Electromagnetism and Electromagnetic Induction

Physics
13

13.1 Magnetism

Figure 13.1 shows the use of a large electromagnet to lift and remove scrap iron and steel. Since iron and steel pieces are attracted towards this strong electromagnet, it is easy to move them using this method.

Figure 13.1 – Use of an electromagnet to remove scrap iron and steel

There are two main types of magnets known as **electromagnets** and **permanent magnets**. In electromagnets, magnetism exists only while a current is passing through the coil of the electromagnet. In permanent magnets, magnetism is a characteristic of the material of the magnet and it remains in the magnet permanently.

Both types of magnets are used in many instruments for various purposes. Magnets are used in controlling most domestic appliances and robots by electric motors, in applications involving magnetic cards, in medical equipment such as MRI machines and in various other scientific and technological instruments. Therefore, it is useful to have a good knowledge about the behaviour, operation and applications of magnets.

Figure 13.2

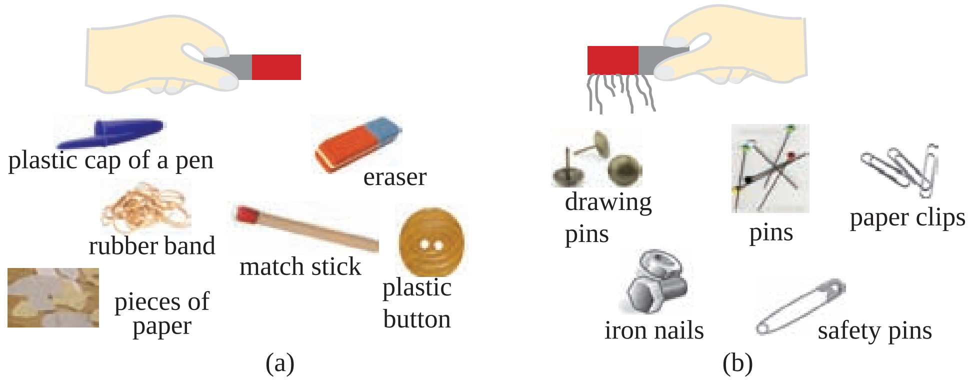


Figure 13.3 (a) - Objects which are not attracted (b) - attracted by magnets

Objects made of magnetic materials such as iron, steel, nickel are attracted by magnets. Objects made of materials such as plastic, wood, paper and rubber are not attracted by magnets.

13.1.1 Magnetic Field

Around any magnet, there is a region within which the magnet has an influence. This region is known as the **magnetic field**. A magnetic field is not perceptible to the eye. Therefore we cannot see a magnetic field. However, it can influence another magnet or a moving charge. It has been found that some animals such as birds use the earth's magnetic field for navigation.

One way of determining whether there is a magnetic field in a certain region is to use a compass. A compass is a small light-weight magnet mounted on a pivot in such way that it could rotate freely around the pivot. In the absence of any magnetic influence other than the earth's magnetic field, a compass aligns along the north-south direction. Let us engage in activity 13.1 to investigate the field near to a bar magnet.

Activity 13.1

Apparatus required: A compass, a piece of glass, A piece of iron, A magnet, A piece of plastic, a piece of brass

- Place the compass on a table and observe the deflection of its indicator by bringing close to it, a piece of glass, a piece of iron, a magnet, a piece of plastic and a piece of brass one at a time.

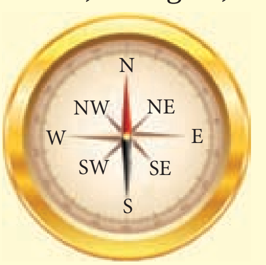


Figure 13.4

You will observe that the indicator of the compass deflects only when a magnet is brought close to it. From this we can conclude that the magnet gives rise to a magnetic field in its vicinity.

For extra knowledge

Naturally occurring magnets have been known to man as far back as thousands of years. The compass was invented by Chinese in the eleventh century AD.

When a compass is placed at a point in a region where a magnetic field exists, the direction of the compass needle shows the direction of the magnetic field at that point. This direction can vary from point to point. In addition, the strength of the magnetic field can also vary from point to point. Therefore, a magnetic field is a physical quantity with a magnitude and a direction.

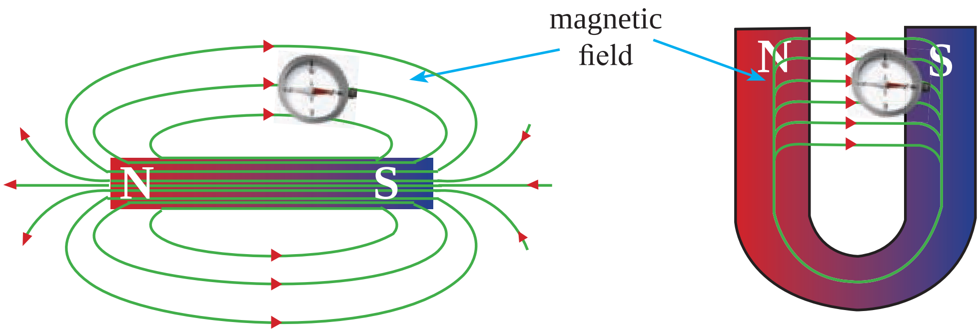


Figure 13.5 – Finding the direction of a magnetic field using a compass

13.2 Magnetic Effect of a Current

When an electric current flows through an electric conductor, a magnetic field is created in the vicinity of the conductor. Danish scientist Hans Christine Oersted was the first to observe a magnetic effect in the vicinity of a current carrying conductor.

Figure 13.6 - Hans Christine Oersted

Let us now engage in activity 13.2 to observe a magnetic effect (field) due to a straight conductor carrying a current.

Activity 13.2

Apparatus required: a compass, a straight copper wire, a few batteries, connecting wires and a switch

- Place the compass on the table with its indicator along the north-south direction and next place the copper wire *AB* above the compass and along the north-south direction.

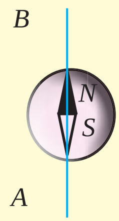


Figure 13.7

- Connect a battery and a switch to *AB* using connecting wires.
- Close the switch S and allow a current to pass through *AB*. The compass indicator will show a deflection towards the left hand sides.
- Stop the current flow by opening switch S and observe the compass needle. You will observe that the indicator returns to its original position.

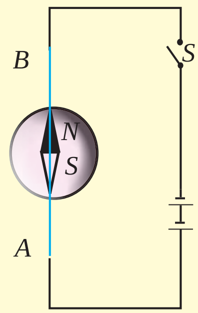


Figure 13.8

- Now place the compass horizontally above the wire *AB* and observe what happens when a current flows through *AB*. You will observe that the indicator deflects in the opposite direction.
- Now change the terminals of the battery and allow a current to flow in the opposite direction (*BA*). Place the compass below the wire *AB*. You will observe that the compass needle deflects towards the right hand side.
- Now place the compass above the wire and allow the current to pass in the direction *BA*. You will be able to observe that the compass indicator deflects in the opposite direction.

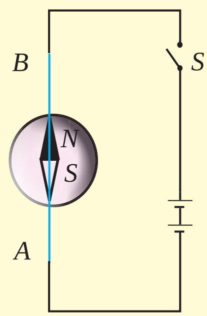


Figure 13.9

The indicator deflects only when it is subjected to the influence of a magnetic effect. That is, in the presence of a magnetic field. This activity would show you that a magnetic field is created when a current flows through a conductor.

It will be clear to you from the above activity that the direction of the magnetic field in the vicinity of a current carrying conductor depends on the direction of the current flow.

13.2.1 Direction of the Magnetic Field due to a Current through a Straight Conductor

Let us now investigate about two rules that could be used to find the direction of the magnetic field due to a current flowing through a straight conductor.

- ### Maxwell's corkscrew rule

Maxwell's corkscrew rule can be used to find the direction of the magnetic field due to a current flowing through a conductor.

When a corkscrew is rotated in such a way that its tip moves in the direction of current flow, then the magnetic field lines produced by the current are in the direction of rotation of the corkscrew.

A corkscrew is an instrument used to open bottles with cork lids. Normal screws show the same behavior as corkscrews.

(a) According to Figure 13.10 (a), when a current flows from *A* to *B*, the direction of the resulting magnetic field is anti-clockwise.

(b) According to Figure 13.10 (b), when a current flows from *B* to *A*, the direction of the resulting magnetic field is clockwise.

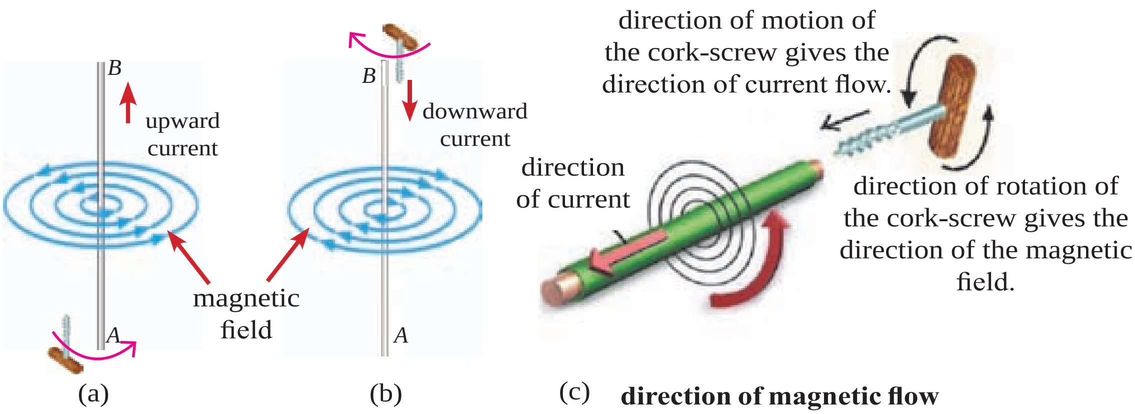


Figure 13.10 – Magnetic field around a current carrying conductor

- ### Right hand grip rule

Right hand grip rule is another simple rule for finding the direction of the magnetic field due to a current carrying conductor.

