Hale School Physics 3A 2012

Electromagnetism

Year 12 Study Notes

Name:

Teacher:

Set:

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Revision of Current Electricity

This area of study requires that students use the fundamental relationships and concepts of electricity dealt with in unit 2B in year 11. The following are regarded as being prerequisites:

- Perform simple calculations using: $F = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{d^2}$ for two point charges in a vacuum.
- Define the SI unit of electric charge and solve problems using the expression q = It.
- State that the direction of conventional current is that in which the flow of positive is referenced.
- Explain and use the formulae for electrical work and power: Work = qV = VIt; P = VI
- Be able to calculate the energy consumed by and the cost of operating common electrical appliances.
- Draw and interpret simple circuit diagrams including the use of standard symbols for resistor (fixed and variable), light bulb, switch, ammeter, voltmeter, dry cell and power supply.
- Describe the flow of electrical current through series and parallel circuits.
- State Ohm's Law and state the conditions under which it applies.
- Define ‘resistance’ and state its unit.
- State the factors that affect electrical resistance.
- Perform calculations using the relationship V = IR
- Describe the effect of having resistors connected in series.
- Perform simple calculations using the relationship: $R_t = R_1 + R_2 + ...$
- Describe the effect of having resistors connected in parallel.
- Perform simple calculations using the relationship: $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + ...$
- Perform calculations to determine I, V and R in different parts of simple and compound circuits.
- Connect components in simple circuits and measure values of current and potential difference using ammeters and voltmeters.
- Identify sources of electrical energy in simple circuits.
- Identify energy transformations which occur in electrical devices.

EXERCISE 1: Current Electricity

DATA: Elementary Charge (e) = 1.6×10^{-19} C Mass of an electron $m_e = 9.11 \times 10^{-31}$ kg

1. The heating current of an electric radiator is 4.00 A.
   a) What charge passes every minute?
   b) How many electrons pass in this time?

2. What is the pd of an electric circuit if 2.00×10^2 J of energy is changed to different forms when 25.0 C of charge passes? If the charge flows in 10.0 seconds what is the current?

3. What is the pd across an electrical circuit if 3.60×10^3 J of energy is liberated per second when a current of 15.0 A flows?

4. An electric radiator converts 6.48×10^6 J of electrical energy to heat in one hour. Calculate the potential difference across the terminals of the radiator, given that the current taken is 8.00 A.

5. An electric current of 6.00 A is maintained with a potential difference of 35.0 V. Calculate the electric charge that passed round the circuit and the electrical energy loss per minute.

6. An accumulator is charged with 1.80×10^5 C for 10.0 hours. If the emf is constant calculate the current maintained during this time.

7. An electric furnace takes an electric current of 12.0 A when connected to a 2.40×10^2 V supply. Calculate: a) the resistance of the furnace and b) the current taken by the furnace if the voltage supply is reduced to 2.20×10^2 V.

8. Calculate the current through a lamp which has a resistance of 1.50×10^2 Ω and is connected to a 2.40×10^2 V supply.

9. An electron was accelerated by a pd of 2.00×10^3 V. Determine the work done on the electron and its velocity.

10. A pd of 3.00×10^2 V is applied between two plates that are 5.00 m apart in a vacuum. Calculate the work done on an electron placed between the plates and hence the velocity of the electron after it has moved 2.00 m. (Potential gradient is uniform).

11. Three batteries each of emf 2.00 V and internal resistance 0.0100 Ω are joined in series and used to supply current to the circuit.
    a) What is the total emf of the supply?
    b) How much electrical energy per coulomb is supplied using i) one battery, ii) all batteries?
    c) What is the total internal resistance of the supply?
    d) What current would be driven through a resistance of 1.97 Ω ?

12. a) What is the resistance of a 240 V, 60.0 W globe?
    b) How much energy is supplied by the bulb in 2.00 minutes?

13. An electric heater provides a resistance of 25.0 Ω to an electric current of 8.50 A. Calculate the potential difference across the terminals of the heater.

14. The current through a moving coil meter is 0.40 mA when measuring a potential difference of 6.00 V. Determine: a) the resistance of the meter.
    b) the current when measuring a potential difference of 10.0 V.

15. Find the internal resistance of an electrical source if it has an E.M.F. of 6.00 V but will only deliver 0.50 A of current across a globe of resistance 10.0 Ω.

16. Three lamps are connected in series to a 24.0 V supply. Two of the lamps each have a resistance of 12.0 Ω, while the current is 0.60 A. Calculate:
    a) the resistance of the third lamp b) the potential difference across this lamp.

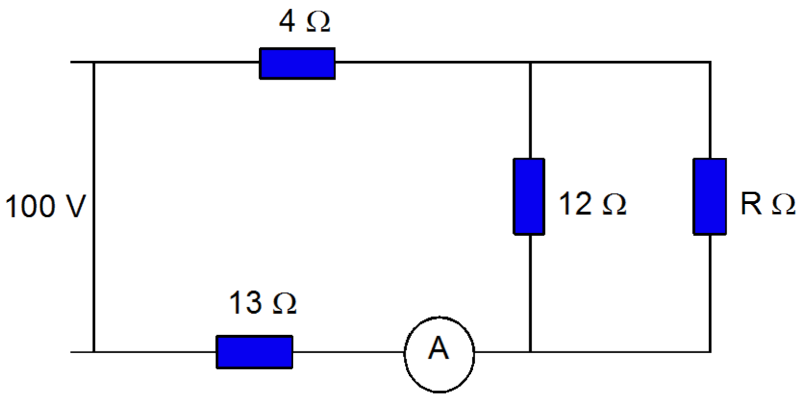
17. Three resistors of 5.00, 10.0 and 15.0 Ω respectively are connected in series. If the current is 4.00 A, determine: a) the total resistance b) the potential difference across each resistor c) the total voltage.

18. Four coils having resistances of 10.0, 15.0, 30.0, and 45.0 Ω respectively. They are connected in parallel to a 24.0 V battery with an internal resistance of 0.50. Calculate:
a) the total circuit resistance. b) the voltage available at the terminals of the battery.
c) the potential difference across the coils. d) the current in each coil.

19. Six lamps each having a resistance of 24.0 V are to be connected to a 50.0 V supply. Calculate the current in each lamp if they are connected in: a) series b) parallel. State, with reason, which circuit will give the brighter lights.

20. Six 40.0 W lamps of equal resistance are connected in parallel to a 240 V supply. Calculate the:
a) current in each lamp b) main circuit current c) resistance of each lamp.

21. If the ammeter reading A in the circuit shown above is 5.00 A determine the coil resistance R and the potential across each coil.



22. A small electric motor is rated at 400 W and takes a current of 1.80 A from a 240 V supply. Calculate the efficiency of the motor.

23. The power of the heating element in an electric iron is 875 W when connected to a 225 V supply. Calculate the current taken by the iron and the resistance of its heating element.

24. A lathe is provided with a small electric motor for driving a coolant pump. If the efficiency of the motor is 90% calculate the power output when a current of 50.0 mA is taken at 420 V. Also determine the energy provided by the motor during a continuous run of one hour.

ANSWERS

1 a)240 C, b) 1.50 x 10^{21}
2 8.00 V, 2.50 A
3 240V
4 225V
5 3.60 x 10^{2} C, 12.60 kJ
6 5.00A
7 a) 20.0 Ω b) 11.0 A
8 1.60A
9 3.20 x 10^{-16} J, 2.65 x 10^{7} ms^{-1}
10 1.92 x10^{-17}J, 6.49 x$10^{6}$$ms^{-1}$
11 a) 6.00 V b) 2.00 J C^{-1} c) 0.03 d) 3.00 A
12 a) 960 Ω b) 7200
13 212.5V
14 a) 15.0 kΩ b) 0.667mA
15 2.00 Ω
16 a)16.0 Ω b) 9.60 V
17 a) 30.0 Ω b) 20.0 V, 40.0 V and 60.0 V, c) 120 V
18 a) 5.00 Ω b) 21.6 V c) 21.6 V d) 2.16 A 1.44 A
19 a) 347.2 mA b) 2.083 A
20 a) 0.167 A b) 1.00 A c) 1440 Ω
21 4.00 Ω 20.0 V across 4.00 Ω 65.0V
22 92.59%
23 3.889A, 57.86 Ω
24 18.9 W 68.04 kJ

Magnetism

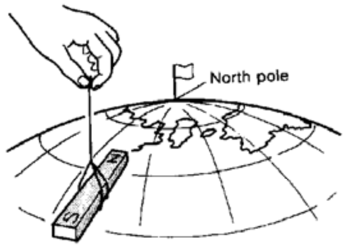
Magnets do not attract all metals. A magnet will attract **ferromagnetic materials.** These materials contain either iron, nickel, cobalt or an alloy containing one or more of these elements.

Magnetic Poles

No matter what their shape, all magnets have two poles (dipoles).

Magnetic poles are points where the strength of the magnetic force is greatest.

Observing magnet behaviour



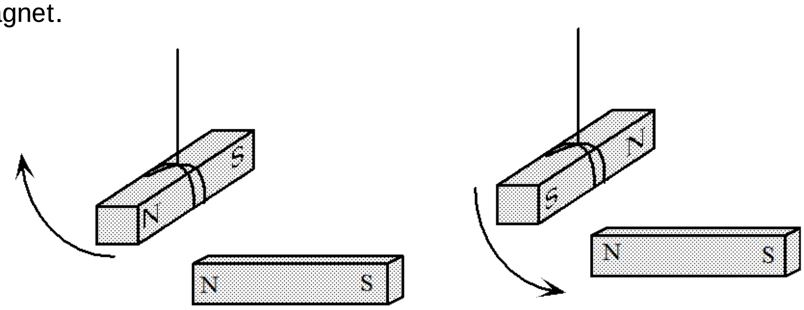
1. When a magnet is freely suspended, its magnetic axis will align itself in a north – south direction.

The pole that points in a northerly direction is termed the **North seeking pole** or simply "north pole".

Similarly the south seeking pole points in a southerly direction.

2. When two strong magnets are brought close together it is observed that **like poles repel** and **unlike poles attract**.

This can be demonstrated by observing the interaction between a freely suspended magnet brought close to fixed magnet.

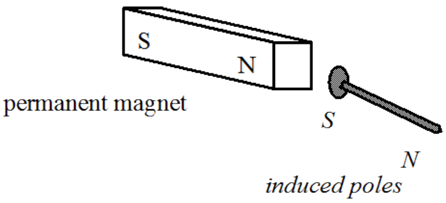


3. Induced magnetism - When a permanent magnet is brought close to say an iron nail, the nail is attracted to the magnet.

This occurs because the nail itself becomes magnetised.

The nail is said to become an **induced magnet** and has associated **induced poles**.

The induced pole closest to the permanent magnet has the opposite polarity to the adjacent pole of the permanent magnet.



Question: When a magnet is brought close to an un-magnetised object, it is observed to attract it. Explain why this occurs.

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The Domain Theory of Magnetism

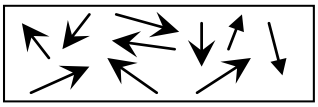
Each electron in an atom behaves as if it is a tiny magnet because of the way it **spins** as it moves around the nucleus.

For most materials the motion of the electrons results in the cancellation of this magnetic property.

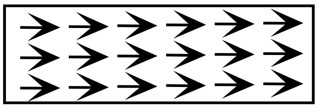
However **ferromagnetic** materials are composed of a large number of magnetised regions called **domains**.

Each domain is a crystalline structure consisting of atoms arranged with their electron spin axes aligned. Thus each domain behaves as a tiny magnet.

In an demagnetised piece of ferromagnetic material the domains are arranged randomly in such a way that the net magnetic effect is zero.



When a material is magnetised the domains become aligned, to a degree, in one direction.



Facts consistent with the Domain Theory

The facts below are consistent with the domain theory of magnetism. In each case explain the observed phenomenon in terms of the theory.

1. It is impossible to create a magnet with a single north or south pole.

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2. Breaking a magnet results in the formation of new magnets.

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3. Magnetism in ferromagnetic materials cannot be increased indefinitely.

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4. Magnetism can be destroyed by heating, vibration or striking the magnet.

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5. Harder materials have more permanent magnetism.

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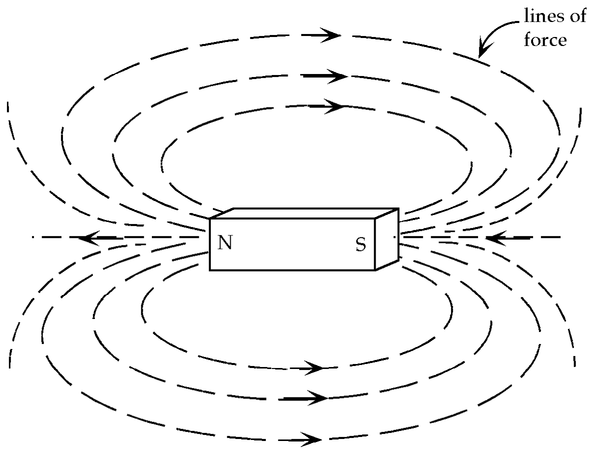
Magnetic Fields



Magnetic Field

A region where a magnetic material experiences a force is said to contain a magnetic field.

The lines of force (or magnetic flux) represent the path followed by a free magnetic north pole placed in the field.

The closeness of the lines is an indication of the relative strength of the field.

The closer the lines the stronger the magnetic field and thus the greater the force exerted on a magnetic material placed at that point.

Magnetic field lines form closed loops.
(unlike electric fields)

Magnetic field lines continue inside a magnet.

Note that the magnetic lines of force are not parallel or equidistant.

Question 1: With reference to the magnetic field shown, indicate where the magnetic field strength is (i) greatest (ii) weakest.

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Question 2: Explain why the direction of the magnetic field is always from the north pole and towards the south pole of the magnet.

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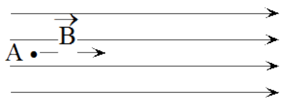
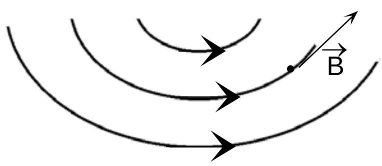
Magnetic Field Strength

Magnetic field strength $\vec{B}$ is a vector quantity and thus has direction as well as magnitude.

The direction of $\vec{B}$ at a given point in the field is the direction of the field at that point.

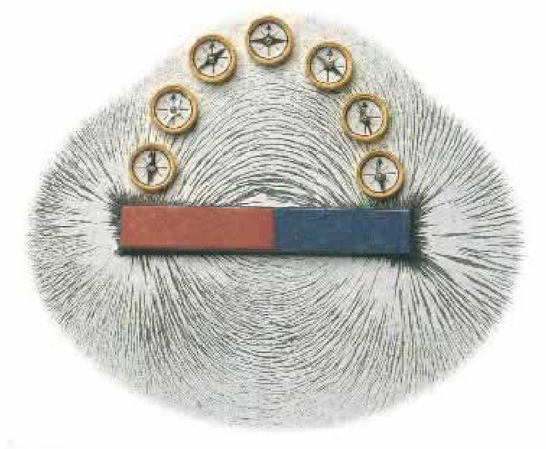


In a uniform field, $\vec{B}$ is in the direction of the field lines.



In a curved field $\vec{B}$ is in the direction of a tangent to the curve at that point.

Plotting a Magnetic Field



If a freely suspended magnet is placed in a magnetic field, it will align its magnetic axis in the direction of the field.

Small plotting compasses consist of freely suspended magnets and thus may be used to plot the direction of a magnetic field at a given point.

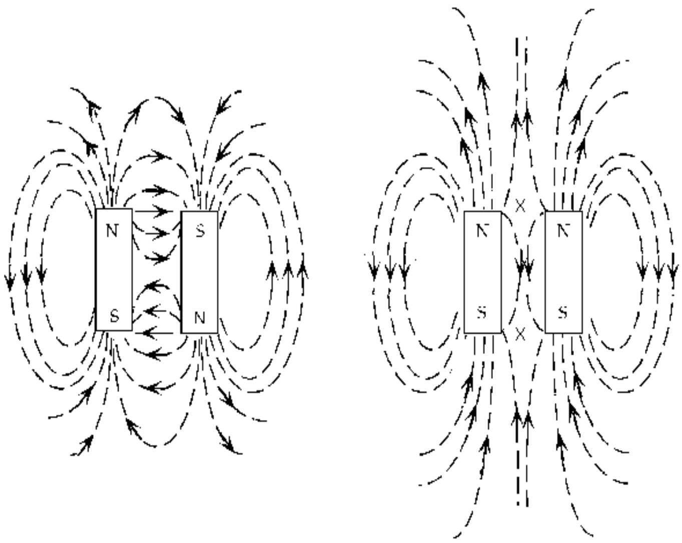
The field surrounding a bar magnet can be mapped using iron filings.

If iron filings are sprinkled about a bar magnet then they will align themselves along the lines of flux.

When iron filings are placed in a magnetic field each fragment of iron becomes a tiny induced magnet.

The iron filings thus align themselves in the direction of the field "head to tail" forming a line of iron filings.

Interaction of Magnetic Fields



Magnetic fields interact to produce resultant or composite fields.

The diagram illustrates the fields resulting from the interaction of adjacent bar magnets.

The resultant field can largely be determined from the vector addition of the component fields.

Flux lines associated with magnetic fields cannot intersect.

To do so would mean that the field has two directions at the point of intersection of the field lines. This cannot occur.

In the diagrams above, X represents "null points" in the field.

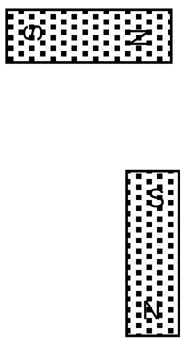
These are points where the field strengths due to each magnet cancel producing a resultant zero field strength.

The diagrams below represent pairs of adjacent magnets. Draw the **resultant** fields associated with each pair of magnets. Indicate the direction of magnetic field

(a)

(b)

(c)

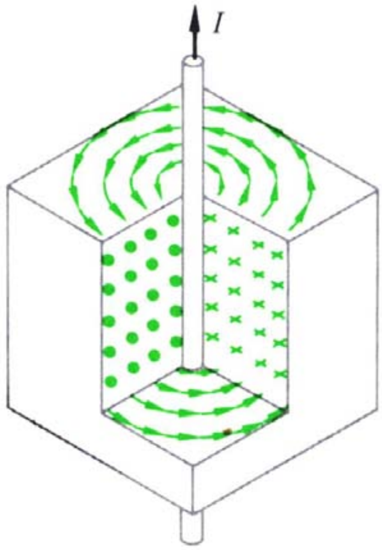


Representation of Magnetic Fields

It is often advantageous to represent magnetic fields moving either into or out of the page.

