

UNIVERSITY OF AGRICULTURE, ABEOKUTA, NIGERIA.

DEPARTMENT OF PHYSICS

PHS 102: GENERAL PHYSICS II (3 UNITS)

PART 1

BY

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Course Content

Electric charges, fields, potential, Coulomb's law, Direct current and measuring instruments; the potentiometer method. Chemical, thermal and magnetic effects of current.

Suggested references:

1. University Physics W. Sears
2. Fundamentals of Physics by J. Walker
3. Advance level Physics by Nelkon and Parker
4. College Physics by Frederick, J Beuche and Eugene Hecht
5. UNIVERSITY PHYSICS by Young and Freedman, Pearson
International Edition (12th edition)

1.0 ELECTRIC CHARGE, CONDUCTORS AND INSULATIONS

The fundamental quantity in electrostatics is electric charge. There are two kinds of charge, positive and negative. Charges of the same sign repel each other; charges of opposite sign attract. Charge is conserved; the total charge in an isolated system is constant.

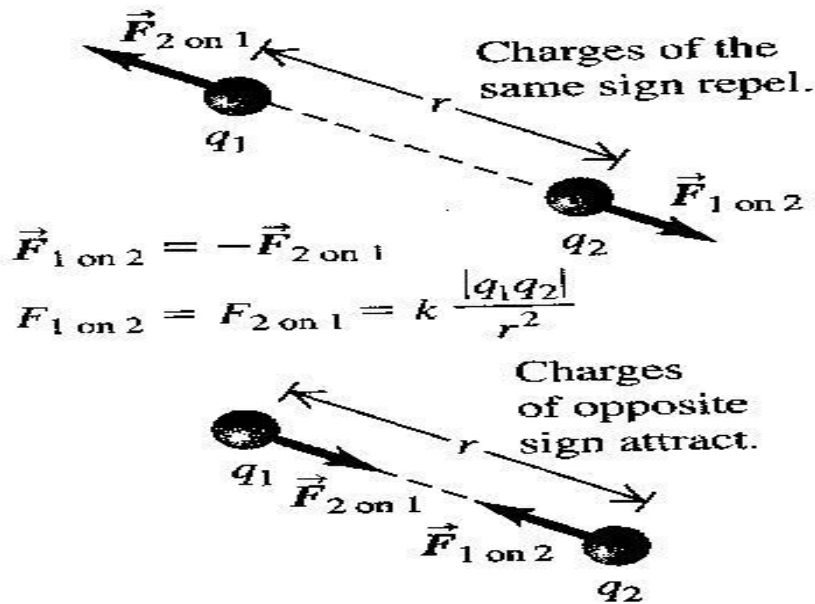
All ordinary matter is made of protons, neutrons and electrons. The positive protons and electrically neutral neutrons of an atom are bound together by the nuclear force; the negative electrons surround the nucleus at distances much greater than the nuclear size. Electric interactions are chiefly responsible for the structure of atoms, molecules and solids.

Conductors are materials that permit electric charge to move easily within them. Insulators permit charge to move much less readily. Most metals are good conductors; most nonmetals are insulators.

1.1 Coulomb's Law

Coulomb's Law is the basic law of interaction for point electric charges. For charges q_1 and q_2 separated by a distance r , the magnitude of the force on either charge is proportional to the product $q_1 q_2$ and inversely proportional to r^2

$$F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \text{ where } \frac{1}{4\pi\epsilon_0} = 8.988 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2 \quad 1$$



The force on each charge is along the line joining the two charges - repulsive if q_1 and q_2 have the same sign, attractive if they have opposite signs. The forces form an action-

reaction pair and obey Newton's third law. In S.I Units, the unit of electric charge is the coulomb, abbreviated C.

Example 1.1:

An α particle is the nucleus of a helium atom. It has mass $m = 6.64 \times 10^{-27} \text{ kg}$ and charge $q = 2e = 3.2 \times 10^{-19} \text{ C}$. Compare the force of the electric repulsion between two α particles with the force of gravitational attraction between them.

Solution:

$$F_e = \frac{1}{4\pi\epsilon_0} \frac{q^2}{r^2}, \quad F_g = G \frac{m^2}{r^2}$$

Therefore, the ratio of the electric force to the gravitational force is

$$\begin{aligned} \frac{F_e}{F_g} &= \frac{1}{4\pi\epsilon_0 G} \frac{q^2}{m^2} = \frac{9.0 \times 10^9 \text{ N} \cdot \text{m}^2 / \text{C}^2}{6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2 / \text{kg}^2} \frac{(3.2 \times 10^{-19} \text{ C})^2}{(6.64 \times 10^{-27} \text{ kg})^2} \\ &= 3.2 \times 10^{-35} \end{aligned}$$

This astonishingly large number shows that the gravitational force in this situation is completely negligible in comparison to the electric force.

Example 1.2:

Two point charges, $q_1 = +25 \text{ nC}$ and $q_2 = -75 \text{ nC}$, are separated by a distance of 3.0 cm. Find the magnitude of (a) the electric force that q_1 exerts on q_2 ; and (b) the electric force that q_2 exerts on q_1 .

Solution:

$$\begin{aligned} F &= \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \\ &= 9.0 \times 10^9 \text{ N} \cdot \text{m}^2 / \text{C}^2 \frac{(+25 \times 10^{-9} \text{ C})(-75 \times 10^{-9} \text{ C})}{(0.03 \text{ m})^2} \end{aligned}$$

$$F = 0.019 \text{ N}$$

(b) Newton's third Law applies to the electric force. Even though the charges have different magnitude, the magnitude of the force that q_2 exerts on q_1 is the same as the magnitude of the force that q_2 exerts on q_1 : $F_{2 \text{ on } 1} = 0.019 \text{ N}$.

