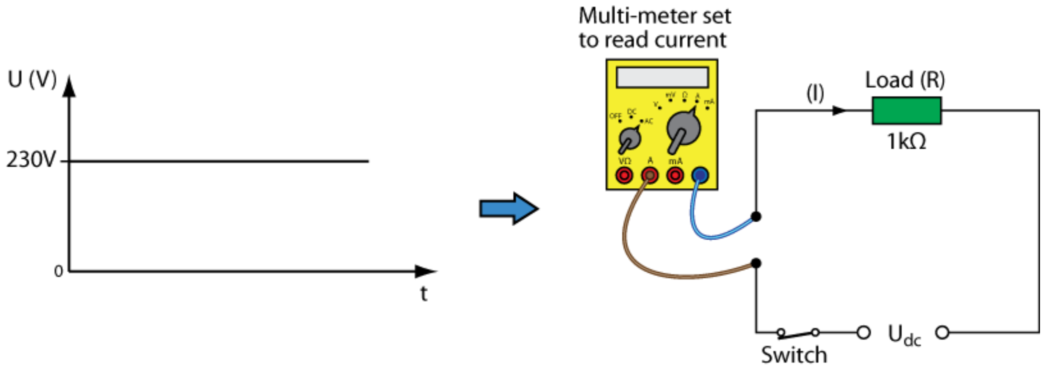
Earlier the term; ***equivalent d.c. heating effect*** was used. This requires further explanation because it is so important.

Have a look at the diagram below; assume that a supply having the sine wave shown is applied to the terminals of the circuit.




From your studies on resistors you will recall that; $I = \frac{U}{R}$, what reading will be displayed on the meter? It is difficult to tell since the sine wave varies from 0V to a maximum of 325V then back to zero again!

What if the supply was d.c. as shown below, what reading would be shown on the meter?



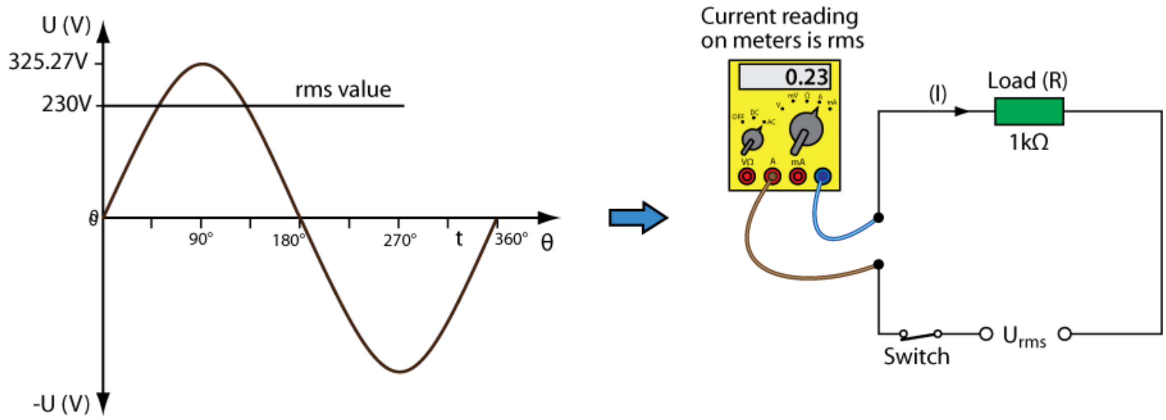

This is easy, it is just; $I = \frac{U}{R} = \frac{230}{10^3} = 0.23A$.

With this current flowing, the resistor will get warm.

The formula to use for heat is $P = I^2 \times R = 0.23^2 \times 10^3 \approx 53W$

If we want the same heating effect from our a.c. circuit, we need the voltage to be 230V.

If we superimpose the d.c. waveform onto the sine wave we can determine whereabouts the rms value is. Remember, the rms value provides the ***equivalent d.c. heating effect.***




The value of voltage we get into our homes is roughly 230V, but be aware that for short instances of time all our electrical equipment sees 325V!

