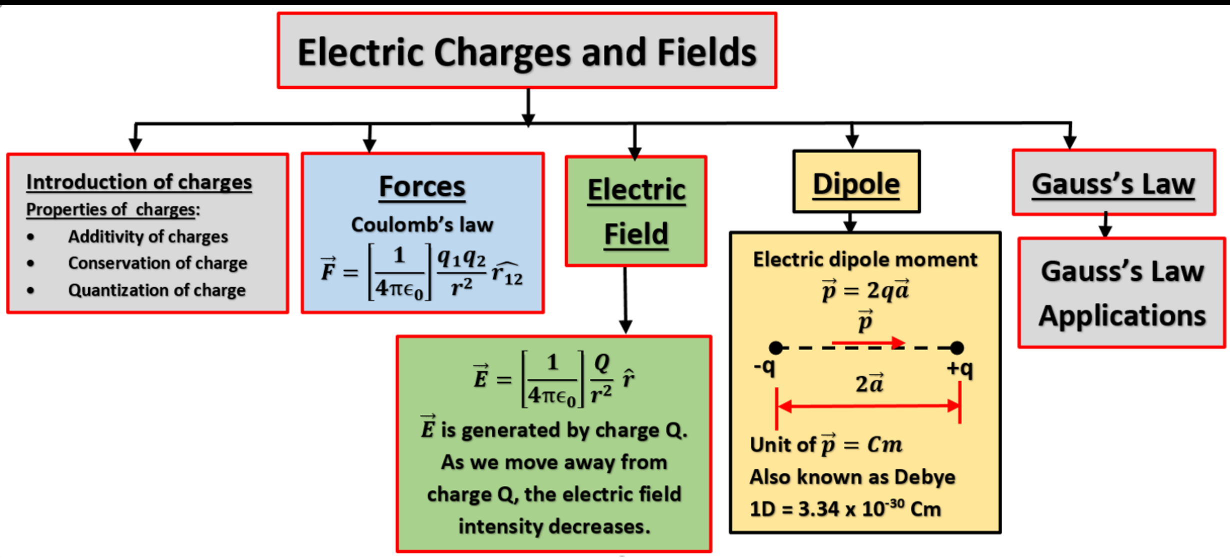
Chapter 1: Electric Charges and Fields [Electrostatics ; Charges at rest]

Syllabus as per NCERT book

1. Introduction
2. Electric Charge
3. Conductors and Insulators
4. Charging by Induction
5. Basic Properties of Electric Charge
6. Coulomb's Law
7. Forces between Multiple Charges
8. Electric Field
9. Electric Field Lines
10. Electric Flux
11. Electric Dipole
12. Dipole in a Uniform External Field
13. Continuous Charge Distribution
14. Gauss's Law
15. Applications of Gauss's Law

Grouping of Syllabus

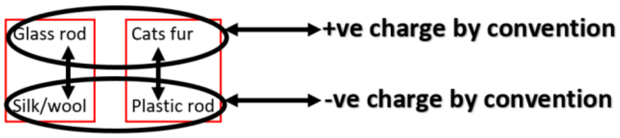
Introduction Electric Charge Conductors and Insulators Charging by Induction Basic Properties of Electric Charge	
Coulomb's Law (CL) Forces between Multiple Charges	• CL in terms of "displacement vector" & "position vector" • Problems related to forces between charges
Electric Field Electric Field Lines Electric Flux	
Electric Dipole Dipole in a Uniform External Field Continuous Charge Distribution	
Gauss's Law Applications of Gauss's Law	



Main topics for discussing this chapter (Highlights only)

Main topics

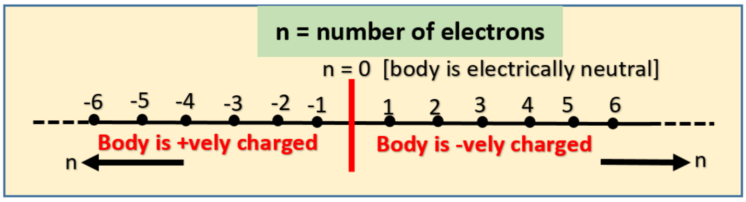
- Background 2500 yrs back …amber ---- wool …ignored
- 1600 → Gilbert suggested more materials
- Rubbing Vs friction
    - Frictional electricity
    - Static electricity
    - Electrostatics
- On being electrified, the material is said to have acquired "charge".
    - "Electrified material" is aka "charged material"
- Electron was discovered by JJ Thomson in 1897
- **"e" is the smallest unit of charge called as "elementary charge" [$e = 1.6 \times 10^{-19}C$]**
- It is so small that we don't experience the quantization of charge in daily life.



