Contents

9.3 Motors and generators: 1. Motors and magnetic forces

Background: Moving charged particles are deflected by a magnetic field. Since the particles have mass, there must be a force to cause the change of direction. The force acts only while a charged particle is moving within a magnetic field.

Electric current in a conductor consists of a flow of charged particles, electrons, moving with a net velocity. When these particles move through a magnetic field, they experience a force, but are constrained by being inside the conductor. The force is therefore transferred to the conductor, causing it to move relative to the external magnetic field.

An electric motor is a device that transforms electrical energy into mechanical energy by using the motor effect.

For interest: **Thomas Davenport** built the first working electric motor in 1833. His design was successful because he used a commutator and brushes. (*The American Society of Mechanical Engineers*)

perform a first-hand investigation to demonstrate the motor effect

- You should **perform** a first-hand investigation to make the motor effect happen by carrying out a planned procedure, recognising where and when modifications to the materials and structures are needed and analysing the effect of these adjustments. Your teacher may plan an investigation for you or you may choose one similar to the following procedure.

Sample procedure:

One of the simplest and safest ways to produce the motor effect is to show how a wire that is free to move will move when a current is passed through it while it is in a magnetic field.

Clamp two strong bar magnets horizontally with opposite poles no more than a centimetre apart. Suspend a wire vertically through the space between the magnets, so that its lower end is free to move. Connect the ends of the wire to a DC power supply with light, flexible leads that allow the wire to move. Switch the current on briefly, then off, observing any movement of the suspended wire. Any movement of the wire would demonstrate the motor effect.

Experiment with various voltage settings on the power supply, the direction of the magnetic field and the direction of the current in the wire. You could use electromagnets, instead of permanent magnets. Systematically observe and record the effects of any changes you make to the variables in the procedure.

identify that the motor effect is due to the force acting on a current-carrying conductor in a magnetic field

- The force on a current-carrying conductor in a magnetic field causes the conductor to move relative to the magnetic field. This movement is referred to as the motor effect.

discuss the effect on the magnitude of the force on a current-carrying conductor of variations in:

- **the strength of the magnetic field in which it is located**
- **the magnitude of the current in the conductor**
- **the length of the conductor in the external magnetic field**
- **the angle between the direction of the external magnetic field and the direction of the length of the conductor**

- The force on a charged particle moving in a magnetic field is proportional to the strength of the magnetic field. Therefore, the stronger the magnetic field, the greater the force on a current-carrying conductor in the magnetic field and vice versa.

- Increasing the potential difference across a conductor increases the drift velocity of electrons within the conductor, thus increasing the current in proportion. Each moving charged particle experiences a force due to the magnetic field in proportion to its velocity. Therefore, the magnitude of the force on a current-carrying conductor varies in proportion to the magnitude of the current in the conductor.

- The longer the section of current-carrying conductor in a magnetic field, the more moving electrons simultaneously experience a force due to the field. Therefore, the magnitude of the force on a current-carrying conductor varies in proportion to the length of the conductor in the magnetic field.

- The force on a charged particle moving in a magnetic field is at its maximum when the particle is moving at right angles to the direction of the magnetic field and zero when the particle is moving parallel to the field. The direction of the drift velocity of electrons in a conductor is along the length of the conductor. Thus, the magnitude of the force on a current-carrying conductor in a magnetic field varies with the angle between the direction of the length of the conductor and the direction of the magnetic field. The force is at a maximum when the angle between the conductor and the magnetic field is 90° and zero when the conductor lies parallel to the field.

solve problems and **analyse information** about the ***force on current-carrying conductors in magnetic fields*** **using** $F = BIl \sin\theta$

- You are required to perform numerical calculations using the formula $F = BIl \sin\theta$. You will need to select from different strategies which could be used to **solve the problem**. This could include rearranging the equation if necessary to have the required variable as the subject of the equation, then substituting known values of variables into the equation to calculate the value of the required variable.

  Note that when the current-carrying conductor is at **right angles** to the direction of the magnetic field, sin θ = 1.0 and the equation $F = BIl \sin\theta$ reduces to $F = BIl$. When the current-carrying conductor is **parallel** to the direction of the magnetic field, θ is zero, sin θ is zero and therefore F is zero.

Sample problem

Calculate the current necessary to produce a force of 5.0 x 10^{-3} N on a 0.10 m long conductor at right angles to a magnetic field of strength 2.5 x 10^{-3} T.

Conductor and field are at right angles, so $F = B\,I\,l$

Rearrange the equation to have current by itself:

$I = F / B\,l$ = 5.0 x 10^{-3} / (2.5 x 10^{-3} x 0.1) = 20 A

Test yourself

A conductor of length 0.20 m and carrying a current of 2.0 A lies in a magnetic field of strength 1.0 x 10^{-5} T. The conductor experiences a force of 2.0 x 10^{-6} N. Calculate the angle between the length of the conductor and the direction of the magnetic field.

Problem:

A conductor of length 0.20 m and carrying a current of 2.0 A lies in a magnetic field of strength 1.0 x 10^{-5} T. The conductor experiences a force of 2.0 x 10^{-6} N. Calculate the angle between the length of the conductor and the direction of the magnetic field.

Solution:

sin 90°="1

$F = B\, I\, l \sin \theta$

Rearrange the equation to get sin θ alone:

$\sin \theta = F / B\, I\, l$
$= (2.0 \times 10^{-6}) / (1.0 \times 10^{-5} \times 2.0 \times 0.20) = 0.5$

therefore, $\theta = 30°$

The conductor lies at an angle of 30° to the direction of the magnetic field.

- You must be able to **analyse** information about the force on current-carrying conductors in magnetic fields using the given equation. You will need to identify the relationship between the force and each other variable in turn by substituting constant values for the other three variables into the equation. You could use a graph to analyse any relationship.

Example of how you can analyse information using an equation

You may be asked to predict what will happen to the force if the length of conductor in the field is doubled.

Select arbitrary constant values for magnetic field strength, current and angle between field and conductor. Then the equation reduces to:

$$F = \text{constant} \times l$$

Thus F is directly proportional to l, so if length is doubled, the force is doubled.

Example of how you can analyse information using a graph

You may be asked to analyse the effect on the force of changing the strength of the magnetic field.

Set realistic values for the current, the length of the conductor and the angle between field and conductor. Select a range of values for magnetic field strength and calculate for each the magnitude of the force. Use a graph to plot values of force against the corresponding value of magnetic field strength. Use the shape and slope of the line in your answer to the question.

describe *qualitatively and quantitatively the force between long parallel current-carrying conductors*: $\frac{F}{l} = k\frac{I_1 I_2}{d}$

Qualitative description:

- The force between the conductors exists because the magnetic field due to the current in each conductor interacts with the magnetic field due to the current in the other conductor. The direction of the force (attraction or repulsion) depends on the relative directions of the two currents. If the two currents are flowing in the same direction, each conductor experiences an attractive force, that is, towards the other conductor. If the currents are flowing in opposite directions, each conductor experiences a repulsive force.

- The magnitude of the force between the two conductors depends on the magnitude of the current in each wire, increasing or decreasing with the product of the two currents. The force also depends on the distance of separation between the two conductors, increasing as the conductors are brought closer together, and decreasing as they are moved apart.

- The force between the conductors depends on the length of the parallel conductors, being larger for longer conductors. We usually speak of the "force per unit length" which varies only with the magnitude of the two currents and with the distance between the conductors.

A quantitative description is provided by the equation $\frac{F}{l} = k\frac{I_1 I_2}{d}$, where:

F is the force between the conductors

$I1$ and $I2$ are the currents in the two conductors, respectively

d is the distance of separation between the conductors, and

l is the length of the parallel conductors.

- Because force is a vector quantity, the **direction** of the forces involved is important and must be specified.

- Force, *F*, between two long parallel current-carrying conductors is:
  - proportional to the product of the two currents, $I1$ and $I2$
  - inversely proportional to the separation, *d*, between the conductors
  - proportional to the length, *l*, of the parallel conductors.

- Force per unit length between two long parallel current-carrying conductors is:
  - proportional to the product of the two currents,$I1$ and $I2$
  - inversely proportional to the separation, *d*, between the conductors
  - independent of length.

- The *k* in the equation is an experimentally derived constant which has the value 2 x 10^{-7} T m A^{-1}.

solve problems using: $\frac{F}{l} = k\frac{I_1 I_2}{d}$

- You must be able to **solve** numerical problems and perform calculations involving the equation given. You will need to be able to identify the nature of the problem by identifying the given data as well as the unknown variable whose value is required by the problem. You will need to be able to calculate the value of the unknown variable from values given for the other variables. This could involve changing the subject of the equation.

Sample problem: Calculate the magnetic force between two parallel conducting wires of length 100 m that are 1 m apart if both carry a current of 100 A when:

- the two currents flow in the same direction
- the two currents flow in opposite directions.

Solution:

Unknown: force, *F*

Given data: length l = 100 m; currents $I1$ = $I2$ = 100 A; distance d = 1 m.

$$\frac{F}{l} = k\frac{I_1 I_2}{d}$$

$$F = lk\frac{I_1 I_2}{d}$$

$$F = 100 \times 2 \times 10^{-7}\ \frac{100 \times 100}{1}$$

$$F = 0.2\ N$$

The force between the current-carrying conductors is 0.2 N.

(a) Since the currents are in the same direction, the force is an attractive force of 0.2 N.

(b) Since the currents in the conductors are flowing in opposite directions, the force is a repulsive force of 0.2 N.

define ***torque as the turning moment of a force using***: $\tau = Fd$

- Torque is defined as the turning moment of a force, that is, $\tau = Fd$, where:
  - τ is the torque
  - F is the component of the applied force perpendicular to the axis of rotation
  - d is the perpendicular distance from the axis to the line of action of the force.
  - The force is applied acting in a clockwise or anticlockwise direction about an axis of rotation.

Applying the definition of torque

This relationship tells you that the rotational effect of a force applied to a body that is allowed to rotate about an axis depends on two factors: the magnitude of the net applied force, *F,* and the perpendicular distance *d* from the axis of rotation to the line of action of the force. This means that the turning effect of a given force applied at a larger distance from the turning axis is greater than the effect of that same force applied closer to the turning axis. This rotational effect is called the turning moment of the force, or torque.

To put this in an everyday context, try to push open a door using the handle: you should find it easy. Now try to open the same door by pushing on the door immediately adjacent to the hinge: you should find that a greater force is needed. This is because the torque required to open the door is fixed but you have reduced the distance from the turning axis, the hinge, to the line of action of the force. To produce the same torque you must apply a greater force.

Note that this discussion assumes that the force is applied perpendicular to the axis. Any component of an applied force parallel to the axis will not produce a torque about that axis.

describe the forces experienced by a current-carrying loop in a magnetic field and describe the net result of the forces

The forces experienced by a current-carrying loop in a magnetic field depend on the orientation of the loop relative to the magnetic field. You will need to describe both the direction and the relative magnitude of particular forces, in addition to the net result of all forces.

Assume, for simplicity of discussion, that the axis of a rectangular coil is perpendicular to the magnetic field, and that the long sides of the coil are parallel to the axis and equidistant from it.

- Each long side of the coil experiences a force whose magnitude does not change throughout a rotation of the coil, since the sides always remain perpendicular to the field. The force on each long side can be shown, by the right-hand palm rule, to be always in the same direction throughout a rotation of the coil, opposite in direction to the force on the other long side, and always perpendicular to the axis.

- Each end of the coil will experience a force which varies from zero, when the plane of the coil is parallel to the field, to a maximum when the plane of the coil is perpendicular to the field. The forces on the two ends can be shown, by the right-hand palm rule, to be opposite in direction, always parallel to the axis, and alternating in direction through a full rotation of the coil.

- The force on each long side produces a torque about the axis. As the forces are in opposite directions, and their lines of action are on opposite sides of the axis, they produce a torque in the same direction. Thus, their effect is to rotate the coil about its axis. The net torque is at its maximum when the plane of the coil is parallel to the field, as the perpendicular distance, *d*, to the line of action is maximum, and reduces to zero as the plane of the coil rotates to be perpendicular to the field, as the line of action of each force is then through the axis (*d* = zero). The direction of the torque alternates through a complete rotation of the coil: its direction is always to rotate the coil to be perpendicular to the field.

- As the forces on the two ends are always opposite in direction, and always parallel to the axis, their net effect is zero.

- For any current-carrying loop in a magnetic field, free to rotate about any axis, the net effect of the forces will be such as to rotate the loop to lie perpendicular to the magnetic field. A current-carrying loop orientated in a plane at right angles to a magnetic field will experience no net force.

The Right Hand Rule Physics 232 ▸ Michigan State University

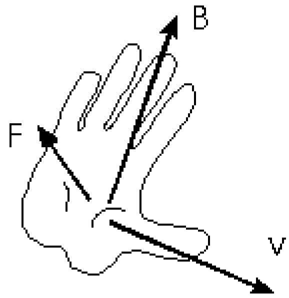
physics232 Elementary Physics II
MICHIGAN STATE UNIVERSITY

The right-hand rule

Remember the magnitude of the force felt by a charge ***q*** moving with velocity ***v*** through a magnetic field ***B*** is:

$$F = qvB\sin\theta$$

As stated previously, the direction of the force is perpendicular to both ***v*** and ***B***. Of course, if both ***v*** and ***B*** are pointed in the plane of the screen, ***F*** could be either into or out of the screen to be perpendicular to both vectors. One uses the right-hand rule to determine the direction of ***F***.



