Unit 10

D.C Circuits

Teaching Periods 15 **Weightage %** 10

In this unit student should be able to:

- Recall the concept of resistance.
- Indicate the value of resistance by reading color code on it.
- Define the resistivity and explain its dependence upon temperature and also derive the mathematical relationship between them.
- Solve problems using the equation of resistivity.
- Understand the effects of the internal resistance of e.m.f on the terminal potential difference.
- Distinguish between e.m.f and p.d. using the energy consideration.
- Explain the internal resistance of sources and its consequences for external circuits.
- Describe some sources of e.m.f.
- Describe the conditions for maximum power transfer.
- Describe thermocouple and its functions.
- Explain variation of thermoelectric e.m.f. with temperature.
- Identify the function of thermistor in fire alarms and thermostats that control temperature.
- Sate Kirchhoff's first law and appropriate the link to conservation of charge.
- Sate Kirchhoff's second law and appropriate the link to conservation of energy.
- Derive the equation by using Kirchhoff's laws, a formula for the combined resistance of two or more resistors connected in series and parallel.
- Describe the Wheatstone bridge and hoe it is used to find unknown resistance.
- Describe the working of rheostat as a potential; divider in circuit.
- Describe the function of potentiometer to measure and compare potentials without drawing any current from it.

10.1 Resistors:

In electronic circuits resistors usually serve two main purposes to

1. Limit the current flow to a specified value
2. Provide a desired reduction in voltage, or current.

Fig:10.1 Resistor

Resistance is a measure of the opposition to current flow in an electrical circuit.

Suppose we maintain a potential difference across the ends of a conductor. How does the current ***I*** that flows through the conductor depend on the potential difference ΔV. For many conductors, the current is proportional to the potential difference.

George Simon Ohm (1789-1854) first observed this relationship, which is now called **Ohm's law**:

DO YOU KNOW?

Physical size of resistor has its correlation with its power rating. Larger the physical size higher will be the value of its power rating. tolerance is the amount by which the resistance of a resistor may vary from its marked value.

According to Ohm's law:

$$\Delta V = IR$$

$$I = \Delta V/R$$

Hence the electrical resistance **R** is defined to be the ratio of the potential difference for voltage **ΔV** across a conductor to the current **I** through the material

$$R = \Delta V / I \qquad \ldots(10.1)$$

In SI units, electrical resistance is measured in ohms (symbol Ω, the Greek capital omega), defined as

$$1\Omega = 1V/A$$

10.1.2 Resistor Color Code:

Basically a standard describes the way to measure and quantify important properties. There are many standards exist for resistors. Probably, the most common and well-known standard available is the color code marking for carbon resistors. The basis of this system is the use of colors for numerical values, as listed in Table 10.1.

We need to understand how to apply color code system in order to get the correct value of the resistor. We can summarize the different weighted positions of each colored band which makes up the resistors color code in the table 10.2.

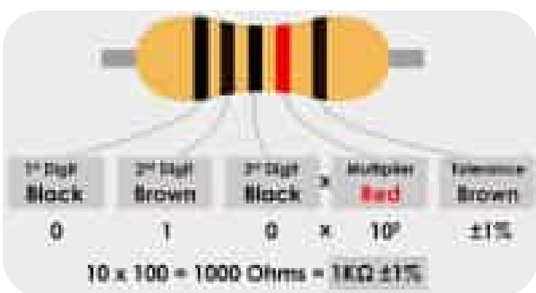
Table.10.1

Colour	Value	Multiplier	Tolerance
Black	0	10^0	-
Brown	1	10^1	-
Red	2	10^2	-
Orange	3	10^3	-
Yellow	4	10^4	-
Green	5	10^5	-
Blue	6	10^6	-
Violet	7	10^7	-
Grey	8	10^8	-
White	9	10^9	-
Gold	-	10^{-1}	5%
Silver	-	10^{-2}	10%
None	-	-	20%

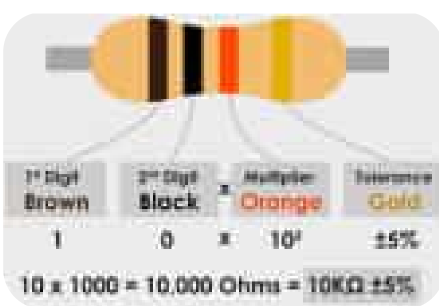
Table 10.2

Number of Colored Bands	3 Colored Bands (E6 Series)	4 Colored Bands (E12 Series)	5 Colored Bands (E48 Series)	6 Colored Bands (E96 Series)
1st Band	1st Digit	1st Digit	1st Digit	1st Digit
2nd Band	2nd Digit	2nd Digit	2nd Digit	2nd Digit
3rd Band	Multiplier	Multiplier	3rd Digit	3rd Digit
4th Band	–	Tolerance	Multiplier	Multiplier
5th Band	–	–	Tolerance	Tolerance
6th Band	–	–	–	Temperature Coefficient

In a 4 band resistor the first band nearest to the lead gives the first digit, the next band marks the second digit and the third band is the multiplier, which gives the number of zeroes after the two digits. In fig.10.2 (4 Band Resistor) the first stripe is brown for 1 and the next strip is black for 0 and third stripe is orange, a multiplier which means add 3 zeroes to 10. Therefore, the value of R is 10,000 Ω or 10K Ω. The fourth band is golden, which means that the resistor has a tolerance of 5%. Therefore, the resistance value lies between 9.5K Ω and 10.5KΩ. If the tolerance band would be left blank, the result is a 3 band resistor. This means that the resistance value remains the same, but the tolerance is 20%.



Resistance of 5 Band Resistor

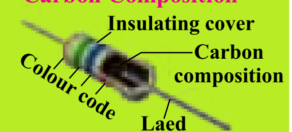


Resistance of 4 Band Resistor

Fig:10.2 (4 and 5) Band Resistors

DO YOU KNOW?

Carbon Composition



Wire Wound Resistor

Surface Mount Resistors

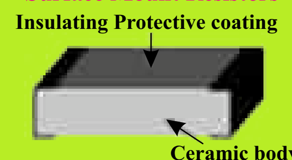
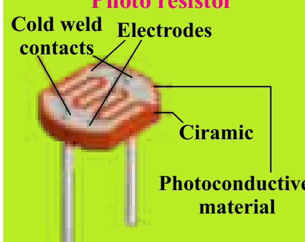


Photo resistor



Non-ohmic materials are substances that do not follow Ohm's Law
Semiconductor materials: Materials like silicon (Si), germanium (Ge), and gallium arsenide (GaAs) are non-ohmic.

10.2 Resistivity and its dependence upon temperature:

Resistance depends on size and shape. Returning to the analogy with fluid flow: a longer pipe offers more resistance to fluid flow than does a short pipe and a wider pipe offers less resistance than a narrow one. By analogy, we expect a long wire to have higher resistance than a short one everything else being the same and a thicker wire to have a lower resistance than a thin one.

Fig:10.3 Resistivity

The electrical resistance of a conductor of length L and cross-sectional area A can be written:

$$R \propto L/A$$

$$R = \rho L/A \qquad \ldots\ldots(10.2)$$

The constant of proportionality ρ, which is an intrinsic characteristic of a particular material at a particular temperature, is called the resistivity of the material. The SI unit for resistivity is Ω.m. The resistivity of various substances at 20°C is listed in table 10.3.

10.2.1 Resistivity Depends on Temperature:

Resistivity does not depend on the size or shape of the material, but it does depend on temperature. Two factors primarily determine the resistivity of a metal:

1. The number of conduction electrons per unit volume and the rate of collisions between an electron and an ion.
2. The sensitive to changes in temperature. At a higher temperature, the internal energy is greater; the ions vibrate with larger amplitudes. As a result, the electrons collide more frequently with the ions.

Table10.3 Material resistivity and temperature coefficient

Material	Resistivity ρ (ohm m)		Temperature coefficient α per degree C	Conductivity σ x 10^7 /Ωm
	Conductor			
Silver	1.59	$\times 10^{-8}$	.0038	6.29
Copper	1.68	$\times 10^{-8}$	.00386	5.95
Copper	1.724	$\times 10^{-8}$	...	...
Copper, annealed	1.72	$\times 10^{-8}$	.00393	5.81
Aluminum	2.65	$\times 10^{-8}$	.00429	3.77
Tungsten	5.6	$\times 10^{-8}$	.0045	1.79
Iron	9.71	$\times 10^{-8}$	.00651	1.03
Platinum	10.6	$\times 10^{-8}$	.003927	0.943
Manganin	48.2	$\times 10^{-8}$	.000002	0.207
Lead	22	$\times 10^{-8}$	...	0.45

Mercury	98	$x10^{-8}$	.0009	0.10
Nichrome(Ni,Fe,Cr alloy)	100	$x10^{-8}$	.0004	0.10
Constantan	49	$x10^{-8}$	...	0.20
Semi conductors				
Carbon* (graphite)	3.60	$x10^{-5}$	-.0005	...
Germanium*	1.500	$x10^{-3}$	-.05	...
Silicon*	0.1-60	...	-.07	...
Insulator				
Glass	1.10000	$x10^{9}$	...	...
Quartz (fused)	7.5	$x10^{17}$	...	...
Hard rubber	1.100	$x10^{13}$	...	...