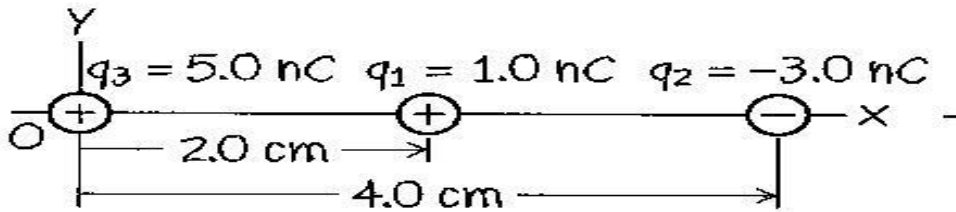
1.2 Superposition of Forces

The principle of superposition of forces states that when two or more charges each exert a force on a charge, the total force on that charge is the vector sum of the exerts by the individual charges.

Example 1. 3:

Two point charges are located on the positive x-axis of a coordinate system. Charges $q_1 = 1.0\text{nC}$ is 2.0cm from the origin, and charge $q_2 = -3.0\text{nC}$ is 4.0 cm from the origin. What is the total force exerted by these two charges on a charge $q_3 = 5.0\text{nC}$ located at the origin? Gravitational forces are negligible.

Solution:



We first find the magnitude $F_{1 \text{ on } 3}$ of the force of q_1 or q_3 :

$$F_{1 \text{ on } 3} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} = 9.0 \times 10^9 \text{N} \cdot \text{m}^2 / \text{C}^2 \frac{(1.0 \times 10^{-9} \text{C})(5.0 \times 10^{-9} \text{C})}{(0.02 \text{m})^2}$$

$$F_{1 \text{ on } 3} = 1.12 \times 10^{-4} \text{N} = 112 \mu\text{N}$$

This force has a negative x-component because q_3 is repelled (that is, pushed in the negative x- direction) by q_1 .

The magnitude $F_{2 \text{ on } 3}$ of the force of q_2 on q_3 is

$$F_{2 \text{ on } 3} = \frac{1}{4\pi\epsilon_0} \frac{q_2 q_3}{r^2} = 9.0 \times 10^9 \text{N} \cdot \text{m}^2 / \text{C}^2 \frac{(3.0 \times 10^{-9} \text{C})(5.0 \times 10^{-9} \text{C})}{(0.04 \text{m})^2}$$

$$F_{2 \text{ on } 3} = 8.4 \times 10^{-5} \text{N} = 84 \mu\text{N}$$

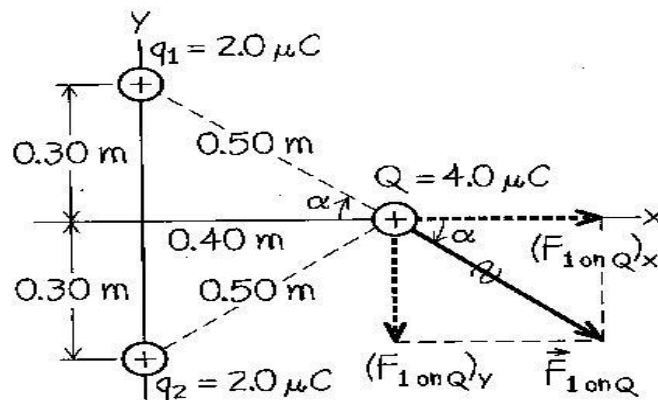
This force has a positive x-component because q_3 is attracted (that is, pulled in the positive x-direction) by q_2 . The sum of the x-components is

$$F_x = -112 \mu\text{N} + 84 \mu\text{N} = -28 \mu\text{N}$$

There are no y- or z-components. Thus the total force on q_3 is directed to the left, with magnitude $28 \mu\text{N} = 2.8 \times 10^{-5} \text{N}$.

Example 1.4:

Two equal positive point charges $q_1 = q_2 = 2.0\mu\text{C}$ are located at $x = 0, y = 0.30\text{m}$ and $x = 0, y = -0.30\text{m}$, respectively. What are the magnitude and direction of the total (net) electric force that these charges exerts on a third point charge $Q = 4.0\mu\text{C}$ at $x = 0.40\text{m}, y = 0$?



The magnitude of force q_1 on Q is

$$F_{1\text{ on } Q} = \frac{1}{4\pi\epsilon_0} \frac{q_1 Q}{r^2}$$

$$= 9.0 \times 10^9 \text{ N} \cdot \text{m}^2 / \text{C}^2 \frac{(4.0 \times 10^{-6} \text{ C})(2.0 \times 10^{-6} \text{ C})}{(0.5\text{m})^2}$$

$$= 0.29\text{N}$$

The angle α is below the x-axis, so the components of this force are given by :

$$(F_{1\text{ on } Q})_x = (F_{1\text{ on } Q}) \cos\alpha = (0.29\text{N}) \frac{0.4\text{m}}{0.5\text{m}} = 0.23\text{N}$$

$$(F_{1\text{ on } Q})_y = -(F_{1\text{ on } Q}) \sin\alpha = -(0.29\text{N}) \frac{0.3\text{m}}{0.5\text{m}} = -0.17\text{N}$$

The lower charges q_2 exerts a force with the same magnitude but at an angle α above the x-axis. From symmetry we see that its x-component is the same as that due to the upper charge, but its y-component has the opposite sign. So the components of the total force \vec{F} on Q are:

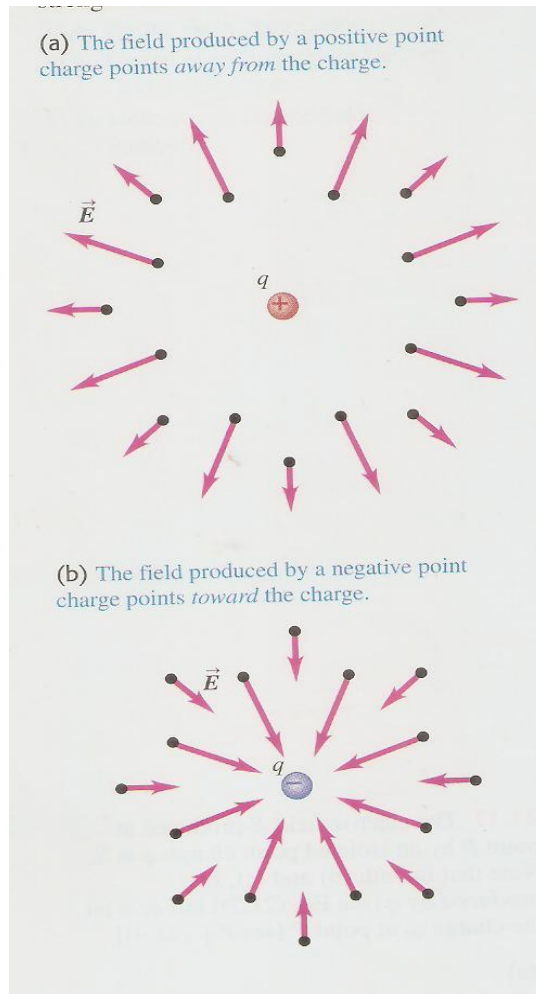
$$F_x = 0.23\text{N} + 0.23\text{N} = 0.46\text{N}$$