To find the direction of ***F*** use your right hand and:

1. Point your thumb into the direction of ***v***.
2. Point your fingers into the direction of ***B***.
3. The direction of the force will be out of your palm. Your fingers will curl into the direction of the force.

If the charge is negative, one must remember the direction of the force will be opposite. To calculate the force on a segment of wire, use the direction of the current ***I*** instead of ***v***.

If you had used your left hand the force would have been directed oppositely. It seems as if this violates fundamental American principles of equality. However, we will learn that the direction of ***B*** is also determined through a right-hand rule, and the application of two right-hand rules to get to something meaningful (the force) means that two left-hand rules would have given the same result. Thus the laws of electromagnetism do not favor right-handed vs. left-handed people, they only favor consistency. If a physical result depended on the right-handed rule that would constitute *violation of parity*. This indeed occurs in weak decays which will be studied at the end of this course. In weak decays, if one considers a nucleus where the charge rotates as your fingers wrap around your right hand, the emitted electrons all go along the direction of your thumb. Curiously enough, if one did the same experiment with antimatter, one would have to use one's left hand to find the direction of the emitted antielectrons.

Examples for magnetic fields and forces

Example #1

Problem:

A current of 10.0 amps moves through a wire of diameter, ***d*** = 3.0 *mm*. The density of free electrons in the wire is 5.0E27 electrons/m^3. What is the average velocity of the electrons in the current?

Solution:

The current in a wire is given by the charge per unit length times the velocity of the charge.

$$F = qvB\sin\theta$$

The charge per unit length is the charge per volume times the cross-sectional area of the wire.

$$\frac{Ne}{L} = e \cdot density \cdot \pi r^2$$

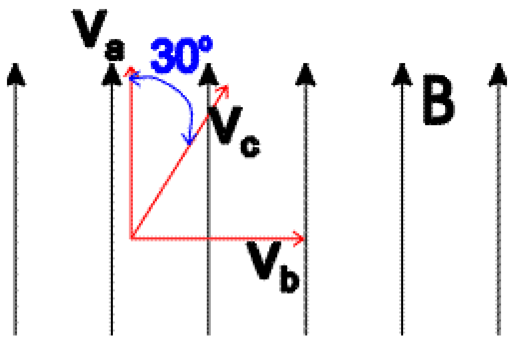
One can then solve for the velocity using the first equation.

1.77E-3 *m/s*, pretty slow!

Example #2

Problem:

In the figure below, the magnetic field has a strength of 0.75 *T*. Three charged particles ***a***, ***b***, and ***c***, each with a velocity of 500 *m/s* and charge of 4.0 m*C* travel with the directions shown. What is the magnitude of the force on each particle?



Solution:

$$\tau = wF = wIhB$$

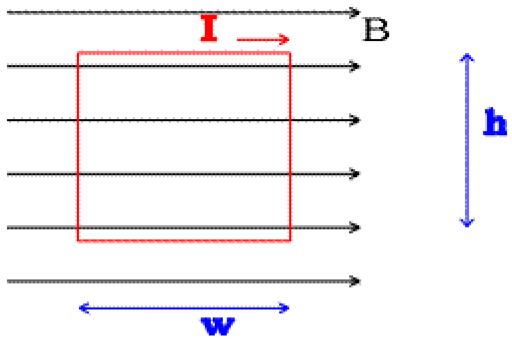
F_a = 0, F_b = 1.5E-3 *N* , F_c = 7.5E-4 *N*

Example #3

Problem:

In the figure below, what are the net force and torque on the loop?

DATA: ***I*** = 3.0 amps, ***w*** = 0.5 *m*, ***h*** = 0.7 *m*, ***B*** = 1.5 *T*



Solution:

All the forces cancel out, but there is a force out of the screen from the right segment and a force into the screen on the left segment. These make the loop want to twist, and give it a torque:

$$\tau = wF = wIhB$$

F = 0, t = 1.575 *Nm*

Example #4

Problem:

An proton makes a 30 *cm* circular orbit in a 2.5 *T* magnetic field. What is the velocity of the proton?

DATA: mass of proton = 1.67E-27 *kg*, *e* = 1.602E-19 *C*.

Solution:

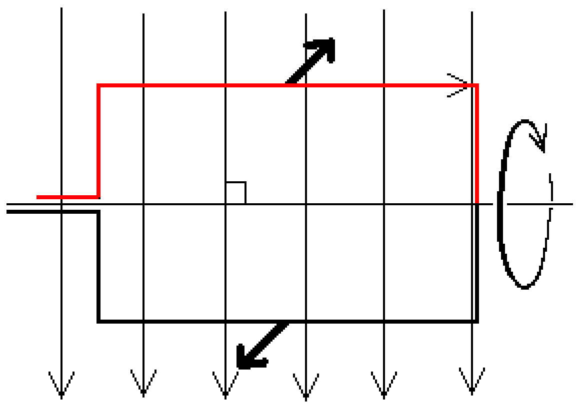
Use the relation:

$$R = \frac{mv}{qB}$$

to solve for the velocity.

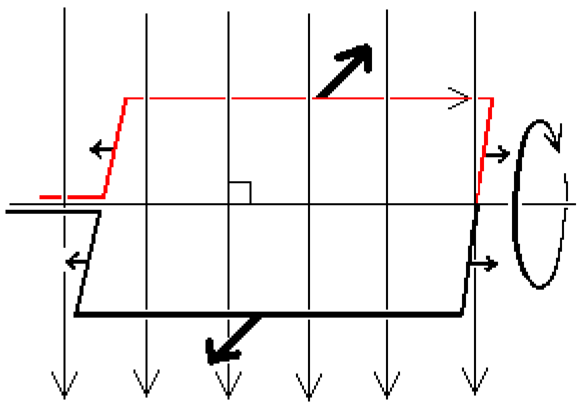
v = 7.2E7 *m/s*

1.



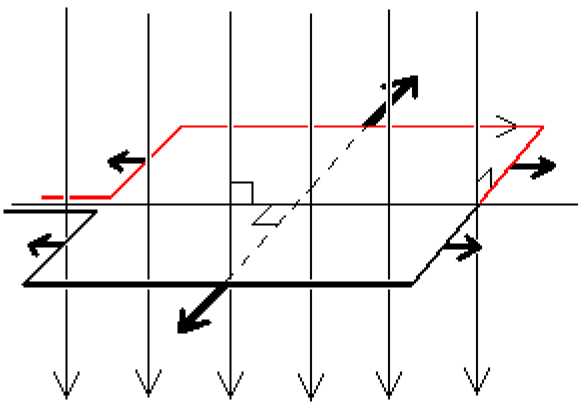
In this position torque is maximum and in clockwise direction. Force on the ends is zero.

2.



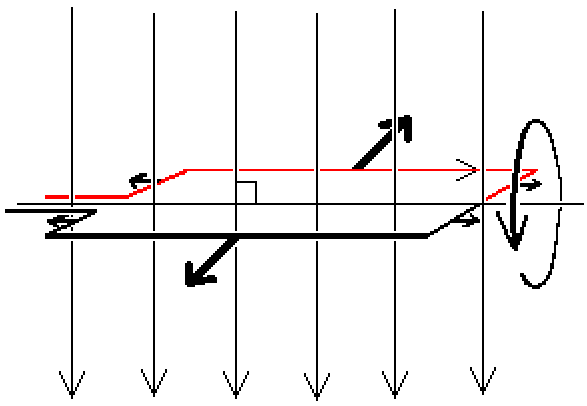
Force on the ends is outwards.

3.



In this position torque is zero. Force on the ends is maximum.

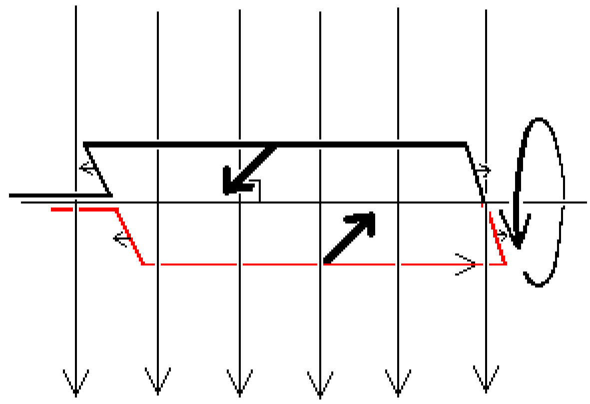
4.



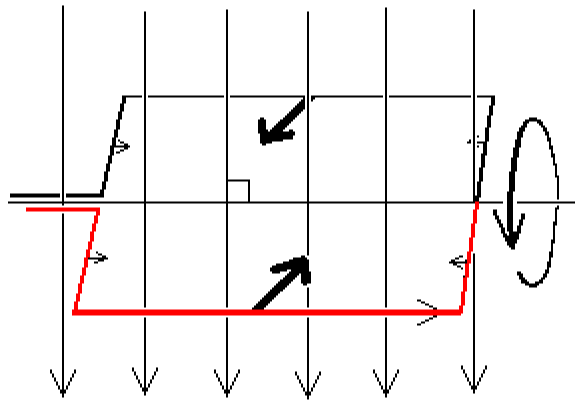
The torque is anti-clockwise.

5.

6.



The torque is anti-clockwise.



Force on the ends is inwards.

solve problems and analyse information about simple motors using $\tau = nBIA\cos\theta$

Deriving the equation:

From $\tau = Fd$ and $F = BIl\sin\theta$, when θ = 90°, we get $\tau = BIld$ for each side of the coil. However, the net torque on the coil is twice the torque on one side, that is, for the coil, $\tau = 2BIld$.

Now the length of the coil is *l*, and its width is *2d*, so that *2ld* is the area of the coil, *A*. Thus, when the coil lies in a plane parallel to the field, the net torque on a coil is given by $\tau = BIA$.

This reduces to zero when the coil is perpendicular to the field. Thus, torque on a coil varies as the cosine of the angle between the plane of the coil and the field. That is $\tau = BIA\cos\theta$.

This applies to a coil of only one turn. Typically, coils used in motors are made with many turns, each of which contributes to the torque. Thus, for a coil of *n* turns, with its axis perpendicular to the magnetic field, the net torque is given by $\tau = nBIA\cos\theta$.

Note that, in this case, θ is the angle between the plane of the coil and the direction of the magnetic field. It is assumed in this derivation that the sides of the coil producing a torque are always perpendicular to the field.

In practice, motors are not constructed with rectangular coils, nor are the coils flat, but the relationship still applies. Text books use the simplified example of a flat, rectangular coil because it is easier to follow its derivation.

- **Solve problems** using the equation by selecting a strategy, such as rearranging the equation as necessary, then substituting given numerical values for known variables, so that you can calculate the value of the unknown variable. You should ensure that you can rearrange any equation successfully to change the subject of the equation to the unknown variable as required.

- **Analyse** information about simple motors by using the equation as a mathematical model to explain the factors involved in producing the torque. You should be able to predict the effect on the torque of changing any of the other variables.

Sample analysis

Suggest ways in which the torque produced by a simple electric motor could be increased.

From the equation, you can see that the torque produced by the motor is proportional to the strength of the magnetic field, to the number of turns in each armature coil, to the area of cross-section of a coil and to the current drawn by the motor. Therefore, an increase in any one of these would lead to an increase in torque. For instance, the number of turns in the armature coil(s) could be increased, or stronger permanent magnets could be used to provide the magnetic field.

describe ***the main features of a DC electric motor*** **and the role of each feature**

This dot point would be well supported by an activity involving the dismantling of a simple commercial electric motor from a child's battery-operated (DC) toy. Web sites are listed below that describe the procedure and identify the parts of the motor. If care is taken the motor can be reassembled and made functional again after the activity. Alternatively, this activity could be replaced by observation of a laboratory model DC electric motor that has all the main components exposed.

- A table is an efficient means of presenting a description of the main features or parts of a DC electric motor and the role of each feature.

Part	Description	Role of the part
For the external magnets, one of the following arrangements is used:		
A. a pair of permanent magnets in a simple motor	Two permanent magnets on opposite sides of the motor, with opposite poles facing each other. The pole faces are curved to fit around the armature.	The magnets supply the magnetic field which interacts with the current in the armature to produce the motor effect. The shape of the pole faces makes the magnetic field almost uniformly radial where the coil passes.
B. pairs of electromagnetic coils in a more complex motor	Each stator coil (or "field" coil) is wound on a soft iron core attached to the casing of the motor. The coils are shaped to fit around the armature.	Each opposed pair of stator coils produces a magnetic field similar to that provided by a pair of permanent magnets. The iron core concentrates the field.
Other parts:		
Armature	The armature consists of a cylinder of laminated iron mounted on an axle. Often there are longitudinal grooves into which the coils are wound.	The armature carries the rotor coils. The iron core greatly concentrates the external magnetic field, increasing the torque on the armature. The laminations reduce eddy currents which might otherwise overheat the armature.
Rotor coil(s)	There may be only one, in a very simple motor, or several coils, usually of several turns of insulated wire, wound onto the armature. The ends of the coils are connected to bars on the commutator.	The coils provide torque, as the current passing through the coils interacts with the magnetic field. As the coils are mounted firmly on the rotor, any torque acting on the coils is transferred to the rotor and thence to the axle.
Split-ring commutator	The commutator is a broad ring of metal mounted on the axle at one end of the armature, and cut into an even number of separate bars (two in a simple motor). Each opposite pair of bars is connected to one coil.	The commutator provides points of contact between the rotor coils and the external electric circuit. It serves to reverse the direction of current flow in each coil every half-revolution of the motor. This ensures that the torque on each coil is always in the same direction.
Brushes	Compressed carbon blocks, connected to the external circuit, mounted on opposite sides of the commutator and spring-loaded to make close contact with the commutator bars.	The brushes are the fixed position electrical contacts between the external circuit and the rotor coils. Their position brings them into contact with both ends of each coil simultaneously, as each coil is positioned at right angles to the field, to maximise torque.
Axle	A cylindrical bar of hardened steel passing	The axle provides a centre of rotation for

	through the centre of the armature and the commutator.	the moving parts of the motor. Useful work can be extracted from the motor via a pulley or cog mounted on the axle.