- **Static electricity on body → electrons are responsible , not protons → since it is very difficult to pull-out protons from the nucleus.**
- **Properties of electric charge:**
    - Additivity of charges
    - Conservation of charges
    - Quantization of charges ($e = 1.6 \times 10^{-19}C$)
        - Due to this, the total charge on a body is integral multiple of elementary charge. That is …if Q is the charge on a given body, then it is be equal to Q = ne ; **where n is an integer** and e is the elementary charge = $1.6 \times 10^{-19}C$. A body cannot have any random charge as per quantization principle. This was suggested by Faraday and experimentally confirmed by Millikan in 1912.
        - If a neutral body has gained one electron, what is the charge on the body → Q = ne = 1xe = e → the body has the charge of an electron. The body is said to be –vely charged and with a charge = e ⟹ Q = -e
- **A body can be charged positively by losing some of its electrons ; similarly, a body can be charged negatively by gaining electrons. Therefore, the gaining and losing of electrons by the body will automatically satisfy quantization of charge on the body.**

- A body has -1C charge. How many electrons are there in the body?
    - Q = ne → $n = Q/e = -1C/ -1.6\times10^{-19}C = (10/16)\times 10^{19} = + 6.25 \times 10^{18}$ electrons
    - A body having -1C charge has 6.25×10^{18} excess (indicated by + for 'n') electrons

- A body has +1C charge. How many electrons are lost in the body?
    - Q = ne → $n = Q/e = +1C/ -1.6\times10^{-19}C = -(10/16)\times 10^{19} = - 6.25 \times 10^{18}$ electrons
    - A body having +1C charge has 6.25×10^{18} deficit (indicated by - for 'n') of electrons



Explanation of the above diagram:

- [n = 0] represents that no electron is removed from or added to the body. Hence the body is neutral.
- [n = 1,2,3 etc…] represents so many electrons being **added** to the body and the body is said to be negatively charged.
- [n = -1,-2,-3 etc…] represents so many electrons being **removed** from the body and the body is said to be positively charged.

Hence, a body can be charged positively by losing some of its electrons ; similarly, a body can be charged negatively by gaining electrons. Therefore, the gaining and losing of electrons by the body will automatically satisfy quantization of charge on the body.

- Like charges repel and unlike charges attract

Main topics for discussing this chapter (Highlights only)

Main topics

Electric Field ($\vec{E}$)

- $\vec{E}$ introduction
  - Force on a "test charge" [The test charge should not disturb the source charge]
  - Capacitor
  - e-m theory
- One example on page 23
- Field lines (don't use the word "lines of force")
- Force due to +ve charge, -ve charge and the dipole
- System of charges → Find $\vec{E}$
- Problems on $\vec{E}$

Dipole

- Why we need to study dipole → chemistry molecules and properties
  - Electronegativity (oxygen → 3.5, H → 2.1)
  - Non-polar molecules [cl-cl, CO_2, CH_4 etc…]
  - Polar molecules (H_2O, Hcl) → electrical imbalance
- Electric dipole definition ; Electric dipole moment $\vec{p} = 2q\vec{a}$
  - Direction of P *is from* $-$ *ve charge to the* $+$ *ve charge*
  - Unit of dipole (Cm) [also Debye D ; 1 D = 3.34 x 10^{-30} Cm]
- Electric field $\vec{E}$ created by the dipole
  - Any general point p
  - Special cases
    - Axial point ; $E = \frac{2\vec{p}}{4\pi\epsilon_0 r^3}$
    - Equatorial point ; $E = \frac{\vec{p}}{4\pi\epsilon_0 r^3}$
- Problems on dipole [page 40a]
- When dipole is placed in an External Electric field
  - Uniform electric field [net force = 0 ; $\vec{\tau} = \vec{p}\, x\, \vec{E}$ = PE sinθ]
    - Couple acts on dipole → called restoring couple
    - Moment of this restoring couple is called Torque
    - Direction of torque (vector method)
  - Non-uniform electric field
    - $\vec{p}$ *parallel to* $\vec{E}$
    - $\vec{p}$ *antiparallel to* $\vec{E}$

Continuous charge distribution

Electric Flux

- We know that $\vec{E}$ is visualized by field lines
- $\Delta\phi = \vec{E}.\vec{\Delta S}$ = E ΔS cosθ
- Unit of electric flux : Nm^2C^{-1} or Vm

Gauss law in electrostatics $\phi = q/\epsilon_0$ where q is the total charge enclosed by the closed Gaussian surface S → prove that using a sphere. (page 43)

- Gauss law is another way of expressing coulomb's law.
- Net flux through a cylinder = 0 [no charge enclosed by surface → page 44]
- $\varphi = \frac{q}{\epsilon_0}$; LHS represents electric field due to all charges both inside and outside the Gaussian surface ; RHS represents charges enclosed by surface S

Application of Gauss law:

- Field due to an infinitely long straight uniformly charged wire
- Field due to a uniformly "charged" infinite plane sheet
- Field due to a uniformly charged thin spherical shell / non-conducting sphere
  - Field at points outside the shell
  - Field at points inside the shell
  - Field at points on the shell

Unification of Electricity, Magnetism and light [Informative]

- In olden days, electricity and magnetism were treated as separate subjects
- Electricity deals with "charges" on glass/plastic rods, cat's fur, batteries, lighting etc… [Note that Franklin named 2 types of charges as (1) positive and another (2) negative.
- Magnetism described interaction of magnets, iron filings, compass needle etc…

- In 1820, Oersted found that the compass needle is deflected by passing an electric current through a wire placed near the compass needle **** [Note: Electron was discovered by J.J. Thompson in 1897]

Ampere and Faraday said

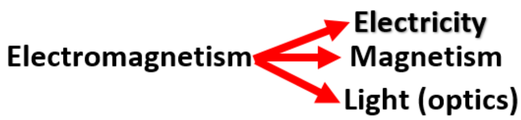
- Electric charges in motion produce magnetic fields
- Moving magnets generate electricity.