Whenever rms is mentioned, you not only have a visual picture of where on a sine wave that point is but why it is used.

**Exercise 4.**

1) What is the period if the frequency is 75 Hz?

2) If the cycle is 7.6 ms, what will be the frequency?

3) What maximum voltage do I need to achieve an rms voltage of 254 V? State the peak and the peak-to-peak voltage also.

4) If I have a peak supply voltage of 440 V, what will be the rms voltage? State also the average value of voltage.

5) A capacitor with a voltage rating of 150V is to be connected to a 200V a.c supply, is this acceptable?

6) Determine the angles for the following cosine values:

   i) 0.5
   ii) 0.57
   iii) 0.85
   iv) 0.95

7) Determine the angles for the following sine values:

   i) 0.5
   ii) 0.57
   iii) 0.85
   iv) 0.95

8) Why can you not get a cosine or sine value greater than 1?

You have done well to get this far. Now attempt the final exercise. It should take you no more than two sessions to complete.

**B&B Training Associates**

**Engineering Learning Materials**

Attempt all questions.

All marks are shown in the right-hand margin.

You should aim to pass with a 85 % minimum mark.

Anything less than this mark should lead you to re-read the text.

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1) State the unit and symbol of magnetic flux. 2

2) State the unit and symbol of magnetic flux density. In addition, state the formula related to flux density. 3

3) A coil has a flux density of 0.3 T. If the coil is 25 mm×25 mm what will be the magnetic flux? 4

4) How can the direction of a magnetic field be determined in a d.c. conductor? What rule should be used? 4

5) Calculate the mmf produced by a 1 500 turn coil when it carries a current of 2.5 A. 3

6) A coil has a resistance of 8 Ω and is connected to a battery of emf 12 V. If the mmf produced by the coil is 25 A. Determine the number of turns on the coil. If the diameter of the former is 20 mm, state how long the conductor will be. 6

7) A conductor has an effective length of 9.5 m. If the flux density is 100 mT and the current is 500 mA. What will be the force exerted on the conductor? 4

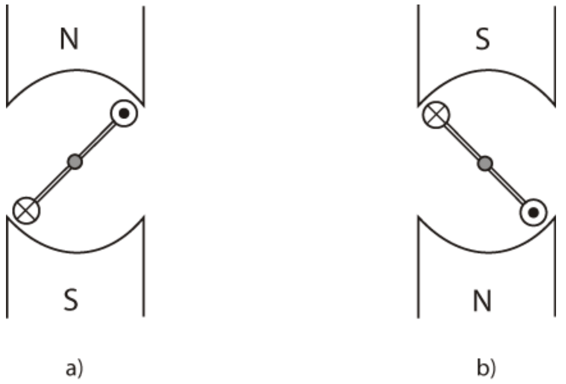
8) A conductor of length 3m and flux density 0.25 T has a velocity of 20 $ms^{-1}$. What is the induced emf? 4

9) What will be the emf induced in a circuit of inductance 0.2 H when the current changes from 20 mA to 70 mA in 3 μs? 4

10) The current in an air-cored coil rises from 5 A to 20 A in 0.15 s. The average value of the induced emf is 150 V. State the inductance of the coil. 4

11) A magnet has an area of 750 $cm^2$. If the magnetic flux is 75 mWb what will be the flux density? 4

12) State the direction of rotation of the coils shown.




2

13) Two coils have a mutual inductance of 0.75 mH. Calculate the induced emf in one coil when the current in the other coil falls from 32 A to 2.4 A in 0.1 s. 4

14) An emf of 300 V is induced in a coil when the current changes. If the mutual inductance is 400 mH and the time taken for the current to change is 0.05 s, what will be the change in current value in the coil? 4

15) Draw a diagram showing the lines of magnetic flux for two bar magnets, spaced 4 cm apart with similar poles facing each other. 2

**Total marks** 60