If the conductor is held with the right hand in such a way that the thumb is directed towards the direction of current flow, then the direction of the other four fingers around the conductor indicates the direction of the magnetic field.

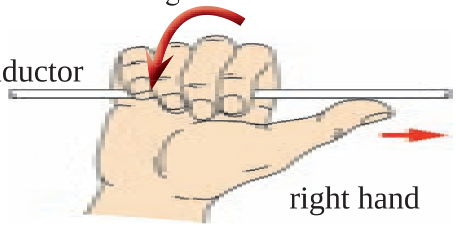


Figure 13.11 – Finding the direction of magnetic field from the direction of current flow

Figure 13.12 shows how the direction of the magnetic field due to a current carrying conductor is marked in a diagram.

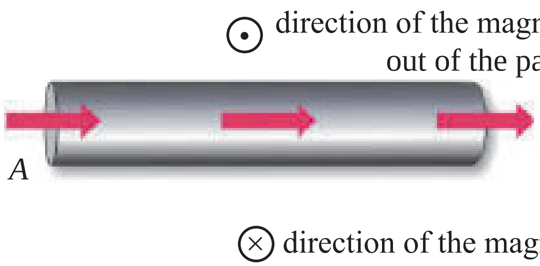


Figure 13.12 – Indicating the magnetic fields perpendicular to the plane of the page directed into and directed out of the page in a diagram

Suppose that a current flows through the conductor in Figure 13.12 along the direction *AB*. Then, according to the right hand rule, the magnetic field is directed towards you (from the page) in the region above the conductor while it is directed away from you (into the page) in the region below the conductor. A dot inside a circle ($\odot$) is used to indicate a magnetic field coming out of the page while a cross inside a circle ($\otimes$) is used to indicate a magnetic field going into the page.

13.2.2 Force Acting on a Current Carrying Conductor Placed in a Magnetic Field

You have learnt that a magnetic field is established in the vicinity of a conductor that carries a current. Let us now engage in Activity 13.3 in order to find out whether a force acts on a current carrying conductor placed in a magnetic field.

Activity 13.3

Apparatus required: A U-magnet, a piece of conductor, two brass or some other conducting rods, two dry cells

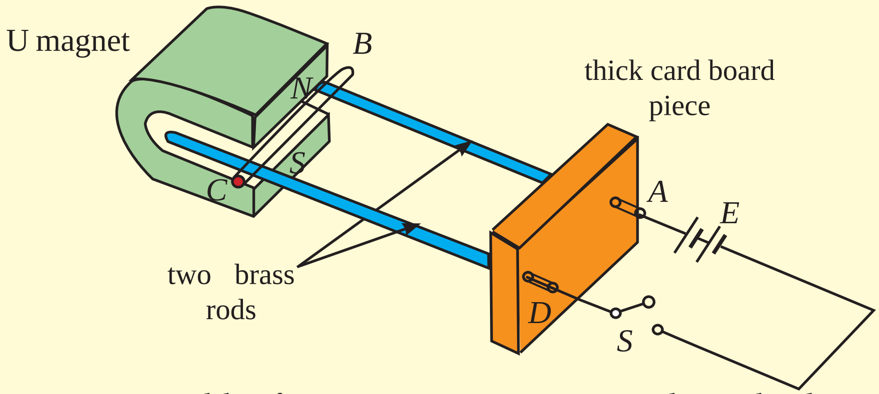


Figure 13.13 - modeling force acts on a current carrying conductor placed in a magnetic field

- Place the U-magnet on a table and place the two brass rods as shown in the figure by inserting them through two holes pierced in the thick card board. Connect the two dry cells and the switch *S* to the ends *A* and *D* of the brass rods.
- Next place the conductor *BC* on the two brass rods between the north and south poles of the magnet.
- Allow a current to flow by closing the switch *S*. Then a current flows from the cells through the brass rods along the direction *AB* and through the conductor in the direction *BC* and reaches the cell from the direction *CD*.
- When the current flows, you will observe that the conductor *BC* moves along the brass rods away from the magnet (to the right hand side).
- Now repeat the above step by changing the cell terminals to change the direction of the current. Now you will observe that the conductor *BC* moves along the brass rods towards the magnet (to the left hand side).
- Repeat the above step after changing the top and bottom poles of the magnet. You will observe that the direction of motion of the conductor *BC* is opposite to that of the above steps.

A conductor placed in a magnetic field moves when a current flows through the conductor as a result of a force acting on it. The direction of the force is indicated by the direction of motion of the conductor.

In the activity above, the direction of the magnetic field and the direction of the current through the conductor have been arranged to be perpendicular to each other.

You will be able to observe that the motion of the conductor takes place in a direction perpendicular to both of the above directions.

The magnitude of the resulting force depends on the following three factors.

- The magnitude of the current through the conductor
- The length of the conductor between the rods
- The strength of the magnetic field

The force increases as the above three factors are increased and it decreases when the above three factors are decreased. That is, the force is directly proportional to the three factors given above.

• Fleming's left hand rule

Fleming's left hand rule can be used to find the direction of the force acting on a conductor placed in a magnetic field when a current flows through the conductor.

Keep the thumb, index finger and the middle finger of the left hand perpendicular to one another and point the middle finger in the direction of the current flow and the index finger along the direction of the magnetic field. Then the direction pointed by the thumb will be the direction of the force acting on the conductor.

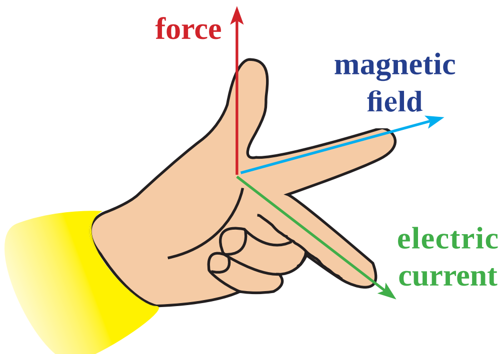
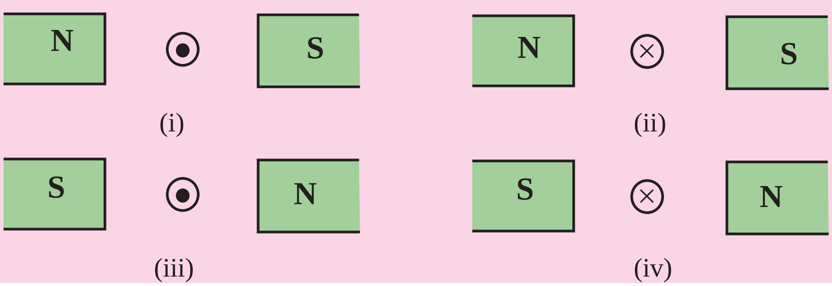


Figure 13.14 – Finding the direction of the force on the conductor based on the directions of the current and the magnetic field

Exercise 13.1

(1) Find and mark the direction of the force acting on the conductor using Fleming's left hand rule in each of the figures given below for the magnetic fields and currents indicated.



The action of a force on a current carrying conductor placed in a magnetic field is a very useful phenomenon in our daily lives. Electric motors, loud speakers, galvanometers, voltmeters and ammeters (analog) are some of the instruments constructed based on this phenomenon.

13.2.3 Loud Speaker

Figure 13.15 shows the outward appearance and the cross section of a loud speaker. A loud speaker generates a sound when a current that varies according to the wave form of the sound is allowed to pass through the coil in the loud speaker.

The main components of a loud speaker are a light-weight cardboard cone, a conducting coil and a ring-magnet. The end of the cone with the larger diameter and the magnet are fixed to a supporting metal frame as shown in Figure 13.15(b).

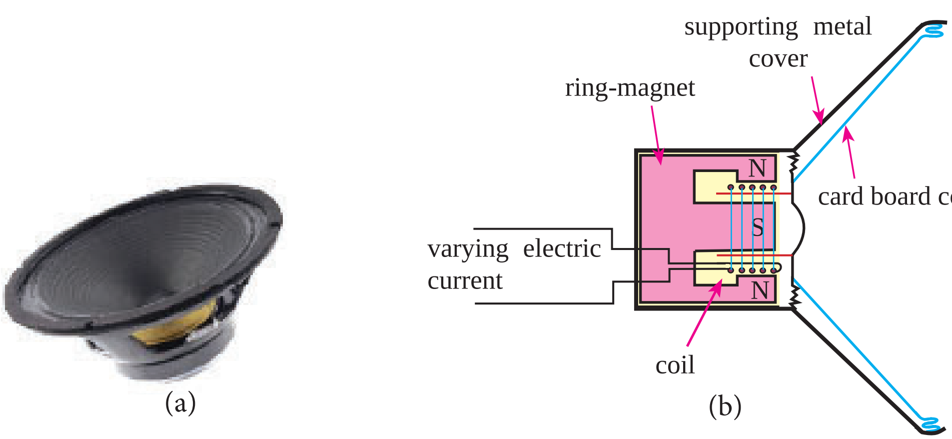


Figure 13.15 (a) – A loud speaker (b) A cross section of a loud speaker

The coil is connected to the end of the cone with the smaller diameter in such a way as to allow the coil to freely move forward and backward in the region between the poles of the magnet. When a time-varying current flows through the coil, the force exerted on the conductor by the magnet vibrates the coil forward and backward according the variation of the current and the cone too vibrates accordingly, generating sound waves.

13.2.4 Direct Current Motor (DC Motor)

Toy motor cars, hybrid cars, electric cars and electric trains are operated using DC motors.

A hybrid car

An electric car

An electric train

Figure 13.16

Let us engage in activity 13.4 to construct a DC motor.

