Section I
Electrical Fundamentals

(i) Basic Atomic Theory

All matter is made up of tiny particles called atoms. These atoms are, in turn, made up of protons, neutrons, and electrons. Protons and electrons are oppositely charged and attracted to each other (this physical force of attraction is supplemental to and much greater than the gravitational force that exists between them).

Protons (p^+) are positively charged. Electrons(e^-) are negatively charged. The magnitude of their charges is equal. Neutrons are uncharged. Most atoms exist in an uncharged or (charge) neutral state. Hence, there are equal numbers of protons and electrons in a neutral (uncharged) atom.

The neutrons and protons exist tightly bound together in the nucleus. The electrons 'revolve' around the nucleus at various distances.

The mass of an e^- is $9.11x10^{-28}$g and that of a p^+ or neutron is $1.672x10^{-24}$g. Hence the mass of a p^+ or neutron is roughly 2000 times that of an e^- !!!

Protons, neutrons and electrons can be considered to roughly spherical in shape (Bohr model). The radii of all is approx $2x10^{-15}$m.

For the Hydrogen (H) atom (which has one p^+ and one e^-), the orbit followed by the e^- about the neucleus is roughly
$5x10^{-11}$m. From these dimensions, this setup is equivalent to a marble revolving around another marble a quarter of a mile away !!!

The number of protons an atom has in its neucleus is known as the <u>atomic number</u> of the atom. It is this number that distinguishes one type of atom (or element) from another. For example, Hydrogen (H) atoms have one proton in the neucleus (atomic number is 1) whereas Heluim (He) has two (atomic number 2). Hydrogen and Helium are therefore said to be different elements.

Elements are arranged on the periodic table in the order of increasing atomic number. Elements are simply materials made up of a single type of atom (e.g. Hydrogen (H), Helium (He), Copper (Cu)). There are 110 elements known to man.

The electrons in an atom revolve in concentric shells about the nucleus. Each shell can contain $\underline{2n^2}$ electrons – where n is the shell number. So the first shell (closest to the neucleus, n=1) can contain a maximum of two electrons. The second shell can contain a maximum of eight electrons, the third eighteen and so on.

Since the nucleus is positively charged, an attractive force exists between it and the electrons revolving about it. As the distance between the nucleus and shells increases, the binding forces between the nucleus and the electrons diminishes as we move towards the outermost shell.
Due to these weaker binding forces, it is easier (and sometimes quite easy) to remove an electron from the outermost shell.

Molecules are combinations of atoms that are chemically bound together. This ‘chemical binding’ is the result of atoms ‘sharing’ electrons in their outermost shells.

E.g. The water (H_2O) molecule consists of two atoms of Hydrogen chemically bound with one atom of Oxygen (O).

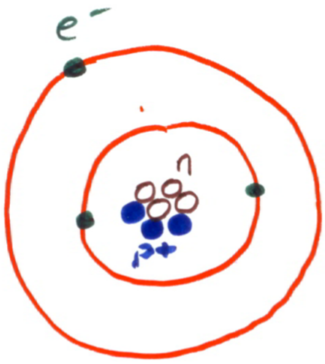
The carbon dioxide (CO_2) molecule consists of one atom of Carbon chemically bound with two atoms of Oxygen.

Diagrams (Atoms):

THE HYDROGEN ATOM (H)

- 1 Proton
- 1 Electron

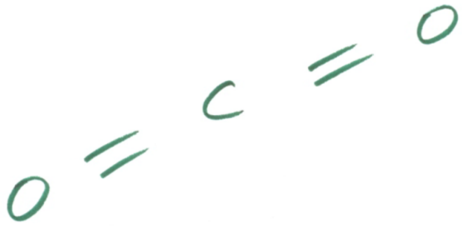
THE LITHIUM ATOM (Li)



- 3 Protons
- 4 Neutrons
- 3 Electrons

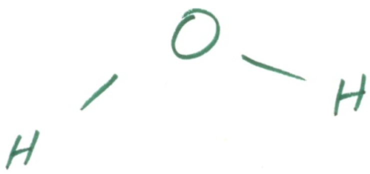
Diagrams (Molecules):

The Carbon Dioxide Molecule (CO_2):



'—' ≡ 1 'shared' e^-

The Water Molecule (H_2O):



(ii) Charge

Recall from atomic theory that protons are said to be positively charged and electrons are said to be negatively charged. A force of attraction exists between unlike charges and a force of repulsion exists between like charges. This force is given by Coulomb's Law.