- The unification was achieved by Maxwell who put forward 4 equations, which becomes basis for quantum theory.

Lorentz Force:

- Suppose there is a point charge q moving (with a velocity v and located a "r" at a given time t) in presence of both electric field $[\vec{E}(r)]$ and the magnetic field $[\vec{B}(r)]$. The force experienced by the point charge q due to $\vec{E}$ and $\vec{B}$ fields is given by
- $\vec{F} = q\vec{E}(r) + q[\vec{v}\ x\ \vec{B}(r)] \ \ --\rightarrow \ \ F_{electric} + F_{magnetic}$. In simplified notation, we can write
- $\vec{F} = q\vec{E} + q[\vec{v}\ x\ \vec{B}]$ ----- (1) * $\vec{v}\ x\ \vec{B}$ *is the cross product of* v *and* B. Explanation of equation (1) is as follows
- Force is $\perp^r$ to the plane containing $\vec{v}$ *and* $\vec{B}$
- If $\vec{v}$ *and* $\vec{B}$ *are* $\perp^r$ *to each other*, then we can use **Fleming's Left Hand Rule (FLHR)** to find the direction of force.
- If $\vec{v}$ *and* $\vec{B}$ *are not* $\perp^r$ *to each other*, then we can use **right hand thumb + folded fingers rule** to find the direction of force $\vec{F}$.

- Maxwell also argued that "light" is also e-m in nature and tis speed can be found by making purely electric and magnetic measurements. Therefore, optics is intimately related to electricity and magnetism.



- Therefore, E-M Force is one of the fundamental forces in nature.

Introduction

- Experience of seeing or feeling something in nature in our daily life leads to several branches of physics.
- Examples:
  - Seeing a spark or hearing a crackle when take off our synthetic clothes or sweater, particular in dry weather.
  - Electric discharge → Lightening is a common example.
  - Sensation of electric shock while touching a tap or car door
- These are all due to static electricity (static means anything that does not move or change with time)
- Electrostatics deals with the study of forces, fields and potentials arsing due to static charges.

- Electric charges:

Positive charge	Negative charge
Glass rod ↔	Silk or wool
Cat's fur ↔	Plastic rod

- If 2 glass rods rubbed with wool or silk cloth are brought close to each other m they repel each other.
- The 2 strands of wool or 2 pieces of silk cloth, with which the glass rods are were rubbed also repel each other.
- However, the glass rod and wool (or silk cloth) attracted each other

- Similarly, 2 plastic rods rubbed with cat's fur repelled each other, but attracted the fur
- However, plastic rod attracts the glass rod and repel the silk or wool with which the glass rod is rubbed.
- The glass rod repels the cat's fur.

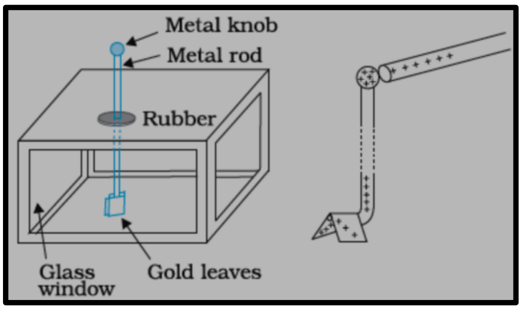
- Thus, there must be 2 types of charges. Benjamin Franklin in 1750 suggested that there are 2 types of charges → positive and negative. **Note : electron was discovered by JJ Thomson in 1897*
- By convention, charge on glass rod or cat's fur is called "positive" and the charge on plastic rod or silk (wool) is called "Negative"

- If an object possesses an electric charge, it is said to be electrified or charged. When it has no charge, the object is said to be neutral.

Informative: [from Nootan's book]

- About 2500 years back, a philosopher Thales observed that when a material named "amber" is rubbed with wool, the amber acquires the property of attracting light bodies such as pieces of paper, straws etc. However, this observation was not given any importance for about 2000 years.
- In 1600, Gilbert discovered that like amber several other materials such as glass, ebonite etc. also on being rubbed attract light bodies.
- Clearly, this property in the materials is developed due to rubbing (that is by friction). On acquiring this property the material is said to be electrified and the cause due to which this property is developed is called "frictional electricity".
- On being electrified, the material is said to have acquired "charge". Hence an electrified material is also called as "charged material".
- Frictional electricity is also known as "static" electricity because the charge acquired by the material cannot flow from one point to the other.

Gold-leaf electroscope (GLE):



- GLE is an instrument which is used for detecting the presence of electric charge and its [polarity (that is + or – sign of charge). GLE is also used for measuring the potential difference.
- A simple apparatus to detect charge on a body is the gold-leaf electroscope [See fig]. It consists of a vertical metal rod housed in a box, with two thin gold leaves attached to its bottom end.
- When a charged object touches the metal knob at the top of the rod, charge flows on to the leaves and they diverge.
- The degree of divergence is an indicator of the amount of charge.