An “x” represents a magnetic field into the page

while a “•” represents a magnetic field out of the page.



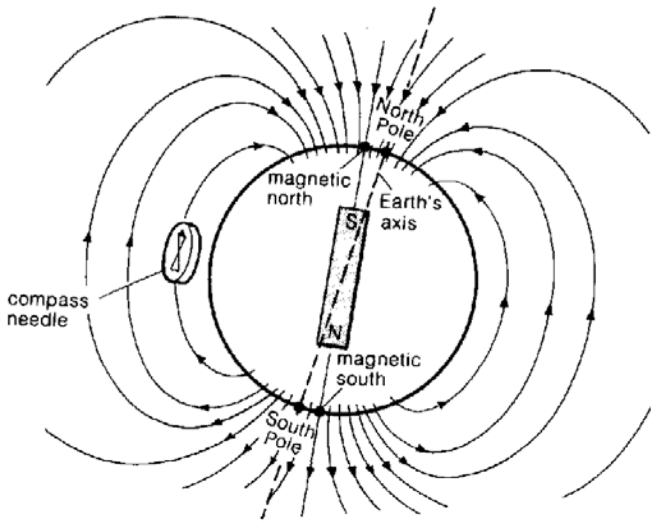
Earth's Magnetic Field

The Earth's magnetic field is similar to that produced by an imaginary large bar magnet located inside the earth.

A line extended through the poles of this imaginary magnet is termed the Earth's magnetic axis.

The Earth's magnetic axis makes an angle of approximately 11^0 with the earth's polar axis (a line extended through the Earth's geographic poles).

At any given point on the Earth's surface a freely suspended magnet or magnetic compass will align itself along the line of flux which passes through that point.



The magnetic field strength at the surface of the Earth varies between 30 μT and 60 μT.

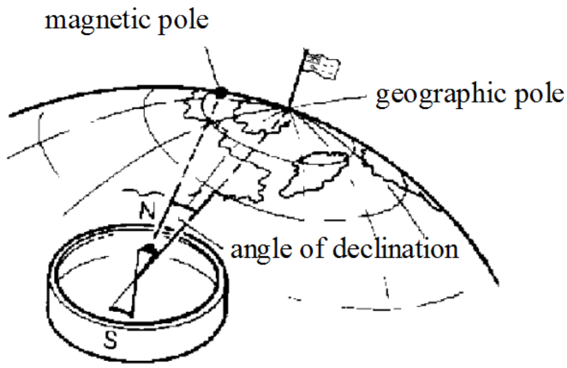
Magnetic Declination

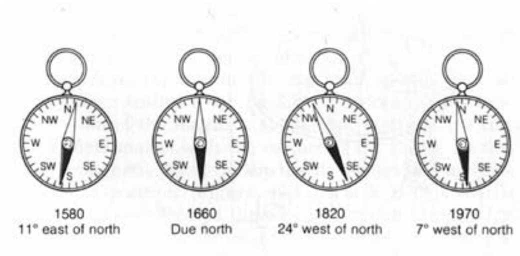
The angle between magnetic north and true (geographic) north is called the magnetic declination.

Magnetic declination varies from place to place on the Earth's surface.

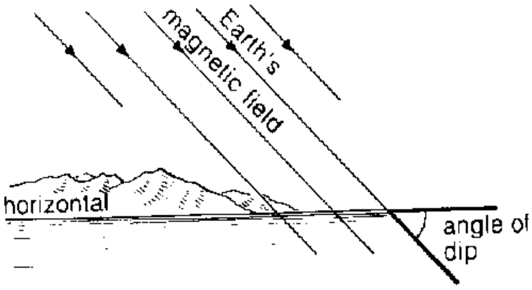
Currently in Perth, the magnetic declination is approximately -2.5^0 (the negative sign indicates that magnetic north is west of true north in Perth).

Since the Earth’s magnetic field periodically changes in both direction and strength, the magnetic declination for points on the Earth’s surface also change with time.





Magnetic Inclination (Magnetic Dip)



The angle that the Earth's magnetic field makes with the horizontal at any point is referred to as magnetic inclination or magnetic dip.

Note from the diagram at the top of the previous page, that the Earth's magnetic field, at most locations, is not tangent to the Earth's surface.

In fact the angle of dip is only 0^0 at the magnetic equator.

In the southern hemisphere the magnetic field points out of the ground at the angle of dip

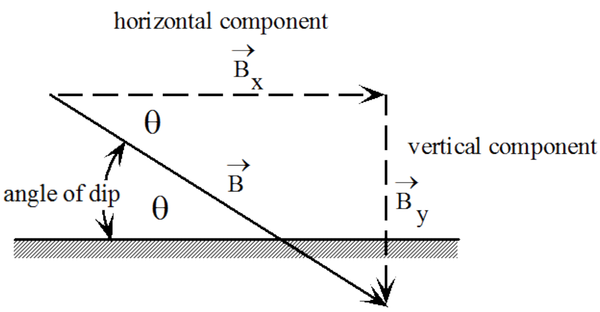
(and vice versa in the northern hemisphere).

The angle of dip in Perth is approximately 66^0

Magnetic inclination is measured using a dip circle.

This consists of a freely suspended compass needle mounted in a vertical plane with is axis oriented along the magnetic meridian (ie magnetic north-south direction).

The magnetic flux at any point on the Earth's surface can be resolved into vertical and horizontal components.



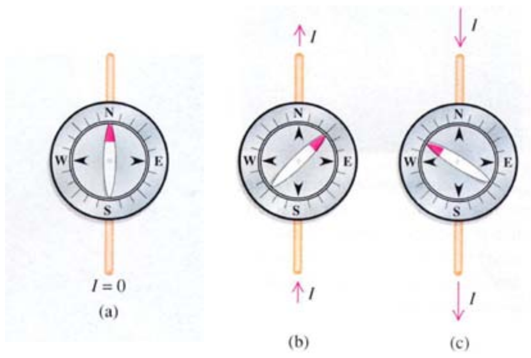
The Earth's magnetic flux dips into the earth in the northern hemisphere and out of the Earth in the southern hemisphere.

Therefore the diagram is for the northern hemisphere.

At Perth $B_x = 2.3 \times 10^{-4}$ T, $B_y = 5.3 \times 10^{-4}$ T

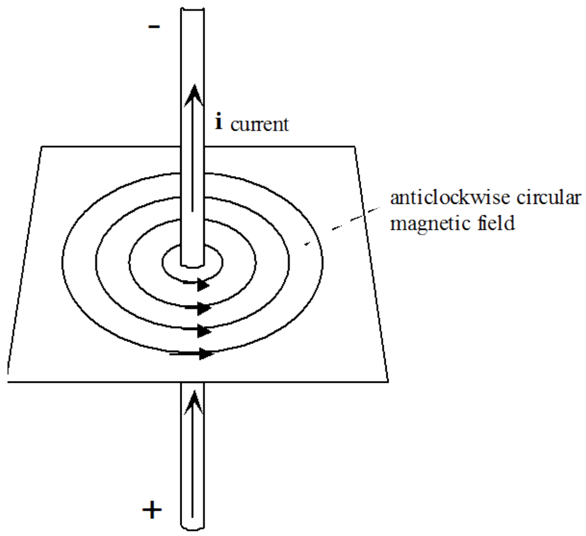
Magnetic Fields Surrounding Conductors

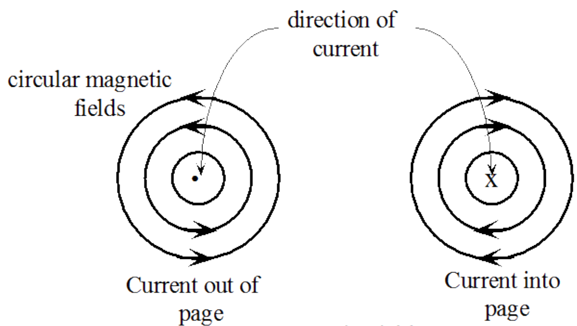
1. Magnetic Field about a Straight Conductor



Oersted (1819) observed a compass needle was deflected by a wire carrying a current. i.e. that charge moving in the wire was responsible for a magnetic field around the wire.

That is, electric currents create magnetic fields.



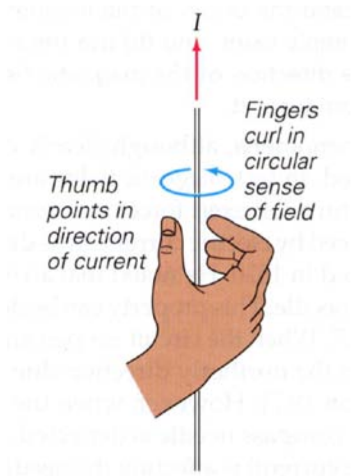


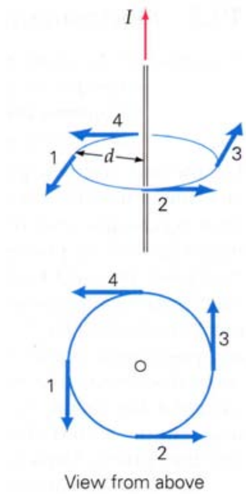
Magnetic Field Around Conductors

Direction of the Field

The magnetic field is circular in shape and its direction depends upon the direction of current flow in the conductor.

The direction of the field around a conductor is found using the **Right Hand Grip Rule 1.**





Right Hand Grip Rule 1:

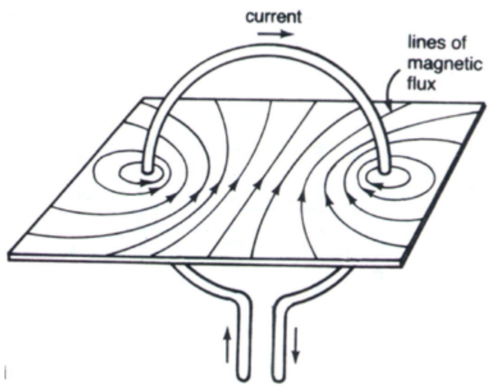
Grasp the conductor with the right hand.

With the thumb in the direction of the current, the fingers will indicate the direction of the magnetic field.

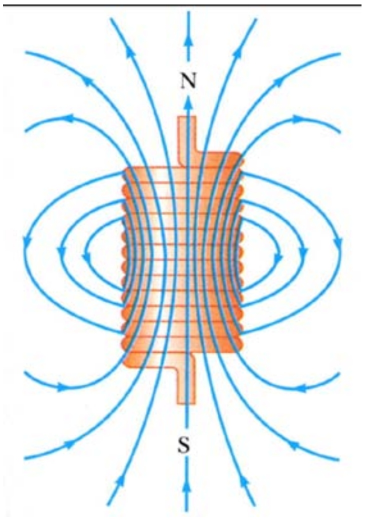
2. Magnetic Field about a Current Carrying Loop

A resultant field forms from all the flux lines circling the wire.

The flow of current in the loop results in a concentration of magnetic flux inside the loop in a direction at right angles to the plane of the loop.



Magnetic Field about a Solenoid

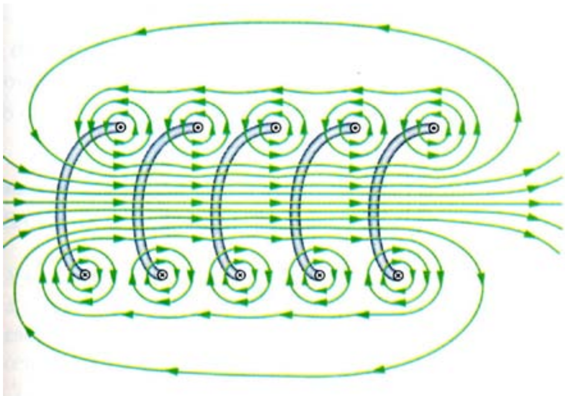


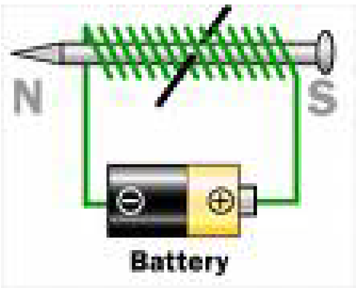
A solenoid is a coil consisting of a number of turns.

The magnetic field associated with a solenoid is equal to the vector sum of the individual fields due to each loop.

The resultant field at the centre of the coil is strong, as all the field vectors are in the same direction.

The total field is similar to that of a bar magnet.





A solenoid may sometimes be used in place of a bar magnet.

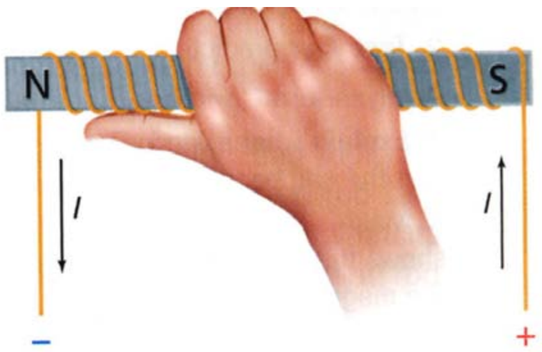
The solenoid has two associated poles.

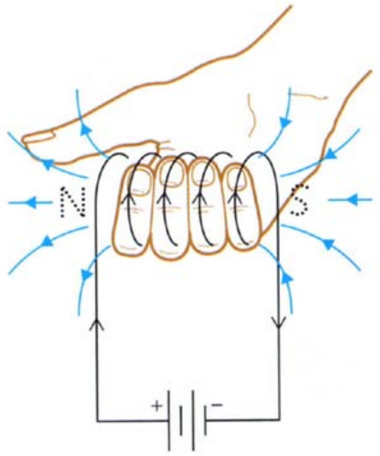
The location of each pole depends upon the direction of flow of current in the solenoid.

Right Hand Grip Rule 2:

To determine the location of the north pole, grasp the solenoid with the right hand with the fingers in the direction of current flow.

The thumb will point to the north pole of the solenoid.





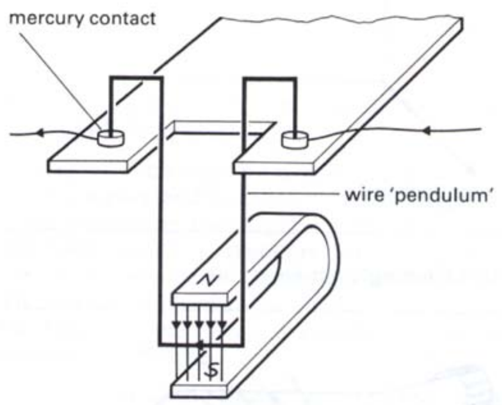
Force on a Current Carrying Conductor

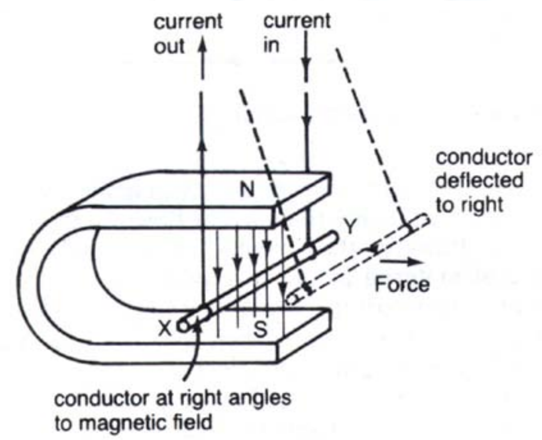
A magnet can exert a force on an electric current.

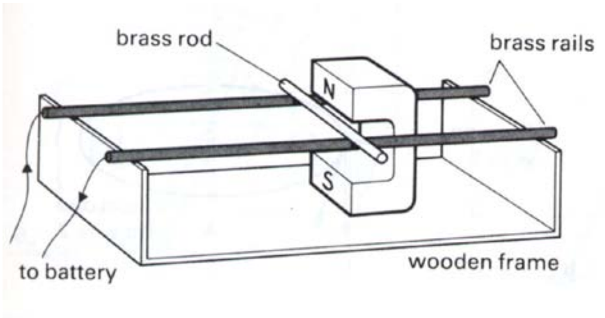
When a current bearing wire cuts a magnetic field a force acts on the conductor.

The force is due to the interaction between the fixed magnetic field and the magnetic field associated with the charges moving in the conductor.

The force (F) on the conductor which cuts a magnetic field at right angles is found to be proportional to the strength of the field, the current in the conductor and the length of the conductor.







That is, $F \propto B, \quad F \propto I, \; and \; F \propto l$

≥ $F \propto BIl$

≥ $F = k \times BIl$

F = Force (in Newton (N)

B = Magnetic Field Strength (in Tesla (T)

I = Current (in Amp (A)

l = length of Conductor (in meter (m)

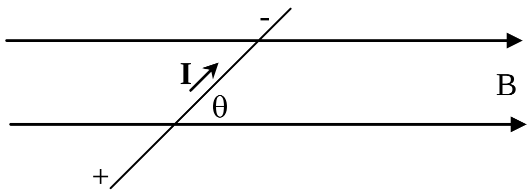
k = constant of proportionality

The SI unit for magnetic field strength (also called magnetic induction or magnetic flux density) the tesla (T) is defined such that k = 1

Thus $\boxed{F = BIl}$ where the conductor is perpendicular to the magnetic field

For a conductor which cuts the field at an angle θ, the relationship is: $\boxed{F = BIl \sin\theta}$

Force on this wire is directed into the page.



Note: If the conductor runs parallel to the magnetic field, then $\theta = 0^{o}$ and thus no force will act on the conductor.

The Direction of the Force on the Conductor

The direction of the force on a current is perpendicular to both the current and the direction of the magnetic field.

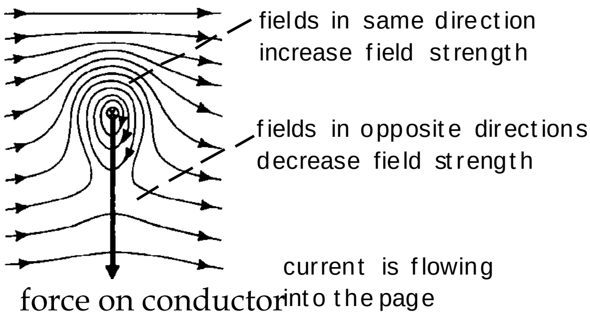
In the diagram the current is flowing <u>into</u> the page and the magnetic field is flowing from left to right.

The field associated with the conductor interacts with the magnetic field in which it is placed.

