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1.1 THE ELECTRIC CHARGE

- In a *dry weather night*, one may see "light **sparks**" while taking out a woolen sweater or when the fingers touch a metallic object. About four hundred years ago, one labelled these effects as *electric phenomena*. Objects that generate electric phenomena are known as "*electrically active*".
As a result of multiple observations, one could note that:
a) two " *electrically active* " objects can ***attract*** or ***repeal*** each other .
b) an object that behaves normally as *electrically neutral* may become *electrically active* after *friction.* Normally, a glass rod does not exert any action on other objects; but, after **rubbing it** to a piece of fur or silk, the rod becomes "*electrified* ". Even it can **attract** "*electrically neutral* " light objects. One says that, initially, the glass rod is *electrically inactive* and *after rubbing* it becomes ***electrically active***.

The scientific research has shown that *electric action* is at the origin of light, chemical reaction, many proprieties of materials and even at the function of human nervous system.

Some materials, known as *magnetic materials*, *attract* **iron** objects even without a *"preliminary friction"* . As you will see in this course, the origin of magnetic action is related to electric phenomena.

- Newton used the *gravitational mass* "**m**" to quantify and measure the *gravitational action* of an object on other objects. Similarly, one has introduced the *net electric charge* " **q** or **Q** " to quantify and measure the *electrical action* of an *electrically active* object on other objects.

- ***Electrostatics*** deals with the electric *action* due to a ***charged object at rest*** . As we will see in this course, a *charged object in motion,* besides the electrical action, produces magnetic effects, too.

- The experiments show that *the same charged* object may **attract** or **repel** *another charged* object. One has introduced the ***sign of electric charge*** to explain its two opposite possible actions.
There exist only two kind of charges; positive and negative. **Two charges of the same sign (+/+ or -/-) repel each other and two charges of different sign (+/-) attract each other**.

Experiments: (a) Two *neutral* polystyrene balls;
(b) A glass rod is charged by rubbing with silk. Then, the charged rod touches the two balls.
(c) The rod touches one ball and the silk the other one.

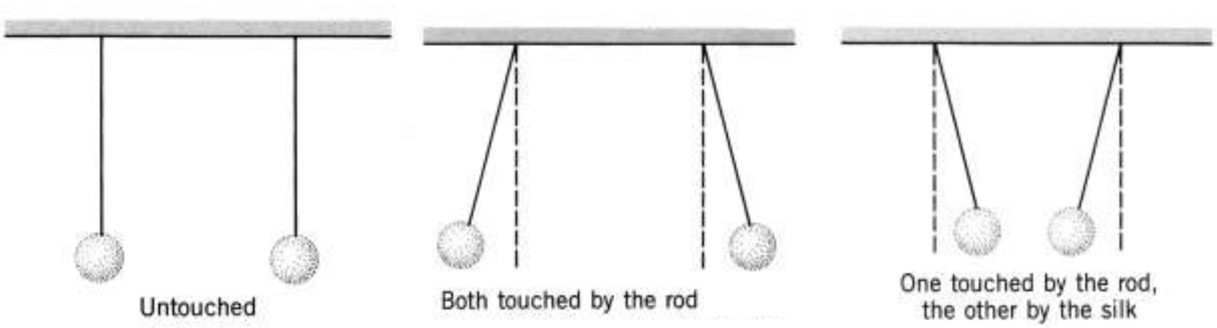


Fig1 (a- zero net charge) (b- same sign charge) (c- opposite sign charge)

Comment: When rubbed, the *glass rod* gets a "+" charge and *silk a* "-" *charge*. (This signs assignment is an arbitrary labelling by Benjamin Franklin). Next, by *touching* the balls, the rod and silk *transmit* a part of their charges to the polystyrene balls. (***b***) As two balls get charged with the *same sign* they *repel* each other ;
(***c***) As the balls get charged with *opposite sign* they *attract* each other.