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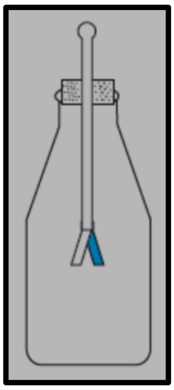
Schematics of a simple electroscope:

- Students can make a simple electroscope as follows [**See Fig** →→→→→→→→→
- Take a thin aluminium curtain rod with ball ends fitted for hanging the curtain. Cut out a piece of length about 20 cm with the ball at one end and flatten the cut end.
- Take a large bottle that can hold this rod and a cork which will fit in the opening of the bottle. Make a hole in the cork sufficient to hold the curtain rod snugly. Slide the rod through the hole in the cork with the cut end on the lower side and ball end projecting above the cork.
- Fold a small, thin aluminium foil (about 6 cm in length) in the middle and attach it to the flattened end of the rod by cellulose tape. This forms the leaves of your electroscope. Fit the cork in the bottle with about 5 cm of the ball end projecting above the cork. A paper scale may be put inside the bottle in advance to measure the separation of leaves.
- The separation is a rough measure of the amount of charge on the electroscope.



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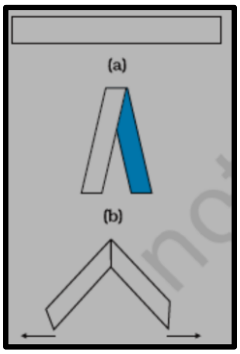
Paper strip experiment:

- To understand how the electroscope works, use the white paper strips we used for seeing the attraction of charged bodies. Fold the strips into half so that you make a mark of fold. Open the strip and iron it lightly with the mountain fold up, as shown in Fig →→→→→
- Hold the strip by pinching it at the fold. You would notice that the two halves move apart. This shows that the strip has acquired charge on ironing. When you fold it into half, both the halves have the same charge. Hence they repel each other. The same effect is seen in the leaf electroscope. On charging the curtain rod by touching the ball end with an electrified body, charge is transferred to the curtain rod and the attached aluminium foil. Both the halves of the foil get similar charge and therefore repel each other.
- The divergence in the leaves depends on the amount of charge on them. Let us first try to understand why material bodies acquire charge.



- You know that all matter is made up of atoms and/or molecules. Although normally the materials are electrically neutral, they do contain charges; but their charges are exactly balanced.
- Forces that hold the molecules together, forces that hold atoms together in a solid, the adhesive force of glue, forces associated with surface tension, all are basically electrical in nature, arising from the forces between charged particles.
- Thus the electric force is all pervasive and it encompasses almost each and every field associated with our life. It is therefore essential that we learn more about such a force.

- To electrify a neural body, we need to add or remove one kind of charge in the neutral body.
- When we say that a body is charged , we always refer to this as excess charge or deficit of charge.
- A body can be charged positively by losing some of its electrons
- Similarly, a body can be charged negatively by gaining electrons.

- Ex: when we rub a glass rod with silk, some of the electrons from the rod are transferred to the silk cloth. Thus, the rod gets positively charged and the silk gets –vely charged.
- Note that no new charge gets created in the process of rubbing. Also, the number of electrons that are transferred is a very small faction of the total number of electrons in the material body.
- Only the less tightly bound electrons in the material body can be transferred from it to another by rubbing.
- Therefore, when a body is rubbed with another, the bodies gets charged and that is why we have to stick to certain pairs of materials to notice charging on rubbing the bodies.

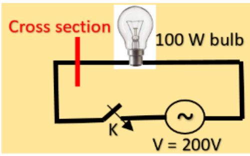
- Number of electrons = number of protons. Hence the atom as a whole is neutral. This is why there is no electrical attraction or repulsion in ordinary bodies.

- When somehow one or more electrons are extracted from an atom, the atom becomes +vely charged. A +vely charged body means deficiency of electrons in its atoms.

- Conversely, if an atom is given one or more electrons, it becomes –vely charged. Thus, negatively charged body means excess of electrons.
- **For the electrification of a body, only electrons are responsible, not the protons because it is not easy to remove the proton from the nucleus.**

- Later we will know the formula q = ne ; for electrons n = number of electrons ; q is the charge on the body
- e = charge on electron = -1.6 x 10^{-19} C ; charge on proton = +1.6 x 10^{-19} C
- Example : for electron if charge on the body is -1 C ; the number of excess electrons that the body has is given by
- $n = \frac{q}{e} = \frac{-1\,C}{-1.6\,x\,10^{-19}C} = \frac{10}{16}x\,10^{19} = \frac{5}{8}x\,10^{19} = +6.25\,x\,10^{18}$ (which is an integer)
- There are $6.25\,x\,10^{18}$ electrons in a body whose charge = - 1C. The body is having $6.25\,x\,10^{18}$ excess electrons
- Similarly, for a charge of +1 C, $n = \frac{q}{e} = \frac{1\,C}{-1.6\,x\,10^{-19}C} = -\frac{10}{16}x\,10^{19} = -6.25\,x\,10^{18}$. The negative sign of n indicates that the body is having $6.25\,x\,10^{18}$ deficit of electrons. Don't say that the body has $6.25\,x\,10^{18}$ excess protons. It is only that the electrons take part in deciding the charge on the body.