With less time to accelerate between collisions, they acquire a smaller drift speed, thus, the current is smaller for a given electric field. Therefore, as the temperature of a metal is raised, its resistivity increases. The metal filament in a glowing incandescent light bulb reaches a temperature of about 3000 K; its resistance is significantly higher than at room temperature. For many materials, the relation between resistivity and temperature is linear over a fairly wide range of temperatures (about 500°C):

$\Delta R \propto R_o$

$\Delta R \propto \Delta T$

$R_E = \rho_o(1 + \alpha\Delta T)$

$\rho_t = \rho_0 (1+\alpha \Delta T)$ …(10.3)

Where, ρ_t = resistivity at temperature T ^{0}C

ρ_0= resistivity at temperature T_0 ^{0}C

α = linear temperature coefficient of resistivity and has SI units $^0C^{-1}$ or K^{-1}. The temperature coefficients for some materials are listed in table 10.3.

Note that for semiconductors, $\alpha < 0$. A negative temperature coefficient means that the resistivity decreases with increasing temperature. It is still true, as for metals that are good conductors that the collision rate increases with temperature. However, in semiconductors the number of carriers (conduction electrons or holes) per unit volume increases with increasing temperature: with more carriers, the resistivity is smaller.

DO YOU KNOW?

The resistivity of good conductors is small. The resistivity of pure semiconductors is significantly larger. By doping semiconductors (introducing controlled amounts of impurities), their resistivity can be changed dramatically, and Insulators have very large resistivity (about a factor of 10^{20} larger than for conductors). Some materials become superconductors ($\rho = 0$) at low temperatures. Once a current is started in a superconducting loop, it continues to flow indefinitely without a source of emf.

10.2.2 Conductance and Conductivity:

It is defined as "The measure of how easily flow of charges (electrical current) can pass through a material" or Conductivity is the ability of a material to conduct electricity and quantifies the effect of matter on current flow in response to an electric field.

Conductance is the reciprocal, or inverse, of resistance. The greater the resistance, the less the conductance and vice versa. It is denoted by symbol "σ" and its unit is the mho "℧", The unit of the mho has been replaced by the unit of *Siemens* (abbreviated by the capital letter "S").

Conductivity is denoted by Greek letter sigma (σ) and is the reciprocal of the resistivity i.e. 1/ρ. It is measured in siemens per meter (S/m). Since electrical conductivity σ = 1 /ρ, the previous expression for electrical resistance, R can be rewritten as a function of conductivity.

$$R = L / \sigma A \qquad \ldots(10.4)$$

DO YOU KNOW?

Mercury was the first superconductor discovered (by Dutch scientist Kammerlingh Onnes in 1911). As the temperature of mercury is decreased, its resistivity gradually decreases--as for any metal – but at mercury's critical temperature (T_c = 4.15 K) its resistivity suddenly becomes zero.

Worked Example 10.1

Calculate the resistance of 100 meter rolls of 2.5mm^2 copper wire if the resistivity of copper at 20ºC is 1.72 x 10^{-8} Ω meter.

Solution:

Step 1: Write the known quantities and point out quantities to be found

Resistivity of copper at 20ºC = ρ = 1.72 x 10^{-8} Ω meter

Coil length = L = 100m

Resistance = R = ?

Cross-sectional area of the conductor = A= 2.5mm^2 = 2.5 x 10^{-6} m^2.

Step 2: Write the formula and rearrange if necessary

$$\rho = R\,A/L$$
$$R = \rho\,L/ A$$

Step 3: Put the values in formula and calculate

$R = (1.72 \times 10^{-8}) \times 100/(2.5 \times 10^{-6})$

$$\mathbf{R = 0.688\ \Omega}$$

Result: Resistance will be **688 milli-ohms** or **0.688 Ohms.**

Worked Example 10.2

A 20-meter length of cable has a cross-sectional area of $1 mm^2$ and a resistance of 5 ohms. Calculate the conductivity of the cable.

Solution:

Step 1: Write the known quantities and point out quantities to be found
DC resistance = R = 5 ohms
Cable length = L = 20m
Cross-sectional area of the conductor $= A = 1 mm^2 = 1 \times 10^{-6}\ m^2$.
Conductivity = σ = ?

Step 2: Write the formula and rearrange if necessary

$\sigma = L/RA$

Step 3: Put the values in formula and calculate
$=20/5 \times 1 \times 10^{-6}) = 4 \times 10^{6}$ S/M

$\sigma = 4 MS/m$

Thus, Conductivity of Cable is 4MS/m

10.3 Internal Resistance:

Internal resistance is the opposition to the flow of current within a battery, or other sources of voltage, causing heat generation. Due to this reason a cell becomes hot after a period of time.

10.3.1 The effects of Internal resistance of a source of e.m.f on the terminal potential difference:

The internal resistance of a source of electromotive force (e.m.f) has a significant effect on the terminal potential difference across the source. An ideal voltage source is often represented as an ideal voltage source V in series with an internal resistance r. In real-world sources like batteries or power supplies, the internal resistance is a physical characteristic that affects the terminal voltage when a load is connected.

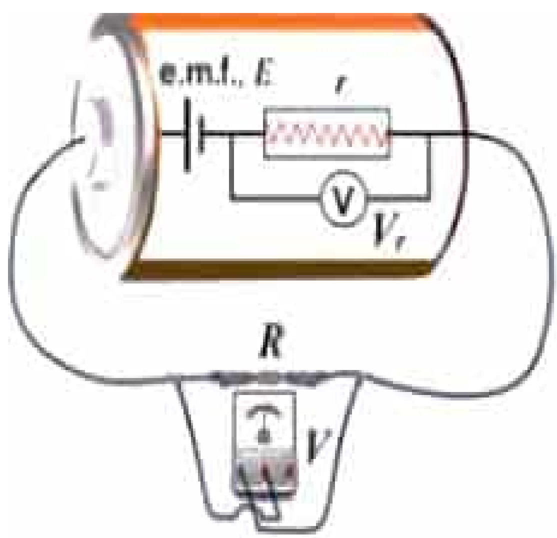


Fig:10.4
Internal resistance of a source

When a load (external circuit) is connected to the voltage source, current flows through both the load and the internal resistance of the source. The flow of current through the internal resistance causes a voltage drop across it, leading to a reduction in the terminal

potential difference compared to the ideal voltage source.
Here's how the internal resistance affects the terminal potential difference:

Terminal Potential Difference V_t:

The terminal potential difference V_t is the voltage measured across the terminals of the voltage source when a load is connected. It is the voltage that is available to the external circuit for doing useful work.

Voltage Drop across Internal Resistance:

As current flows through the internal resistance r of the source, there is a voltage drop across it, given by Ohm's Law: $V_{internal}$ =Ir, where I is the current flowing through the circuit.

Terminal Potential Difference Equation:

The terminal potential difference V_t can be calculated as the difference between the ideal voltage of the source V and the voltage drop across the internal resistance:

$$V_t = \mathbf{E} - V_{internal}$$

$$V_t = \mathcal{E} - Ir \;......(10.5)$$

The terminal potential difference V_t is reduced from the ideal voltage V due to the presence of the internal resistance r. The larger the internal resistance, the greater the voltage drop across it, resulting in a more significant reduction in the terminal potential difference.

10.3.2 Energy consideration in e.m.f and potential difference:

The electromotive force $\mathscr{E}$ (e.m.f). It is actually the amount of energy that it provides to each coulomb of charge, whereas the potential difference is the amount of energy used by the one coulomb of charge. The e.m.f transfers the energy in the entire circuit,

The Potential difference V. It is the measure of energy between any two points on the circuit. The electrical energy is gained by the e.m.f in the circuit, whereas electrical energy is lost by the potential difference in the circuit.
The electromotive force can be induced in the magnetic, electric. In contrary, the potential difference can only be generated in an electric field.

DO YOU KNOW?