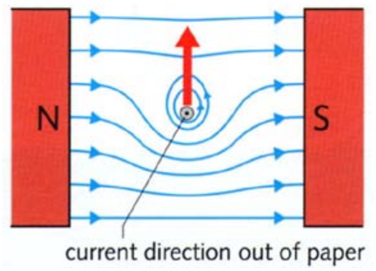
In the diagram, the vector addition of the two fields results in a greater resultant field strength above the conductor and a lower resultant field strength below the conductor.

The tendency is for the field to “even out”, i.e. for the wire to move to reduce the concentration of flux lines (in this case above it).

This produces a downward force on the conductor away from region of increased field strength and towards the region of reduced strength.



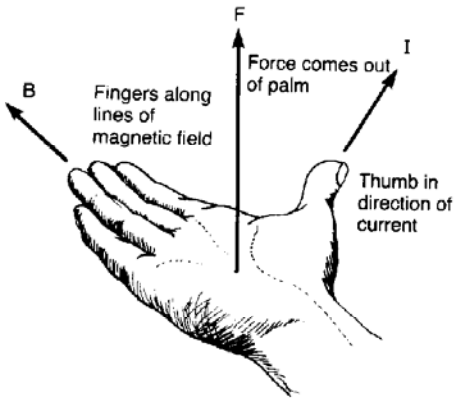
The catapult effect.



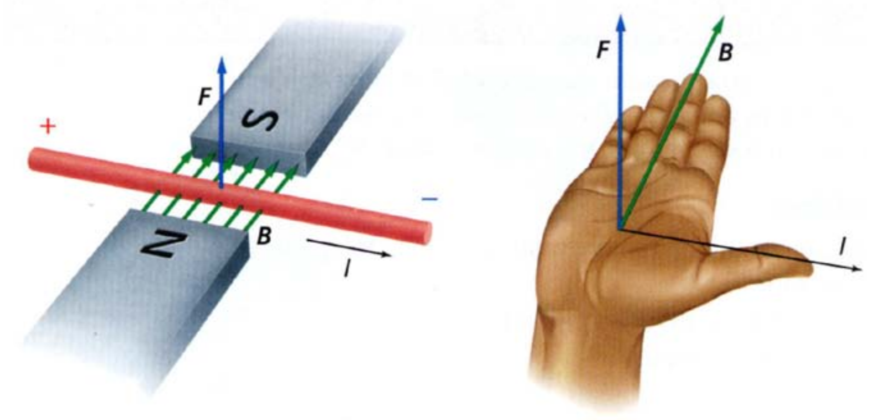
The direction of the force on the conductor can also be predicted using the **Right Hand Palm Rule.**

To determine the direction of the force acting on a conductor which cuts a magnetic field:

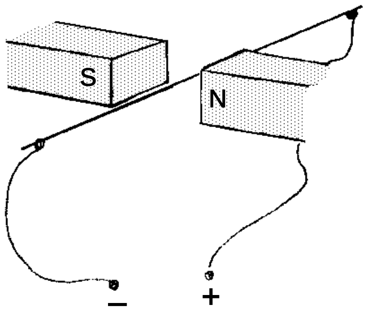
- fingers in the direction of the field;
- thumb in the direction of conventional current (ie positive to negative (+ → –)
- palm then gives the direction of the force (push) on the conductor.

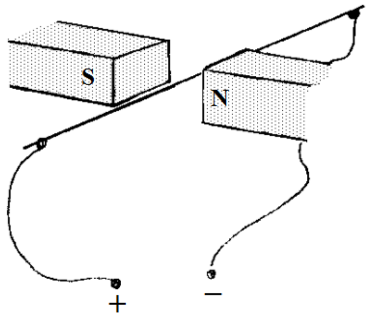


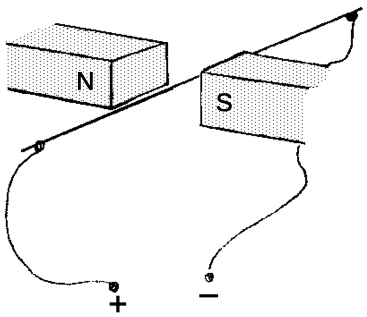
Note if considering electron current direction (ie - → +) use the left hand.

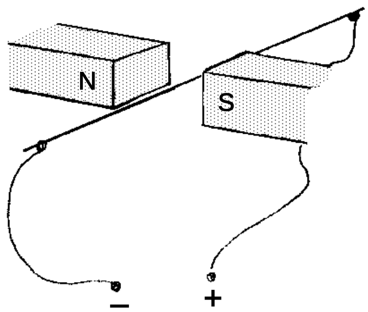


PROBLEMS: Determine the direction of the force acting on the conductor in each of the following cases.

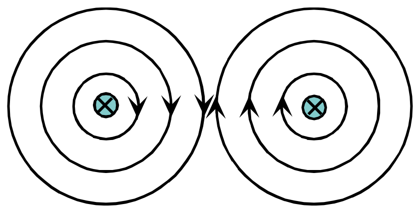








Interaction Between Two Parallel Conductors



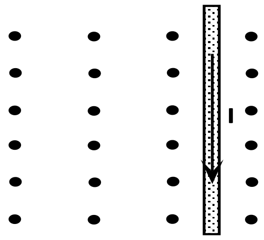
Two adjacent parallel conductors will produce magnetic fields that will interact to either attract or repel each other.

When currents in the conductors flow in the <u>same direction</u> (called *parallel* currents) the conductors attract.

When currents in the conductors flow in <u>opposite directions</u> (called *anti-parallel* currents) the conductors repel.

Exercise: Carefully sketch the **<u>resultant</u>** magnetic field for the following arrangements:

Example 1: A conductor 2.00 m long carries a current of 5.00 A running from north to south in a horizontal plane. If it passes through a vertically upward magnetic field of strength 2.00×10^{-4} T, calculate the force on the conductor.



$F = B I l$

$F = 2.00 \times 10^{-4} \times 5.00 \times 2.00$

$F = \underline{2.00 \times 10^{-3}}$ N to the left

Example 2: A conducting loop lies in a field of strength 2.00×10^{-4} T. Both loop and field are in a horizontal plane. If a current of 10.0 A flows in the loop, find the force acting on each section.

$B = 2.00 \times 10^{-4}$ T ; $I = 10.0$ A

$F_{AB} = F_{ED} = 0$ N (wire parallel to field)

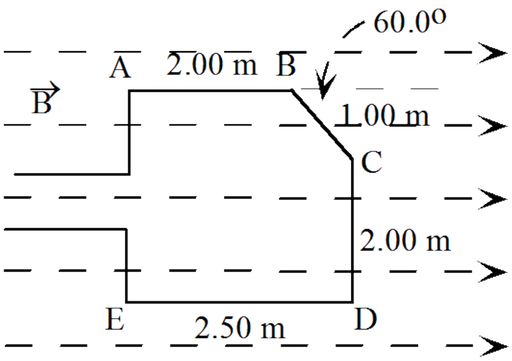
$F_{CD} = B I l = 2.00 \times 10^{-4} \times 10.0 \times 2.00$

$F_{CD} = \underline{4.00 \times 10^{-3}}$ N

$F_{BC} = B I l \sin\theta$

$F_{BC} = 2.00 \times 10^{-4} \times 10.0 \times 1.00 \times \sin 60^0$

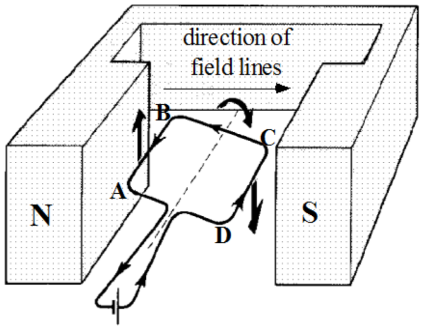
$F_{BC} = \underline{1.73 \times 10^{-3}}$ N



Problem 1: A wire carrying a 30A current has a length l = 12cm between the pole faces of a magnet at an angle $\theta = 60^0$. The magnetic field is approximately uniform at 0.90 T.

Ignore the field beyond the pole faces. What is the magnitude of the force on the wire?

The Motor Effect

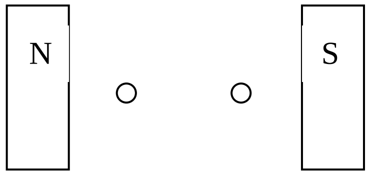


If the conductor is shaped as a loop and placed in a magnetic field as shown, then forces produced on the loop create a turning effect or torque.

Consider a loop ABCD carrying current I in a field of strength B. The direction of the forces acting on the coil can be determined using the "right hand palm rule".

ABCD is in the plane of the field and r is the radial distance from AB and CD to the axis of rotation of the coil.

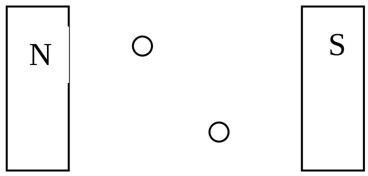
The direction of the current flowing in BC and AD is parallel to the magnetic field.



Thus there is no moment acting on these sides of the coil.

$F_{AD} = F_{BC} = 0$ N (since AD and BC are parallel to the field)

However the current flowing in AB and CD is at right angles to the magnetic field and thus produces an upward force on AB and a downward force on CD.

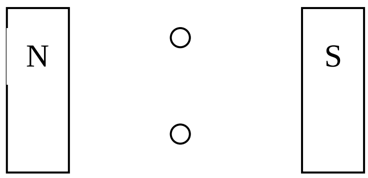


The magnitude of these forces is given by:

$F_{AB} = B\,I\,l$ (up) and $F_{CD} = B\,I\,l$ (down)

Both F_{AB} and F_{CD} produce clockwise rotation of the coil.

Thus there is a net torque or turning effect on the coil.



The torque or turning effect due to the forces acting on a single loop is given by:

$$\tau = \Sigma \dot{M}$$

$$\tau = (F_{AB} \times r) + (F_{CD} \times r)$$

$$\tau = 2\,F\,r = 2\,B\,I\,l\,r$$

But the area of the loop, $A = 2\,r \times l$

Thus for a loop lying in the plane of the magnetic field:

$$\tau = B\,I\,A$$

τ = torque (Nm)
B = Magnetic Field Strength
I = electric current (A)
A = Area (m^2)

Where the plane of the loop is at θ^o to the magnetic field then:

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

For a coil consisting of N turns the torque or moment is given by:

$$\tau = N\,B\,I\,A\cos\theta$$

Problem 2: A circular coil of wire has a diameter of 32 cm and contains 100 loops. The current in each loop is 4.00 A. The coil is placed in a 1.50 T field. Determine the maximum and minimum torque exerted on the coil by the field.

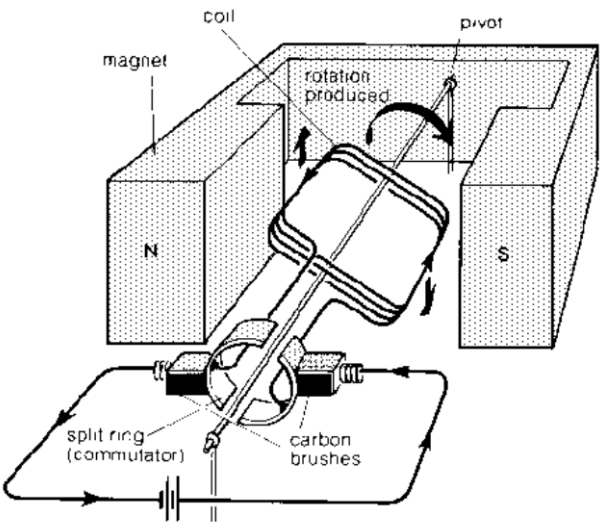
Simple DC Electric Motor

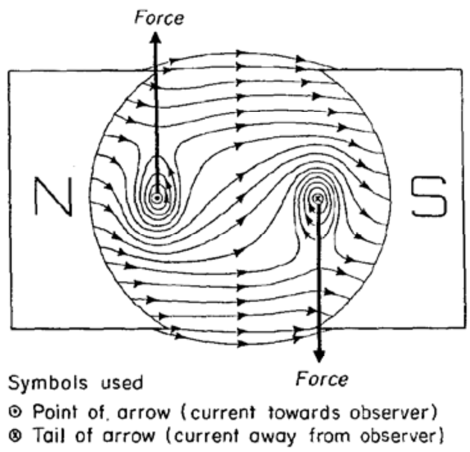
The purpose of electric motors is to change electrical energy into mechanical energy.

The simple DC electric motor consists of 4 basic elements:

1. The **armature** or coil. This is the part that rotates.
2. The **magnetic field.** This is provided by a permanent magnet in the diagram below.
3. The **commutator**. This reverses the direction of the current in the coil each half turn.
4. The **conducting brushes.** These take the current to and from the armature.

When an electric current passes through the coil it produces a turning effect or torque on the coil.





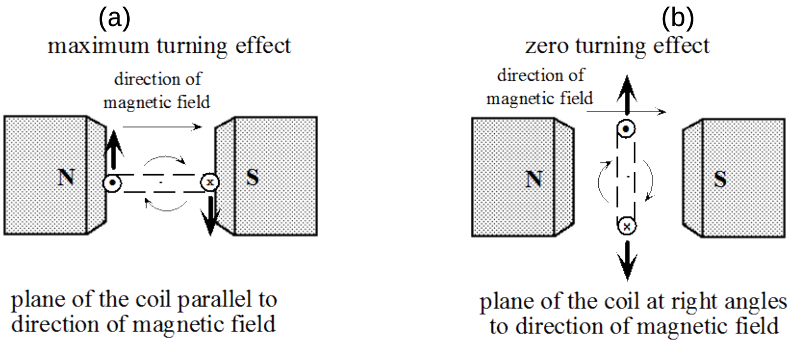
Magnetic field pattern in a simple electric motor

When the plane of the coil is parallel to the magnetic field B, as shown in (a) below, the perpendicular distance from the axis of rotation to the line of action of the force is a maximum.

This produces the maximum turning effect or maximum torque.

When the plane of the coil is perpendicular to the magnetic field B, as shown in (b) below, the perpendicular distance from the axis of rotation to the line of action of the force is zero as the line of action of the force passes through the axis of rotation.

This produces the zero turning effect or zero torque.



The coil will rotate in a clockwise direction until it reaches the vertical.

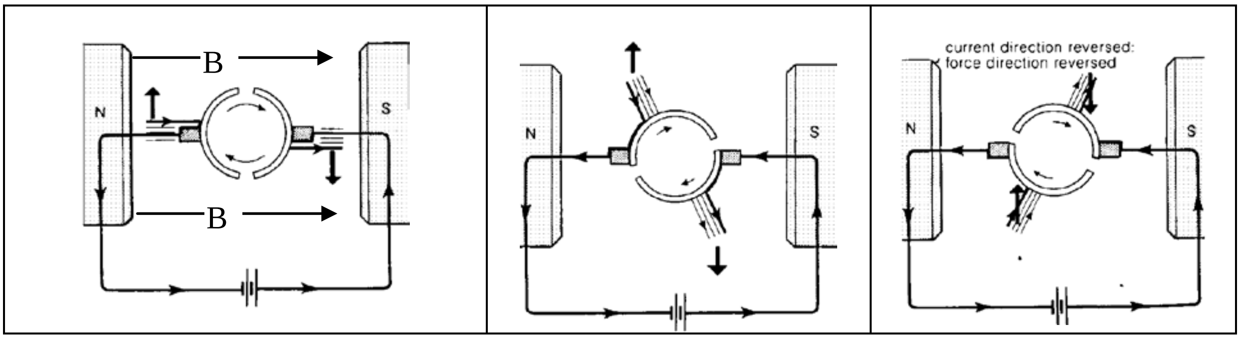
At this point there is no torque acting on the coil and thus it will move no further.

Note that if the coil rotates past the vertical, the forces acting will cause the coil to return back to the vertical position.

The Split Ring Commutator

The split ring commutator enables the coil to continue turning in a clockwise direction.

Note that the magnetic field is from the N-pole to the S-pole. (i.e left to right in the diagrams below)



The commutator achieves this by reversing the direction of the current in the coil each half turn.

So that current continues to flow through the coil as it turns, graphite contacts, called ‘brushes’, are pushed lightly against the commutator by springs.

Each side of the coil is connected to one of the segments on the commutator.

As the coil passes through the vertical position, the segments to which the brushes are connected interchange.

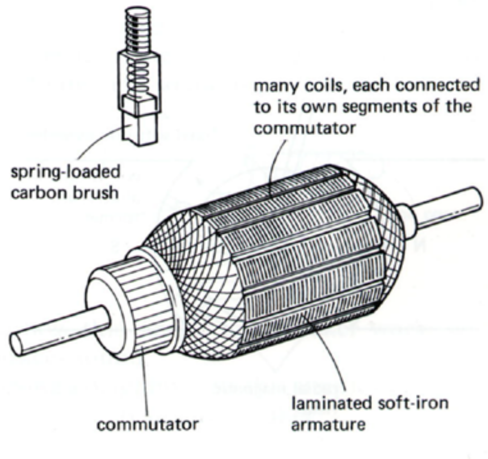
This results in the current flowing in the coil such that it continues to rotate in a clockwise direction.

Practical Motor Design

The magnetic field produced will be much stronger if an electromagnet is used. This would produce a greater torque.

In real motors the poles of the magnets are generally curved. This ensures a steady torque because the armature is always lies parallel to the magnetic field.

Exercise: List and briefly describe the advantages of some other practical Designs.



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The Moving Coil Loudspeaker

An example of the motor effect on coils in a magnetic field is a loudspeaker.

A moving coil loudspeaker consists of a tubular permanent magnet that produces a strong radial field.

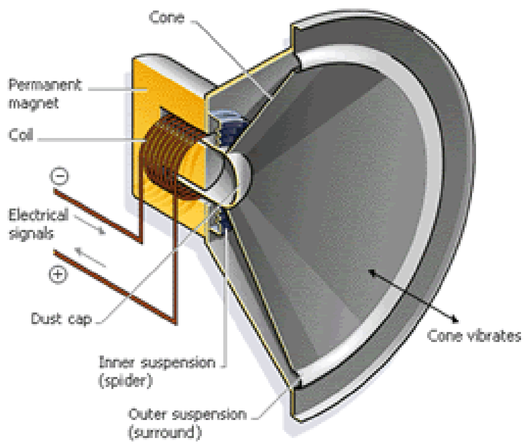
A wound coil is attached to stiff paper cone (as shown in the diagram).

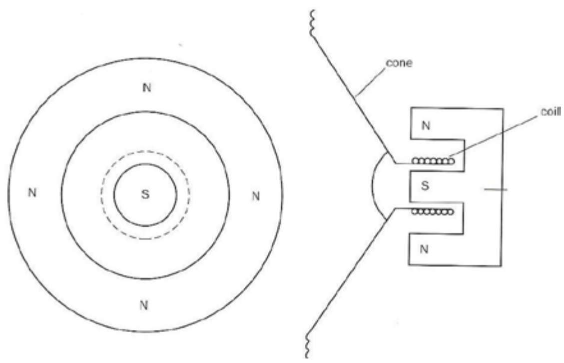
When operating, a varying direct electrical current flows through the coil.