- The extensive research about the ***amount of electric charge*** "q" contained in objects has revealed that:

- There exists a *minimum amount* of electric charge (*elementary charge*) contained in an object; $\mathbf{q_{min} \equiv e}$
- Electrons and protons contain both this *amount of* electrical *charge* but the electron charge is negative and proton charge is positive ($q_{el.} = -\,e$; $q_{pr.} = +\,e$). The neutrons have no electric charge ($q_n = 0$).
- A *neutral atom* contains equal number of electrons and protons and consequently, it has *zero net electric charge* (Ex. Atom of He has [2pr +2neut] +2el; its net. el. charge= [+2e+0]+[-2e]) = 0). A macroscopic object contains a huge number of atoms; so, it contains a big number of elementary electric charges.
  An object that contains only neutral atoms is electrically neutral.
- Electrically charged atoms (or molecules) are called ***ions***. An atom (or molecule) that have lost one or several electrons *becomes a positively charged* ***ion***; if it hosts additional electrons it becomes *negatively charged* ***ion***. A macroscopic object may contain ions but, if its ***total charge*** is zero, it will be electrically neutral. An object is electrically **charged** only if its **total charge is unbalanced**.
- When two *neutral* materials but "*electrically different* " (i.e. located far to each other in triboelectric table) get in touch to each other, a small amount of electric charge get transferred from one to the other, *even without friction*. If one rub them to each other, the transfer of electric charges is enhanced and one can observe easier the effects related to the electric charge.
- The same object may get the two kinds of charges depending on the other object in contact.
  Ex: a) *Silk* rubbed on a Glass rod --- *Silk* get " - " charge and Glass rod get " + " charge.
  b) *Silk* rubbed on a Teflon rod --- *Silk* get " + " charge and Teflon rod get " -" charge.
  Note that a direct outcome of this conventional sign labelling chosen by B. Franklin is the " - " sign of electron charge and " + " sign of charge of proton.

Table #1 The triboelectric effect table.

- Human hands (usually too moist, though) **Acquires a positive charge " + "**
- Rabbit Fur
- Glass
- Human hair
- Nylon
- Wool
- Fur
- Lead
- Silk
- Aluminum
- Paper
- Cotton
- Steel
- Wood
- Amber
- Hard rubber
- Nickel, Copper
- Brass, Silver
- Gold, Platinum
- Polyester
- Styrene (Styrofoam)
- Saran Wrap
- Polyurethane
- Polyethylene (like Scotch Tape)
- Polypropylene
- Vinyl (PVC)
- Silicon
- Teflon **Acquires a negative charge " - "**

(This list is adapted from Nature's Electricity, by Charles K. Adams.)

The triboelectric effect is the transfer of electric charges between two different neutral material brought into contact.

The **relative position** of two substances in the triboelectric table tells what sign of charge they will get.
Glass rubbed by silk causes a charge transfer such that they get charged ; glass get the charge " +q " and silk get the charge " -q ".
The farther is the separation in the table, the greater is the amount of the charge ”q” transferred.

1.2 THE QUANTITATIVE DEFINITION OF ELECTRIC CHARGE

-The definition of mass unit (1kg) is based on a ***standard***, which does not change, even for a very long time. One cannot define the unit of electric charge in the same way because it is very difficult to keep it constant in time; the experimental measurements show that *electric charges leak easily*. For this reason, one defines the electric charge unit as a *derived unit* based on its relation to the standard of *current rate (1A in SI system)*. One can measure the current with a high accuracy and precision at any time. The ***definition of current*** is ***:***

$$I = \frac{dq}{dt} \qquad (1)$$

If one measures a *current rate* **1 Ampere**, this means that an electric charge q = **1 Coulomb** *(unit amount of electric charge in SI system)* pass through each cross section of conductor during **1 sec**.
Note that one coulomb (1 C) corresponds to a large amount of electric charge. Typically, the charge acquired by objects through rubbing is of order ~ 10^{-8} C but a lightning bolt transfers around ~20C of electric charge.

-As the minimum amount of charge is " **e** ", it comes out that any electrical charge is a multiple of " **e** ". Milliken measured for the first time (1909) the charge of electron (i.e. basic amount **e**) and found that it is

$$e \cong 1.602 * 10^{-19} C \qquad (2)$$

Remember that ; $q_{electron} = -e$; $q_{proton} = +e$; $q_{neutron} = 0e$

- ***<u>Electric charge</u>*** **<u>conservation rule</u>**: " *If a charged object is perfectly <u>isolated</u> , its electric charge is conserved. Also, an <u>isolated system</u> containing several charged objects conserves its total electric charge* ". This rule allows the electric charge transfers inside the same object or from one object to another object inside the system, but the ***<u>net charge</u>*** of the isolated object or the whole system does not change with time. *In practice, one isolates a charged object by avoiding its contact with conductors or damp air.*