Problem : How many electrons flow per second at the cross section (see diagram) from a 100 W/200V bulb



- When switch K is closed, the bulb will glow.
- Power of the bulb = 100W rated at a voltage of 200 V ;
- Power P = VI, I = P/V = 100W/200V = 0.5 A
- The rms value of the current in the circuit I = 0.5 A
- Assuming the current is steady, the current is given by rate of flow of charge → I = q/t
- If we take any cross section in the circuit, the charge crossing the cross section per second is given by q = It = 0.5 x 1 = 0.5 C
- Therefore, the number of electrons crossing in one second is given by $n = \frac{q}{e} = \frac{0.5\,C}{1.6\,x\,10^{-19}C} \approx 3\,x\,10^{18}$

In the above problem, for a 200W/200V rated bulb, n = $6\,x\,10^{18}$ *electrons crossing the cross section* per second.

Sec 1.3 of NCERT book: Conductors and Insulators / (and semiconductors)
➢ Some substances readily allow passage of electricity through them , others do not. Those which allow electricity to pass through easily are called "conductors". They have elective charges (electrons) that are comparatively free to move inside the material. Metals, human and animal bodies and earth are conductors.
➢ Most of the non-metals like glass, porcelain plastic nylon, wood offer high resistance to the passage of electricity through them. They are called Insulators.
➢ Most substances fall into one of the two classes stated above (there is a third category called semiconductors that would be discussed elsewhere).
➢ When some charge is transferred to a conductor, it readily gets distributed over the entire surface of the conductor.
➢ In contrast, if some charge is put on an insulator it stays at the same place (see next chapter for why this happens)
➢ This property of materials tells you why a nylon or plastic comb gets electrified on combing dry hair or on running; but a metal object like spoon does not. The charges on metal leak through our body to the ground as both are conductors of electivity.
➢ The process of sharing the charges with the earth is called "grounding" or "earthing" which prevents damage to the electrical appliances and causing injury to the humans.

Q : A +vely charged glass rod attracts a suspended pith ball. Is the ball necessarily negatively charged ?

➢ No. The +vely charged rod can attract an uncharged ball as well as a –vely charged ball.

Q: If the glass rod repels the pith ball, then is the ball necessarily positively charged ?

➢ Yes, the positively charged glass rod can repel the pith ball only the ball is positively charged. In fact, repulsion is a surer test of electric force between charges.

Q : How many electrons must be removed from a piece of metal to give it +1.0 x 10^{-7} C of charge ?

➢ We can use the formula Q= ne, where Q is the charge on metal we want by removing electrons from metal.

Given Q = +1.0 x 10^{-7} C ; e = -1.6 x 10^{-19} C ; n = Q/e = $\frac{+1.0\ x\ 10^{-7}\ C}{-\ 1.6\ x\ 10^{-19}C} = -6.25\ x10^{11}$

The negative sign of n indicates electrons are removed from the metal ; So, to make the metal +vely charged to get finally +1.0 x 10^{-7} C , $6.25\ x10^{11}$ electrons to be removed from the metal.

Q : Calculate the charge carried by 12.5 x 10^{18} electrons.

➢ q = ne = (12.5 x 10^{18}) x (-1.6 x 10^{-19} C) = -1.25 x 1.6 = -2 C

Q : The charge on a conductor is -1.6 C. How many electrons are in excess on it than the normal neutral state?

➢ q = ne ; n = q/e = $\frac{-1.6\ C}{-\ 1.6\ x\ 10^{-19}C} = 10^{19}\ elecrons\ are\ in\ excess$

Q: A conductor has 2.4 x 10^{-18} C of positive charge. How many electrons are in excess or short?

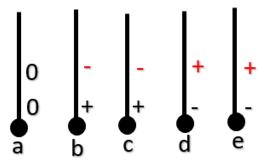
➢ q = ne ; n = q/e = $\frac{+\ 2.4\ x\ 10^{-18}C}{-\ 1.6\ x\ 10^{-19}C} = -\frac{240}{16} = \ -15\ shortage\ of\ electrons$

Q: An isolated metallic conductor is +vely charged. Will it mass increase, decrease or remains the same ? What if the conductor is –vely charged ?

➢ If metallic conductor is +vely charged, it would have lost some electrons → hence mass will decrease

➢ If metallic conductor is -vely charged, it would have gained some electrons → hence mass will increase

Q: 5 balls marked a to e are suspended using separate threads. Pairs (b,c) and (d,e) show e-s repulsion, while pairs (a,b), (c,e) and (a,e) show e-s attraction, What is the nature of charge of ball "a" ?



➢ Since (b,c) and (d,e) show e-s repulsion, b and c must be both +ve or both negative. Same for Pairs d and e. **So, balls b, c ,d, e must be all charged balls. Otherwise e-s repulsion cannot happen ; e-s repulsion can happen only when both the balls are charged]. So b, c ,d, e balls are charged ones, what about the ball "a" (see fig).**

➢ Since +vely charged or –vely charged balls can attract uncharged (neutral) ball, **the ball "a" must be neutral**.

