

# MOTORS & GENERATORS

## *What is this topic about?*

To keep it as simple as possible, (K.I.S.S.) this topic involves the study of:

### 1. ELECTROMAGNETIC FORCES & MOTORS

### 2. GENERATORS & POWER PRODUCTION

### 3. TRANSFORMERS & THEIR USES

### 4. MORE ON MOTORS

...all in the context of society's use of electricity

## *but first, an introduction...*

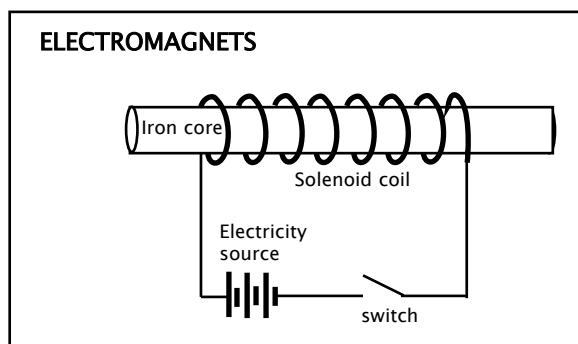
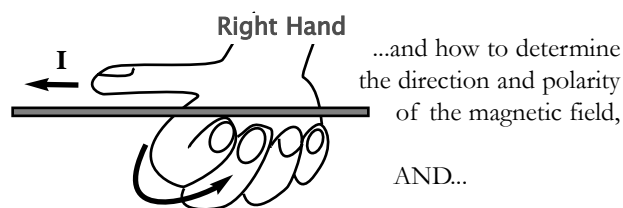
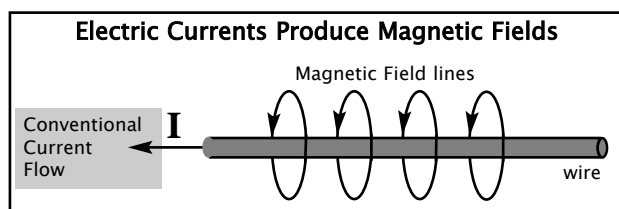
### What Has Gone Before...

In the Preliminary Course you studied a topic about electricity, including:

**Electric Charges & Fields,  
Current, Voltage & Ohm's Law,  
Electric Circuits, Power & Energy,  
Magnetic Effects of Electricity.**

**It would be very wise  
To revise**

In particular, it will be very useful to remind yourself about:



### What Happens Next...

In this topic you will learn how and why Electric Motors work.

People often don't realize how much we depend on the humble electric motor.



You will learn about how we generate the electricity society needs,



Photo: Griszka

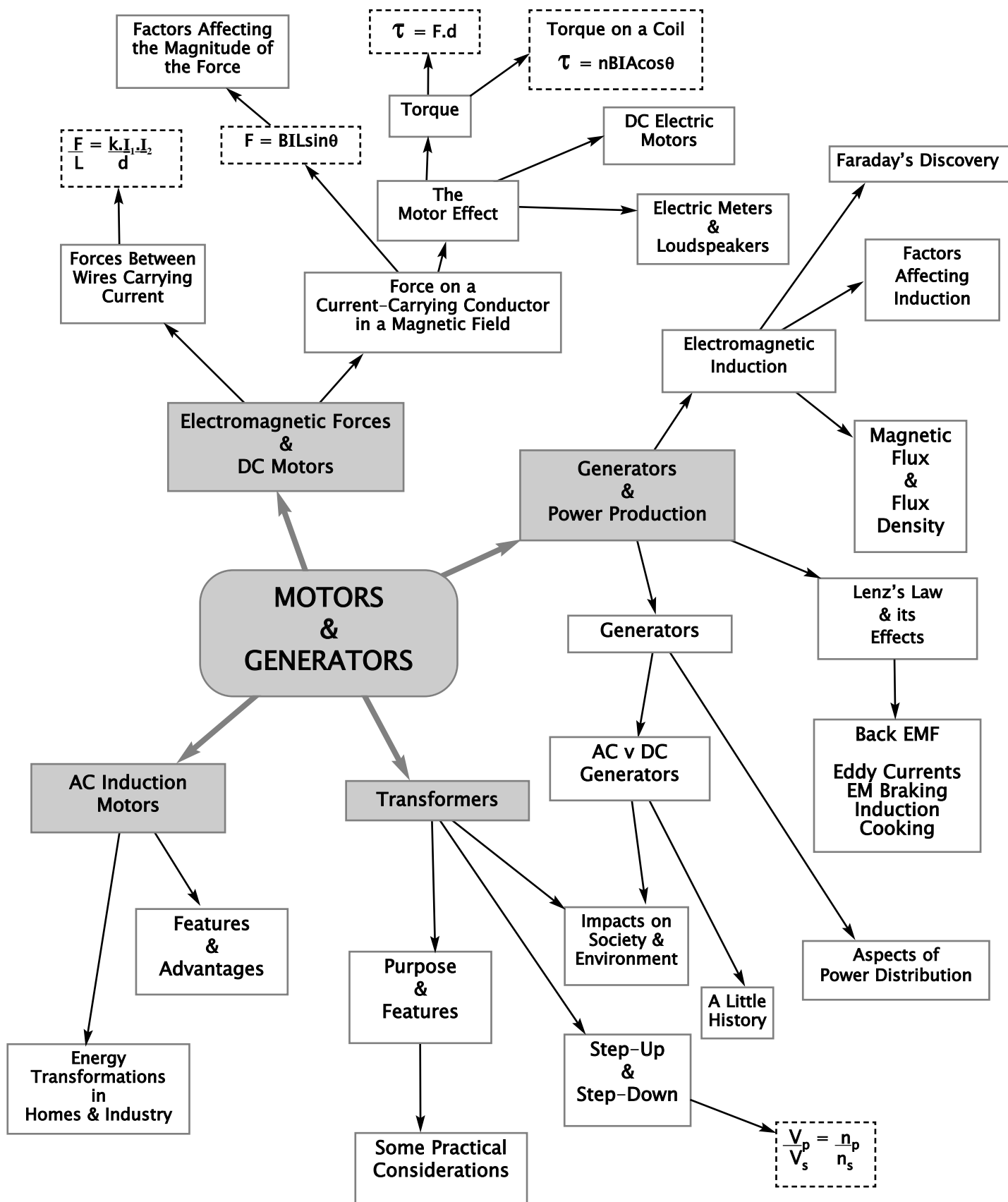


Photo: Andy King

...and how it is distributed and transformed to meet our needs.

## CONCEPT DIAGRAM ("Mind Map") OF TOPIC

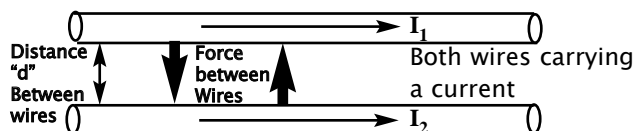
Some students find that memorizing the OUTLINE of a topic helps them learn and remember the concepts and important facts. As you proceed through the topic, come back to this page regularly to see how each bit fits the whole. At the end of the notes you will find a blank version of this "Mind Map" to practise on.



# 1. ELECTROMAGNETIC FORCES & MOTORS

## The Force Between Two Conductors Carrying a Current

It was discovered in 1820 that a wire carrying an electric current produces a magnetic field. Almost immediately, Andre-Marie Ampere investigated the way that TWO wires, both carrying current, would exert a force on each other.

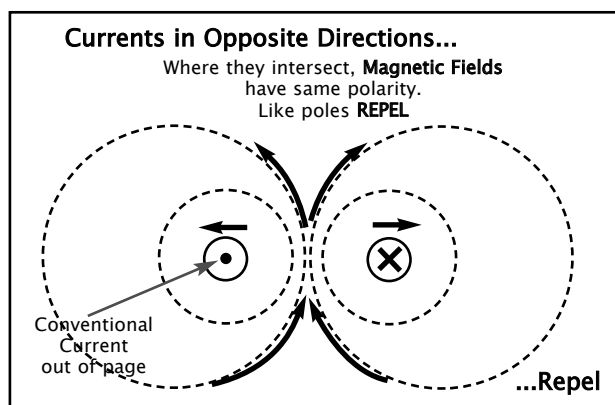
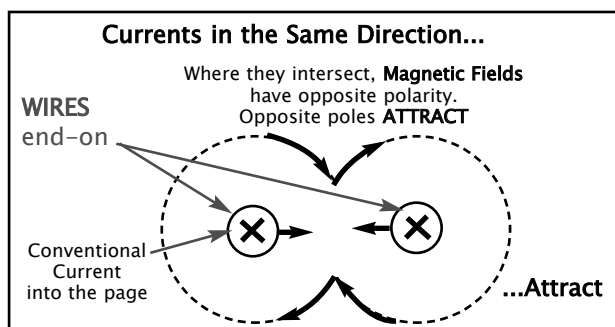


If the wires carry current in the SAME direction, the force ATTRACTS the wires.

If the currents flow in OPPOSITE directions, the force REPELS the wires.

The explanation for the forces is quite simple...

If you look at the wires end-on, and use the “Right-Hand Grip Rule” to visualize their magnetic fields:



Ampere found that the size of the force depends upon a number of factors:

- the amount of current in the wires
- the distance between the wires (separation)
- the length over which the wires run parallel

For his contribution, we name the unit of current after Ampere.

Mathematically,

$$\frac{F}{L} = \frac{k \cdot I_1 \cdot I_2}{d}$$

F = Force in newtons (N) ) F/L refers to the “force  
L = Length in metres (m) ) per unit of length”

k = the “magnetic force constant” =  $2.00 \times 10^{-7}$

$I_1$  &  $I_2$  = the currents in the wires, in amps (A)  
d = the separation distance, in metres (m)

### Example Problem:

Two long, straight, parallel wires are carrying 5.60A and 12.3A in the same direction. The wires are 2.50cm apart.

- Calculate the force per metre between them.
- If the parallel section of the wires runs for 4.75m, find the total force acting in this section.

### Solution:

$$\begin{aligned} \text{a) } \frac{F}{L} &= \frac{k \cdot I_1 \cdot I_2}{d} = 2.00 \times 10^{-7} \times 5.60 \times 12.3 / 0.025 \\ &= 5.51 \times 10^{-4} \text{ N/m, attraction.} \end{aligned}$$

i.e. Each 1 metre of parallel wires has a force of 0.000551N acting between the wires.

Note that the force is attracting the wires because the currents are in the same direction. If the currents flowed in the opposite directions, the same force would be repelling the wires.

$$\text{b) } \frac{F}{L} = 5.51 \times 10^{-4} \text{ newtons per metre}$$

$$\begin{aligned} \text{So, } F &= 5.51 \times 10^{-4} \times 4.75 \\ &= 2.62 \times 10^{-3} \text{ N attraction.} \end{aligned}$$

**TRY THE WORKSHEET at the end of the section**

You'll notice that the force is very small in the example given. In fact, this type of force is very weak and in general electrical wiring is totally insignificant.

However, the point is that it shows that electrical currents create magnetic fields and forces, and that electrical currents can interact with magnetic fields and with other currents.

This is the basis of ELECTRIC MOTORS, GENERATORS and TRANSFORMERS... read on.

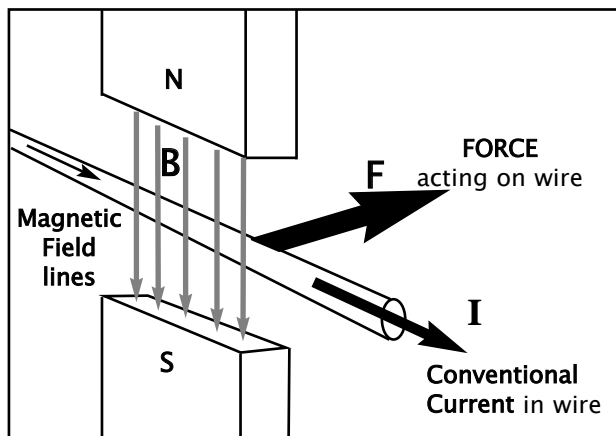
In fact, the technical definition of the “ampere unit” is based upon measurement of the force between 2 parallel wires carrying current.

You are not required to know the gruesome details.

## The Motor Effect

Although the force between 2 wires each carrying a current is rather weak, the effect can be much more powerful if more than one wire is involved, and if the magnetic fields involved are a lot stronger.

If, for example, a wire is carrying a current through a reasonably powerful magnetic field, the wire will experience a significant, noticeable force. This is called “The Motor Effect”.

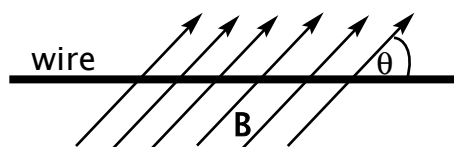


### Factors Affecting the Magnitude of the Force

- The Strength of the Magnetic Field ( $B$ )
- The Current ( $I$ ) carried in the wire
- The Length ( $L$ ) of wire within the magnetic field
- The Sine ratio of the angle ( $\sin\theta$ ) between the wire and the magnetic field lines

$$F = B.I.L.\sin\theta$$

$F$  = Force, in newtons (N)  
 $B$  = Magnetic Field strength, in tesla (T)  
 $I$  = Current, in amps (A)  
 $L$  = Length of wire within the field, in metres (m)  
 $\theta$  = Angle between wire and field. See below



### Measurement of Magnetic Field:

The “strength” of a magnetic field can be thought of as the “density” of the magnetic force lines passing through an area of space. The symbol used is “ $B$ ”. The unit of measurement is the “tesla” (T), named after an engineer/inventor who made great contributions to the practical development of electricity generation.

You will learn more about the man Tesla, and the tesla unit later in this topic.

Since the force is directly proportional to each of these factors, it follows that any increase in the

- magnetic field strength
- or • current
- or • length of wire within the field

will increase the force, in proportion.

### What about the angle?

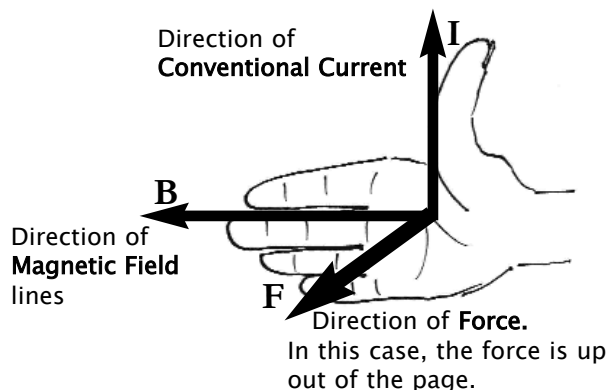
You know that  $\sin 0^\circ = 0$   
 and  $\sin 90^\circ = 1$

Therefore, the maximum force on the wire occurs when the wire and the field lines are at right angles. If the wire is parallel to the field lines,  $\theta = 0^\circ$  and the force is zero.

