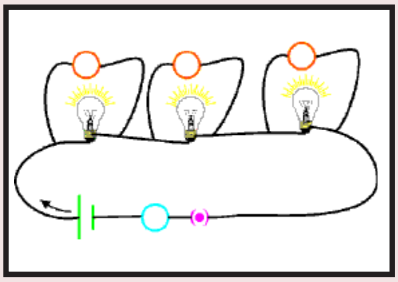
Chapter

11

Electric Current



In previous classes, you had learnt about electric current, battery, electric circuit and its components.

- What do you mean by electric current?
- Which type of charge (positive or negative) flows through an electric wire when it is connected in an electric circuit?
- Is there any evidence for the motion of charge in daily life situations?

In class VIII you learned about lightning. Lightning is an electric discharge between two clouds or between cloud and earth. This electric discharge through air appears to us as an electric spark or lightning.

Lightning is a live example which provides evidence for the motion of charge in the atmosphere.

- Does motion of charge always lead to electric current?

Let us see.

Activity 1

Situation 1: Take a bulb, a battery, a switch and few insulated copper wires. Connect the ends of the copper wires to the terminals of the battery through the bulb and switch. Now switch on the circuit and observe the bulb.

- What do you notice?

Situation 2: Remove the battery from the circuit and connect the remaining components to make a complete circuit. Again switch on the circuit and observe the bulb. Does the bulb glow?

Situation 3: Replace the copper wires with nylon wires and connect the nylon wires to the terminals of the battery through a bulb and switch. Now switch on the circuit and observe the bulb. Does the bulb glow?

After doing these activities you will notice that the bulb glows only in situation 1.

- Can you predict the reason for the bulb not glowing in situations 2 and 3?

In class VII, you have learnt that the battery stores chemical energy and this energy converts into electric energy and makes the bulb to glow as you observed in situation 1 i.e. the battery supplies the required energy to make the bulb glow. But in situation 3, though there is a battery in the circuit, the bulb does not glow because the connecting wires (nylon wires) are not able to carry the energy from source (battery) to bulb.

Hence, the nature of the substance plays an important role in the transfer of energy from battery to bulb. The material which transfers energy from battery (source) to the bulb is called a conductor and the material which cannot transfer energy from battery (source) to the bulb is called a non conductor.

- Why do all materials not act as conductors?
- How does a conductor transfer energy from source to bulb?

Let us see.

Electric current

Drude and Lorentz, scientists of the 19^{th} century, proposed that conductors like metals contain a large number of free electrons while the positive ions are fixed in their locations. The arrangement of the positive ions is called lattice.

Let us understand the behaviour of electrons in lattice space. Assume that a conductor is an open circuit. The electrons move randomly in lattice space of a conductor as shown in figure 1. When the electrons are in random motion, they can move in any direction. Hence, if you imagine any cross section as shown in figure 1, the number of electrons, crossing the cross section of a conductor from left to right in one second is equal to that of electrons passing the cross section from right to left in one second. It means that net charge moving along a conductor through any cross section is zero when the conductor is in open circuit.

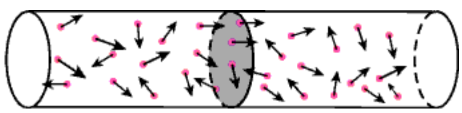


fig-1: Random motion of electrons (in open circuit)

- What happens to the motion of electrons when the ends of the conductor are connected to the battery?

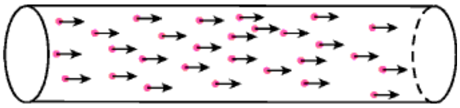


fig-2: Ordered motion of electrons

When the ends of the conductor are connected to the battery through a bulb, the bulb glows because energy transfer takes place from battery to the bulb. The electrons are responsible for this transfer of energy. If the electrons are responsible for transfer of energy from battery to bulb, they must have an ordered motion. When the electrons are in ordered motion, there will be a net charge crossing through any cross section of the conductor. See figure 2. This ordered motion of electrons is called electric current.

Thus we can say that electric current is ordered motion of charges.

Let us define electric current quantitatively,

Electric current is defined as the amount of charge crossing any cross section of the conductor in one second.

Let Q be the charge crossing through any cross section of the conductor in a time interval t. Then the amount of charge crossing through that cross section in one second is Q/t. Therefore,

Electric current = electric charge/time interval

$I = Q/t$

The SI unit of electric current is ampere denoted by A.

1 Ampere = 1 Coloumb/1 Second

1 A = 1 C/s

- Why do electrons move in specified direction?

When the conductor is not connected to the circuit through a battery, the electrons inside the conductor are in random motion but when the conductor is connected to a battery, the electrons move in a specified direction. This shows that something causes the electron to move it in a specified direction. When the ends of the conductor are connected to the terminals of a battery a uniform electric field is set up throughout the conductor. This field makes the electrons move in a specified direction.

- In which direction do the electrons move?
- Do the electrons accelerate continuously?
- Do they move with a constant speed?

The free electrons in the conductor are accelerated by the electric field and move in a direction opposite to the direction of the field. When electrons are in motion under the influence of the field, they collide with lattice ions, lose energy and may even come to a halt at every collision. They are again accelerated by the electric field and make collisions with other lattice ions. In this way they continue to move along the conductor.

The motion of electron is shown in figure 3.

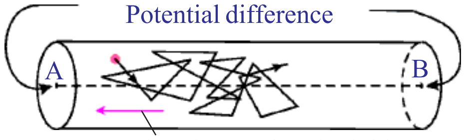


fig-3: Motion of electron

Hence, we assume that electrons in the conductor move with a constant average speed. We call this speed as drift speed or drift velocity.

Let us calculate the drift speed of free charges quantitatively.

Consider a conductor with cross sectional area A. Assume that the ends of the conductor are connected to a battery to make the current flow through it. Let v_d be the drift speed of the charges as shown in figure 4 and n be the number of charges present in the conductor in an unit volume (charge density). The distance covered by each charge in one second is v_d. Then the volume of the conductor for this distance is equal to Av_d (see figure 4). The number of charges contained in that volume is equal to nAv_d. Let q be the charge of each carrier. Then the total charge crossing the cross sectional area at position D in one second is $nqAv_d$. This is equal to electric current. Hence,

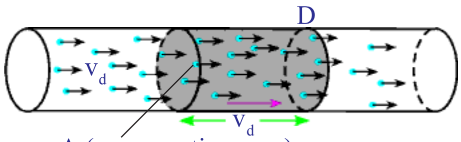


fig-4: Drift of positive charges

Electric current $I = nqAv_d$ .... (1)

Therefore, $v_d = I/nqA$ .... (2)

We know that the charge carriers in a conductor are electrons. The magnitude of electric charge 'e' is 1.602×10^{-19}C.

Let us calculate the drift speed of electron in a copper wire carrying a current of 1A and cross sectional area $A = 10^{-6}\,m^2$. The electron density of copper that was found experimentally is $n = 8.5 \times 10^{28} m^{-3}$. Substituting these values in equation (2) with q = e, we get,

$v_d = 1/(8.5 \times 10^{28} \times 10^{-6} \times 1.6 \times 10^{-19})$

$v_d = 7 \times 10^{-5}$m/s = 0.07mm/s

This shows that the electrons are moving very slowly.