Electro-motive force can be expressed as a voltage, and is defined as the total amount of energy (in joules) per unit charge (in coulombs) supplied to the circuit.

$$\mathscr{E} = \frac{E}{Q}$$

E= the energy in joules
Q = the charge in coulombs
$\mathscr{E}$ = the electro-motive force

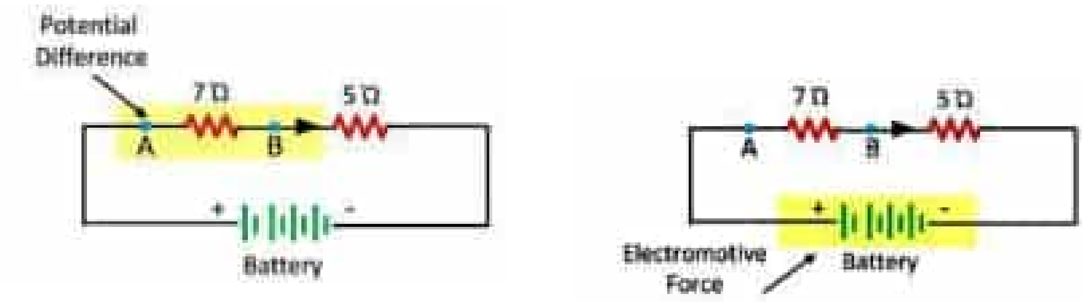


Fig: 10.5 emf and potential difference

The potential difference between the two point charges is expressed by the formula shown below.

$$\text{Potential Difference} = \frac{Energy\ or\ Work}{Charge}$$

$$V = \frac{E\ or\ W}{Q}\ \text{volts}$$

$$\text{EMF} = \mathcal{E} = \frac{W}{Q}\ \text{volts} \quad \ldots\ldots(10.6)$$

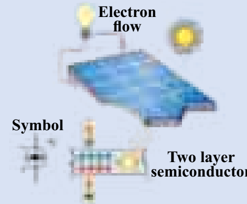
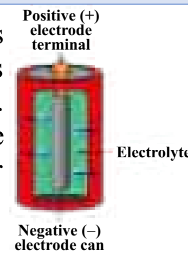
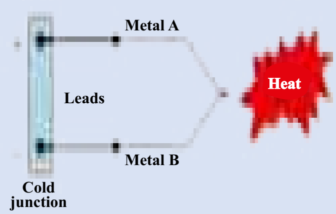
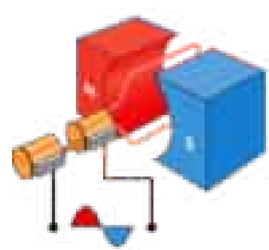
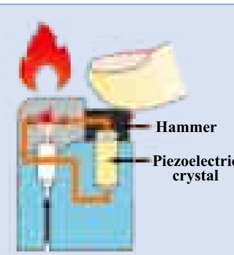
10.3.3 The internal resistance of sources and its consequences for external circuits:

It is important to understand the consequences of the internal resistance of emf sources, such as batteries. Internal resistance affects the performance of emf sources by reducing the potential difference across the external circuit components, which ultimately decreases its ability to supply current and lowers its power output. As the internal resistance of the battery is difficult to measure directly and can change over time, the analysis of circuits is done with the terminal voltage of the battery, as we have done in the previous sections. The internal resistance of a battery can increase for many reasons. For example, the internal resistance of a rechargeable battery increases as the number of times the battery is recharged. The increased internal resistance may have two effects on the battery. First, the terminal voltage will decrease. Second, the battery may overheat due to the increased power dissipated by the internal resistance.

The internal resistance ‘r’ of a battery can behave in complex ways. It generally increases as a battery is depleted, due to the oxidation of the plates or the reduction of the acidity of the electrolyte. However, internal resistance may also depend on the magnitude and direction of the current through a voltage source and its temperature. The internal resistance of rechargeable nickel-cadmium cells, for example, depends on how many times and how deeply they have been depleted. A simple model for a battery consists of an idealized emf source $\mathcal{E}$ and an internal resistance ‘r’.

10.3.4 Sources of emf:

There must be a source of electromotive force (emf) or voltage for electrons to flow. This emf source can be produced from different primary energy sources. These primary sources supply energy in one form, which is then converted to electric energy. Some Primary sources of electromotive force include:

S.No.	Primary Source of emf	Example	
1.	**Light**	A solar or photovoltaic cells and solar module or panel converts solar light to electric energy. These are made up of semiconducting, light-sensitive material which makes electrons available when struck by the light energy.	
2.	**Chemical Reaction**	A battery or voltaic cell directly converts chemical energy into electric energy. It consists of two electrodes and an electrolyte solution. One electrode connects to the (+) or positive terminal (anode), and the other to the (−) or negative terminal (cathode).	
3.	**Heat**	Thermocouple converts heat energy directly into electric energy. When we supplied heat to the hot junction, electrons start moving from one metal to the other. This creates a negative charge on one and a positive charge on the other.	
4.	**Mechanical-Magnetic**	An electric generator converts mechanical-magnetic energy into electric energy. To produce mechanical energy, a generator should be driven by an engine, a turbine or any other machine.	
5.	**Piezoelectric Effect**	In this type a substance is used which produces an electric charge when a mechanical pressure is applied. Certain crystals like quartz are piezoelectric in nature. They generate an electric charge when they are compressed or struck. A common example of piezoelectricity is the piezo gas igniter.	

10.4 Power Dissipation in Resistors:

It is a fact that resistors always dissipate power. Where does a resistor's power go? By Conservation of Power, the dissipated power must be absorbed somewhere, actually

"The current flowing through a resistor makes it hot; its power is dissipated by heat".

As the charges Q moves through a resistor, it loses a potential energy W=VQ where V is the potential drop across the resistor. This energy converted into energy of vibration of the atoms into which the charges (electrons) were bumping and has all been converted into heat. This conversion of potential energy into heat refer to as ***dissipation***. Hence the power dissipated in a resistor is the energy dissipated per time. If an amount of charge Δq moves through the resistor in a time Δt, the power loss is

$$P = \frac{\Delta q V}{\Delta t} = IV \quad .....(10.7)$$

Where ***I*** is the current through the resistor and ***V*** is the voltage drop across it.

The formula P = I V also gives the power generated by a battery if ***I*** is the current coming from the battery and ***V*** is its voltage.

From Ohms Law, power may also be shown as,

$$\text{Power} = I(IR)$$
$$\text{Power} = I^2R$$
$$\text{Power} = (V/R)^2R$$
$$\text{Power} = \frac{V^2}{R}$$

If V is in Volts and I in Amperes, then

Power = I × V = Amperes x Volts = coulomb / second x joule / coulomb = joule / second

Thus resulting units of power is joule per second. The SI unit of power is the watt, where 1 watt = 1 joule per second.

Finally, we have

1 watt = 1 ampere × 1 volt

It is a common misconception that Power and Energy/Electricity are same. Interestingly, they have a very different meaning. Power is the rate at which electricity is used and energy is the actual consumption. To give an analogy, power is similar to speed but energy is the actual distance travelled.

So, Power × Time = Energy

DO YOU KNOW?

The English unit of power is horsepower (hp), which is related to the watt by the conversion factor: 1 hp = 746 watt.

DO YOU KNOW?

A unit is represented in kWH or Kilowatt Hour on the electricity bills. This is the energy/electricity actually used. If we use 1000 Watts or 1 Kilowatt of power for 1 hour then we consume 1 unit or 1 Kilowatt-Hour (kWh) of electricity. It means that the electricity meter reading represents the actual usage of electricity. Similarly, a 100-Watt bulb if kept on for 10 hours will consume:
100 x 10 = 1000 Watt-Hour = 1 Kilowatt-Hour (kWH) = 1 units (on our meter).

10.4.1 Condition for Maximum power transfer:

The maximum power transfer theorem states that, maximum external power can be obtained from a source with a finite internal resistance, if the resistance of the load is equal to the

resistance of the source. This Theorem is another useful circuit analysis method; it ensures that the maximum amount of power will be dissipated in the load resistance when the value of the load resistance is exactly equal to the resistance of the power source.
Consider a circuit in which we have load resistance R_L (Variable 0-100 Ω), internal resistance R_S= 25 Ω and a voltage supply Vs. = 100V. We can find the value of the load resistance, R_L that will give the maximum power transfer in this circuit as shown in figure 10.6.
By using the Ohm's Law equations:

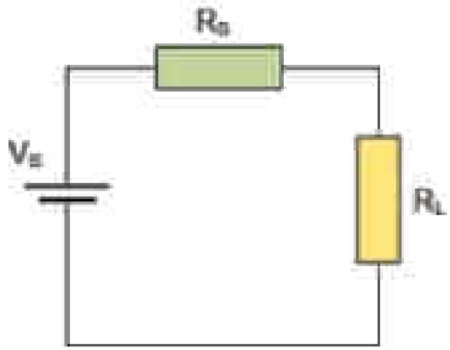


Fig:10.6 Maximum power

$$I = \frac{V_S}{R_S + R_L} \quad \text{and} \quad P = I^2 R_L \qquad ......(10.8)$$

In the table below we have determined the current and power in the circuit for different values of load resistance.

Table 10.4

R_L (Ω)	I (amps)	P (watts)
0	4.0	0
5	3.3	55
10	2.8	78
15	2.5	93
20	2.2	97
25	2.0	**100**
30	1.8	97
40	1.5	94
60	1.2	83
100	0.8	64

Using the above data, we can plot a graph of load resistance, R_L against power, P for different values of load resistance.
We can see that the **Maximum Power Transfer** occurs when $R_S = R_L = 25Ω$. It is called a "matched condition" and in this case maximum power is transferred. Also notice that power is zero for an open-circuit (zero current condition) and also for a short-circuit (zero voltage condition). The graph for the power against load resistance is shown below.

