



YABELLO IFA BORU SPECIAL BOARDING SECONDARY SCHOOL

PHYSICS SHORT NOTE FOR GRADE 10

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UNIT 4

CURRENT ELECTRICITY

- **Electricity:** is a form of energy resulting from the existence of charged particles (such as electrons or protons), either statically as an accumulation of **charge** or dynamically as a **current**.
- There are two types of Electricity: Static Electricity and Current Electricity.
- The difference between the two is based simply on whether the electrons are at rest (static) or in motion (dynamic).

- **Static electricity** is a buildup of an electrical charge on the surface of an object.
- It is considered “static” due to the fact that there is no current flowing (i.e the charge is not moving or its at rest or stationary).
- It is usually caused by rubbing materials together.
- The result of a build-up of static electricity is that objects may be attracted to each other or may even cause a spark to jump from one to the other.

- **Current electricity** is named for the way electrons move. They 'flow' in one direction like a river current. The study of electrons in motion like this is called **Electrodynamics**.
- Materials that can conduct electricity are able to have an electric current flowing through them.
- **Current electricity** is the electricity that powers our homes and electrical devices.
- Electricity is used to operate your cell phone, power trains and ships, run your refrigerator, and power motors in machines like food processors.
- Electric energy must be changed to other forms of energy such as heat, light or mechanical in order to be useful.
- There are two kinds of current electricity: **direct current (DC)** and **alternating current (AC)**.
- With direct current, electrons move in one direction. Batteries produce direct current.
- In alternating current, electrons flow in both directions. AC generator produce alternating current.

4.1 Electric current and its SI unit

- Electric current is defined as the rate of flow of electric charges. It is produced by moving electrons.
- It is denoted by I and measured in amperes (A) [named after French Physicist Andrei Marie Ampere]. The ampere is one of the fundamental units of the SI system.
- Unlike static electricity, current electricity must flow through a conductor, usually copper wire.
- Current with electricity is just like current when you think of a river. The river flows from one spot to another, and the speed it moves is the speed of the current.
- With electricity, current is a measure of the amount of energy transferred over a period of time.
- That energy is called a flow of electrons. One of the results of current is the heating of the conductor. When an electric stove heats up, it's because of the flow of current.

- The size of an electric current is equal to the rate of flow of charge with time (ratio of charge to time).

$$I = \frac{Q}{t}$$

- The Ampere is equal to coulomb per second: $1A = \frac{1C}{1s}$

Example:

1. 120 C of charge passes in 1 minute. What is the current?

Solution:

$$I = \frac{Q}{t} = \frac{120C}{60s} = 2A$$

2. How long will a current of 5A take to pass 100 C of charge?

Solution:

$$I = \frac{Q}{t} \implies t = \frac{Q}{I} = \frac{100C}{5A} = 20s$$

What are the charges that flow round a circuit?

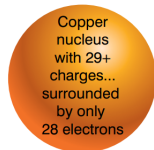
- To answer this question we must first look in rather more detail at the structure of an atom.
- All its positive charges are located in the central part, the nucleus.
- Each chemical element has a different number of positive charges in its nucleus, from one to nearly 100.
- Take copper as an example: it has 29 positive charges in the nucleus. This means that an uncharged copper atom must have 29 negative electrons as well. They orbit round the nucleus, and each one has its own path.

- The first two electrons orbit in the innermost shell, the next eight fill the second shell and the following 18 just complete the third shell. That leaves a solitary electron as the first member of a new fourth shell.



$$k = 2, \quad l = 8, \quad m = 18, \quad n = 1$$

- It is this electron that accounts for the behaviour of copper as a conductor. It is comparatively easy to remove this electron, changing an uncharged copper atom into what we call a copper ion with an overall single positive charge.

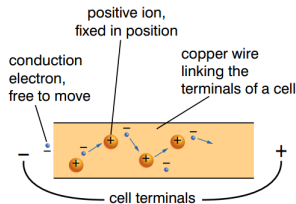


the ion has
an overall
positive charge...



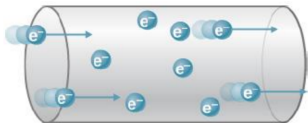
...and here is the
29th electron with
its negative charge

- In a copper wire the atoms are packed close together just as in any other solid. More precisely, what are packed together are the positive ions; the complete atoms except for those single outer electrons. They are there as well, so the metal as a whole is uncharged.
- In each copper atom 28 of the electrons are still firmly bound in orbit around their nucleus, fixed in its place in the solid. The 29th electrons we call the **conduction electrons**. They remain trapped within the metal as a whole, but otherwise are free to drift about inside it.
- They are the charges that move when an electric current flows down the wire. Being negative they will be repelled from the cell's negative terminal and attracted to the positive one.



- All metals have these extra one or two outer electrons, so they will all conduct electricity. With most other elements, every electron without exception is tightly bound to its own nucleus, so most other elements are **insulators**. Insulator is a material that resists the flow of electric charge.
- When electrons move through a conducting wire, they do not move at a constant velocity, that is, the electrons do not move in a straight line at a constant speed. Rather, they interact with and collide with atoms and other free electrons in the conductor. Thus, the electrons move in a zigzag fashion and drift through the wire.

- Electrical signals move very rapidly. Telephone conversations carried by currents in wires cover large distances without noticeable delays. Lights come on as soon as a light switch is moved to the 'on' position. The high speed of electrical signals results from the fact that the force between charges acts rapidly at a distance. Thus, when a free charge is forced into a wire, as in Figure below, the incoming charge pushes other charges ahead of it due to the repulsive force between like charges. These moving charges push on charges farther down the line.

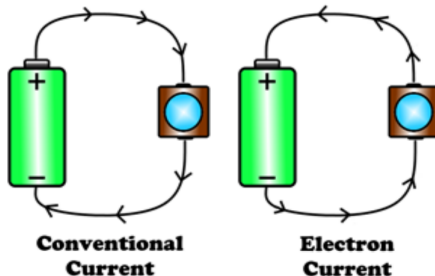


- The repulsion between like charges makes it difficult to increase the number of charges in a volume. Thus, as one charge enters, another leaves almost immediately, carrying the signal rapidly forward.