$$F_y = -0.17\text{N} + 0.17\text{N} = 0$$

The total force on Q is the + x-direction, with magnitude 0.46N .

1.3 Electric Field:

Electric Field \vec{E} , a vector quantity, is the force per unit charge exerts on a test charge at any point, provided the test charge is small enough that it does not disturb the charges that cause the fields. The electric field produced by a point charge is directed radially away from or toward the charge.



$$\vec{E} = \frac{\vec{F}_0}{q_0} = \frac{1}{4\pi\epsilon_0} \frac{q}{r^2} \hat{r}$$

Example 1.5:

What is the magnitude of the electric field at a field point 2.0m from a point charge $q = 4.0\text{nC}$?

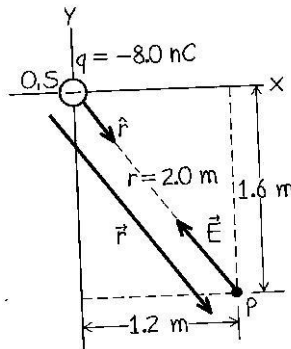
Solution:

$$E = \frac{1}{4\pi\epsilon_0} \frac{|q|}{r^2} = 9.0 \times 10^9 \text{N} \cdot \text{m}^2 / \text{C}^2 \frac{4.0 \times 10^{-9} \text{C}}{(2.0 \text{m})^2}$$

$$E = 9.0 \text{N/C}$$

Example 1.6:

A point charge $q = -8.0 \text{nC}$ is located at the origin. Find the electric – field vector at the field vector at the field point $x = 1.2 \text{m}$, $y = -1.6 \text{m}$.



The distance from the charge at the source point S (which in this example is at the origin 0) to the field point P is : $r = \sqrt{x^2 + y^2} = \sqrt{(1.2 \text{m})^2 + (-1.6 \text{m})^2} = 2.0 \text{m}$

The unit vector \hat{r} is directed from the source point to the field point. This is equal to the displacement vector \vec{r} from the source point to field point, divided by its magnitude r ;

$$\hat{r} = \frac{\vec{r}}{r} = \frac{(1.2 \text{m})_i + (-1.6 \text{m})_j}{2.0 \text{m}} = 0.60_i - 0.80_j$$

Hence the electric – field – field vector is

$$\begin{aligned} \vec{E} &= \frac{1}{4\pi\epsilon_0} \frac{q}{r^2} \hat{r} \\ &= (9.0 \times 10^9 \text{N} \cdot \frac{\text{m}^2}{\text{C}^2} \frac{-8.0 \times 10^{-9} \text{C}}{(2.0 \text{m})^2}) (0.60_i - 0.80_j) \\ &= (-11 \text{N/C})_i + (14 \text{N/C})_j \end{aligned}$$

1.4 Superposition of Electric Fields

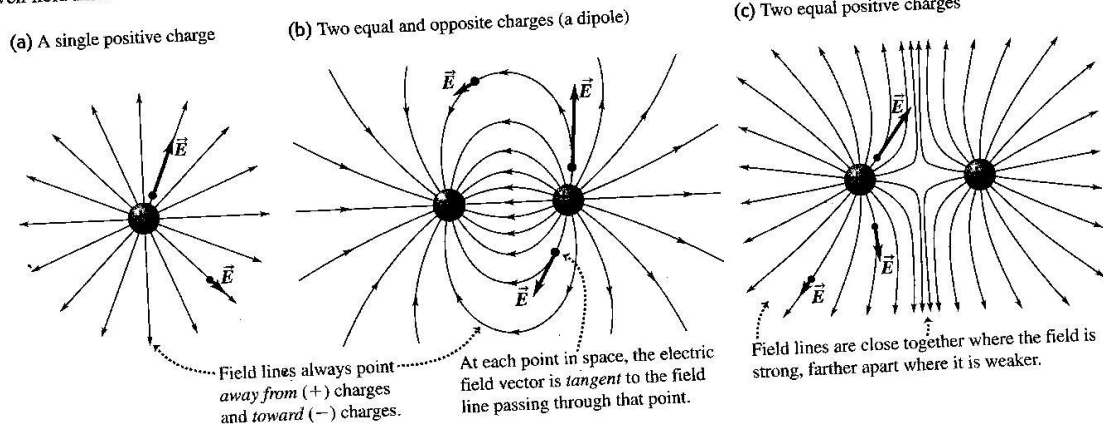
The principle of superposition of electric fields states that the electric field \vec{E} of any combination of charges is the vector sum of the fields caused by the individual charges.

Charge distributions are described by linear charge density λ , surface charge density δ , and volume charge density ρ .

1.5 Electric field lines

Field lines provide a graphical representation of electric fields. At any point on a field line, the tangent to the line is in the direction of E at that point. The number of lines per unit area (perpendicular to their direction) is proportional to the magnitude of E at the point.

iven field line.



The actual field vectors have been drawn at several points in each pattern. Notice that in general, the magnitude of the electric field is different at different points on a given field line; a field line is not a curve of constant electric field magnitude!

1.6 Electric Potential

Potential energy – short revision

The work – energy principle basically says:

$$W = \Delta E$$

$$W = \vec{F} \cdot \Delta \vec{r}$$

In this most basic form, the energy is just kinetic energy (if you are not going near the speed of light). BUT ...if you have a force that is conservative (meaning the work done does not depend on the path you take), then you can make it a potential energy and move it to the other side.