Note that, the ***<u>electric charge conservation</u>*** **rule (**or principle**)** is equally **valid in microscopic world.**
Ex: a) Chemical reaction: The *<u>system of two ions</u>* inside an electrolytic solution (Na^+ and Cl^-)
Before the chemical reaction (*ions far to each other*) and after reaction (*ions tightly bound together*).
If an interaction between system parts (inside system) happens $Na^+ + Cl^- \Rightarrow NaCl(neutral)$
The total *charge of system* does not change: before (+e) + (-e) = 0C ; after 0C
b) Beta (β^-) radioactivity; One neutron is decomposed in a proton, an electron and an antineutrino.

$$n \Rightarrow p + e + \bar{\nu}$$

Total charge of system: before the event 0C : after the event *(+e*) + (-*e*) + (*0e*) *= 0C*

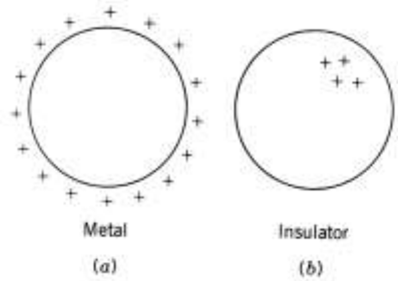
1.3 CONDUCTORS AND INSULATORS

-The following classification of materials is based on the ability of electric charges to move through them.

a) **Insulators**; materials where the charge *<u>cannot move freely</u>* (rubber, plastic, *distillated* water,..)
b) **Semiconductors**; essentially insulator materials which conducting ability is increased in a ***controlled manner*** by adding small amounts of *impurities* (carbon, siliceous, germanium,..) that bring a controlled number of unbalanced free electric charges into the volume of main material.
c) **Conductors**; material where charges *<u>move almost freely</u>* (metals, ionic solutions, tap water, human body, earth.).
d) **Superconductors**; materials where the charge *<u>moves perfectly freely</u>* (special materials).

When electric charges are transferred *on a conductor(ex. a metal)*, due to reciprocal electric repeal and the free motion possibility, they are distributed instantaneously over its entire surface. In the case of a *perfect insulator(ex. glass)* the charges remain concentrated around the area of contact with charging object (fig 2).

Fig.2



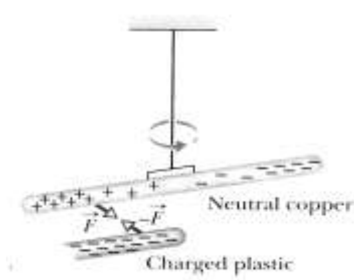
- The ***conductivity*** of a material depends on the ***outer*** and loosely bound ***valence electrons of its atoms***.
  a) In the case of metals, the valence electrons escape easily from atom structures and practically move freely through the metal volume. These free electrons are at origin of conductivity of metal.
  b) In case of insulator materials, valence electrons are bound strongly and they cannot through the material volume.
  c) The impurities in semiconductor materials are sources of free electrons and the amount of impurities decides about the number of available free electrons in a semiconductor.
  d) A fluid (*liquid or gas*) may be a very good insulator (*if there are no ions inside it*) or a good conductor (*if there are free ions inside it*) but its electric conductivity is always lower compared to that of a metal because the *ions are less mobile that electrons* (due to their much larger mass).
  Ex. (tap water is a conductor of electricity because it contains free ions, but the distilled water is an insulator because it does not contain free ions)

- One may eliminate the ***excess charge*** of a conductor by " **grounding** " i.e. connecting it via a wire to the **earth** which is **a conductor** behaving as **large container of charges**. If the excess charge is ' - ' the grounding transfers " *free e-* " to the earth; if the excess charge is ' + ' the grounding transfers " *free e-* " from the earth to the object allowing the object to get a neutral (zero) net charge. (Ex: lighting-rods)
Note: The human body is a good conductor but its skin is an insulator which insulates pretty well for low values of electric fields. Note that the skin cannot insulate for high values of field.