How electric motors work **Inside an electric motor *HowStuffWorks.com***

How electric motors work Electromagnets and Motors, *HowStuffWorks.com*

Stripped down motor *Exploratorium, The Museum of Science, Art and Human Perception, San Francisco, USA* (As motors go,this is about as simple as it gets.)

identify that the required magnetic fields in DC motors can be produced either by current-carrying coils or permanent magnets

- The required magnetic fields in DC motors can be produced by permanent magnets shaped to fit around the armature.

- Alternatively, electromagnets can be produced by winding coils around iron cores attached to the case of the motor and passing current through these coils at the same time as through the rotor coils. These stator coils are wound so that pairs of coils facing the rotor coils have magnetic fields the same as would be produced by pairs of permanent magnets with their north and south poles facing each other.

identify data sources, gather and process information to qualitatively describe the application of the motor effect in:

  - **the galvanometer**
  - **the loudspeaker**

- **Identify data sources** by first determining the type of data that must be collected. You need to find information about galvanometers and about loudspeakers that is specifically about how the motor effect is produced and used in these devices.

- Continue by looking for such information on the Internet, in CD-ROMs and in books, including text books, popular scientific journals, technical manuals and encyclopaedia. Skim and scan the information to identify keywords in the text. Ask yourself whether the information presented is explicitly concerned with the motor effect at work in either a galvanometer or a loudspeaker, and discard sources that are irrelevant. Look for diagrams that will help your description.

  You should also examine a demonstration galvanometer or a partially dismantled loudspeaker, if one is available.

  The following web sites could be a start for you in gathering the information:

  Moving coil galvanometer *citycollegiate.com*

  How speakers work *HowStuffWorks.com*

  Dynamic loudspeaker principle *Hyper Physics, Georgia State University, USA*

- **Gather information** that is relevant to the required description of applications of the motor effect by summarising important sections of text and drawing diagrams as appropriate. Collate information on the same topic from different sources.

- **Process** the information you gather by comparing different sources to assess the reliability of the information. Use the information to compile, in your own words, a qualitative description of how the motor effect is applied in each device.

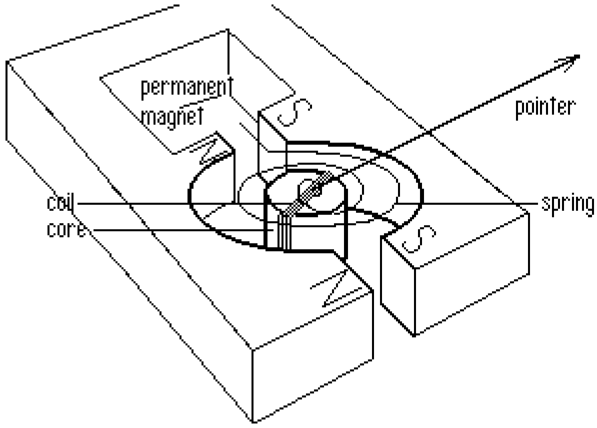
Sample descriptions

A galvanometer

In a galvanometer, the motor effect is used to measure the magnitude of an electric current. The current is passed through a coil suspended in the field of a permanent U-shaped magnet. The resulting motor effect produces a torque on the coil in proportion to the magnitude of the current.

The pole faces of the magnet are curved to surround the coil and there is a soft iron core inside the coil. These features ensure that the magnetic field is perpendicular to the coil and is of relatively constant value within the range of rotation of the coil. Thus, the torque on the coil remains proportional to the current as the coil rotates.

The motor effect on the coil is opposed by a coil spring whose restoring force is proportional to the angle of rotation of the coil. When the torque due to the motor effect is balanced by the restoring force of the spring, a pointer attached to the coil indicates the magnitude of the current on a suitable scale.



A loudspeaker

The motor effect is used in a loudspeaker to produce sound from an audio frequency electrical signal. The alternating current signal is passed through a coil which is suspended in the field of a permanent magnet. This induces a motor effect, causing the coil to vibrate as the force on the coil due to the magnetic field changes direction at the same frequency as the input signal. The speaker cone attached to the coil also vibrates, producing sound waves in the surrounding air.

9.3 Motors and generators: 2. The generator

Syllabus reference (October 2002 version)

outline *Michael Faraday's discovery of the generation of an electric current by a moving magnet*

- In 1820, Hans Christian Oersted and Andre Marie Ampere discovered that an electric current produces a magnetic field. Faraday's ideas about conservation of energy led him to believe that since an electric current could cause a magnetic field, a moving magnetic field should be able to produce an electric current. Faraday demonstrated this in 1831.

- Faraday attached two wires through a sliding contact to touch a rotating copper disc located between the poles of a horseshoe magnet. This was the same as moving a magnetic field near an electric circuit. This induced a continuous direct current. Faraday had invented the first electric generator. Prior to this, continuous electricity could only be produced by batteries or galvanic cells.

- Faraday's explanation was that the electric current was induced in the moving disc as it cut a number of lines of magnetic force emanating from the magnet (the magnetic field). The wires allowed the current to flow in an external circuit where it could be detected.

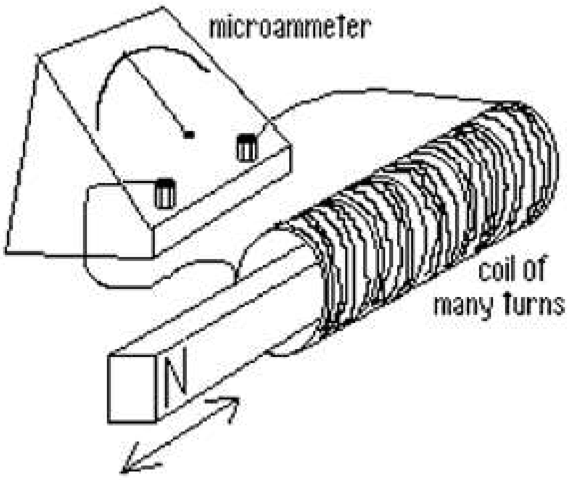
perform an investigation to model the generation of an electric current by moving a magnet in a coil or a coil near a magnet

- You should **perform** a first-hand investigation to model the generation of an electric current by carrying out a planned procedure, recognising where and when modifications to the materials and structures are needed and analysing the effect of these adjustments. Your teacher may plan an investigation for you or you may choose one similar to one of the following procedures.

Sample procedures

An electric current can be produced either by moving a magnet inside a coil or by moving a coil near a magnet, for example, by rotating it.

Connect an air-cored solenoid coil to a centre-reading galvanometer graduated in microamperes (µA). The coil should have a large number of turns or loops of fine wire, around 300–500, and have space to fit a bar magnet through it.



Select the strongest bar magnet or disc magnet that will fit into the coil. Move the magnet inside the coil and observe any movement of the galvanometer needle. A reading on the galvanometer demonstrates that an electric current has been generated.

Alternatively, a hand-operated demonstration AC/DC generator, of the kind found in most school science laboratories, can be used. The coil is rotated between the poles of either a horseshoe magnet or a pair of bar magnets with oppositely orientated poles.

Output from the generator can be tested in various ways:

- Connect a lamp across the output terminals, with a centre-reading galvanometer graduated in milliamps (mA) in series with the lamp, and a voltmeter in parallel with the lamp.
- Connect the output terminals to a CRO or a digital voltmeter.

Turn the generator by hand at different speeds and in each direction. Use the switch on the generator to change between AC and DC. Systematically observe and record the effects of any changes you make to the variables in the procedure.

An excellent Java applet of a simple generator can be seen at the following web site. The speed of coil rotation and the direction rotation can be changed and the commutator can be swapped for slip rings. The effect of these changes on the direction and magnitude of current produced can be seen.

How Do Electric Generators Work by Mark Orwell, eHow editor, eHow, How to do just about everything, USA

How an Electric generator Works Wisconsin Valley Improvement Company, Wausau, Wisconsin, USA

define magnetic field strength B as magnetic flux density

- Visualising a magnetic field involves imagining a large number of invisible **magnetic flux lines** "flowing" out of the north pole and into the south pole of a magnet. The magnetic flux lines are shown close together near the poles where the magnetic field is strongest but further apart at greater distances from the magnet. The magnetic field of a strong magnet is represented by showing a larger number of magnetic flux lines than for the field of a weaker magnet.

- **Magnetic flux density** is a measure of the number of magnetic flux lines passing through a unit area (one metre squared) and is represented diagrammatically by the number of magnetic flux lines drawn in a particular area. **Magnetic field strength *B*** at a point is **defined** to be the same as magnetic flux density.

describe the concept of magnetic flux in terms of magnetic flux density and surface area

- **Magnetic flux** Φ is the amount of magnetic field threading or "flowing through" a certain area A, such as the area inside a flat coil of wire. This is represented diagrammatically by the total number of magnetic flux lines that pass through area A.

- The stronger the magnetic field at a point, the higher the magnetic flux density B is at that point and the more magnetic flux lines there are cutting or threading a given area. B is a measure of magnetic flux per unit area perpendicular to the direction of the field at a point in the field.

- To find the total amount of flux passing through area A, we need to multiply the magnetic flux density B by the number of square metres in area A. This can be expressed mathematically as flux = flux density × area, or $\Phi = B \times A$.

- In SI units, magnetic flux is measured in Webers (Wb) and magnetic flux density is measured in Webers per square metre (Wb m^{-2})

plan, chose equipment or resources for, and perform a first-hand investigation to predict and verify the effect on a generated electric current when:

- **the distance between the coil and magnet is varied**
- **the strength of the magnet is varied**
- **the relative motion between the coil and the magnet is varied**

- **Plan the investigation** by identifying the dependent variable and all of the independent variables involved. Plan to change only one variable at a time, and develop strategies to ensure that all other independent variables are kept constant. Plan how you will identify, measure and record changes in the dependent variable. When planning to investigate the effect of changing the relative motion between the coil and the magnet, consider changes in relative speed, changes in relative direction of motion and changes in rotation.

- **Choose equipment or resources** by identifying and setting up the most appropriate combination of equipment needed to undertake the investigation. Consider what type of coil would be best to use. Consider also how you could choose magnets of different strength without changing any of the other variables.

- **Perform the first-hand investigation** by following your planned procedure. Before making a change to any variable, try to **predict** the effect of the change on the generated electric current by using what you have already learnt. **Verify** the effect by making the change and observing the size and direction of any generated current. Systematically record the effect of each change you make to the materials and procedure. When making observations, only write down what you can actually see happening. Remember that you cannot see magnetic flux lines.

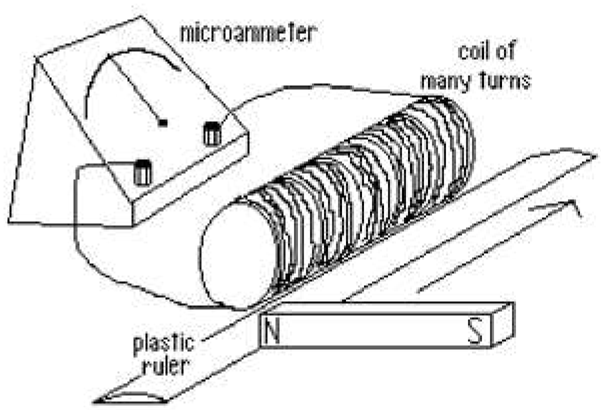
Sample procedure

Distance between magnet and coil, strength of magnet and relative motion between coil and magnet are all independent variables. Each of these will be varied in turn while the others are held constant. The dependent variable, the current generated, will be measured with a centre-reading galvanometer graduated in microamperes (μA) which will indicate both the direction and the magnitude of any current generated. Choose a coil with a large number of turns, around 300–500, of fine insulated wire and with a cross sectional diameter large enough to fit a bar magnet through it. Select a pair of bar magnets that are of similar dimensions but different strength.

Varying the distance between the magnet and the coil

Lay a plastic ruler flat on the bench along the length of the coil as a distance guide for the magnet. Place the magnet at right angles to the coil against the edge of the ruler and slide it smoothly. Now turn the ruler on its edge so that only the thickness of the ruler separates the magnet from the coil, and slide the magnet along the ruler again.

For each trial, try to predict the effect of the change you make. Observe and record the direction and maximum deflection of the galvanometer needle to verify your prediction. Control other variables by using the same end of the same magnet and moving it at the same speed and in the same direction for each trial.



Varying the relative motion between the magnet and the coil

Using the experimental set-up just described, with the ruler on its edge, vary the relative motion between the magnet and the coil by:

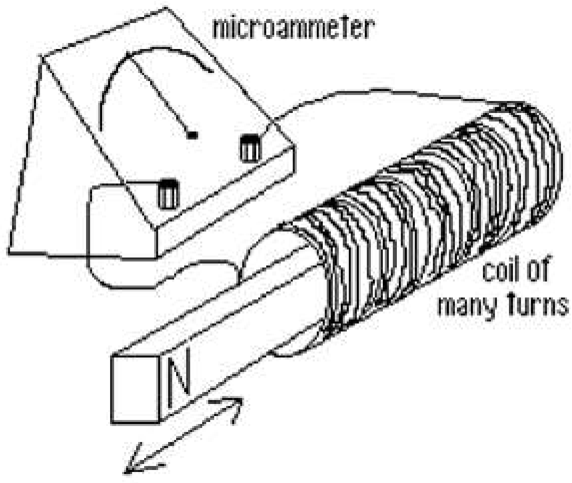
- moving the magnet smoothly at different speeds;
- moving the magnet smoothly at the same speed in each direction;
- using each pole of the magnet in turn.