- Why does a bulb glow immediately when we switch on?

When we switch on any electric circuit, irrespective of length of the connecting wire (conductor) an electric field is set up throughout the conductor instantaneously due to the potential difference of the source (battery) connected to the circuit. This electric field makes all the electrons to move in a specified direction simultaneously.

- How can we decide the direction of electric current?

The equation $I = nqAv_d$ Indicates that the values of n and A are positive. The direction of electric current is determined by the signs of the charge q and drift speed v_d. For electrons (negative charges), q is negative and v_d is positive. Then the product of q and v_d is negative. This negative sign shows that the direction of electric current is opposite to the flow of negative charge. For positive charges the product of q and v_d is positive. Hence, the direction of electric current can be taken as the direction of flow of positive charges.

- How can we measure electric current?

Usually an ammeter is used to measure electric current. It is always connected in series to the circuit.

- Where do the electrons get energy for their motion from?

Potential Difference

When the ends of a conducting wire are connected to the terminals of a battery, an electric field is setup throughout the conductor. This field exerts a force on the charge (electron). Let F_e be the force exerted by the electric field on a free charge q. The free charges accelerate in the direction of the electric field (If the free charges are electrons, then the direction of electric force on them is opposite to the direction of electric field). It means the electric field does some work to move free charges in a specified direction.

- Can you find the work done by the electric force?

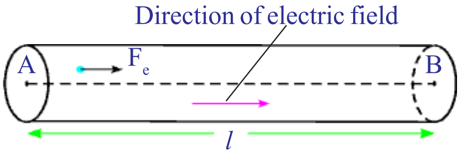


fig-5

Let the electric force made the charges move through a distance 'l' from A to B as shown in figure 5. We know that, the work is the product of force and distance along the direction of force.

Hence, work done by the electric force on a free charge q is given by

$W = F_e\, l$

What is the work done by the electric force on unit charge?

Work done by the electric force on unit charge = $W/q = F_e\, l/q$

Work done by the electric force on unit positive charge to move it through a distance 'l' from A to B is called potential difference between those points. Potential difference is denoted by a symbol V. The potential difference between two points separated by a distance l in a conducting wire is given by,

$V = W/q = F_e\, l/q$

This potential difference is also called voltage. The SI unit of potential difference is "Volt" and it is denoted by V.

1 Volt = 1 Joule/1 Coulomb

1V = 1J/C

- What is the direction of electric current in terms of potential difference?
- Do positive charges move in a conductor? Can you give an example of this?

Let us recall your experience of electrolysis and electroplating and conductivity of fluids that you had learned in earlier classes. When electric current is allowed to pass through fluids, the positive ions (cations) and negative ions (anions) move in opposite directions. The direction of the motion of positive charges in an electrolyte is always in the direction of the electric field while negative charges move in a direction opposite to that of positive charges. Thus for conduction in fluids there exists motion of both positive and negative charges. Whereas in case of metal conductors there will be only motion of electrons. (The positive charges are fixed in the lattice)

If positive charges move from point A to B in a conductor, the electric field does positive work so W/q is positive for free positive charges. You can say that the direction of the electric field is from A to B and the point A is at high potential and point B is at low potential. As negative charges always move in a direction opposite to the electric field we consider that electrons move from low potential to high potential.

We know that in a battery or cell a constant potential difference is maintained till the battery is completely discharged.

- How does a battery maintain a constant potential difference between its terminals?
- Why does the battery discharge when its positive and negative terminals are connected through a conductor?

To answer this, we need to know about how a battery or a cell works.

A battery consists of two metal plates (electrodes) and a chemical (electrolyte). The electrolyte (chemical) between the two metal plates consists of positive and negative ions which move in opposite directions (see figure 6). The electrolyte exerts a certain force on these ions and makes them move in a specified direction. Let us call this force as a chemical force (F_c). Depending upon the nature of the chemical, positive ions move towards one of the plates and accumulate on that plate. As a result of this accumulation of charges on this plate it becomes positively charged (called anode). Negative ions move in a direction opposite to the motion of positive ions and accumulate on the other plate. As a result of this the plate becomes negatively charged (called cathode). This accumulation of different charges on respective plates continues till both plates are sufficiently charged.

But the ions in motion experience another force when sufficient number of charges are accumulated on the plates. Let us call this force as electric force (F_e). The direction of this force is opposite to the direction of chemical force F_c and the magnitude of this force depends on the amount of charge accumulated on the plates.

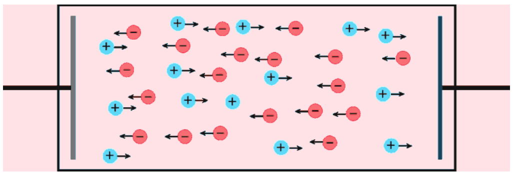
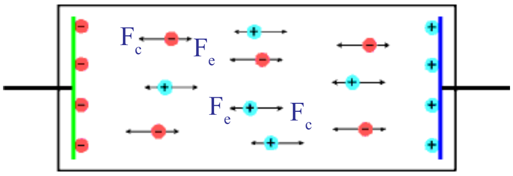


fig-6



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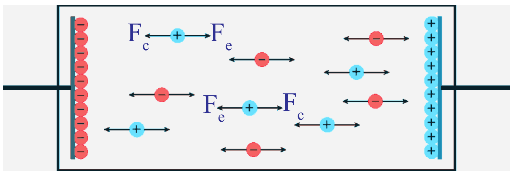

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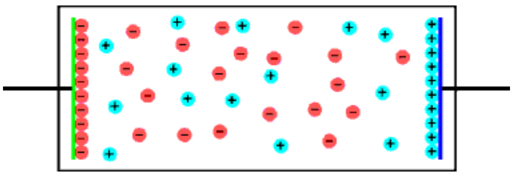

fig-9

The motion of ions continue towards their respective plates if the chemical force F_c is stronger than electric force F_e. See figure 7. The accumulation of charges on plates is continuous till the electric force F_e becomes equal to chemical force F_c. At this situation there will not be any motion in ions due to balance of forces F_e and F_c. It is shown in figure 8. The new battery that we buy from the shop is at a stage where the ions in the electrolyte are under the influence of balanced forces. See figure 9. This is the reason for the constant potential difference between the terminals of a battery.

The amount of charge accumulated on the plates depends on nature of the chemical used in the battery.

- What happens when the battery is connected in a circuit?

When a conducting wire is connected to the terminals of the battery, a potential difference is created between the ends of the conductor. This potential difference sets up an electric field throughout the conductor (the direction of electric field is from positive terminal to negative terminal in the conductor).

We know that the conductor contains large number of electrons. The electrons near the positive terminal of the battery are attracted by it and start to move towards positive terminal. As a result, the amount of positive charge on this plate decreases. So the electric force F_e becomes weaker than chemical force F_c and chemical force pulls negative ions from the positive plate (anode) and makes them move towards the negative plate (cathode). The negative terminal pushes one electron into the conductor because of stronger repulsion between negative terminal and negative ion. Hence, the total number of electrons in the conductor remains constant during the current flow. The above said process continuous till equilibrium is attained between the forces F_e and F_c.