The interaction between the magnetic field due to current flowing in the coil and the field due to the permanent magnet causes the coil to move rapidly back and forth.

Thus the paper cone vibrates and produces a sound.

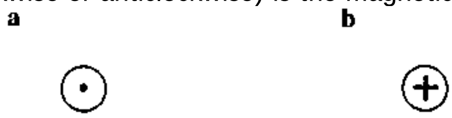
The large surface area of the cone results in efficient transfer of energy to the air, in which the sound wave is propagated.





EXERCISE 2: Magnetic Force

1. In which direction (clockwise or anticlockwise) is the magnetic field around each wire?

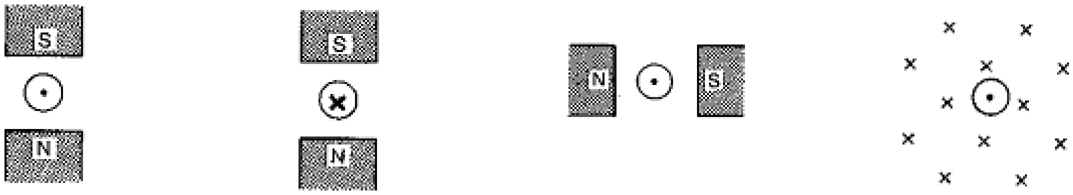


2. Determine the force on a wire 1.00 m long, carrying a current of 1.00 A, and placed at right angles to a magnetic field of flux density (induction) 0.500T.

3. What force would a 20.0 cm length of wire placed at right angles to a uniform field of flux density 0.0500 T experience, if the wire a) carries a current of 10.0 A
b) has a resistance of 1.00 kΩ and a potential difference of 100 V is applied across its ends?

4. What force does a magnetic field of induction 0.250 T exert on a wire 10.0 cm long carrying a current of 5.00 A at right angles to the field?

5. Find the direction of the force acting on the wires in each case.
a) b) c) d)



6. A wire 1.00 m long carries a current of 5.00 A and makes an angle of 30.0^0 to a uniform magnetic field of induction 2.50 T. Determine the magnitude of the force on the wire.

7. Calculate the magnitude and direction of the force on a wire 0.0500 m long, carrying a current of l0.0 A from north to south, if it is placed in a magnetic field of induction 0.500 T directed from east to west.

8. A magnetic field of flux density 0.0400 T is set up and a wire 12.0 cm long is placed in the field initially at right angles to the field.
a) What is the magnitude of the force on the wire if it carries a current of i) 1.0 A ii) 1.0 mA?

b) The wire is now shifted so that it lies at various angles to the field. One ampere of current is passed through it. Determine the force on the wire at angles of 0^0, 10^0, 20^0, 30^0, 40^0, 50^0, 60^0, 70^0, 80^0 and 90^0. Hence plot a graph of force against angle between the wire and the field.

9. What is the direction of the force due to the Earth's magnetic field on a wire carrying a current vertically upwards?

10. A scientist is testing a magnetic field. He uses a wire l0.0 cm long in an electrical circuit. An ammeter connected to the circuit shows that a current of 10.0 A flows through the wire. When he points the wire north-south there is found to be no force on the wire. However when he turns it through 90° so it is pointed vertically upwards the force is found to be 1.2×10^{-2} N. Determine the direction and magnitude of the magnetic field under test.

11. Determine the value of the current flowing through a wire of length 20.0 cm placed at right angles to a magnetic field of strength 0.600 T, if the force acting on the wire is measured as 1.20 N.

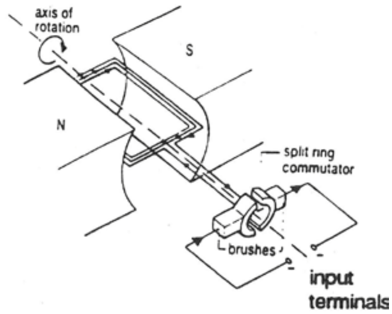
12. A wire of length 50.0 cm, carrying a current of 2.50 A, is placed at 30.0^0 to a magnetic field. The force the wire experiences is 5.00×10^{-3} N. Determine the magnetic field flux density.

13. Find the angle at which 0.100 m of wire carrying a current of 150 mA must be placed to a magnetic field of strength 1.0 x 10^{-4} T, if it is to experience a force of 1.50 μN.

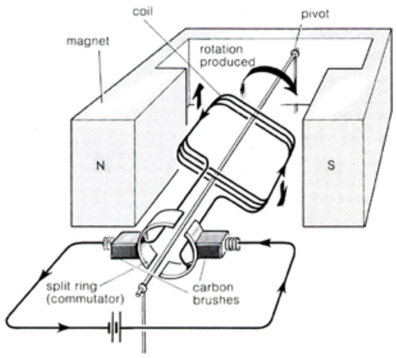
14. Describe three ways in which a magnetic field can be plotted. For each method, how is the relative strength of the field determined?

15. Draw graphs to illustrate how the force on a wire carrying current "I" in a uniform magnetic field of induction of strength B will vary with:

    a) the magnitude of the current "I" in the wire;
    b) the magnitude of the external field B;
    c) the angle θ of the wire to the lines of magnetic field.

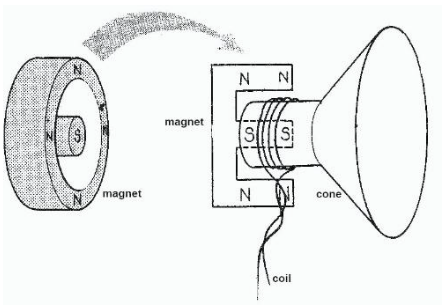


16. Determine the maximum torque of a simple motor if the Magnetic Flux Density is 1.52 T, the coil consists of 48 turns of wire 6.55 cm long by 4.15 cm wide and the current supplied is 3.75 A .



17. The diagram represents a simplified model of a D.C electric motor. The model consists of 144 square coils of insulated wire of length 45.0 mm. The coil is pivoted between the poles of a magnet with a field strength of 8.00 x 10^{-3} T.

    Calculate the maximum torque that could be generated by this model when the current supplied is 2.50 A.



18. A moving coil loudspeaker contains a wire of 60 turns, each of radius 1.6 cm, placed in a radial field of flux density 0.06 T as shown.

    N.B: the wire of the coil is at right angles to the magnetic field at all times.

    Determine the force on the coil when the wire carries a current of 0.65 A.

ANSWERS

1. a) anti-clockwise b) clockwise
2. 0.5 N in a direction given by the right-hand palm rule
3. a) 0.1 N in a direction given by the right-hand palm rule
   b) 0.001 N in a direction given by the right-hand palm rule
4. 0.125 N in a direction given by the right-hand palm rule
5. a) up page b) left c) right d) no force (current parallel to field)
6. 6.25N
7. 0.25 N into page
8. a) i 4.8 x 10^{-3}N ii 4.8 x 10^{-6}N
9. west
10. 1.2 x 10^{-2}T
11. 10 A
12. 8.0 x 10^{-3} T
13. 90°

Electromagnetic Induction

1. Magnetic Flux (Φ)

Magnetic Flux is a measure of the amount of magnetic field through an area.

It can be thought of as the number of field lines (also called **lines of flux**) through an area.

This is why **Magnetic Field Strength** is sometimes called **Magnetic Flux Density**.

The amount of magnetic flux (Φ) which cuts through an area (A) is measured in weber (Wb).

The Magnetic Field strength (B) is defined as the amount of flux per unit area.

≥ Magnetic Field Strength = $\frac{\text{Magnetic flux}}{\text{Area}}$

≥ $$B = \frac{\Phi}{A}$$

B = Magnetic field strength OR Magnetic flux density (Wb m^{-2} or T)
Φ = Magnetic flux (Wb)
A = Area (m^2)

This formula assumes that the lines of flux (i.e. magnetic field lines) are <u>perpendicular to the Area.</u>

A magnetic field has a magnetic flux density of 1 T if one line of magnetic flux (1 Wb) passes through an area of 1 m^2 perpendicular to the field.

1 tesla = 1 weber per metre^2 i.e. 1 T = 1 Wb m^{-2}

The total magnetic flux cutting an area is therefore given by $\Phi = BA$

Example 1: What is the total flux threading an area of 2.00 cm^2 if the magnetic induction is 0.400 mT ? [magnetic induction = magnetic field strength = magnetic flux density]

Φ = ?

A = 2.00×10^{-4} m^2

B = 0.400×10^{-3} T

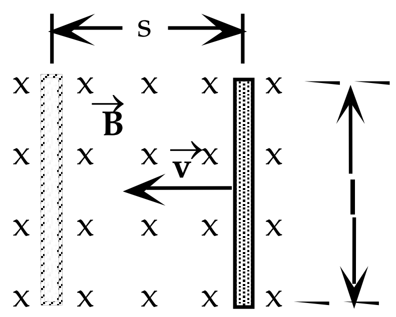
$\Phi = BA$

$\Phi = 0.400 \times 10^{-3} \times 2.00 \times 10^{-4}$

Φ = <u>8.00×10^{-8}</u> Wb

2. Rate of cutting flux by a straight conductor

Consider a conductor of length (l) that is moving with velocity (v) through a magnetic field of induction (B).



The conductor travels through a displacement (s) in time (t).

Rate of cutting flux $\frac{\phi}{t} = \frac{BA}{t} = \frac{B\lambda s}{t}$ but $\frac{s}{t} = v$

≥ $$\frac{\phi}{t} = B\lambda v$$

Φ = Magnetic flux (Wb)
t = time (s)
B = Magnetic flux density (T)
l = length (m)
v = velocity (ms^{-1})

Example 2: A conductor of length 2.00 m cuts a magnetic field of induction 50.0 mT at right angles moving at 20.0 ms^{-1} . Determine the flux cut per second.

λ = 2.00 m

B = 50.0 x 10^{-3} T

v = 20.0 ms^{-1}

$$\boxed{\frac{\phi}{t} = B \lambda v}$$

$$= 50.0 \times 10^{-3} \times 2.00 \times 20.0$$

$$\frac{\phi}{t} = \underline{2.00 \text{ Wb s}^{-1}}$$

Exercise 3: Magnetic Flux

1. What is the total flux threading an area of 1.56 x 10^{-2} m^2 if the flux density is 50.2 T?

2. If 6.089 x 10^{-4-} Wb threads an area of 165 mm^2, what is the magnetic flux density?

3. At a certain place on the earth's surface, the horizontal component of the earth's magnetic field is 4.50 x 10^{-5} T. A wire oriented at right angles to this horizontal component is moving vertically so it cuts the field at right angles with a speed of 25.0 ms^{-1}. If the wire is 12.0 m long, what is the magnetic flux cut per second?

4. A strong magnetic field has a flux density of 3.00 Wb m^{-2}. Calculate the magnetic flux threading an area, at right angles to the field, of a) 0.0500 m^2 b) 0.0500 cm^2.

5. A coil has a cross-sectional area of 4.0 cm^2 and the flux density inside the coil is 2.00 x 10^{-2} T. Find the total magnetic flux inside the coil.

6. The flux density in a cylindrical iron rod of diameter 2.00 cm is 2.10 T. What is the total magnetic flux inside the rod?

7. The rectangular coil of a galvanometer measures 3.00 cm x 6.00 cm and sits between the poles of a horse-shoe magnet which produces a magnetic flux of 6.46 x 10^{-2} Wb. Find the:
   a) magnetic flux density produced by this magnet within the coil
   b) force exerted on the 6.00 cm sides of the coil if it carries a current of 12.0 μ A.

8. The plane of a single rectangular coil of cross-sectional area 3.00 x 10^{-2} m^2 sits vertically in a horizontal magnetic field of flux density 1.50 T. If the coil rotates once every 4.00 s, calculate the flux threading the coil after a) 1.00 s b) 2.00 s c) 4.00 s d) 0.50 s.

9. Distinguish between the quantities magnetic flux and magnetic induction.

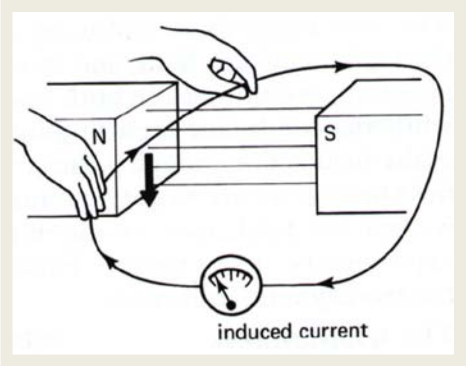
10. a) Determine the magnetic flux enclosed by a loop of wire of area 3.50 cm^2 immersed in a magnetic field with induction 6.00 mT if the loop cuts the lines of force at right angles.
    b) How does your answer change if the loop is rotated so that it makes an angle of 60° to the lines of force?
    c) How much flux is enclosed by the loop if it is placed parallel to the lines of force?

ANSWERS

1. 7.83 x 10^{-3} Wb
2. 3.69 T
3. 1.4 x 10^{-2} Wb s^{-1}
4. (a) 1.50 x 10^{-1} Wb (b) 1.50 X 10^{-5} Wb
5. 8.0 x 10^{-6} Wb
6. 6.60 x 10^{-4} Wb
7. (a) 35.9 T (b) 2.58 x 10^{-5} N

8. (a) zero (b) 4.50×10^{-2} Wb (c) 4.50×10^{-2} Wb (d) 3.18×10^{-2} Wb
10 a) 2.10×10^{-6} Wb b) 1.82×10^{-6} Wb c) 0

Induced EMF and Faraday's Law



As we have seen with the motor effect, if a current carrying coil is placed in a magnetic field it will cause motion.

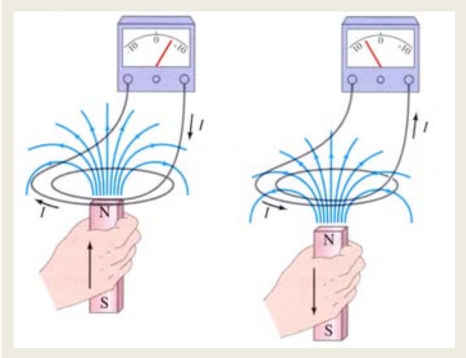
The same principle will work in reverse.

Michael Faraday (in 1831) discovered that when a coil is moved in a magnetic field it will cause a force on the charged particles within the coil and thus cause a current to flow in the coil.

This is the generator effect and the current is called an induced current.

This is the principle by which electricity is produced by a generator where mechanical energy is transformed into electrical energy.

Induced Emf



Emf stands for electro-motive-force.

It means potential difference and is measured in volts.

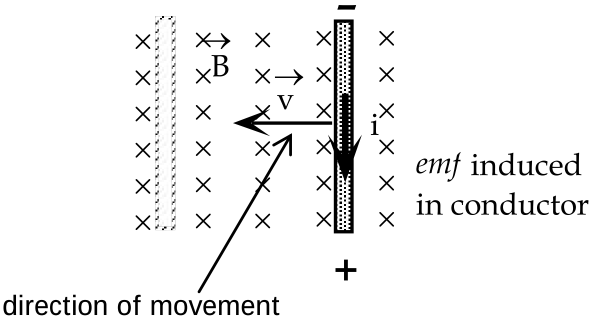
If a conductor is located in a magnetic field and there is a change in the magnetic field or movement of the conductor relative to the field, then an emf (ε) will be induced in the conductor.

The emf (i.e. potential difference) is induced between the ends of the conductor.

The right hand palm rule can be used to determine which end of the conductor is positive.

Check for yourself that when this rule is applied to the diagram the ends have the polarity as shown.

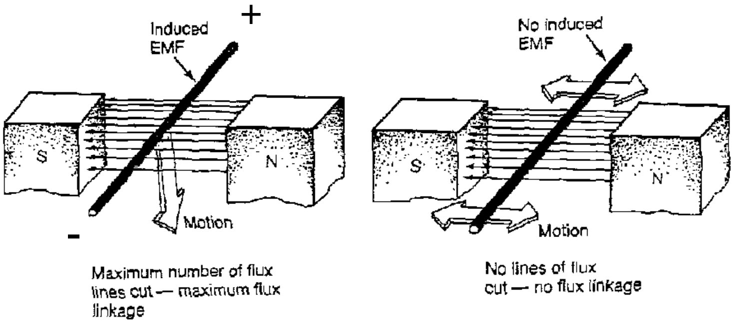
Note that there is no current flow in this case because the conductor is not part of a complete circuit.



<u>NOTE</u>:
It is relative motion, i.e. magnet or coil moving, that induces the emf.

If the conductor does not cut the field i.e. the conductor is parallel to the field or the field does not cut the conductor, then no emf is induced.

It is a <u>changing</u> magnetic field, not just a magnetic field, that induces the emf.

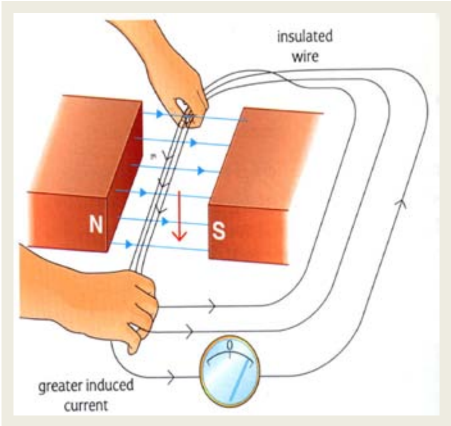


A conductor moves across a magnetic field

Faraday's Law

"Induced Emf is directly proportional to the rate of change of magnetic flux."

The faster the magnetic flux through a circuit changes, the greater will be the emf induced.



This can occur by one, or more, of the following:

- Change the velocity with which the magnet or coil moves.
- Change the strength of the magnetic field.
- Change the area of the coil.

$$emf = -\frac{\Delta\Phi}{t}$$

emf = potential difference (V)
$\Delta\Phi$ = change in magnetic flux (Wb)
t = time (s)

The negative sign in the equation is there to comply with the right hand rule
ie fingers → field; palm → direction of movement; thumb → " **–** " direction of induced current.