Warning: you cannot have a force and have that force do both work AND be a potential energy.

If you make the work done by a force a potential energy then that change in potential energy will be:

$$\Delta PE = -\vec{F} \cdot \Delta\vec{r}$$

There is one small problem. What if the force is not constant? In that case, this really doesn't work, but you get the idea (you would need some calculus to fix this for this non – constant forces). But that is potential energy in a nutshell.

1.6.1 Electric Potential

As an example, let me start with the case of a constant electric field. This is not so crazy of an idea. It is a pretty good assumption to say the electric field inside of a parallel plate capacitor makes a constant electric field (where one side of the capacitor has a positive charge and one side has a negative charge of the same magnitude).

Now suppose that I take a positive charge from the negative side of the capacitor and move it to the positive side. During this time there is an electric force on the charge in the opposite direction it moves. The work done by the electric force would be:

$$W_E = F \Delta r = -qE\Delta r$$

If I now consider this work as a potential energy, it would have to be negative. So, moving from the negative side to the positive side the change in electric potential energy would be

$$\Delta U_E = qE\Delta r$$

I will leave it as a homework question, but it is not too difficult to show that this change in potential energy does not depend on the path the charge takes from one side to the other. What if I change the charge that I am moving? Well, then the change in electric potential energy would be different.

How about I just find the change in electric potential energy per unit charge? I could write that as

$$\frac{\Delta U_E}{q} = \Delta V$$

And this is the electric potential – though it is often called just “potential”. Really it is the change in electric potential and it has units of Joules per Coulombs or Volts. Some people even call this the voltage (but I like to call it potential difference – to emphasize that I am dealing with a charge).

2.0 Direct Current Circuits

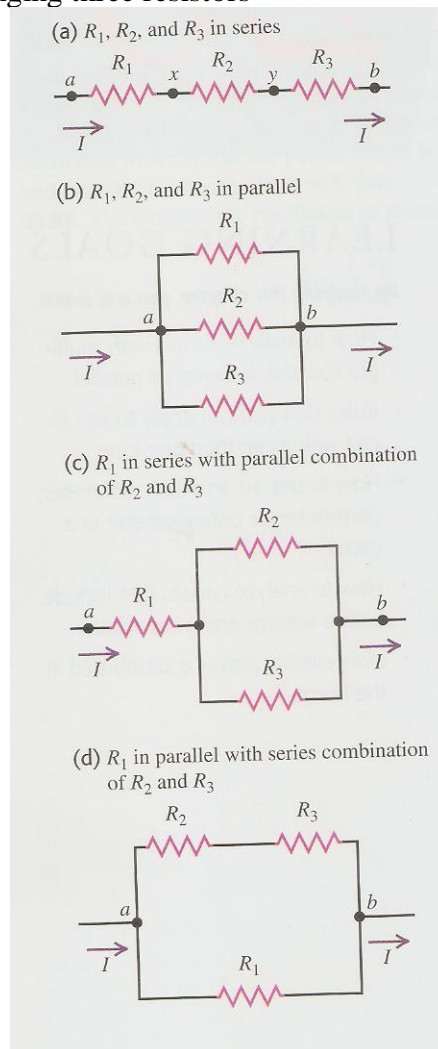
2.1 Resistors in Series and Parallel

When several resistors R_1, R_2, R_3, \dots , are connected in series, the equivalent resistance R_{eq} is the sum of the individual resistances. The same current flows through all the resistors in a series connection. When several resistors are connected in parallel, the reciprocal of the equivalent resistance R_{eq} is the sum of the reciprocals of the individual resistances. All resistors in a parallel connection have the same potential difference between their terminals.

(resistors in series), $R_{eq} = R_1 + R_2 + R_3 + \dots$ (i)

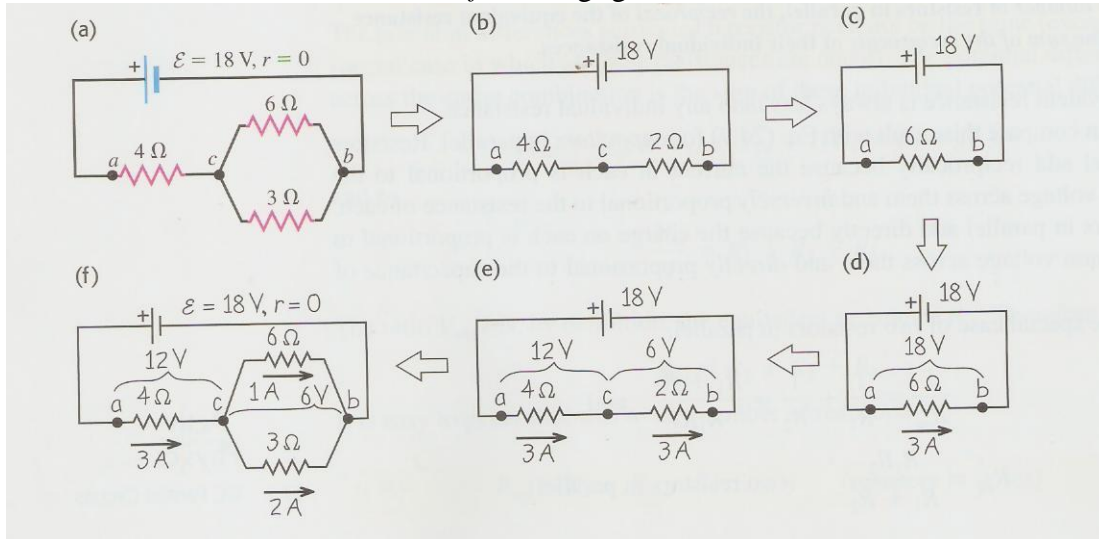
(resistors in parallel), $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$ (ii)

Four different ways of arranging three resistors



Example 2.1

Compute the equivalent resistance of the network in the figure below, and find the current in each resistor. The source *emf* has negligible internal resistance.