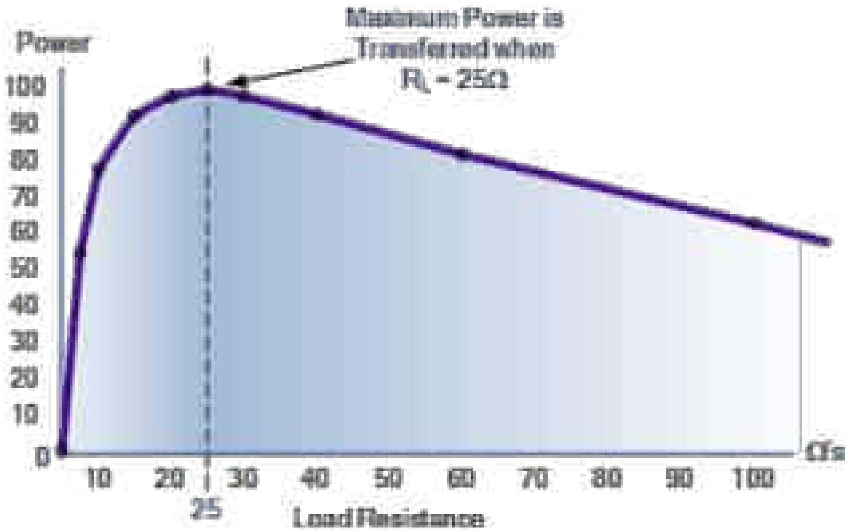


Fig:10.7 Maximum Power transfer

Self-Assessment Questions:

1. A given battery has a 12V emf and an internal resistance of 0.1Ω. Calculate its terminal voltage when connected to a10 Ω load. If the internal resistance grows to 0.5Ω, find the current and terminal voltage.
2. What causes the terminal voltage to be greater than the emf in Cars and in batteries for small electrical appliances and electronic devices while recharging them?
3. A battery that produces a potential difference V is connected to a 5-W light bulb. Later, the 5-W bulb is replaced with a 10-W light bulb. In which case does the battery supply the greatest current?

10.5 Thermoelectricity:

We know that there are various methods for the generation of electricity. It can be generated from wind, using windmills, from water, with the help of hydroelectric power plants, from sun, using solar panels. Similarly, electricity can also be generated from heat energy as well. So thermoelectricity is the electricity generated from heat energy. In thermoelectricity, the conversion of heat energy into electrical energy takes place with the help of a thermocouple.

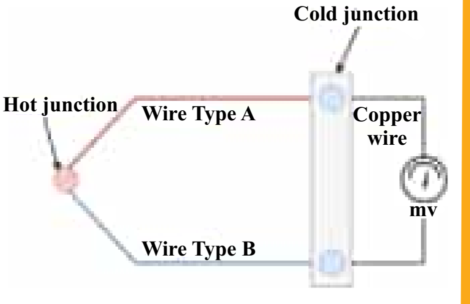


Fig:10.8 Thermocouple

10.5.1 Thermocouple and its function:

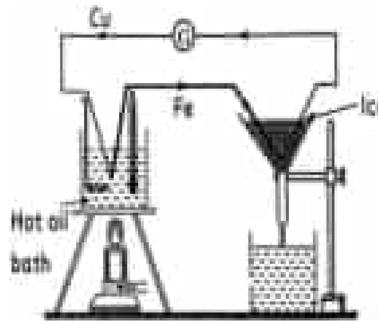
The thermocouple is basically a device for measuring temperature. Unlike a thermometer, which relies on the thermal characteristics of a material, a thermocouple is used to measure the temperature at one specific point in the form of EMF or an electric current. It comprises of two dissimilar metal wires that are connected together at one junction where temperature can be measured. The change in temperature of the metal wire stimulates the voltages. It is useful for signaling electronic systems that control household gas devices, such as water heaters and boilers.

10.5.2 Variation of thermoelectric e.m.f with temperature:

Variation of thermoelectric emf with temperature can be studied using an iron-copper thermocouple as shown in Fig.10.10. One junction is dipped in an oil bath and other junction is kept at melting ice (temperature kept constant). Now we observe that:

- The galvanometer shows no deflection when the temperature of both junctions are same (0°C), so thermal emf is also zero
- As the temperature of the hot junction is increased gradually, and the cold junction is remain at 0°C, thermo emf also increase till it becomes maximum. Temperature of the hot junction at which the thermo emf becomes maximum is called neutral temperature (T_n).

- If we increase the temperature of the hot junction beyond neutral temperature, thermo emf starts to decrease and becomes zero and changes its polarity at a temperature called inversion temperature (T_i)
- As the temperature is increased beyond T_i, the direction of thermal emf is reversed. The inversion temperature depends upon the temperature of cold junction and nature of metals used in the thermocouple.



The variation of thermal emf with temperature (T) is given by

$$E=\alpha T+1/2\beta T^2$$

Where, α and β are constant whose value depends upon material of conductor and the temperature difference of two junctions.

If Tc is the temperature of cold junction, then we can write,

$T_i - T_n = T_n - T_c$ or,

$2T_n = T_c + T_i$

Therefore,

$$T_n = \frac{T_c + T_i}{2} \quad ......(10.9)$$

So, the neutral temperature lies between the inversion temperature and temperature of cold junction.

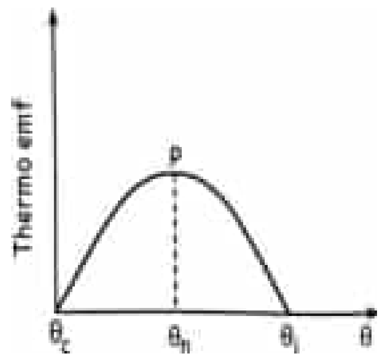


Fig:10.9
Variation of thermoelectric emf

10.5.3 The function of thermistor in fire alarms and thermostats that control temperature:

Fire Alarm:

A thermistor is a variable resistor whose resistance changes with temperature. Its temperature detection can be used in fire alarms for the detection of fires. Fire Alarm Circuit is a simple circuit that detects the fire and activates the Siren Sound or Buzzer.

In this fire alarm circuit, the resistance of the thermistor is approximately in kilo-ohms at normal temperature. During fire, the resistance reduces to a few ohms as the temperature increases which switches ON the *transistor. Once the transistor is turned ON, the current from Vcc starts to flow via buzzer which produces a beep sound. For unidirectional conduction a **Diode is used and the use of capacitor removes sudden transients from the thermistor.

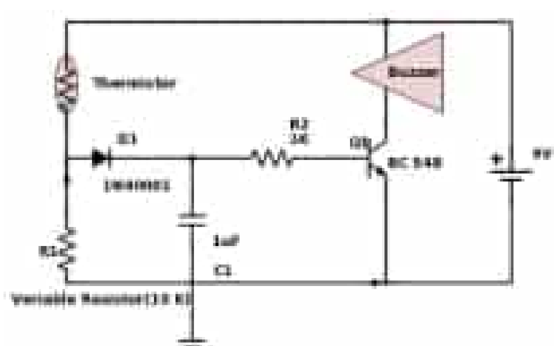


Fig: 10.10 Fire Alarm

Thermostats:

Thermostat is formed by two Greek words thermo and statos, thermos means heat and statos means stationary or fixed. Thermostat is used to control the devices or home appliances according to the temperature, like turn on/off air conditioner, room heaters etc.

The thermostat circuit compromises of a voltage divider circuit and output "ON and OFF" circuit.

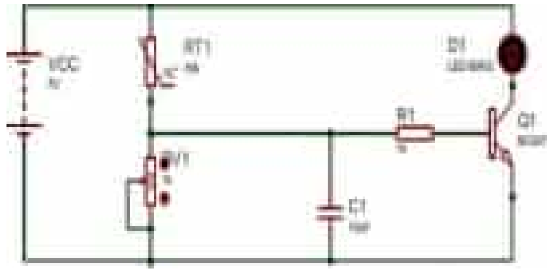
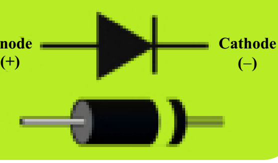


Fig: 10.11 Thermostat

Voltage divider circuit comprises of the thermistor and a variable resistor. Voltage divider circuit output is connected to the base of NPN transistor through a 1kΩ resistor. Voltage divider circuit makes it possible to sense the variation in voltage caused by variation in resistance of Thermistor. LED will be switched On, only if temperature crosses a particular value

DO YOU KNOW?

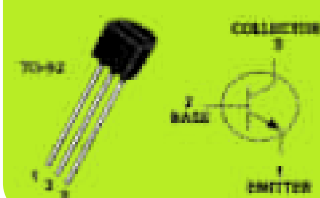
A diode is a two-terminal electronic component that conducts electricity primarily in one direction.



