Electric charge and Coulomb's Law

A) Basic Concepts

1) Electrostatics

Electrostatics is the study of electric charges at rest. Static means anything that does not move or change with time. In electrostatics we deal with forces and fields arising from static charges.

2) Charge

Bodies rubbed against each other are said to be 'electrified' if they exert forces on each other. The idea of 'electric charge' arose from the studies of interactions between 'electrified' bodies. There are many pairs of materials known, which when rubbed against each other attract light objects like pieces of paper or straw. They also exert forces on each other.

After extensive study of interaction among various electrified bodies, the concept of 'electric charge' was proposed to explain the electric interaction.It was concluded that there were only two kinds of the entity which is called electric charge. Following the lead of American scientist Benjamin Franklin, these two kinds of charges are called ***positive*** and ***negative*** charges. Just as gravitational force between two bodies arise due to their masses, electrical force between two bodies arise due to their charges.

There is only one kind of gravitational force, attractive. But the electrical force can be attractive or repulsive. It is found that:**(i)** ***like charges repel each other*** **and (ii)** ***unlike charges attract each other.***

3) Electric charge and the structure of matter

The universe is made of only two things ; matter and radiation. Radiation is pure energy consisting of packets called photons and it has no charge, but matter can have charge. Matter is made of fundamental particles. **Electric charge is an intrinsic characteristic of fundamental particles of matter**. A fundamental particle of matter may be +vely charged, -vely charged, or neutral. **A particle endowed with charge is able to exert a force of electrical nature on any other particle endowed with charge.** Thus. electric charge, like mass, is one of the fundamental attributes of the particles of which matter is made.

4) Atomic structure

The basic unit of matter is an atom. Each atom has a nucleus which contains +vely charged particles called protons and neutral particles called neutrons. Outside the nucleus there are –vely charged electrons which orbit around the nucleus. Though proton and electron are oppositely charged, the magnitudes of their charges are equal (denoted by e). **The smallest observable charge in the universe is the charge of an electron/proton of magnitude e.** The value of e has been measured by careful experiments. It is found that **$e = 1.602192 \times 10^{-19}$C.** But in numerical calculations we will use the approximate vale $e = 1.6 \times 10^{-19}$C

Smallest observable **charge e**	=	$\mathbf{1.6 \times 10^{-19}}$**C**
charge of electron **-e**	=	$\mathbf{-1.6 \times 10^{-19}}$**C**

charge of proton +e $= +1.6 \times 10^{-19}$C

The masses of the constituent particles of the atom with the desired accuracy for our purposes are given below:

mass of electron m_e $= 9.1 \times 10^{-31}$ kg
mass of proton m_p $= 1.6726 \times 10^{-27}$ kg
mass of neutron m_n $= 1.6749 \times 10^{-27}$ kg

Mass of neutron is slightly greater than that of proton. Electron is much lighter compared to proton and neutron. Mass of a proton is 1836 times the mass of electron.

An atom is electrically neutral because of the following reasons :

(a) The number of protons in the nucleus is the same as the number of electrons outside the nucleus.
(b) The charge of a proton and the charge of an electron have opposite signs,
(c) The magnitudes of the charges of proton and electron are exactly equal.

The neutrality of an atom can be changed either by adding electrons to it or by removing electrons from it. When one or more electrons are added to a neutral atom, it becomes a ***negative ion***. On the other hand when one or more electrons are removed from a neutral atom, it becomes a ***positive ion***.

Ordinarily, a macroscopic body is made of neutral atoms and the body as a whole is electrically neutral.When electrons are added to a neutral body, it becomes negatively charged, and when electrons are removed from a neutral body, it becomes positively charged.

5) Conductors and Insulators

Some substances readily allow the passage of electric charge through them. They are called conductors. Substances in which electric charges do not move freely are called insulators. Equivalently, we can say that conductors are substances which offer low resistance to the passage of electricity through them and insulators are substances which offer a high resistance to the passage of electricity through them. Conductors have charge carriers which are free to move inside the material. Metals are good conductors. When a metal piece is formed from its atoms, some of the outer electrons of individual atoms get detached from them and move freely within the substance. These electrons are called ***free electrons***. Free electrons are free to move anywhere inside the material, but they cannot leave the material. Metals are good conductors because they have very large number of free electrons. Compared to good conductors like metals, the number of free electrons in insulators is very less.

B) Methods of charging a body

When the charge neutrality of a body is changed, we say the body is charged. A neutral body can be charged either by the addition of charges or by the removal of charges. Normally, charging is done by addition or removal of electrons. There are three methods of charging a body: (1) charging by friction, (ii) charging by conduction and (iii) charging by induction.