Electromotive force (emf)

When the ends of the conductor are connected to the terminals of a battery, the electrons in the conductor move with a drift speed from negative terminal to positive terminal because of the electric force acting on them. At the same time negative ions of equal amount of charge move from positive terminal to negative terminal against the electric force (F_e) because of the chemical force acting on them within battery. Thus, some chemical energy is spent to move ions in the battery. It means that an amount of work is done by the chemical force (F_c).

Let us assume that work done by the chemical force to move a negative charge q from positive terminal to negative terminal against the electric force F_e be 'W' and also assume that the magnitude of chemical force F_c is equal to magnitude of electric force (F_e).

The work done on negative charge q by the chemical force, $W = F_c d$ where 'd' is the distance between the terminals. Then work done by the chemical force to move 1 Columb charge from positive terminal to negative terminal is given by, $W/q = F_c d/q$. We know that $F_c = F_e$, then we get $W/q = F_e d/q$.

This W/q is the work done by the chemical force on unit negative charge to move it from positive terminal to negative terminal. This is called emf (ε).

$\varepsilon = W/q = F_e d/q$

Generally, emf is defined as the work done by the chemical force to move unit positive charge from negative terminal to positive terminal of the battery.

- How can we measure potential difference or emf?

Generally a volt meter is used to measure potential difference or emf across an electric device like battery. It must be connected in parallel to the electric device to measure the potential difference across the ends of the electric device.

When a battery in a torch is used for several weeks, the light from its bulb becomes dim. We say that the battery or cell in the torch is discharged. What does it mean?

- Is there any relation between emf of battery and drift speed of electrons in the conductor connected to a battery?

Ohm's law

Lab Activity

Aim: To show that the ratio V/I is a constant for a conductor.

Materials required: 5 dry cells of 1.5V each, conducting wires, an ammeter, a volt meter, thin iron spoke of length 10cm, LED and key.

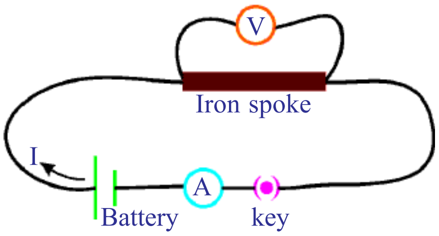

fig-10

Procedure: Connect a circuit as shown in figure 10. Solder the conducting wires to the ends of the iron spoke. Close the key. Note the readings of current from ammeter and potential difference from volt meter in table 1.

Table:1

Sl.No.	Potential difference (V)	Current (I)	V/I

Now connect two cells (in series) instead of one cell in the circuit. Note the respective readings of the ammeter and volt meter and record the values in table 1. Repeat the same for three cells, four cells and five cells respectively. Record the values of potential difference (V) and current (I) corresponding to each case in the table 1. Find V/I for each set of values. What do you notice? The ratio V/I is a constant. We can write this mathematically as

$V \propto I$

From this experiment we can conclude that the potential difference between the ends of the iron spoke (conductor) is directly proportional to the current passing through it (assuming the temperature of the iron spoke is constant during the flow of current through it).

Draw a graph between V and I taking the current (I) along y-axis and potential difference (V) along x-axis with appropriate scale. You will get a straight line graph passing through the origin as shown in figure 11.

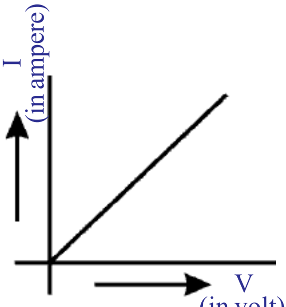

fig-11

Repeat the process by using a LED instead of iron spoke. The long terminal of the LED is connected to the positive terminal of the battery and short terminal of the LED is connected to negative terminal of the battery. Note the values of current 'I' and potential difference 'V' in each case and record the values in table 1 (draw this table in your notebook). Find V/I for each set of values I and V. You will notice that the ratio V/I is not a constant. Draw a graph between V and I for LED. You will get a curved graph as shown in figure 12.

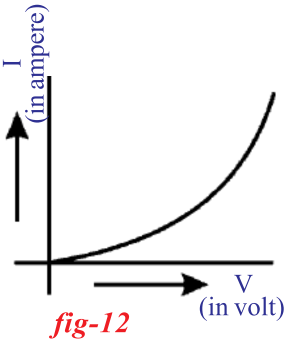

fig-12

From the above lab activity we can conclude that the ratio between V and I is constant for some materials at constant temperature. This fact was established by German Physicist, George Simon Ohm and it is popularly known as Ohm's law.

We can define Ohm's law as follow.

The potential difference between the ends of a conductor is directly proportional to the electric current passing through it at constant temperature.

Let V be the potential difference between the ends of the conductor and I be the current passing through it.

$V \propto I$ (temperature is constant)

$V/I = \text{Constant}$

This constant is called resistance of the conductor. It is denoted by 'R'. Then we get $V/I = R$.

$V = IR$

The SI unit of resistance is ohm. The symbol of ohm is Ω.

1 Ohm = 1 Volt/1 Ampere

$1\ \Omega = 1\text{V/A}$

- Can you guess the reason why the ratio of V and I in case of LED is not constant?
- Do all materials obey Ohm's law?
- Can we classify the materials based on Ohm's law?

Based on Ohm's law materials are classified into two categories. Those which obey Ohm's law are called ohmic materials. For example, metals are ohmic materials. Those which do not obey Ohm's law are called non ohmic materials. For example, LEDs are non ohmic materials.

Limitations of Ohm's Law

Ohm's law is valid for metal conductors provided the temperature and other physical conditions remain constant. The resistance of the material changes with temperature. Hence for changing temperature the V-I graph for a conductor will be non-linear. Ohm's law is not applicable to gaseous conductors. It is also not applicable to semiconductors such as germanium and silicon.

- What is resistance?
- Is the value of resistance the same for all materials?

When a conductor is connected to a battery the free electrons start moving with a drift speed in a specified direction. During the motion, the electrons collide with positive ions (fixed) of the lattice and come to halt. This means that they lose mechanical energy in the form of heat. Due to the electric field that was set up by the battery throughout the conductor, these electrons regain the energy from the field and proceed to move. The motion of electrons is obstructed by the lattice ions. The obstruction offered to the flow of electrons in a conductor by lattice ions depends upon the nature of the material.

Therefore, the **resistance** of a conductor is defined as the obstruction to the motion of the electrons in a conductor. The material which offers resistance to the motion of electrons is called **resistor**.

- Is there any application of Ohm's law in daily life?
- What causes electric shock in the human body – current or voltage?

Let us see.

Electric shock

Let us assume that human body is a resistor. The resistance of the human body generally varies from 100 Ω (if body is wet with salt water) to 5,00,000 Ω (if the skin is very dry). Let us calculate the amount of current that flows through the human body. Let us assume you have touched the two electrodes of a battery of 24V with dry fingers in such a way that the circuit is complete. Let your body resistance be 1,00,000Ω. Then the current flowing through your body is given by I = 24/100000 = 0.00024A. This current is very small. When such small current passes through the human body, it does not affect the functioning of various organs inside the body.

- Do you know the voltage of mains that we use in our household circuits?
- What happens to our body if we touch live wire of 240V?