Self-Assessment Questions:
1. Do thermocouples tell you the temperature?
2. Why are two different metals required in a thermocouple?
3. What are the common causes of thermistor failure?

DO YOU KNOW?

A transistor is a miniature semiconductor that regulates or controls current or voltage flow in addition to amplifying and generating these electrical signals and acting as a switch/gate for them.



10.6.1 Kirchhoff's Laws:

Kirchhoff's laws were stated by German Physicist Gustav Robert Kirchhoff (1824–1887) in 1847. In Physics, Kirchhoff's laws quantify the way in which current flows through a circuit and the voltage varies around a loop in a circuit. These laws help in simplifying the circuits having multiple resistance networks which are usually very time taking to solve through the combination of resistors in series and parallel. Kirchhoff's laws can be applied to solve all types of circuits because they are not limited to specific configurations involving series and parallel connections

10.6.1 Kirchhoff's first law: (Current Law):

You should remember the idea that current may be divided where a circuit splits into two separate branches. The total amount of current remains same after it splits. We would not expect some of the current to disappear, or extra current to appear from nowhere. This is the basis of **Kirchhoff's first law**, also known as Kirchhoff's junction rule, which states that **"the current that flows into a junction-any electrical**

connection-must equal the current that flows out of the same junction". The law can be restated as "the algebraic sum of currents in a network of conductors meeting at a point is zero. The Kirchhoff's Current law is a consequence of the law of conservation of charge. Since charge does not continually build up at a junction, the net rate of flow of charge into the junction must be zero.

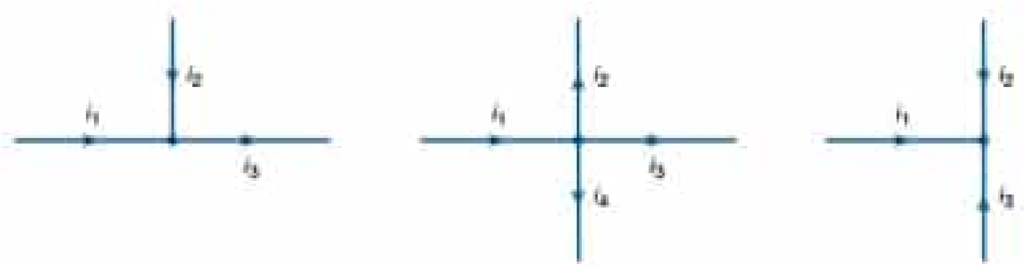
We can write Kirchhoff's first law as an equation:

$$\Sigma I_{in} = \Sigma I_{out} \quad \ldots\ldots(10.10)$$

When applying the current law, let current flowing into a junction be positive and current flowing out the junction be negative; then we can say that the net current flowing into a junction is zero.

$$\Sigma I = 0 \qquad \ldots\ldots(10.11)$$

We can also explain Current law diagrammatically as shown in the figures below.



(a) (b) (c)

Fig:10.12 Kirchhoffs current law

- In figure A, $\mathbf{i_1 + i_2 = i_3}$ or $\mathbf{i_1 + i_2 - i_3 = 0}$
- In figure B, $\mathbf{i_1 = i_2 + i_3 + i_4}$ or $\mathbf{i_1 - i_2 - i_3 - i_4 = 0}$
- In figure C, $\mathbf{i_1 + i_2 + i_3 = 0}$

10.6.2 Kirchhoff's second law:

Recall your understanding that the electric potential at any point should have a unique value, it cannot depend on the path one takes to arrive at that point therefore, if a closed path is followed in a circuit i.e. starting and ending at the same point, the algebraic sum of the potential changes must be zero. Think of taking a hike in the mountains, starting and returning at the same spot. No matter what path you take, the algebraic sum of all your elevation changes must equal zero.

The second law, known as Kirchhoff's loop rule or Kirchhoff's voltage law, states that the sum of electromotive forces in a loop equals the sum of potential drops in the loop.

Equation for Kirchhoff's second law:

The Kirchhoff's second law equation can be written as:

$$\Sigma E = \Sigma V \quad \ldots\ldots(10.12)$$

Where ΣE is the sum of the e.m.f.s and ΣV is the sum of the potential differences. We can also write as:

$$\Sigma \Delta V = 0 \qquad \ldots..(10.13)$$

Kirchhoff's second law is based on the principle of conservation of energy. When a charge, moves around the circuit, it **gains** energy as it passes through each source of e.m.f. and **loses** energy as it moves through each Potential difference (p.d). During its motion around a closed loop, or circuit charge will end up back to where it started in the circuit and therefore back to the same initial potential with no loss of voltage around the loop. it must have the same energy at the end as at the beginning. So: **energy gained passing through sources of e.m.f. = energy lost passing through components with p.d.s** For any path in a circuit with same start and end points. (Potential rises are positive: potential drops are negative.). This is well illustrated in the Fig.10.13.

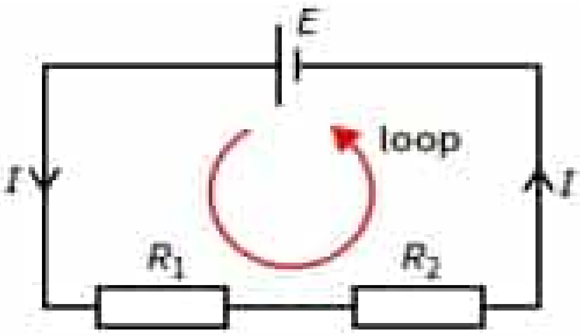


Fig:10.13
Kirchhoff's 2nd law

Consider a simple series circuit which contains a cell and two resistors of resistances R_1 and R_2, the current I must be the same all the way around, and we need not concern ourselves further with Kirchhoff's first law. For this circuit, we can write the following equation:

$$E = IR_1 + IR_2$$

e.m.f. of battery = sum of p.d.s across the resistors

Directions and Signs:

when the direction of motion is from negative terminal to the positive terminal, the e.m.f of battery is taken as positive. If we move in the opposite direction to the current, then the potential differences of the resistances are taken as positive. It is shown in Fig.10.14.

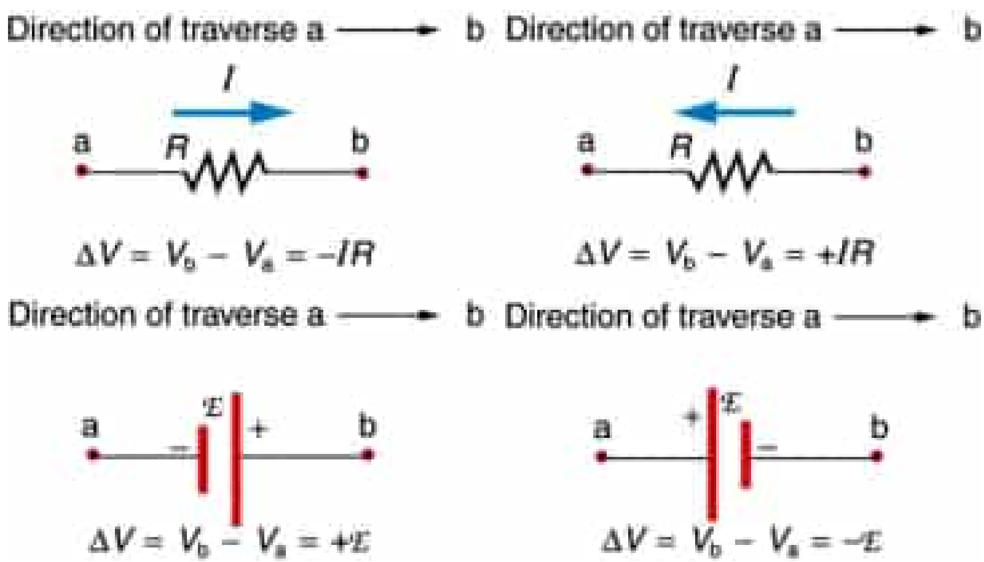


Fig: 10.14 Directions of e.m.f and p.d

10.6.3 Kirchhoff's laws for series and parallel resistors combinations:

You are already familiar with the formulae used to calculate the combined resistance R of two or more resistors connected in series or in parallel. To derive these formulae, we have to make use of Kirchhoff's laws.