1) Charging by friction

If one body is rubbed against another, both of them get charged, one +vely and the other –vely. This method of charging of bodies is known as charging by friction.

When two bodies come in close contact a fraction of the electrons of one body goes to the other body. As a result a positive charge appears on the surface of the first body and an equal negative charge appears on the surface of the second body.When we move the bodies apart they retain these charges. Notice that both the bodies acquire the same amount of charge, but of different signs. The body which loses electrons acquires +ve charge and the body which gains electrons acquires –ve charge.

eg. 1. When a glass rod is rubbed with silk cloth, glass loses electrons and silk gains electrons. Glass becomes +vely charged and silk becomes –vely charged.
2. When a plastic rod is rubbed with fur, plastic gains electrons and fur loses electrons. Plastic becomes –vely charged and fur becomes +velycharged.

2) Charging by conduction/charging by contact

When a charged body(either charged positively or negatively) is brought in contact with an uncharged body, some charge will be transferred to the uncharged body, and the two bodies will be charged with the same sign. This is called charging by conduction or charging by contact. For example, we can charge a metal ball by touching it with an electrically charged plastic rod. Some of the excess electrons on the rod goes over to the ball, leaving the rod with a smaller negative charge. The final charges on the two bodies will in general be different. But if a charged conducting ball is brought in contact with another ball identical with the first, then the final charge on both will be the same. Both the balls will have half of the initial charge which was present on the first ball.

Question: A is a metal ball with a charge Q on it. B and C are uncharged metal balls which are identical to A in all respects. First B is brought in contact with A, and then B is brought in contact with C. What are the final charges on the three balls?

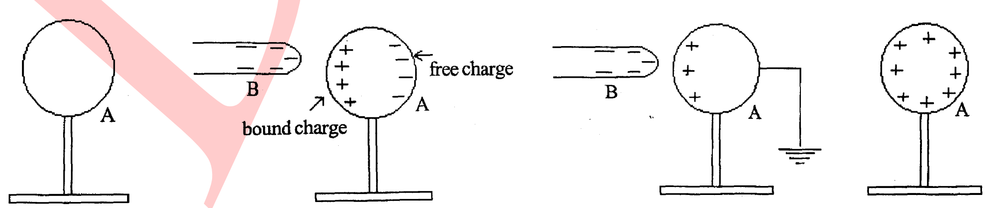
Answer: When B is brought in contact with A, the charge Q is equally shared between them, and both have charges Q/2 on them. When B and C are brought in contact, the charge Q/2 on B is equally shared between them. So the final charge on A is Q/2, and B and C have charge Q/4 on each.

3) Charging by induction

In charging by induction, a charged body imparts charge to another body without any contact between the two. In the following steps we describe how a negatively charged rod is used to impart positive charge on a metal sphere.

1. A is an uncharged metallic sphere supported on insulating stand. The metal sphere has very large number of free electrons, but as a whole it is electrically neutral.

2. A charged plastic rod B is brought close to the sphere A. Due to repulsion from the negatively charged rod, free electrons in A move away from B. As a result the near end of A becomes +vely charged and the far end becomes –vely charged. These charges appearing on the sphere are called **induced charges**. The induced charge on A near the rod B is called **bound charge**, and the induced charge on the farther side is called **free charge.**



3. When the sphere A is grounded, the –ve charge (electrons) flows to the ground, and the free charge disappears. The +ve charge(bound charge) remains because it is held there due to the attractive force of the external charge B.

4. Remove the earthing and then take the plastic rod B away. The +ve charge spreads uniformly over the sphere A. The sphere now has a permanent positive charge. (If the rod is moved away while the sphere is still earthed, electrons from the ground will move to the sphere to cancel the +ve charge and the sphere will become neutral. So the earthing should be removed before we take the rod away.)

Here A has become charged with the help of B eventhough there was no physical contact between A and B. In a similar manner as described above, with the help of a positively charged rod we can impart a permanent negative charge on a metal sphere.

Note : The following points may be noted about electrostatic induction

(a) Inducing body does not lose or gain charges.
(b) The nature of the induced charge is always opposite to that of inducing charge.
(c) Induced charge can be less than or equal to inducing charge but never greater than the inucing charge.