Solution

Figures *b* and *c* show successive steps in reducing the network to a single equivalent resistance. From equation (ii) the 6Ω and 3Ω resistors in parallel in figure *a* are equivalent to the single 2Ω resistor in figure *b*.

$$\frac{1}{R_{eq}} = \frac{1}{6\Omega} + \frac{1}{3\Omega} = \frac{1}{2\Omega}. \quad R_{eq} = 2\Omega$$

From equation (i) the series combination of this 2Ω resistor with the 4Ω resistor is equivalent to the single 6Ω resistor in figure *c*.

To find the current in each resistor of the original network, we reverse the steps by which we reduce the network. In the circuit shown in figure *d*, the current is

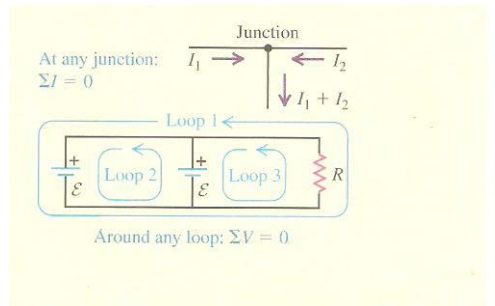
$$I = \frac{V_{ab}}{R} = \frac{18V}{6\Omega} = 3A.$$

So the current in the 4Ω and 2Ω resistors in figure *e* is also $3A$. The potential difference V_{cb} across the 2Ω resistor is therefore $V_{cb} = IR = (3A)(2\Omega) = 6V$. This potential difference must also be $6V$ in figure *f*. Using $I = \frac{V_{cb}}{R}$, the currents in the 6Ω and 3Ω resistors in figure *f* are $\left(\frac{6V}{6\Omega}\right) = 1A$ and $\left(\frac{6V}{3\Omega}\right) = 2A$ respectively.

2.2 Kirchhoff's Rules

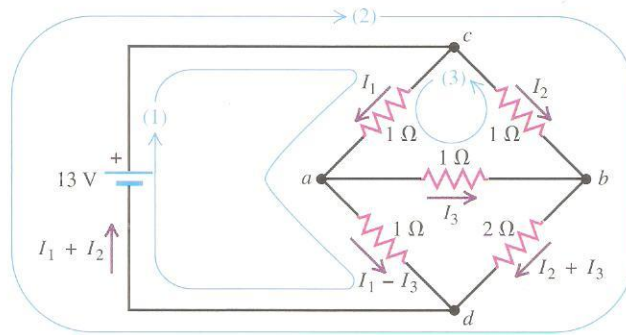
Kirchhoff's junction rule is based on conservation of charge. It states that the algebraic sum of the currents into any junction must be zero. Kirchhoff's loop is based on

conservation of energy and conservative nature of electrostatic fields. It states that the algebraic sum of potential differences around any loop must be zero. Careful use of consistent sign rules is essential in applying Kirchhoff's rules.



Example 2.2:

The figure below shows a bridge circuit. Find the current in each resistor and the equivalent resistance of the network of five resistors.



Solution

We apply the loop rule to the three loops shown. Obtaining the following three equations.

$$13V - I_1(1\Omega) - (I_1 - I_3)(1\Omega) = 0 \tag{1}$$

$$-I_2(1\Omega) - (I_2 + I_3)(2\Omega) + 13V = 0 \tag{2}$$

$$-I_1(1\Omega) - I_3(1\Omega) + (I_2)(1\Omega) = 0 \tag{3}$$

This is a set of three simultaneous equations for the three unknown currents. They may be solved by various methods; one straightforward procedure is to solve the third equation for I_2 , obtaining $I_2 = I_1 + I_3$, and then substitute this expression into the second equation to eliminate I_2 , when this is done, we are left with the two equations.

$$13V = I_1(2\Omega) - (I_3)(1\Omega) \tag{1'}$$

$$13V = I_1(3\Omega) + (I_3)(5\Omega) \tag{2'}$$

Now we can eliminate I_3 by multiplying equation (1') by 5 and adding the two equations. We obtain

$$78V = I_1(13)\Omega, \quad I_1 = 6A.$$

We substitute this back into equation (1') to obtain $I_3 = -1A$, and finally from equation (3) we find $I_2 = 5A$. The negative value of I_3 tells us that its direction is opposite to our initial assumption.

The total current through the network is $I_1 + I_2 = 11A$, and the potential drop across it is equal to the battery *emf*—namely, 13V. The equivalent resistance of the network is

$$R_{eq} = \frac{13V}{11A} = 1.2\Omega.$$

Example 2.3

In the circuit of example 2 above, find the potential difference V_{ab} .

Solution:

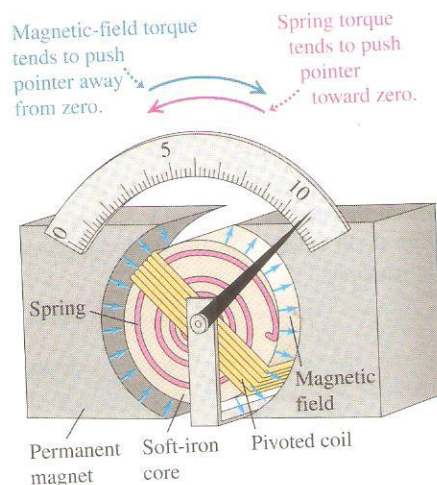
The simplest path to follow is through the centre 1Ω resistor. We have found $I_3 = -1A$, showing that the actual current direction in this branch is from left to right. Thus, as we go from b to a , there is a drop of potential with magnitude

$$IR = (1A)(1\Omega) = 1V, \text{ and } V_{ab} = -1V.$$

That is, the potential at point a is 1V less than that at point b .