Activity 13.4

Apparatus required: A dry cell, insulated copper wires, two needles with large holes, some clay, cello tape, A knife for cutting wires, A small (ring) magnet.

- First construct the magnetic coil. In order to do this, wrap about 30 windings of the copper wire around a cylindrical object such as a somewhat large pen, starting from the middle of the wire. Wind the free ends of the wire several times around the coil to prevent it from unwinding.
- Use the knife to remove the insulation of the wire as shown in figure 18 near the free ends. Removal of the insulation should only be done in about half of the wire and on the same side at each end.
- Next, pass the two ends through the needle holes and mount the coil on the needles horizontally as shown in figure 3.

- Fix the needles on to the terminals of the dry cell using cello tape as show in the figure 4.
- Use clay to fix the dry cell rigidly.
- Finally attach the circular magnet on the cell using clay.

You will be able to observe the copper wire rotating. If it does not rotate, give it a slight push with your hand. Then it will start rotating.

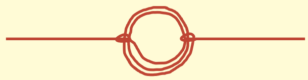


figure 1

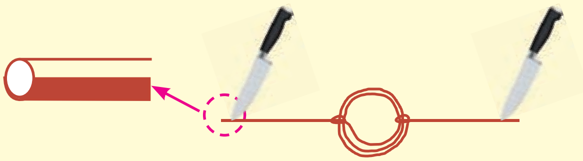


figure 2

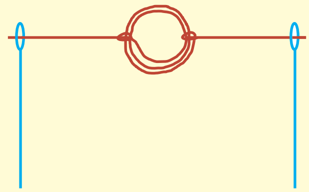


figure 3

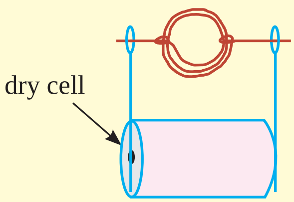


figure 4

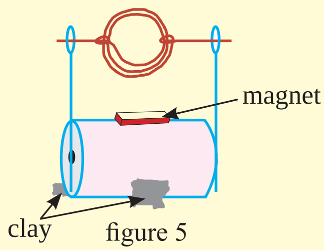


figure 5

In this case too, the magnetic field exerts a force on the conductor when a current flows through it. Since the conductor in this case is a coil, two forces act on the coil in two opposite directions (a couple) as shown in figure 6 causing it to rotate.

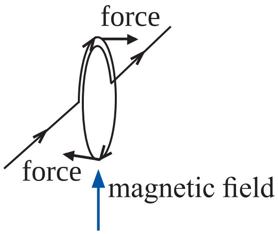


figure 6

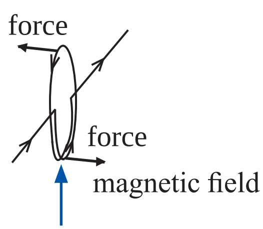


figure 7

The reason for removing the insulation in only one side of the coil at the two ends is to prevent a current from flowing through the coil in the second half a cycle (after the first half cycle). Otherwise, the couple will act in the opposite direction in the second half cycle as shown in figure 7 and the coil will tend to rotate in the opposite direction. If however the current is prevented from flowing in the second half cycle, the coil will continue to rotate in the same direction during the second half cycle too in the first half cycle.

- **Main parts of the DC motor**

Armature

In normal DC motors, there is a coil much like the coil you used in the previous activity. Since a motor is used to rotate some load, the coil of a DC motor must be strong enough to withstand an external load. Therefore the coil is wrapped around a steel or iron core as shown in the figure 13.17. This coil, together with the core, is known as the **armature.**

Figure 13.17 - Armature

The function of the armature is to give rise to a rotation by generating a couple when a current is passing through it.

Magnetic Poles

A magnetic field is required to exert a force on a coil when a current flows through the coil. In normal DC motors this magnetic field is obtained by poles of a permanent magnet arranged around the armature as shown in the figure 13.18.

Figure 13.18- Magnetic Poles

Commutator

In the motor you constructed, the insulation was removed only on one side of the wire near the ends. That was because the coil would rotate in two opposite directions if the insulation is completely removed. Therefore, in your motor, the current flows through the coil only in one half of each cycle. When the current flows only during half a cycle, the load that the motor can rotate is restricted. Therefore a more suitable way for the current to flow would be to let the current to flow in one direction during half of a rotation cycle and to let the current to flow in the opposite direction in the next half cycle. A **commutator** is used to alternate the direction of current flow in this manner.

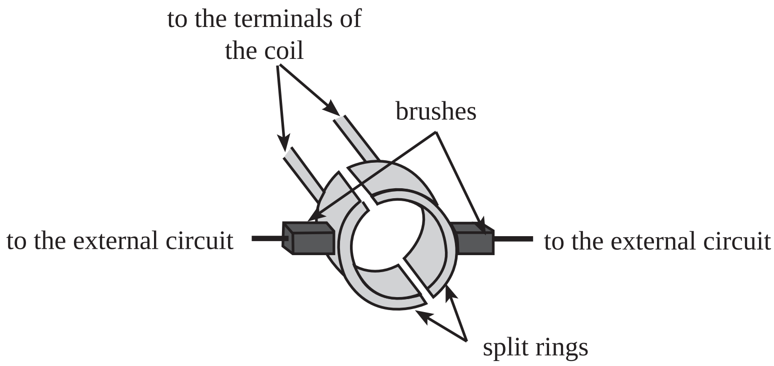


Figure 13.19 - Commutator

The commutator consists of two metallic split rings and two parts known as brushes that can be adjusted to brush against the split rings as shown in the figure 13.19. The two ends of the coil are connected to the two split rings and they rotate with the armature. The two brushes maintain contact with the split rings without rotating themselves. These two brushes are connected to the external circuit that provides current to the motor.

• Operation of a DC Motor

Figure 13.20 shows the appearance of a motor with all of the above components assembled together. Figure 13.21 shows a simplified figure that can be used to understand the operation of the motor easily. In the Figure 13.21 the coil of the motor is shown by a single loop *ABCD*. This coil is placed between two magnetic poles. The coil is connected to the split rings *X* and *Y* while the brushes *P* and *Q* are connected to the battery *S*.

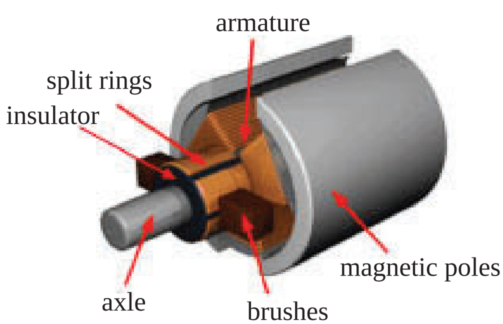


Figure 13.20 – Main parts of a dc motor

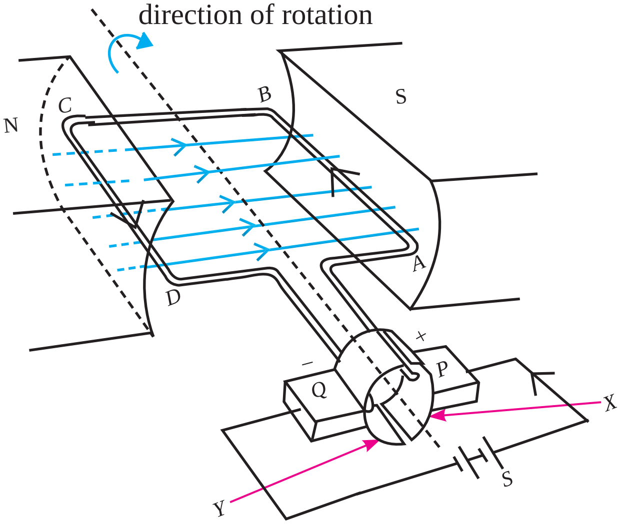


Figure 13.21 – Modeling the operation of a DC motor

- When a current is made to flow through the motor, the current enters the split ring *X* through the brush *P* and flows through the wire loop *ABCD*, reaches the split ring *Y* and passes to the external circuit through the brush *Q*.
- The current passes through the loop placed in the magnetic field along the directions *AB* and *CD*.
- Find the direction of the force acting on *AB* and *CD* by applying Fleming's left hand rule. You will find that the force on *AB* acts downwards while that on *CD* acts upwards. The armature will rotate clockwise due to the resulting couple.
- Let us now consider what happens when the coil and the two split rings have rotated by 180^{o} and their positions are inverted. This position is shown in Figure 13.22.
- At this point, brush *P* is in contact with split ring *Y* while brush *Q* is in contact with split ring *X*. Then the current enters from brush P to split ring *Y*, flows in the direction *DCBA* and reaches split ring *X* and leaves from brush *Q*.

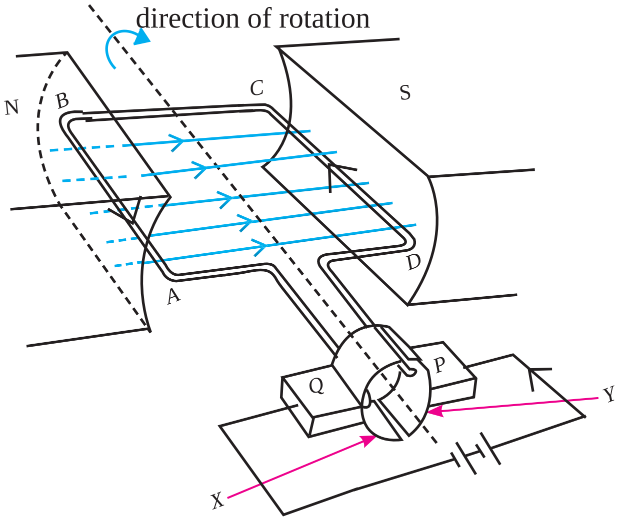


Figure 13.22 – Modeling the operation of a DC motor

- In this situation, current flows along the directions *DC* and *BA* in the coil.
- When Fleming's left hand rule is applied it will be clear that the motion of *AB* is upwards while that of *CD* is downwards. The resulting couple rotates the armature further in the clockwise direction.
- If the direction of the current is changed by changing the battery terminals, the directions of the forces also change to the opposite directions and the direction of rotation of the armature will be in the anti-clockwise direction.
- In the operation of the DC motor, the electric energy given to the motor is converted to mechanical energy.