Coulomb's Law:

The force between any two point charges is proportional to the product of the charges and inversely proportional to the square of the distance between them.

Mathematically:

$$\vec{F} = \frac{1}{4\pi\varepsilon}\frac{q_1 q_2}{r^2}\hat{r}$$

where:

- $\vec{F}$ is the force
- ε is a constant for the medium known as the electrical permittivity.
- q_i is the charge.
- r is the distance between the charges
- $\hat{r}$ is the unit vector in the direction of the force.

$$\varepsilon = \varepsilon_0.\varepsilon_r$$

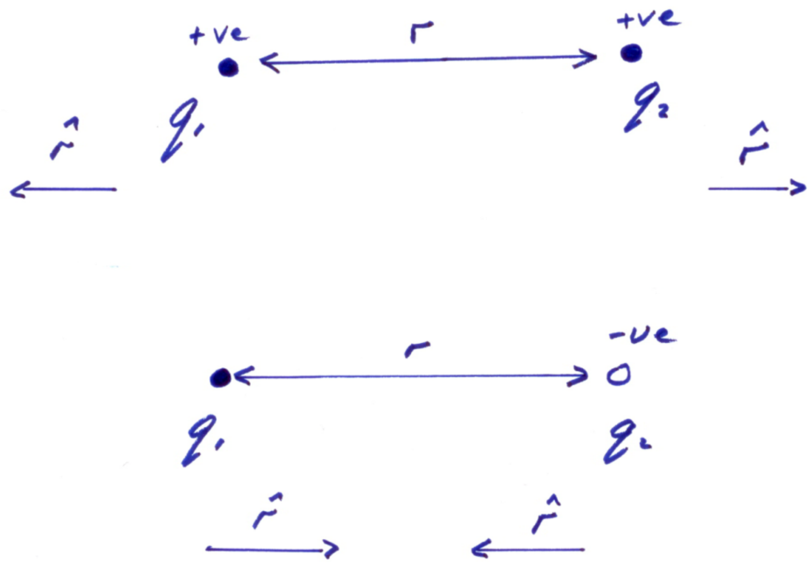
where:

- ε_0 is the electrical permittivity of free space

(= $8.9\times10^{-12} C^2N^{-1}m^{-2}$)

- ε_r is the relative permittivity of the medium.

Diagram:



Example:

Calculate the magnitude of the force in air between two point charges of 4nC each if the distance between them is 5mm.

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2} = \frac{1}{4\pi.8\cdot 9\times 10^{-12}}\frac{(4\times 10^{-9})^2}{(5\times 10^{-3})^2} = 5\cdot 7mN$$

Note: If multiple charges exist, the force on any one charge equals the vector sum of the forces exerted on it by the other charges.

(iii) Voltage

Electrical Potential:

When wind blows from one point to another we say there is a pressure difference between these two points.
Likewise, when water flows from one point to another, we say there is a pressure difference or a difference in height as the case may be.
All of the above result phenomena result from a difference in the potential energy of that quantity between the two points.

Potential Energy (or Stored Energy):
is the energy of a body due to its state or position.

e.g. a rock at the edge of a cliff, a wound up clock, etc.

When charge flows from one point to another we say there is an electrical potential difference between these two points.

The (Electrical) Potential Difference (p.d.) *between two points is the work done in bringing a unit positive charge from one point to another.*

Potential difference is a scalar quantity. Its unit (dimension) is the volt.

Mathematically:

$$v(t) = \frac{dW(t)}{dq(t)}$$

One Volt *is the potential difference between two points if the work done in bringing a charge of one Coulomb from one point to the other is one Joule.*

Electromotive Force (E.M.F.)
The emf in any closed loop is the work done in bringing unit positive charge around that loop.

In practical terms the EMF is the ‘driving’ or supply voltage.