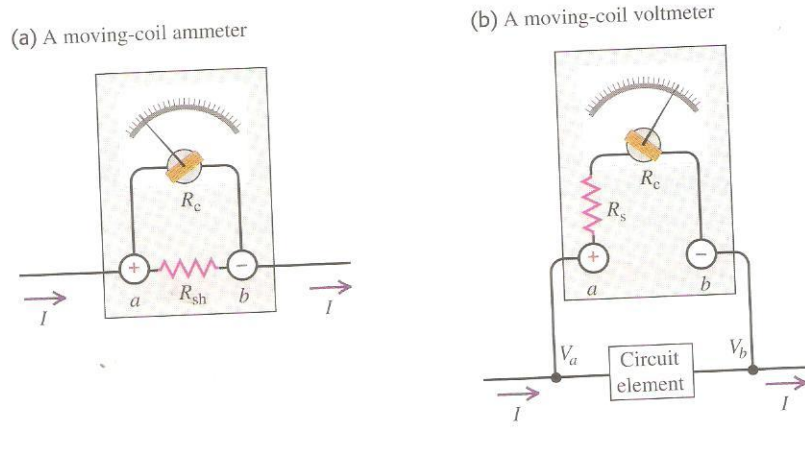
2.3 Electrical Measuring Instruments

A d'Arsonval galvanometer is used to measure potential difference (voltage), current, or resistance. A pivoted coil of fine wire is placed in the magnetic field of a permanent magnet. Attached to the coil is a spring, similar to the hairspring on the balance wheel of a watch. In the equilibrium position, with no current in the coil, the pointer is at zero. When there is a current in the coil, the magnetic field exerts a torque on the coil that is proportional to the current. As the coil turns, the spring exerts a restoring torque that is proportional to the angular displacement.



Thus, the angular deflection of the coil and pointer is directly proportional to the coil current, and the device can be calibrated to measure current.

For a larger current range, a shunt resistor is added, so some of the current bypasses the metre coil. Such an instrument is called an ammeter. If the coil and any additional series resistance included obey ohm's law, the meter can also be calibrated to read potential difference or voltage. The instrument is then called a voltmeter. A good ammeter has very low resistance; a good voltmeter has very high resistance.



Example 2.4

What shunt resistance is required to make the 1.00mA , 20.0Ω meter into an ammeter with a range of 0 to 50mA ?

Solution

We want to make the ammeter to be able to handle a maximum current $I_a = 50\text{mA} = 50 \times 10^{-3}\text{A}$. The resistance of the coil is $R_c = 20\Omega$, and the meter shows full-scale deflection when the current through the coil is

$$I_{fs} = 1.00 \times 10^{-3}\text{A. Using eq. } I_{fs}R_c = (I_a - I_{fs})R_{sh}$$

$$R_{sh} = \frac{I_{fs}R_c}{I_a - I_{fs}} = \frac{(1.00 \times 10^{-3}\text{A})(20\Omega)}{(50 \times 10^{-3}\text{A}) - (1.00 \times 10^{-3}\text{A})} = 0.408\Omega$$

Example 2.5

How can we make a galvanometer with $R_c = 20\Omega$ and $I_{fs} = 1.00\text{mA}$ into a voltmeter with a maximum range of 10.0V ?

Solution

The maximum allowable voltage across the voltmeter is $V_v = 10.0\text{V}$. We want this to occur when the current through the coil (of resistance $R_c = 20\Omega$) is $I_{fs} = 1.00\text{mA}$. We find the series resistance R_s using equation $V_v = I_{fs}(R_c + R_s)$.

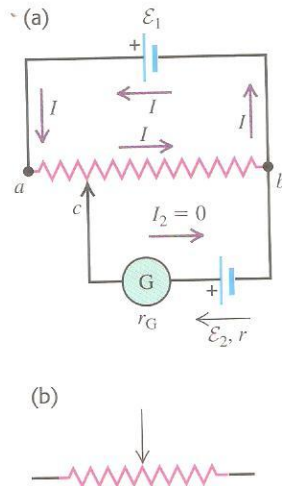
$$R_s = \frac{V_v}{I_{fs}} - R_c = \frac{10.0V}{0.001A} - 20\Omega = 9980\Omega$$

2.3 The Potentiometer

The potentiometer is an instrument that can be used to measure the *emf* of a source without drawing any current from the source. It balances an unknown potential difference against an adjustable, measurable potential difference.

The principle of the potentiometer is shown in the figure below. A resistance of wire *ab* of total resistance R_{ab} is permanently connected to the terminals of a source of known *emf* ϵ_1 . A sliding contact *C* is connected through the galvanometer *G* to a second source whose *emf* ϵ_2 is to be measured. As contact *c* is moved along the resistance wire, the resistance R_{cb} is proportional to the length of wire between *c* and *b*. To determine the value of ϵ_2 , contact *C* is moved until a position is found at which the galvanometer shows no deflection; this corresponds to zero current passing through ϵ_2 . With $I_2 = 0$, Kirchhoff's loop rule gives $\epsilon_2 = IR_{cb}$.

With $I_2 = 0$, the current *I* produced by the *emf*, has the same value no matter what the value of the *emf* ϵ_2 . We calibrate the device by replacing ϵ_2 by a source of known *emf*; then any unknown *emf* ϵ_2 can be found by measuring the length of wire *cb* for which $I_2 = 0$. Note that for this to work, V_{ab} must be greater than ϵ_2 .



3.0 Thermal, Chemical and Magnetic Effects of Electric Current

3.1 Thermal Effect of Electric Current: Joule's Law

The electric current in a conductor is due to the motion of electrons. During their motion, electrons collide with the oscillating positive ions in the conductor and impart part of their energy to them. Ions oscillate faster and their increased energy is manifested as heat.

The heat energy released in a conductor on passing an electric current is called the "Joule heat" and effect is called the "Joule effect".

The potential difference of V volt applied between two ends of a conductor means that V joule of electrical energy is utilized and converted into heat when one coulomb charge passes through the conductor.