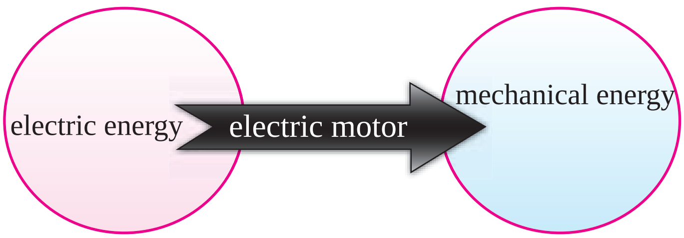
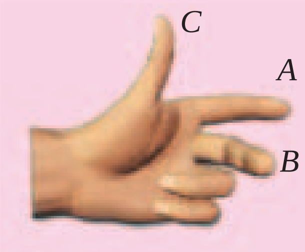


Figure 13.23 – Energy transformation in electric motor

Exercise 13.2

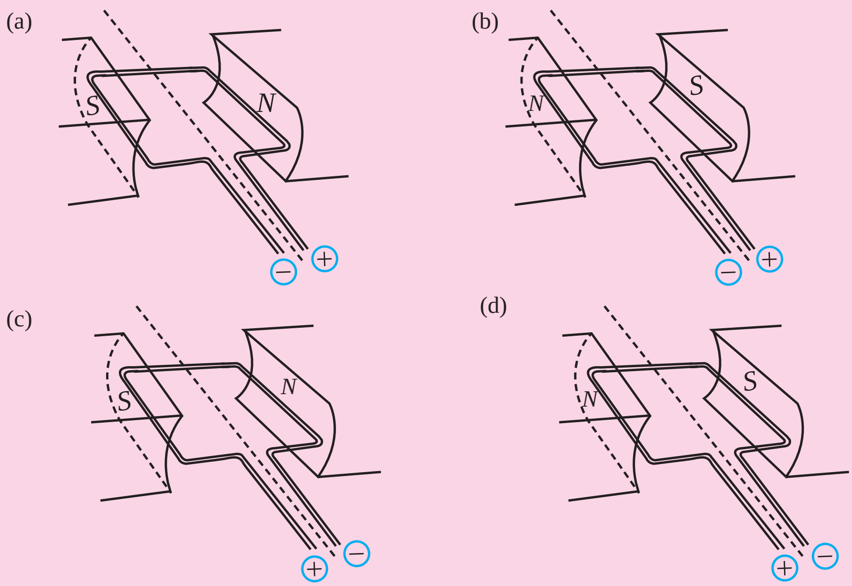
(1) The figure below shows how a student used his left hand in order to apply Fleming's left hand rule.



(i) For what purpose is Fleming's left hand rule used?

(ii) Directions of what physical quantities are represented by the fingers *A*, *B* and *C* in the above figure?

(iii) Write down what happens to the wire in the following cases using Fleming's left hand rule.



(2) The figure below shows the cross section of a loud speaker.

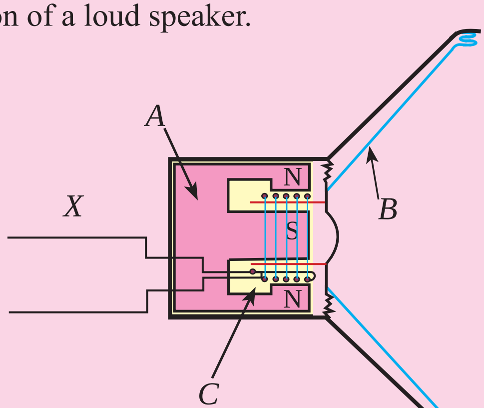
(i) Label parts *A*, *B* and *C* of the figure.

(ii) Write down a special characteristic of the current entering from the terminal *X*.

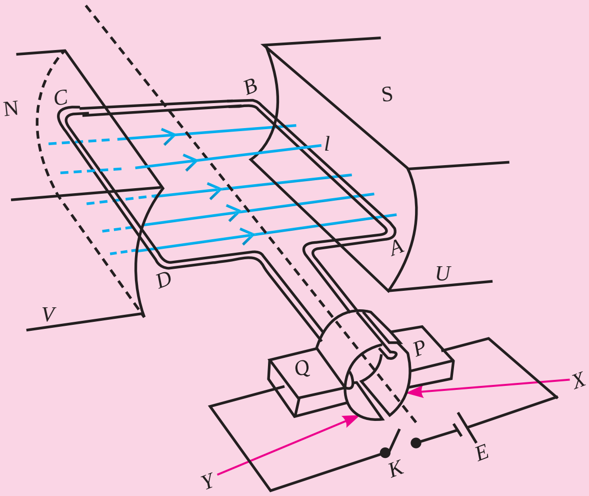
(iii) Explain the operation of the loud speaker.

(iv) Write down the energy transformation taking place in a loud speaker.

(v) Write down the functions of each of the parts *A*, *B* and *C*.



(03) The figure below shows the main parts of a DC motor.



(i) Label parts *P*, *Q* of the above figure.

(ii) What are the components labeled *X* and *Y*?

(iii) Indicate the direction of current flow in terms of the letters given when the switch *K* is closed.

(iv) What is the direction of rotation of the motor when switch *K* is closed?

(v) Write down the functions of each of the components given below in the motor above.

(a) *V* and *U* (b) *E* (c) *P* and *Q* (c) *X* and *Y*

(vi) Write down the changes that take place in the operation of the motor under each of the changes given below.

(a) Interchanging the battery terminals
(b) Increasing the strength of the magnet

13.3 Electromagnetic Induction

We studied the motion caused by electricity in the previous section. We will next focus on producing an electric current by a conductor that is moving in a magnetic field.

When there is a current flow through a conductor placed in a magnetic field, a force is exerted on the conductor causing it to move. Electromagnetic induction is the inverse of this. That is, if a conductor placed in a magnetic field is set in motion, then an electromotive force is created between the terminals of the conductor.

The generation of an electromotive force between the terminals of a conductor when the conductor is kept at rest in a changing magnetic field or when the conductor is moving in a constant magnetic field is known as **electromagnetic induction**.

Electromagnetic induction was first introduced to the world by Michael Faraday. An important law known as Faraday's law regarding this was presented by him in 1831.

The phenomenon of electromagnetic induction is used in magnetic cards used to enter shops and offices by employees, and the magnetic cards (credit and debit cards) used to make payments. Electricity, essential for the daily activities of the modern world, is mainly generated by converting the energy produced from sources such as oil, coal and nuclear power into electric energy through electromagnetic induction.

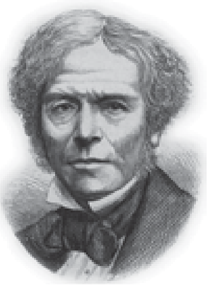


Figure 13.24 – Michael Faraday (1791 - 1867)

Figure 13.25

Let us now demonstrate electromagnetic induction by a simple activity.

Activity 13.5

Apparatus required: A bar magnet, The inner tube from a reel of thread, About one metre length of gauge 28 copper wire, A center zero galvanometer

- Form a coil by winding the copper wire around the thread reel and connect its two ends to a center zero galvanometer.
- Now do the movements given in the table below and fill the table by observing whether there is a deflection in the galvanometer or not.
- Observe the relative magnitudes of the deflections in steps 8 and 9.

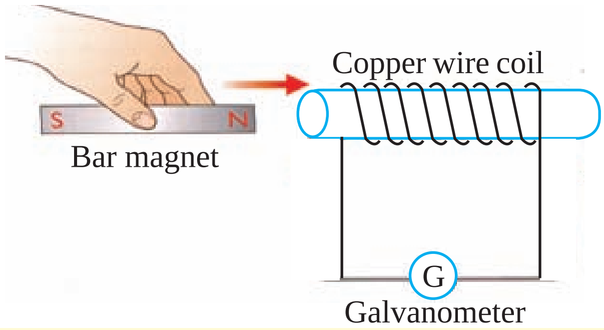


Figure 13.26 – Demonstrating electromagnetic induction

Motion of the magnet	Motion of the coil	Whether there is a deflection in the galvanometer or not
Towards the coil	Stationary	
Stationary near the coil	Stationary	
Away from the coil	Stationary	
Stationary	Towards the magnet	
Stationary	Away from the magnet	
Away from the coil	Away from the magnet	
Towards the coil	Away from the magnet (without changing gap)	
Rapidly towards the coil	Stationary	
Slowly towards the coil	Stationary	

It can be seen from the above activity that there is a deflection in the galvanometer for every motion where there is a change in the relative distance between the coil and the magnet.

- The galvanometer produces a deflection when there is a current passing through it. In order to create a current, there must be a source of electromotive force in the circuit. However there is no such source in the circuit above.
- In this case, an electromotive force has been created by the relative motion between the coil and the magnet. Such an electromotive force is known as an **induced electromotive force**.
- When the magnet and the coil get closer to each other or further away from each other, the magnetic field lines linked to the coil either increase or decrease. Since a deflection is observed in the galvanometer only at such instances, one can conclude that there must be a variation in the magnetic field lines linked to the coil in order to induce an electromotive force.

- A larger deflection is observed in the galvanometer when the magnet is moved rapidly than when it is moved slowly because the electromotive force induced in the coil is directly proportional to the rate of change of the magnetic field lines.

There are several factors affecting the magnitude of the induced electromotive force. Faraday's experiments showed these factors as,

(i) the number of turns (windings) in the coil,
(ii) strength of the magnet, and
(iii) speed of motion of the magnet or coil.