The current passing through our body when we touch a live wire of 240V is given by I = 240/100000 = 0.0024A. When this quantify of current flows through the body the functioning of organs inside the body gets disturbed. This disturbance inside the body is felt as electric shock. If the current flow continues further, it damages the tissues of the body which leads to decrease in resistance of the body. When this current flows for a longer time, damage to the tissues increases and thereby the resistance of human body decreases further. Hence, the current through the human body will increase. If this current reaches 0.07A, it effects the functioning of the heart and if this much current passes through the heart for more than one second it could be fatal. If this current flows for a longer time, the person in electric shock is being killed. See the table 2 that describes the effects of electric current on human body.

Table-2

Current in ampere	Effect
0.001	Can be felt
0.005	Is painful
0.010	Causes involuntary muscle contractions (spasms)
0.015	Causes loss of muscle control
0.070	If through the heart, causes serious disruption ; probably fatal if current lasts for more than 1 s

From the above discussions, we can conclude that an electric shock can be experienced when there is a potential difference exists between one part of the body and another part. When current flows through human body, it chooses the path which offers low resistance. The resistance of a body is not uniform throughout it. For example, skin offers more resistance than the organs inside the body. As long as current flow continues inside the body the current and resistance of human body goes on changing inversely. Hence, the electric shock is a combined effect of potential difference, electric current and resistance of the human body.

- Why doesn't a bird get a shock when it stands on a high voltage wire?

There are two parallel transmission lines on electric poles. The potential difference between these two lines is 240V throughout their lengths. If you connect any conducting device across these two wires, it causes current to flow between the wires. When the bird stands on a high voltage wire, there is no potential difference between the legs of the bird because it stands on a single wire. So no current passes through the bird. Hence, it doesn't feel any electric shock.

Do you know?

A multi meter is an electronic measuring instrument that combines several measurement functions in one unit.

Digital multi meter displays the measured value in numerals.

A multi meter has three parts

Display: The display usually has four digits and the ability to display a negative sign.

Selection knob: The selection knob allows the user to set the multi meter to read different functions such as milliamps (mA) of current, voltage (V) and resistance (Ω).

Ports: Multi meters generally have two ports. One is usually labelled as 'COM' (common or ground port). This is where black test lead is connected. The other is labelled as mAVΩ port where the red lead is conventionally plugged in.

WARNING: Most multi meters can measure AC quantities also, but AC circuits can be dangerous. So measure DC quantities only.

Factors affecting the resistance of a material

Temperature and resistance

Activity 2

Measure the resistance of the bulb when it is in open circuit using a multi meter. To measure the resistance of a bulb set the multi meter as ohm meter and place the multi meter knob at 20K Ω. Now place the leads of the multi meter on the terminals of the bulb. The meter will show one of the following readings.

- 0.00 or 1 or the actual resistance of the bulb.

– If the multi meter reads 1, or displays OL, it's overloaded. You will need to try a higher mode such as 200K Ω or 2M Ω etc.
– If the multi meter reads 0.00 or nearly 0, then you need to lower the mode to 2K Ω or 200 Ω.

Note the value of resistance in your note book. Connect a circuit with components as shown in figure 13. Switch on the circuit. After few minutes, measure the resistance of the bulb again as explained above. Note this value in your note book. What difference do you notice between these two readings? The value of resistance of the bulb in second instance is more than the resistance of the bulb in open circuit.

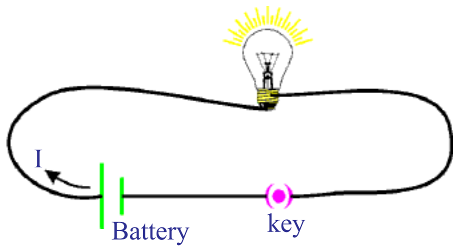

fig-13

- What could be the reason for increase in the resistance of the bulb when current flows through it?

You will notice that the bulb gets heated. The increase in temperature of the filament in the bulb is responsible for increase in resistance of the bulb. Hence we can conclude that there is a relation between resistance of the bulb and its temperature.

Thus the value of resistance of a conductor depends on temperature for constant potential difference between the ends of the conductor.

Nature of material and resistance

Activity 3

Collect different metal rods of the same length and same cross sectional area like copper, aluminum, iron etc. Make a circuit as shown in figure 14. P and Q are the free ends of the conducting wires. Connect one of the metal rods between the ends P and Q. Switch on the circuit. Measure the electric current using the ammeter connected to the circuit and note it in your notebook. Repeat this with other metal rods and measure electric currents in each case. What do you notice? The values of current are different for different metal rods for a constant potential difference.

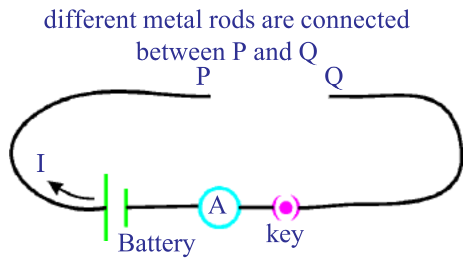

fig-14

From this activity, we conclude that the resistance of a conductor depends on the material of the conductor.

- What happens to the resistance of a conductor if we increase its length?

Let us find out.

Length of the conductor and resistance

Activity 4

Collect iron spokes of different lengths with the same cross sectional areas. Make a circuit as shown in figure 14. Connect one of the iron spokes, say 10cm length, between P and Q. Measure the value of the current using the ammeter connected to the circuit and note the value in your note book. Repeat this for other lengths of the iron spokes. Note corresponding values of currents in your note book. What do you notice? The current decreases with increase in the length of the spoke. Thus the resistance of each spoke increases with increase in the length for a constant potential difference.

From this activity, we can conclude that the resistance (R) of a conductor is directly proportional to its length (l) for a constant potential difference.

i.e.

$R \propto l$ (at constant temperature and cross sectional area)

.... (1)

- Does the thickness of a conductor influence its resistance?

Let us find out.

Crosssection area and resistance

Activity 5

Collect iron rods of equal lengths but different cross section areas. Make a circuit as shown in figure 14. Connect one of the rods between points P and Q. Note the value of the current using the ammeter connected to the circuit and note it in your note book. Repeat this with other rods. Note the corresponding values of currents in each case and note them in your note book. You will notice that the current flowing through the rod increases with increase in its cross sectional area. Hence, the resistance of a rod decreases with increase in the cross section area of the rod.

From this activity, we conclude that the resistance of a conductor is inversely proportional to its cross section area.

i.e.

$R \propto 1/A$ (at constant temperature and length of the conductor)

.... (2)

From the equations (1) and (2), we get

$R \propto l/A$ (at constant temperature)

$R = \rho l/A$

Where, ρ is a proportionality constant and it is called specific resistance or resistivity. See figure 15 to get clear picture of this equation.

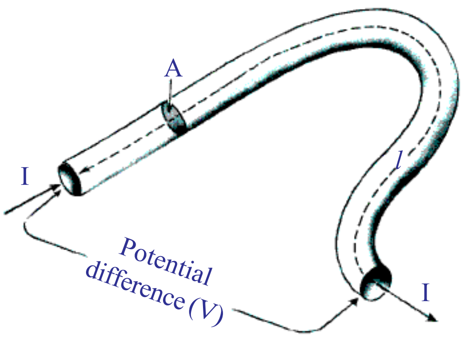

fig-15

Specific resistance depends on the temperature and nature of the material where as the resistance of the conductor depends on nature of material, temperature and geometrical factors like length and cross section area of the conductor.