Conventional current and Electron current

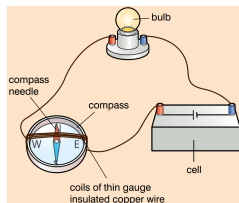
- Conventional current or simply current, behaves as if positive charge carriers cause current flow. Conventional current flows from the positive terminal to the negative. Perhaps the clearest way to think about this is to pretend as if movement of positive charge carriers constituted current flow.
- Electric currents have been investigated since the first cell was invented around 1800. It soon became obvious that charges were flowing round the circuit, but there was no way of telling whether they were positive charges going one way or negative charges going the other.
- It was agreed to picture the flow as positive charges repelled from the positive plate, and this was referred to as conventional current.

- When the electron was discovered in 1895, it was realized that the guess had been wrong. However, so firmly fixed was the idea that even today we still mark on our circuits the “conventional current” flowing from the positive pole of the cell to the negative.
- You must understand, however, that the electron flow is really negative charge going the opposite way. This is referred as **electron current**.



Galvanoscope(Galvanometer)

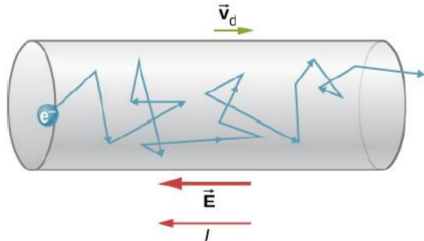
- Galvanoscope is an instrument that detects the presence of an electric current.



- You can use a compass needle to make a simple galvanoscope. Simply wrap a few turns of thin insulated copper wire around a compass, connect the ends as shown in Figure below, to a 1.5 V cell and a 1.5 V light bulb. When the wires are connected as shown, the bulb will light and the compass needle will move around in one direction.
- If you want to investigate this further, disconnect the cell, turn it round and reconnect it the other way round. The needle should move in the opposite direction.

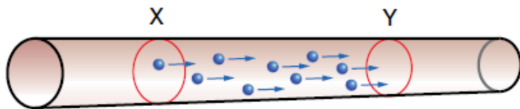
Drift Velocity

- Good conductors have large numbers of free charges. In metals, the free charges are free electrons.
- In fact, good electrical conductors are often good heat conductors too, because large numbers of free electrons can transport thermal energy as well as carry electrical current.
- Figure below shows how free electrons move through an ordinary conductor. The distance that an individual electron can move between collisions with atoms or other electrons is quite small.



- The electron paths thus appear nearly random, like the motion of atoms in a gas. But there is an electrical field in the conductor that causes the electrons to drift in the direction shown (opposite to the field, since they are negative). The **drift velocity** ($\vec{v}_d$) is the average velocity of the free charges. Drift velocity is quite small, since there are so many free charges.
- The free electrons moving in a conductor make many collisions with other electrons and other particles. A typical path of one electron is shown. The average velocity of the free charges is called the drift velocity ($\vec{v}_d$) and for electrons, it is in the direction opposite to the electrical field. The collisions normally transfer energy to the conductor, requiring a constant supply of energy to maintain a steady current.

Calculating the number of electrons that pass a point at a given length of time when the current in the wire is known



- The wire shown in Figure above carries a current of I amperes. There are n free electrons per cubic meter of wire. Each electron carries a charge of e coulombs, the cross-sectional area of the wire is A square meters and the average drift speed of the electrons in this material is v meters per second.
- Drift speed is the average speed that an electron attains in an electric field.

- Assuming that it takes **t** seconds for an electron to pass from X to Y (and using the formula distance = speed × time), distance X-Y is **vt** metres.
- The volume of wire between X and Y is therefore **Avt** cubic metres. The number of electrons between X and Y is therefore **nAvt**.
- As each electron carries a charge of **e** coulombs, the total charge passing point Y in **t** seconds is **nAevt**. The current, **I**, is the charge per time:

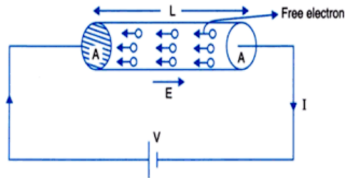
$$I = \frac{Q}{t} = \frac{nAevt}{t} = nAev$$

- As the charge carried by an electron is known to be $1.6 \times 10^{-19} \text{C}$, the number of electrons passing through a wire can be calculated if the current in the wire is known.

Example

1. A current of 5 A is flowing through a 2 mm diameter wire. The drift speed of electrons in the wire is 10^{-5}m/s and the charge on the electron is $1.6 \times 10^{-19}\text{C}$. Calculate the number of electrons passing a point in the wire in a second.
2. In the conductor shown in the following figure, if a current of 15A flowed for 1hr,

- a) What amount of charge would move through the cross-section in this time?
- b) How many electrons pass across the cross-section?



Solution:

1.

$$Area = \pi r^2 = \pi \left(\frac{d}{2}\right)^2 = \pi \left(\frac{2 \times 10^{-3} m}{2}\right)^2 = \pi \times 10^{-6} m^2$$

$$n = \frac{I}{Aev} = \frac{5A}{\pi \times 10^{-6} m^2 \times 1.6 \times 10^{-19} C \times 10^{-5} m/s}$$
$$= 9.947 \times 10^{29} \text{ electrons}/m^3$$

2.

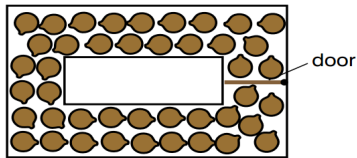
$$Q = It = 15A \times 3600s = 54000C = 5.4 \times 10^4 C$$

$$n = \frac{Q}{e} = \frac{5.4 \times 10^4 C}{1.6 \times 10^{-19}} = 3.38 \times 10^{23} \text{ electrons}$$

Study of electric charges in a metallic conductor

- If conductor is connected to the battery, we can detect an electric current. Where does this electric current keep coming from and where does it keep going to?
- To start investigating the answer to this, look at Figure, which shows the top view of a corridor that ends up where it started. The whole place is filled with people who form a kind of endless queue.

The door is shut, which means that nobody in the queue can move forward.
- Once the door is opened (once the circuit is switched on), all the people in that corridor can immediately start moving. They can keep circulating round and round the corridor, thus forming a continual current.