➢ +vely charged or –vely charged ball cannot repel uncharged (neutral) ball, therefore, repulsion is the surer test of electric force between (both) charged bodies.

Q : Can an object or a body possess a charge of 2.8 x 10^{-18} C?

q = ne ; n = q/e = $\frac{2.8\ x\ 10^{-18}\ C}{-\ 1.6\ x\ 10^{-19}C} = 17.5\ which\ is\ not\ an\ integer$. As per quantization of electric charges, the number of elementary charges must be an integer. Since n is not an integer in this case, the object cannot have the given charge.

Info :

➢ Rate of flow of electric charge through a conductor is called electric current in the conductor. So, I = q/t or q = It

➢ Charge of electron = -e [$e = \ 1.6\ x\ 10^{-19}C$]

➢ Charge of proton = +e

➢ Charge of α-particle = +2e

➢ e is the smallest unit of charge, it is called "elementary charge"

➢ The value of elementary charge is so small that we do not experience the quantization of charge in daily life

1.4 Charging by Induction

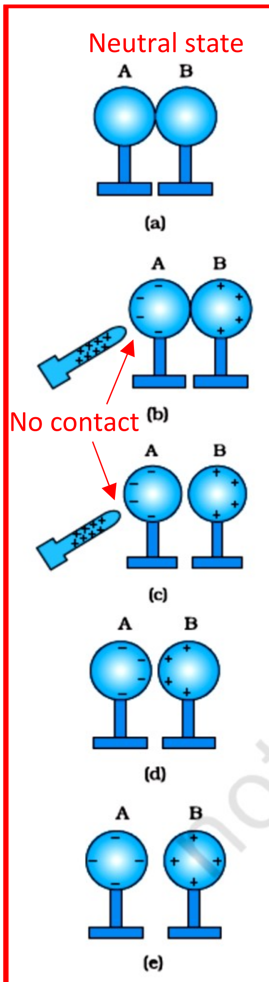


FIGURE 1.4 Charging by induction.

When we touch a pith ball with an electrified plastic rod, some of the negative charges on the rod are transferred to the pith ball and it also gets charged. Thus the pith ball is *charged by contact*. It is then repelled by the plastic rod but is attracted by a glass rod which is oppositely charged. However, why a electrified rod attracts light objects, is a question we have still left unanswered. Let us try to understand what could be happening by performing the following experiment.

(i) Bring two metal spheres, A and B, supported on insulating stands, in contact as shown in Fig. 1.4(a).

(ii) Bring a positively charged rod near one of the spheres, say A, taking care that it does not touch the sphere. The free electrons in the spheres are attracted towards the rod. This leaves an excess of positive charge on the rear surface of sphere B. Both kinds of charges are bound in the metal spheres and cannot escape. They, therefore, reside on the surfaces, as shown in Fig. 1.4(b). The left surface of sphere A, has an excess of negative charge and the right surface of sphere B, has an excess of positive charge. However, not all of the electrons in the spheres have accumulated on the left surface of A. As the negative charge starts building up at the left surface of A, other electrons are repelled by these. In a short time, equilibrium is reached under the action of force of attraction of the rod and the force of repulsion due to the accumulated charges. Fig. 1.4(b) shows the equilibrium situation. The process is called *induction of charge* and happens almost instantly. The accumulated charges remain on the surface, as shown, till the glass rod is held near the sphere. If the rod is removed, the charges are not acted by any outside force and they redistribute to their original neutral state.

(iii) Separate the spheres by a small distance while the glass rod is still held near sphere A, as shown in Fig. 1.4(c). The two spheres are found to be oppositely charged and attract each other.

(iv) Remove the rod. The charges on spheres rearrange themselves as shown in Fig. 1.4(d). Now, separate the spheres quite apart. The charges on them get uniformly distributed over them, as shown in Fig. 1.4(e).

In this process, the metal spheres will each be equal and oppositely charged. This is *charging by induction*. The positively charged glass rod does not lose any of its charge, contrary to the process of charging by contact.

Example 1.1 How can you charge a metal sphere positively without touching it?

Solution Figure 1.5(a) shows an uncharged metallic sphere on an insulating metal stand. Bring a negatively charged rod close to the metallic sphere, as shown in Fig. 1.5(b). As the rod is brought close to the sphere, the free electrons in the sphere move away due to repulsion and start piling up at the farther end. The near end becomes positively charged due to deficit of electrons. This process of charge distribution stops when the net force on the free electrons inside the metal is zero. Connect the sphere to the ground by a conducting wire. The electrons will flow to the ground while the positive charges at the near end will remain held there due to the attractive force of the negative charges on the rod, as shown in Fig. 1.5(c). Disconnect the sphere from the ground. The positive charge continues to be held at the near end [Fig. 1.5(d)]. Remove the electrified rod. The positive charge will spread uniformly over the sphere as shown in Fig. 1.5(e).