Resistors in series:

Take two resistors of resistances R_1 and R_2 connected in series (Figure 10.15). According to Kirchhoff's first law, the current in each resistor is the same. The p.d. V across the combination is equal to the sum of the p.d.s across the two resistors:

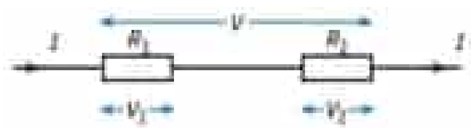


Fig: 10.15 Ressistors in series

$V = V_1 + V_2$

Since $V = IR$, $V_1 = IR_1$ and $V_2 = IR_2$, we can write:

$IR = IR_1 + IR_2$

Cancelling the common factor of current I gives:

$R = R_1 + R_2$

For three or more resistors, the equation for total resistance R becomes:

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

Resistors in parallel:

For two resistors of resistances R_1 and R_2 connected in parallel (Figure 10.16), we have a situation where the current divides between them. Hence, using Kirchhoff's first law, we can write:

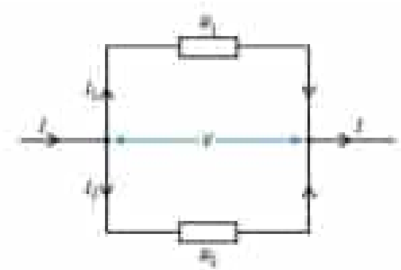


Fig: 10.16
Ressistors in parallel

$I = I_1 + I_2$

If we apply Kirchhoff's second law to the loop that contains the two resistors, we have:

$I_1R_1 - I_2R_2 = 0$ V

(Because there is no source of e.m.f. in the loop).

This equation states that the two resistors have the same p.d. V across them. Hence we can write:

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

$I_1 = V/R_1$

$I_2 = V/R_2$

Since, $I = I_1 + I_2$

Therefore, $V/R = V/R_1 + V/R_2$

Cancelling common factor V from both sides

$1/R = 1/R_1 + 1/R_2$

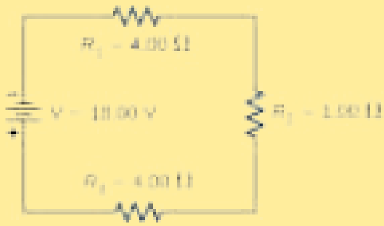
For more resistors the equation for total resistance will be

$1/R = 1/R_1 + 1/R_2 + 1/R_3 + 1/R_4 + \ldots\ldots$

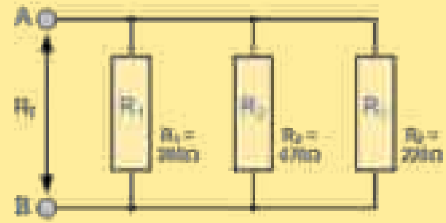
Worked example 3

Determine the equivalent resistance for each of the two circuits shown below:

(a)



(b)



Solution:

In Circuit (a) the three resistors R_1, R_2 and R_3 are connected in series.

We know that equivalent resistance of series resistors is given as,

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

$\therefore R_{eq} = 4 + 1 + 4 = 9\ \Omega$

In Circuit (b) the three resistors R_1, R_2 and R_3 are connected in parallel.

We know that equivalent resistance of parallel resistors is given as,

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

$$= \frac{1}{200} + \frac{1}{470} + \frac{1}{220} = 0.0117$$

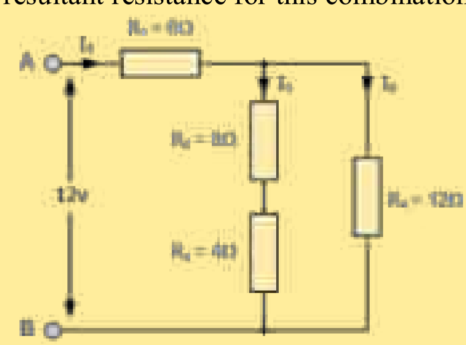
$$\text{therefore } R_T = \frac{1}{0.0117} = 85.67\Omega$$

Worked example 4:

Find the equivalent resistance of the given circuit

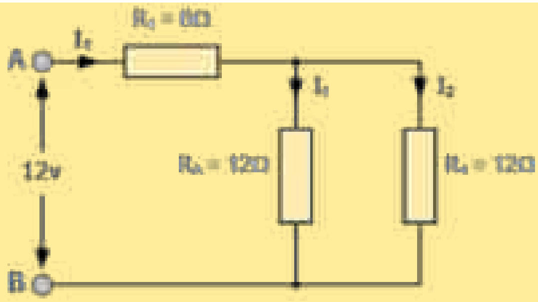
Solution:

We can see that the two resistors, R_2 and R_3 are actually both connected together in a "SERIES" combination. The resultant resistance for this combination would therefore be:



$R_2 + R_3 = 8\Omega + 4\Omega = 12\Omega$

So we can replace both resistor R_2 and R_3 above with a single resistor R_A of resistance value 12Ω

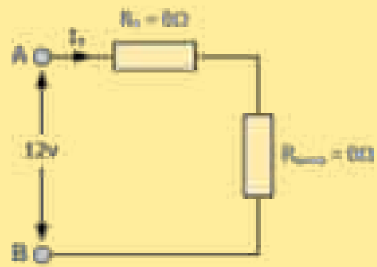


Now our circuit has a single resistor R_A in "PARALLEL" with the resistor R_4. Using the formula for two parallel connected resistors we can find out its equivalent single resistor.

$$R_{(eq)} = \frac{1}{R_A} + \frac{1}{R_4} = \frac{1}{12} + \frac{1}{12} = 0.1667$$

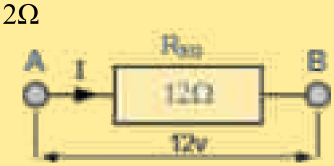
$$R_{(combination)} = \frac{1}{R_{(eq)}} = \frac{1}{0.1667} = 6\Omega$$

The resultant circuit would be:



The two remaining resistances, R_1 and $R_{(comb)}$ are connected together in a "SERIES" combination so resultant will be:

$R_{(ab)} = R_{comb} + R_1 = 6\Omega + 6\Omega = 12\Omega$



Thus equivalent resistance is of 12Ω. It means the original four resistors connected together in the original circuit above can be replaced by a 12Ω resistor.

Self-Assessment Questions:

1. Can we apply Kirchhoff's laws in the presence of magnetic field?
2. Is it true that Kirchhoff's first law supports law of conservation of charge?
3. Can Kirchhoff's rules be applied to simple series and parallel circuits or are they restricted for use in more complicated circuits that are not combinations of series and parallel?

10.7 Balanced Potential:

Although in today's world digital instruments are providing very accurate measurements but they are costly. However, simple instruments like Wheatstone Bridge and Potentiometer are still providing precise measurements using Balanced potential condition, where no current flows.

10.7.1 Wheatstone Bridge and its uses:

The **Wheatstone Bridge** also known as the resistance bridge is a diamond shaped circuit which was invented by Samuel Hunter Christie in 1833 and Sir Charles Wheatstone later popularized it in 1843. Wheatstone bridge is a setup with four arms (resistors) and the ratio of two of them is kept at a fixed value. The two other arms are balanced, one of which is the unknown resistor whereas the resistance of the other arm can be varied. **A balanced bridge is a Wheatstone bridge circuit with zero output voltage.** When no current passes through a galvanometer, the bridge circuit is said to be balanced. The balancing or null condition is used to compute unknown resistance. The Wheatstone bridge circuit gives a very accurate measurement of resistance. Meter bridge, Carey Foster bridge, Wien bridge and many other instruments are based on the Wheatstone bridge principle.

Principle of Wheatstone Bridge:

The Wheatstone bridge works on the principle of null deflection. In normal conditions, current flows through the galvanometer and the bridge is said to be in an unbalanced condition. Adjusting the known resistance and variable resistance a condition is achieved when no current flows through the galvanometer i.e. a balanced condition.

Working of Wheatstone Bridge:

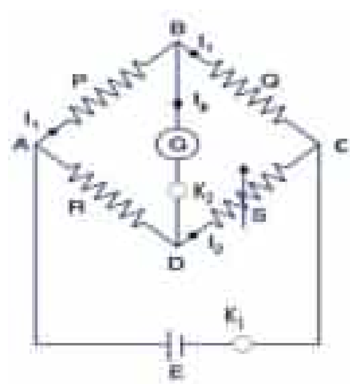


Fig: 10.17
Wheatstone Bridge

Wheatstone Bridge Principle states that if four resistance P, Q, R and S are arranged to form a bridge as shown in figure 10.17 with a cell E and one key K1 between the point A and C and galvanometer G and tapping key K_2 between the points B and D, closing K_1 first and K_2 later on, if the galvanometer shows no deflection then bridge is balanced.
Current distribution in the circuit is shown in the figure. Total current by cell is I, it distributed to P and R as I_1 and $I-I_1$. Th current through galvanometer is I_g.
Current in Q is I_1-I_g and through S current is $I-I_1+I_g$. Resistance of galvanometer is G.
If we apply Kirchhoff's 2nd law in ABDA, we get

$$I_1P + I_g G - (I-I_1) R = 0 \qquad \text{.......(i)}$$

Now apply Kirchhoff's 2nd law in BCDB, we get

$$(I_1 - I_g) Q - (I-I_1+I_g) S - I_g G = 0 \qquad \text{.......(ii)}$$

If value of R is such that the galvanometer shows no deflection that is $I_g = 0$. Putting this value in equation (i) and (ii) we get

$$\frac{P}{Q} = \frac{R}{S} \quad \text{……(iii)}$$

Equation (iii) relating the four resistors is called the **balance condition for the galvanometer** to give zero or null deflection.
A practical device using this principle is called the **meter bridge**.