Other variables are controlled by using the ruler to maintain the same distance between the magnet and the coil and by using the same magnet in each trial.

Now insert one end of the magnet into the coil and vary the relative motion between the magnet and the coil by:

- moving the magnet smoothly into the coil at different speeds;
- moving the magnet smoothly at the same speed into the coil and out of the coil;
- using each pole of the magnet in turn;
- moving the magnet right through the coil and out the other end.

Control other variables by using the same magnet for each trial and by keeping the end of the magnet within and central to the coil to minimise the effect of changing distance.



For each trial, try to predict the effect of the change you make. Observe and record the direction and maximum deflection of the galvanometer needle to verify your prediction.

Varying the relative motion by rotating the coil in the field

Use a hand-operated demonstration AC/DC generator, of the kind found in most school science laboratories, to investigate the effect of changing the relative motion between the coil and the field by rotation of the coil. The coil is rotated between the poles of either a horseshoe magnet or a pair of bar magnets with oppositely orientated poles. Observe the orientation of the coils to the magnetic field. When the plane of the coil is parallel to the direction of the field, the long sides of the coil are moving at right angles to the field. When the plane of the coil is perpendicular to the field, the long sides of the coil are moving parallel to the field.

Connect a microammeter to the generator output terminals and turn the generator slowly. Observe the size of the induced current when the long sides of the coil are moving perpendicular to the field, parallel to the field and at intermediate angles.

Using magnets of different strength

Repeat any of the above procedures using another magnet of different strength. Try to predict the effect of changing to a stronger or weaker magnet. Observe and record the direction and maximum deflection of the galvanometer needle to verify your prediction. Control other variables by using two magnets of similar dimensions.

Sample observations

For a magnet of constant strength and the same relative motion between the coil and the magnet, the generated electric current increases as the distance between the coil and magnet decreases.

For a constant distance between the coil and the magnet, and the same relative motion between the coil and the magnet, the generated electric current increases as the strength of the magnet increases.

For a constant distance between the coil and the magnet and for a magnet of constant strength:

- the direction of the generated electric current changes when the direction of the relative motion between the coil and the magnet is reversed;
- the direction of the generated electric current changes when the polarity of the magnet is reversed; and
- the magnitude of the generated electric current increases as the speed of the relative motion between the coil and the magnet is increased.

For a coil rotating in a magnetic field, the induced current varies smoothly from a maximum when the long sides of the coil are moving at right angles to the field, to zero when the long sides are moving parallel to the field

describe generated potential difference as the rate of change of magnetic flux through a circuit

- Whenever there is relative motion between a conductor in a circuit and a magnetic field, the circuit cuts the magnetic flux. The rate at which the flux is cut can be increased by:
  - decreasing the distance between the conductor and the magnetic field, as the flux lines are closer together nearer the magnet;
  - increasing the strength of the magnet, as there are more flux lines in the same space in a stronger field than in a weaker field;
  - increasing the speed of the relative motion between the conductor and the magnetic field, as the conductor cuts more flux lines per unit time; and
  - increasing the angle between the direction of motion of the conductor and the direction of the magnetic field from near zero towards 90 degrees, as the conductor cuts the maximum number of flux lines per second when its motion is at right angles to the field.

- Each of these changes also causes an increase in the current flowing in the circuit, and therefore the potential difference. Thus the generated potential difference increases as the rate of change of flux in the circuit increases.

- The generated potential difference or electromotive force (emf) is **defined** to be equal to the rate of change of flux in the circuit.

- Quantitatively, the potential difference or emf (ε) induced in a conductor is the amount of flux cut $(\Delta\Phi)$ divided by the time taken (Δt).

  In other words, $\varepsilon = \dfrac{\Delta\Phi}{\Delta t}$.

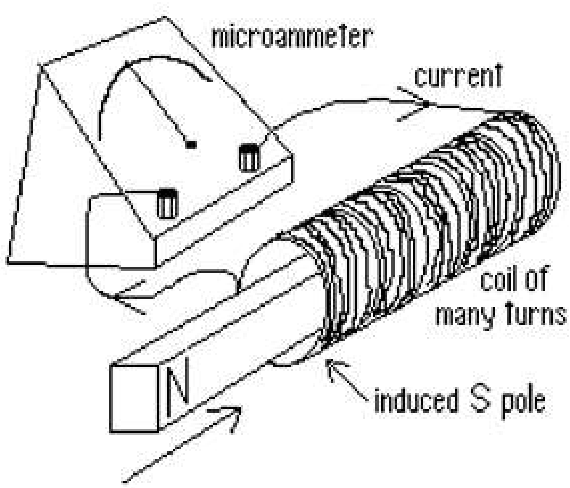
  This is Faraday's Law of electromagnetic induction. Where the circuit involves a coil, with multiple loops of the circuit cutting the same flux, the emf generated is in proportion to the number of coil turns (N) that cut the flux.

  In this case, the emf generated is $\varepsilon = N\dfrac{\Delta\Phi}{\Delta t}$.

account for *Lenz's Law in terms of conservation of energy and relate it to the production of back emf in motors*

- Lenz's law was first proposed by Heinrich Lenz (1804–1864). This law says: if an induced current flows, its direction is always such as to oppose the change in flux that produced it.

- Consider the example where a current is produced by inserting a magnet into a coil connected into a circuit with a galvanometer to show current flow direction. If the south pole of a bar magnet is inserted into the coil the current induced in the coil will flow in a direction such that it produces a south pole opposing the insertion of the bar magnet. Pushing the bar magnet against that field means that work must be done.



- If the same magnet is pulled out of the coil from the same end the current induced in the coil will be in the opposite direction so that it produces a north pole that attracts the south pole of the magnet being withdrawn. This attraction means work must be done to pull the magnet out of the coil.

- Lenz's law follows from the Law of Conservation of Energy. That law says energy cannot be created nor destroyed but can simply change form. In the case of the magnet and coil, energy must be transferred to the coil to produce the induced current flow (electrical energy). That energy is the work done in inserting the coil or withdrawing it.

- It is therefore necessary that work must be done against the magnet moving relative to the coil if it is to generate the emf in the coil. If it were not so, the induced magnetic field would accelerate the magnet, thus increasing the induced emf which, in turn would increase the strength of the induced field, further accelerating the magnet, and so on, contravening the Law of Conservation of Energy.

- Electric motors use an external emf applied to the coils to produce an electtric current in the coils positioned in an external magnetic field. This current produces a magnetic field that interacts with the external magnetic field. As the coils rotate in the external magnetic field, an emf is induced in the coils due to the constantly changing magnetic flux threading the coils. By Lenz's Law, this induced emf is in the opposite direction to the external supply emf causing the rotation, and it has the effect of reducing the net emf applied to the coils. Because the induced emf is in the opposite direction to the supply emf, it is known as the **back emf**.

explain **that**, *in electric motors, back emf opposes the supply emf*

- Back emf is the emf induced in the coils of a motor as they spin in the external magnetic field of the stator.

- By Lenz's law the direction of that induced emf opposes the emf causing the motion of the armature. The current generated in the motor is an eddy current. The direction of the motor eddy current is such that it opposes the supply emf that produces the motion in the motor. The net emf applied to the coils equals the supply emf minus the back emf.

- The back emf increases as the speed of the motor increases, until the net emf is just sufficient to provide the energy for the work the motor is doing, against its own internal friction and any load that is applied to it. If there were no back emf, the motor would continue to spin faster and faster indefinitely.

- When a greater load is applied to the motor, the armature rotates more slowly and the back emf is reduced. This allows a greater current to flow through the coils, resulting in an increased torque to match the extra load.

- At low speeds, when the back emf is small, the motor coils are protected by a series resistor from the large currents that could flow and burn out the motor. This resistor is switched out at higher speeds when the back emf replaces the role played by the resistor at low speed.

gather, **analyse** and **present information** to **explain** ***how induction is used in cooktops in electric ranges***

- **Gather** the information about how induction cooktops work from as many sources as possible such as the Internet, magazines and advertising material. You might also consider doing field research by seeking information from the sales staff at your local electrical appliance store.

- **Analyse** the information by eliminating both extravagant advertising claims and minor details of difference between competing brands to find the general principles of operation of induction cooktops.

- **Present** the information using diagrams or pictures supported by text.

Sample information

Each cooking area on the ceramic induction cooktop has one or more coils wound on ferromagnetic material under it. A high frequency alternating current is passed through these coils producing a fluctuating magnetic field. When a ferromagnetic-based pan is placed over the coils, eddy currents are induced in the base because of the fluctuating magnetic field. The eddy currents are trapped within the pan because the ceramic cooktop is an electrical insulator.

The pan must be made from a metal that has a high internal resistance to this induced AC current. The resistance to the rapidly oscillating currents within the pan results in heat being produced directly in the base of the pan. That heat is dissipated to the food in the pan and does the cooking. The ceramic cooktop itself is not heated other than by heat lost from the pan. The induction cook top works best when used with pans made of ferromagnetic metals such as stainless steel and cast iron.

An Internet site that gives the basics of an induction cooktop is **Induction Cooking: How it Works** The Owlcroft Company, USA. Scroll past Here's the basic idea, until you reach the box with 'Induction is a third method...'

gather secondary information to **identify** ***how eddy currents have been utilised in electromagnetic braking***

- To **gather information** efficiently from secondary sources, make sure that the information clearly identifies a use of electromagnetic braking, and that the braking effect occurs through the induction of eddy currents. Discard any information that is not relevant.

- Use the information gathered to **identify** at least two examples where eddy currents are used to provide an electromagnetic braking effect. Outline how the eddy currents are produced and how this causes the braking effect.

Sample information

Eddy currents are used for electromagnetic braking in many free-fall amusement park rides. A copper plate attached to the ride capsule passes between fixed strong magnets near the bottom of the ride, inducing eddy currents and associated magnetic poles in the copper plate. Each fixed magnet in turn induces a like pole as the plate approaches and an opposite pole as the plate leaves. The combined effect of interaction between the permanent and the induced fields slows the ride down smoothly because the strength of the eddy currents in the plate is directly proportional to the speed of the plate moving between the poles. As the ride slows the braking force is reduced.

Some trains use electromagnets close to the metal rails to induce eddy currents in the rails. These eddy currents produce magnetic fields in the rails, a like pole ahead of each electromagnet and an opposite pole behind it. The interaction between the magnetic fields opposes the forward motion of the electromagnets and the train to which they are attached. Because the strength of the induced eddy currents is proportional to the speed of the train, the braking force is reduced as the train slows, resulting in a smooth stop.

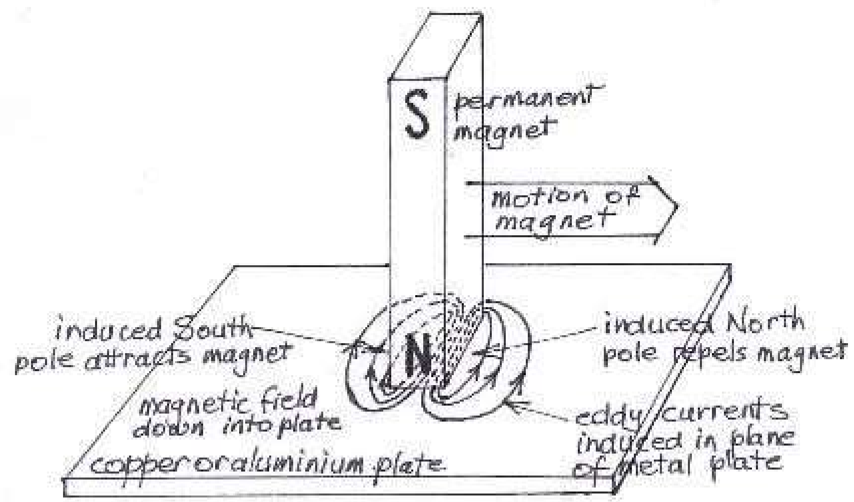
Triple beam balances commonly used in school laboratories have an aluminium plate fixed to the end of the beam. As the beam swings, the plate passes through the field of a permanent horseshoe magnet. Eddy currents are induced in the plate, setting up magnetic fields and damping the motion of the balance.

explain *the production of eddy currents in terms of Lenz's Law*

- An eddy current is a closed loop current that flows in a conductor, such as the iron core of a coil of an electromagnetic brake plate, when there is relative motion between the object and a magnetic field. The eddy current, flowing in a closed loop, acts like the current in a coil or solenoid and produces its own magnetic field. The polarity of this magnetic field depends on the direction in which the eddy current circulates.

- Lenz's Law says if an induced current flows, its direction is always such that it will oppose the change of flux that produces it. That is, the polarity of the magnetic field produced by the eddy current is such that it opposes the relative motion of the magnetic field that induced the eddy current.

- Consider the north pole of a magnet moving over and close to the face of an aluminium plate. By Lenz's Law, the circulation of an eddy current ahead of the moving magnet should produce a north pole that will repel the moving magnet. The direction of current flow to produce a north pole agrees with the direction of the induced emf in a conductor moving relative to a magnetic field, that is, down the plate within the region of the moving field. Similarly, Lenz's Law predicts that an eddy current induced behind the moving magnet will produce a south pole that will attract the moving magnet. Together these two induced poles oppose the motion of the magnet over the aluminium plate.