If Q coulomb charge passes through the conductor in t seconds resulting in current I , the heat energy produced is

$$\begin{aligned} W &= VQ && \text{joule} \\ W &= VIt && \text{joule} \\ W &= I^2 Rt && \text{joule } (V = IR \text{ according to ohm's law}) \end{aligned}$$

$$W = \left(\frac{V^2}{R}\right)t \quad \text{joule}$$

The electric power, i.e., the electrical energy supplied per unit time or converted into heat energy per unit time in a resistance R , is

$$\begin{aligned} P &= VI && \frac{\text{joule}}{\text{second}} (= \text{watt}) \\ P &= I^2 R && \frac{\text{joule}}{\text{second}} (= \text{watt}) \\ P &= \left(\frac{V^2}{R}\right) && \frac{\text{joule}}{\text{second}} (= \text{watt}) \end{aligned}$$

Thus, mechanical unit of energy, joule = watt.second which is an electrical unit of energy. This being too small, kilowatt-hour (kwh) = 3.6×10^6 joule used as a practical unit of electrical energy.

R is the ohmic resistance of the conductor value of which does not depend upon V or I . Considering R as a constant,

$$P \propto I^2 \text{ or } P \propto V^2$$

In fact, all electrical appliances are rated to operate for a given potential difference and hence in household wiring, they are connected in parallel. Therefore, V is same for all whereas I varies. Hence, it is more convenient to use the formula $P = \left(\frac{V^2}{R}\right)$.

Joule's Law: "the heat produced per unit time, on passing electric current through a conductor at a given temperature, is directly proportional to the square of the electric current".

To express heat produced in calories, the following relation given by joule is used.

$W = JH$, where W is mechanical energy in joule,

H is heat energy in calorie and

$J = 4.2$ joule/calorie is joule's constant or mechanical equivalent of heat.

$$H(cal) = \frac{I^2 R t (joule)}{J}$$

3.1.1 Practical Applications of Joule Heating

Joule heat is used in domestic appliances such as electric iron, toaster, oven, kettle, room heater, etc. It is also used in electric bulbs to produce light. The temperature of the filament of the bulb rises considerably when current flows through it and it emits light. Hence it should be made of a high melting point such as tungsten, whose melting point is 3380°C . Also it should be thermally isolated from the surrounding as far as possible. Only a small fraction of electric power supplied to the bulb is converted into light. Normally a bulb emits 1 candela of light per watt of electric power consumed.

Another common application of joule heat is fuse wires used in circuits. It consists of a piece of metal wire having low melting point (such as aluminum, alloy of tin/lead, copper etc.) and is connected in series with an appliance. If a current larger than a specified value flows, the fuse wire melts and breaks the circuit thus protecting the appliance.

3.2 Chemical Effect of Electric Current

3.2.1 Introduction

- Solid and molten metals are good conductors of electricity due to free electrons. When current flows through metals, only heating occurs and no chemical effect is observed.
- Most liquids have no free electrons and hence do not conduct electricity, e.g., water.
- When an acid, base or an inorganic salt is added to water it dissociates into positive and negative ions which conduct electricity. The solutions which conduct electric current are called electrolytes and the vessel containing it along with electrodes is called an electrolytic cell.
- Inorganic salts like NaCl and KCl conduct electric current even in solid form.
- Normally, the solutions of organic compounds are non-conductors.
- In NaCl crystal Na^+ and Cl^- ions are bound to each other due to electrostatic attraction. About 7.9eV ($1\text{eV} = 1.6 \times 10^{-19}$ joule) energy is required to separate

them. Only 0.03eV thermal energy is available at room temperature which is insufficient to break NaCl crystal.

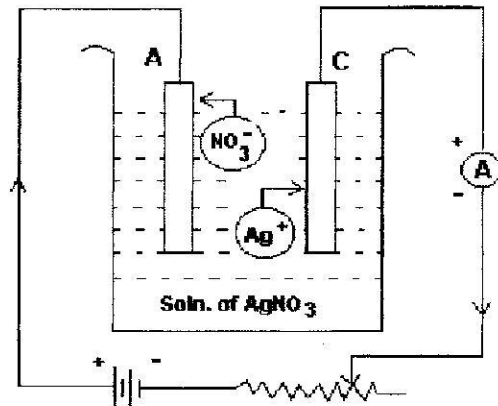
When NaCl is added to water, polar water molecules get arranged in space between the ions which reduce attraction between them. Also, due to a specific distribution of charge inside them, some water molecules stick to each other forming a cluster around the ions. Each cluster is electrically polarized which reduces the strength of electric field between the ions. For this reason, dielectric constant, K , of water is very high which reduces the electric field between Na^+ and Cl^- ions to $1/K$ times and they get dissociated. Due to its high dielectric constant, water acts as a good solvent. Ions dissociated this way participate in conduction of electric current.

- At room temperature, electric conductivity of electrolytes is 10^{-5} to 10^{-6} times that of metals because
 - (i) The number density of ions is less compared to the number density of electrons in metals,
 - (ii) Viscosity of solution increases electrical resistance and
 - (iii) Drift velocity of ions is less compared to electrons due to their larger mass.

3.2.2 Electrolysis

The device in which electrolysis occurs is called an electrolytic cell or voltameter which is used to study the chemical effects of electric current.

Refer to the figure shown to understand the working of an electrolytic cell.



Here aqueous solution of AgNO_3 is used as an electrolyte and two plates A and C silver are partially immersed in it which are the electrodes. The electrodes are connected to a battery from which current enters the electrolyte through A and leaves through C.

AgNO_3 dissociates into Ag^+ and NO_3^- ions in the electrolyte. NO_3^- ions (anions) move towards the anode A and Ag^+ ions (cations) move towards the cathode C.

Each Ag^+ ion, on reaching the cathode, picks up an electron from it and reduces to become a neutral atom of silver and deposits on cathode. ($\text{Ag}^+ + e^- \rightarrow \text{Ag}$). This process of plating of Ag on the cathode is called electroplating.

NO_3^- ion reaching the anode oxidizes Ag to Ag^+ ion and the electron so released goes to the positive terminal of the battery through the wire. AgNO_3 formed dissociates maintaining concentration of Ag^+ and NO_3^- ions ($\text{Ag} + \text{NO}_3^- \rightarrow \text{Ag}^+ + \text{NO}_3^- + e^-$). Thus, Ag^+ ion lost at the cathode is obtained back at the anode.