10.7.2 Working of rheostat as a potential divider:

A rheostat is a variable resistor, used for controlling the flow of electric current by increasing or decreasing the resistance. The term rheostat is derived from the Greek word "rheos" and "statis" which means current controlling device.
A potential divider is used for getting a variable potential from a fixed potential difference. A potential difference V is provided with the help of a battery across the ends of a variable resistor. If R is the resistance of the wire, the current flowing in the resistor is
$I = V/R$.
Let R_{BC} be the resistance of the portion BC of the wire. The current passing through this portion is also I. The PD between the points B and C is given by $V_{BC} = I\,R_{BC}$

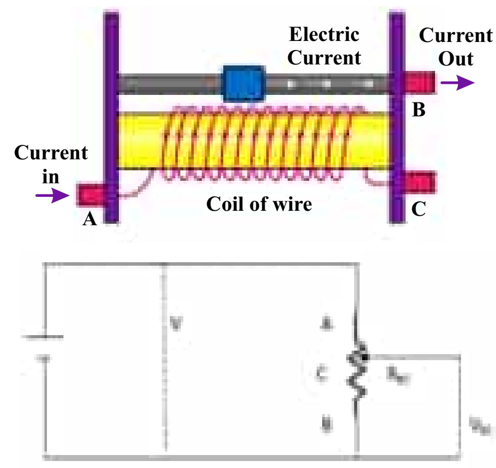


Fig: 10.18
Rheostat as a potential divider

R_{BC} increases as we go away from A and decreases as C comes close to A. This changes the ratio R_{BC} to R and hence a variable voltage can be obtained. If V is regarded as input PD to the potential divider and V_{BC} as the output PD, then V_{BC} can be tapped off and applied to another circuit.

10.7.3 Potentiometer:

A Potentiometer is a three terminal device, consists of a resistance **R** in the form of a wire on which a terminal **C** can slide as shown in Fig. 10.19. It is used to compare the e.m.f. of two cells, to measure the internal resistance of a cell, and for accurate measurement of potential difference across a resistor. In many applications it is also used as a variable resistor. It consists of a long wire of uniform cross-sectional area.

Fig:10.19 Potentiometer

Principle of Potentiometer:

It works on the principle based on the fact that the potential difference across any two points of a wire is directly proportional to the length of the wire, which has a uniform cross-sectional area and the constant current flowing through it.

10.7.3 Describe the function of Potentiometer to measure and compare potentials without drawing any current from the circuit:

Consider a potentiometer of length AB. There are two cells of e.m.fs $\mathcal{E}_1$ and $\mathcal{E}_2$. Now the positive ends of the cells are connected to point 'A' and the negative ends of the cells are connected to the jockey through galvanometer (G). When the key is closed and the jockey is moved along wire AB to find the null point (P) where there is no deflection in the galvanometer (G). Let P_1 be the null point when cell $\mathcal{E}_1$ is connected and corresponding length between the end A of the wire to the null point P_1 be 'l_1'. The potential difference across this length balances emf $\mathcal{E}_1$.

$\mathcal{E}_1 = Kl_1$………. (i)

Where, K is the potential gradient of the wire.

Then disconnect the cell of e.m.f $\mathcal{E}_1$ and connect the cell of e.m.f $\mathcal{E}_2$ in the circuit. Let P_2 be the null point and let 'l_2' be the length between the end A of the wire to the null point P_2. Then we have $\mathcal{E}_2 = Kl_2$ …….. . (ii)

By dividing equation (i) by equation (ii), we get

$\boldsymbol{\mathcal{E}_1 / \mathcal{E}_2 = l_1/l_2}$

As we measure the value of l_1, l_2 we can compare the emf of two cells.

Note: The wire should be uniform, and its resistance must be higher. It is also kept in mind that the emf of the battery connected across the wire should be greater than the emf to be compared.

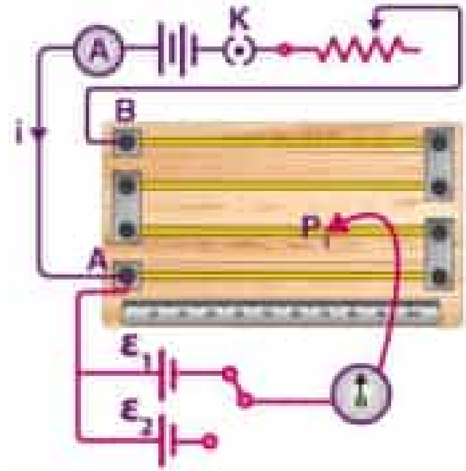


Fig: 10.20(a)
Function of Potentiometer

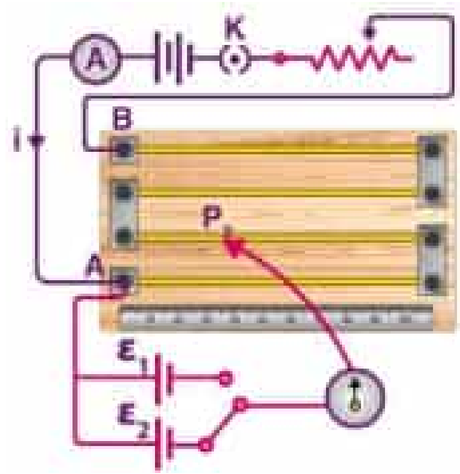


Fig: 10.20(b)
Function of Potentiometer

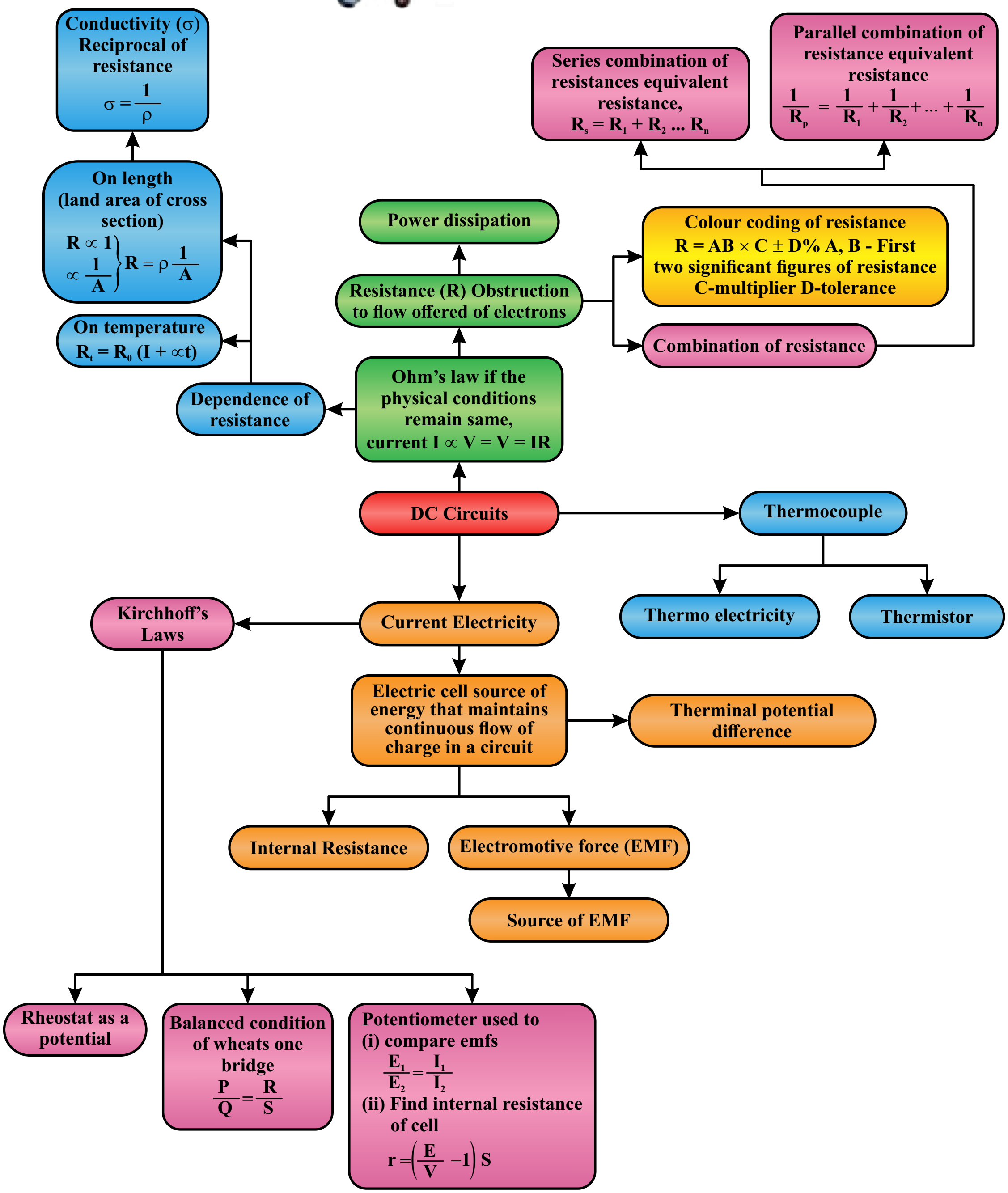
Self-Assessment Questions:

1. In a potentiometer of 5 wires, the balance point is obtained on the 2^{nd} wire. To shift the balance point to the 4^{th} wire, what should be done?
2. When is Wheatstone bridge most sensitive?
3. When rheostat works as a potential divider, which resistance is taken?