C) Properties of electric charge

There are four properties of electric charge: (i) additivity, (ii) conservation, and (iii) invariance, and (iv)quantization,

1) Additivity

Electric charge is an algebraic quantity which can take both +ve and –ve values. Suppose we have a charged body, with various amounts of +ve and –ve charges distributed over different parts of it. Then the total charge of the body is the algebraic sum of all these individual charges, each being taken with its proper sign. We say electric charge is additive. **If a system contains n charges $q_1, q_2, q_3, \ldots, q_n$, then the total charge of the system is $q_1 + q_2 + q_3 \ldots + q_n$.** Just like mass, charge is a scalar quantity. It has magnitude but no direction. But mass is always positive, but charge can be positive or negative. Therefore charges should be added algebraically, with their signs. to get the total charge.

2) Conservation

If a certain amount of charged matter is contained in a certain region of space, and no charged matter is allowed to enter or leave this region, then the total charge within this volume will never change. We say, ***the total charge of an isolated system is conserved.***

All processes taking place in a isolated system obey the law of conservation of charge. It is not possible to change the net charge carried by any isolated system, although charge carrying particles may be created or destroyed. Some processes where charges are created or destroyed in equal and opposite amounts in conformity with the law of conservation of charge are given below.

e.g. 1. Pair production

$\gamma \text{ ------> } e^- + e^+$

A gamma ray photon gets converted to an electron(e^-) and a positron(e^+). A positron has the same mass as that of the electron, but it has a charge +e. The sum of the charges of electron and proton is zero. The charge of the photon is also zero.

2. Pair annihilation

$e^- + e^+ \text{ ------> } \gamma + \gamma$

An electron and a positron combine to produce two gamma-rays.

3. Chemical reaction

$$NaCl \text{ -----> } Na^{+} + Cl^{-}$$

NaCl dissociates into a positive ion Na^{+} and a negative ion Cl^{-}. The two ions are having equal and opposite charges.

4. Radio active decay of neutron

$$n \text{ -----> } p^{+} + e^{-} + \bar{\nu} \text{ (antineutrino)}$$

A neutron decomposes into a proton, electron, and an antineutrino. The antineutrino is chargeless.

Any one or more of the above given processes happening within an isolated system will not change the net charge of the system.

3) Invariance

The magnitude of electric charge does not depend on the reference frame. In other words, it does not depend on whether the charge is at rest or it moves, the magnitude of the charge is the same in both the situations. We may say that charge is independent of velocity. This property of charge contrsts with that of mass. Mass of a body depends on its velocity. According to theory of relativity the mass of a body increses with velocity.

4) Quantization

The smallest observable amount of charge is that of an electron. Its magnitude is denoted by **e**. A neutral body gets charged by the addition or removal of electrons. Hence **the charge on any body is always an integer multiple of the charge of an electron**. This is known as **quantization of electric charge**

The charge q on any body can be written as,

$$\boxed{q = \pm ne}$$

where n = 1, 2, 3, ---

Example 1: How many electrons will make a total negative charge of one coulomb?

Solution: **q = ne**

$$n = \frac{q}{e} = \frac{-1\,C}{-1.6\times10^{-19}\,C} = \mathbf{6.25\times10^{18}}$$

Example 2 : A glass rod is rubbed with a silk cloth. The glass rod acquires a charge of $+19.2 \times 10^{-19}$ ***C.***

(i) Find the number of electrons lost by glass rod.

(ii) Find the negative charge acquired by silk.

(iii) Is there transfer of mass from glass to silk?

Solution: (i) Number of electrons lost by glass rod

$$n = \frac{q}{e} = \frac{19.2\times10^{-19}}{1.6\times10^{-19}} = \mathbf{12}$$

(ii) Charge on silk $= \mathbf{-19.2 \times 10^{-19}C}$

(iii) Since an electron has a finite mass ($m_e = 9.1 \times 10^{-31}$ kg), there will be transfer of mass from glass rod to silk cloth.

Mass transferred **M = nm$_e$** = 12 × (9.1 × 10^{-31}) = **1.092 × 10^{-29} kg**

Example 3: Calculate the total positive or negative charge on a 6.35 g copper coin. Given Avogadro's number = 6×10^{23} ; for copper Z = 29 and A = 63.5.

Solution: 63.5 g of copper has 6×10^{23} atoms.

No. of atoms in 1g copper $=\dfrac{6\times10^{23}}{63.5}$

No. of atoms in 6.35 g copper $=\dfrac{6\times10^{23}\times6.35}{63.5}=6\times10^{22}$

ie no. of atoms $n' = 6\times10^{22}$

no. of electrons $n = n'Z$

$= 6\times10^{22}\times29$

$q = \pm ne$

$= 6\times10^{22}\times29\times1.6\times10^{-19}\,C \quad = \pm\mathbf{2.78\times10^{5}\,C}$