- Of course when the door was opened the people filling the corridor found themselves free to move round the circuit, but they did not have to do so. Likewise charges will not circulate to give a current unless there is something that keeps 'pumping' them round. That is the job of the cell (electromotive force emf).

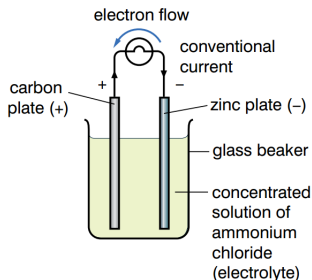
Source of Electricity

I. Electric energy from chemicals

- An **electrochemical** cell is one device that makes current flow round a circuit.
- It is a device capable of deriving electrical energy from chemical reactions.
- Such cells have:
 - Two electrodes (Anode and Cathode) made of two different conductors.
 - An electrolyte solution (a solution that conducts electricity) which reacts with the electrodes, and a conductive wire through which electrons can flow.

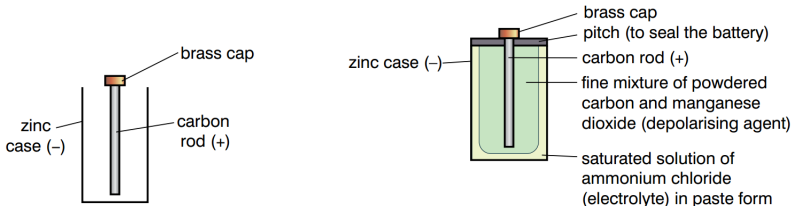
- Some cells are more powerful than others. An ordinary torch cell (usually referred to as a battery) is rated at 1.5 volts.
- We call this the electromotive force (e.m.f) of the cell.
- Electromotive force is a source of energy causing current to flow in an electrical circuit.
- It is the cell that pumps the charge round the circuit, and for the time being it is sufficient to think of the e.m.f. as its “electrical pumping strength”.
- All other things being equal, the greater the e.m.f. of the cell the greater the current that it will drive round a circuit.
- They cause coulombs of charge to flow round a circuit at a rate of amperes.
- There are many different types of cells. Figure below illustrates the principles of one common form, which we call a dry cell.

- Dry cell is an electrochemical cell containing electrolyte in the form of a paste.
- Experiment shows that the carbon plate is the positive one, the zinc is the negative, and the e.m.f. is very close to 1.5 V.



- Such a cell is about as portable as a glass of water, and we now see how it has been converted into the tough flashlight cell (commonly known as a battery) we are familiar with.

- The negative zinc (Zn) plate is shaped to form the casing of the cell (Figure below).
- The carbon rod (graphite) runs down the centre in the form of a rod (with a brass cap on the top, because carbon is easily damaged).
- The concentrated solution of ammonium chloride (NH_4Cl) that has to go into the space between them is made much less runny by forming it into a paste or jelly.
- It is for this reason that the design is called a dry cell.

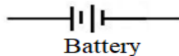
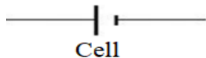


- The positive plate is both the carbon rod (graphite) down the centre and the thick layer of powdered carbon that surrounds it.
- Mixed in with the powdered carbon (C) is manganese dioxide (Mn_2O), another chemical in powder form.
- While the cell is giving a current it suffers from polarization: the formation of a film of hydrogen gas on the positive plate which 'clogs' the cell up.
- The manganese dioxide is there to deal with this problem by supplying oxygen to convert this unwanted hydrogen to water.
- Sometimes the mixture of black powders is held in place round the central carbon rod with a cloth bag, but in other batteries it is just the 'stiffness' of the ammonium chloride paste that keeps it there.

- This simple dry cell contains a negative electrode (a zinc sheath which encloses the battery materials) and a positive electrode (the carbon rod and the carbon and manganese dioxide mixture that surrounds the rod).
- An electrolyte paste separates the two electrodes and facilitates a chemical reaction between them.
- This reaction causes a current to flow (that is, makes the electrons move) through a conductor that connects the positive and negative electrodes.
- As the cell runs down, the zinc casing gets thinner and thinner, and when it gets very old the ammonium chloride may seep out from holes in the casing as a white corrosive paste.
- There is nothing unique about carbon, zinc and ammonium chloride solution: any combination of two different metals (or one metal and carbon) placed in a solution of an electrolyte will produce a voltage.
- Other combinations are available, such as the alkaline cell, which uses potassium hydroxide for the electrolyte.

What is Cell and Battery?

- Cell is a smaller unit while battery is larger. We many times use term battery in place of cell as working of both is same. Both convert chemical energy into electrical energy.
- The difference between cell and battery is that cell is a single unit which converts chemical energy into electrical energy while battery is a group of cells which all converts chemical energy into electrical energy.
- Figure of a cell and battery is given below for your better understanding. We use different symbols to represent cell and battery. Symbols o f both are given below.



Primary cells and secondary cells

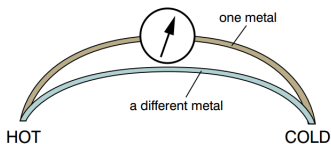
- Cells that produce their voltage directly from chemical energy stored in the ingredients which make them up are known as primary cells.
- When all their chemicals have reacted, you have to buy a new one. The dry cell is one of these.
- There are also secondary cells, which have first to be charged up by forcing a current 'backwards' through them.
- The commonest types of these are the increasingly popular rechargeable cells and the lead-acid accumulators that make up the battery in a car.
- The major difference between a primary cell and the secondary cell is that primary cells are the ones that cannot be charged but secondary cells are the ones that are rechargeable.
- Internal resistance of primary cells is very high, whereas secondary cells possess low internal resistance.

II. Electric energy from heat

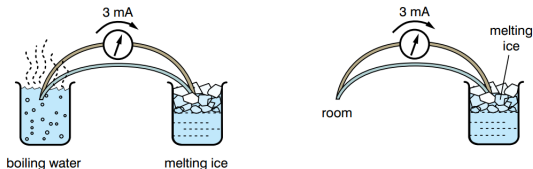
- We have seen how electric energy can come from chemicals and we now see that it can also come from heat; this is called **thermoelectricity**.
- Thermoelectric materials generate power directly from the heat by converting temperature differences into electric voltage.
- If two different metals are joined in a circuit, and if one junction between the metals is hotter than the other, a very small voltage (a few millivolts, mV) is generated.
- This effect is known as the **Seebeck effect** after the German physicist Thomas Seebeck (1770 –1831) who discovered it.
- The circuit must be made from two different metals, any two, although some pairs may be better than others.