Summarizing,

- 1) Electric current is due to the motion of electrons in the external conducting wire and due to the motion of ions in the electrolyte.
- 2) Anode loses silver which gets deposited on the cathode.
- 3) Concentration of AgNO_3 is maintained.
- 4) Cathode is made of the metal which is to be plated, e.g., for silver-plating of copper, cathode is made of copper.
- 5) Anode is made of the metal of which is to be done and electrolyte must be a compound of that metal.

3.2.3 Faraday's Laws of Electrolysis

Law 1: "Mass m of the substance liberated at the electrode from the electrolyte, on passing electric current through the electrolyte, is directly proportional to the amount of charge (Q) passing through it."

Thus, $m \propto Q$. $\therefore m = ZQ = Zit$, where I is the current for time t .

" Z is called electrochemical equivalent of the substance liberated and is defined as the mass of the substance liberated from an electrolyte on passing one ampere current for one second, i.e., one coulomb of charge."

Its unit is g/C or kg/C.

Law 2: "When the same current is passed for the same time through different electrolytes, the masses of elements liberated at electrodes are directly proportional to their respective chemical equivalents."

Chemical equivalent (e) of any element is the ratio of its atomic mass to its valency. It is also called gram equivalent.

Let e_1 and e_2 be the chemical equivalents of two substances and m_1 and m_2 be their masses liberated at the electrodes when the same current I passed through two electrolytic cells for the same time t . Then,

$$\frac{e_1}{e_2} = \frac{m_1}{m_2} = \frac{Z_1 It}{Z_2 It} \qquad \therefore \frac{e_1}{Z_1} = \frac{e_2}{Z_2} = F$$

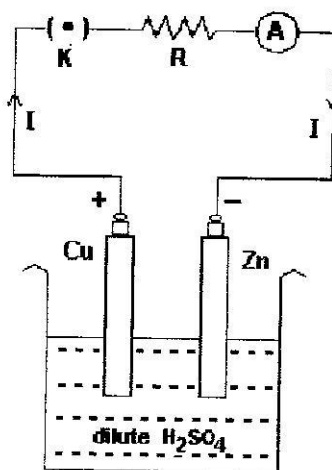
Where F is Faraday's constant having value 96500 coulomb/mole. This means that 96500C charge is required to liberate, through electrolysis, 1 mole of an element having valency 1. It also means that the amount of substance liberated at the electrode when 96500 C charge is passed through an electrolyte is

$$m = \frac{\text{atomic mass}}{\text{valency}} = \text{chemical equivalent}$$

3.2.4 Electrochemical Cells

The device used to convert chemical energy into electrical energy is called an electrochemical cell.

When a metal plate (electrode) is immersed into an electrolyte, positive or negative ions from the electrolyte move towards it and a net *e.m.f.* is developed between it and the electrolyte. When two electrodes of different metals are immersed into the electrolyte, a net *e.m.f.* is generated between them. The electrode at higher electric potential is called the positive electrode and the one having lower potential is called the negative electrode. Steady electric current flows on completing the electric circuit by connecting the two electrodes with a conducting wire. Such a device is called an electrochemical cell.



Electrochemical cells are of two types:

- 1) Primary cells: the cells that get discharged only and cannot be recharged after use are called the primary cells.
- 2) Secondary cells: The cells which can be recharged after use and restored to original condition are called the secondary cells.

3.2.5 Voltaic Cell

Italian scientist Volta prepared such a cell for the first time. Hence it is known as voltaic cell in his memory.

Dilute H_2SO_4 is used as an electrolyte. Positive charge deposits on copper electrode and negative charge on zinc electrode. So copper electrode is at a higher potential than the zinc electrode.

3.3 Magnetic Effects of Electric Currents

3.3.1 Introduction

The branches of electricity and magnetism were unified by scientists like Oersted, Rowland, Faraday, Maxwell and Lorentz.

The branches of Physics covering a combined study of electricity and magnetism is known as electromagnetism or electrodynamics. It is useful in study of subjects like plasma physics, magneto-hydrodynamics and communication.

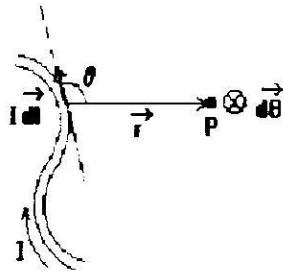
3.3.2 Oersted's Observation

In 1819 A.D., a school teacher from Denmark, observed that magnetic field is produced around a wire carrying electric current. If a conducting wire is kept parallel to the magnetic needle and electric current is passed through it, needle gets deflected and aligns itself perpendicularly to the length of the wire.

3.3.3 Biot-Servart's Law

The intensity of magnetic field due to a current element $I\vec{dl}$ at a point having position vector \vec{r} with respect to the electric current element is given by the formula.

$$\vec{dB} = \frac{\mu_0 I \vec{dl} \times \hat{r}}{4\pi r^2} = \frac{\mu_0 I \vec{dl} \times \vec{r}}{4\pi r^3} \quad \text{and} \quad |dB| = \frac{\mu_0 I dl \sin \theta}{4\pi r^2},$$



Where \vec{dB} = magnetic intensity in tesla (T) or weber/m²,

$I\vec{dl}$ = current element (product of electric current and length of small line element \vec{dl} of the conductor)

μ_0 = magnetic permeability of vacuum

= $4\pi \times 10^{-7}$ tesla metre per ampere (T m A^{-1})

$\hat{r} = \text{unit vector along the direction of } \vec{r} = \frac{\vec{r}}{|\vec{r}|}$
and $\theta = \text{angle between } \vec{dl} \text{ and } \vec{r}$

The direction of \vec{dB} is perpendicular to the plane formed by \vec{dl} and \vec{r} . As \vec{dl} and \vec{r} are taken in the plane of the figure, the direction of \vec{dB} is perpendicular to the plane of the figure and going inside it, as shown by \otimes .

On integrating the above equation, we get the total intensity at the point P due to the entire length of the conducting wire as

$$\vec{B} = \frac{\mu_0 I}{4\pi} \int \frac{\vec{dl} \times \hat{r}}{r^2} \quad \text{or} \quad \vec{B} = \frac{\mu_0 I}{4\pi} \int \frac{\vec{dl} \times \vec{r}}{r^3}$$