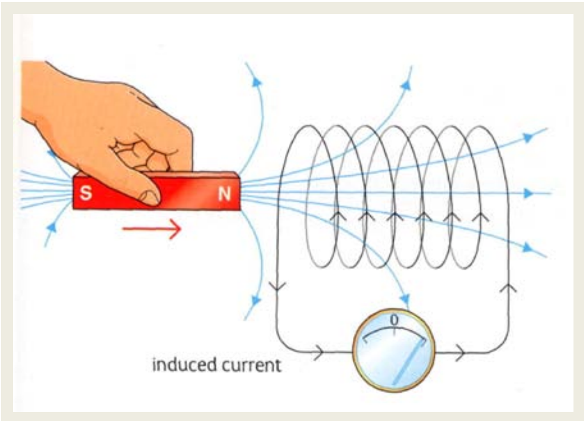
In a coil of N turns the emf induced is N times the emf induced in a single loop.

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

Faraday's law can be written mathematically as: $emf = -\frac{N\Delta\Phi}{t} = -N\frac{\Phi_2 - \Phi_1}{t} = -NA\frac{B_2 - B_1}{t}$

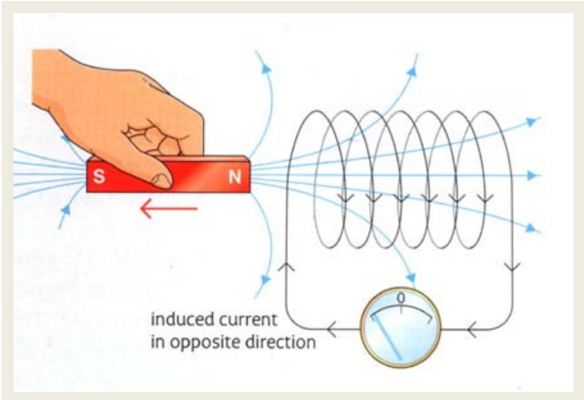
Lenz's Law - direction of the induced current

"An induced current always flows in such a direction as to oppose by its own magnetic field, the motion or change that induced it."



As the magnet's North pole moves toward the front of the coil, the induced current flows in a direction that produces a magnetic field that opposes this motion.

i.e a North pole to repel the incoming North.



As the magnet's North pole is withdrawn from the front of the coil, the induced current flows in a direction that produces a magnetic field that opposes this motion.

i.e a South pole to attract the retracting North.

Explanation:
Lenz's law is a consequence of conservation of energy.

If the emf and its induced current helped its own production, then an infinite amount of energy would be created from a finite amount of work.

Clearly, this would be a violation of the law of conservation of energy.

INDUCED EMF IN A STRAIGHT CONDUCTOR

Emf due to Movement of a Straight Conductor in a Magnetic Field

Since the rate at which flux is cut by a straight conductor is given by: $\frac{\phi}{t} = B \lambda v$

AND $\varepsilon = \frac{\Delta\Phi}{t}$ then it follows that:

$$\varepsilon = B l v$$

Where ε = potential difference (V)
B = Magnetic Flux density (T)
l = length (m)
v = velocity (ms^{-1})

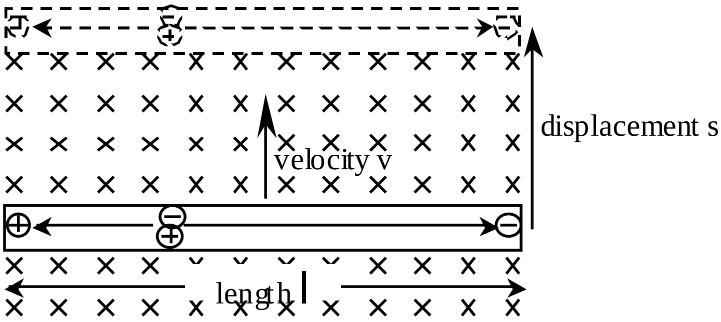
Consider a conductor moving through a magnetic field with velocity "v" as shown in the diagram.

The force on charge within the conductor is given by F = Bvq

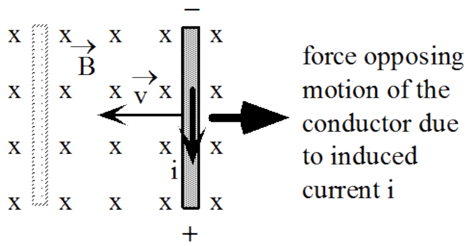
The direction of the force on each charge can be found using the right hand palm rule.

In the diagram above positive charges experience a force to the left and so they accumulate on the left hand end of the conductor.

The negative charges experience a force to the right and so they accumulate on the right hand end of the conductor.



According to Lenz's law when a conductor cuts a magnetic field the induced current in the conductor is in a direction such that the force produced opposes the motion of the conductor.

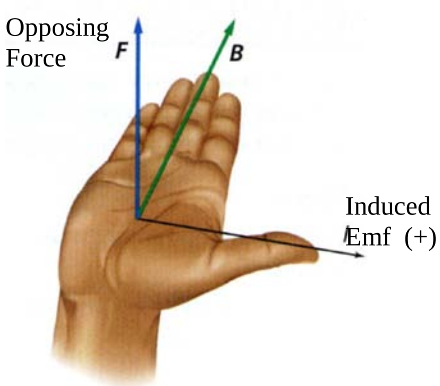


The polarity of the conductor can be found using the right hand rule.

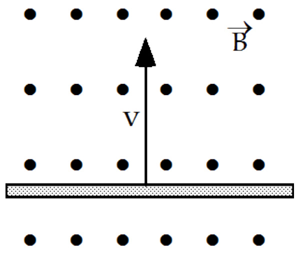
If the fingers of the right hand are placed in the direction of the magnetic field and the palm in the direction of the force opposing motion then the thumb points in the direction of the induced emf (thumb points to the positive terminal).

Note the relationship between the direction of the induced current and the polarity of the ends of the conductor.

In this case the direction of the induced emf indicates the direction in which positive charge is forced to move.



Example 1: Calculate the emf induced if a wire 0.500 m long is moved
a) horizontally across a vertical magnetic field of 0.100 T at 10.0 ms^{-1}
b) at 30.0° to the horizontal through the same field at the same speed.



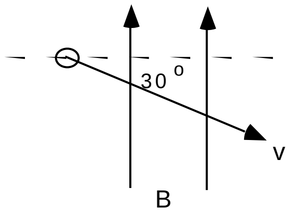
a)

λ = 0.500 m $\varepsilon = B \lambda v$

B = 0.100 T = 0.100 x 0.500 x 10.0

v = 10.0 ms^{-1} = **0.500 V**

b) The effect of cutting the field at other than 90° is to reduce the rate of cutting the magnetic flux and thus the emf.

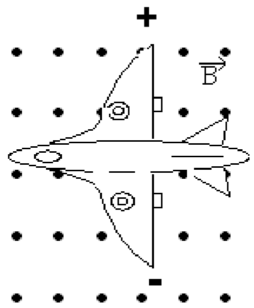


$\varepsilon = B \lambda v \cos 30°$ where v cos 30° is the velocity at 90° to the field direction.

= 0.100 x 0.500 x 10.0 cos 30°

ε = **0.433 V**

Example 2: A plane is moving at 6.00 x 10^2 kmh^{-1} due west and in level flight. The vertical component of the Earth's magnetic field is 4.80 x 10^{-4} T, up. Determine the induced emf in the wing if it is 12.4 m long.



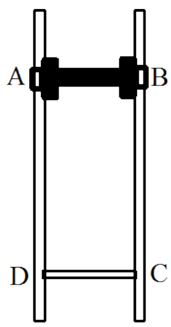
B = 4.80 x 10^{-4} T up $\varepsilon = B \lambda v$

ε = ? $\varepsilon = (4.8 \times 10^{-4}) \times (12.4) \times \frac{600}{3.6}$

v = 6.00 x 10^2 kmh^{-1}

λ = 12.4 m ε = **0.992 V**
(right wing positive)

Example 3: A train axle AB is 2.80 m long and moving at 72.0 kmH^{-1} in a region where the vertical component of the Earth's magnetic field is 5.20 x 10^{-4} T. A rod CD connects the rails. Determine the current in the circuit ABCD, if it has a resistance of 0.800 Ω



λ = 2.80 m $\varepsilon = B \lambda v$ also $\varepsilon = IR$

v = 20.0 Ms^{-1} $I R = B \lambda v$

B = 5.20 x 10^{-4} T $I = \frac{B l v}{R}$

R = 0.800 Ω $I = \frac{(4.80 \times 10^{-4})(12.4)(20.0)}{0.800}$

i = ? ≥ I = **0.0364 A**

Example 4: A spinning helicopter blade of length λ has a potential difference induced between the central axis of rotation and the moving tip of the metal blade.

What is the relationship between the potential difference induced on the blade and the frequency of rotation of the blade if the blade cuts the magnetic field at 90°?

$\varepsilon = B \lambda v$ but v at the centre is 0 ms^{-1} and v at the tip is $\frac{2\pi l}{T}$

i.e. $\varepsilon = Bl \frac{1}{2}\left(\frac{2\pi l}{T} + 0\right)$ but frequency $= \frac{1}{T}$

$\varepsilon = Bl\, f \pi l$

$\varepsilon = \mathbf{B} l^2 f \pi$

INDUCED EMF IN A COIL

Emf due to Changing Flux in Coil or Loop

When there is a change in the field strength of flux linking a loop or coil, an emf is induced as a result of the change.

For a single loop $\varepsilon = -\frac{\Delta \phi}{t}$ and $\Delta\phi = \Delta(BA)$

so $\varepsilon = -\frac{\Delta B A}{t}$

Where ΔB is the change in magnetic field strength
and A is the cross sectional area of the loop

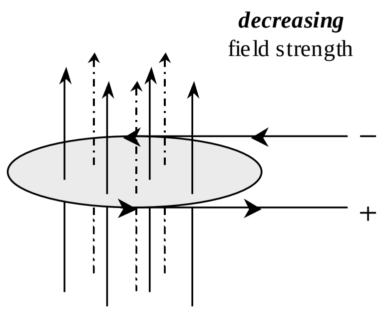
For a coil of N turns $\boxed{\varepsilon = -\frac{N \Delta B A}{t}}$

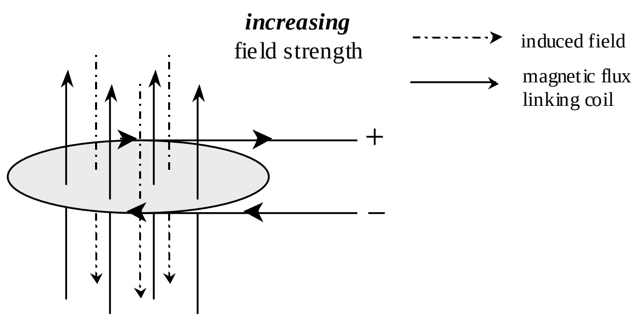
Direction of Induced Emf in a Coil

Lenz's Law indicates that the current induced in a coil, due to a change in field strength, must produce a magnetic field of its own that will oppose the original change in flux.

Note: Make sure you realise that there are **TWO (2)** distinct magnetic fields being discussed.

1. An external magnetic field that must be changing to induce an electric current.
2. The magnetic field produced by the induced current. This tends to oppose change in the first.





Decrease in the magnetic field strength linking a coil.

The induced current creates an induced field in the **same** direction as the decreasing field.
The induced current is produced by a decreasing magnetic field. So the direction of the induced current will tend to increase the field in that original direction.

Increase in the field strength linking a coil.

The induced current creates an induced field in the **opposite** direction to the increasing field.

Example 5: A 500 turn coil of diameter 10.0 cm is placed at right angles to a magnetic field of strength 0.020 T which increases to 0.900 T in 5.00 s. Find the induced emf.

N = 500

d = 0.100 m

A = π r^2

A= 7.85 x 10^{-3} m^2

B_1 = 0.020 T

B_2 = 0.900 T

t = 5.00 s

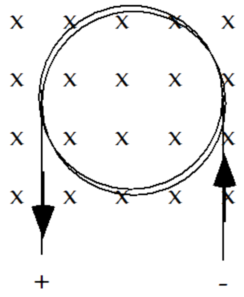
$$\Delta\Phi = \Phi_2 - \Phi_1 = (B_2 - B_1)A$$

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

$$emf = -\frac{N(B_2 - B_1)A}{t}$$

$$= -\frac{500(0.900 - 0.020)(7.85 \times 10^{-3})}{5.00}$$

emf = **0.691 V**



Direction of induced current opposes the increase in the magnetic field strength.

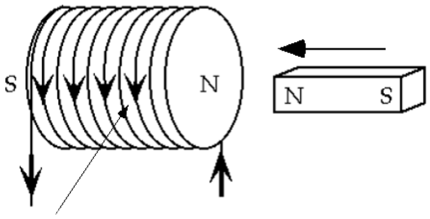
Emf Due to Changing Flux in Solenoid

When the magnetic field linking a solenoid is changed the current induced in the solenoid produces a magnetic field that opposes the change.

When a bar magnet approaches a solenoid the induced current in the solenoid is such that the resultant magnetic field opposes the field of the approaching magnet.

If the magnet is moved away from the solenoid then the induced current flows in the opposite direction reversing the magnetic poles of the solenoid.

Thus the solenoid attracts the magnet opposing its motion away from the solenoid.



the direction of induced current is such that a north pole forms in the end of the solenoid closest to the approaching magnet

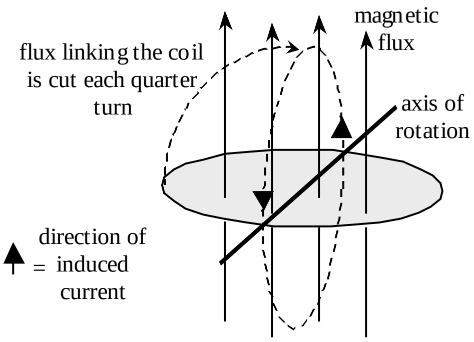
Emf Induced in a Rotating Coil

When a coil rotates in a magnetic field the flux which threads the coil is cut once each 1/4 rotation of the coil.

The flux linking the coil is cut 4 times per rotation.

If the coil rotates with a frequency f then flux is cut $4f$ times per second

The emf induced by a coil of N turns rotating with frequency f is thus given by $\varepsilon = \frac{\Delta\phi}{t} = 4fNBA$



Direction of Induced Current

In the example shown in the diagram, the magnetic flux linking the coil changes from maximum linkage in the horizontal position to zero linkage in the vertical position.

Thus flux linking the coil decreases through this part of the turn and the induced current is in a direction to oppose the change.

Example 6: A coil of area 0.100 m^2 and with 25 turns rotates in a magnetic field of strength 0.400 T. Determine the rate of change of flux (i.e. the flux cut per second if the coil rotates at 5.00 rotations per second.

A = 0.100 m^2
B = 0.400 T
$\frac{\Delta\phi}{t} = ?$
f = 5.00 Hz
N = 25 turns

$$\frac{\Delta\phi}{t} = 4fNBA$$

$$= 4 \times 5.00 \times 25 \times 0.400 \times 0.100$$

$$\frac{\Delta\phi}{t} = \mathbf{20.0\ Wb\ s^{-1}}$$

Example 7: A coil of 50 turns and with a coil area of 20.0 cm^2 is spinning in a magnetic field of 0.500 T so that maximum emf is produced. If the coils spins once in 0.400 s what is the induced emf as the flux linkage goes from its maximum to zero?

N = 50

A = 20.0×10^{-4} m^2

Δt = 0.100 s

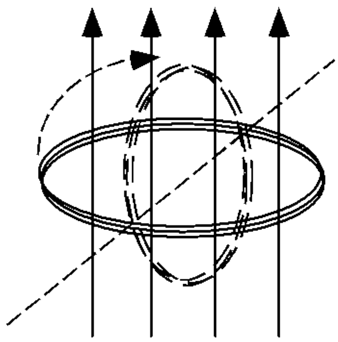
B = 0.500 T

$$\text{emf} = \frac{-N\Delta\phi}{\Delta t} \quad \text{but } \phi = BA$$

$$\text{emf} = \frac{-N(A_2 - A_1)B}{\Delta t}$$

$$\text{emf} = -\frac{50\,(0 - 20.0\times10^{-4})(0.500)}{0.100}$$

$$\text{emf} = \mathbf{0.500\ V}$$



Problem 1: A coil of area 0.100 m^2 rotates in a magnetic field of strength 0.400 T. Determine the flux cut per second if the coil rotates at 5.00 rotations per second.

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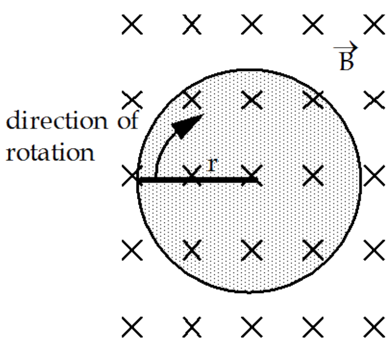
Problem 2: A coil has 2.50×10^3 turns and an area of $500.0\ cm^2$. It rotates at 4.00×10^3 rotations per minute in a magnetic field of strength 40.0 mT at 90^0 to the axis of rotation. Determine the magnitude and direction of the average induced emf (assuming $\Delta\Phi$ is constant♦).

EMF IN A ROTATING CIRCULAR DISC

When a conducting disc rotates such that it cuts a magnetic field, it induces an emf between its centre and its circumference.

Consider a disc of radius **r** rotating in a magnetic field as shown:



When the disc moves through one complete turn, the radius **r** cuts all the flux linking the disc.

Flux cut by radius in one rotation $\Delta\Phi = BA$ (A = area of disc)

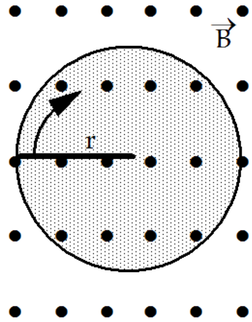
$$emf = -\frac{N\,\Delta\Phi}{t}$$ where N is the number of rotations

$$\varepsilon = \frac{N}{t} \times BA$$

but $\frac{N}{t}$ is the number of rotations per second or frequency of rotation so $\varepsilon = f\,B\,A$

♦ Note the value determined is based on the assumption that the rate of change of flux is constant. In fact ε varies sinusoidally and as such $\varepsilon_{max} = 2\pi f N B A$ and $\varepsilon_{rms} = \sqrt{2}\ \pi f N B A$

Example 8: A metal circular disc of radius 50.0 cm rotates clockwise at 2.00×10^3 revolutions per second in an upward magnetic field of 0.500 T parallel to its axis. Determine the emf between the circumference and the centre.



$r = 5.00 \times 10^{-1}$ m $\qquad \varepsilon = f B A$

$f = 2.00 \times 10^3$ Hz $\qquad \varepsilon = f B\pi r^2$

$B = 0.500$ T $\qquad \varepsilon = 2000 \times 0.5 \times \pi \times (0.5)^2$

$\varepsilon =$ **785 V**

Exercise 4: Electromagnetic Induction 1

1. Determine the magnitude of the e.m.f. induced in a conductor of length 1.00 m moving at a speed of 1.00 ms^{-1} at 90.0° to a uniform magnetic field of 1.00×10^{-4}T.