9.3 Motors and generators: 3. Generators for large scale power production

Syllabus reference (October 2002 version)

plan, choose equipment or resources for, and perform a first-hand investigation to demonstrate the production of an alternating current

- **Plan** this first-hand investigation by describing ways in which an AC current can be produced and explaining why this works. You should first think about how to produce a direct electric current, then about how to produce a current flowing in the opposite direction. You should also think about how you will know when a current is flowing and in which direction. Finally you should think about how to make the current alternate in direction in a regular manner.

- You should **choose equipment** for this investigation by identifying items that would be suitable to produce an electric current. Choose an instrument that can be used to measure the size of current that will be produced and can also indicate the direction of the current. Consider using datalogging technology so that you can record the size and direction of the current over a period of time. Alternatively, you might consider using equipment that can display the voltage characteristics of the alternating current on the screen of a cathode ray tube.

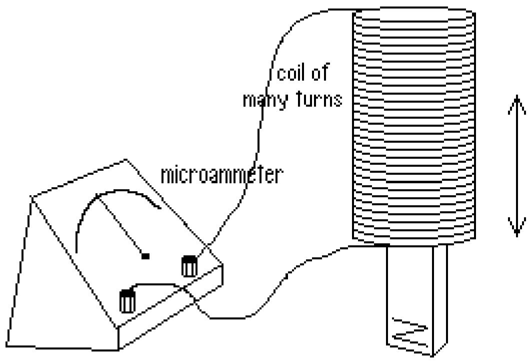
- You should then **perform** the investigation by carrying out the procedure you have planned. Experiment with different combinations of equipment until you are able to demonstrate the production of an alternating current. Try to identify variables that can be changed, and carefully record the results of any changes you make.

Sample investigation

An electric current can be produced by moving a wire in a circuit near a permanent magnet or by moving the magnet near the wire. The magnet can be either moved back-and-forth or rotated end-for-end. As the magnet is moved one way, a current is induced: as it is moved the other way, a current is induced in the opposite direction. The current can be detected by a galvanometer.

A coil shows the effect more clearly than a single wire, as the effect is enhanced by having the magnetic flux cutting the many turns of wire in a coil. The current produced is usually small and is best indicated with a microammeter or a galvanometer scaled in microamps (mA). A centre-reading galvanometer will also indicate the direction of the current.

Connect the ends of the coil to the terminals of the galvanometer. Stand the permanent magnet on its end on the bench and place the coil vertically over the magnet. Move the coil upwards and note the direction of movement of the galvanometer needle. Move the coil downwards and again note the direction of movement of the galvanometer needle. Now move the coil rhythmically up and down while observing the galvanometer needle. Record all of your observations. Movement of the galvanometer needle back and forth indicates the production of an alternating current.

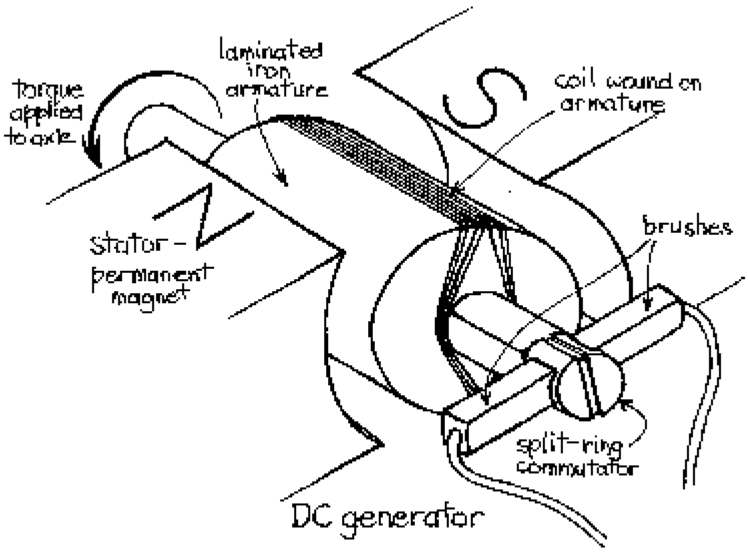


Change the speed at which you move the coil up and down, and change the displacement with each movement. Repeat the investigation with a stronger magnet or with a coil of a different number of turns. Each time you make a change, record your observations and try to account for any changes you notice in the magnitude or the frequency of the alternating current you produce.

describe *the main components of a generator*

- The following table contains a description of the main components of a generator.

Component of generator	Description
Rotor	In its simplest form, the rotor consists of a single loop of wire made to rotate within a magnetic field. In practice, the rotor usually consists of several coils of wire wound on an armature.
Armature	The armature is a cylinder of laminated iron mounted on an axle. The axle is carried in bearings mounted in the external structure of the generator. Torque is applied to the axle to make the rotor spin.
Coil	Each coil usually consists of many turns of copper wire wound on the armature. The two ends of each coil are connected either to two slip rings (AC) or two opposite bars of a split-ring commutator (DC).
Stator	The stator is the fixed part of the generator that supplies the magnetic field in which the coils rotate. It may consist of two permanent magnets with opposite poles facing and shaped to fit around the rotor. Alternatively, the magnetic field may be provided by two electromagnets.
Field electromagnets	Each electromagnet consists of a coil of many turns of copper wire wound on a soft iron core. The electromagnets are wound, mounted and shaped in such a way that opposite poles face each other and wrap around the rotor.
Brushes	The brushes are carbon blocks that maintain contact with the ends of the coils via the slip rings (AC) or the split-ring commutator (DC), and conduct electric current from the coils to the external circuit.



[compare](#) the structure and function of a generator to an electric motor

- Electric motors and generators have several structural features in common. Each consists of a stator that provides a magnetic field and a rotor that rotates within the magnetic field. In both motors and generators the magnetic field may be supplied either by permanent magnets or by electromagnets. The rotor in both an electric motor and a generator consists of coils of wire wound on a laminated iron armature and connected through brushes to an external circuit.

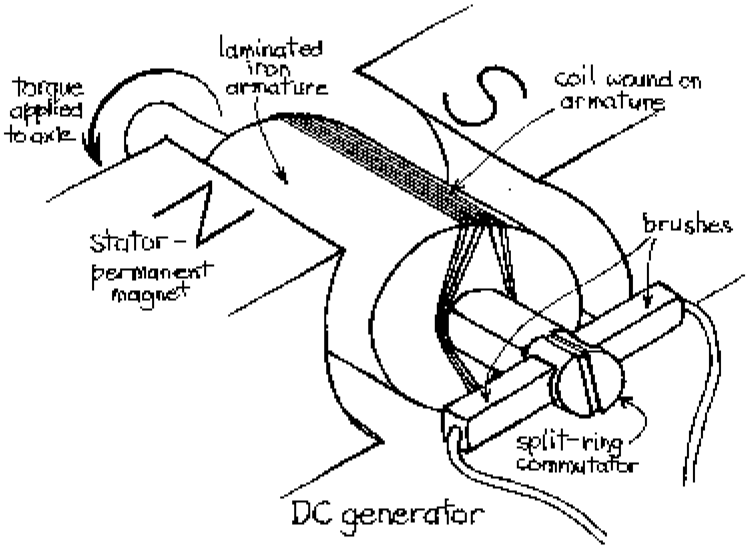
- An electric motor and a DC generator are similar in that their rotor coils are connected to the external circuit through a split-ring commutator. An AC generator is different as its rotor coils are connected to the external circuit through slip rings. An **AC induction motor** *Wolfram Mathematica 2011* is different from a generator as its rotor coils are not connected to an external circuit and its field is always supplied by electromagnets.

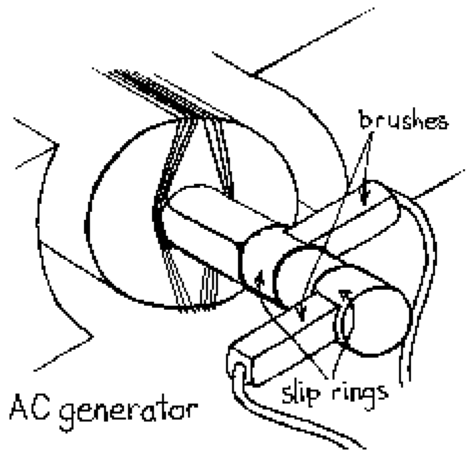
- The function of an electric motor is the reverse of the function of a generator. An electric motor converts electrical energy into mechanical (usually rotational) energy. A generator converts mechanical (usually rotational) energy into electrical energy. A motor rotates when current is supplied while a generator supplies current when rotor is made to rotate. It is possible to have a DC motor act as a generator by providing the energy to rotate the armature containing the coils.

describe the differences between AC and DC generators

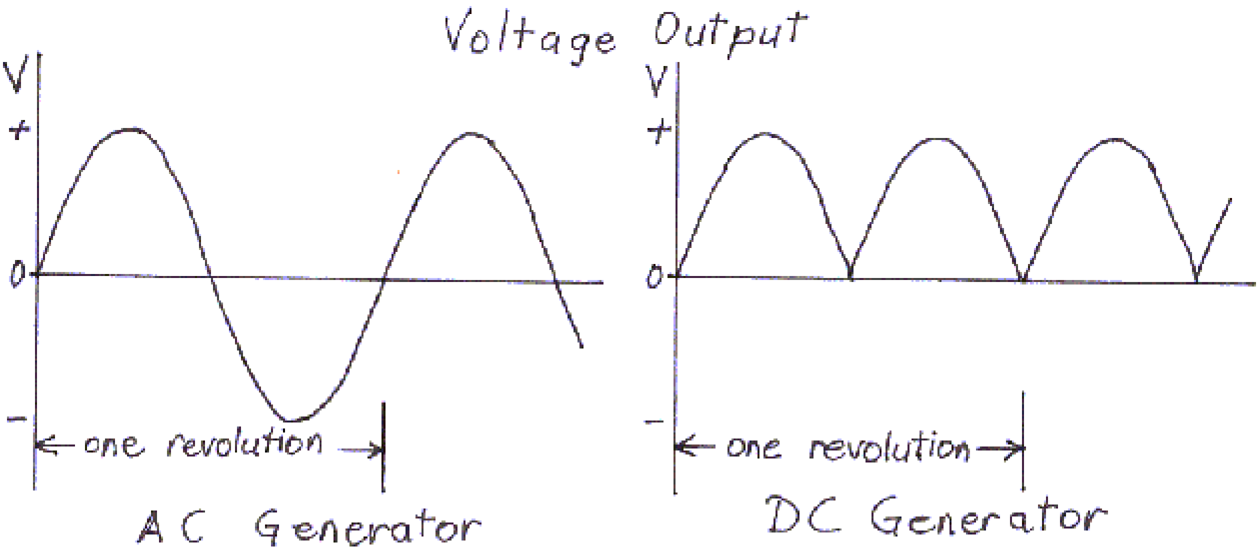
- The essential difference between an AC and a DC generator is the nature of the connection between the rotor coils and the external circuit.

- In an AC generator, the brushes run on slip rings which maintain a constant connection between the rotating coil and the external circuit. This means that as the induced emf changes polarity with every half-turn of the coil, the voltage in the external circuit varies like a sine wave and the current alternates direction.





- In a DC generator, the brushes run on a split-ring commutator which reverses the connection between the coil and the external circuit for every half-turn of the coil. This means that as the induced emf changes polarity with every half-turn of the coil, the voltage in the external circuit fluctuates between zero and a maximum while the current flows in one constant direction.



The following Internet site contains a simple animation of an AC generator: **AC-DC: Inside the AC Generator**
The American Experience Online, Public Broadcasting Service (PBS), USA

gather secondary information **to** **discuss** ***advantages/disadvantages of AC and DC generators and relate these to their use***

- In **gathering** your information you should ensure that you use a variety of sources including written texts and the Internet. You should also gather relevant information by interviewing people such as auto electricians or electrical engineers. You should make sure that the information you collect relates directly to how and where AC and DC generators are used and how each is best suited to its use. An auto electrician could probably explain, for instance, why the AC generator, or alternator, has replaced the DC generator in motor cars and give some good insights into the relative advantages of each of these devices.

Sample information

The relative advantages and disadvantages of AC and DC generators relate to two features of their design: DC generators use a split-ring commutator, while AC generators use slip rings; and in DC generators the output current is induced in the rotor, whereas the roles of the rotor and the stator can be reversed in an AC generator.

The commutator of a DC generator consists of a number of metal bars separated by narrow gaps filled with insulating material. As the brushes remain in contact with the commutator under spring pressure, they are constantly striking the leading edge of each successive bar. This wears the brushes and they need to be replaced regularly. The commutator bars also wear down until the insulating material between them prevents the brushes from making proper contact with the bars, reducing the efficiency of the generator. Pieces of metal worn from the commutator bars can become lodged in the gaps, causing a short between bars and reducing the output of the generator.

In contrast, the slip rings of an AC generator have continuous, smooth surfaces, allowing the brushes to remain continuously in contact with the slip ring surface. Thus the brushes in an AC generator do not wear as fast as in a DC generator. There is no possibility of creating an electrical short circuit between segments in an alternator because the slip rings are already continuous. An AC generator therefore requires less maintenance and is more reliable than a DC generator. Most commercial generators are AC generators.

In a DC generator the current is generated in the rotor and is then drawn from the windings through the commutator and out via the brushes. The larger the current required, the heavier the rotor coils must be, placing high demands on bearings and supporting structures. In addition, drawing large currents through the commutator-brush connection increases the likelihood of electric arcs forming as the brush breaks contact with each bar in turn. This reduces the efficiency of the generator and creates radio “noise”. This limits the usefulness of DC generators to relatively low current applications.