The thermocouple thermometer

- The Seebeck effect is used in the thermocouple thermometer to measure temperature.
- It consists of a circuit made from any two different metals and includes a sensitive meter to measure small currents (Figure below).
- If one of the junctions between the metals is hotter than the other, a small voltage is generated, which drives a tiny current round the circuit.
- The larger the temperature difference, the greater the current.



- When using a thermocouple thermometer, it is usual to hold one junction at 0°C by keeping it immersed in melting ice. The other junction acts as the probe to investigate the temperature to be measured, as in Figure below.



- In the first part of Figure above, a temperature difference of 100°C between boiling water and melting ice shows a current of 10mA (milliamperes, thousandths of an ampere).
- Each 1mA therefore indicates a difference of 10°C .
- Thus when the probe is at room temperature and a current of 3mA is measured, the junction at room temperature must be 30°C hotter than the cold junction, which is at 0°C .
- Room temperature is therefore 30°C .

Example

One junction of a thermocouple thermometer is immersed in melting ice and the other in boiling water. A current of 20 mA is recorded. The thermocouple thermometer is then used to measure the temperature of a liquid. One junction is immersed in melting ice and the other in the liquid whose temperature is to be measured. A current of 5.5 mA is recorded. What is the temperature of the liquid?

Solution

In the first, calibration, measurement, 20 mA represents a temperature difference of 100°C .

Therefore 1 mA represents a temperature difference of 5°C .

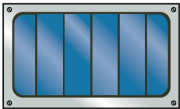
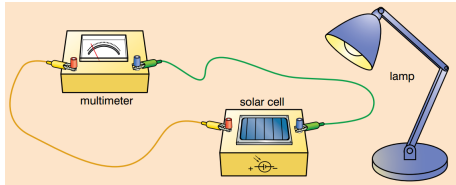
In the temperature measurement, the temperature difference between the junctions is $5.55 = 27.5^{\circ}\text{C}$.

The junction immersed in melting ice is at 0°C .

The temperature of the liquid being measured is therefore $0 + 27.5 = 27.5^{\circ}\text{C}$.

III. Electric Energy from Light

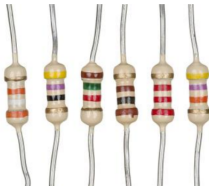
- When light, particularly ultraviolet light, is shone on a clean metal surface, the surface will emit electrons. These electrons are known as **photoelectrons**, and the emission of photoelectrons is called the **photoelectric effect**.



- Photovoltaic cell (solar cell) does this for us.

4.2 Ohm's law and electrical resistance

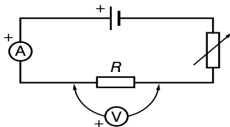
- **Resistance** is defined as the measure of the opposition to the flow of current through the conductor.
- Resistance is a property of a material that controls the amount of current that flows through it.
- It is denoted by R , and measured in ohms (Ω).
- A **resistor** is a passive component in a circuit which provides resistance to the flow of current.
- In electronic circuits, resistors are used to reduce current flow.



Measuring the resistance of a resistor

The principle is simple: Apply a voltage across the resistor, and measure the size of the resulting current through resistor and the potential difference across the resistor.

The variable resistor is there to alter (change) the potential difference and the corresponding current.



Then record the value of potential difference (voltage) across resistor and the corresponding current through the resistor

p.d. V across R (volts)	current I through R (amperes)	$R = \frac{V}{I}$ (ohms)
Average		

- **Ohm's law** states that the current through a conductor between two points is directly proportional to the voltage across the two points.
- Introducing the constant of proportionality, the resistance, one arrives at the usual mathematical equation that describes this relationship:

$$V \propto I$$

$$V = RI$$

- Where **I** is the current through the conductor in units of amperes, **V** is the voltage measured across the conductor in units of volts, and **R** is the resistance of the conductor in units of ohms.

- More specifically, Ohm's law states that the R in this relation is constant, independent of the current.
- If the resistance is not constant, the previous equation cannot be called Ohm's law.
- For a metal wire at a constant temperature, the current that flows through it is proportional to the potential difference (the voltage drop) between its ends.
- In other words, if the voltage drop across the wire doubles, charge will flow through it at exactly twice the rate (that is, the current doubles too).
- Put yet another way, $\frac{V}{I}$ stays constant: the wire's resistance does not change.
- Notice that Ohm's law will apply only if the temperature of the conductor does not change.

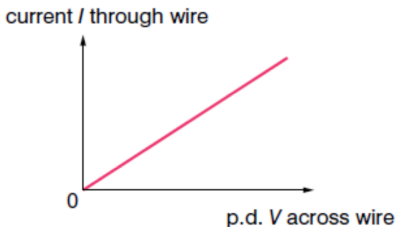
Example

1. A 12 V car battery is connected to a circuit for which total resistance is 6Ω . What current will flow?
2. A 12 V battery is connected to a circuit. If the current is $2mA$, what must the resistance of the circuit be?
3. What voltage battery would be needed to send a current of 3 A round a circuit for which the total resistance is 4Ω ?

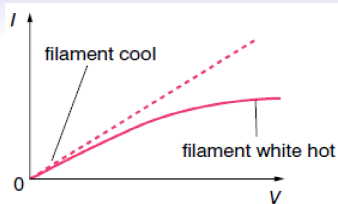
Factors affecting the resistance of a conductor

A) Effect of heat on resistance

- If you display the current and voltage readings measured when studying a resistor at constant temperature in the form of a graph of the current through the resistor plotted against the voltage drop applied across it, you should get a straight line (Figure).
 - Double the potential difference (p.d.) across the wire and you will double the current flowing through it.

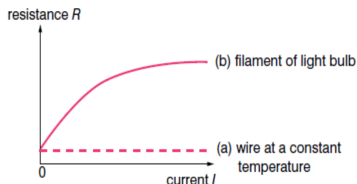


- However, if you use a light bulb as your resistor and take a range of readings such that the filament of the bulb is varied from not even red-hot to brilliantly white-hot, the graph of your readings will form a curve (Figure).