SUMMARY

- In an electronic circuit, resistors are the electrical components that regulate the flow of electrical current. These resistors vary in their construction, power dissipation capacities, and tolerance to various parameters.
- There are many standards exist for resistors to measure and quantify important properties. Probably, the most common and well-known standard available is the color code marking for carbon resistors.
- Resistivity is the electrical resistance of a conductor of unit cross-sectional area and unit length. Resistivity is a characteristic property of each material and useful in comparing various materials on the basis of their ability to conduct electric currents.
- Conductance is the measure of how easily flow of charges (electrical current) can pass through a material. Mathematically, conductance is the reciprocal, or inverse, of resistance.
- The internal resistance of a battery/cell is the resistance of its electrodes which opposes the flow of current offered by battery and cell itself. The electro-motive force can be expressed as a voltage, and is defined as the total amount of energy (in joules) per unit charge (in coulombs) supplied to the circuit.
- The maximum power transfer theorem states that, maximum external power can be obtained from a source with a finite internal resistance, if the resistance of the load is equal to the resistance of the source.
- Thermoelectricity is the electricity generated from heat energy.
- Variation of thermoelectric emf with temperature can be studied using an iron-copper thermocouple. One junction is dipped in an oil bath and other junction is kept at melting ice (temperature kept constant).
- A thermistor is a variable resistor whose resistance changes with temperature. Its temperature detection can be used in fire alarms for the detection of fires and in thermostat for temperature control of home appliances.
- Kirchhoff's first law (current Law) states that "the current that flows into a junction-any electrical connection-must equal the current that flows out of the same junction". $\Sigma I_{in} = \Sigma I_{out}$
- The Kirchhoff's second law (voltage law) states that "the sum of electromotive forces in a loop equals the sum of potential drops in the loop i.e $\Sigma E = \Sigma V$".
  Kirchhoff's laws can be used to find equivalent resistance of resistors. For three or more resistors in series or parallel.
- The Wheatstone bridge circuit gives a very precise measurement of resistance. The Wheatstone bridge works on the principle of null deflection.
- A Potentiometer is a three terminal device used to compare the e.m.f. of two cells, to measure the internal resistance of a cell, and for accurate measurement of potential difference across a resistor.

CONCEPT MAP


Conductivity (σ) Reciprocal of resistance $\sigma = \frac{1}{\rho}$
On length (land area of cross section) $R \propto l$, $\propto \frac{1}{A}$ } $R = \rho \frac{l}{A}$
On temperature $R_t = R_0 (I + \propto t)$
Dependence of resistance
Power dissipation
Resistance (R) Obstruction to flow offered of electrons
Ohm's law if the physical conditions remain same, current $I \propto V = V = IR$
Series combination of resistances equivalent resistance, $R_s = R_1 + R_2 ... R_n$
Parallel combination of resistance equivalent resistance $\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}$
Colour coding of resistance $R = AB \times C \pm D\%$ A, B - First two significant figures of resistance C-multiplier D-tolerance
Combination of resistance
DC Circuits
Thermocouple
Thermo electricity
Thermistor
Kirchhoff's Laws
Current Electricity
Electric cell source of energy that maintains continuous flow of charge in a circuit
Therminal potential difference
Internal Resistance
Electromotive force (EMF)
Source of EMF
Rheostat as a potential
Balanced condition of wheats one bridge $\frac{P}{Q} = \frac{R}{S}$
Potentiometer used to
(i) compare emfs $\frac{E_1}{E_2} = \frac{l_1}{l_2}$
(ii) Find internal resistance of cell
$r = \left(\frac{E}{V} - 1\right) S$

EXERCISE

Section (A): Multiple Choice Questions (MCQs)

1. Kirchhoff's laws are useful in determining:
   a) current flowing in a circuit b) emf and voltage drops in a circuit
   c) power in a circuit d) only emf in a circuit
2. The resistance of a superconductor is:
   a) finite b) infinite
   c) changes with every conductor d) zero
3. Reciprocal of resistance is called:
   a) conductance b) resistivity c) resonance d) capacitance
4. The graphical representation of Ohms law is:
   a) parabola b) hyperbola c) ellipse d) straight line
5. A potential difference is applied across the ends of a wire. If the potential difference is doubled, then the drift velocity of free electrons will:
   a) be quadrupled b) be doubled c) be halved d) remain unchanged
6. Internal resistance is the resistance offered by:
   a) Capacitor b) resistor c) Conductor d) source of emf
7. Power dissipation in a resistor can be calculated using which formula:
   a) $P = V^2 / R$ b) $P = I^2 \times R$ c) $P = V \times I$ d) $P = R / (V \times I)$
8. What is a potentiometer primarily used for?
   a) Measuring electric current
   b) Measuring electric charge
   c) Measuring potential difference (voltage)
   d) Measuring electric resistance
9. A heat-sensitive device whose resistivity changes with the change in temperature is called:
   a) conductor b) resistor c) thermistor d) thermometer
10. A wire of uniform area of cross-section A length L and resistance R is cut into two parts. The resistivity of each part:
    a) Becomes zero b) is halved c) Is doubled d) remains same

CRQs:

1. Why is the terminal voltage of a cell less than its emf?
2. Why is a potentiometer preferred over a voltmeter for determining the emf of a cell?
3. Nichrome and copper wires of same length and same radius are connected in series. Current I is passed through them. Which wire gets heated up more? Justify your answer.
4. Explain why the terminal potential of a battery decreases when the current drawn from it in increased?
5. What are thermistors? Write their importance.
6. State Kirchhoff's Laws.
7. If Copper and Aluminum wires of the same length have same resistance, which has the larger diameter? And why?

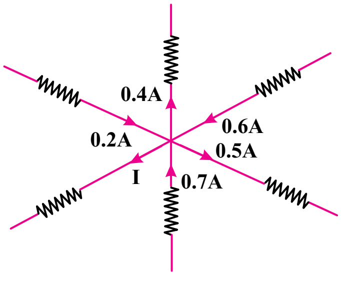
8. What is the difference between potential difference and emf?

ERQs:

1. State the principle of working of a meter bridge. Explain how it is used to find an unknown resistance.
2. Define thermoelectricity. Explain the working of a Fire Alarm system using thermistor.
3. Define resistivity. Explain dependence of resistivity on temperature.
4. What is a rheostat? How can we use a rheostat as a potential divider?
5. State the underlying principle of a potentiometer. Describe briefly, giving the necessary circuit diagram, how a potentiometer is used to measure the internal resistance of a given cell?

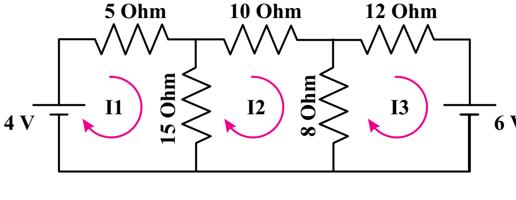
Numericals:

1. The storage battery of a car has an emf of 12 V. If the internal resistance of the battery is 0.5Ω, what is the maximum current that can be drawn from the battery? **(Ans:24A)**
2. A negligibly small current is passed through a wire of length 12m and uniform cross-section 4.0×10^{-7} m^2, and its resistance is measured to be 6.0 Ω. What is the resistivity of the material at the temperature of the experiment? **(Ans: 2×10^{-7} Ω m)**
3. In a potentiometer arrangement, a cell of emf 1.20 V gives a balance point at 40.0 cm length of the wire. If the cell is replaced by another cell and the balance point shifts to 74.0 cm, what is the emf of the second cell? **(Ans: 2.22 V)**
4. **(a)** Three resistors 1 Ω, 2 Ω, and 3 Ω are combined in series. What is the total resistance of the combination? **(Ans: 6 Ω)**
   (b) If the combination is connected to a battery of emf 24 V and negligible internal resistance, obtain the potential drop across each resistor.
   (Ans:V_1 = 4V, V_2 = 8V, V_3 = 12V)
5. From the given circuit find the value of I.



(Ans: I= 0.6A)

6. In a meter bridge with a standard resistance of 15 Ω in the right gap, the ratio of balancing length is 5:3. Find the value of the other resistance. **(Ans: P = 25 Ω)**
7. By using KVL find Current flowing through 10 Ω resistance.



Ans:$I_{10\Omega}$ =0.0341A(*clockwise*)