The SI unit of resistivity is Ω - m.

The reciprocal of resistivity is called conductivity (σ).

The values of resistivity of material determine their conductivity. Metals with low resistivity behave as good conductors. Metals such as copper are therefore used for making electric wires. The filament of an electric bulb is usually made of tungsten, because of its higher resistivity values and melting point (3422^0C).

The values of resistivity of insulators are very high of the order of 10^{14} to 10^{16} Ω-m. Alloys like Nichrome (Nickel, chromium and iron) and Manganese (86% copper, 12% manganese, 2% nickel) have 30-100 times larger values of resistivity than those of metals. This makes them suitable for use in the heating elements of electric irons, toasters etc. These alloys also have the advantage that their resistance varies very little with temperature and they do not oxidise easily. The resistivity of materials such as silicon and germanium are 10^5 to 10^{10} times more than that of metals, but 10^{15} to 10^{16} times less than that of insulators. Such materials are called semiconductors. Semiconductors are used to make diodes, transistors and integrated Circuits (ICs). ICs are used in all sorts of electronic devices, including computer, TV, mobile phones etc.

Table 3
Resistivity of various materials

Material	$\rho_{(\Omega\text{-m})}$ at 20 °C
Silver	1.59×10^{-8}
Copper	1.68×10^{-8}
Gold	2.44×10^{-8}
Aluminium	2.82×10^{-8}
Calcium	3.36×10^{-8}
Tungsten	5.60×10^{-8}
Zinc	5.90×10^{-8}
Nickel	6.99×10^{-8}
Iron	1.00×10^{-7}
Lead	2.20×10^{-7}
Nichrome	1.10×10^{-6}
Carbon (Graphite)	2.50×10^{-6}
Germanium	4.60×10^{-1}
Drinking water	2.00×10^{-1}
Silicon	6.40×10^{2}
Wet wood	1.00×10^{3}
Glass	10.0×10^{10}
Rubber	1.00×10^{13}
Air	1.30×10^{16}

- How are electric devices connected in circuits?

Electric Circuits

A closed path created by the connecting wires through a battery along which electrons can flow is called a circuit. For a continuous flow of electrons in the circuit it must be a complete circuit with no gaps left in between. Usually a gap is provided in the circuit by an electric switch that can be opened or closed to either cut off or allow current flow through the circuit. Circuits may have more than one device (called as component) that receives electric energy from the source. These devices are commonly connected in the circuit either in series or in parallel.

When the components of the circuit are connected in series, there will be a single path for flow of electrons between the terminals of the battery, generator or wall socket (which is simply and extension of these terminals). When these components are connected in parallel, they form branches and each branch provides a separate path for the flow of electrons.

Both the series and parallel connections have their own distinctive characteristics. We shall briefly study circuits, using these two types of connections.

Series connection of resistors

Activity 6

Take different bulbs. Measure their resistances with a multi meter. Note their values in your book as R_1, R_2, R_3.

Connect them as shown in figure 16.

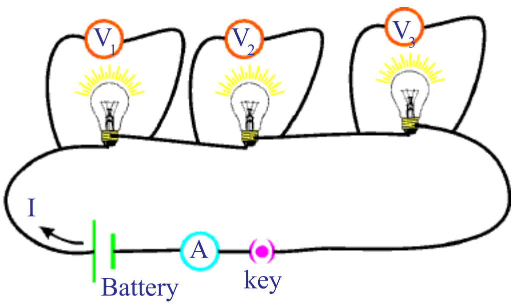

fig-16

Measure the potential difference between terminals of the battery connected to the circuit. Measure the potential differences between the ends of each bulb and note them as V_1, V_2 and V_3 from voltmeters in your note book. Compare the potential difference of the battery and resistors.

- What do you notice?

The sum of the potential differences of the bulbs is equal to potential difference across the combination of the resistors. Then we get,

$$V = V_1 + V_2 + V_3 \qquad \text{.........................} (1)$$

Measure the value of the current flowing in the circuit with help of the ammeter. Note its values in your book as I.

- What do you notice?

Equivalent resistance of a series connection:

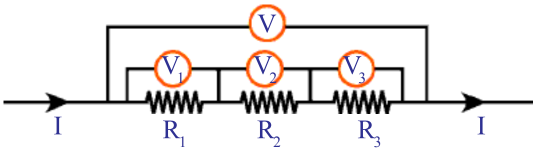

fig-17

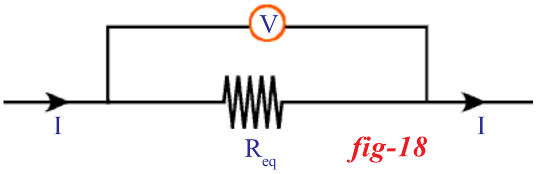

fig-18

Observe figure 17. In this figure the bulbs are shown as resistors with symbols.

In series connection of resistors there is only one path for the flow of current in the circuit. Hence, the current in the circuit is equal to I.

According to Ohm's law,

Potential difference across R_1 is, $V_1 = IR_1$

Potential difference across R_2 is, $V_2 = IR_2$

Potential difference across R_3 is, $V_3 = IR_3$

Let R_{eq} is the equivalent resistance of the combination of resistors in series.

- What do you mean by equivalent resistance?

If the current drawn by a resistor is equal to the current drawn by the combination of resistors then the resistor is called as equivalent resistor (provided the source in the circuit is constant).

So, we have $V = I R_{eq}$

Substituting the values of V_1, V_2, V_3 and V in the equation (1), we get

$IR_{eq} = IR_1 + IR_2 + IR_3$

$R_{eq} = R_1 + R_2 + R_3$

From the above equation you can conclude that the sum of individual resistances is equal to their equivalent resistance when the resistors are connected in series.

- What happens when one of the resistors in series breaks down?

When one of the resistors in series breaks down, the circuit becomes open and flow of current cannot take place in the circuit. This is the reason why household electrical appliances are not connected in series.

- Can you guess in what way household wiring has been done?

Let us see

Parallel Connection of resistors

Activity 7

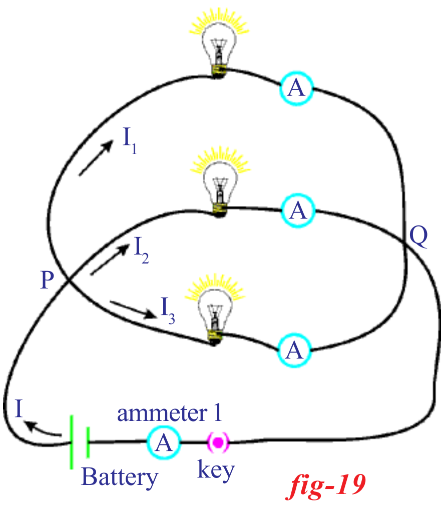

fig-19

Use the bulbs used in activity 6 and connect these bulbs as shown in figure 19.