- As you increase the voltage and the lamp glows more brightly, the current does not rise as rapidly as expected.
- As the filament becomes white hot, its temperature increases by at least several hundred degrees.
- The resistance of metals rises with temperature, and that is why a hot bulb does not conduct as well as a cool one.
- Instead of taking current and voltage readings, it is useful to measure the resistance of a light bulb at as wide a range of currents as possible.
- At one extreme, readings should be taken when the current is so small that the filament is not even glowing feebly red; at the other extreme the bulb should be brighter than normal.

- Use these readings to plot a graph of resistance against current, as in Figure.
- If the temperature had not changed, the resistance would have been constant (line (a)). As it is, the resistance rises markedly (line (b)).



- Notice that the line will not pass through the origin.
- If you continue the curve back so it approaches or equals zero, you will have the resistance of the bulb when it is cold (that is, at room temperature).
- At its working temperature the resistance of the bulb may well have risen to ten times that value.

- Generally, the resistance of a metal increases in an approximate straight line if you plot it against its temperature. The increase in the value of the resistance as it warms up depends on:
 - The rise in the wire's temperature, ΔT . The greater the rise, the bigger the increase.
 - How many ohms of resistance it possesses. Since this will vary with its temperature, we work on the basis of its resistance at 0°C and call it R_0 . The greater the number of ohms at the start, the greater the increase in resistance will be.
 - The metal it is made from.
- Putting these together, we can say, the increase in resistance:

$$\Delta R = R_0 \alpha \Delta T$$

$$R - R_0 = R_0 \alpha \Delta T$$

$$R = R_0(1 + \alpha \Delta T)$$

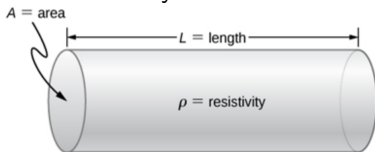
- Where R_0 is the original resistance of resistor, alpha (α) is a constant, which varies from one metal to another. We call it the metal's temperature coefficient of resistance. The units of α have to be K^{-1} (*kelvin*⁻¹) in order to give an answer that is in ohms.
- You will probably be working in degrees Celsius rather than kelvin, but there is no need to worry, remember that a rise in temperature of $10^{\circ}C$ is exactly the same as a rise of $10K$.

Example

1. A copper resistor ($\alpha = 4.3 \times 10^{-3} K^{-1}$) whose value is 10.0Ω at $0^{\circ}C$ is warmed from that temperature up to $150^{\circ}C$. Work out its resistance when hot.
2. A carbon resistor at room temperature ($20^{\circ}C$) is attached to a $9.0V$ battery and the current measured through the resistor is $3.0mA$.
 - a) What is the resistance of the resistor measured in ohms?
 - b) If the temperature of the resistor is increased to $60^{\circ}C$ by heating the resistor, what is the current through the resistor ($\alpha = 5 \times 10^{-4} K^{-1}$)?

B) Effect of length and diameter of resistor on resistance

- The resistance of a metal wire at a given temperature is determined by three factors:



- Its length L , in meters: the resistance is proportional to L , so if the length doubles so does the resistance.
 - Its area of cross-section $\mathbf{A}$, in m^2 : the resistance is inversely proportional to $\mathbf{A}$, so a wire with twice the cross-sectional area will have only half the resistance.
 - The material from which the wire is made: copper, for example, is a better conductor than iron.
- Thus the resistance R of a wire can be expressed in the form:

$$R = \rho \frac{L}{A}$$

- The symbol ρ (the Greek letter rho) is a constant, the value of which depends on the material from which the wire is made: the value for iron will be greater than the value for copper. We call ρ the **resistivity** of the material (i.e the degree to which a material resists the flow of electric current), it is defined by the equation above.
- The units of resistivity are Ωm : ohms multiplied by meters. To see this, consider the units of the right-hand side. They will be $\frac{\Omega mm}{m^2}$, which works out correctly to give the resistance in ohms (Ω).
- The reciprocal of the resistivity is called conductivity (σ): the ability of a material to conduct electric current.

$$\sigma = \frac{1}{\rho} \quad \text{or} \quad \rho = \frac{1}{\sigma}$$

$$R = \rho \frac{L}{A} = \frac{1}{\sigma} \frac{L}{A} = \frac{L}{\sigma A}$$

Example

1. What is the resistance of a copper cable that has a cross sectional area of 1cm^2 and a length of 2 km? The resistivity of copper is $210^{-8}\Omega\text{m}$.

Some circuit symbols



cell



switch



battery



ammeter



resistor



variable resistor



voltmeter



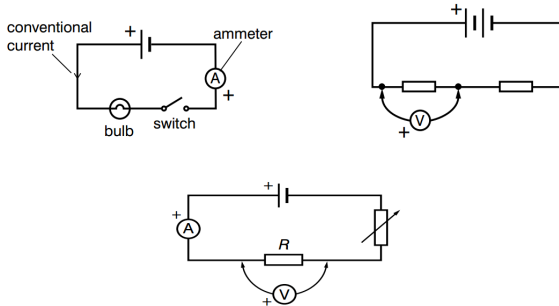
capacitor

The correct position for ammeter and voltmeter in a circuit

- **Ammeter** is an instrument that measures the size of a current.
- To measure the current through a device or component, the ammeter is placed in **series** with the device or component. A series connection is used because objects in series have the same current passing through them.
- Ammeter is fitted into the circuit so the current to be measured flows through it. In order that the ammeter does not reduce the current it has been put in to measure, it is essential that the instrument allows the current to flow through it freely (has a **low resistance**).

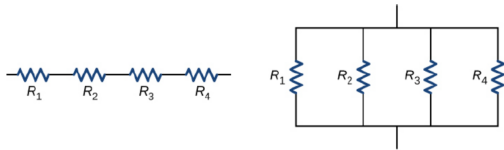
- **Voltmeter** an instrument used to measure potential difference in a circuit.
- A voltmeter is connected in parallel with whatever device it is measuring. A parallel connection is used because objects in parallel experience the same potential difference.
- Unlike an ammeter, the voltmeter is not part of the circuit.
- The voltmeter indicates the difference between the two points, which we call it the **potential difference** (p.d.) between the ends of the resistor, and measure it in volts. Sometimes we speak of it as the voltage drop (or just the **voltage**) across the resistor.
- Ideally a voltmeter should draw no current from the circuit it is investigating. It must therefore have a very **high resistance**.