13.3.1 Direction of the current induced in a straight conductor placed in a magnetic field and connected to a closed circuit

When a straight conductor is placed in a magnetic field perpendicular to the field and moved in a direction perpendicular to both the magnetic field and the conductor, an electromotive force is induced across the ends of the conductor. If the conductor is connected to a closed circuit, a current flows through the conductor due to the induced electromotive force. The direction of current flow can be found using Fleming's right hand rule.

- **Fleming's right hand rule**

When the first three fingers of the right hand are oriented perpendicular to one another and the thumb is pointed in the direction of motion of the conductor and the index finger along the direction of the magnetic field that intersects the conductor, the middle finger shows the direction of the current flowing through the conductor.

Figure 13.27 illustrates the right hand rule.

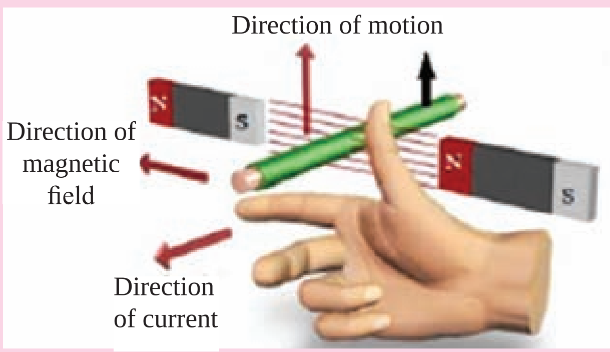
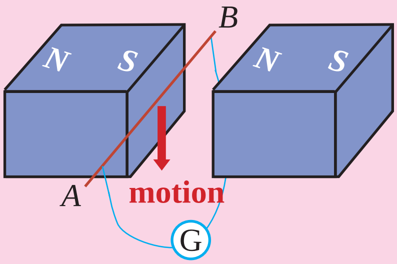


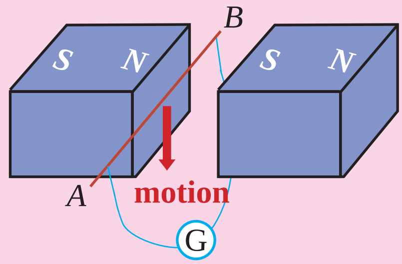
Figure 13.27 – Illustrating Fleming's right hand rule

Exercise 13.3

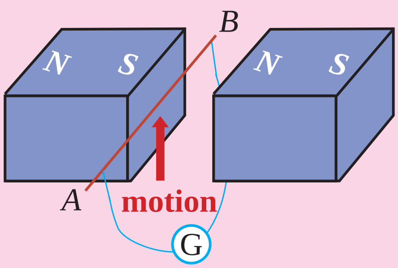
(01) Find and mark the direction of induced current flow using Fleming's right hand rule in each of the instances given below.



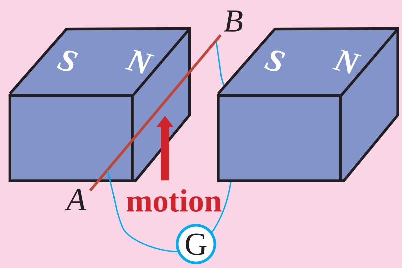
(i)



(ii)



(iii)



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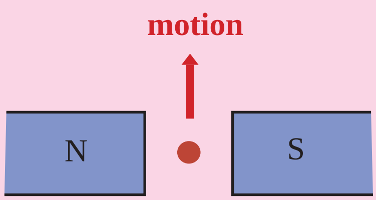
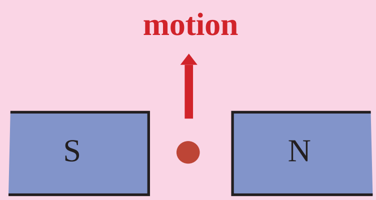
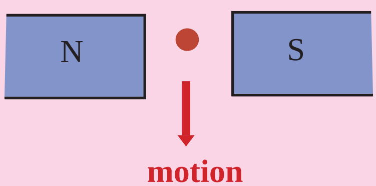


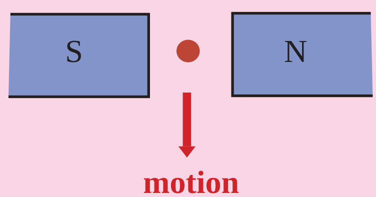
(v)



(vi)



(vii)



(viii)

13.3.2 Applications of Electromagnetic Induction

- **Alternating current dynamo**

Figure 13.28 shows an alternating current dynamo. A rectangular coil *ABCD* consisting of a number of turns of an insulated copper wire wound around it is connected to an axle that can be rotated around its axis. A strong magnetic field is applied across the coil using a north and a south pole placed on either side of the coil as shown in the figure. Terminal *A* of the coil *ABCD* is fixed to a coaxial copper ring *P* and the other terminal *D* is fixed to another identical copper ring *Q*. *P* and *Q* are known as brushing rings.

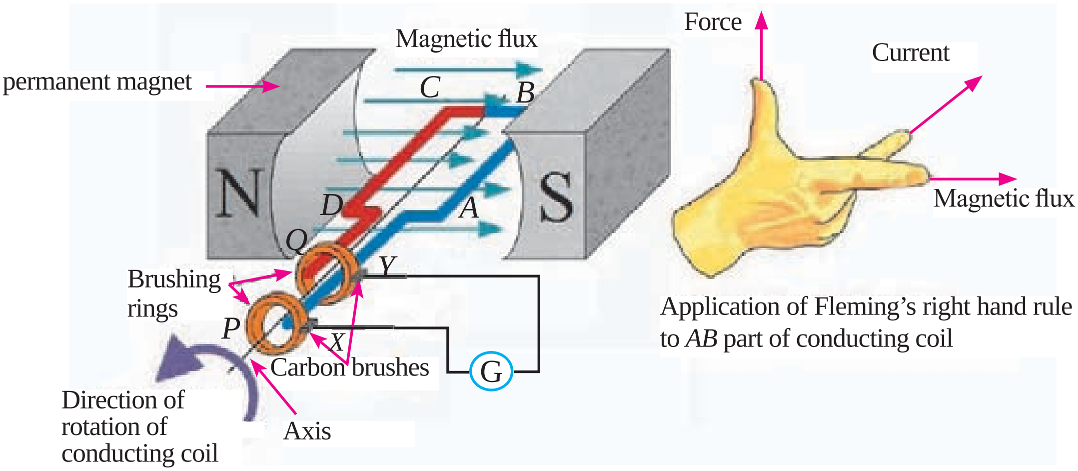


Figure 13.28 – Induced current in a conducting loop rotating in a magnetic field

Two brushes *X* and *Y* made of carbon are mounted in such a way that they brush against the brushing rings. The coil is connected to the external circuit which consists of a center zero galvanometer through the brushes *X* and *Y*. The part consisting of the coil *ABCD*, brushing rings and the axle is known as **the armature**.

Since the arms *AB* and *CD* of the coil intersect the magnetic field across the coil when the coil is rotating, an electromotive force is induced across these arms. Since the circuit is closed, a current passes through the arms *AB* and *CD* of the circuit and the direction of this induced current can be found using Fleming's right hand rule. If the coil is rotated in an anticlockwise direction as shown in the figure, according to Fleming's right hand rule the induced current flows from *A* to *B* since the arm *AB* is moving up and from *C* to *D* since the arm *CD* is moving down. Since both currents through the arms *AB* and *CD* are induced in the same cyclic direction, a current flows through the coil in the direction *ABCD*. The current flow across the galvanometer in the external circuit is from *Y* to *X*. Then the galvanometer indicator deflects to the left.

Figure 13.29 shows how the induced voltage in the coil varies with time when the *ABCD* coil shown in Figure 13.28 is rotated anti-clockwise in the magnetic field.

The upper part of the figure 13.29 shows how the coil (armature) rotates in the magnetic field.

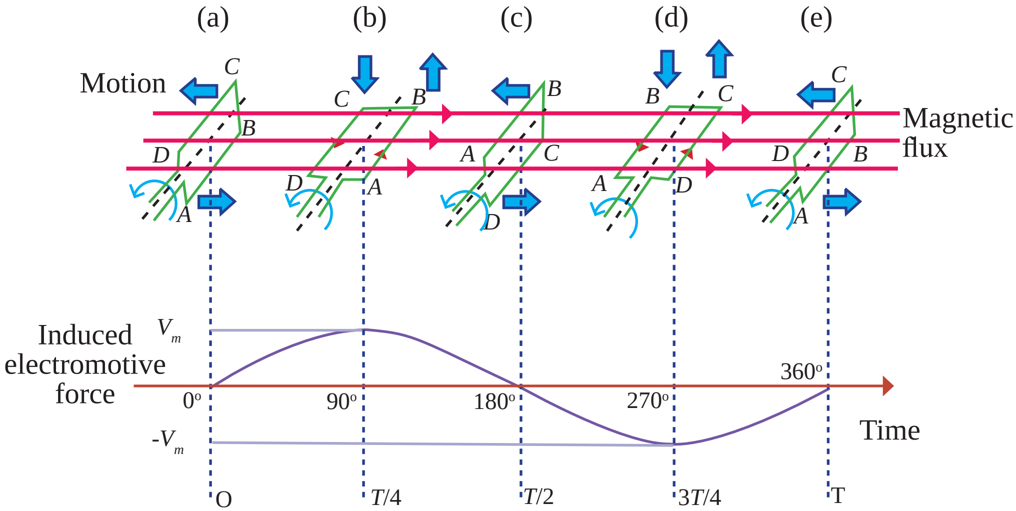


Figure 13.29 – Production of an alternating current

- Since the arms *AB* and *CD* are moving parallel to the magnetic field when the rotating coil is in position (a), the conductors do not intersect the magnetic field lines. Therefore an electromotive force is not induced in the arms *AB* and *CD*. Therefore the galvanometer does not show a deflection.
- While the coil is rotating from position (a) to position (b), the rate at which the field lines are intersected by the coil increases. Therefore, the galvanometer deflection increases accordingly.
- Position (b) is the position of the coil after the coil has rotated by 90° from position (a). At this position, the field lines are intersected perpendicularly by the coil in the upward motion of *AB* and downward motion of *CD*. Then a current flows in the direction *ABCD* as described above causing a deflection to the left of the galvanometer.
- While the coil is moving from position (b) to position (c), the coil is rotating from 90° to 180° and the electromotive force during this period keeps decreasing and becomes zero at position (c). When the coil rotates from position (c) to (d), the coil is rotating from 180° to 270°. During this time *AB* moves down and *CD* moves up intersecting the field lines. Using Fleming's right hand rule one can find that the induced currents flow from *D* to *C* and *B* to *A*. Therefore, the induced current flows through the coil in the direction *DCBA*. This causes a deflection to the right hand side of the galvanometer in the external circuit.