### Direction of the Force

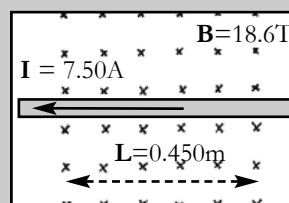
In the diagram at left, notice that the magnetic field lines, and the current direction, and the resulting force are all at right angles to each other.

The simplest way to determine the direction of the force is “THE RIGHT-HAND PALM RULE”



### Example Problem:

A wire carrying 7.50A of current is within a magnetic field 0.450m wide, with a strength of 18.6T. The field is directed into the page as shown.



What force (including direction) acts on the wire?

Solution:

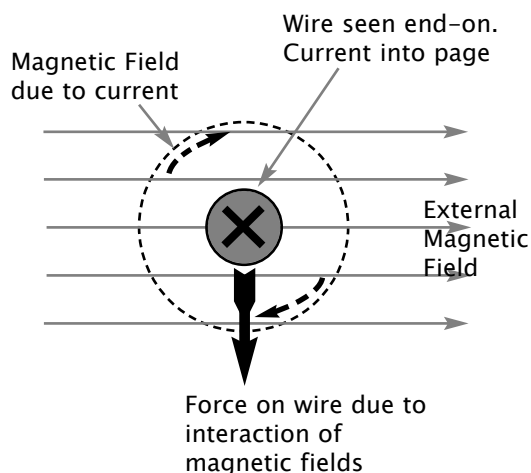
$$\begin{aligned} F &= B.I.L.\sin\theta \\ &= 18.6 \times 7.50 \times 0.450 \times \sin 90^\circ \\ &= 62.8\text{N.} \end{aligned}$$

The Right-Hand Palm Rule shows that the force is directed down the page.

**TRY THE WORKSHEET** at the end of the section

## What Causes the Motor Effect?

As you can probably figure out for yourself, the force on the wire is due to the external magnetic field interacting with the field produced by the current in the wire.

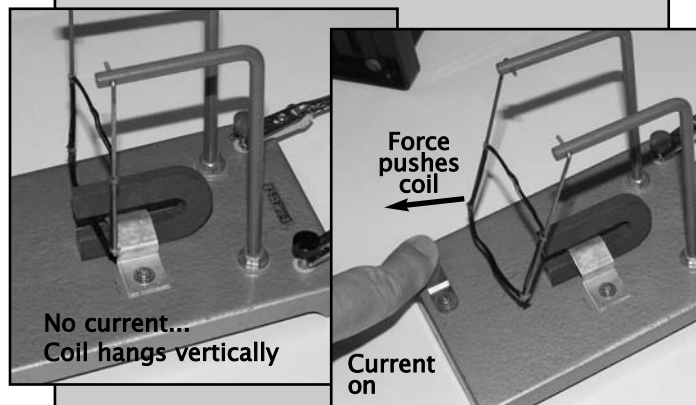


Verify the direction of the force using the RH Palm Rule.

### Practical Investigation of the Motor Effect

You will have done some experimental work in class to see the Motor Effect in action.

There are many possible ways to do this, but a simple example is shown below.



The “external magnetic field” is provided by a horse-shoe magnet (U-shaped). This produces a magnetic field passing around the bottom wires of the rectangular coil.

Current passes through the rectangular coil of wire. Only the bottom, horizontal strands of wire are properly within the external field.

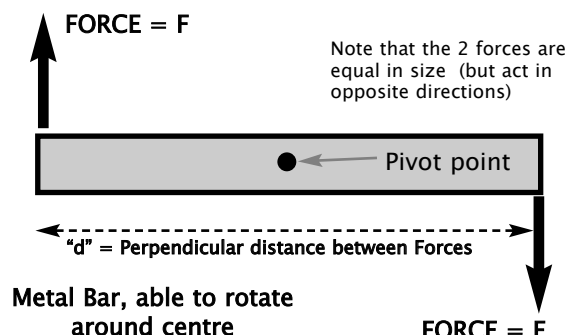
The wire is free to swing and deflects, as shown, when current flows.

Reversing either the current direction, or the polarity of the magnetic field, will reverse the force on the coil and the way it deflects.

## The Concept of Torque

Before we go any further, it is necessary for you to learn about the way that one or more forces can cause things to **rotate**.

One particularly important situation is shown in the following diagram:



Applying forces in this way will cause things to rotate. The size of this “turning effect” is usually measured by a quantity called “Torque”.

Torque is a measure of the “turning moment” of a force, or more commonly a pair of forces, causing rotation as shown above. Mathematically,

$$\tau = F.d$$

$\tau$  = Torque, measured in newton-metres (N.m)

Note that the Greek letter “tau” is used for Torque  
F = Force, in newtons (N)

d = perpendicular distance between forces, in metres(m)

Note: the syllabus requires you know the definition of “torque”, but not to solve problems with this particular equation.

## Torque and Motors

Motors and engines are usually used to turn wheels and axles to drive vehicles, or rotate machinery, tools, etc. The key word is “rotate”.

Because they rotate things, it is appropriate to measure the effect of any engine or motor by its Torque.

You might recall from a previous (Preliminary) topic that

$$\text{Work done} = \text{Force} \times \text{distance} = \text{Energy by a force}$$

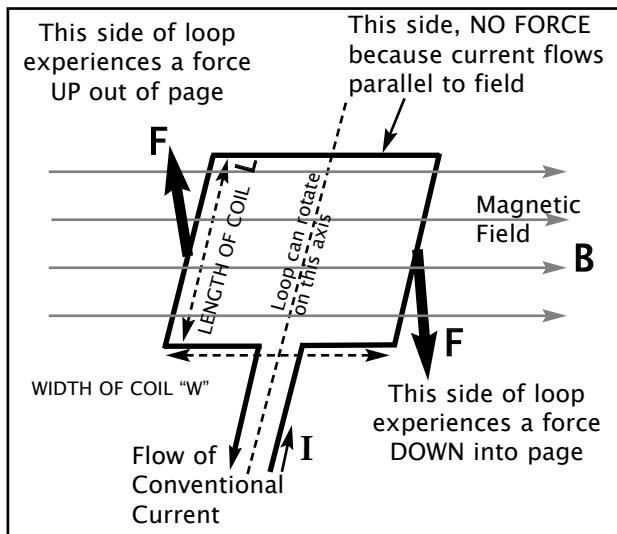
Since Torque is also equal to Force x distance, it means that when you consider the torque provided by a motor, you are dealing with the energy being converted by the motor.

In the case of an electric motor, the energy conversion is:

**ELECTRICITY → KINETIC ENERGY**

## Torque on a Loop of Wire Carrying Current in a Magnetic Field

Previously, you learned how a straight wire carrying current through magnetic field experiences a force. What if the wire forms a loop?



If this loop of wire is able to rotate, the forces on each side will provide a Torque and cause it to rotate about its central axis.

The force on each side is  $F = B.I.L$  (assume  $\theta=90^\circ$ )

Remember that Torque = Force x distance between forces so the Torque on the loop is  $\tau = B.I.L.W$

However, the factor  $(L \times W) =$  the AREA of the loop, so

$$\tau = B.I.A$$

This is the torque provided by just one wire in the loop. If the loop is a coil made up of “n” strands of wire, then

$$\tau = n.B.I.A$$

Finally, it can be shown that as the coil rotates, there are positions where the forces on the wires do NOT cause rotation, so the torque varies with the angle between the plane of the coil, and the field.

$$\tau = nBIACos\theta$$

$\tau$  = Torque on the coil, in newton-metres (N.m)  
 n = number of loops of wire in the coil  
 B = strength of the magnetic field, in tesla (T)  
 I = current flowing in wires, in amps (A)  
 A = Area of coil, in square metres (m<sup>2</sup>)  
 $\theta$  = angle between plane of coil and mag.field

Note that  $Cos\ 0^\circ = 1$   
 $Cos\ 90^\circ = 0$

so maximum Torque occurs when the plane of the coil lies “flat” in the field ( $\theta=0^\circ$ ). When the coil is “upright” in the field ( $\theta=90^\circ$ ), the Torque is zero.

### Example Problem:

A rectangular coil (just like in the diagram at the left) made up of 50 loops of wire, is carrying a current of 5.65A through a magnetic field of 20.0T strength. The dimensions of the coil are 4.50cm x 8.25cm.

What is the torque on the coil at the instant when it lies at  $60^\circ$  to the field lines?

### Solution:

$$\tau = nBIACos\theta$$

$$\therefore \tau = 50 \times 20.0 \times 5.65 \times (0.0450 \times 0.0825) \times Cos60 = 10.5\ N.m.$$

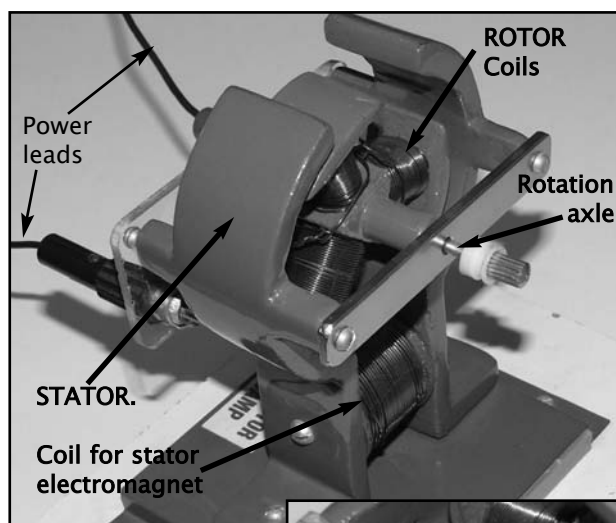
Notice that the dimensions of the coil were given in cm, but must be converted to metres; S.I. units must be used!

**TRY THE WORKSHEET**, at the end of this section

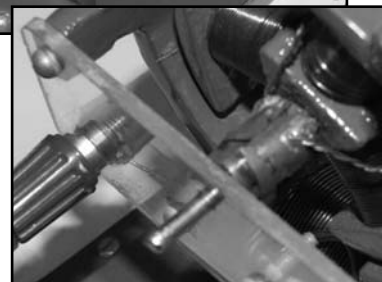
## Structure of a Simple DC Motor

Basically, an electric motor is nothing more than a coil of wire, built onto an axle so that it can rotate within a magnetic field.

When current is switched on in the coil, the magnetic forces create a torque which rotates the coil.



Close-up of back of motor showing Commutator & Brushes



In small, simple motors (such as in a child's toy car) the magnetic field is provided by a permanent magnet. In more powerful motors, the field is provided by an electromagnet, as in the “demonstration” motor above.

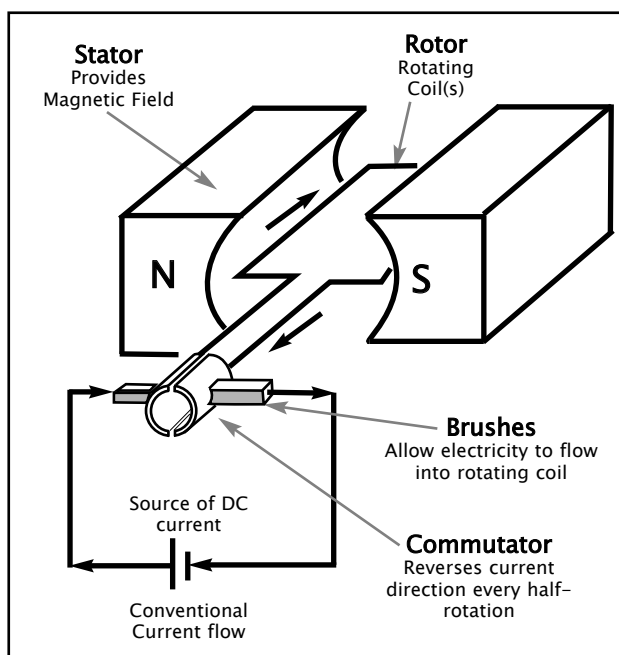
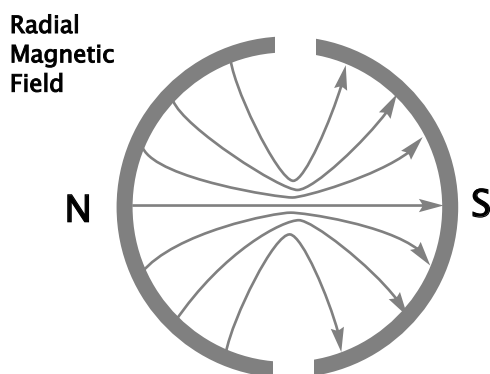
The tricky bit is to supply electric current to a rotating coil, and to maintain a steady, continuous torque... read on...

## Main Features of a Simple DC Motor

Refer to the photo on the previous page.

- **The Rotor** is the part that rotates. It is a coil of wire (or often several coils) mounted on an axle to allow rotation.
- **The Stator** is the part that remains stationary. It may be a permanent magnet, or an electromagnet. Its purpose is to provide the magnetic field.

Often, the magnetic poles are shaped in such a way to create a "Radial Magnetic Field"... one in which the lines of force are directed like the spokes of a bicycle wheel... radii of a circle. This means the plane of the coil is always "flat" in the field ( $\theta = 0^\circ$ ) throughout its rotation. Since  $\cos 0^\circ = 1$ , the result is maximum torque at (nearly) all positions.



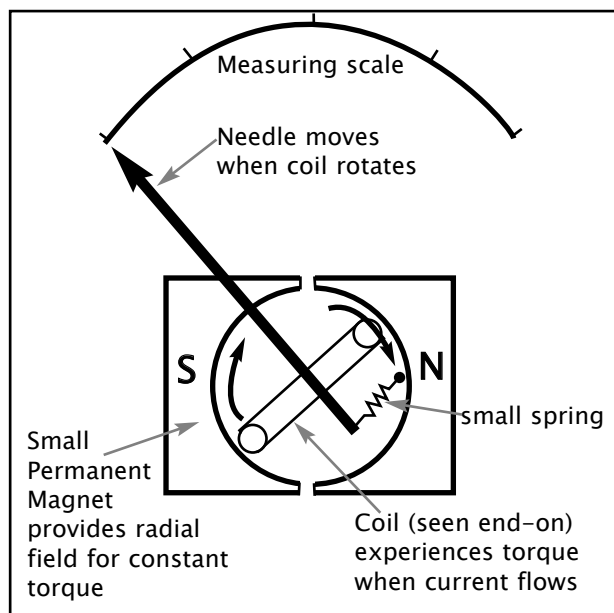
- **The Brushes** are fine, flexible metal wires, or (more commonly) a spring-loaded stick of graphite. The brushes maintain electrical contact onto the rotating metal ring.
- **The Commutator** is a metal cylinder, split into 2 pieces. As it rotates, the direction of current in the coil is reversed every half-rotation. This way, the torque is always in the same rotational direction, even though the coil has turned over.