Measure the potential difference across each bulb using a voltmeter or multi meter. Note these values in your note book. What do you notice? The potential difference at the ends of each bulb is the same. These bulbs are said to be in parallel conne ction. Measure electric currents flowing through each bulb using ammeters. Note these values.

Let I_1,I_2 and I_3 be the currents flowing through R_1, R_2 and R_3 resistors respectively.

- How much current is drawn from the battery?
- Is it equal to individual currents drawn by the resistors?

Measure the current (I) drawn from the battery using the ammeter 1. You will notice that the current drawn from the battery is equal to the sum of individual currents drawn by the bulbs.

Hence we can write

$$I = I_1 + I_2 + I_3 \qquad \text{..................} (1)$$

Equivalent resistance of a parallel connection

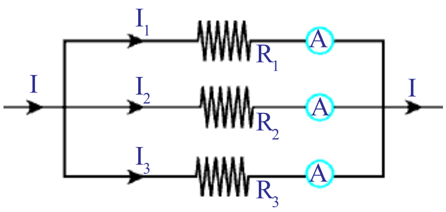

fig-20

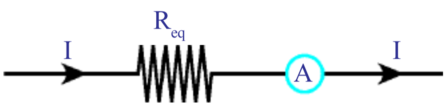

fig-21

The schematic circuit of figure 19 is shown in figure 20.

According to the Ohm's law,

Current through R_1 is, $I_1 = V/R_1$

Current through R_2 is, $I_2 = V/R_2$

Current through R_3, is, $I_3 = V/R_3$

Let R_{eq} be the equivalent resistance of the resistors is parallel. It is shown in figure 21.

Then we get; $I = V/R_{eq}$

Substituting the values I, I_1, I_2 and I_3 in equation (1), we get

$$V/R_{eq} = V/R_1 + V/R_2 + V/R_3$$

$$1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3$$

Let two resistors R_1 and R_2 are connected in parallel,

$$1/R_{eq} = 1/R_1 + 1/R_2$$

$$R_{eq} = R_1R_2/(R_1+R_2)$$

The equivalent resistance of a parallel combination is less than the resistance of each of the resistors.

You can use this result to explain why the resistance of a metal wire is inversely proportional to its area of cross section. Let us imagine a thick wire as a parallel combination of several thin wires. Then the resistance of the combination is less than that of each thin wire. In other words, the resistance of a thick wire is less than that of a thin wire.

Though the methods discussed in the previous section for replacing series and parallel combination of resistors by their equivalent resistances are very useful for simplifying many combinations of resistors, they are not sufficient for the analysis of many simple circuits particularly those containing more than one battery.

Let us see.

Kirchhoff's laws

Two simple rules called Kirchhoff's rules are applicable to any DC circuit containing batteries and resistors connected in any way.

Junction Law

See figure 19.

We have seen that the current divides at P. The current drawn from the battery is equal to the sum of the currents through the resistors. P is called junction. The junction is a point where three or more conducting wires meet.

At any junction point in a circuit where the current can divide, the sum of the currents into the junction must equal the sum of the currents leaving the junction. This means that there is no accumulation of electric charges at any junction in a circuit.

From figure 22, we have

$I_1 + I_4 + I_6 = I_5 + I_2 + I_3$

This law is based on the conservation of charge.

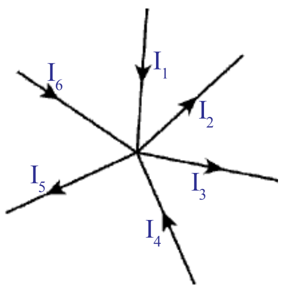

fig-22

Loop Law

The algebraic sum of the increases and decreases in potential difference across various components of the circuit in a closed circuit loop must be zero. This law is based on the conservation of energy.

Let us imagine in a circuit loop the potential difference between the two points at the beginning of the loop has a certain value. As we move around the circuit loop and measure the potential difference across each component in the loop, the potential difference may decrease or increase depending upon the nature of the element like a resistor or a battery. But when we have completely traversed the circuit loop and arrive back at our starting point, the net change in the potential difference must be zero. Thus, the algebraic sum of changes in potential differences is equal to zero.

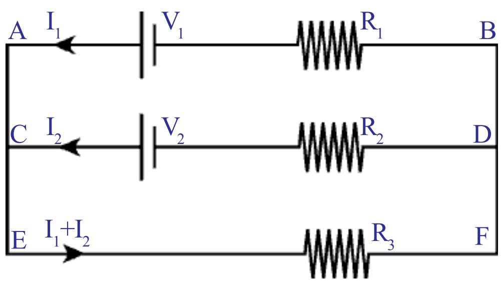

fig-23

Let us apply Loop law to the circuit shown in figure 23.

For the loop ACDBA,

$-V_2 + I_2R_2 - I_1R_1 + V_1 = 0$

For the loop EFDCE

$-(I_1+I_2) R_3 - I_2R_2 + V_2 = 0$

For the loop EFBAE

$-(I_1+I_2) R_3 - I_1R_1 + V_1 = 0$

Example

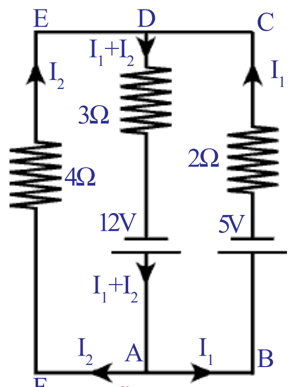

fig-E

Find electric current drawn(fig-E)from the battery of emf 12V.

Solution:

Let $I = I_1+I_2$ be the current drawn from emf 12V.

From the figure E. Using the loop law,

For the loop DABCD,

$-3 (I_1+I_2) + 12 - 2I_1 - 5 = 0$ .... (a)

For the loop DAFED,

$-3 (I_1+I_2) + 12 - 4I_2 = 0$ .... (b)

Solving the equation (a) & (b)

We get $I_1 = 0.5$ A and $I_2 = 1.5$ A

Total current drawn is then $I = 0.5 + 1.5 = 2A$

- You might have heard the sentences like "this month we have consumed 100 units of current". What does 'unit' mean?
- A bulb is marked 60W and 120V. What do these values indicate?

Let us see.

Electric power

The electric appliances that we use in our daily life like heater, cooker, fan, and refrigerator etc. consume electric energy. Let us consider a conductor of resistance 'R' through which an electric current 'I' passes.

We know that when current passes through conductor, heat energy is generated.

Consider that a charge Q Coulomb passes through a point A, moves to point B in the time interval ‘t’ seconds as shown in figure 24. Let V be the potential difference between the points A and B. The work done by electric field in time ‘t’ is given by

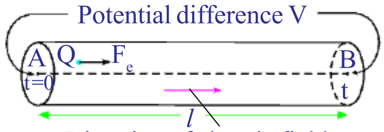

fig-24

$W = QV$ ....(1)

This work is equal to the energy lost by the charge while passing through the conductor.

- What is the energy lost by the charge in 1 see?

  It is equal to W/t.

  From equation (1), we get

  $W/t = QV/t$ ....(2)

In above equation Q/t represents the current (I) flowing through the conductor and W/t represents the work done per second.

In lower classes you had studied that power is nothing but the rate of doing work. Hence, W/t represents electric power (P).