Since the induced electromotive force becomes maximum in the horizontal positions of the coil when the field lines are intersected perpendicularly (in positions (b) and (d) when plane *ABCD* of the coil is parallel to the magnetic field), the current flow becomes maximum at those positions. The induced electromotive force becomes zero for vertical positions of the coil (positions (a), (c) and (e)).

When the coil rotates continuously in this manner, it can be seen that the current flow in the external circuit alternates its direction. We can see that the direction of current flow oscillates periodically since the galvanometer deflects to the left in (b), becomes zero in (a), (c) and (e) and deflects to the right in (d) repetitively. That is, the current changes its direction in each half cycle during one complete cycle of rotation of the coil. The variation of this alternating current or the induced electromotive force with time can be represented by a sinusoidal wave as shown in Figure 13.28.

When the plane of the coil is parallel to magnetic field, the EMF becomes a maximum in + or – direction. when the plane of the coil is perpendicular to the magnetic field, EMF becomes zero.

• Moving coil magnetic microphone

Figure 13.30 shows a diagram of a moving coil magnetic microphone. When a sound reaches the diaphragm of the microphone, the diaphragm vibrates in and out. Then the light coil attached to it also vibrates accordingly. Since the coil vibrates in a magnetic field, the magnetic flux linked to the coil changes inducing an electromotive force in the coil. Since the coil moves in both directions, the direction of the electromotive force alternates. This generates a small alternating current (flowing in both directions) in the microphone that varies corresponding to the variations of the sound reaching the diaphragm.

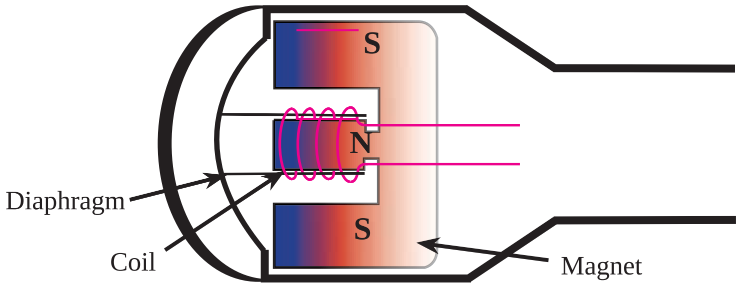


Figure 13.30 – Cross section of a moving coil microphone

• Bicycle Dynamo

Figure 13.31 shows the internal components of a bicycle dynamo. When its rough head is arranged to touch a tire of a bicycle, it rotates fast when the tire is rotating.

Then the cylindrical magnet connected to the rough head also rotates. Since the magnetic field linked to the coil wound around the soft iron changes now, an electromotive force is induced in the coil.

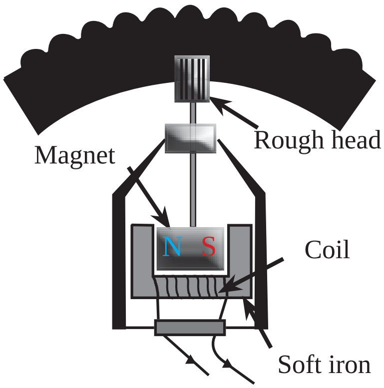


Figure 13.31 – A bicycle dynamo

As a result of winding the dynamo coil around a soft iron it is possible to link most of the magnetic field lines through the coil which increases the induced electromotive force.

Since the direction of the magnetic field alternates when the magnet rotates, the direction of the induced current also alternates its direction. Therefore the output from a bicycle dynamo is an alternating current.

When the bicycle is ridden fast, the speed of the wheels increases. Then the head of the dynamo which is in contact with the tire also rotates fast increasing the rotation speed of the magnet. The increased rate of change of the magnetic field linked to the coil increases the induced electromotive force which gives rise to a larger current. Therefore, the brightness of the bicycle lamp increase with the speed of the bicycle.

An energy transformation takes place in a dynamo. In order to generate electricity, the dynamo has to be rotated. Therefore in a dynamo, the energy is converted from mechanical energy to electric energy.

13.3.3 Direct Currents and Alternating Currents

Figure 13.32(a) shows a circuit connecting a battery, a resistor and a center-zero galvanometer in series. (The resistor prevents a large current from passing through the galvanometer). The constant deflection of the galvanometer will show that the current in the circuit is constant. When the current is plotted against time, a straight line can be obtained as shown in figure 13.32(b).

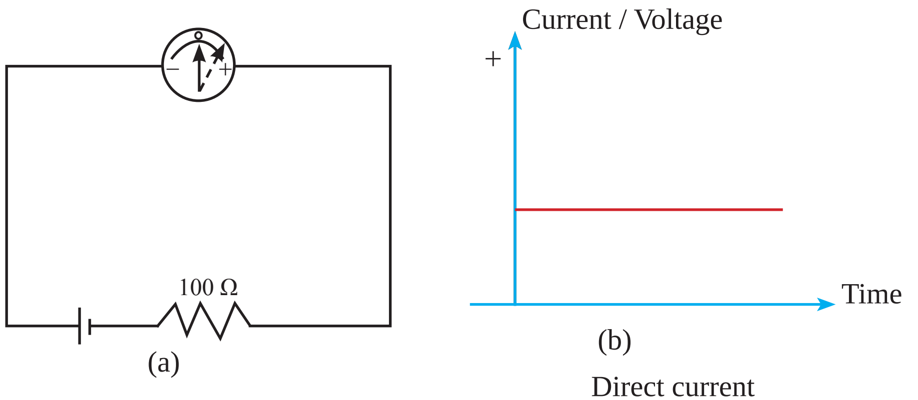


Figure 13.32 – A DC current circuit

If we connect a resistor and a center zero galvanometer in series to the alternating current dynamo discussed above as shown in Figure 13.33(a) and slowly rotate the armature of the dynamo, you will observe that the galvanometer indicator would oscillate in the positive and negative directions around the zero. Therefore when the current (or voltage) is plotted against time, a curve such as that shown in Figure 13.33(b) will be obtained.

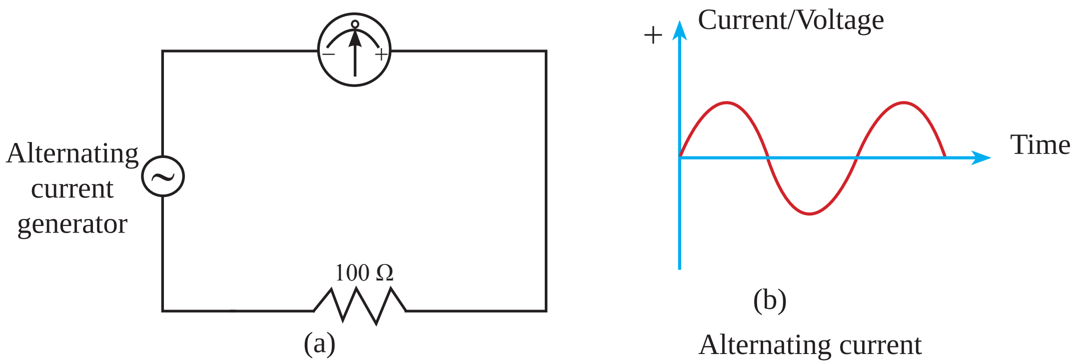


Figure 13.33 – An alternating current circuit arrangement

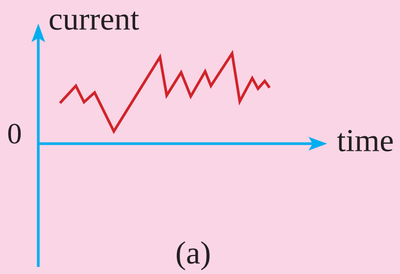
In the first case (Figure 13.39) the direction of current flow does not vary with time. Such currents whose direction does not vary with time are known as **direct currents**.

In the second case (Figure 13.33) the direction of current flow varies with time and such currents whose direction varies with time are known as **alternating currents**.

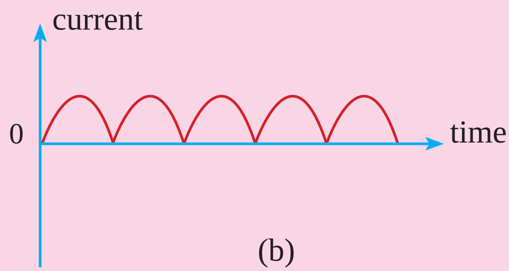
Exercise 13.4

(1) Write down some instances where alternating currents and direct currents are used.

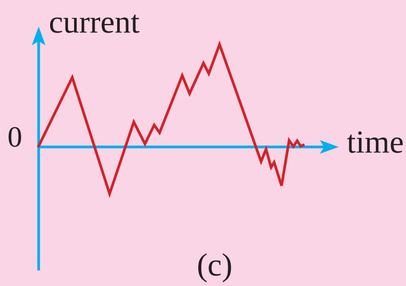
(2) Several graphs showing the variation of current with time are given below. Indicate which type of current is represented by each of them giving reasons for your answer.