(iv) Current

Electric Current:

When charge (or charged particles) move (flow) from one point to another, we have electrical current.

Electric Current *is the rate of charge flow with respect to time.*

Mathematically:

$$i(t) = \frac{dq(t)}{dt}$$

Electric Current is a scalar quantity. Its unit is the Ampere.

One Ampere *is one coulomb per second.*

Ampere's Discovery

Ampere discovered that when currents flow, they exert a force of attraction/repulsion on each other. This force cannot be explained by Coulomb's Law. Currents attract if both are moving in the same direction and repel if moving in opposite directions. This phenomenon which is the result of magnetic fields generated by moving charge (current) is used to define the unit of electrical current, the Ampere or 'Amp'.

The Ampere *is that constant current which when maintained in two straight parallel conductors, placed 1m apart in a vacuum and of infinite length, causes each to exert a force of $2x10^{-7}$N on the other.*

This gives rise to the definition of the unit of charge, the Coulomb:

The Coulomb *is that quantity of charge transferred when a current of 1 Ampere flows for 1 second.*

(v) Power

Current and Voltage

By definition:

Current: $$i(t) = \frac{dq(t)}{dt}$$

Voltage: $$v(t) = \frac{dW(t)}{dq(t)}$$

Electric Power

Electric Power is defined as the rate of energy expenditure.

The unit of power is Joules/sec (J/s) or Watt (W).

$$p(t) = \frac{dW(t)}{dt}$$

But:

$$dw(t) = p(t)dt = v(t)dq(t)$$

$$p(t) = v(t)\frac{dq(t)}{dt}$$

Hence:

$$\boxed{p(t) = v(t)i(t)}$$

DC Power

The instantaneous dc power equals the average dc power.

i.e.

$$\boxed{P = VI}$$

(vi) Materials

Conductors

A conductor is a material which, on application of an emf, facilitates current (i.e. charge transfer) well.

The reason for this is simple: Conductors are composed of atoms or molecules where a relatively large number of electrons, for whatever reason, are loosely bound in their atomic or molecular structure.

This means that on application of an emf, these electrons will move in the direction of relatively positive charge (i.e. the cathode) while the relatively negative charge region (i.e. the anode) will replenish the supply of electrons. Hence current!

Copper is a very good conductor which is one of the reasons copper is normally used in electrical wiring (the other is that it is relatively cheap)

The reason metals tend to make good conductors is because they have electrons in their outer shells which as a result of their position or state are loosely bound to the nucleus.

Good conductors can be viewed as a ‘sea’ of electrons available for conduction. i.e. an application of a small emf will cause these electrons will move.

Example

Consider Silver (Ag), a good conductor.

100g of Ag contains 6.02g x 10^{23} atoms. The density of Ag is 10.5g/cm^3.

Therefore1cm^3 of Ag contains:

$$\frac{(6.02\times10^{23})(10.5)}{100} \approx 6\times10^{22}\ \ atoms$$

Statistically speaking, each atom of Ag has 1 electron available for conduction at room temperature. So 1cm^3 of Ag has approx. 6x10^{22} electrons available for conduction.

Dielectrics (a.k.a. Insulators):

A dielectric is a material which, on application of an emf, facilitates electric current poorly.

The reason for this is again simple: Insulators are composed of atoms or molecules which have their electrons tightly bound to the nucleus/nuclei which means that on application of an emf few electrons will move i.e. low current.

Semiconductors

A semiconductor is a material which, on application of an emf, facilitates a 'moderate' current flow.

Semiconductors are a class of materials which fall between conductors and dielectrics. Examples include Silicon (Si) and Germanium (Ge).

As opposed to conductors, where approx. 1 electron per atom is available for conduction, in semiconductors, this figure is typically of the order of 1 electron in every 10^8 atoms.

Example

Consider Silicon (Si), a common semiconductor. 28.1g of Silicon contains $6.02x10^{23}$ atoms. The density of Silicon is $2.33g/cm^3$.

So $1cm^3$ of Silicon contains $5x10^{22}$ atoms.

Therefore there are approximately $5x10^{14}$ e^-/cm^3 available for conduction in Silicon at room temperature