1.4 CHARGING BY INDUCTION

- Due to the mobility of its charges, a *neutral conducting object* ***can*** *get charge polarization by induction*; that is without touching other charged objects. In fig.3, a negatively charged plastic rod attracts nearby end of an *neutral cooper rod*. This happens because the free electrons in this end of cooper rod are repelled by the *negative* charge on plastic rod. Forced to move to the other end of cooper rod, these electrons leave the closer end with *unbalanced positive charge*; consequently, the plastic rod attracts this end.
Note that the net total charge of cooper rod is still zero but it has opposite *charges induced at its ends*. One says that ***the induction*** produces a ***polarized charge*** in a neutral object or simply " ***polarizes the object*** ". Besides, by a middle cut of cooper rod, one can get two half ***rods charged*** equally but with ***opposite sign***.

Fig. 3

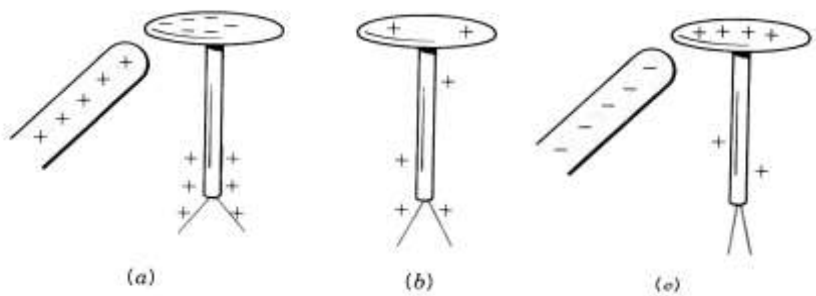


Notes: a) In *solid conductors*, only the free electrons (-e) can move; the positive ions remain fixed to the corners of crystal lattice cells.

b) In the case of *insulators, the induction can polarize the charges only inside the molecule but the* electrons cannot escape out of these molecules. This does produce a charge polarization of the whole object but it is much smaller compared to that of conducting materials.
Also, one cannot produce two charged pieces by cutting a polarized insulator.

- The *electroscope* is a device that makes use of *electric induction* to detect the presence of electric charge in an object (rod in fig4.a) without touching it. Also, one may use the electroscope to *compare the sign* of charges in two different charged objects (by touching the first object fig4.b ; then approaching the other one /c). Note that, one cannot measure the amount of electric charge in an object by an electroscope.

Fig. 4



1.6 COULOMB'S LAW

In 1785, Charles Coulomb discovered *by experimental measurements* the basic law of electrostatics; i.e. the mathematical expression for the electric force between ***two point electrical charges***.

The **magnitude of electrostatic force exerted on each of two point charges (q, Q) at a distance " *r* "is**

$$F = k\frac{q*Q}{r^2} \qquad (3)$$

The vector form of Coulombs law is written as follows

$$\vec{F}_{qQ} = F_{qQ} * \hat{r} = k\frac{q*Q}{r^2}\hat{r} \qquad (4)$$

The unit vector $\hat{r}$ has *no dimensions*, has unit magnitude and is directed from the "**charge that exerts the force to the charge on which the electrostatic force is applied**".

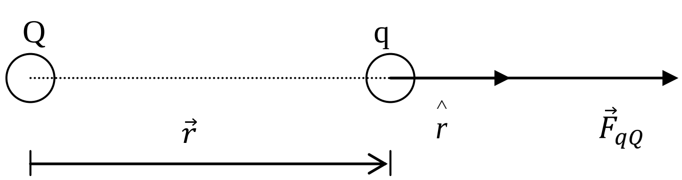


Fig.5 "Q" the source of force; "q" experiences the force; If Q&q have the same sign, the force is repulsive.

One must ***include the signs*** for " q " and " Q " in expression (4) to get the direction of the exerted force $\vec{F}$. If the two charges have the *same sign*, there is a *repulsive force*; if they have *opposite signs* there is an *attractive force*. The two charges in figure 5, have the same sign; so, the force acting on charge " q " is a repulsive force. The force acting on " Q " has the same magnitude but it is directed in opposite direction.