## Other Applications of the Motor Effect

### The Galvanometer

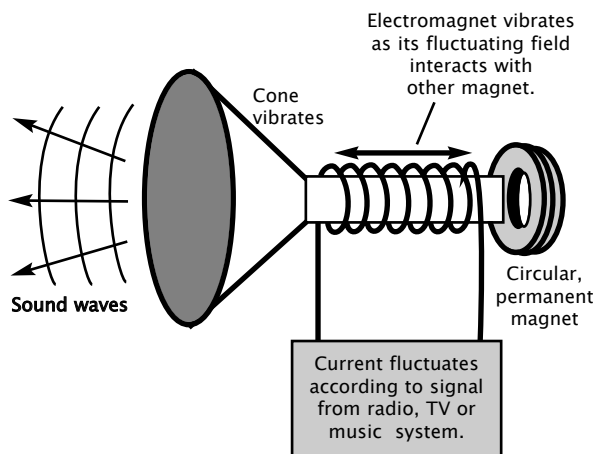
All electrical meters, ammeters and voltmeters, are based on a device called a "galvanometer", named in honour of Luigi Galvani, one of the pioneers of Electrical Science.

The galvanometer works because of the Motor Effect; the more current that flows through its coil, the greater the torque on the coil, and the greater the deflection of the meter needle, working against a small spring. The needle then points to a scale of measurements, which can be calibrated to read either current or voltage.



### The Moving-Coil Loudspeaker

was explained in a Preliminary topic. Electrical current (modulated with a signal from radio, microphone, etc) creates a fluctuating magnetic field around a coil. This field interacts with a nearby magnet, and the coil vibrates rapidly back-and-forth. The attached speaker cone vibrates too, and sends compression waves (sound) into the air.





## Worksheet 1

### Part A

Fill in the blanks. Check your answers at the back

Two parallel wires, both carrying a)..... will exert a b)..... on each other. The reason is because each wire will produce a c)..... around itself, and these 2 fields interact with each other. If the wires carry current in the same direction, the force will d)..... the wires. If the current flow e)....., the force will f)..... the wires. The magnitude of the force per unit of g)..... is proportional to h)..... in the wires, and i)..... proportional to the distance between them.

If a wire is carrying current through a j)..... field, it will experience a k)..... The magnitude of the force depends upon 4 factors:

- The strength of the Magnetic field, measured in l).....
- The m)..... flowing in the wire
- The n)..... of the wire that is within the o)....., and
- The p)..... between wire & field.

This force on a wire is the basis of electric motors and is called the “q)..... Effect”. The directions of current, field & force are all at r)..... to each other, and can be determined by the “s)..... Rule”.

“Torque” is a measure of the t)..... effect of a pair of forces which cause something to u)..... around a pivot point or axle. A loop or coil of wire, carrying current within a v)....., will experience a torque, because the force acting on the opposite sides of the coil will be w).....

The size of the torque depends on 5 factors:

- The x)..... which make the coil
- The strength of the y).....
- The z)..... flowing in the coil
- The aa)..... of the coil, and
- The angle between the ab)..... of the coil, and the field. Maximum torque occurs when the angle is ac)..... Zero torque occurs at an angle of ad)..... degrees.

A simple DC motor has just 4 main parts:

- The Rotor, made up of a ae)..... mounted on an axle to allow it to af).....
- The ag)..... which provides the magnetic field, from either a ah)..... magnet, or an ai).....
- The Brushes, which maintain aj)..... contact between the electricity supply and the rotating coil.
- The ak)....., which causes the current to al)..... every half-turn.

The Motor Effect is also involved in the operation of a am)....., and a moving-coil loudspeaker. In an electric meter, the needle moves along a calibrated scale because of the an)..... on a coil inside a ao)..... (shape) magnetic field. In a loudspeaker, the sound is produced by ap)..... of a speaker cone. In turn, this is made to vibrate by a coil's magnetic field aq)..... with a permanent magnet.

### Part B Practice Problems Answers at back

#### Force Between Parallel Wires Carrying Current

1.

Calculate the force per unit of length between 2 long, parallel wires carrying 15.3A and 12.7A and separated by 1.00cm. State the direction of the force, given that the currents are in opposite directions.

2.

Two long, parallel wires are carrying equal currents. The wires are 10.0cm apart. The force between them is found to be  $8.25 \times 10^{-5}$  N per metre of length, attracting each other. Find the magnitude, and relative direction, of the currents in the wires.

3.

Two wires run parallel for a length of 1.48m. The total force acting between them over this length is  $6.44 \times 10^{-4}$  N when they are carrying currents of 8.90A and 14.5A. How far apart are they?

4.

Two power cables, both carrying 30.0A of current in the same direction, are separated by a distance of 8.00cm. The cables run parallel over a distance of 25.0m. What is the total force (including relative direction) acting between them?

**Worksheet continues, next page...**

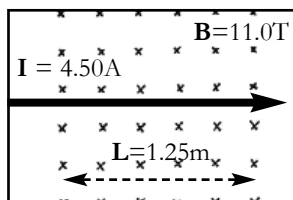


## Part B Practice Problems (continued)

### Force on a Wire Carrying Current Through a Field

5.

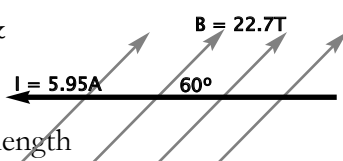
A wire is carrying 4.50A of current through a 11.0T field, directed as shown. The length of wire in the field is 1.25m.



Find the magnitude and direction of the force on the wire.

6.

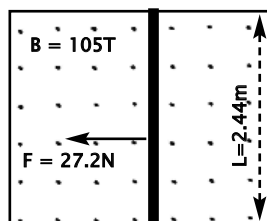
Find the magnitude & direction of the force which would act on the wire shown. The length of wire within the field is 0.385m.



7.

The vertical wire runs for 2.44m through a 105T field directed out of the page. The force on the wire is 27.2N left.

Find the magnitude and direction of the current in the wire.



8.

A wire is carrying 8.00A of current over a length of 0.287m through a magnetic field of 7.50T. A force of 3.72N acts on the wire. Find the angle between the wire and the field lines.

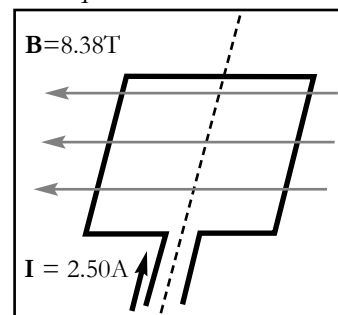
**Remember that for full marks in calculations, you need to show FORMULA, NUMERICAL SUBSTITUTION, APPROPRIATE PRECISION and UNITS**

**FULLY WORKED SOLUTIONS IN THE ANSWERS SECTION**

### Torque on a Coil in a Field

9.

Calculate the amount of torque on a coil of 200 turns of wire carrying 1.50A in a field of strength 5.25T. The area of the coil is  $1.20 \times 10^{-3} \text{m}^2$ . Assume that the field is radial, so that the torque is always at a maximum (i.e.  $\theta = 0^\circ$ )



10.

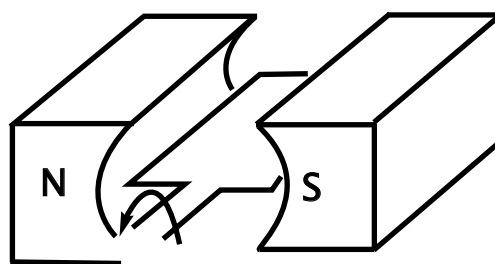
The coil shown is 20cm square and composed of 35 turns of wire.

- Find the torque on the coil when it lies "flat" in the field (i.e.  $\theta = 0^\circ$ ).
- Will the coil rotate clockwise or anti-clockwise as viewed from the lower end?

11.

The torque achieved by a small electric motor is found to be 3.86Nm, when a current of 3.20A flows through the rotor coil which has an area of  $0.00262 \text{m}^2$ . The stator provides a radial field of 4.60T. (assume  $\theta = 0^\circ$ ) How many turns of wire in the coil?

12.



The rectangular coil shown is 8.00cm x 5.00cm and is rotating anti-clockwise due to the torque on it. The magnetic field of 22.3T gives maximum torque of 12.3Nm at the position shown. The coil consists of just 12 turns of wire.

- What is the current?
- Determine the direction of conventional current flow (clockwise or anti-clockwise around the coil diagram?)

## 2. GENERATORS & POWER PRODUCTION

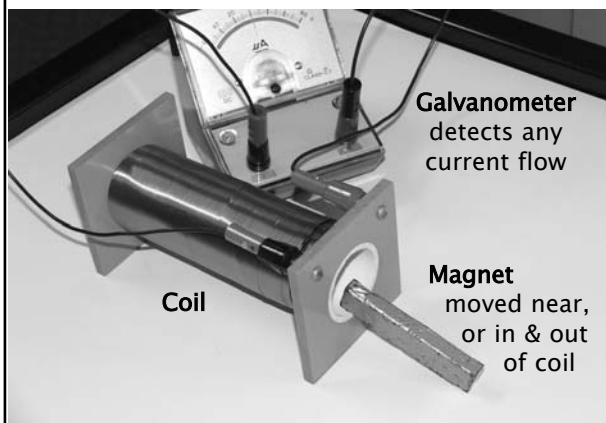
### Electromagnetic Induction

If electrical currents produce magnetic fields, and interact to produce forces and movement, shouldn't the opposite occur too? So went the argument among scientists about 150 years ago. Many experiments were carried out before **Michael Faraday** (1791-1867) proved the idea correct.

Faraday discovered that if there is relative movement between a magnetic field and a conductor, then a current will be "induced" in the conductor. This is called "Electromagnetic Induction", and is the basis of the electrical generator and all of society's large-scale power production.

#### A Simple Demonstration of Induction

You may have done a simple experiment to see, first-hand, electromagnetic induction.



When the magnet is moved near, or into the coil, the galvanometer needle registers a flow of current.

It doesn't matter whether the magnet moves, or the coil moves... as long as there is relative movement.

You may have investigated the factors which can effect the nature of the induced current...

- Using a stronger magnet produces more current.
- The closer the magnet is to the coil, the more current.
- The faster the movement, the more current.

also...

- Reversing the direction of movement reverses the current flow. Reversing the polarity of the magnet also reverses the current flow.

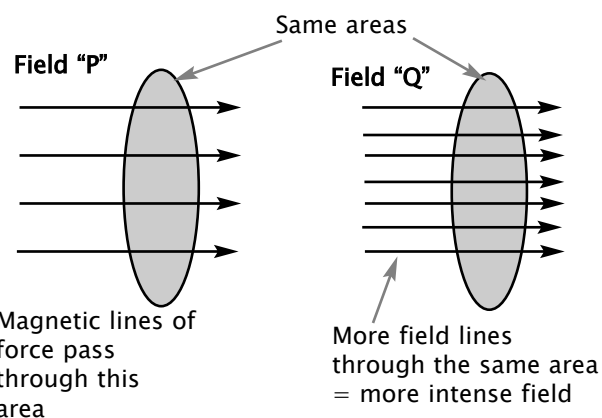
In practice, Induction usually produces AC electricity... Alternating Current which flows back-and-forth.

### Magnetic Flux & Flux Density

To explain his discovery of induction, Faraday introduced the concept that a magnetic field is made up of a series of "lines of force". He showed that if a conductor moves so that it "cuts through" these field lines, then a current is induced to flow in the conductor.

He invented the idea of "magnetic flux" as a measure of how many field lines are cut by the moving conductor. From this concept arises the idea of

#### Magnetic Flux Density



The "Magnetic Flux Density" is what we have been calling "Magnetic Field Strength".

#### Magnetic Field Strength = Magnetic Flux Density

It is a measure of the intensity of a magnetic field, in terms of the number of force-field lines per unit of area.

Symbol used in equations = "**B**"  
Unit of measurement = tesla (T)

Faraday discovered that when there is relative motion between a conductor and a magnetic field, a voltage (or "EMF" = ElectroMotive Force) is created.

Size of  
the EMF

$\propto$   
is proportional to

Rate of change of the  
**FLUX**  
through the conductor

The voltage created then causes current to flow through the circuit according to Ohm's Law.

Faraday developed the mathematical equations relating the induced voltage to rate of change of flux. The syllabus does NOT require you to know these, but you DO need to know the definitions above.

**Electromagnetic Induction is, of course, the basis of the electric generator. Read on...**

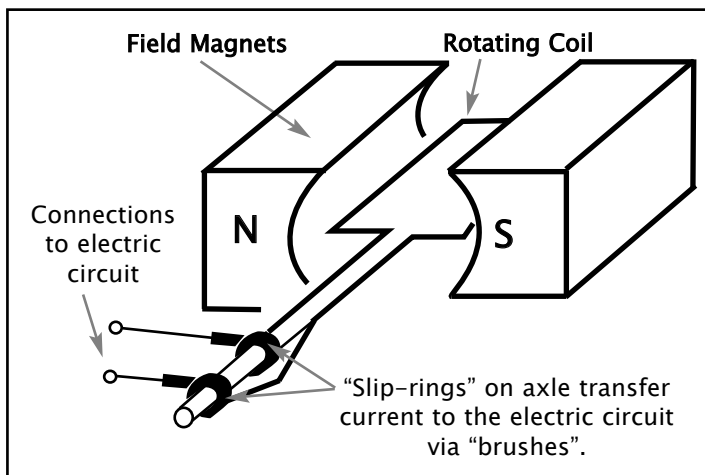
## Generators

The main components of an electric generator are basically the same as an electric motor. In a motor, electric current in a coil inside a magnetic field, causes the coil to rotate.

**ELECTRICAL ENERGY** → **KINETIC ENERGY**

In a generator, rotating a coil inside a magnetic field induces a current to flow in the coil.

**KINETIC ENERGY** → **ELECTRICAL ENERGY**



A simple motor can be a generator, and a simple generator can act as a motor...