2. A train travels south with a uniform velocity of 108 kmh^{-1}. If the vertical component of the Earth's magnetic field is 5.00×10^{-5} T, calculate the magnitude of the induced e.m.f. in a 2.00 m axle of the train.

3. A wire of length 50.0 cm moves through a magnetic field of flux density 1.00×10^{-2} T at a steady speed of 10.0 ms^{-1}. What e.m.f. is induced in the wire, if between the wire and magnetic field there is an angle of: a) 90^0 b) 60° c) 30° d) 0°?

4. A conductor of length 20.0 cm has an e.m.f. of 1.00×10^{-2} V induced across its ends when it moves at right angles to a uniform magnetic field of flux density 0.500 T. At what speed is the conductor moving?

5. A straight wire is moved at right angles to the Earth's magnetic field (flux density 1.0×10^{-4} T) at a speed of 10.0 ms^{-1}. If the induced e.m.f. is registered as 1.00 mV, determine the length of wire in the field.

6. A wire of length 50.0 cm is moved at an angle of 30.0° to a uniform magnetic field of 1.0×10^{-6} T with a speed of 2.50 ms^{-1}. a) What e.m.f. is induced in the wire? b) If the wire is connected to a circuit of resistance of 1.00 Ω, what current will flow in the circuit? c) What force must be applied to ensure the wire continues to move at 2.50 ms^{-1}?

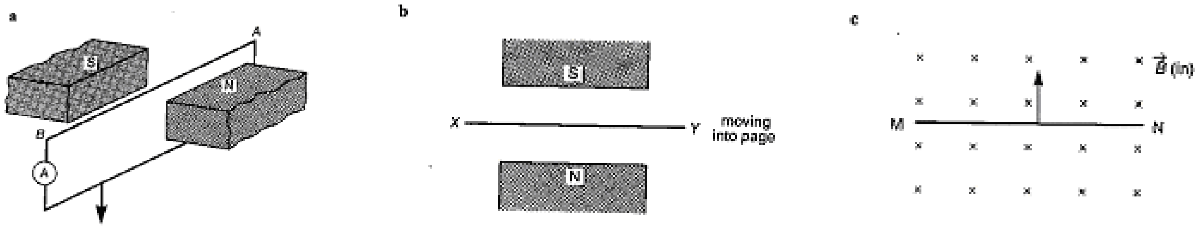
7. A conducting rod 25.0 cm long has a resistance of 2.00 Ω. When it is moved at right angles to a uniform magnetic field at 3.00 ms^{-1} a current of 10.0 mA flows through the rod. Determine the flux density of the magnetic field.

8. A wire 20.0 cm long is moved downwards at a steady speed of 0.500 ms^{-1} at right angles to a uniform magnetic field of flux density 0.0500 T. Find the magnitude and direction of the induced e.m.f.

9. The induced e.m.f. between the tips of the wings of an aircraft is 1.00×10^2 mV. The wing tips are 30.0 m apart flying at right angles to the Earth's magnetic field of 1.00×10^{-4} T. At what speed is the aircraft flying?

10. A coil of wire has 1.00×10^2 turns. It is moved from a region of magnetic flux 3.00×10^{-5} Wb to a region of magnetic flux 2.00×10^{-5} Wb in 0.100 s. What e.m.f. is induced in the coil?

11. Determine the direction of the induced current in the wire in each of the following situations:



12. When a wire is moved through a magnetic field a current is induced, and the direction of this current is such that it sets up a magnetic field which opposes the motion that is causing the current (Lenz's law). Discuss the logic of this law in terms of the principle of conservation of energy.

13. A thin aluminium disc is spinning rapidly about a central axis. When it is placed between the poles of a horseshoe magnet it quickly stops. a) Why does it stop? b) What happens to the energy it had as it was spinning? c) A similar disc has a slot cut in it from its central axis to the outside of the disc. When this is set spinning and moved between the poles of the same magnet it keeps spinning? Why?

14. Imagine you are pulling a loop of copper wire slowly out of a strong uniform magnetic field. How would the effort you need change if a) you pulled the wire quickly b) the electrical resistance of the wire was increased c) you turned the whole system through 90°?

15. Many artificial satellites orbit the Earth. These satellites have metal surfaces. Will the Earth's magnetic field induce currents in these satellites? Does it depend on the orbit of the satellite?

ANSWERS

1. 1.0x 10^{-4} V
2. 3.0x10^{-3} V
3. a) 0.05 V b) 0.043V c) 0.025V d) 0
4. 0.l ms^{-1}
5. 1 m
6. a) 6.25 x 10^{-7}V b) 6.25 x 10^{-7} A c) 1.56 x 10^{-l3} N
7. 2.67 x 10^{-7}T
8. 5.0 x 10^{-3} V in direction predicted by Lenz's law
9. 33.3 ms^{-1}
10. 0.0l V
11. a) from B to A b) from X to Y c) from N to M

Exercise 5: Electromagnetic Induction 2

Where no other information is provided assume problems refer to the northern hemisphere.

1. A stiff piece of wire 7.2 m long is moved vertically upward in the earth's magnetic field, whose horizontal northward component is 20 μT. The wire is horizontal, points east and west and moves at 25 ms^{-1}. What is the difference of potential between the ends and which end is positive?

2. If the wire of Q1 moves horizontally toward the north at the same speed and the vertical component of the earth's field is 50 μT downward, what is the difference of potential between the ends and which end is positive?

3. In Fig.1, let l = 0.8m, v= 3 ms^{-1}, B = 1.5 T and R = 5Ω
   a) What is the generated EMF?
   b) What is the current?
   c) What is the power expended in heating the resistor?
   d) What is the magnitude of the magnetic force?
   e) What is the rate at which the applied force does work?

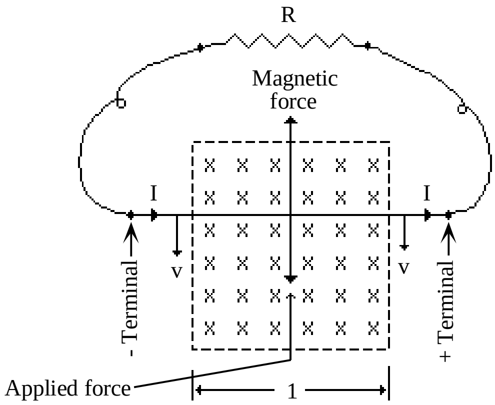


Fig. 1 A protype electric generator

4. In Fig.1, if l = 0.600 m, B = 0.800 T, R = 8.00Ω and F = 0.200 N, find the:
   a) current b) EMF c) speed d) rate of doing work
   e) the rate of heat generation.

5. A 50-turn coil of the type shown in Fig.3 has an area of 1.00 cm^2. If this coil is moved toward a magnet as in Fig.2 in such a way that the mean flux density through the coil changes at the rate of 0.400 Ts^{-1}, what voltage is induced in the coil?

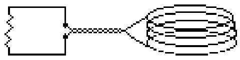


Fig.3 An N-turn coil

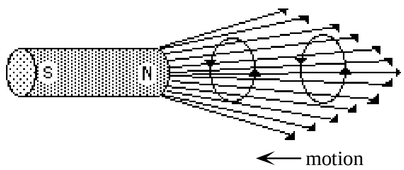


Fig.2 Motion of a loop of wire in the vicinity of a magnet.

6. A "harbour loop" is a coil of wire of extensive area laid out on the floor of a harbour entrance to detect the entrance of submarines by means of the voltage induced by the submarine's natural magnetism.

   a) If the flux through the loop changes at the maximum rate of 0.00600 Wbs^{-1} as the submarine passes over the near side of the loop, what is the maximum voltage induced in a 50-turn loop?
   b) If the earth's vertical field may be expected to vary as fast as 0.300 x 10^{-3} μTs^{-1}, what is the maximum area the harbour loop can have if the voltage generated by fluctuations in the earth's field is to be less than 1% of the voltage generated by the submarine in a)?

7. The "search coil" of a magnetic mine is a long permalloy rod of 4.00 cm^2 cross-sectional area, wound with 2.50 x 10^4 turns of wire. When the external field component parallel to the rod changes by x Tesla, the average flux density in the rod changes by (5.00 x 10^3) x T, provided the externally applied field is sufficiently small - a condition adequately satisfied by the earth's field and by ship's fields. When a ship passes over the mine, the field component parallel to the rod changes by 0.500 μT during a period of 20.0 s. Find the average voltage induced in the search coil in this period.

8. If the rod of the magnetic mine of Q7 is wound with 1.00 x 10^5 turns of wire and if the field component parallel to the rod changes by 15.0 μT during a period of 10.0 s when a high-speed battleship passes over, find the average induced voltage during this period.

9. A square loop of wire 75.0 mm on a side lies with its plane perpendicular to a uniform magnetic field of 0.800 T. a) Find the magnetic flux through the loop. b) If the coil is rotated through 90.0^0 in 0.0150 s in such a way that there is no flux through the loop at the end, find the average emf induced during the rotation.

10. A small "search" coil with an area of 125 mm^2 has 50 turns of very fine wire. This coil is placed between the pole pieces of a small magnet and then suddenly jerked out. If the average induced emf is 0.0700 V when the coil is pulled to a field-free region in 0.0600 s, a) what is the magnetic intensity between the poles? b) what was the original flux through each turn?

11. A coil of 275 turns with an area of 0.0240 m^2 is placed with its plane perpendicular to the earth's field and is rotated in 0.0250 s through a quarter turn, so that its plane is parallel to the earth's field. a) What is the average emf induced if the earth's field has an intensity of 8.00×10^{-5} T? b) What was the original flux through each turn?

12. The secondary of an induction coil has 1.20×10^4 turns. If the flux linking the coil changes from 7.40×10^{-4} to 4.0×10^{-5} Wb in 1.80×10^{-4} s, how great is the induced emf?

13. The magnetic induction **B** in the core of a spark coil changes from 1.40 to 0.10 T in 0.210ms. If the cross-sectional area of the core is 4.50×10^2 mm^2, find the a) original flux through the core. b) What is the average emf induced in the necessary coil if it has 6.00×10^3 turns?

14. A jet aircraft is flying due south at 3.00×10^2 ms^{-1} at a place where the vertical component of the earth's magnetic field is 8.00×10^{-5} T. a) Find the potential difference between wing tips if they are 25.0 m apart. b) Which tip has the higher potential?

15. An axle of a truck is 2.40 m long. a) If the truck is moving due north at 30.0 ms^{-1} at a place where the vertical component of the earth's magnetic field is 9.00×10^{-5} T, find the potential difference between the two ends of the axle. b) Which end is positive?

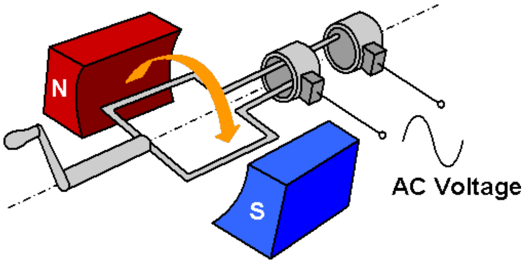
16. A horizontal wire 0.800 m long is falling at a speed of 5.00 ms^{-1} perpendicular to a uniform magnetic field of 1.10 T, which is directed from east to west. a) Calculate the magnitude of the induced emf. b) Is the north or south end of the wire positive?

17. An emf of 3.50 V is obtained by moving a wire 1.10 m long at a rate of 7.00 ms^{-1} perpendicular to a uniform magnetic field. What is the intensity of the field?

ANSWERS

1	0.00360V west end				
2	9.00 mV west end				
3	a) 3.60V	b) 0.720A	c) 2.59W	d) 0.863N	e) 2.59W
4	a) 0.417A	b) 3.33V	c) 6.94ms^{-1}	d) 1.39W	e) 1.39W
5	2.00mV				
6	a) 0.300V, b) $2.00 \times 10^5 m^2$				
7	1.25mV				
8	0.300V				
9	a) 0.0045Wb,	b) 0.3V			
10	a) 0.672T	b) 84.0μWb			
11	a) 0.0211V	b) 1.92μWb			
12	46.0kV				
13	a) 630μWb	b) 16.7kV			
14	a) 0.600V	b) left			
15	a) 6.48mV	b) left			
16	a) 4.40V	b) north			
17	0.455T				

THE GENERATOR



The generator is a means of providing electrical energy by electromagnetic induction.

The generator converts mechanical energy into electrical energy.

The simple generator shown consists essentially of a coil of wire called the **armature** that rotates between the **poles of a magnet**.

The coil is normally wound onto a **soft iron core** which effectively increases the magnetic field strength.

As the coil rotates, its individual conductors cut across the lines of force that exist between the poles of the magnet.

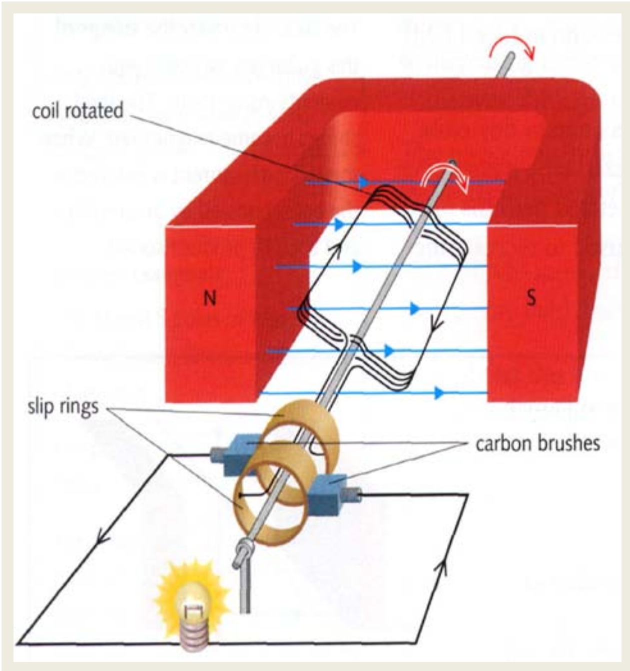
This results in an induced emf in each of the turns of the coil.

The induced emf's in each turn of the armature establish A potential difference between the ends of the coil.

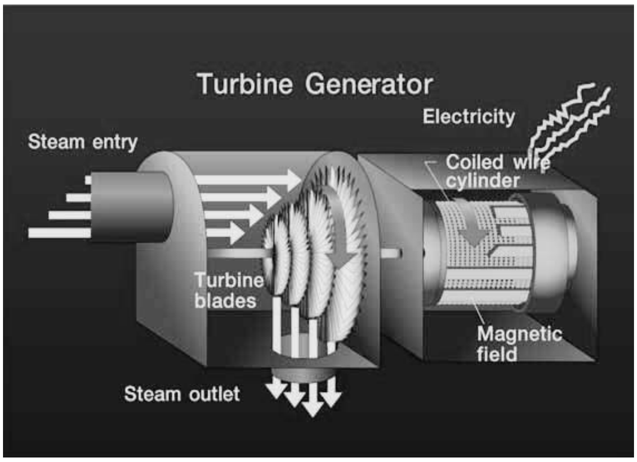
These are connected to two **slip rings** (mounted on the axle) that rotate with the armature.

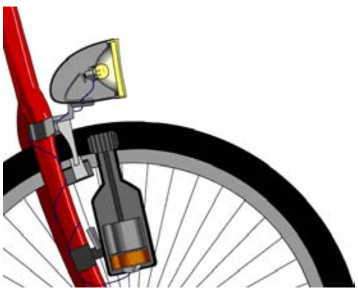
The slip rings make contact with two carbon or copper **brushes** that connect them with an external circuit.

The carbon brushes are fixed and held in place by springs.



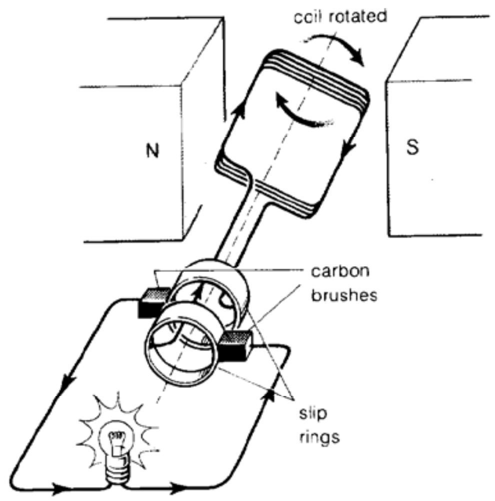
In this case the electrical energy produced is used to power a light globe.

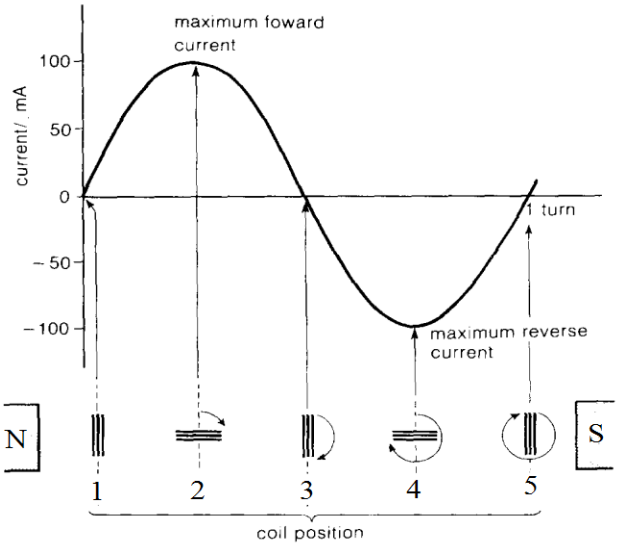




The Alternating Current (AC) Generator

Consider the diagram below…





During one half turn of the armature, the left hand side of the coil moves upward through the magnetic lines of force.

During the next half turn, this part of the armature coil moves downward.

As the armature rotates, this part of the coil keeps cutting the magnetic lines of force alternately upward and downward in rapid succession.

This is also true of the right half of the armature coil.

As a result, the current induced in the coil reverses its direction every half turn of the armature.

This results in an alternating (ac) electrical current.

An alternating current is one that flows first in one direction and then in the opposite direction.