- It is important that you connect the ammeter the correct way around; otherwise the current would try to twist it backwards.
- The terminal on it marked '+' needs to be joined to the positive side of the battery, as shown in Figure. (Sometimes the terminals are color-coded.
- The '+' terminal will be red, and the '-' terminal black.)



4.3 Combinations of resistors (Resistors Network)

- We shall now look at **resistors** connected in electric circuits in different ways - in **series** and in **parallel**.
- If several resistors are connected together and connected to a battery, the current supplied by the battery depends on the equivalent (total or net) resistance of the circuit.
- The equivalent resistance of a combination of resistors depends on both their individual values and how they are connected.
- The simplest combinations of resistors are series and parallel connections (figure below).



Series Combination of Resistors

- In a series circuit:
 - i. The current through each resistor are the **same** and equal to the total current in the circuit.
 - ii. The total potential difference (voltage) across the circuit is the **sum** of all the potential difference (voltage) dropping across each resistor.

$$I = I_1 = I_2 = I_3$$

$$V = V_1 + V_2 + V_3$$

From Ohm's Law

$$R = \frac{V}{I} \implies V = IR$$

$$V_1 = I_1 R_1, V_2 = I_2 R_2, V_3 = I_3 R_3$$

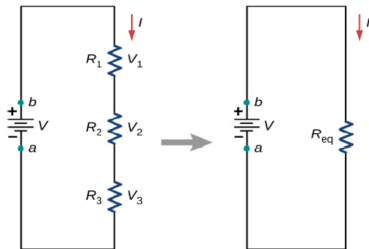
$$V = V_1 + V_2 + V_3$$

$$IR = I_1 R_1 + I_2 R_2 + I_3 R_3$$

$$IR = IR_1 + IR_2 + IR_3$$

$$IR = I(R_1 + R_2 + R_3)$$

$$R = R_1 + R_2 + R_3$$



- The above expression can be generalized to any number of resistors in a series network.
- For resistors connected in a series combination, the equivalent resistance is equal to the sum of individual resistances in the circuit.

$$R = R_1 + R_2 + R_3 + \dots$$

NOTE: In the series combinations of resistors, the total (equivalent) resistance is greater than the **largest** resistance in the circuit.

Parallel Combination of Resistors

- In a parallel circuit:
 - i. The voltage across each resistors are the **same** and equal to the total voltage across the circuit.
 - ii. The total current in the circuit is the **sum** of all the current passing through each resistor.

$$V = V_1 = V_2 = V_3$$

$$I = I_1 + I_2 + I_3$$

From Ohm's Law

$$R = \frac{V}{I} \implies I = \frac{V}{R}$$

$$I_1 = \frac{V_1}{R_1}, I_2 = \frac{V_2}{R_2}, I_3 = \frac{V_3}{R_3}$$

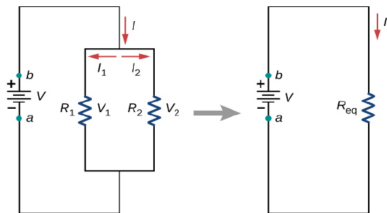
$$I = I_1 + I_2 + I_3$$

$$\frac{V}{R} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

$$\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$\frac{V}{R} = V \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right)$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$



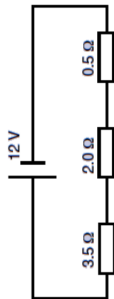
- The above expression can be generalized to any number of resistors in a parallel network.
- For resistors connected in a parallel combination, the reciprocal of the equivalent resistance is equal to the sum of reciprocals of individual resistances in the circuit.

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$

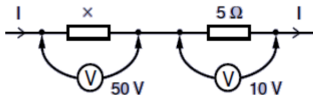
NOTE: In the parallel combinations of resistors, the total (equivalent) resistance is less than the **least** resistance in the circuit.

Example

1. Two resistors of 10Ω and 15Ω are connected. What is their combined resistance if they are connected?
a) in series. and b) in parallel.
2. Consider the resistors connected in the following circuit.
Calculate:
 - a. The equivalent resistance.
 - b. The total current through the circuit.
 - c. The current through each resistors.
 - d. The voltage across each resistors.

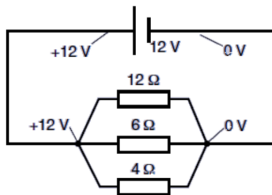


3. Calculate the size of resistor X in Figure below



4. A circuit consists of a 2Ω resistor and a 3Ω resistor in parallel. A 3 V battery is connected to the circuit.
- How big a current is drawn from it?
 - Calculate the voltage dropped across each resistors.
5. For the circuit shown in Figure.

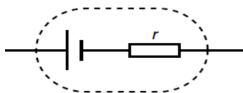
- Calculate the voltage drop across each resistor
- Calculate the current through each resistor
- Calculate the effective resistance of the circuit



4.4 E.m.f., internal resistance of a cell and terminal p.d

- The **e.m.f or electromotive force** (ϵ) is the energy supplied by a battery or a cell per coulomb of charge (Q) passing through it.
- The magnitude of e.m.f is equal to V (potential difference) across the cell terminals when there is no current flowing through the circuit.
- Electromotive force is a source of energy causing current to flow in an electrical circuit.
- A cell pumps charge round a circuit, its effectiveness at doing this is called its electromotive force (e.m.f.), in volts.
- Volts do not flow round a circuit. Volts cause coulombs of charge to flow at a rate of amperes.
- If we know the resistance R of a circuit, we can predict the current I that a battery will send round it, from Ohm's law $I = \frac{V}{R}$.

- **Internal Resistance** (r) is the resistance which is present within the battery that resists the current flow when connected to a circuit .
- Thus, it causes a voltage drop when current flows through it.
- It is the resistance provided by the electrolyte and electrodes which is present in a cell.
- Internal resistance varies between different cells, but it is what finally sets a limit to the current a cell can supply.
- A 1.5 V torch cell (represented in Figure below by the dotted line) typically has an internal resistance of up to an ohm. This means that even if you short-circuit the cell, there is still an ohm (1Ω) of resistance. The biggest current it can deliver is 1A.