### Comparison: Simple Motor & Generator

#### Structure

Very similar. Both consist of one or more coils of wire which can rotate inside a magnetic field. The field can be provided by either permanent magnets, or electromagnets.

Both require “brushes” to maintain electrical contact with the rotating coil to pass current into the coil (motor) or carry induced current out of the coil (generator).

#### Function

Opposites.

Motors use electricity to produce movement in the coil.

Generators use movement of the coil to produce electricity

#### Practicalities

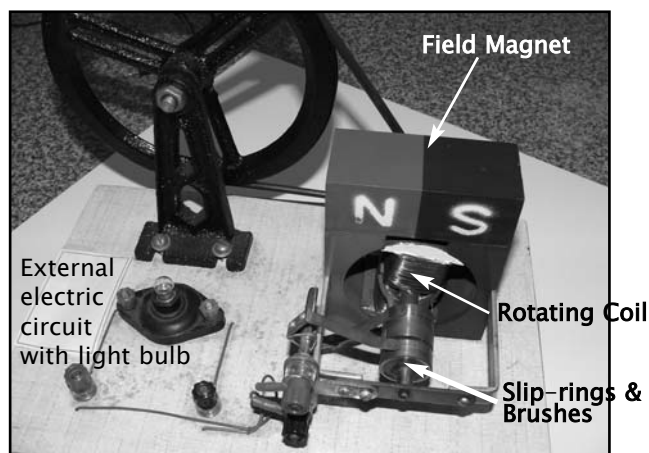
In reality, motors and generators are built very differently for practical reasons.

For example, in power stations the generators are built to have the coils of wire stationary while the magnets do the rotating. This makes it simpler and more efficient to transfer the electricity to the power grid, without having massive currents sparking through the brushes.

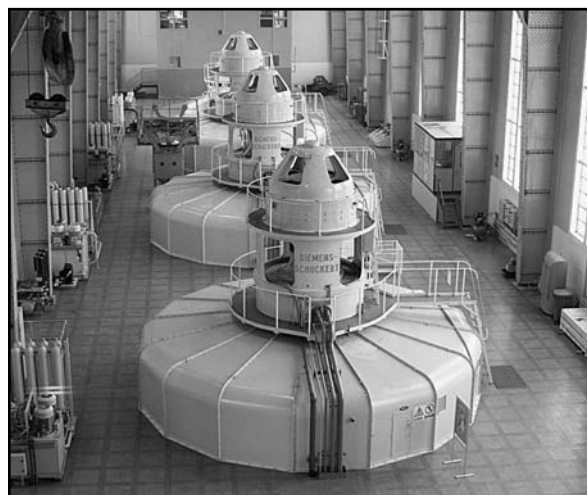
## What Makes the Generator Turn?

To get electricity from a generator you must make the coil (or the magnetic field) rotate. How?

In this simple, school demonstration generator, you simply wind the handle.



In this “Hydroelectric” power station, (below) these generators are being turned by the movement of water falling through huge turbines.

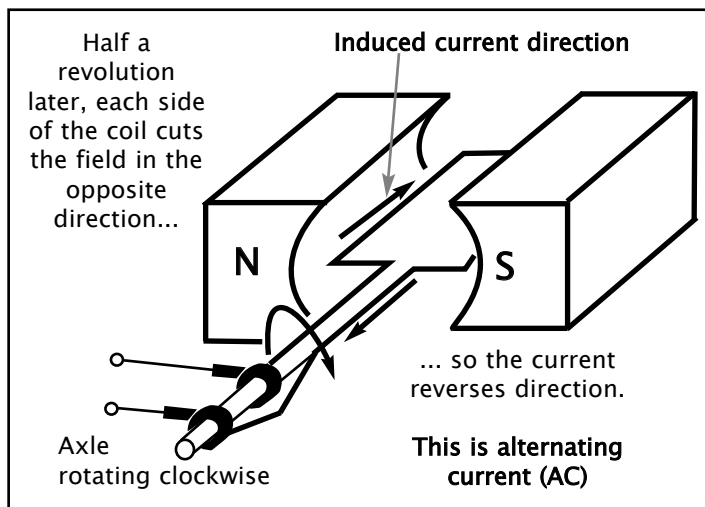


The power of the wind makes these generators spin.

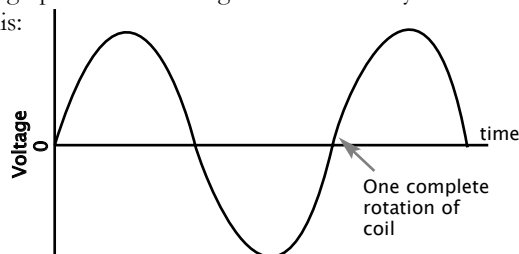


## AC and DC Generators: Differences

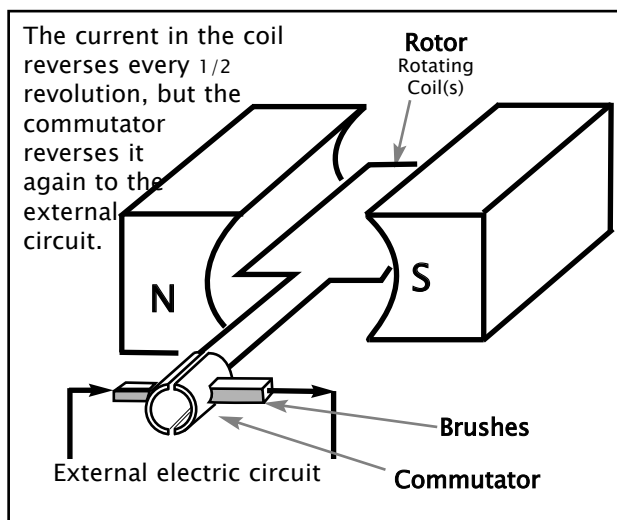
In a simple generator as described previously, the induced current will reverse direction every 1/2 revolution of the coil.



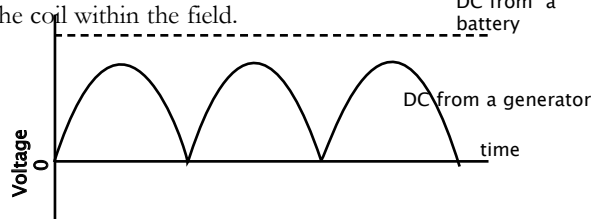
A graph of the EMF generated this way would look like this:



It is also possible to make a generator which will produce direct current (DC) which flows in the same direction.



The electricity produced flows only in one direction, (DC) but fluctuates according to the position of the coil within the field.



## Advantages & Disadvantages

The fact that our “mains” electricity supply is Alternating Current (AC) tells you that there must be advantages to generating electricity as AC, rather than DC.

One major advantage of AC has nothing to do with the generators, but relates to transmission of power and the ease of altering the voltage in a transformer. This will be studied a little later. For now, simply note that there ARE major reasons to do with distribution and usage, which make AC preferable to DC.

In terms of the generators themselves, any advantages & disadvantages relate to their structure:

### Disadvantage of a DC Generator

No matter how well it is made, the commutator is the weakness of a DC generator. Because it is a split-ring structure, the brushes must spark and wear out as the commutator revolves. This is inefficient in terms of transferring electricity to the external circuit, and causes maintenance problems as the brushes wear out and need to be replaced.

### Advantage of an AC Generator

Instead of a commutator, the AC generator has continuous “slip-rings” so there is much less sparking and less wear on the brushes.

Additionally, as already mentioned, an AC generator can be built with the massive, heavy coils stationary and the magnets doing the revolving on the inside. This simplifies the engineering and maintenance and eliminates entirely the use of slip-rings and brushes to carry the generated electricity. (However, smaller amounts of electricity still need to pass through brushes and slip-rings to supply the rotating electromagnets.)

## Energy Losses in Power Lines

Our modern electricity system consists of a relatively small number of large power stations, with the electricity needing to be distributed in power lines over hundreds of kilometers.

Although the wires (usually aluminium) are made to be of low resistance, over long distances there could be major energy losses due simply to the resistance causing heating in the wires.

However, the energy loss due to resistance heating is much greater at higher currents. So to minimise energy losses, electricity is carried at very high voltage and very low current. Typically, long-distance power is distributed at 250,000 volts or more, but only tiny currents, like 0.01 amp.

The fact that AC can be readily “stepped-up” to high voltage for transmission, then “stepped-down” for consumer use is a major advantage of AC electricity. The “step-up” & “step-down” is done by transformers.

## More on Power Lines

Power lines are not usually covered with a sheath of insulation. That's why it is deadly to touch them with a ladder, or similar.

To prevent the electricity being conducted to the ground, the power lines are supported on their poles or towers by non-conducting insulators.

The insulators are usually ceramic or glass and often disc-shaped to create a longer path for a spark to jump.



Power lines and supporting structures need to be protected from lightning strikes. Metal towers are well "earthed" in that they can safely carry a lightning strike into the ground. Wooden poles may be equipped with a "lightning rod"... a thick metal cable running from the top down into the ground.

To protect the wires themselves, an extra wire called a "shield conductor" may be strung above the power cables. It is not supported by insulators, but electrically connected to the metal towers. Lightning will strike the "shield conductor" instead of the power lines, and be safely conducted to ground through the metal tower.



### Effects on Society

The development of AC generators has led to the widespread availability of low-cost energy. This has:-

- resulted in many improvements in life-style, with "labour-saving devices" such as washers, etc, and the comforts of air-conditioning and the convenience of refrigerators and freezers, etc.
- promoted the development of electrical and electronic inventions, leading to modern communications systems and computer networks for finance, business and entertainment, to name just a few areas.

Like it or hate it, the fact is that the modern technological world, and the life-style most people enjoy, with good health and many comforts, is a direct result of electricity.

## A Little History... Edison v Westinghouse

In the early days of electricity generation and usage the famous inventor, Thomas Edison, was pioneering electricity supply. He favoured the use of DC electricity and had set up hundreds of DC power stations around the New York area. His advantage was that he had invented the light bulb, and now stood to make a fortune selling both the bulbs and the electricity to run them.

His main competitor was the Westinghouse company, which wanted to set up an AC electricity system.

In 1884, Nikola Tesla arrived in America from Serbia. He was an engineer and inventor and had developed new, improved versions of AC generators, motors and transformers. He got a job with the Edison company, but soon left and went to work for Westinghouse. Tesla sold his inventions to Westinghouse, who built the first large-scale AC power station at Niagara Falls.

Long distance transmission of AC electricity soon proved more economical than the multiple power stations and short-range Edison DC system. Also, Tesla's new electric motor, which ran only on AC, proved very economical and reliable for factories, elevators and a host of new consumer machines like vacuum cleaners and washing machines.

The modern electrical world became established, and it was AC electricity that became the standard.

Nikola Tesla's contribution has been recognised by the naming of the unit of magnetic field strength (magnetic flux density) after him.

## Effects of the Development of AC Generators on Society and the Environment

The syllabus asks you to "assess" these effects. This means to measure or "weigh-up" the positives and the negatives, to both society and to the environment.

It can be argued that the effects on human society are nearly all positive, while environmental effects are all negative.

### Effects on the Environment

Although much progress has been made toward controlling pollution, the generation of electricity is linked to a number of enormous environmental problems:-

- Much of our electricity is still generated by coal-burning power stations. The burning of coal is a major contributor to the "Greenhouse Effect" and "Global Warming".
- Nuclear Power stations are "greenhouse-friendly", but carry risks of disasters such as the 1986 nuclear accident at Chernobyl.
- Even development of hydro-electricity involves massive disruption to ecosystems, when rivers are dammed and valleys flooded to provide for power stations.

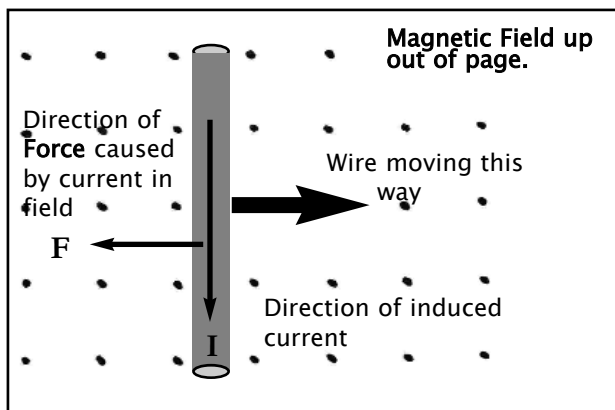


## More About Electromagnetic Induction...

### Lenz's Law

Consider a conducting wire being pushed across a magnetic field. Because the wire is cutting the field lines, there will be an induced EMF, and (if there's a circuit available) current will flow..

BUT, when a current flows the Motor Effect will occur and create a force on the wire. Which way will it push the wire?



Heinrich Lenz figured it all out 150 years ago. The induced current will create a magnetic field (and Motor Effect force) which will oppose the motion that produced it in the first place.

### Lenz's Law

The direction of an induced EMF (and current) is such that it produces a magnetic field opposing the change that produced the EMF

Lenz's Law arises as a consequence of the principle that energy cannot be created from nothing... the "Law of Conservation of Energy".

Look at the diagram above. If the induced current flowed the other way, then the motor effect force would act to the right. This would accelerate the motion of the wire. Since it would move faster, it would cut more field lines (greater "flux change" Faraday would say) and thereby induce a greater EMF and greater current. This would produce more force and accelerate the wire even more... and so on. This would mean energy being created from nothing!

In the diagram above, the induced current must flow as shown, so that its own magnetic field opposes the motion of the wire, and so Conservation of Energy is not violated.

This is why:

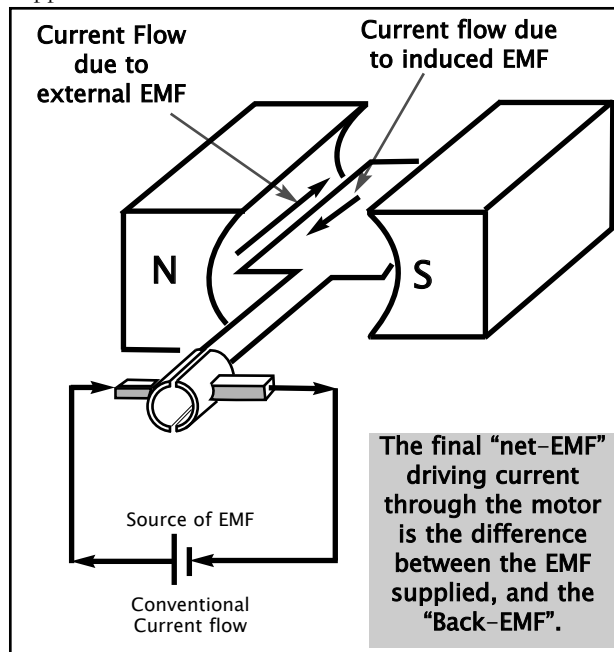
- when you push a magnet into a coil, you may feel an opposing force... the current induced in the coil is creating a magnetic field which repels the one you're pushing.
- When you wind the handle of a generator, the force required is much greater than expected... Lenz's Law opposes you!