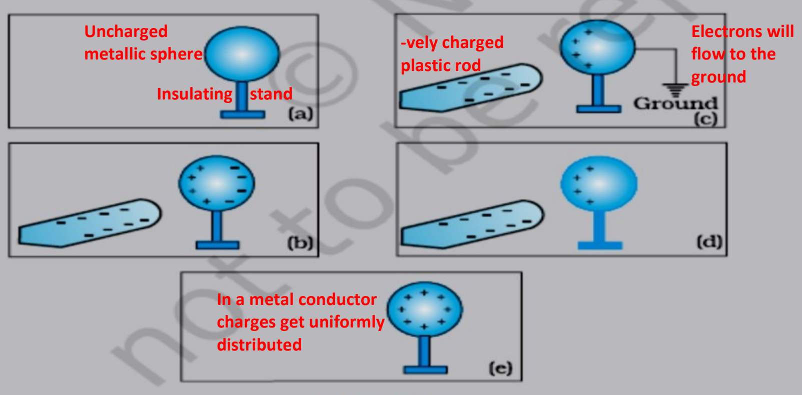


FIGURE 1.5

In this experiment, the metal sphere gets charged by the process of induction and the rod does not lose any of its charge.

Similar steps are involved in charging a metal sphere negatively by induction, by bringing a positively charged rod near it. In this case the electrons will flow from the ground to the sphere when the sphere is connected to the ground with a wire. Can you explain why?

Not easy to remove protons (+ve charge) from the nucleus of a metallic sphere, hence protons cannot flow to ground.

Basic properties of electric charge:

- **Additivity of charges**
- **Conservation of charge**
- **Quantization of charge**

Additivity of charges

- Additivity of electric charges means that the total charge of a system is the algebraic sum (i.e. the sum taking into account proper signs) of all individual charges in the system.
- Charges are scalars like mass of a body
- If a system contains n charges q_1, q_2……q_n, then the total charge of the system is $q_1 + q_2 +.......+q_n$
- Charge has magnitude but no direction, similar to mass. However, there is one difference between mass and charge. Mass of a body is always positive whereas charge can be either positive or negative.
- Proper signs have to be used while adding the charges in a system.
- Eg : Five charges +1, +2, -3, +4 and -5 in some arbitrary unit → total charge of the system is +1+2-3+4-5 = -1 in the same unit
- Eg: +q, +2q, -3q, +4q, -5q → yields -1q

Conservation of charge [charge is conserved]

- Conservation of electric charges means that the total charge of an isolated system remains unchanged with time. This means that when bodies are charged through friction, there is a transfer of electric charge from one body to another, but no creation or destruction of charge.
- It is not possible to create or destroy net charge carried by any isolated system although the charge carrying particles may be created or destroyed in a process.
- Sometimes nature creates charged particles ; a neutron turns into a proton and an electron. The proton and electron thus created have equal and opposite charges and the total charge is zero before and after the creation.

Quantization of charge

- If a body contains n_1 electrons and n_2 protons, the total amount of charge on the body is $Q = (n_2 \times e) + (n_1 \times (-e)) = (n_2 - n_1)e$. Therefore $Q = (n_2-n_1)e$; since n_1 and n_2 are integers, their difference is also an integer. Thus the charge on a body is always an integral multiple of e and can be increased or decreased also in steps of e.
- Experimentally it is established that all free charges are integral multipoles of a basic unit charged denoted by "e". thus charge q on a body is always given **$q = ne$**, where n is any integer (positive or negative).
- The basic unit of charge is the charge that an electron or proton carries.
- By convention, the charge on an electron is taken to be negative. Therefore, charge on an electron is written as –e
- Hence, the charge on a proton is taken to be positive. Therefore, the charge on a proton is written as +e
- The fact that electric charge in a system is always an integral multiple of e is termed as "quantization of charge".
- There are a large number of situations in physics where certain physical quantities are quantized.
- The quantization of charge was first suggested by Faraday (using laws of electrolysis). It was later in 1912 experimentally demonstrated by Millikan
- 1 coulomb is the charge flowing through a wire in 1s if current is 1A.

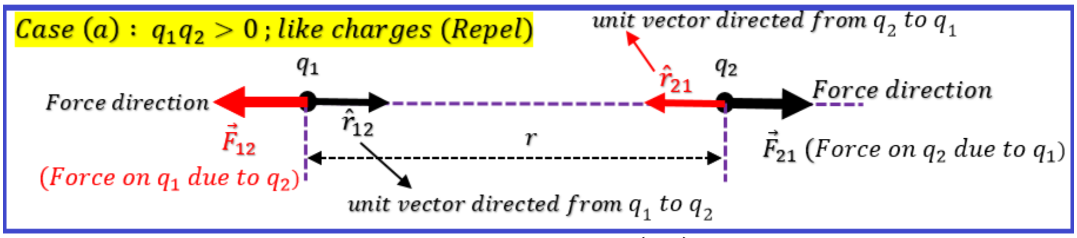
State and explain Coulomb's law in electrostatics (*in terms of "Displacement Vector"*)

Ans: **According to coulomb's law, the mutual electrostatic force (of attraction or repulsion) between two point charges q_1 and q_2 is proportional to the product of q_1 and q_2 and inversely proportional to the square of the distance "r" separating them.**