- **Terminal p.d** is the voltage (p.d) across the terminal of the cell or battery.

- The relationship between a cell's e.m.f. (ϵ) and internal resistance (r) and the current (I) and resistance (R) in a circuit is given by the expression:

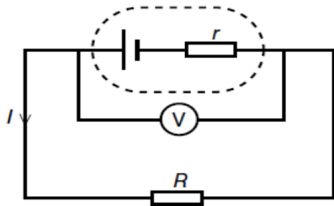
$$e.m.f = p.d \text{ across } r + p.d \text{ across } R$$

$$\epsilon = Ir + IR$$

$$\epsilon = I(r + R)$$

IR : Terminal p.d (voltage) or external voltage.

Ir : Internal voltage i.e the voltage dissipated internally.



Example:

In the circuit shown in Figure above, the cell's e.m.f. is 10 V and its internal resistance is 2Ω . Find the p.d. across the terminals of the cell when it is connected to a 3Ω resistor.

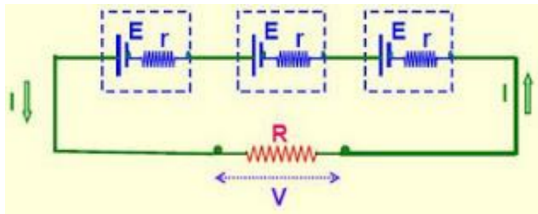
Combinations of identical cells in series and parallel

Combination of cells in series

When external resistance is negligible in comparison to the internal resistance, then the cells are connected in parallel to get maximum current.

Cells are connected in series when they are joined end to end so that the same quantity of electricity must flow through each cell.

- i. The emf of the battery is the sum of the individual emfs
- ii. The current in each cell is the same and is identical with the current in the entire arrangement.
- iii. The total internal resistance of the battery is the sum of the individual internal resistances.



Assume the e.m.f of one cell is ϵ_0 and all cells are identical.

The total e.m.f of the battery is: $\epsilon = \epsilon_0 + \epsilon_0 + \epsilon_0 = 3\epsilon_0$

The total internal resistance of the cells: $r_{eq} = r + r + r = 3r$

The total resistance of the circuit is $R_{eq} = 3r + R$

From the Ohm's law:

$$I = \frac{V}{R} = \frac{\epsilon}{R_{eq}} = \frac{3\epsilon_0}{3r + R}$$

We can generalize this for “n” number of cell:

$$I = \frac{n\epsilon_0}{nr + R}$$

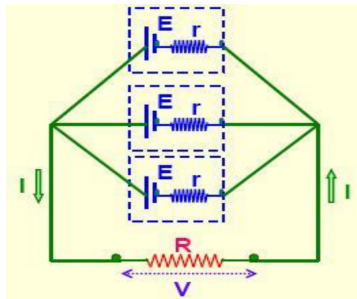
When internal resistance is negligible ($r = 0$) in comparison to the external resistance, then the cells are connected in series to get maximum current.

$$I = n \frac{\epsilon_0}{R}$$

Combination of identical cells in Parallel

Cells are said to be connected in parallel when they are joined positive to positive and negative to negative such that current is divided between the cells.

- i. The emf of the battery is the same as that of a single cell.
- ii. The current in the external circuit is divided equally among the cells.
- iii. The reciprocal of the total internal resistance is the sum of the reciprocals of the individual internal resistances.



Assume the e.m.f of one cell is ϵ_0 and all cells are identical.

Total emf of the battery $\epsilon = \epsilon_0$

The reciprocal of the total Internal resistance in the battery is equal to the sum of the reciprocal of individual internal resistance in the battery.

$$\frac{1}{r_{eq}} = \frac{1}{r} + \frac{1}{r} + \frac{1}{r} = \frac{3}{r} \implies r_{eq} = \frac{r}{3}$$

Total resistance of the circuit: $R_{eq} = R + r_{eq} = R + \frac{r}{3}$

The total current through the circuit will be:

$$I = \frac{\epsilon}{R_{eq}} = \frac{\epsilon_0}{(R + \frac{r}{3})} = \frac{3\epsilon_0}{3R + r}$$

We can generalize this for “n” number of cell:

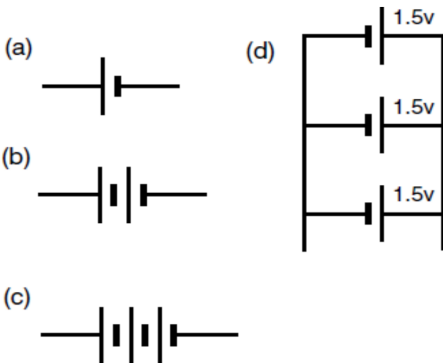
$$I = \frac{n\epsilon_0}{nR + r}$$

When internal resistance is negligible ($r = 0$) in comparison to the external resistance, then the cells are connected in series to get minimum current.

$$I = \frac{\epsilon_0}{R}$$

Example

In Figure below, (a), (b) and (c) show cells connected in series, (d) shows cells connected in parallel. Each cell has an e.m.f. of 1.5 V. Calculate the total e.m.f in each cases.



4.5 Electric energy and power

- **Electric energy** depends on both the voltage involved and the charge moved. This is expressed most simply as:
Electrical Energy(U) = charge moved(q) $\times$ the p.d through which the charge moved(V).

$$U = qV$$

- Power is the rate at which energy is moved, and so electric power is:

$$\text{electrical power} = \frac{\text{electrical energy}}{\text{time}}$$

$$P = \frac{U}{t} = \frac{qV}{t} = IV$$

- From Ohm's law ($V = IR$), three expressions for electric power are listed together here for convenience:

$$P = IV = \frac{V^2}{R} = I^2 R$$

- The word 'power' here means the rate at which energy is being supplied or converted. Power is measured in the units of joules per second (J/s), or watts (W).
- The electrical energy produced by a current of I amperes flowing through a p.d. of V volts for a time t seconds is given by:

$$\text{Energy} = VIt$$

- Power is the energy produced by an electrical appliance in one second. Thus, if $t = 1$:

$$\text{Energy} = VI \times 1 = VI$$

.