Lenz's Law has a number of practical consequences...

### Back EMF in a Motor

As dealt with earlier, an electric motor rotates due to the torque on the coil due to the applied current interacting with the magnetic field.

However, as the coil rotates through the magnetic field, induction also occurs, creating an induced EMF. Lenz's Law guarantees that the induced EMF will act against the supplied EMF.

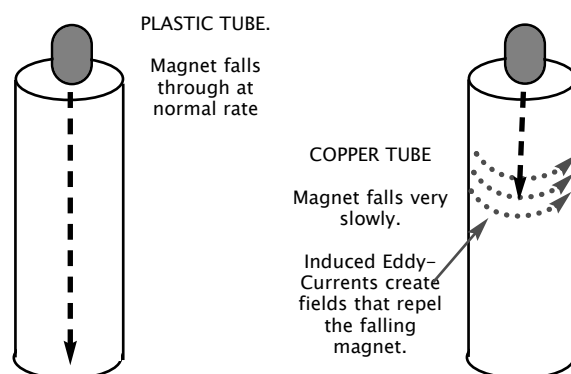


### Eddy Currents

Even when there is no designed electrical circuit present, whenever there is relative motion between a conductor and a magnetic field, an EMF is induced and currents will flow. In a flat sheet or tubes of metal the induced currents often flow in circles... these are called "Eddy Currents"

Lenz's Law guarantees that the eddy currents will create magnetic fields to oppose the motion that produced them.

Example: Get a small, but powerful "super-magnet" and drop it through a plastic tube. Then drop it through a copper, or aluminium tube.



## Electromagnetic Braking

This “braking effect” can be very useful.

In some amusement rides, the passenger seat or car is equipped with small, powerful magnets. At the end of the ride, there are sheets of copper which the magnets move past. (Or, vice-versa... the magnets are in the track and copper plate is onboard the car.)

Either way, eddy currents are induced in the copper sheets. These currents produce magnetic fields. These fields interact with the magnets to produce a force opposing the motion. This smoothly slows the ride to a stop.

The beauty of this system is that:

- it requires no power input to operate.
- it involves no contact surfaces or moving parts that can wear out.
- it is “fail-safe”, so that in an emergency it will still work and safely stop the moving ride.

Some trains use electromagnets (can be turned on/off as needed) to induce eddy currents in the rails below the train. As always, Lenz’s Law ensures that the induced currents create fields to oppose the motion, and acts as brakes.

## Induction Cooking

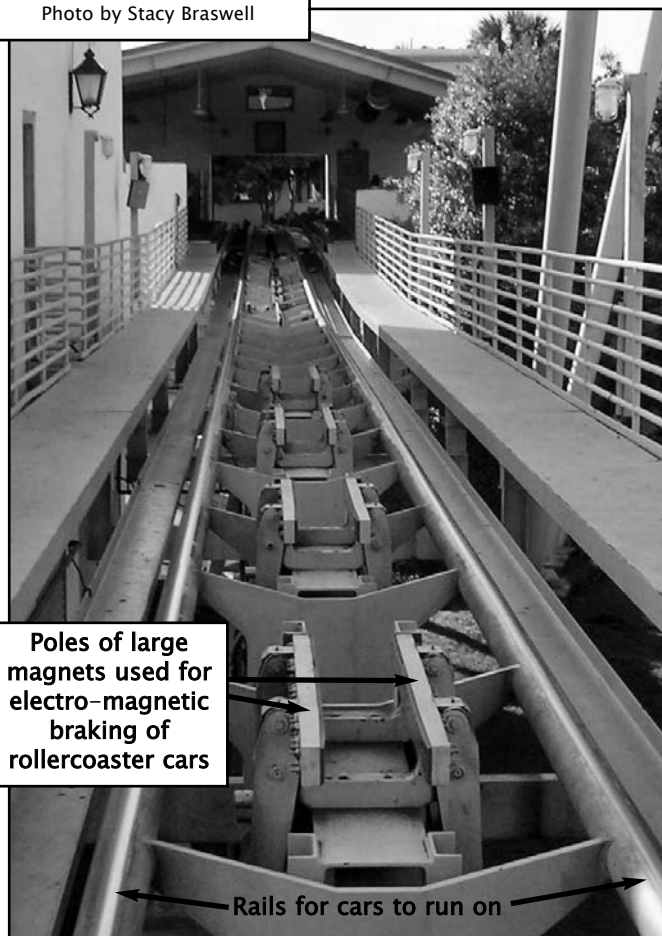
An “Induction Stove” has a flat ceramic top with no visible heating elements.

Under the top are electromagnet coils. When switched on, these produce oscillating magnetic fields. If a steel saucepan is on top, eddy currents are induced in the pan, which gets hot due to the resistance of the metal to the eddy currents. This heat cooks the food in the pan.

The advantages of such a cooker are that:

- heat is produced directly in the saucepan, rather than a heating “element”. This is much more efficient in energy terms, and thereby cheaper to operate.
- the flat ceramic top is easy to clean.

**Rollercoaster Terminal**  
Photo by Stacy Braswell



Poles of large magnets used for electro-magnetic braking of rollercoaster cars

Rails for cars to run on



## Worksheet 2

### Fill in the blanks Check your answers at the back

Electromagnetic Induction was discovered by Michael a)..... It is the basis of the electrical b)..... and all large-scale electricity production.

A simple experiment to investigate induction can be done with a coil, a galvanometer and a c)..... Any d)..... movement between e)..... and ..... will induce a flow of f)..... in the coil. The magnitude of the induced current can be increased by:

- using a g)..... magnet
  - moving the magnet h)..... to the coil
  - making the motion i).....
- If the direction of movement is reversed, then the current j)..... Reversing the polarity of the magnet k)..... the current.

The strength of a magnetic field is technically known as "Magnetic l)....." This is a measure of the number of m)..... lines passing through a given n)..... Faraday discovered that, in electromagnetic induction, the size of the o)..... induced is proportional to the rate of change of p)..... through the conductor.

In a simple generator, a coil is made to q)..... inside a magnetic field, which can be provided by either r)..... magnets, or by s)..... Current is t)..... in the coil and this is passed into the external circuit by u)..... in contact with rotating "v)....." which are mounted on the axle. Overall, the structure is very similar to an electric w)....., but the energy transformation is exactly the opposite.

As the coil rotates, every half-revolution it cuts the magnetic field in the opposite direction, so the x)..... is reversed. The result is that it generates y)..... electricity. It is possible to generate DC by mounting a z)..... on the rotating axle to aa)..... the current again each half-turn. However, DC generators have the disadvantage that the commutator causes a lot of ab)....., and the brushes wear out quickly. AC generators have the advantage that the ac).....-rings do not spark as much and do not wear out brushes as fast. In practice, AC generators are often built with the ad)..... stationary, and the ae)..... rotating. This doesn't need any slip-rings to connect the coils to the af)..... at all.

Another major advantage of AC generation is to do with energy losses in transmission lines. Energy loss due to ag)..... heating is higher at higher ah)..... levels. Therefore, to minimize energy loss, it is best to transmit electricity at ai)..... voltage and very aj)..... current. Since AC electricity is easily stepped up or down by a ak)....., it is far better when power needs to be carried over long distances.

Transmission power lines use al)..... made from glass or am)....., to prevent electricity running to earth through support poles and towers. They are protected from the effects of an)..... strikes by extra wires called ao)..... strung above the power cables and connected to the supporting towers. This allows lightning to be conducted harmlessly to the ap).....

In the early days of commercial electricity production, the aq)..... company favoured the use of ar)..... electricity. Hundreds of local as)..... stations were built, since DC cannot be distributed over long distances without massive loss of at)..... Nikola au)....., a Serbian immigrant, invented improved versions of AC av)....., ..... and transformers. These were used by the Westinghouse company to build the first large power station producing AC at aw)..... Falls. Tesla's new AC motor was very successful too, and this contributed to the acceptance of AC as the standard.

The effect of large-scale electricity generation: On society the impacts are mostly ax)....., including many ay).....-saving devices, and leading to the development of modern az)..... systems for ba)....., ..... and ..... On the environment the impacts are mainly bb)..... For example, a lot of electricity generation involves burning of bc)..... which is a major contributor to the bd)..... and be).....

Lenz's Law states that the induced bf)..... is such that it's magnetic field bg)..... the change that produced it in the first place. This arises as a consequence of the Law of bh)..... It is because of this effect that electric motors are limited by "bi).....". The effect can be useful, such as in electromagnetic bj)..... of amusement rides and trains, or in bk)..... cooking. These effects involve the induction of bl)..... currents in a conductor.

**COMPLETED WORKSHEETS  
BECOME SECTION SUMMARIES**

### 3. TRANSFORMERS & THEIR USES

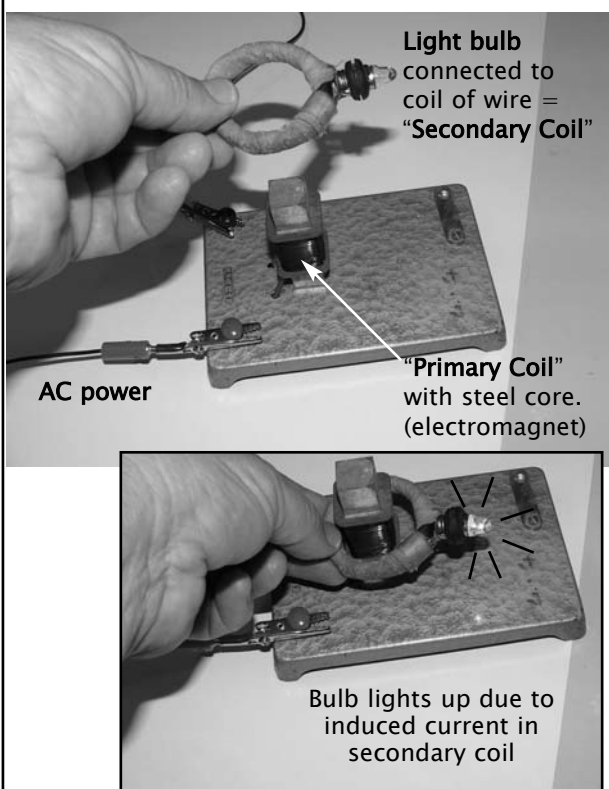
#### Purpose and Basic Nature of Transformers

It has already been mentioned that the great advantage of using AC electricity is that it can be “stepped-up” to very high voltages for efficient distribution, then “stepped-down” again for convenient and safe usage by consumers.

It is this stepping-up & down of the voltages that is the purpose and function of a transformer.

#### Practical Investigation

There are many possible investigations you may have done in class to see the basic operation of a transformer. One simple example is shown.



#### Explanation

The AC supply to the primary coil (an electromagnet) produces a fluctuating magnetic field. The field lines keep building, collapsing and reversing direction.

This moving field constitutes a “magnetic flux” through the wires of the secondary coil, and so EMF is induced.

This causes current to flow, which lights the bulb.

#### Note:

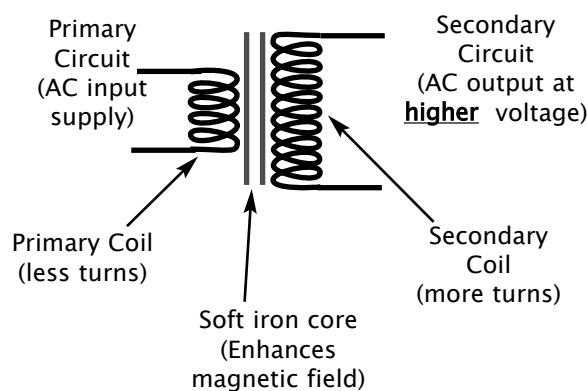
This will NOT work with DC electricity from a battery. The key to the induction in the secondary coil is the fluctuating field caused by the AC supply. (You WILL get induction with “DC” from a school power pack because it fluctuates quite a lot)

#### Step-Up, Step Down

Transformers work by inducing a new EMF and current in the “secondary coil”. Whether the secondary voltage is higher or lower than the primary voltage, is simply a matter of the ratio between the number of “turns” of wire in each coil.

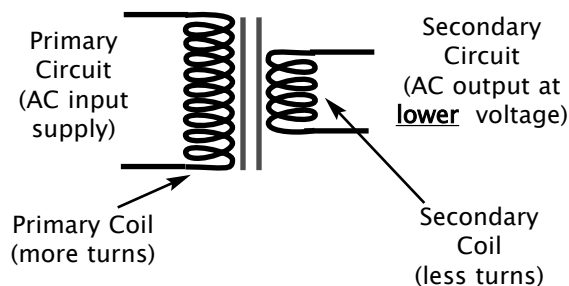
Faraday discovered that the size of the induced EMF is proportional to the number of turns of wire in the coil. In a transformer, if the number of turns in the secondary coil is greater than in the primary, then the induced EMF is higher too... the transformer “steps-up” the voltage.

#### Schematic Diagram of “STEP-UP” Transformer



In a “step-down” transformer, the opposite is true... the secondary coil has less turns than the primary, and the induced EMF is lower.

#### Schematic Diagram of “STEP-DOWN” Transformer



#### Current in Primary and Secondary Circuits

If you use a “step-up” transformer to get a higher voltage, does this mean you just got something for nothing?

No, of course not! If the voltage goes up, the current goes down in the same proportion.

(Assuming perfect transformation of energy)

## The Transformer Equation

There is a simple relationship between the voltages and the number of turns of wire in the coils of a transformer.

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

$V_p$  = Voltage in the primary coil.

$V_s$  = Voltage in the secondary coil.

$n_p$  = No. of turns of wire in the primary coil.

$n_s$  = No. of turns of wire in the secondary coil.

(Assumes 100% efficiency in energy transfer)

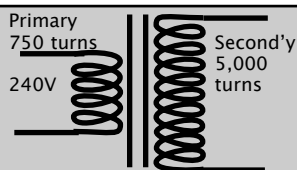
### Example Problem:

A transformer has 750 turns of wire in the primary, and 5,000 turns in the secondary coil.