Electric power $P = VI$ ....(3)

This equation can be used to calculate power consumption by any electric device that is connected in a circuit.

According to the ohm’s law,

$V = IR$

We can write equation (3) as

$P = I^2R = V^2/R$

The equation P = VI can also be used to know the power that can be extracted from a battery or any source. In such case we modify the equation P = VI as $P = \varepsilon I$.

Where ε is the emf of the battery.

Le us consider an example to understand power consumption.

A bulb is marked 60W and 120V. This means that if this bulb is connected to 120V source, it will able to convert 60J of electrical energy into heat or light in one second.

From the marking of bulb we can measure the resistance of the bulb.

From the relation $P = V^2/R \Rightarrow R = V^2/P$

Substituting the values V and P in above equation, we get

$R = 120 \times 120/ 60 = 240\ \Omega$

Thus, the bulbs marked as 60W and 120V will offer a resistance of 240 Ω to the flow current through it in normal condition.

If this bulb is connected to the 12V a battery, the consumption by the bulb is given by

$P = V^2/R = 12 \times 12/ 240 = 3/5 = 0.6$ W

Since watt is a small unit of power, a bigger unit Kilowatt is generally used to express power consumption.

1 KW = 1000 W = 1000 J/S

You might have seen the current bill that comes to your home every month. In that bill, consumption of electricity is marked in units. What does the unit represent?

The unit of electric power consumption is equal to 1 KWH (one Kilo Watt Hour).

$$1 \text{ KWH} = (1000 \text{ J/S}) (60 \times 60 \text{ S}) = 3600 \times 1000 \text{ J} = 3.6 \times 10^5 \text{ J}$$

- What do you mean by overload?
- Why does it cause damage to electric appliances?

We frequently hear news about overload of current and damages caused by this overload.

Electricity enters our homes through two wires called lines. These line wires have low resistance and the potential difference between the wires is usually about 240V. These two line wires run throughout the household circuit, to which we connect various appliances such as fan, TV, refrigerator etc.

All the electric devices of our home are connected at different points between these two wires. This means all the electric appliances are in parallel connection. Hence, potential drop across each device is 240V. If we know the value of resistance of the electric device, we can calculate the current passing through it using the equation I = V/R. For example, the current passing through a bulb with resistance 240 Ω is 1 A.

Based on the resistance of each electric device, it draws some current from the supply. Total current drawn from the mains is equal to the sum of the currents passing through each device (Junction law).

If we add more devices to the household circuit the current drawn from the mains also increases.

- What happens when this current increases greatly?

To answer this, observe the values noted on digital meters fixed at your home. You will notice the following values on the meter.

Potential difference: 240 V

Current: 5 – 20A

This means the line wires that are entering the meter have a potential difference of 240V. The minimum and maximum limit of current that can be drawn from the mains is 5 – 20A. Thus, the maximum current that we can draw from the mains is 20A. When the current drawn from the mains is more than 20A. Overheating occurs and may cause a fire. This is called over loading. See figure 25. If we switch on devices, such as heater shown in figure 25, the current drawn from the mains exceeds the max limit 20A.

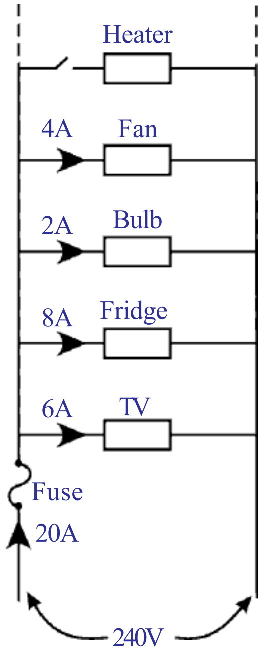

fig-25

- How can we prevent damage due to overloading?

To prevent damages due to overloading we connect an electric fuse to the household circuit as shown in figure 25. In this arrangement, the entire current from the mains must pass through the fuse. The fuse consists of a thin wire of low melting point. When the current in the fuse exceeds 20A, the wire will heat up and melt. The circuit then becomes open and prevents the flow of current into the household circuit. So all the electric devices are saved from damage that could be caused by overload.

Thus we can save the house holding wiring and devices by using fuses.

Note: The value of overload current varies from the household currents to factories.

Think and discuss

- What do you mean by short circuit?
- Why does a short circuit damage electric wiring and devices connected to it?

Key words

Charge, Potential difference, Electric current, Multi-meter, Ohm's law, Resistance, Resistivity, Kirchhoff's laws, Electric power, Electric energy.

What we have learnt

- Electric potential difference between points in an electric circuit is the work done to move a unit positive charge from one point to another.
- Electric current is expressed as the amount of charge flowing through a particular cross section 0area in unit time.
- A multi-meter is an electronic measuring instrument that combines several measuring functions (electric potential difference, electric current and electric resistance) in one unit.
- **Ohms law:** The current through a conductor element is proportional to the potential difference applied between its ends, provided the temperature remains constant. Mathematically V=IR.
- Ohm's law is valid for metal conductors at constant temperature. It is not applicable for gaseous conductors and semiconductors.
- Resistance is the opposition that a substance offers to the motion of electrons.
- Resistance of a wire depends on the material of the wire, its length and its area of cross section $R \alpha\, l/A$.
- The resistivity of a material is the resistance per unit length of a unit cross section of the material.
- Two or more resistors are said to be connected in series if the same current flows through them.
- Two or more resistors are said to be connected in parallel if the same potential difference exist across them.
- **The junction law:** At any junction point in a circuit where the current can divide, the sum of the currents into the junction must equal the sum of the currents leaving the junction.
- **The loop law:** The algebraic sum of the increases and decreases in potential difference across various components of a closed circuit loop must be zero.
- Electric power is the product of potential difference and the current. SI unit of power is watt (W).
- Electrical energy is the product of power and time. Units of electrical energy W-s and KWH.

Improve your learning

1. Explain how electronflow causes electric current with Lorentz – Drude theory of electrons.(AS1)
2. How does a battery work? Explain. (AS1)
3. Write the difference between potential difference and emf. (AS1)
4. How can you verify that the resistance of a conductor is temperature dependent? (AS1)

5. What do you mean by electric shock? Explain how it takes place. (AS1)
6. Derive $R = \rho l/A$. (AS1)
7. How do you verify that resistance of a conductor is proportional to the length of the conductor for constant cross section area and temperature? (AS1)
8. Explain Kirchhoff's laws with examples. (AS1)
9. What is a value of 1 KWH in Joules? (AS1)
10. Explain overloading of household circuit. (AS1)
11. Why do we use fuses in household circuits? (AS1)
12. Deduce the expression for the equivalent resistance of three resistors connected in series. (AS1)
13. Deduce the expression for the equivalent resistance of three resistors connected in parallel. (AS1)
14. Silver is a better conductor of electricity than copper. Why do we use copper wire for conduction of electricity? (AS1)
15. Two bulbs have ratings 100 W, 220V and 60 W, 220 V. Which one has the greater resistance? (AS1)
16. Why don't we use series arrangement of electrical appliances like bulb, Television, fan and others in domestic circuits? (AS1)
17. A wire of length 1m and radius 0.1 mm has a resistance of 100 Ω. Find the resistivity of the material. (AS1)
18. Why do we consider tungsten as a suitable material for making the filament of a bulb? (AS2)
19. Are the head lights of a car connected in series or parallel? Why? (AS2)
20. Why should we connect electric appliances in parallel in a household circuit? What happens if they are connected in series?
21. Suppose that you have three resistors each of value 30 Ω. How many resistors can you obtain by various combinations of these three resistors? Draw diagrams in support of your predictions. (AS2)
22. State Ohm's law. Suggest an experiment to verify it and explain the procedure. (AS3)
23. a. Take a battery and measure the potential difference. Make a circuit and measure the potential difference when the battery is connected in the circuit. Is there any difference in potential difference of battery? (AS4)
    b. Measure the resistance of a bulb (filament) in open circuit with a multi-meter. Make a circuit with elements such as bulb, battery of 12V and key in series. Close the key. Then again measure the resistance of the same bulb (filament) for every 30 seconds. Record the observations in a proper table. What can you conclude from the above results? (AS4)