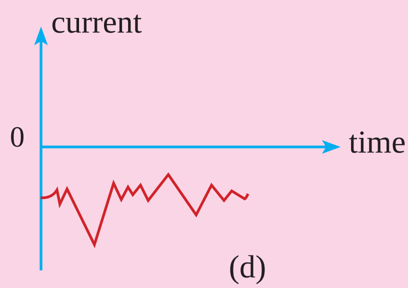
(a)



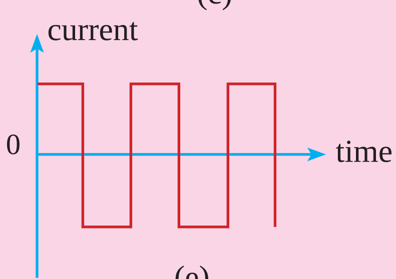
(b)



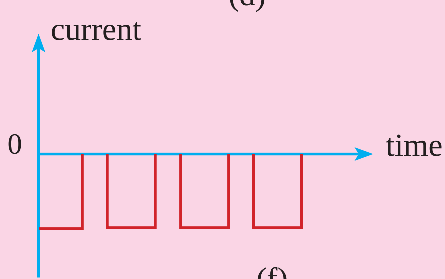
(c)



(d)



(e)



(f)

13.3.4 Transformers

Transformers are useful because they allow you to change the voltage of a supply. Transformers are used in power packs and in electric appliances such as computers and radios.

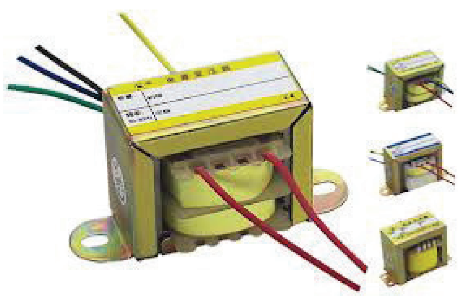


Figure 13.34

Activity 13.6

Apparatus required: about two meters of copper wire of gauge 28, a bundle of soft iron wires, two dry cells, a center zero galvanometer, a switch

- Wrap about 100 turns of insulated copper wire around the bundle of soft iron wires in order to form a coil as shown in the figure.
- Now form another similar coil on the same soft iron wire rope at about a distance of one centimeter from the first.

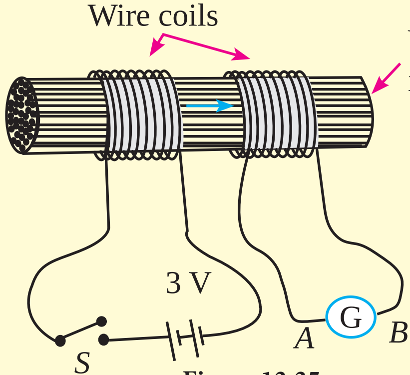


Figure 13.35

- Connect a switch and two 1.5 V dry cells in series to one of the two coils above. Connect the other coil to a center zero galvanometer.

- Now observe the deflection of the galvanometer by turning the switch *S* on and off and fill the table given below by crossing off the incorrect words.

Switch *S*	Galvanometer deflection	Conclusion
Turned on	Deflects to the right/left	A current flows in the second circuit from A to B/B to A.
Turned on continuously	There is a/no deflection	A current flows/does not flow.
Turned off	Deflects in the opposite direction (to the left/right)	A current flows/does not flow in the opposite direction.
Turned off continuously	There is a/no deflection	A current flows/does not flow.

You will be able to draw the following conclusions from the above activity.

- A current is induced in the second circuit at the instant that a current starts to flow in the first circuit.

- When the current in the first circuit is flowing continuously, the current in the second circuit ceases to flow.
- At the instant that the current flow through the first circuit is turned off, a current is induced in the second circuit in a direction opposite to the direction of current flow before.
- When the current flow in the first circuit ceases, the induced current in the second circuit becomes zero.

In this activity there is no magnetic field through the coils before a current passes through the first coil. A magnetic field is generated when a current begins to flow through the first coil. This magnetic field also passes across the second coil through the soft iron wires. As a result of this change in the magnetic field through the second coil, an electromotive force is induced in it which causes a current to flow through the galvanometer giving rise to a deflection in the galvanometer.

When a current is continuously flowing through the first circuit, the magnetic field remains constant and there is no variation in the magnetic field through the second coil. Therefore an electromotive force is not induced in it. Then the galvanometer deflection is zero.

When the switch in the first circuit is opened, the current flow is terminated. The magnetic field caused by the current too diminishes together with the current. As a result of the diminished magnetic field, the magnetic field through the second coil changes and therefore an electromotive force is induced in the second coil. This induced electromotive force has a direction opposite to that of the previous occasion. Therefore the galvanometer deflection occurs in the opposite direction.

When there is no current flow through the first coil, an electromotive force is not induced in the second coil as there is no variation in the magnetic field. Therefore the galvanometer deflection is zero. Therefore we can conclude that an electromotive force is induced in the second coil whenever there is a “change” caused by the first coil in the magnetic field through the second coil.

If we connect an alternating voltage to the first coil, instead of a battery, then as the magnetic field varies continuously, a similar alternating voltage difference is induced in the second coil too. Such a combination of coils linked by a magnetic field is known as a **transformer**. Transformers only work with ac currents and ac voltages. They will not work with dc currents and dc voltages. Transformers work with alternating currents or voltages and with changing direct currents only. They do not work with cons that direct currents.

The figure below shows the symbol used to represent a transformer in circuit diagrams.

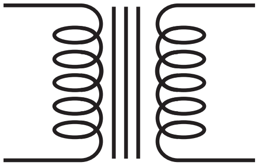


Figure 13.36

The straight lines between the two coils represent the soft iron core.

• Construction of a Transformer

Figure 13.37 shows a simple arrangement of a transformer. It has two insulated copper coils wrapped around a soft iron ring.

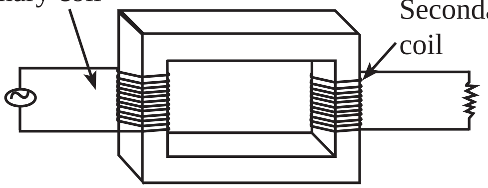


Figure 13.37 – A Simple transformer

Primary coil	Secondary coil
Number of turns N_P	Number of turns N_S
Electromotive force V_P	Induced electromotive force V_S

Normally one coil of a transformer is connected to an alternating power supply while the other is connected to a load (a resistor or an electric appliance operated with an alternating power supply). The first coil that supplies power to the transformer is known as the primary coil or the "**input**". The second coil from which power is taken out of the transformer is known as the **secondary coil** or the "**output**". The voltage supplied to the primary is denoted by V_P and the voltage given out by the secondary is denoted by V_S.

The alternating voltage V_P applied to the primary gives rise to an alternating current flow in the primary circuit which in turn gives rise to an alternating magnetic field. This alternating magnetic field is linked to the secondary coil by the soft iron core and this varying magnetic field induces an alternating voltage V_S in the secondary coil.

The relation between the voltages and the number of turns of a transformer can be expressed as follows.

$$\frac{\text{Number of turns in the primary}}{\text{Number of turns in the secondary}} = \frac{\text{Voltage difference in the primary coil}}{\text{Voltage difference in the secondary coil}}$$

$$\frac{N_P}{N_S} = \frac{V_P}{V_S}$$

According to this relationship, by varying the ratio between the number of turns N_P in the primary and the number of turns N_S in the secondary, an output voltage larger than or smaller than the input voltage can be obtained.

- **Step-up Transformers and Step-down Transformers**

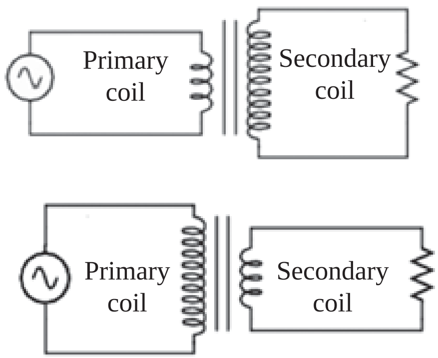


Figure 13.38

Transformers that give an output voltage larger than the input voltage are called **step-up transformers**. They have a larger number of turns in the secondary coil than that in the primary coil.

Transformers that give an output voltage smaller than the input voltage are called **step-down transformers**. They have a smaller number of turns in the secondary coil than that in the primary coil.

- **Applications of transformers**

- Alternating current electricity generated in electric power stations are stepped up to high voltages such as 132 000 V (132 kV) or 220 000 V (220 kV) using step-up transformers before supplying to the national power grid.
- Step-down transformers are used in power substations that distribute power obtained from main power transmission stations to homes.

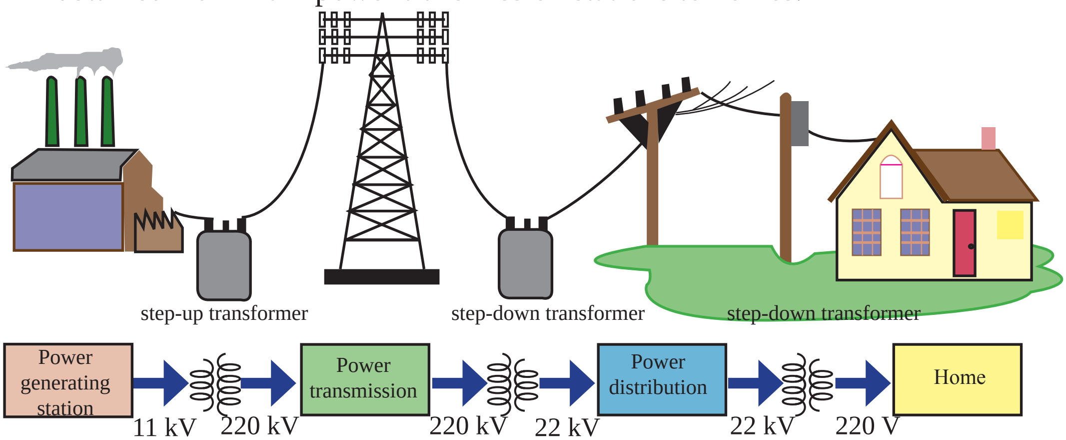


Figure 13.39

- In order to obtain high voltages used in microwave ovens and X ray tubes, step-up transformers are used.
- They are also used in power packs and in electric appliances such as computers and radios.