Input voltage is 240V AC.

a) Find the output voltage.

b) Is this a “step-up” or “step-down” transformer?



Solution: a)

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

$$240 / V_s = 750 / 5,000$$

$$\therefore V_s = 240 \times 5,000 / 750$$

$$= 1,600 \text{ V.}$$

b) Step-up transformer, since it has more turns in the secondary coil, and the output voltage is higher than input.

**TRY THE WORKSHEET, at the end of section**

## Conservation of Energy in a Transformer

You will recall from a Preliminary topic that

**Electrical Power = Voltage x Current**

$$P = V.I$$

and that Power is the the amount of Energy being transformed per second.

In a step-up transformer, the voltage increases, and the current decreases by the same factor, so that:

Primary coil Power = Secondary coil Power

$$V_p I_p = V_s I_s$$

Energy per second = Energy per second  
in Primary coil in Secondary coil

Therefore, the Law of Conservation of Energy is obeyed.

(Note: you are NOT required to solve problems using this relationship, but should be able to describe the situation)

### Energy Losses in Transformers

The description above assumes that a transformer works with 100% efficiency. This is often assumed for solving simple problems, but you need to be aware that, in the real world, nothing is perfect.

Real transformers are not perfect, and always lose some energy in the process of altering the voltage. The main loss of energy is by resistance heating, not only in the coils, but due to “Eddy Currents” induced in the iron core.

Once the transformer starts to heat up, the situation gets worse, because (as covered in Preliminary topic) resistance in a metal increases with temperature.

A number of methods are used to minimize the energy losses:

- The iron core is not one large piece of iron, but is made of thin sheets of iron, laminated together, but insulated from each other. This way the eddy currents induced in the core are smaller, and cannot circulate very far.

- The coil wires are thicker on the higher current side of the transformer (depending whether step-up or step-down). Thicker wires have less resistance, so this minimizes resistance heating in the coils.

- Transformers are designed to radiate heat away so they stay as cool as possible, to reduce resistance. Large transformers may have cooling oil circulating through a heat exchanger, rather like the radiator system of a car engine.

In the photo on the left, the transformers are equipped with small metal “radiators” to quickly lose heat to the air.

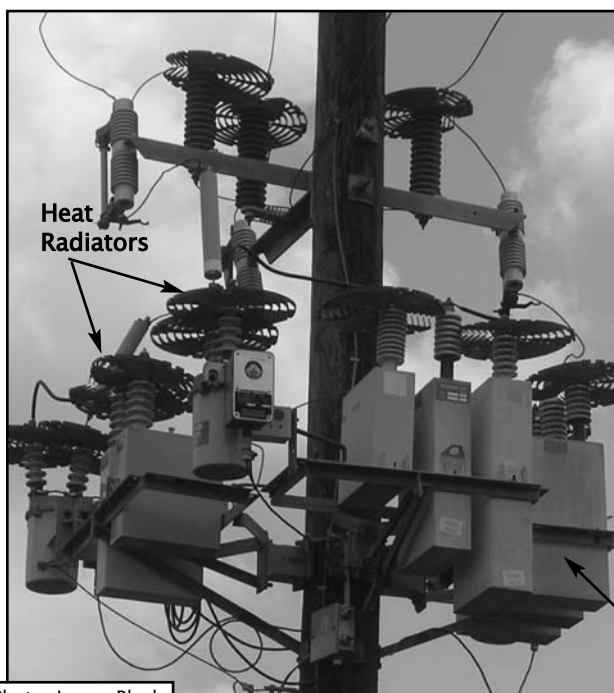
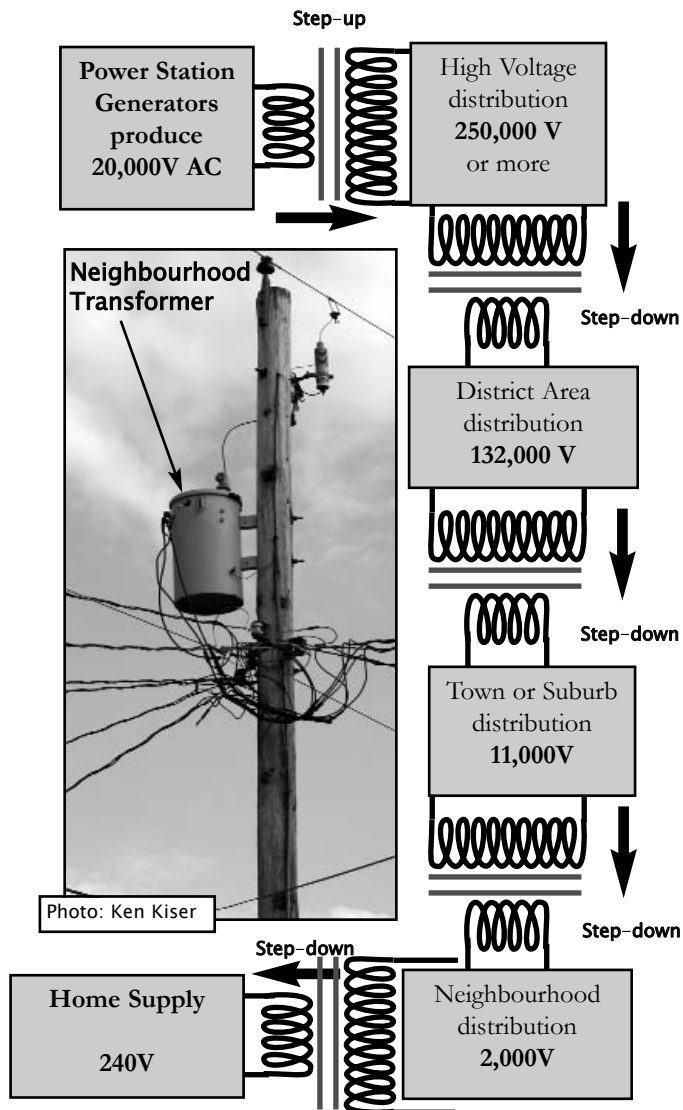


Photo: James Black

## From Power Station to Home... the Role of Transformers

Even though there is some loss of energy in a transformer, it is still worth it. The advantage is the way AC can be stepped-up to very high voltages and efficiently distributed over long distances from large, economical power stations.

The typical chain of transformations is:



## Transformers inside the Home

Even after all this transforming going on before the electricity gets into your home, it's still not finished.

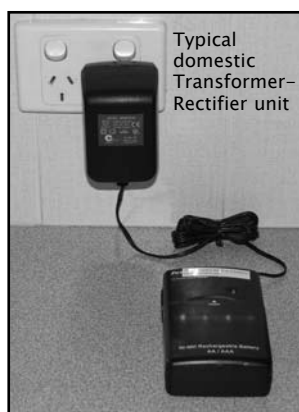
Many appliances inside your home need a transformer because they need more, or less, voltage than the 240V supply.

For example:

- TV picture-tubes need 1,500V to operate. Much of the weight of a TV set is the step-up transformer inside.



- Many electronic devices need only low voltages, such as 12V or less. Smaller gadgets often have the necessary transformer in a "box" combined with the electric plug.



A lot of smaller devices not only run on low voltage, but often need DC instead of AC.

Their transformers are also "rectifiers" to produce direct current.

## Impacts of the Development of Transformers on Society

The syllabus requires you to be able to discuss the impact of transformers on society. Development of transformers was, of course, an integral part of the development of our modern electrical supply system, based on large power stations and long-distance transmission of high voltage AC.

The history and social impacts have already been outlined... see page 13.

**Worksheet 3**
**Part A**

**Fill in the blanks. Check answers at the back**

The purpose and function of a transformer is to  
a).....  
This allows electricity to be stepped-up to  
b)..... voltages for efficient, long-distance  
c)....., and then  
d)..... again for convenient safe use by consumers.

The basic structure of a transformer is simple: it consists of e)..... coils, called the f)..... and .....  
The coils are arranged one inside the other, with a core of g)..... in the centre. If h)..... electricity flows in the i)..... coil, it creates a j)..... magnetic field. This, in turn, k)..... an EMF in the secondary coil, at a l)..... voltage.

A “step-up” transformer has more turns of wire in its m)..... coil, and its output voltage is n)..... than the input. A “step-down” transformer has more turns in its o)..... coil and its output voltage is p).....

In a perfect transformer, the input and output q)..... will be equal, because of the Law of r)..... of .....  
This means that if voltage is stepped up, then s)..... will be lower.

In reality, there are t)..... in any transformer, mainly due to u).....

This is partly due to resistance in the coils, but mainly because of resistance to v)..... currents induced in the iron core. Once some heat is produced, the resistance w)..... at higher temperatures. To minimize these energy losses:

- transformers are designed to x)..... heat.
- thicker wires in coils reduce y).....
- the iron core is made from z)..... sheets of iron, aa)..... together to minimize the ab)..... currents.

The electricity generated at a power station is usually stepped ac)..... to at least ad)..... volts for long-distance transmission. It will then be stepped-ae)..... in 4 or 5 separate transformers at district, suburb and af)..... levels, before entering your home at ag)..... volts.

Even inside the home there may be many transformers working. For example, a ah)..... requires about 1,500V and has a step-ai)..... transformer to do this. Small electronic equipment often runs on aj)..... voltage ak)..... current. These devices often have a “transformer - al).....” unit combined with their electricity plug.

**COMPLETED WORKSHEETS  
BECOME SECTION SUMMARIES**

**Part B Practice Problems Transformers**

**1.**

A transformer has 2,000 turns in its primary and 200 turns in its secondary coil. Input is 240V AC.

- a) Find its output voltage.
- b) Is this a step-up or step down transformer?

**2.**

At an electricity “sub-station” the voltage is stepped-down from 66,000V to 11,000V. The massive transformer has 52,000 turns of wire in its primary coil. How many turns in the secondary coil, to the nearest thousand.

**3.**

The 240V plug-in “recharger” for a mobile phone contains a transformer with 50 turns in its secondary coil. Its output is 6.0V DC.

- a) How many turns in the primary coil?
- b) Apart from being a transformer, what else must this unit do?
- c) Explain why this “other” function must be done after the step-down transformer function is achieved.

**Remember that for full marks  
in calculations, you need to show  
FORMULA, NUMERICAL SUBSTITUTION,  
APPROPRIATE PRECISION and UNITS**



## 4. MORE ON MOTORS

### The Induction Motor Principle

Back in the early days of commercial electricity, when Edison's DC system was "fighting it out" with Westinghouse's AC system, one of the factors that finally led to a victory for AC was Tesla's Induction Motor.

#### Practical Investigation

You may have carried out an experiment similar to this:

Copper or aluminium disk  
suspended on a thread

Disk begins  
to rotate,  
"chasing"  
the magnet

Magnet

N S

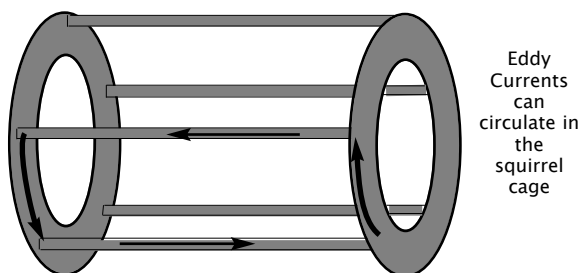
Magnet rotated underneath metal disk.  
(e.g. by attaching to a drill)

#### Explanation

The moving magnet induces "Eddy Currents" in the metal disk. These in turn create their own magnetic fields. These magnetic fields interact with each other so that the disk experiences a torque, and begins to rotate, "chasing" the rotating magnet.

The Induction Motor works on this same principle:

- **The Stator** is a series of coils, fed with AC current in such a way that the magnetic fields "rotate" by a rippling on-and-off in sequence around the outside.
- **The Rotor** is mounted on an axle for rotation. It contains a laminated iron core to intensify magnetic fields. The main part, however, is a copper frame known as the "squirrel cage" because it resembles an exercise wheel for a caged pet.



The moving magnetic fields produced by the stator coils induce "Eddy Currents" in the squirrel cage. These can circulate freely in the copper cage, and produce their own magnetic fields.

The squirrel cage fields interact with the rotating stator fields such that the rotor experiences torque, and rotates to "chase" the stator fields.

### Features of the Induction Motor

- No external current needs to be fed into the rotor, so there is no need for any slip-rings or commutator. This simplifies the motor, reduces maintenance, and makes it less likely that anything can wear out or need replacing.

Therefore, the motor is reliable and low-maintenance.

- The motor works only on AC, and rotates at a constant speed according to the frequency of the AC supply.

This can be a limitation, and means that gears or pulleys are needed to run machinery either faster or slower than the motor speed.

Apparently the simplicity and reliability advantages far outweigh the limitations, because it is estimated that about 95% of the millions of electric motors in the world are AC Induction types!

### Electrical Energy Conversions

The final point to be made in this topic is the same as one of the first points made in the related Preliminary topic...

**Electricity is so useful  
because it is so easily converted  
into so many other energy forms,  
quickly, efficiently & cleanly**

Examples: In the home, electricity is converted into:

- **Heat**, by stoves, toasters, kettles, etc.
- **Light**, by light bulbs and fluoro tubes.
- **Sound**, by hi-fi speakers.
- **Microwaves**, in a microwave oven.
- **Radio waves**, by a cordless, or mobile phone.
- **Infra-red waves**, by a radiant heater, or TV remote.
- **Kinetic & mechanical energy**, by a blender or drill.