Example

1. A 60 W light bulb is switched on for 2 minutes. How many joules of electrical energy does it convert into heat and light in that time?
2. If the potential difference across a working electrical motor is 50 V and the current is 2 A, calculate the power of the motor.
3. Two heating coils A and B produce heat at a rate of 1 kW and 2 kW, respectively, when connected to 250 V mains.
 - a) Calculate the resistance of each resistor.
 - b) Find the power they would produce when connected in series to the mains.
4. Calculate the power of a water heater that draws a current of 10 A from a 220 V supply.

Cost of electrical energy

- The more electric appliances you use and the longer they are left on, the higher your electric bill.
- This familiar fact is based on the relationship between energy and power.
- You pay for the energy used. For example, the more light bulbs burning, the greater P used; the longer they are on, the greater t is.
- The energy unit on electric bills is the kilowatt-hour ($\text{kW} \cdot \text{h}$) , consistent with the relationship $U = Pt$.
- It is easy to estimate the cost of operating electrical appliances if you have some idea of their power consumption rate in watts or kilowatts, the time they are on in hours, and the cost per kilowatt-hour for your electric utility.

- Kilowatt -hours, like all other specialized energy units such as food calories, can be converted into joules.
- The electrical energy (U) used can be reduced either by reducing the time of use or by reducing the power consumption of that appliance or fixture. This not only reduces the cost but also results in a reduced impact on the environment.
- To calculate the cost of electrical energy we use the following equation:
 - The total cost = number of units (in kWh) $\times$ cost of each unit
- Electricity is distributed to homes and businesses and the quantity supplied is measured in kilowatt hours (KWh).

- A kilowatt hour is the energy used by a 1 kW appliance working for 1 hour. Consumers of electricity are charged for each kWh used.
- How many joules are there in 1 kWh?
- One kWh = energy transformed by 1 kW (1000 W) for 1 hour (3600 s) = energy when 1000 J are transformed each second for 3600 s = $1000 \times 3600 = 3\,600\,000\text{ J} = 3.6\text{ MJ}$
- According to the Ethiopian Electric Power Corporation (EEPCo.), the cost of one kilowatt-hour (1kw.h) is 0.273 **birr**.

$$1kWh = 0.273\text{ birr}$$

Example

1. How many units (kWh) are used by:
 - a) a 3 kW electric fire used for 2 hours,
 - b) a 100 W light bulb used for 15 hours?
2. A 1.5 kW electric fire is accidentally left on overnight for eight hours. How much money has been wasted?
3. A current of 4 A flows through an electric fire for 1 hour. The supply voltage is 240 V. What energy is transformed by the fire in 1 hour?.
4. The Ethiopian Power Corporation is distributing power saving lamps to the public free of cost. If an 11 W (0.011 kW) power saving bulb is used in place of the equivalent 60 W (0.06 kW) conventional lamp, and each type of bulb is used for 10 hours a day for four weeks (seven days a week), how much would the customer of the Ethiopian Power Corporation save?

4.6 Electric installation and safety rules

- Various safety features are incorporated into mains electrical installations; one of these features is the fuse, which uses the heating effect studied earlier in this unit.

- **An electrical fuse** is a safety device that operates to provide protection against the overflow of current in an electrical circuit.
- It consists of thin piece of wire in a glass tube that has metal connectors on each end.
 - It is designed to be used in a circuit to allow a current of a certain size to pass through it.
 - If the current in the circuit increases beyond this point, the fuse heats up and then breaks, causing the current in the circuit to stop.
 - The fuse is a very useful safety device, protecting appliances from surges of current.



- A Fuse is normally made up of elements like zinc, copper, aluminum and silver.
- A Fuse acts as a circuit breaker and breaks the circuit in case any fault occurs in the circuit.
- **Calculating the Fuse rating**
- A fuse rating is the current need to blow(break) the fuse.
- Using the guide that the fuse is rating at 125% of the normal operating current, then it can be calculated as follow.

$$Power = Current \times voltage$$

$$current = \frac{power}{voltage}$$

$$Fuse\ rating = \frac{P}{V} \times 125\%$$

- Finally use the next highest fuse rating after the calculation.

- For example, a) If you want to calculate the fuse rating for 500W appliance in Ethiopia (In Ethiopia, the main supply provided to our home is 110v or 220v), then:

$$Fuserating = \frac{P}{V} \times 125\% = \frac{500W}{220V} \times 125\% = 2.841A$$

- Then the next highest fuse rating after calculation is 3A.
- b) If you want to calculate the fuse rating for 1000W appliance in Ethiopia, then:

$$Fuserating = \frac{P}{V} \times 125\% = \frac{1000W}{220V} \times 125\% = 5.682A$$

- Then the next highest fuse rating after calculation is 6A.

- Electrical safety is also increased if appliances are **earthed**.
- This means that if there were a fault in an appliance, any dangerous large current would run harmlessly to the earth and cause the fuse to blow, thus preventing injury.
- **Earthed** circuit connected to the earth, allowing any dangerously large current to be safely discharged.

- **Miniature circuit breakers** (MCBs) can now be used in place of fuses in some appliances.
- They cut off the power if there is a fault that causes the appliance to overheat. They can be re set when the appliance cools down.
- **Earth-leakage circuit breakers** (ELCBs) are used in place of fuses in domestic electricity supply boards, where they are useful in cutting off the supply very quickly if a fault occurs.



Some safety rules while working with electrical instruments and tools

- Avoid water at all times when working with electricity. Never touch or try repairing any electrical equipment or circuits with wet hands. It increases the conductivity of the electric current.
- Disconnect the power source before servicing or repairing electrical equipment.
- Use only tools and equipment with non-conducting handles when working on electrical devices.
- Never use metallic pencils or rulers, or wear rings or metal watchbands when working with electrical equipment.
- When it is necessary to handle equipment that is plugged in, be sure hands are dry and, when possible, wear non-conductive gloves, protective clothes and shoes with insulated soles.

- If an individual comes in contact with a live electrical conductor, do not touch the equipment, cord or person. Disconnect the power source from the circuit breaker or pull out the plug using a leather belt.
- If water or a chemical is spilled onto equipment, shut off power at the main switch or circuit breaker and unplug the equipment.
- Never handle electrical equipment when hands, feet, or body are wet or perspiring, or when standing on a wet floor.