Energy Relation in a Transformer

The efficiency of any instrument is not 100% as they produce other forms of energy (such as heat) apart from what they are intended for. In transformers too, all the energy supplied to the primary cannot be obtained from the secondary. However we will assume here that there is no energy loss in the transformer. Then according the law of energy conservation, efficiency will be 100%. Then the power of the primary coil is equal to the power of the secondary coil.

Power = Potential difference × Current

Therefore following relationship is obtained.

Energy supplied to the primary = Energy obtained from the secondary

In this equation,

$$\therefore \boxed{V_P I_P = V_S I_S}$$

I_p = current in the primary coil
I_s = current in the secondary coil
V_p = Voltage in the primary coil
V_s = Voltage in the secondary coil.

Example

A certain transformer has 500 turns in its primary coil and 5000 turns in its secondary coil. A voltage difference of 12 V is supplied to the primary coil.

(i) Find the voltage difference of the secondary coil.
(ii) If a 2 A current passes through the primary. calculate the current in the secondary coil.
(iii) Which type of a transformer is this?

(i) $N_p = 500$, $N_s = 5000$, $V_p = 12$ V, $V_s = ?$

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

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

$$V_s = \frac{12\text{ V} \times 5000}{500}$$

$$V_s = 120\text{ V}$$

(ii) $V_p = 12$ V, $V_s = 120$ V,
$I_p = 2$ A, $I_s = ?$

From $V_p I_p = V_s I_s$

$$I_s = \frac{V_p\ I_p}{V_s}$$

$$I_s = \frac{12\text{ V} \times 2}{120\text{ V}}\text{A}$$

$$I_s = \frac{2}{10}\text{ A}$$

$$I_s = 0.2\text{ A}$$

(iii) This is a step-up transformer.

Summary

- The direction of the magnetic field existing in the vicinity of a current carrying conductor can be found using the corkscrew rule.
- When a corkscrew is rotated in such way that it moves in the direction of current flow, then the direction of rotation gives the direction of the magnetic field lines.
- A force acts on a current carrying conductor placed in a magnetic field.
- This force is directly proportional to three factors; current flowing through the conductor, length of the conductor and the strength of the magnetic field.
- Fleming's left hand rule can be used to find the direction of the force acting on the conductor.
- According to Fleming's left hand rule, when the thumb, index finger and the middle finger of the left hand are oriented perpendicular to one another so that the middle finger points in the direction of current flow and the index finger is pointed in the direction of the magnetic field, the thumb is pointed in the direction of the force acting on the conductor.
- The operation of instruments such as the DC motor and the loud speaker are based on the force acting on a current carrying conductor placed in a magnetic field.
- In the operation of a motor, electric energy is converted into mechanical energy.
- The generation of an electromotive force in a closed circuit due to a variable magnetic field is known as electromagnetic induction.
- The magnitude of the induced electromotive force depends on the number of turns in the coil, the strength of the magnetic field and the speed of the moving magnet.
- In order to find the direction of current flow due to the induced electromotive force in a straight conductor, Fleming's right hand rule can be used.
- According to Fleming's right hand rule, when the thumb, index finger and the middle finger of the right hand are oriented perpendicular to one another so that the index finger is pointed in the direction of the magnetic field, the thumb is pointed in the direction of motion, then the middle finger points in the direction of current flow through the conductor.
- Bicycle dynamo, moving coil microphone and the transformer are instruments whose operations are based on electromagnetic induction.

- A current whose direction does not depend on time is a direct current.
- A current whose direction depends on time is an alternating current.
- Dry cells and solar cells produce direct currents while the alternating current dynamo produces an alternating current.
- Using a transformer, an alternating voltage can be changed from one value to another value.
- Relations between the primary and secondary coils of a transformer is given by

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \qquad V_p I_p = V_s I_s$$

Exercise 13.5

(1) The primary coil of a transformer has 1000 turns while its secondary coil has 100 turns. An alternating current with a voltage difference of 230 V is supplied to the primary coil. Find the following, assuming that there is no energy loss in the transformer.

(i) The maximum voltage that can be obtained from the secondary.
(ii) Current output of the secondary if the current input of the primary is 5 A.

(2) In a certain transformer the number of turns in the primary coil is 5000 and that in the secondary coil is 500. A voltage difference of 230 V is supplied to the primary coil. If the efficiency of the transformer is 100%,

(i) Find the output voltage of the secondary.
(ii) Find the current input of the primary if the current output of the secondary is 10 A.

(3) The ratio between the number of turns in the primary coil and the secondary coil in a certain transformer is 1:10. An alternating current with a voltage difference of 6 V is supplied to the primary coil. An output current of 20 A is required from the secondary. Find the following assuming that the efficiency of the transformer is 100%.

(i) Voltage output of the secondary.
(ii) Current input to the primary.
(iii) Ratio between the primary voltage and the secondary voltage.
(iv) Ratio between the primary current and the secondary current.

(4) There are many useful applications for electromagnetic induction. The following figure shows a set up used to model the phenomenon of electromagnetic induction.

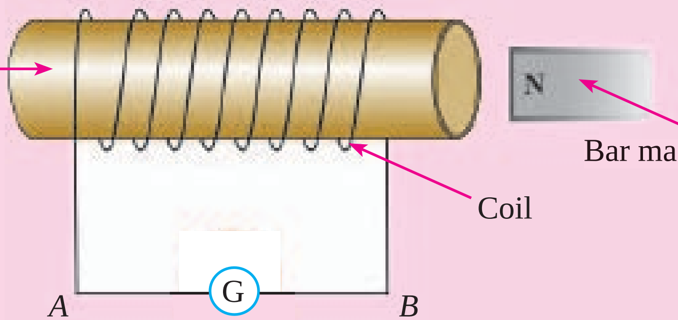


Figure 13.40

(i) Describe electromagnetic induction in a simple manner.
(ii) When the north pole of the bar magnet was brought towards the coil rapidly, a deflection was observed to the right hand side in the center zero galvanometer (G). Is the current flowing through the galvanometer from *A* to *B* or *B* to *A*?
(iii) What is the direction of deflection of the galvanometer when the bar magnet is moved away from the coil?
(iv) What is the direction of deflection of the galvanometer if the South pole of the bar magnet is moved towards the coil?
(v) Write down three factors that the strength of the current flowing through the galvanometer depends on.

(5) The internal components of a bicycle dynamo are shown in the figure below.

(i) Label the parts *A*, *B*, *C* and *D*.
(ii) What is the principle that the operation of a dynamo is based on?
(iii) Describe the operation of the dynamo.
(iv) Is the current output of a dynamo a direct current or an alternating current?
(v) Draw a rough sketch to show the variation of the voltage output of this current with time.
(vi) The brightness of a bicycle lamp depends on the speed at which the bicycle is being ridden. Explain how this happens.
(vii) Write down the energy transformation that takes place when a bicycle lamp is lit up using the bicycle dynamo.

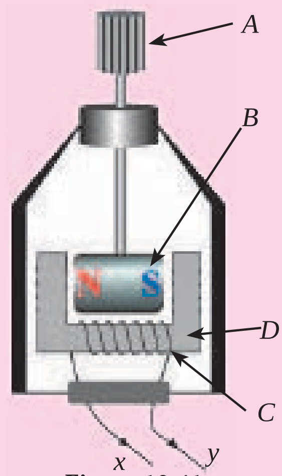


Figure 13.41

(6) The figure below shows a moving coil galvanometer. Name the components labeled as *A*, *B*, *C* and *D* and describe the function of each of them.

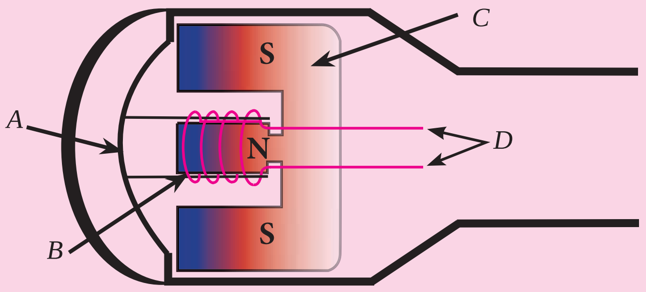


Figure 13.42

Technical terms

Magnetic field	- චුම්බක ක්ෂේත්‍රය	- காந்தப்புலம்
Step - up transformer	- අධිකර පරිණාමකය	- படிகூட்டு நிலைமாற்றி
Step - down transformer	- අවකර පරිණාමකය	- படி குறை நிலைமாற்றி
Magnet	- චුම්බකය	- காந்தம்
Power	- ජවය	- வலு
Coil	- දඟරය	- சுருள்
Transformer	- පරිණාමකය	- விரியலாக்கி
Alternating current	- ප්‍රත්‍යාවර්තක ධාරාව	- ஆடலோட்டம்
Electro magnetic induction	- විද්‍යුත් චුම්බක ප්‍රේරණය	- மின்காந்த தூண்டல்
Induced current	- ප්‍රේරිත ධාරාව	- தூண்டல் மின்னோட்டம்
Electromotive force	- විද්‍යුත්ගාමක බලය	- மின்னியக்கவிசை