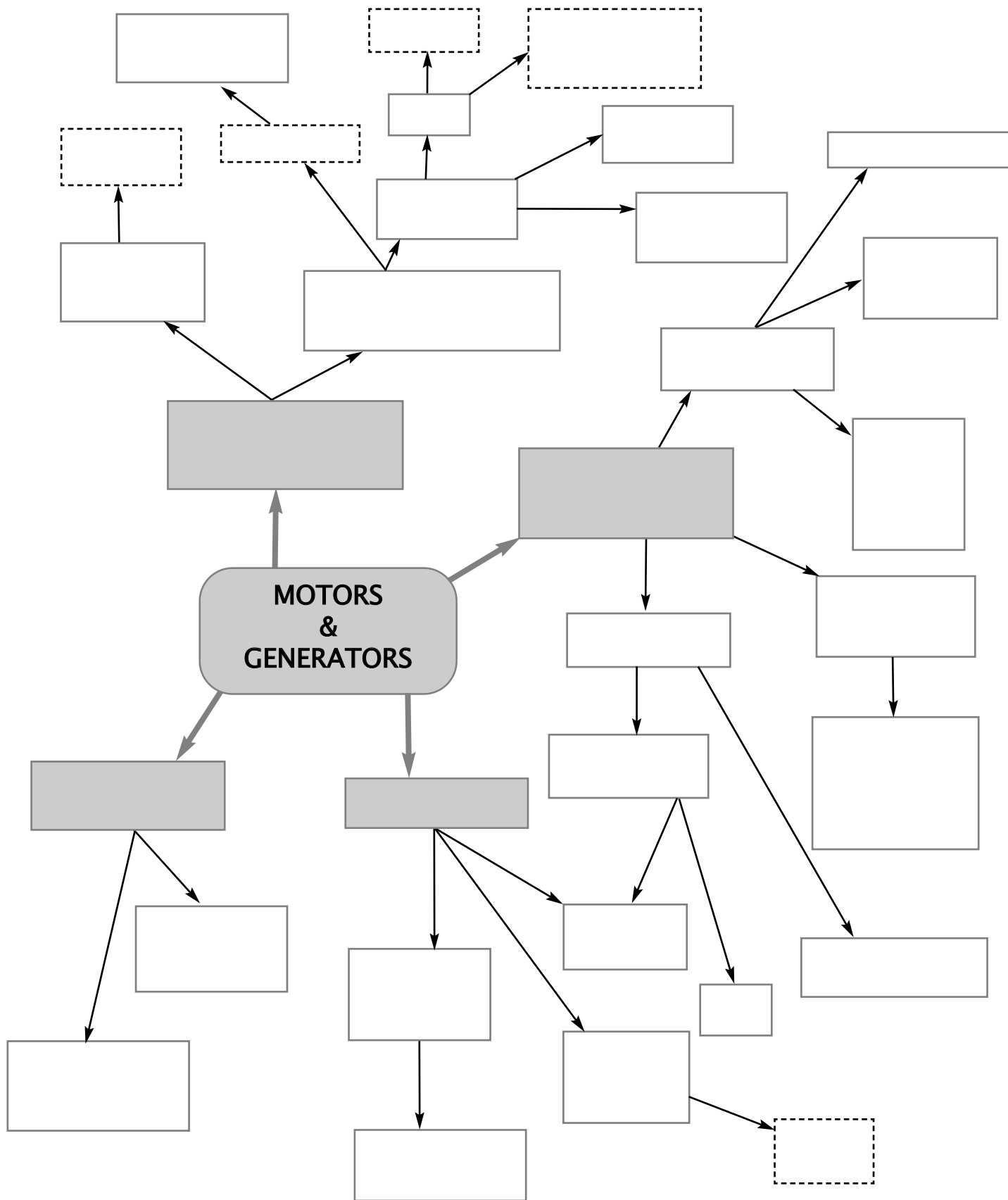
In industry, electricity is converted into:

- **Radio waves**, for radio & TV transmissions.
- **Kinetic & mechanical energy**, in industrial machinery, conveyors and elevators.
- **X-rays**, for medical imaging.
- **Light**, in laser beams for communication.

... and so many more examples.

# **CONCEPT DIAGRAM (“Mind Map”) OF TOPIC**

Some students find that memorizing the **OUTLINE** of a topic helps them learn and remember the concepts and important facts.  
Practise on this blank version.





## Practice Questions

These are not intended to be "HSC style" questions, but to challenge your basic knowledge and understanding of the topic, and remind you of what you NEED to know at the K.I.S.S. principle level.

When you have confidently mastered this level, it is strongly recommended you work on questions from past exam papers.

### Part A Multiple Choice

1. The diagram shows 2 wires carrying the same current, but in opposite directions. The point "X" is mid-way between the wires.



Which vector shows the direction of the magnetic field at point X?

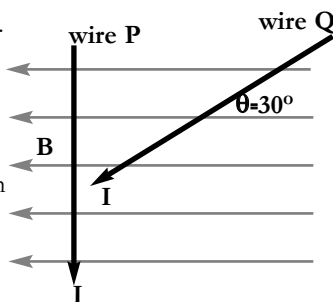
- A. B. C. D.

2. Two long parallel wires are carrying currents  $I_1$  and  $I_2$  in the same direction. The wires are "d" metres apart. The wires exert a force per unit of length on each other. If both currents were doubled and the distance between the wires halved, by what factor would the force per unit length change?

- A. increase, by a factor of 8.  
B. increase, by a factor of 2.  
C. remain the same.  
D. decrease, by a factor of 4.

The diagram is used for questions 3 and 4.

It shows 2 wires P & Q both carrying the same current through the same magnetic field. The length of each wire within the field is the same.



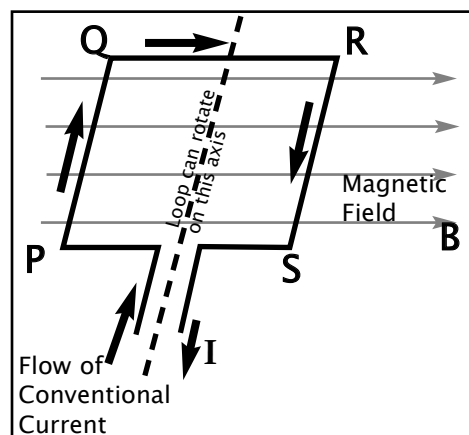
3. The force experienced by wire P would be directed:

- A. to the right  
B. to the left  
C. out of the page  
D. into the page

4. Compared to the force acting on P, the force on wire Q would be:

- A. exactly the same.  
B. about 87% as strong.  
C. exactly half as strong.  
D. zero.

5. The diagram shows a rectangular coil PQRS carrying a current in a magnetic field.



Which line of information (A,B,C or D) correctly identifies the direction of magnetic force acting on side PQ and on side QR?

- |    | Force on PQ | Force on QR |
|----|-------------|-------------|
| A. | out of page | into page   |
| B. | nil         | out of page |
| C. | into page   | up page     |
| D. | into page   | nil         |

6. A "torque" is produced when:

- A. a force causes circular motion.  
B. a force acts on a pivot point, causing acceleration.  
C. a pair of separated forces act in opposite directions.  
D. a pair of forces act in the same direction.

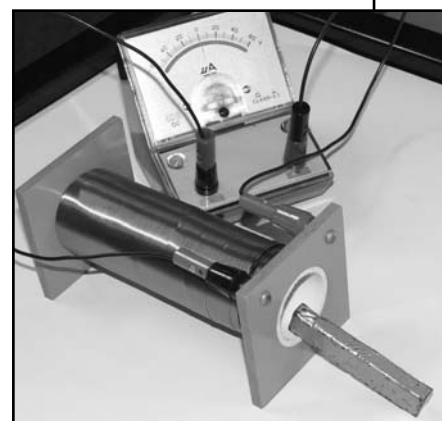
7. Electric motors often have a curved stator structure to give a "radial magnetic field". The benefit of this field is that it:

- A. gives a more constant torque as the coil rotates.  
B. reverses the current each half-revolution.  
C. intensifies the field in the centre of the coil for increased torque.  
D. reverses the field so the coil will turn the other way.

8. In an experiment, Sam noted that when the N pole of the magnet was pushed into the coil, the galvanometer needle moved left.

Which of the following would also cause the needle to move left?

- A. pulling N pole out.  
B. pulling S pole out.  
C. reverse the wire leads, then push N pole in.  
D. push N pole in at other end of coil.



9. The magnetic field “strength” (B) is more correctly known as:  
 A. Magnetic Flux  
 B. Magnetic Flux Density  
 C. the rate of change of Magnetic Flux  
 D. Electromagnetic Force, or EMF
10. In a simple generator with a rotating coil, the function of slip-rings and brushes is to:  
 A. ensure a constant torque on the coil.  
 B. pass current from the external circuit into the coil.  
 C. pass induced current from coil to the external circuit.  
 D. provide the external magnetic field.
11. Which of the following is NOT one of the reasons that we use AC electricity in preference to DC?  
 A. AC generators do not need commutators.  
 B. AC can be readily changed from one voltage level to another.  
 C. AC induction motors are efficient and reliable.  
 D. AC is more readily converted into heat, light, etc.
12. A wire strung above the power lines and connected to the towers without any insulation, is probably:  
 A. to carry the highest voltage electricity.  
 B. a communication wire for electricity workers.  
 C. to protect the wires from lightning strikes.  
 D. a safety cable for maintenance workers.
13. During the early development of electricity supply systems:  
 A. Westinghouse favoured AC, Edison favoured DC.  
 B. Tesla sold his inventions to the Edison company.  
 C. Both Westinghouse and Edison favoured AC supplies.  
 D. The Edison company built the first AC power station.
14. As you push a North pole of a magnet into a coil a current will be induced in the coil. This induced current will create its own magnetic field. You would expect the North pole of this “induced field” to be located:  
 A. at the opposite end of the coil from where you are.  
 B. at the near end of the coil.  
 C. in the middle of the coil, pointing upwards  
 D. in the middle of the coil, pointing downwards.
15. A transformer has 100 turns in its primary coil and 400 in the secondary coil. Its output voltage is 1,000V. Which statement is true?  
 A. This is a step-up transformer, and input voltage=4,000V  
 B. Input was 250V, and this is a step-down transformer.  
 C. It is a step-down transformer, with input = 4,000V.  
 D. Input = 250V, and this is a step-up transformer.
16. Which statement is correct for a “perfect” transformer with 100% efficiency?  
 A. The voltages in each coil are equal.  
 B. The product of (voltage x current) is equal in each coil.  
 C. The currents in each coil are equal.  
 D. A heat exchanger is needed to cool the transformer.

17. In an AC induction motor:  
 A. magnetic fields in the squirrel cage rotor chase the rotating stator fields.  
 B. the rotor fields in the squirrel cage are created by current fed to the coils via a commutator.  
 C. the stator consists of curved magnets to provide a radial field to give constant torque to the squirrel cage.  
 D. the squirrel cage is made of soft iron pieces, laminated together, to minimize the eddy currents.

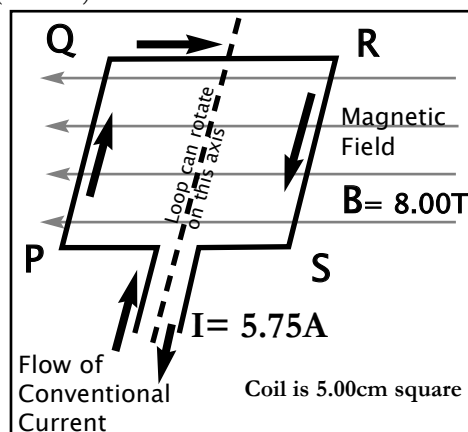
### Longer Response Questions

Mark values shown are suggestions only, and are to give you an idea of how detailed an answer is appropriate.

18. ( 4 marks)  
 Two parallel wires are carrying 12.0A and 7.50A of current in opposite directions. The parallel section of the wires is 1.85m long, and the wires are 1.00cm apart. Calculate the total force (including direction) which will act between these wires.

19. (4 marks)  
 A wire is carrying 9.00A of current in a direction due north. 0.750m of the wire is within a vertical magnetic field, which causes a force of 3.25N to push the wire due east. Find the magnitude and direction of the magnetic field.

20. (8 marks)



The rectangular coil PQRS is made of a single strand of wire. It is carrying current through a field as shown.

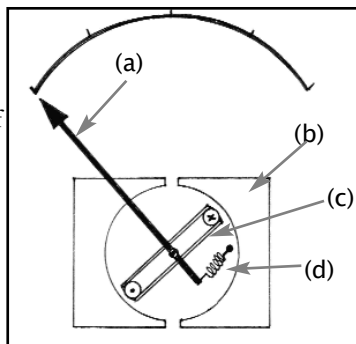
- Find the force acting on side RS, including direction.
- What force acts on side QR?  
Explain your answer.
- Find the torque on the coil at the moment when the plane of the coil is inclined at an angle of  $10^\circ$  to the field lines.

21. (5 marks)  
 a) In a simple DC motor, describe the role of:  
 i) the commutator  
 ii) the stator  
 b) Explain what is meant by a “radial magnetic field”, and describe the advantage it gives in a rotating-coil motor.

22. (8 marks)

The diagram shows the simplified structure of a galvanometer, the basis of all electrical meters.

For each of the parts labelled (a), (b), (c) & (d) identify what that part is, and explain briefly its purpose.



23. (4 marks)

During your studies you will have carried out a first-hand investigation into induction, using equipment similar to that shown in this photo.

What is the effect on the induced current of:

- using a stronger magnet?
- placing the magnet inside the coil and leaving it stationary?
- moving the magnet at a point further from the coil?
- reversing which pole of the magnet is inserted into the coil?



24. (3 marks)

- Give a definition of “magnetic flux density” and state the unit of measurement.
- Complete this statement: “Michael Faraday found that the size of the induced EMF is proportional to.....”

25. (4 marks)

Compare and contrast a simple moving-coil motor and a simple moving-coil electric generator.

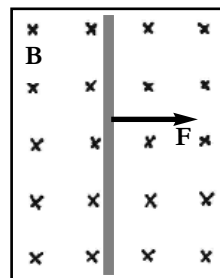
26. (3 marks)

Justify society's choice of AC electricity supply over DC.

27. (4 marks)

Assess the effects of the development of AC generators on society and the environment.

28. (3 marks)



A conducting wire is being acted upon by a force as shown, so that it is moving through a magnetic field. A current is induced in the wire.

The induced current will result in another force acting on the wire.

- In which direction the other force will act?
- Deduce the direction of the current flow in the wire.
- State the scientific principle involved.

29. (4 marks)

Outline the process of “electromagnetic braking”, giving an example of where it might be used, naming the scientific principle responsible, and explaining how braking forces are produced.

30. (4 marks)

A small step-down transformer-rectifier unit has an output of 8.00V from 240V mains input. Its secondary coil contains 60 turns of wire.

- How many turns in the primary coil?
- What is the purpose of the unit being a “rectifier”?

31. (6 marks)

- Describe the basic structure and operation of an AC induction motor.
- Assess the features of the AC Induction Motor.