24. Draw a circuit diagram for a circuit in which two resistors A and B are connected in series with a battery and a voltmeter is connected to measure the potential difference across the resistor A. (AS5)

25. How can you appreciate the role of a small fuse in house wiring circuit in preventing damage to various electrical appliances connected in the circuit? (AS7)

26. In the figure Q-26 the potential at A is ———————— when the potential at B is zero. (AS7)

fig-Q26

27. Observe the circuit and answer the questions given below. (AS7)
    i. Are resistors 3 and 4 in series?
    ii. Are resistors 1 and 2 in series?
    iii. Is the battery in series with any resistor?
    iv. What is the potential drop across the resistor 3?
    v. What is the total emf in the circuit if the potential drop across resistor 1 is 6V?

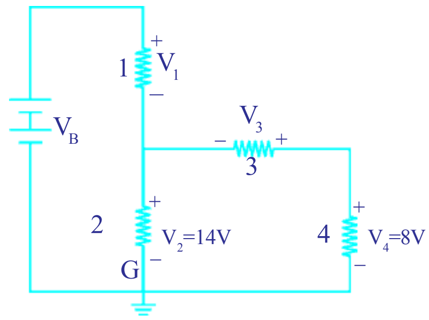

fig-Q27

28. If the resistance of your body is 100000Ω what would be the current that flows in your body when you touch the terminals of a 12V battery? (AS7)

29. A uniform wire of resistance 100Ω is melted and recast into wire of length double that of the original. What would be the resistance of the new wire formed?(AS7)

30. A house has 3 tube lights, two fans and a Television. Each tube light draws 40W. The fan draws 80W and the Television draws 60W. On the average, all the tube lights are kept on for five hours, two fans for 12 hours and the television for five hours every day. Find the cost of electric energy used in 30 days at the rate of Rs. 3.oo per Kwh. (AS7)

Fill in the blanks

1. The kilowatt hour is the unit of..........................
2. A thick wire has a .... resistance than a thin wire.
3. An unknown circuit draws a current of 2A from a 12V battery its equivalent resistance is...................
4. The SI unit of potential difference is ....

5. The SI unit of current is ....

6. Three resistors of values 2Ω, 4Ω, 6Ω are connected in series. The equivalent resistance of combination of resistors is ....

7. Three resistors of values 2Ω, 4Ω, 6Ω are connected in parallel. The equivalent resistance of combination of resistors is ....

8. The power delivered by a battery of emf, 10V is 10W. Then the current delivered by the battery is ....

Multiple choice questions

1. A uniform wire of resistance 50 Ω is cut into five equal parts. These parts are now connected in parallel. Then the equivalent resistance of the combination is [ ]

   a) 2 Ω b) 12 Ω

   c) 250 Ω d) 6250 Ω

2. A charge is moved from a point A to a point B. The work done to move unit charge during this process is called. [ ]

   a) potential at A b) potential at B

   c) potential difference between A and B d) current from A to B

3. Joule/ coulomb is the same as [ ]

   a) 1 - watt b) 1 - volt

   c) 1- ampere d) 1 - ohm

4. The current in the wire depends [ ]

   a) only on the potential difference applied b) only on the resistance of the wire

   c) on both of them d) none of them

5. Consider the following statements. [ ]

   A. In series connection, the same current flows through each element.

   B. In parallel connection, the same potential difference gets applied across each element.

   a) both A and B are correct b) A is correct but B is wrong

   c) A is wrong but B is correct d) both A and B are wrong

Annexure

Can we apply Newton law's to the motion of electrons?

Note: In this explanation, the random motion of electrons is neglected.

Let us consider a conductor of length l and cross sectional area A. Let n be the density of electrons of a conductor.

The current passing through the conductor when the ends of the conductor is maintained at a constant potential difference V is given by

$I = nAev_d$ .... (a)

Where e is the charge of electron and v_d is the drift velocity of electrons.

Work done by the source to move electron between the ends (along the conductor) is given by,

$W = Ve$ .... (b)

We know that the work done by the electric force,

$W = Fl$ .... (c)

Where F is the force applied by the electric field.

From equations (b) and (c), We get

$Fl = Ve \Rightarrow F = Ve/l$

From Newton's second law, we know that F = ma is applicable to any particle. Hence we have,

$ma = Ve/l \Rightarrow a = Ve/lm$ ....(d)

Assuming that the initial velocity (u) of electron is zero. Let v velocity acquired by the electron in a time interval τ (interval between successive collisions). Then u = 0 and t = τ

From equation $v = u + at$

$v = a\tau = Ve\tau/lm$ (from equation d)

Due to collisions with lattice ions, the motion of electrons is restricted. Hence the average velocity of electron in time τ becomes its drift velocity.

Average velocity of electron $v_d = (v+u)/2 = v/2$

Substituting the value of v in above equation, we get

Average velocity = Drift velocity, $v_d = Ve\tau/2lm$

Substituting the value of v_d in equation (a) we get,

$I = nAe(Ve\tau/2lm)$

$I = V(ne^2\tau/2m)(A/l)$

$I\,(2m/ne^2\tau)(l/A) = V$ ....(e)

In the above equation, mass of the electron (m) and charge of the electron (e) are constants because these values are characteristics of the electron.

The electron density (n) of a metal conductor depends on its nature so it is also constant for a particular conductor.

For a given conductor, the length (l) and cross section area (A) are also constants. The value of τ depends on temperature of the conductor. When the temperature increases the random motion of electrons increases hence the value of τ decreases.

For a constant temperature of a conductor the value of τ becomes constant.

Hence $(2m/ne^2\tau)$ (l/A) becomes a constant for a particular conductor at constant temperature. Let this value be R (called resistance of a conductor). The we get

$IR = V$ (from equation e) ....(f)

This is what we call Ohm's law.

Where $R = (2m/ne^2\tau)\ (l/A)$ ....(g)

In the above equation $2m/ne^2\tau$ is the characteristic value of a conductor. The value of resistance R is different for different geomentrical values for a particular conductor (material). Hence $2m/ne^2\tau$ is taken as a constant independent of geomentrical values. Let it be ρ. It is called specific resistance.

$\rho = 2m/ne^2\tau$

From equation (g) we get

$R = \rho l/A$ ....(h)