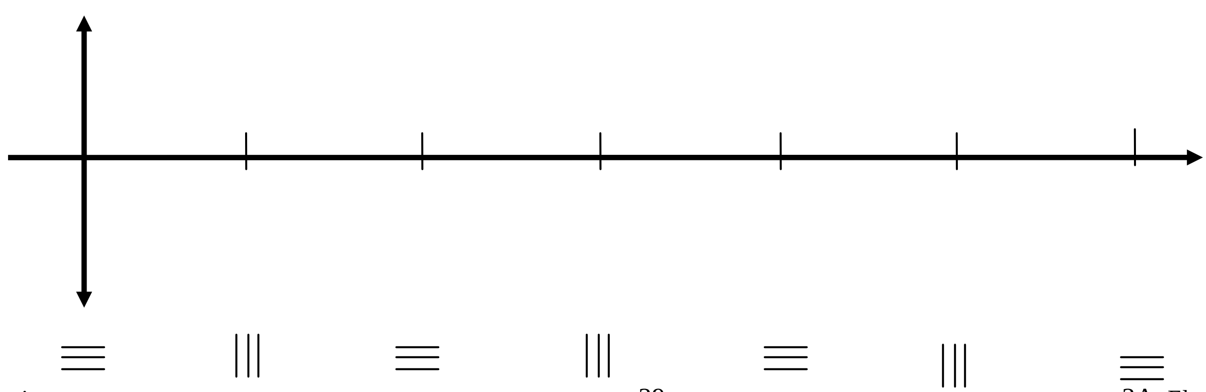
When the current flows back and forth in the circuit once, it is said to have completed one cycle.

The number of cycles it completes per second is called its frequency.

The frequency of the alternating current is equal to the number of revolutions made by the armature per second.

In Australia mains supply electricity has a frequency of 50 Hz.

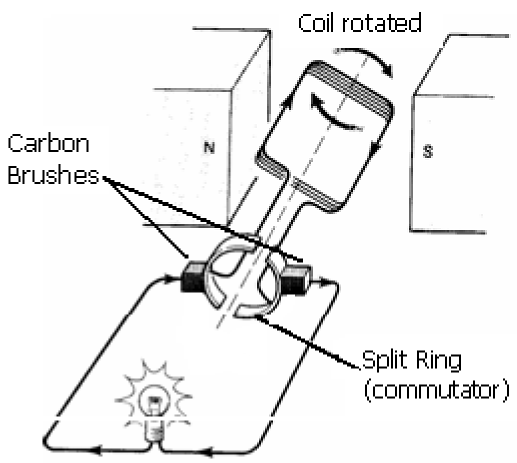
Exercise: Complete the following graph(s) to show the variation of Flux threading and Emf with time

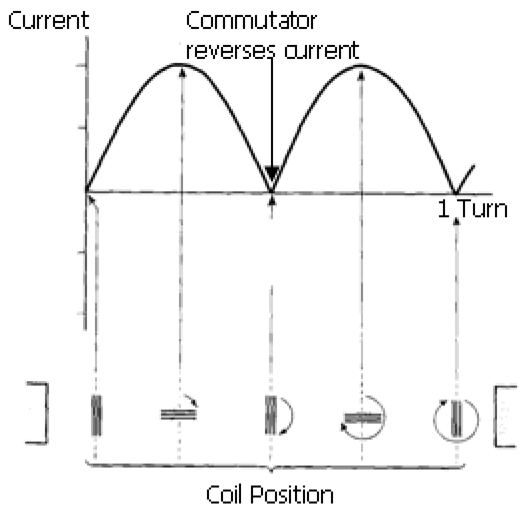


Direct Current (DC) Generator.

To convert an alternating current generator into a direct current generator, it is necessary to remove the slip rings and replace them with a **split ring** commutator.

In this simple case the current rises and falls from zero to a maximum each half cycle. However the current flows in only one direction.





Factors Affecting Emf of a Generator.

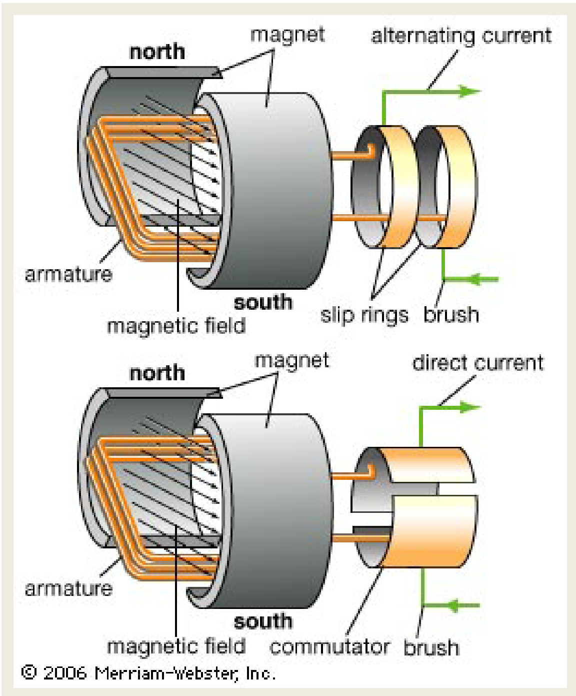
The magnitude of the emf supplied by a generator depends upon the rate at which the wire conductors making up the armature coil cut across the lines of force of its magnet.

The emf of a generator can be increased by :

1) increasing the speed of rotation of the armature,

2) increasing the number of turns on the armature so that more segments of wire will cut the lines of force at the same time;

3) using a stronger magnetic field to provide a greater concentration of lines of force. Further concentration of the lines of force is obtained by means of a high permeability soft iron core on which the armature coil is usually wound.



Generator and Motor Compared.

The dc electric motor and the dc generator have a similar construction. They differ only in use.

In the generator, mechanical energy is supplied to rotate the armature and is converted into electrical energy. In the motor, the process is reversed.

Electrical energy is supplied to rotate the armature and is converted into mechanical energy.

Thus, a generator can be used as a motor and visa versa.

Back Emf.

When a motor is running, its armature coil rotates between the poles of a magnet and an emf is induced in the coil.

In accordance with **Lenz's law,** this induced emf resists the applied emf that is driving the current through the armature coil. It is therefore called a back emf.

The net emf that is effective in sending a current through a motor armature is therefore the applied emf minus the back emf.

Thus, if the back emf of a 240-volt motor is 77 volts, the net emf effective in driving current through the motor is 240 – 77 = 163 volts.

This is another example of the Law of Conservation of Energy.

The induced emf creates a **reverse torque**.

The greater the electric current produced, the larger will be this reverse torque.

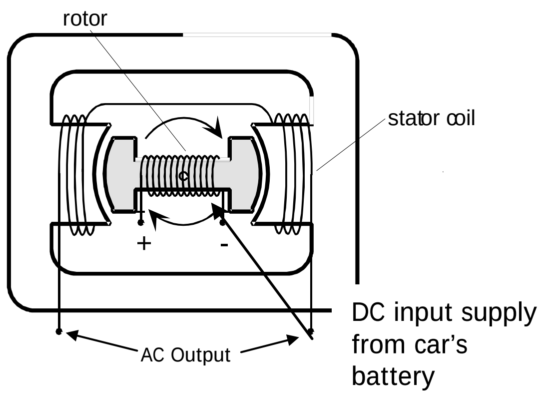
So it gets more difficult to turn the motor.

This means more work must be done to turn the motor when more electrical energy is produced.

Commercial Alternators

Many years ago cars used to use DC generators. However, DC generators produce sparking across the split ring and so there is a lot of wear in the unit.

Single Phase Alternator



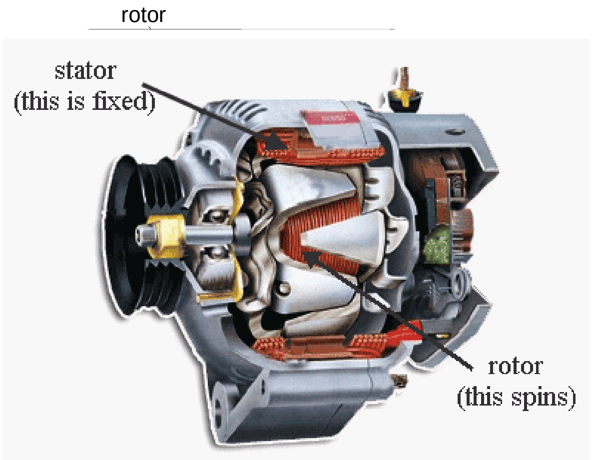
Alternators differ from generators in that they have an electromagnet (called a **rotor**) that rotates inside a fixed stationary set of coils (called the **stator**).

The rotor is fed by DC current from the car's battery, and a belt from the car's engine causes the rotor to rotate.

The changing magnetic field produced by the rotor cuts across the coils in the stator.

This induces an alternating current in the stator coils, and this is the output.

Semiconductor diodes are used to convert the AC to DC electricity to charge the car's battery.

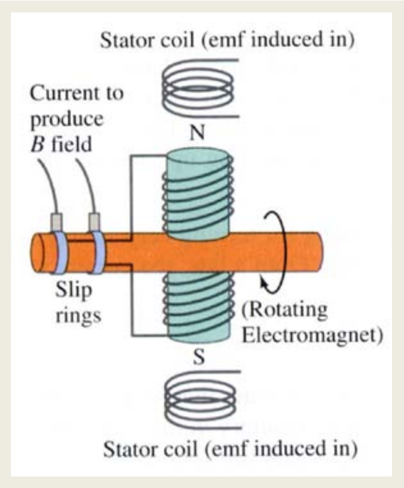


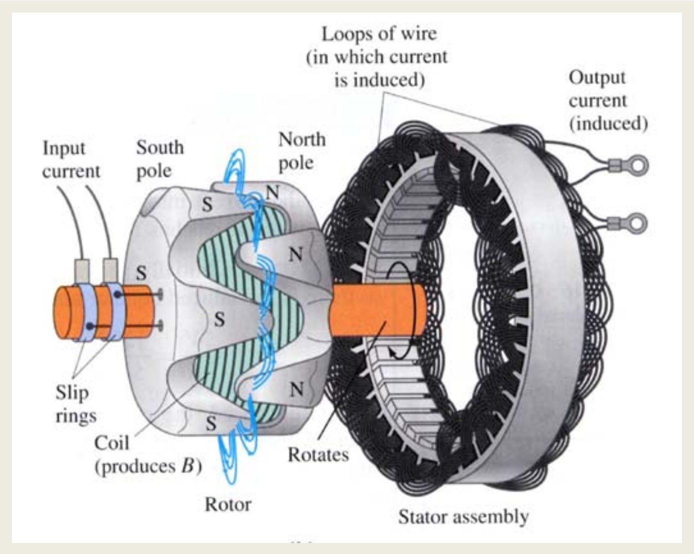
The advantage of the this type of alternator is that the currents produced in the stator coils do not have to pass through slip rings onto brushes to be transmitted.

Thus larger currents can normally be produced.

Modern power stations use large turbines to drive alterna that generate the electric current.

These turbines may be powered by the use of coal, oil, gas or nuclear fuels.





Due to the very high voltages and currents associated with large scale generation, the contacts on the slip rings would produce dangerous sparking and significant energy loss.

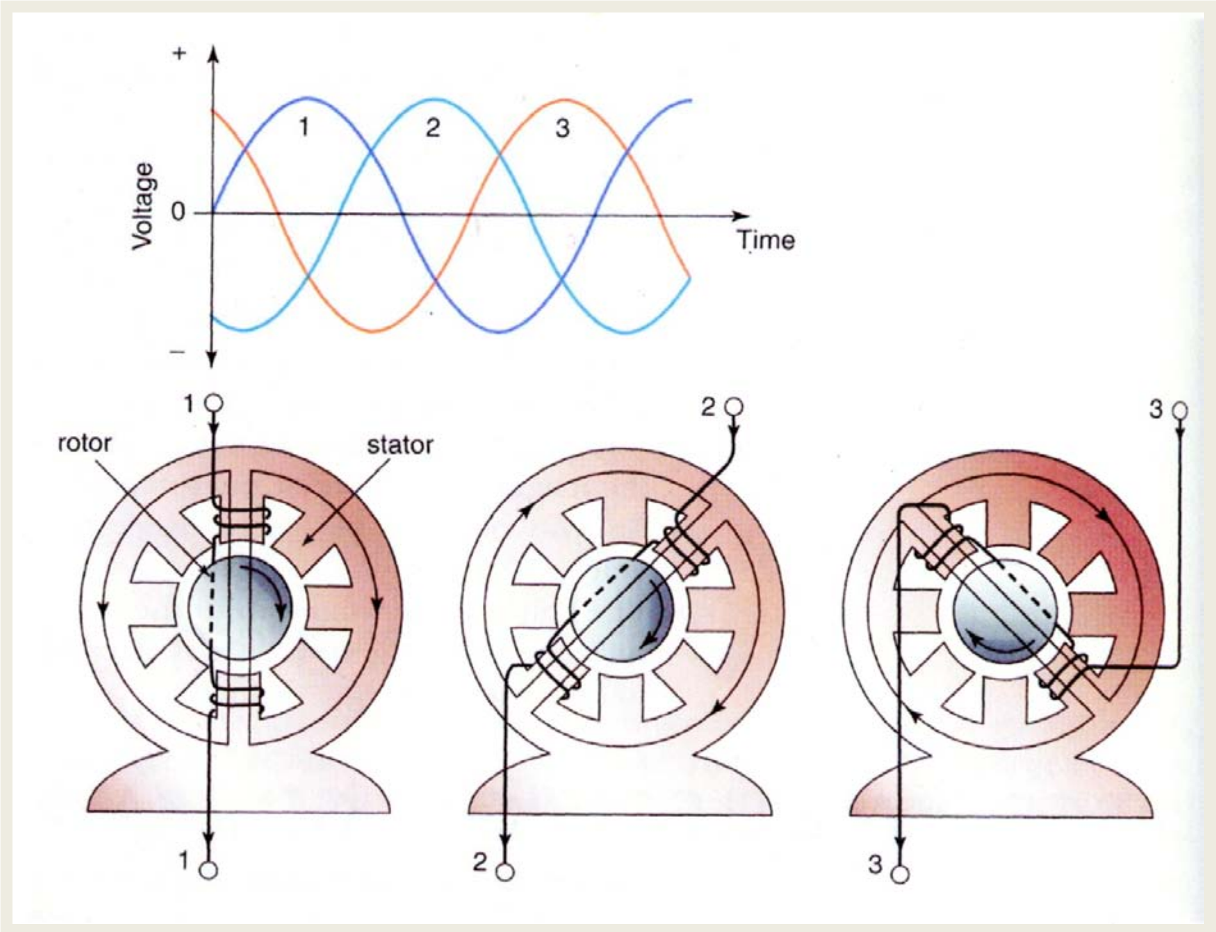
This design keeps the generating coil stationary and uses the slip rings to supply DC current to a rotating solenoid.

A strong magnetic field can be established with a DC current of 5000 A. (larger possible)

Three Phase Alternator

A three phase alternator consists of three pairs of stator coils as shown in the diagram.

This results in three active outputs each 120° out of phase.



TRANSFORMERS

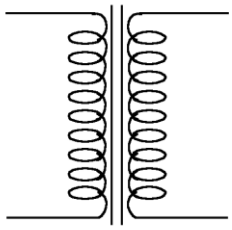
A transformer is a device used to increase or decrease an AC voltage.

A transformer will transfer electrical energy from one circuit to another circuit.

A transformer is an induction device and consists of two conducting coils termed the primary coil and the secondary coil.

If an alternating electrical current passes through the primary coil, a changing magnetic field is produced.

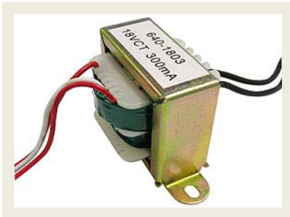
The secondary coil is located so that this magnetic field threads through it.



Circuit Symbol for
a Transformer

A soft iron core is inserted between the coils to intensify the magnetic effect.

Note that both the input and output are AC electricity.



The changing field produced by the primary coil induces an emf in the secondary coil. This process is commonly termed **mutual induction**.

Current in the primary coil must be changing.

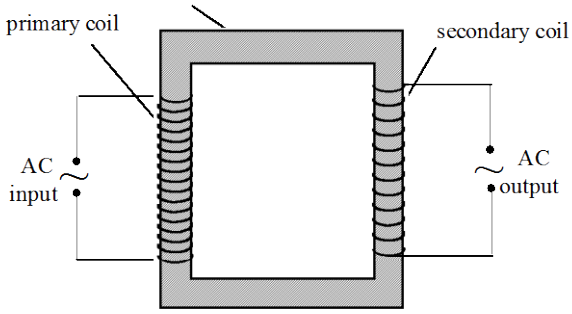
A direct current in the primary will result in no induced current in the secondary coil.

The emf is directly proportional to the number of turns in the primary and secondary windings.

Thus the relationship between the primary voltage V_P and the secondary voltage V_S is given by:

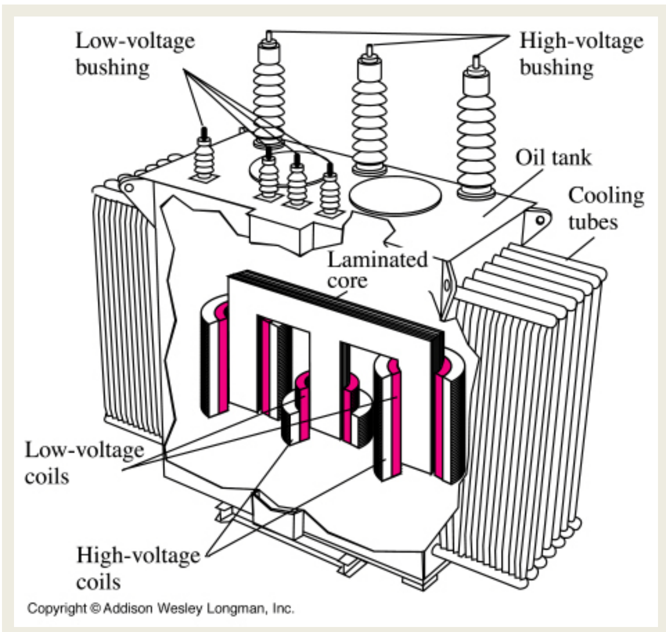
$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

where N_P and N_S are the number of turns in the primary and secondary coils respectively.



Transformer

The frequency of the induced current is the same as the frequency of the input current.



Step Up and Step Down Transformers

A transformer is used to convert between one voltage and another.