In an AC generator designed for high current applications, such as in a power station, the current is produced in the stator windings rather than in the rotor. The rotor is used to create the field magnetization that induces the AC current in the stator when the rotor is rotated. It is much easier to draw the current through a fixed connection in the stator rather than through a commutator from a moving rotor. Thus AC generators are better suited to high current demands than DC generators.

An advantage of a DC generator is that its output can be made smoother by the arranging many coils in a regular pattern around the armature. The brushes are arranged to make contact only with the commutator bars corresponding to the coils producing the greatest emf at a particular time. The result is an output voltage that "ripples" about a mean value rather than fluctuating between zero and the maximum twice per revolution. The more coils, the smoother the output DC voltage ripple. This is an advantage for use with equipment that needs a steady voltage rather than a sinusoidally varying voltage. This cannot be achieved with an AC generator without the addition of a rectifying and smoothing circuit.

An advantage of AC generators is that they can easily be designed to produce three-phase electricity by the use of six stator poles and a single electromagnet rotor. The coils are mounted in opposing pairs spaced evenly around the stator, and connected in pairs to the three phases of the power supply. The rotor induces alternating current in successive pole pairs. The sinusoidally varying voltages are then 120 degrees out of phase with each other. AC generators are ideal for generating electricity on a large scale for distribution over a wide area.

There is a godd article on Wikipedia that outlines some advantages of automative alternators and generators at this link .

analyse secondary information on the competition between Westinghouse and Edison to supply electricity to cities

- Your teacher may have provided you with information from secondary sources on the competition between Westinghouse and Edison. This may be in the form of reprinted articles from journals, information downloaded from Internet sites, an HSC Physics text book or other relevant information. To find further secondary information yourself, use an Internet search engine such as Google with all the words "Edison", "Westinghouse", "AC" and "DC".

- To **analyse** the information, first identify the major difference between Westinghouse and Edison in their technological approach to supplying electricity to cities. Next, describe advantages and disadvantages of each approach. Describe also other reasons why either party held firmly to their preferred method of generating electricity.

Sample analysis

In the late nineteenth century, Edison favoured generating and supplying direct current (DC) electricity while Westinghouse promoted the use of alternating current (AC) electricity.

Edison had the initial advantage that the technology for generating DC was well established and DC worked well over short distances. However, DC could only be generated and distributed at the voltages at which it was used by consumers. This meant that currents in conductors were large, leading to huge and expensive energy losses over distances of more than one or two kilometres. To supply a large city required many power stations throughout the city and an unattractive proliferation of wires to carry the required current.

The great advantage of AC was that, through the use of **transformers** the voltage could be stepped up or down as required. This meant that AC could be generated at moderately low voltages, stepped up to high voltages for transmission over great distances and stepped down again to lower voltages for consumers. The higher voltage meant that AC could be transmitted over greater distances than DC, with smaller energy losses. Power stations could be fewer and further apart and conductors could be lighter.

The economic advantages of AC, including the smaller energy losses and the economy of scale in needing fewer power stations further apart, along with the unattractive web of wires required for DC, supported Westinghouse's solution to the supply of electricity over Edison's. AC received a boost in popularity with Tesla's invention of the **induction motor** which operates only on AC.

Competition was not always open and fair. Edison had a vested interest in DC as he owned hundreds of DC power stations and all of his many electrical inventions to that time ran on DC. Edison attempted to prove that AC was very dangerous by electrocuting animals on stage and convincing authorities to use AC for the first electric chair. He resorted to legal tactics in an attempt to have AC banned and to prevent its use with his inventions. Edison seems to have unreasonably shunned AC electricity. AC eventually came to be the dominant form in which electricity is generated world-wide.

But DC has the advantage of not causing losses through electromagnetic radiation or magnetic induction. With solid-state switching it is now relatively simple to change between DC and AC at high or low voltages. High voltage DC transmission is now practicable. Scientists are striving to develop super-conducting wires for power transmission. If they do, DC could become the preferred current for long distance transmission. There is already a 500 kV DC submarine transmission line carrying 2800 MW over 50 km between the two islands of Shikoku and Kansai in Japan.

discuss the energy losses that occur as energy is fed through transmission lines from the generator to the consumer

- There are two main types of energy loss occurring in transmission lines: those resulting from the resistance of the wires, and those resulting from the induction of eddy currents

Resistive energy losses

- Heat is generated in transmission lines because of the resistance of the wires. The resistance per kilometre is small, but the resistance of a long transmission line is significant. Distances are often great, up to hundreds of kilometres, because power stations are often located in remote places, close to the primary energy source such as a major coal field or a system of dams for a hydroelectric scheme, rarely close to consumers in the city.

- The power loss in transmission lines is given by the relationship: $P = V I$ or $P = I^2 R$. Power loss is proportional to the square of the current. As the resistance of the conductor is relatively constant, power loss is affected most by the size of the current. Increasing the current by a factor of two increases the power loss by a factor of four.

- Energy losses are kept to a minimum by transmitting the electricity at the highest practicable voltage, with the lowest practicable current. Generally, the greater the distance, the higher the voltage. Closer to the consumer, voltages are lower but energy losses are not substantial since distances are shorter and the current is shared by many separate distribution lines.

- The type of electricity transmitted over long distances is predominantly AC, since AC can be changed easily to high voltages and correspondingly low currents by the use of a step-up transformer. With advances in solid state technology it is becoming easier to step DC voltages up and down, and DC is increasingly being used for long distance power transmission.

- Energy losses can also be minimised through careful choice of materials and design of conductors. Transmission lines are typically made of either copper or aluminium, as these metals have low resistivity, that is, they are good conductors. Resistance is inversely proportional to the area of cross-section of the conductor, so the thicker a conductor, the lower the heat losses. However, heavier conductors require more expensive support structures. Aluminium has higher resistivity than copper but it is much lighter than copper, and less susceptible to corrosion. The smaller weight and lower maintenance costs more than compensate for the larger diameter of aluminium needed to carry a certain current. Recent experiments with superconducting materials show some promise for reducing energy losses from high voltage transmission lines even further in the future.

- For energy losses to be minimised, the transmission voltage must be very high. This requires high poles or towers and large insulators. These are expensive to build and maintain and have an adverse effect on the visual environment. Trees must be kept well clear of high voltage transmission lines to avoid damage to the lines during storms and to reduce the possibility of a short to earth. This often requires a wide corridor to be cleared, sometimes through environmentally sensitive areas.
- A modern transmission method using high voltage DC is described in the following wikipedia article

Sample calculations of power loss

Consider an imaginary transmission of electricity from a power station generating 1000 W of power through a transmission line with a resistance of 2 Ω km^{-1}. If the electricity is transmitted at 100 V and 10 A over a distance of 1 km, then the transmission losses will be:

$$P = I^2R = (10\text{ A})^2 \times 2\ \Omega = \mathbf{200\ W}.$$

This leaves 800 W of energy for the consumers from the original 1000 W. The 200 W of power dissipated in this transmission would have been converted into heat.

If the electricity is now transmitted at 10 000V and 0.1 A over a distance of 1 km, then the transmission losses will be

$$P = I^2R = (0.1\text{ A})^2 \times 2\ \Omega = \mathbf{0.02\ W}$$

for the same initial amount of electrical energy. This would leave almost all of the power generated available for consumers.

Inductive energy losses

- Energy is also lost through the induction of eddy currents in the iron core of transformers. This applies both to step-up transformers at the power station and to step-down transformers at the sub-station and on power poles on suburban streets. The circulation of eddy currents in the transformer core generates heat because of the resistance of the iron. The heat represents an energy loss from the electrical system.

- Transformer cores are usually made of laminated iron, consisting of many thin layers of iron sandwiched together, with thin insulating layers separating them. This limits eddy currents to the thickness of one lamina and reduces the corresponding heat loss. Eddy currents may be further limited in transformer cores made of granular ferrites, as used in some recent experiments. The ferrites allow the magnetic flux to change freely but have high resistance to the eddy currents.

- Heat loss inevitably occurs in the core of a transformer. As overheating can damage the transformer, various cooling techniques are used to dissipate the heat. These include cooling fins on the outside of the transformer, radiator pipes to allow cooling oil to circulate by convection and transfer heat to the air, and electric fans to force cooling air to flow around the transformer.

- The induction of eddy currents in metal parts of transmission towers is kept to a minimum by the distance at which the wires are held away from the tower by the insulators.

gather and analyse information to identify how transmission lines are:

  - **insulated from supporting structures**
  - **protected from lightning strikes**

- **Gather the information** by inspecting the transmission lines through a pair of binoculars from a safe distance. Take note of how the conductors are supported off the ground and prevented from touching the support structures. Photograph or draw sketches of the structures you see for later study. Inspect both low tension transmission lines (11 or 22 kV) carried on wooden poles in a suburban street and high tension transmission lines (110 or 220 kV) carried across the country on tall steel towers. Take care to look for any structures capable of carrying a large electric current to the ground.

- **Analyse the information** by making a simple model of a transmission tower or pole to illustrate and explain the insulation and protection strategies you observe. Compare the structures used for low tension and high tension transmission.

Sample information

High voltage transmission lines are kept away from their supporting structures by chain insulators to reduce the likelihood of a discharge between the conductor and the support structure. Insulator chains can be up to around 2 m in length: generally, the higher the voltage, the longer the chain.

Insulators are constructed either of ceramic segments joined together with metal links or of rubber discs with a fibre glass core. Their design reduces the possibility of charge leaking through the insulators themselves. The metal links in ceramic insulators are isolated from each other, and the fibreglass is a non-conductor, so there is no continuity of conduction. The insulator segments are designed to shed water and prevent dust from building up, as either moisture or dust can make a conductive path across the surface of the insulator. The disc-like shape of the segments, whether ceramic or rubber, ensures a long pathway for any spark discharge across the insulator.

Transmission lines and supporting structures have a number of protective features associated with their design. In the event of a transmission tower being struck by lightning, the metal tower itself acts as a conductor to take the charge to the ground. The towers are well earthed, with a large surface area of metal buried in the ground, enabling the charge from any lightning strike to dissipate harmlessly in the earth. Towers are widely spaced to ensure that, should one tower be struck, the adjacent towers suffer no damage from the lightning strike.

Not all the wires on a transmission tower carry the electric current. The uppermost wires are called shield conductors, as they are designed to reduce the chance of a lightning strike to the transmission wires. Shield conductors are connected directly to the transmission towers without the use of insulators so that they can conduct charge between the clouds and the earth as it builds up, to neutralise the charge distribution. If the shield conductors are struck directly by lightning the current is conducted safely to earth.

assess the effects of the development of AC generators on society and the environment

- The development of AC generators has led to the widespread application of some of the useful features of AC electricity. AC generators are simpler and cheaper to build and operate than DC generators. Because AC electricity can easily be transformed, it can be transmitted cheaply over great distances, allowing a wide range of primary energy sources to be exploited. This has allowed the development of extensive, reliable AC electricity networks for domestic and industrial use throughout much of the world. This in turn has had both positive and negative effects on society and the environment.

- The affordability of electricity has promoted the development of a wide range of machines, processes and appliances that depends on electricity. Many tasks that were once performed by hand are now accomplished with a purpose-built electrical appliance and most domestic and industrial work requires less labour. Other new tasks can now be achieved that were formerly impossible, such as electronic communication. However, this has led to a reduction in the demand for unskilled labour and an increase in long-term unemployment. The ready availability of electricity has led to increasing dependency on electricity. Essential services such as hospitals are forced to have a back-up electricity supply, "just in case". Any disruption to supply compromises safety and causes widespread inconvenience and loss of production. A major electricity failure can precipitate an economic crisis. The global electricity industry lobby is very powerful but is not always just. Social values may give way to economic pressures, especially in developing countries where often the poorest people lose their livelihood to make way for new energy developments.

- AC power generating plants can be located well away from urban areas, shifting pollution away from homes and workplaces, thus improving the environment of cities. However, many environmental effects of the growth in the electricity industry are negative. Power transmission lines criss-cross the country with a marked visual impact on the environment, often cutting a swathe through environmentally sensitive areas. Remote wilderness areas can easily be tapped for energy resources such as their hydro-electric potential. Air pollution from thermal power stations burning fossil fuels may be a cause of acid rain. In addition it contributes to the global increase of atmospheric carbon dioxide which is linked to long-term global climate change. Nuclear power stations leave an environmental legacy of radioactive waste that will last many thousands of years.

- The effects of the development of AC generators on society and the environment have been far-reaching. Some effects have changed the way people live, but not always for the better. Many people now enjoy increased convenience and leisure, many new industries flourish on new technologies made possible by electricity, but the dislocation and unemployment experienced by some can be devastating. Many aspects of the development of electricity have led to environmental degradation, often in remote areas where the long-term effects are poorly understood. These effects seem likely to be ongoing, as the compromise between economic interests and social and environmental values often favours the economic. We have not yet learned to live with AC electricity in a sustainable way.

9.3 Motors and generators: 4. Transformers

perform an investigation to model the structure of a transformer to demonstrate how secondary voltage is produced

- When **performing** investigations, it is important that you identify and use safe work practices. Use only low voltage AC, as available from an ordinary laboratory power supply. **This activity must not be attempted using 240 V AC mains supply.** Switch the current on for the shortest time that allows you to make observations and record measurements. If the wiring becomes hot, place a suitable resistive load in series with each coil to limit the current and avoid the risk of burning yourself and damaging the equipment. Your teacher may provide you with an investigation plan, or you could follow one of the procedures below.