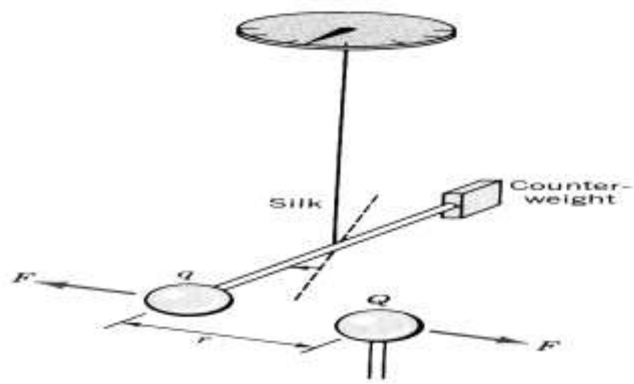
- The magnitude of electrostatic constant " k " in SI system is $k = 9*10^9 Nm^2/C^2$. In majority of electricity books this constant is expressed as $k = 1/4\pi\varepsilon_0$ where $\varepsilon_0 = 8.8510^{-12} C^2/(Nm^2)$ is the ***electric permittivity constant* of vacuum** and the expression (3) appears in the form

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q*Q}{r^2} \qquad (5)$$

One uses this substitution because it simplifies greatly the mathematical expression of all relations in electricity, especially in the theory of electro magnetic fields (Maxwell's theory).

- It is interesting to mention that Coulomb:
  a) measured the magnitude of electric force by using a torsion balance (fig.6)
  b) worked with relative values of electric charge. He used the fact that the charge on a metallic sphere (Q) is distributed equally (Q/2, Q/2) after touching it with another identical sphere. By this procedure he could transfer different quantity of charge (Q/2,Q/4,Q/8,..) on several identical spheres.

Figure 6



- Important notes:

  a) In **electrostatics**, ***all electrical charges*** are considered to be ***at rest***.

  b) When an *excess charge* is transferred on a <u>*conducting sphere*</u>, the charge elements tent to go far from each other (the same sign charges repeal each other). Due to the sphere symmetry, the excess <u>*charge get uniformly distributed*</u> over the sphere surface.

  One may prove that the electric force ***exerted by a charged conducting sphere***:
  1. ***on a point charge*** *"placed "* ***<u>out</u> of the sphere volume is the same as if the total charge of sphere were located at its center***.
  2. ***on a point charge*** *"placed "* ***somewhere <u>inside</u> the sphere volume is zero.***

c) If the distance between two charged objects is much larger than their dimensions one may apply the Coulomb's law as if they were point charges (even if they are not conductors and have not a spherical form) .

d) One has *proved experimentally* that Coulomb's law provides accurate results even for electric forces acting *at molecular and atomic level*. This law does describe perfectly the electric interactions between electrons and protons inside an atom, the action of electric forces on binding of atoms into a molecule and the binding of molecules into a liquid or solid.

THE SUPERPOSITION PRINCIPLE

- If "N " different charges "q_i" apply electric forces on an electrical charge " q_1" , one can find the total electric force exerted on " q_1" by using the principle of linear superposition (fig 7):

$$\vec{F}_1 = \vec{F}_{12} + \vec{F}_{13} + \dots\dots\dots\dots \vec{F}_{1N} \qquad (6)$$

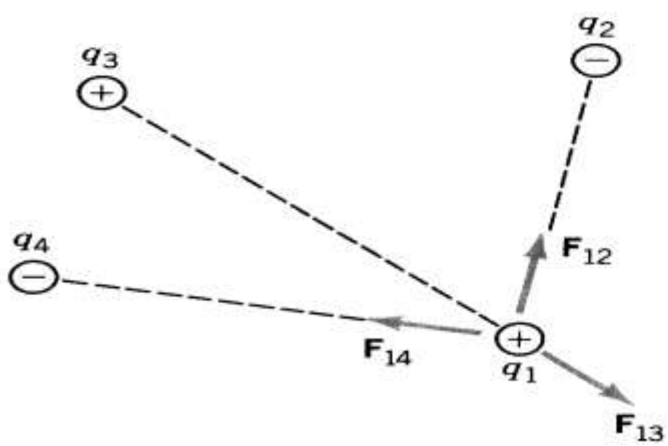


Fig 7

The notation $\vec{F}_{ij}$ means the force exerted on point charge " i " by the point charge " j ".

It is important to remind that in any situations (attraction or repulsion) the interaction between two point charges obeys to the reciprocal relation (third law of Newton).

$$\vec{F}_{ij} = -\vec{F}_{ji} \qquad (7)$$

(Example: For i=1 and j=2 $\vec{F}_{12} = -\vec{F}_{21}$)