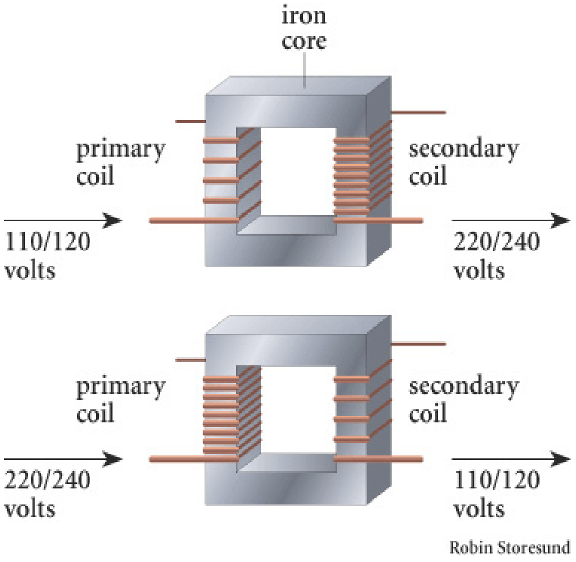
Transformers may be **step up** transformers or **step down** transformers.

A step down transformer is used to produce an output voltage lower than the input voltage.

For example a simple step down transformer may be used to produce a 9 V output to power a portable radio.

A welder incorporates a relatively larger step down transformer.

A step up transformer results in an output voltage higher than the input voltage.



Transformers are designed so that (nearly) all the magnetic flux produced by the current in the primary will also pass through the secondary coil.

Most transformers are reasonably efficient – as high as 99%. However a small amount of energy is wasted which appears as heat.

Eddy Currents

When a conductor either moves in a magnetic field or remains stationary in a changing magnetic field, electromagnetic induction can set up circulating currents in the conductor, called **eddy currents**.

Eddy currents obey **Lenz's** law. They will heat the conductor.

Eddy currents are wasteful in transformers.

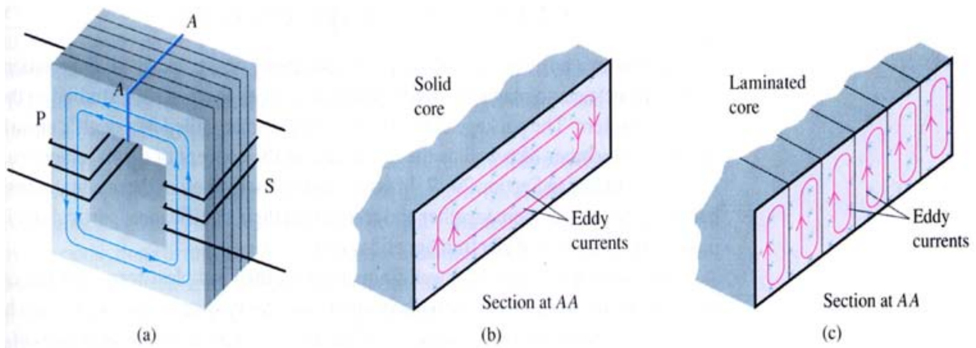
Transformers are often laminated to reduce the effects of eddy currents.

Eddy currents occur because the core is itself a conductor in a changing magnetic field.

They are reduced by making the core from thin sheets of soft iron which are insulated from each other.

The laminated (layered) thin sheets are insulated so that their resistance is high.

Well-designed, large transformers can have efficiencies as high as 99%



(a) (b) (c)

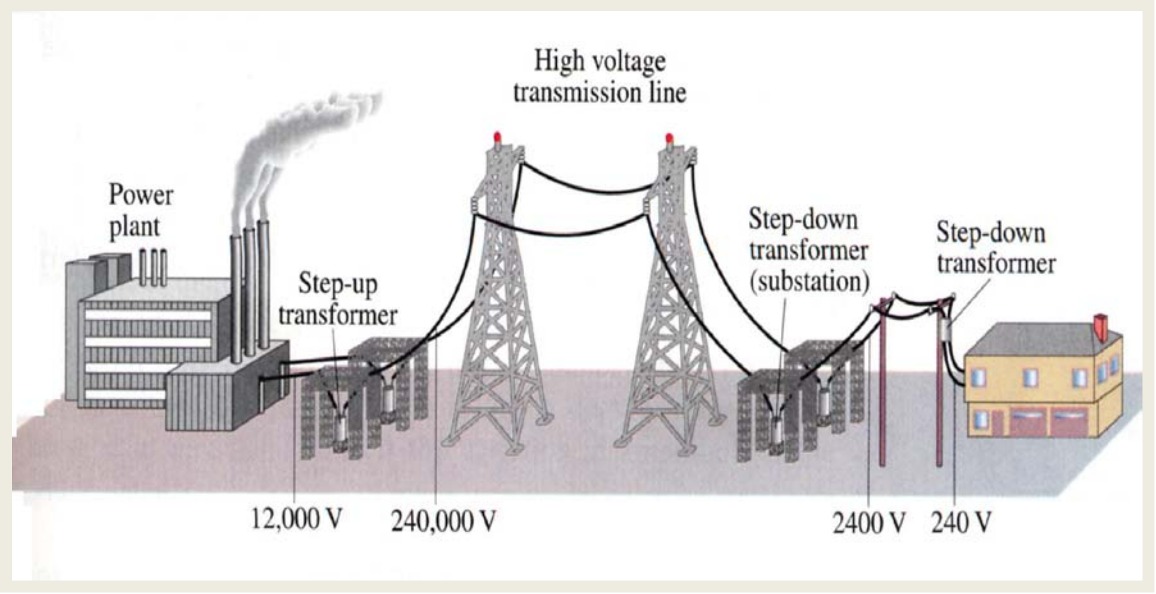
TRANSMISSION OF ELECTRICAL POWER

Mains electrical power is generated in huge alternators sited in power stations, and is sent across the state mainly through overhead cables.

There are many transformers between a power station and the mains sockets in our homes.

Electricity generated by power stations is stepped up by transformers to very high voltages for transmission.

Electricity is transmitted at these voltages to minimise energy loss.



For a given power output from the power station, current is inversely proportional to the transmission voltage since **P = VI**.

Thus for a given power output, if the transmission voltage V doubles, I is halved.

Now the power lost in transmitting the electrical current is directly proportional to the square of the current that flows since

$$P_{LOST} = I^2R$$

Thus by doubling the transmission voltage the power lost due to resistance in the power lines is one quarter.

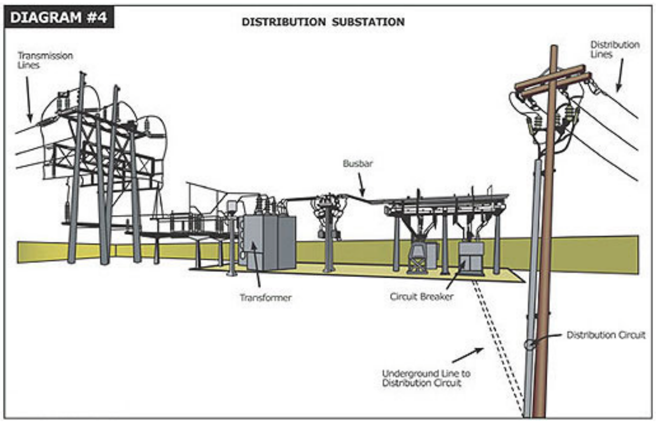
Voltages typically between 200 kV and 700 kV (termed extra high voltage or EHV) are used for long distance transmission, for example between power stations and the cities.

Pylons 15 m high are used to support the power lines which carry this electricity.

It is necessary to have these conductors well away from the ground to stop arcing to earth.

Transformers for domestic and industrial use must successively step down these high voltages.

EHV electricity is reduced in voltage by substations to lower voltages, typically 66 kV, 22 kV and 11 kV.



Using these lower voltages, electrical energy can be transmitted to industry and local areas without the need for the large pylons.

The final stage in this process is the reduction in voltage to 240 V for household use.

Normally this takes place using transformers located on street lamp poles near individual homes.

There is however a disadvantage of using such high voltages.

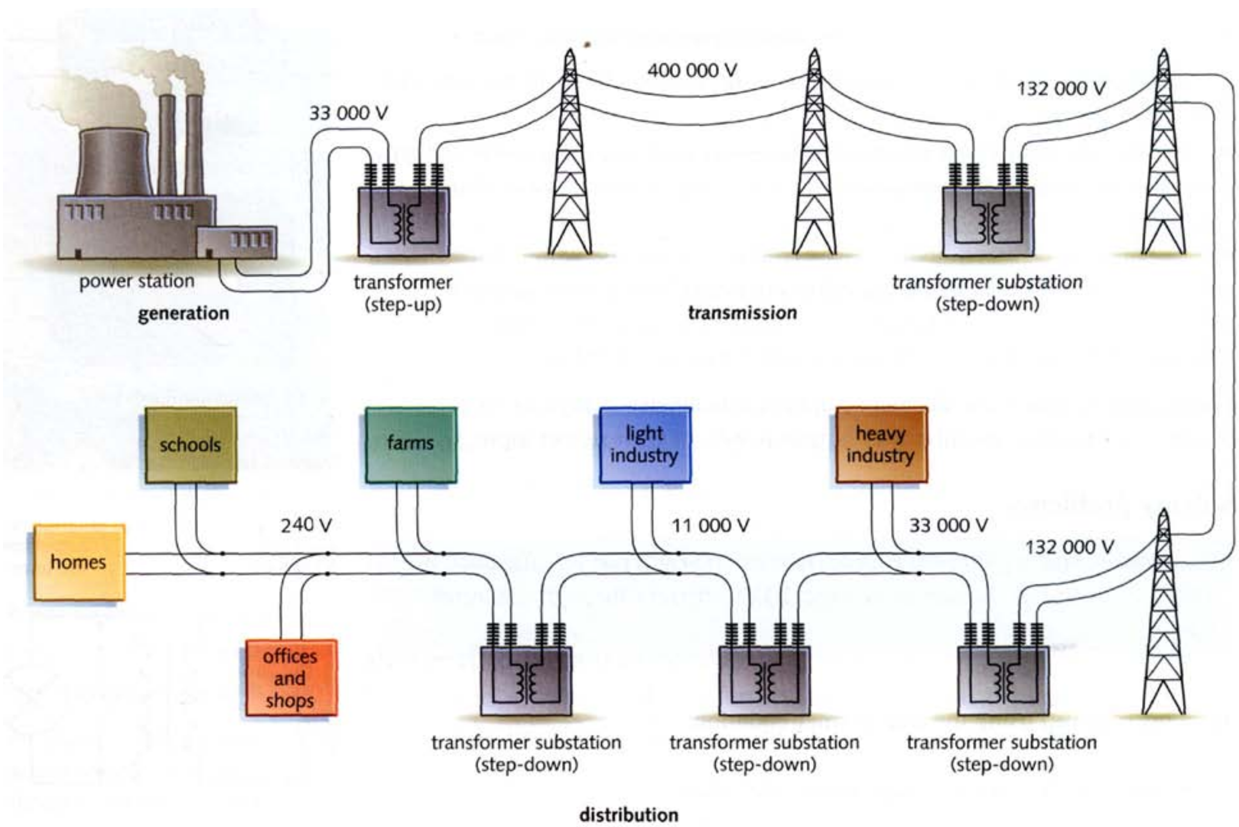
A larger voltage means an increase in the electric field around the wires.

A strong electric field will tend to ionise the air surrounding the wires and thus a small current will flow from the lines.

This current is called the “corona discharge”.

This can sometimes be seen at night when the air is damp.

It appears as a blue aura around the power lines.



Example 1: A power station generates an average of 400 MW of electricity. It supplies electricity to a city 100km away. The transmission lines have a total resistance of 2 Ω. Calculate the power loss in a system if the electricity is transmitted at
a) 240 kV b) 12kV

Approach: We cannot use $P = \frac{V^2}{R}$ directly because although a value for the resistance of the transmission lines is given, we do not know the voltage drop along the lines. So we use P = IV to determine the current in the lines and then the Power loss equation $P_L = I^2 R$ to find the answer.

Solution: a)

$$P_{IN} = IV$$

$$\Rightarrow I = \frac{P_{IN}}{V} = \frac{400\times10^6}{240\times10^3} = 1.67\times10^3$$

Therefore if 400 MW is sent at 240 kV, a current of 1670 A will be sent along the lines.

The Power Loss P_L will be $P = I^2 R = (1.67\times10^3)^2\times2 = 5.58\times10^6$ W

b)

$$P_{IN} = IV$$

$$\Rightarrow I = \frac{P_{IN}}{V} = \frac{400\times10^6}{12\times10^3} = 3.33\times10^4 A$$

Therefore if 400 MW is sent at 240 kV, a current of 1670 A will be sent along the lines.

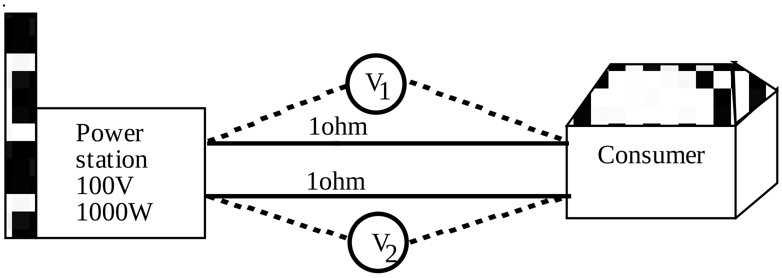
The Power Loss P_L will be $P = I^2 R = (3.33\times10^4)^2\times2 = 2.22\times10^9 W$

Nearly 400 times as much more power would be lost if the electricity was transmitted along the lines at the lower voltage of 12 kV rather than at 240 kV.

Problem 1: Compare the power loss in a system supplying 200 MW along a power line of resistance 10Ω at (a) 66 kV (b) 330 kV.

Exercise:

A model 'power station' produces electricity at 100 V and has a power of 1000 W. The current is taken from the power station to the consumer and back with transmission cables each of which have a resistance of 1 ohm.



1. What is the size of the current that flows in the transmission lines?

---

2. What would be the reading on a voltmeter placed in the position of V_1 ?

---

3. What would be the reading on a voltmeter placed in the position of V_2 ?

---

4. What voltage is available for the consumer?

---

5. How much power is lost from one of the transmission lines?

---

6. How much power is lost from both transmission lines added together?

---

7. How much power is available for the consumer?

8. Write down the efficiency of this system as a percentage.

The ‘power station’ is then altered so that its power remains at 1000W but its voltage is increased to 1000 V. For questions 9 to 16 repeat questions 1 to 8 above with this different information and for question 17 comment on the meaning of the results of your two calculations.

9. What is the size of the current that flows in the transmission lines?

10. What would be the reading on a voltmeter placed in the position of V_1?

11. What would be the reading on a voltmeter placed in the position of V_2?

12. What voltage is available for the consumer?

13. How much power is lost from one of the transmission lines?

14. How much power is lost from both transmission lines added together?

15. How much power is available for the consumer?

16. Work out the efficiency of this system as a percentage.

17. Comment on the meaning of the results of your two calculations.

Exercise 6: Electric Power

1. A transformer for a toy train set plugs into the 240V mains supply and changes it to 12 V in order to draw a current of 60 mA to run its engine (motor).

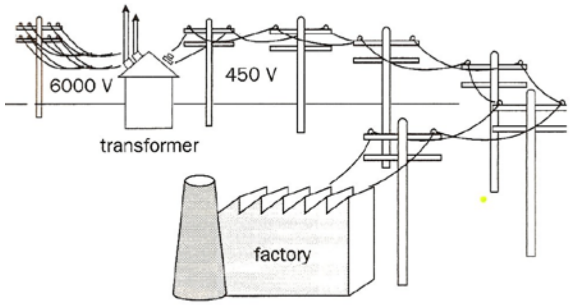
   a) Is the transformer a step-up or step down transformer?
   b) If the primary is known to have 400 turns, how many turns does the secondary consist?
   c) How much power is the train using?
   d) How much power is the transformer taking from the mains?
   e) How much current is the transformer drawing from the mains?

2. You are going to the USA and you need to take a transformer so that your 120 W hair drier, which uses 240 V in Australia, will work on the 110 V mains supply.

   a) Do you require a step-up or step-down transformer?
   b) What is the resistance of your hair drier's heating element?
   c) If the transformer is known to have 55 turns in its primary, how comprise its secondary?
   d) What current will the hair drier draw from the transformer when used in the USA?
   e) What current will the hair drier draw from the mains when used in the USA?
   f) How much power will the hair drier be taking from the mains supply in the USA?
   g) Describe the likely result of using the hair drier in the USA without a transformer?

3. Given a total line resistance of 200 W, calculate the power loss in the transmission lines when 1.0 MW of power is sent as (a) 20 A at 50 kV and (b) 2.0 A at 500 kA

4. The diagram shows AC voltage being supplied to a small factory. The main transmission lines supply power at 6000 V rms. A step-down transformer reduces this to 450 V rms.



Two wires, each of 1.0 km length, connect the transformer to the factory as shown.

24 KW of electric power is being drawn from the output terminals of the transformer.

The total resistance of the two factory supply wires is 0.050 Ω.

a) If the primary winding of the transformer has 500 turns, determine the number of turns in the secondary.
b) Calculate the maximum voltage difference across the input terminals of the step-down transformer.
c) Calculate the rms current flowing in the factory supply wires.
d) Calculate the power loss in the factory supply wires.
e) What voltage is delivered to the factory?

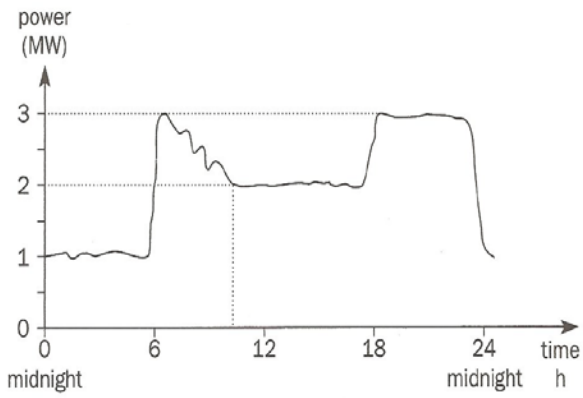
5. The electric power used in a small town at different times of one particular day are plotted on the following graph.

a) At what time was electrical energy being used at the greatest rate?

b) How much electrical energy was used between 10 a.m and noon?

c) What was the most electrical energy used in any one hour period?

d) What was the electrical energy used during the entire day? (answer in MWh)



ANSWERS

1	a) Step-down	b) 20	c) 0.72 W	d) 0.72 W	e) 3 mA	
2	a) Step-up	b) 480 Ω	c) 120	d) 0.5 A	e) 1.1 A	f) 120 W
3	a) 80 kW	b) 800 W				
4	a) 38	b) 8485 V	c) 53 A	d) 142 W	e) 447 V	
5	a) between 6 p.m and midnight	b) 1.44×10^{10} J (or 4 MWh)				
	c) 1.08×10^{10} J (or 3 MWh)	d) approximately 53 MWh				