- This investigation involves the **modelling** of a transformer. You will need to construct a circuit that displays the main features of a transformer, including the physical arrangement of coils and core, the inductive coupling between the coils and the electrical properties of both a step-up and a step-down transformer. You may need to construct several models with different ratios of turns between the primary and secondary coils and with different physical arrangements of the coils.

- When **demonstrating** how the secondary voltage is produced, you will need to show the conditions under which a secondary voltage is best produced and the relationships between the secondary voltage and the primary voltage.

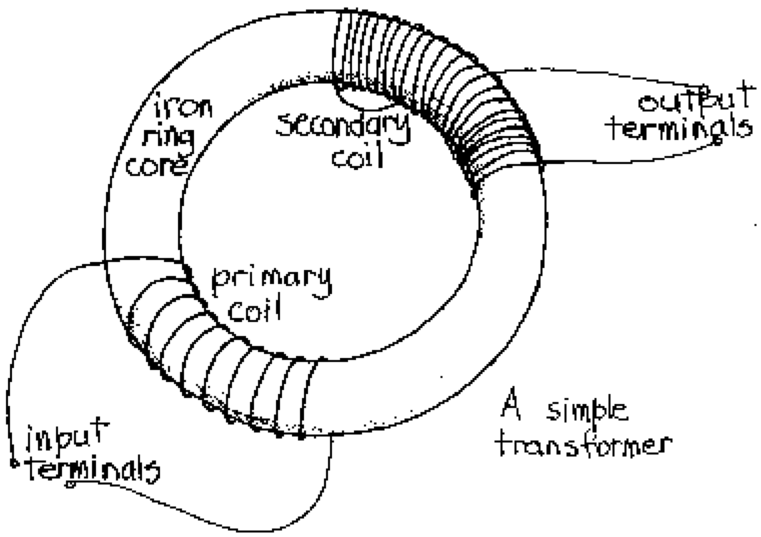
Sample investigation

Look at a dismantled transformer that has been removed from the circuit of a household appliance to familiarise yourself with the essential parts of a transformer. A transformer usually consists of two coils of wire wound on the same iron core. Identify the primary coil, the secondary coil and the laminated iron core that inductively couples the two coils. The primary coil is the input coil connected to the electricity supply. The secondary coil is the output coil connected to the device using the electricity at a voltage other than the supply. It is often possible to identify the parts without destroying the transformer.

Safety Note!

Under no circumstances should a transformer be connected to the power when it is being removed, dismantled or examined, nor should a transformer be reassembled and used again after examination. If you open it up to take a look at it, throw it away.

Make your own ***simple model transformer*** by winding two separate coils of insulated wire onto an iron ring and connecting them into separate complete circuits. Have a significantly different number of turns in each coil.



Connect one coil to the power supply as the primary coil and input a low AC voltage into it. Check with a multimeter whether a voltage is induced in the second coil with the power supply switched on and with it switched off. Compare the output voltage from the secondary coil with the input voltage to the primary coil for several settings of the power supply voltage. Calculate the ratio of the output voltage to the input voltage and compare this with the ratio of the number of turns in each coil.

Reverse the connections to the two coils, so that the secondary coil becomes the primary coil, and repeat the above investigation. Determine which arrangement models a step-up transformer, with secondary voltage higher than primary voltage, and which a step-down transformer.

If you have access to a multi-channel datalogger or a dual-trace oscilloscope, you may be able to simultaneously record or observe the voltage and frequency of both the primary and secondary currents, and also any phase difference between them. Be careful to set the datalogger to a sampling frequency much higher than the input frequency, say 1000 Hz, or the CRO to a much shorter time base, say 1 ms, to avoid the problem of frequency aliasing which can give false readings of frequency.

Use your observations to determine what must happen for a voltage to be detectable in the secondary coil of a transformer. Determine also the relationship between the secondary voltage and the primary voltage in terms of the number of turns in each coil. Comment also on the relationship between the frequency and phase of the primary and secondary voltages.

An alternative method of performing this investigation involves making your model transformer by using a dissectible transformer kit available in many school science laboratories. Such a kit allows you to assemble various configurations of laminated iron core with a limited variety of ready-made coils that fit over the iron core. The number of turns is printed on the outside of each coil, and external terminals allow the coils to be connected into a circuit with a power supply, ammeter, voltmeter, etc. Try various combinations of coils with different core arrangements.

describe the purpose and principles of transformers in electrical circuits

- The domestic supply voltage in Australia is 240 V single-phase AC. Industrial and commercial supply is usually 415 V three-phase AC. Many appliances, such as motors and lights, are designed to operate directly on these voltages.

- However, many domestic and industrial appliances contain components that require voltages well below the supply voltage, such as display panels, printed circuit boards or semi-conductor devices, which typically require between 3 V and 24 V. In addition, some imported appliances run on voltages common in the country of manufacture, such as 110 V in North America. Transformers are placed in the circuit between the AC supply and the component to reduce the supply voltage to that required for the component. Such a transformer is known as a step-down transformer.

- Some components, such as television picture tubes, require voltages well above the supply, around 1500 V. A step-up transformer is placed in the circuit between the AC supply and the component to raise the voltage to that required for the component.

- It is common for the step-up or step-down transformer to be built into the appliance as part of its power supply. Many appliances contain both a step-up and a step-down transformer to supply voltages required by different components. Many step-down transformers are multi-tapped transformers capable of supplying a range of different secondary voltages from the same primary input voltage.

compare *step-up and step-down transformers*

- The following table compares step-up and step-down transformers.

Step-up transformer	Step-down transformer
Consists of two inductively coupled coils wound on a laminated iron core	Consists of two inductively coupled coils wound on a laminated iron core
More turns in the secondary coil than the primary coil	Fewer turns in the secondary coil than the primary coil
Higher output voltage than input voltage	Lower output voltage than input voltage
Lower output current than input current	Higher output current than input current
Used at power stations to increase voltage and reduce current for long-distance transmission	Used at substations and in towns to reduce transmission line voltage for domestic and industrial use
Used in cathode ray television sets to increase voltage to operate the picture tube	Used in computers, radios, and CD players to reduce household electricity to very low voltages for electronic components

identify **the relationship between the ratio of** *the number of turns in the primary and secondary coils and the ratio of primary to secondary voltage*

- The ratio of primary to secondary voltage in a transformer is the same as the ratio of the number of turns in the primary and secondary coils. In a step-up transformer there are more turns in the secondary coil than in the primary coil and the secondary voltage is higher than the primary voltage by the same factor. The reverse is true for a step-down transformer.

- This relationship is expressed mathematically as: $\frac{V_p}{V_s} = \frac{n_p}{n_s}$ where V_p is the voltage in the primary coil, V_s is the voltage in the secondary coil, n_p is the number of turns in the primary coil and n_s is the number of turns in the secondary coil.

explain *why voltage transformations are related to conservation of energy*

- The Law of conservation of energy states that energy cannot be created nor destroyed, but can be transformed from one form into another. All physical systems obey this law. The amount of electrical energy entering a transformer in a certain time must equal the total amount of energy in all forms leaving the transformer in the same period of time. That is, power in equals power out.

- In an "ideal" transformer, all of the magnetic flux produced in the primary coil threads the secondary coil. Thus the rate of change of magnetic flux induced by the primary voltage is equal to the rate of change of magnetic flux inducing an emf in the secondary coil. The relationship between voltage, number of turns and rate of change of flux in the primary coil is given by **Faraday's Law**
$$e = N\frac{DF}{Dt}$$

- The same equation links the number of turns, the rate of change of flux and the induced voltage in the secondary coil. Combining equations for both coils, and allowing for equal rates of change of flux, gives us the so-called "transformer equation" $\frac{V_p}{V_s} = \frac{n_p}{n_s}$

- Thus the voltage transformation that occurs in a transformer is a consequence of the Law of conservation of energy.

  Another consequence of the Law of conservation of energy in an "ideal" transformer is that the power in the secondary coil P_s is equal to the power in the primary coil P_p.

  Now P = V I, so that: $P_p = V_p I_p = V_s I_s = P_s$, or $\frac{I_s}{I_p} = \frac{V_p}{V_s}$

- This means that the ratio of secondary current to primary current is the inverse of the ratio of secondary voltage to primary voltage. The secondary current is less than the primary current in a step-up transformer, and greater in a step-down transformer.

- Real transformers produce heat because of the resistance of the iron core to induced eddy currents. This represents an energy loss to the system as heat is a form of energy. The power output of a transformer cannot exceed the power input, and the useful electrical power output is less than the input by the amount of the power loss through heating within the transformer.

solve problems and analyse information about transformers using: $\frac{V_p}{V_s} = \frac{n_p}{n_s}$

- In **solving problems** about transformers using this equation, you may need to select different strategies, depending on the amount of given data. If only one variable is unknown, you may choose to rearrange the equation as necessary and substitute for known variables. However, solutions may not be unique if two variables are unknown, because this equation deals with ratios rather than actual numbers of turns or voltages. For example, in a problem to design a transformer for a specific task, you may know the input voltage and the required output voltage but you may not know the number of turns in either coil. Other design features may need to be considered, and other strategies used to solve the design problem.

- You can **analyse information** about transformers by using this equation as a mathematical model to make predictions, for instance, about the voltage characteristics of a transformer if you know the number of turns in each coil. You can also analyse the effect on the output voltage of changing the number of turns in the secondary coil while keeping the primary coil the same.

Sample problem

A transformer has 528 turns in the primary coil and 242 turns in the secondary.

1. Explain whether this is a step-up or step-down transformer.
2. If the input voltage is 240 V AC, describe the output voltage.

Solution:

1. The secondary coil has fewer turns than the primary coil so, by the transformer equation, the output voltage is lower than the input voltage. Therefore this is a step-down transformer.

$$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

2. Rearrange the transformer equation to find V_s:
   $V_s = V_p \times n_s / N_p = 240 \times 242 / 528 = 110$ V AC

Sample analysis

A multi-tapped transformer has a number of different connections to the secondary coil, so that different numbers of turns of the secondary coil can be connected into the external secondary circuit. Turns not connected are left open and do not contribute to the transformer output. If the voltage and power input to the transformer remain fixed, explain how the output voltage and current vary with the different secondary connections or "tappings".

Analysis:

As more and more turns of the secondary coil are connected into the circuit, the output voltage increases, since the ratio of secondary to primary turns increases. If the power input is fixed, so is the power output. Thus, as the number of connected secondary turns increases, and the voltage increases, the output current must decrease, since power is the product of voltage and current.

gather, **analyse** and **use available evidence** to **discuss** *how difficulties of heating caused by eddy currents in transformers may be overcome*

- **Gather information** from a range of sources including text books, popular scientific journals and the Internet. Refine your searching technique by looking for articles that specifically mention heating and cooling in transformers.

- **Analyse** the information by looking for cause-effect relationships, such as the cause of the heating and the undesirable effects of the heating. Look also for information on mechanisms used for cooling and how these work to overcome the difficulties of heating.

- **Use available evidence** to organise your information into a logical progression of ideas. Begin your discussion by identifying the source of the heating and the difficulties this causes. Identify at least two mechanisms by which either the cause of the heating can be reduced or the effects of the heating can be dissipated, and describe how each of these helps to overcome the difficulties of heating.

Sample discussion

A transformer has an iron core to concentrate the magnetic field to achieve the maximum possible inductive coupling between the primary and secondary coils. As the changing flux intersects the core, eddy currents are induced in the iron. Heating occurs because of the rather high resistance of the iron to the eddy currents. This heat represents a power loss to the electrical system and excessive heating can damage or destroy the transformer.

One of the best ways to overcome difficulties of heating in transformers is to reduce the size of the eddy currents. Transformer cores are made of laminated iron, that is, many thin sheets of iron pressed together but separated by thin insulating layers. This limits the circulation of any eddy currents to the thickness of one lamina, rather than the whole core, thus reducing the overall heating effect.

Once the transformer does get hot it must be cooled to prevent overheating. Several strategies have been developed to keep transformers cool:

- Heat-sink fins are added to the metal transformer case so that heat dissipation to the environment can occur more quickly over a larger surface area.
- The transformer case may be made of a black material so that the heat produced internally is efficiently radiated to the environment. Most small transformer rectifier units found around the home are coloured black.

- Pad-mounted transformers at ground level have ventilated cases to allow air to remove heat by convection. They may also have an internal fan to assist air circulation to remove excess heat faster.
- The transformer case may be filled with a non-conducting oil that transports the heat produced in the core to the outside where the heat can be dissipated to the environment. The oil may circulate from hotter to cooler regions by convection alone, or circulation may be assisted by a pump. The case may have design features such as cooling tubes and radiator slats to increase the rate of heat dissipation.
- Large transformers such as at substations are always located in the open or in well-ventilated areas to maximise airflow around them for cooling. These are fitted with a combination of cooling mechanisms including pumps to circulate cooling oil through large radiators, and fans to increase the airflow over the radiators. The fans are often thermostatically controlled and cut in at a specified temperature, usually around 50°C.

gather and **analyse secondary information** to **discuss** *the need for transformers in the transfer of electrical energy from a power station to its point of use*

- **Gather** secondary information about why transformers are necessary from a range of sources. Your local power supply authority may have free information pamphlets to read or an information officer you could interview. Most power supply authorities also have informative Internet sites that you could explore. Try to find out also what electricity transmission was like before AC transformers were invented.

- **Analyse** the information to identify the connectedness of concepts such as power, voltage, current and transmission line losses.

- In **discussing** the need for transformers, **draw evidence from your analysis** to identify the transmission issues that make transformers necessary and describe the ways in which transformers solve these problems.