**Remember that for full marks  
in calculations, you need to show  
FORMULA, NUMERICAL SUBSTITUTION,  
APPROPRIATE PRECISION and UNITS**

## Answer Section

### Worksheet 1

#### Part A

- |                             |                                |
|-----------------------------|--------------------------------|
| a) electric current         | b) force                       |
| c) magnetic field           | d) attract                     |
| e) is in opposite direction | f) repel                       |
| g) length                   | h) the product of the currents |
| i) inversely                | j) magnetic                    |
| k) force                    | l) teslas (T)                  |
| m) current                  | n) length                      |
| o) magnetic field           | p) (sine ratio of) angle       |
| q) Motor                    | r) right angles                |
| s) Right Hand Palm          | t) turning                     |
| u) rotate                   | v) magnetic field              |
| w) equal but opposite       | x) current                     |
| y) magnetic field           | z) current                     |
| aa) area                    | ab) plane                      |
| ac) 0°                      | ad) 90°                        |
| ae) coil of wire            | af) rotate                     |
| ag) stator                  | ah) permanent                  |
| ai) electromagnet           | aj) electrical                 |
| ak) commutator              | al) reverse direction          |
| am) galvanometer            | an) torque                     |
| ao) radial                  | ap) vibration                  |
| aq) inter-acting            |                                |

#### Part B Practice Problems

##### Force Between Parallel Wires Carrying Current

1.

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

$$= 2.00 \times 10^{-7} \times 15.3 \times 12.7 / 0.0100 = \mathbf{3.89 \times 10^{-3} \text{ Nm}^{-1}}$$

The force will repel the wires.

2.

$$\frac{F}{L} = \frac{k I_1 I_2}{d} \quad \text{and } I_1 = I_2 = I$$

$$8.25 \times 10^{-5} = 2.00 \times 10^{-7} \times (I^2) / 0.100$$

$$\therefore I = \sqrt{8.25 \times 10^{-5} \times 0.100 / 2.00 \times 10^{-7}} = \mathbf{6.42 \text{ A}}$$

Since force is attracting, the currents must be in same direction.

3.

$$\frac{F}{L} = \frac{k I_1 I_2}{d} \quad \text{so, } F = k I_1 I_2 L / d$$

$$\text{so } d = k I_1 I_2 L / F$$

$$= 2.00 \times 10^{-7} \times 8.90 \times 14.5 \times 1.48 / 6.44 \times 10^{-4}$$

$$= \mathbf{0.0593 \text{ m} (= 5.93 \text{ cm})}$$

4.

$$\frac{F}{L} = \frac{k I_1 I_2}{d} \quad \text{so } F = k I_1 I_2 L / d$$

$$= 2.00 \times 10^{-7} \times 30.0 \times 30.0 \times 25.0 / 0.0800$$

$$= \mathbf{5.63 \times 10^{-2} \text{ N, attraction.}}$$

##### Force on Wire Carrying Current Through a Field (Motor Effect)

5.

$$F = BIL \sin \theta$$

$$= 11.0 \times 4.50 \times 1.25 \times \sin 90^\circ$$

$$= \mathbf{61.9 \text{ N}}$$

RH palm rule shows force is directed up the page.

6.

$$F = BIL \sin \theta$$

$$= 22.7 \times 5.95 \times 0.385 \times \sin 60^\circ$$

$$= \mathbf{45.0 \text{ N}}, \text{ directed vertically into the page.}$$

7.

$$F = BIL \sin \theta, \quad \text{So } I = F / B L \sin \theta$$

$$= 27.2 / 105 \times 2.44 \times \sin 90^\circ$$

$$= \mathbf{0.106 \text{ A}}. \quad (1.06 \times 10^{-1} \text{ A})$$

RH palm rule shows current flows down the page.

8.

$$F = BIL \sin \theta, \quad \text{So } \sin \theta = F / B I L$$

$$= 3.72 / 7.50 \times 8.00 \times 0.287$$

$$= 0.2160$$

$$\therefore \theta = \mathbf{12.5^\circ}$$

##### Torque on a Coil in a Field

9.

$$\tau = n B I A \cos \theta$$

$$= 200 \times 5.25 \times 1.50 \times 1.20 \times 10^{-3} \times \cos 0^\circ$$

$$= \mathbf{1.89 \text{ N.m.}}$$

10.

$$a) \tau = n B I A \cos \theta$$

$$= 35 \times 8.38 \times 2.50 \times (0.20 \times 0.20) \times \cos 0^\circ$$

$$= \mathbf{29.3 \text{ N.m.}}$$

b) RH Palm rule shows left side force is up, right side force down, therefore coil will rotate clockwise.

11.

$$\tau = n B I A \cos \theta \quad \text{so, } n = \tau / B I A \cos \theta$$

$$= 3.86 / 4.60 \times 3.20 \times 0.00262 \times \cos 0^\circ$$

$$= \mathbf{100 \text{ turns.}}$$

12.

$$a) \tau = n B I A \cos \theta \quad \text{so, } I = \tau / n B A \cos \theta$$

$$= 12.3 / 12 \times 22.3 \times (0.0800 \times 0.0500) \times \cos 0^\circ$$

$$= \mathbf{11.5 \text{ A}}$$

b) To rotate as shown, the force on left side of coil must be downward. RH Palm Rule indicates current must flow clockwise around coil.

### Worksheet 2

- |  |                         |
|--|-------------------------|
| a) Faraday                                 | b) generator            |
| c) magnet                                  | d) relative             |
| e) coil & magnet                           | f) current              |
| g) stronger                                | h) closer               |
| i) faster                                  | j) reverses             |
| k) reverses                                | l) Flux Density         |
| m) magnetic field                          | n) area                 |
| o) EMF                                     | p) magnetic flux        |
| q) rotate                                  | r) permanent            |
| s) electromagnets                          | t) induced              |
| u) brushes                                 | v) slip-rings           |
| w) motor                                   | x) current direction    |
| y) alternating current (AC)                | z) commutator           |
| aa) reverse                                | ab) sparking            |
| ac) slip                                   | ad) coil                |
| ae) magnets                                | af) external circuit    |
| ag) resistance                             | ah) current             |
| ai) high                                   | aj) low                 |
| ak) transformer                            | al) insulators          |
| am) ceramic                                | an) lightning           |
| ao) shield conductors                      | ap) ground              |
| aq) Edison                                 | ar) DC                  |
| as) power                                  | at) energy              |
| au) Tesla                                  | av) generators, motors  |
| aw) Niagara                                | ax) positive/beneficial |
| ay) labour                                 | az) electronic/computer |
| ba) communication, entertainment, business |                         |
| bb) negative                               | bc) coal/fossil fuels   |
| bd) Greenhouse Effect                      | be) Global Warming      |
| bf) EMF/current                            | bg) opposes             |
| bh) Conservation of Energy                 | bi) back-EMF            |
| bj) braking                                | bk) induction           |
| bl) eddy                                   |                         |

## Worksheet 3

### Part A

- |                              |                       |
|------------------------------|-----------------------|
| a) change the voltage        | b) higher             |
| c) transmission/distribution |                       |
| d) stepped-down              | e) two                |
| f) primary & secondary       | g) iron               |
| h) AC                        | i) primary            |
| j) fluctuating               | k) induces            |
| l) different                 | m) secondary          |
| n) higher                    | o) primary            |
| p) lower                     | q) power/energy       |
| r) Conservation of Energy    | s) current            |
| t) energy losses             | u) resistance heating |
| v) eddy                      | w) increases          |
| x) lose/radiate              | y) resistance         |
| z) (many) thin               | aa) laminated         |
| ab) eddy                     | ac) up                |
| ad) 250,000                  | ae) down              |
| af) neighbourhood            | ag) 240               |
| ah) TV screen                | ai) up                |
| aj) low                      | ak) DC                |
| al) rectifier                |                       |

### Part B Practice Problems

1.

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

$$\text{so } V_s = V_p \cdot n_s / n_p$$

$$= 240 \times 200 / 2,000$$

$$= 24.0V$$

b) Step-down, because output voltage lower.

2.

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

$$\text{so } n_s = n_p \cdot V_s / V_p$$

$$= 52,000 \times 11,000 / 66,000$$

$$= 8,666$$

$$\approx 9,000 \text{ turns.}$$

3.

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

$$\text{so } n_p = V_p \cdot n_s / V_s$$

$$= 240 \times 50 / 6$$

$$= 2,000 \text{ turns.}$$

b) Rectify AC to DC output

c) Must be done after, because DC cannot easily be transformed, while AC can.

### Practice Questions

#### Part A Multiple Choice

- |      |      |       |       |       |
|------|------|-------|-------|-------|
| 1. B | 5. D | 9. B  | 13. A | 17. A |
| 2. A | 6. C | 10. C | 14. B |       |
| 3. D | 7. A | 11. D | 15. D |       |
| 4. C | 8. B | 12. C | 16. B |       |

#### Part B Longer Response Questions

In some cases there may be more than one correct answer. The following “model” answers are correct but not necessarily perfect.

18.

$$F = k I_1 I_2 L / d$$

$$= 2.00 \times 10^{-7} \times 12.0 \times 7.50 \times 1.85 / 0.0100$$

$$= 3.33 \times 10^{-3} N$$

Force will repel the wires, since currents opposite.

19.

$$F = B I L \sin \theta, \quad \text{so, } B = F / I L \sin \theta$$

$$= 3.25 / 9.00 \times 0.750 \times \sin 90$$

$$= 0.481 T$$

RH Palm Rule shows field is vertically upwards.

20.

a) 
$$F = B I L \sin \theta,$$

$$= 8.00 \times 5.75 \times 0.0500 \times \sin 90$$

$$= 2.30 N$$

RH Palm Rule shows force is into page.

b) Zero, because current flows parallel to field lines.

c) 
$$\tau = n B I A \cos \theta$$

$$= 1 \times 8.00 \times 5.75 \times (0.0500)^2 \times \cos 10^\circ$$

$$= 0.113 N.m$$

21.

a) i) Commutator reverses the direction of current in the coil every 1/2 revolution. This is necessary to keep the torque in the same direction, and keep the coil turning.

ii) The stator provides the magnetic field around the coil. It can be one or more permanent magnets, or electromagnet(s).

b) A “radial” field has its field lines in a pattern like the spokes of a wheel... radii of a circle. This means that the coil lies “flat” in the field ( $\theta = 0^\circ$ ) through most rotation positions. Since the torque on the coil is proportional to  $\cos \theta$ , this ensures maximum torque throughout the rotation.

22.

a) Pointer needle. This rotates with the coil to give the meter reading on the calibrated scale.

b) Permanent magnet. This provides the magnetic field for interaction with the coil. It is shaped to give a radial field for constant torque at all positions.

c) Coil. When current flows in this coil it interacts with the field, and experiences a torque to turn the needle.

d) Spring. This works against the coil, so the needle moves only so far for each level of torque produced. Also returns the needle to the zero mark when power is off.

23.

a) Using a stronger magnet induced more EMF, so more current flowed. (The galvanometer showed a greater deflection)

b) While the magnet was stationary the galvanometer showed no current flow.

c) If moved at a more distant point there was less induced current.

d) Reversing the pole reversed the current flow. (The galvanometer needle deflected in the opposite direction)

24.

a) Magnetic Flux Density is a measure of the intensity of a magnetic field. It can be thought of as the number of “magnetic field lines” passing through a given area of space.

It is commonly known as “magnetic field strength” and measured in teslas(T).

b) “... the rate of change of magnetic flux through the conductor”.

25.

("Compare & Contrast" means you must point out similarities AND differences.)

A simple motor and a simple generator are very similar in structure: both are built from

- one or more coils of wire on an axle. (The "Rotor")
- a magnet to provide a magnetic field. (The "Stator")
- a set of brushes to connect the coil to an external circuit.
- a commutator or set of slip-rings on the coil axle, in contact with the brushes.

The major difference between them is their function:

- A motor uses electricity to produce the rotating movement of the coil. Electricity Kinetic energy.
- A generator produces electricity from the rotation of the coil, usually caused by the rotation of a turbine. Kinetic energy Electricity.

26.

("Justify" means to give reasons why this is correct or true)  
AC electricity has many advantages that make it more suitable than DC for large-scale electricity supply:

- AC can be easily stepped-up or down in voltage by transformers. This allows for efficient distribution over long distances at very high voltages (minimum energy loss) and then convenient and safe usage by consumers at lower voltage.
- AC generators can be constructed without a commutator to carry current to the external circuit. This is more efficient than a DC generator, and requires less maintenance, too.
- AC induction motors are cheap, reliable and efficient.

27.

("Assess" means to measure or weigh up the pros and cons)  
The development of AC generators has had impacts on society that have been mainly beneficial, such as:

- development of many labour-saving and convenience devices (e.g. washing machines, elevators, power tools) which have generally improved peoples' life-style.
- development of electronic devices and computers which are the basis of modern communications, entertainment, business and finance systems.

On the other hand, the impacts on the environment have been mostly negative ones:

- burning of fossil fuels in power stations is a major contributor to the Greenhouse Effect and Global Warming.
- nuclear accidents, such as Chernobyl 1986, carry serious risks to the environment and to people.
- Building dams for hydro-electricity alters watercourses and submerges ecosystems

Overall, the benefits to life-style have been seen by most people as worth the environmental destruction. This attitude is changing as the environmental damage becomes critical, and becomes a global threat.

28.

- It will act left, to counteract the motion.
- RH Palm Rule shows that current must flow up the page (in order to produce a Motor Effect force to the left.)
- Lenz's Law.

29.

- Electromagnetic braking is used to stop some amusement rides (e.g. "Space Shot" rides involving vertical free-fall) and used in some trains.
- It works because of Lenz's Law.
- The moving car/train has strong magnets attached. To brake the car, the magnets move past copper sheets. This induces "eddy currents", and Lenz's Law ensures that these currents will produce fields that oppose the induction magnets. Thus the car is slowed evenly and efficiently.

30.

$$\begin{aligned} \frac{V_p}{V_s} &= \frac{n_p}{n_s} \\ \text{so } n_p &= V_p \cdot n_s / V_s \\ &= 240 \times 60 / 8 \\ &= \mathbf{1,800 \text{ turns.}} \end{aligned}$$

- It converts AC input to DC output.

31.

- The stator is a series of coils which produce magnetic fields that "rotate" when supplied with AC current. The rotor contains a laminated iron core to intensify the fields, but also a copper cage-like structure known as the "squirrel cage". The stator fields induce eddy currents which flow freely in the squirrel cage and produce their own magnetic fields. These interact with the stator fields and "chase" their rotation. The result is a constant torque, so the rotor rotates.

- The AC induction motor has no need for any commutator or slip-rings so it is efficient and low-maintenance.

A disadvantage is that it runs only on AC, and can only run at one speed, determined by the frequency of the AC cycle. Overall, its advantages outweigh this limitation, since over 90% of all electric motors are of this type.

#### NOTICE ANY ERRORS?

Our material is carefully proof-read  
but we're only human

If you notice any errors, please let us know