Sample discussion

Electricity is typically consumed in homes and industry at 240 V or 415 V. If there were no transformers, electricity would have to be generated and distributed at these same voltages. To supply the power demands of even a small town, the current at these voltages would be very large, leading to large and costly transmission losses and possible overheating of conductors. If the power demand were to increase, the number of conductors would need to multiply, to keep the current per conductor within reasonable limits.

For a large city there would need to be many power stations spaced every few kilometres. If different voltages were needed, these would require separate power stations and separate distribution systems, adding to the network of cabling required. The result would be an expensive, unsightly, unreliable web of cables serving consumers only within a limited distance from each power station.

The use of transformers with AC electricity overcomes many of these problems.

It is more efficient to generate electricity at high voltages, such as 23 kV, than at low voltages. Power stations can run efficiently at their design voltage and different transformers can be used to simply step the voltage up for transmission or down for local use as required.

It is much more efficient to use very high voltages, up to 500 kV, for transmission lines, because at these voltages the currents are relatively small and transmission line losses are less of a problem. The higher the voltage, the smaller the line losses, and the greater the distance of transmission, the more important this saving is. Because the current is smaller at high voltages, fewer, smaller conductors are necessary for any particular power load than at lower voltages. High voltages are easily achieved for economical transmission by the use of step-up transformers.

Electrical energy is usually consumed at low voltages, but at widely scattered locations. Transformers are used to progressively step the voltage down from the transmission lines to the consumer. Major transmission lines in the national grid typically carry 330 kV. At regional sub-stations, step-down transformers reduce this to 110 kV for regional distribution. Local sub-station transformers step this down further to 33 kV or 11 kV for distribution along suburban streets. Pole-mounted transformers step this down again for supply to houses and factories at 415/240 V. The stepped-down voltage used at each stage of distribution is chosen to balance the power, and hence the current, requirements, and therefore also the transmission losses, against the area over which distribution is required.

explain the role of transformers in electricity sub-stations

- Electricity from power stations is transmitted through the national grid at very high voltages (up to 500 kV in Australia). The high voltages are necessary to minimise energy loss due to resistance in the conducting transmission wires as the energy is carried over great distances.

- Transmission lines operate at voltages very much higher than those required to operate most industrial and domestic equipment and appliances. These operate at low voltages, typically 240 V single phase or 415 V over three phases, so that design is simpler, the cost of insulation is affordable and operation is safer.

- The role of transformers in electricity sub-stations is to progressively reduce the voltage as it comes closer to the consumer. At each stage, the output voltage is chosen to match the power demand and the distances over which supply is needed.

Example

From the power station to the consumer electricity might be transformed in the following ways: generated in the power station at 23000 V; stepped up at the adjacent sub-station to 330 000 V; transmitted to a Transgrid® substation where it is transformed to 132 000 V; distributed to regional electricity supplier substations and transformed to 33 000 V; further transmitted to a city substation where it is transformed again to 11 000 V; transmitted to local pad or pole mounted transformers and stepped down to 415 V for distribution to consumers.

A typical Transgrid® substation transformer might be rated 330-132 kV and 30 MVA, meaning the primary or input voltage is 330 kV, the secondary or output voltage is 132 kV and the transformer has a power rating of 30 MVA or a capacity to transform 30 MW of electrical power.

discuss why some electrical appliances in the home that are connected to the mains domestic power supply use a transformer

- Electricity supplied to homes is typically 240 V AC. Many domestic appliances are designed to run most efficiently at this voltage. Such appliances are connected directly to the mains supply without the need for a transformer.

- Some appliances contain components that require a transformer because they operate best at lower voltages than the mains supply. In a microwave oven, for example, large, energy consuming parts such as the turntable motor and the microwave transducer may be connected directly to the mains, while the control and display panel is supplied with low voltages from a step-down transformer in a built-in power supply unit.

- Many small portable appliances, such as personal CD players and mobile telephones, have been designed to run on batteries. These require low DC voltages, either as an alternative to batteries or to recharge the batteries. When the whole appliance is designed to run at the same low voltage, a step-down transformer-rectifier may be built into the plug of the power supply lead that connects to the mains supply. Alternatively, a normal power lead connects the mains to a built-in power supply unit that contains a step-down transformer and a rectifier.

- Appliances such as television receivers and computer monitors contain cathode ray tubes that require voltages well above the mains supply, up to around 25 kV, to accelerate electrons toward the screen. These use a built-in step-up transformer to provide the necessary voltage. The power supply unit may contain both a step-up and a step-down transformer.

discuss the impact of the development of transformers on society

- The development of transformers made it possible to transmit electrical energy efficiently over great distances. This has had a range of impacts on society.

- Even very remote communities now have access to grid-supplied high-voltage electricity which is stepped down locally by transformers. This has raised living standards in rural communities through provision of, for instance, electric lighting, refrigeration and air conditioning, and increased the scope of rural industries.

- Large cities have been allowed to spread, because electricity is readily available as an energy source, thanks to transformers. This has led to social dislocation in urban "deserts", as people have moved further from family and friends and workplaces.

- Industry is no longer clustered around power stations or other sources of energy. Power stations can be in remote locations and high-voltage electrical energy can be distributed almost anywhere, to be stepped down near the point of use. This has allowed industries to be decentralised and has facilitated the development of industrial areas away from residential areas. This has relocated pollution away from homes, but it means that many people now spend significant time travelling between home and work.

- With the development of the transformer, people have changed the way they live, as electricity to every home has become an affordable necessity rather than a luxury.

9.3 Motors and generators: 5. AC motors

perform an investigation to demonstrate the principle of an AC induction motor

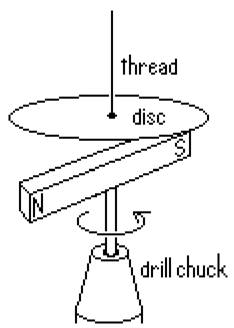
- You should **perform an investigation** to demonstrate the principle of an AC induction motor by carrying out a planned procedure. Your teacher may plan an investigation for you or you may choose one similar to the following procedure. As you follow the procedure, try to recognise where and when modifications to the materials and structures are needed. Carefully record these adjustments and their effects, and analyse these by looking for a relationship between cause and effect.

Sample procedure

One of the simplest and safest ways to demonstrate the principle of an AC induction motor is to show how an aluminium disc that is free to rotate will rotate when a permanent magnet is rotated close to it.

Cut the bottom of an aluminium drink can so that you end up with a round disc. Attach a long fine thread to the centre of the disc so that the disc is balanced and can hang horizontally. Attach the free end of the thread to a high support, such as the edge of a table, so that the disc is hanging freely.

Attach a bar magnet firmly to the end of a pencil so that it forms a "T" with the pencil. Mount the pencil vertically in the chuck of a hand drill so that the magnet is close beneath the suspended aluminium disc. Rotate the hand drill to make the magnet spin in one direction.



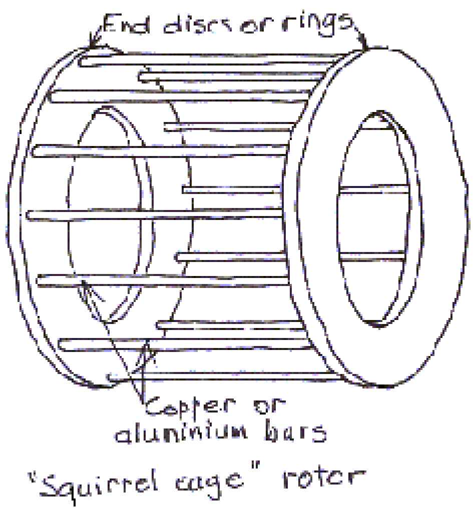
Replace the permanent magnet with an unmagnetised piece of iron or other non-magnetic material. Alternatively, replace the aluminium disc with discs of other metallic and non-metallic materials. Rotate the apparatus at different speeds and in each direction. Systematically observe and record the effects of any changes you make to the variables in the procedure.

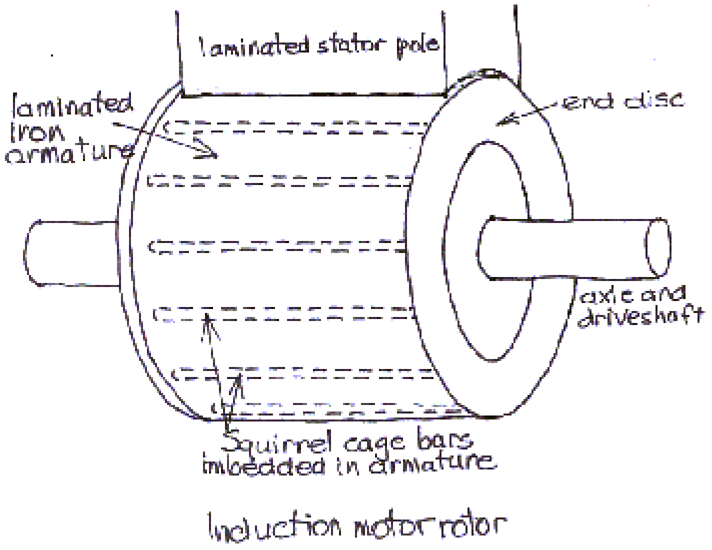
Explanation of the model

In this model the rotating magnetic field of the bar magnet induces a current in the aluminium disc that produces a magnetic field opposing that of the bar magnet. The interaction between the two magnetic fields causes the aluminium disc to spin, chasing the rotating permanent magnet.

describe ***the main features of an AC electric motor***

- There are two main types of electric motors that run on AC: universal motors and induction motors. Universal motors can run on either AC or DC and are essentially similar in construction to a **DC motor**
- An induction motor consists of a stator and a rotor. The stator consists of a series of wire coils wound on soft iron cores that surround the rotor. These are connected to the external power supply in such a way that they produce a magnetic field whose polarity rotates at constant speed in one direction. This is achieved in a three-phase induction motor by connecting consecutive coils in opposing pairs to the three phases of the power supply. Many single-phase induction motors use capacitors to simulate the three-phase effect.
- The rotor consists of coils wound on a laminated iron armature mounted on an axle. The rotor coils are not connected to the external power supply, and an induction motor has neither commutator nor brushes. An induction motor is so named because eddy currents are induced in the rotor coils by the rotating magnetic field of the stator. The eddy currents produce magnetic fields which interact with the rotating field of the stator to exert a torque on the rotor in the direction of rotation of the stator field.
- The rotor coils are often simplified to single copper bars capable of carrying a large current, imbedded in the surface of the armature. The bars are connected at the ends by a ring or disc of copper which allows current to flow in a loop between opposite bars. This physical arrangement is referred to as a squirrel cage because it resembles an exercise wheel for small mammals.





- An induction motor has a fixed maximum speed. The magnetic field of the stator rotates at the frequency of the AC supply. In Australia, induction motors spin at about 3000 revolutions per minute (50 Hz x 60 seconds) without a load, but the speed of the rotor slips behind that of the field as a load is applied.

gather, process and analyse information to identify some of the energy transfers and transformations involving the conversion of electrical energy into more useful forms in the home and industry

Note

An **energy transfer** occurs when energy in one form moves from one object or location to another object or location as the same form of energy, for example, heat transferred by conduction from the electric heating element to the water in a domestic hot water system.

An **energy transformation** occurs when energy is changed from one form to another form within an appliance, for example, electrical energy changed into useful rotational kinetic energy in a food processor. Many energy transformations are not useful, as various forms of energy are converted into waste heat.

- **Gather** information in written and spoken form and by direct observation. Conduct an audit of the uses made of electrical energy in your home. Visit any local industry or ask people who work in local industry what uses are made of electricity in their work place. Browse catalogues from electrical retail stores. **Identify** at least two examples of energy transfers and/or transformations in the home and at least two in an industry.

- **Process** the information by ensuring that the information you collect relates directly to transfers of electrical energy within an appliance or transformations of electrical energy into some more useful energy within the appliances. Compile a list of the types of energy transfers and energy transformations that you have identified in the sites visited.

- **Analyse** that information by identifying groups of appliances in which the same type of energy transfer or transformation occurs. You could use a computer database to organise and sort the information.

Sample information

Electrical energy is **transferred** from the primary coil to the secondary coil in a transformer. This type of energy transfer occurs in plug-in voltage adaptors for many small home appliances, such as CD players and mobile phone rechargers, as well as industrial applications such as welders. Electrical energy is transferred by induction from the stator to the rotor in an induction motor, both in the home and in industry.

Electrical energy is transformed into a range of other useful types of energy both in the home and in industry:

In the home	In industry
Electrical energy is transformed into radiant energy as: ○ light in light globes ○ heat in toaster and kettle ○ microwaves in microwave oven ○ radio waves in cordless phone	Electrical energy is transformed into radiant energy as: ○ X-rays in medical imaging ○ light in laser circuit printing ○ heat in induction ovens ○ microwaves in wood curing ○ radio waves in communication
Electrical energy is transformed into mechanical energy as: ○ rotation in food blender motor ○ vibration in television speaker	Electrical energy is transformed into mechanical energy as: ○ rotation in industrial motors ○ vibration in television speaker ○ kinetic energy and gravitational potential energy in fun park rides
Electrical energy is transformed into chemical energy in recharging rechargeable batteries	Electrical energy is transformed into chemical energy in the electroplating process

Sample analysis

Electrical energy is transformed into heat energy, both in the home and in industry, when large electric currents flow through metals with high resistance. In electric kettles and toasters, current from the mains causes heating in a high-resistance element. In an induction oven, changing magnetic fields cause eddy currents to flow in the metal parts which become hot because of their electrical resistance.