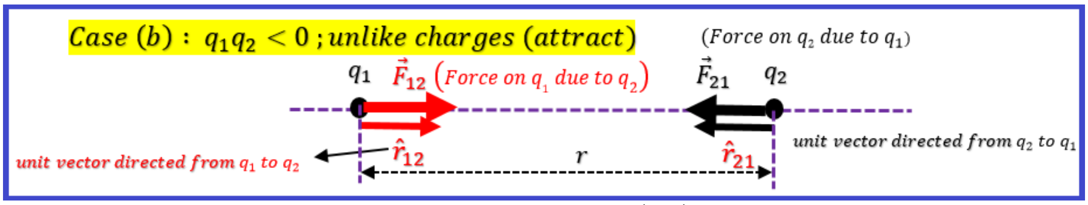
Coulomb's law is a quantitative statement about the force between two point charges. When the linear size of charged bodies are much smaller than the distance separating them, the size may be ignored and the charged bodies are treated as point charges.

Otherwise, if we don't consider "point charges", we need to consider system of charges in the body where charges are distributed in the body and hence it is not possible to set the correct distance "r" between the charges. **Therefore, Coulomb's law is valid only for point charges. It is essential that the entire charge on the body should be concentrated at a single point in the body.**

Since, force is a vector quantity, the direction is along the line joining the two charges.
Thus, if the two point charges are separated by a distance r in vacuum. The magnitude of the force $|\vec{F}|$ between them is given by
$|\vec{F}| = k \frac{|q_1 q_2|}{r^2}$ & the direction is along the line joining the two charges. **The exact direction depends on the polarity of the point charges.**



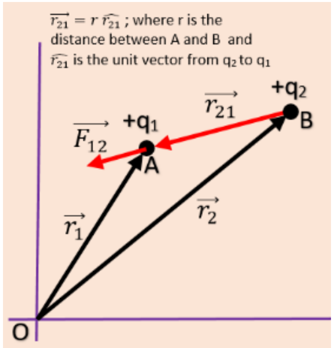
- Force acting on q_1 due to q_2 (represented by $\vec{F}_{12}$): $\vec{F}_{12} = k\frac{(q_1q_2)}{r^2}\hat{r}_{21}$, where $\hat{r}_{21}$ is the unit displacement vector directed from q_2 to q_1
- Force acting on q_2 due to q_1 (represented by $\vec{F}_{21}$): $\vec{F}_{21} = k\frac{(q_1q_2)}{r^2}\hat{r}_{12}$, where $\hat{r}_{12}$ is the unit displacement vector directed from q_1 to q_2
  - **Note that the force direction and the displacement direction should be same.**
  - Since $\hat{r}_{21} = -\hat{r}_{12}$, *and assuming that point charges have same magnitude* $|q_1| = |q_2|$, *therefore* $\vec{F}_{12} = -\vec{F}_{21}$
- Since displacement vector $\vec{r}_{21} = |r|\,\hat{r}_{21}$, we can also write Coulomb's law as $\vec{F}_{12} = k\frac{(q_1q_2)}{r^3}\vec{r}_{21}$ OR $\vec{F}_{21} = k\frac{(q_1q_2)}{r^3}\vec{r}_{12}$
- *where* $k = \frac{1}{4\pi\epsilon_0}$ = 9 x 10^9 Nm^2C^{-2} ; ϵ_0 *is the absolute permittivity of free space (vacuum or air)* = 8.854 x 10^{-12} $N^{-1}\ m^{-2}\ C^2$
- ϵ_r *is the relative permittivity of the medium. It has no units and is a pure number.*
  - $\vec{F}_m = \frac{1}{4\pi\epsilon_0\epsilon_r}\frac{(q_1q_2)}{r^2}$; in free space (vacuum or air) $\epsilon_r = 1$, therefore $\vec{F}_a = \frac{1}{4\pi\epsilon_0}\frac{(q_1q_2)}{r^2}$
- Coulomb discovered his law without the knowing explicitly the magnitude of the charge. In fact, it is the other way round → Coulomb's law can 'now' be employed to formulate a definition for the "unit of charge".
  - In Coulomb's equation, k is some arbitrary positive value.
  - The choice of k determines the size of the unit of charge.
  - In SI unit, $k \approx$ 9 x 10^9 Nm^2C^{-2} → unit of charge that results from this choice of k is called a coulomb
  - Plugging k = 9 x 10^9 Nm^2C^{-2} and $q_1 = q_2$= 1 C , r = 1m, then F = 9 x 10^9 N
  - **∴ 1 C is the charge that when placed at a distance of 1m from another charge of the same magnitude experiences an electrical force of repulsion of magnitude = 9 x 10^9 N**
  - 1C is a really a big unit; in electrostatics, we often use μC or mC



- Force acting on q_1 due to q_2 (represented by $\vec{F}_{12}$): $\vec{F}_{12} = k\frac{(q_1q_2)}{r^2}\hat{r}_{12}$, where $\hat{r}_{12}$ is the unit displacement vector directed from q_1 to q_2
- Force acting on q_2 due to q_1 (represented by $\vec{F}_{21}$): $\vec{F}_{21} = k\frac{(q_1q_2)}{r^2}\hat{r}_{21}$, where $\hat{r}_{21}$ is the unit displacement vector directed from q_2 to q_1
- Remaining specs are same as above.

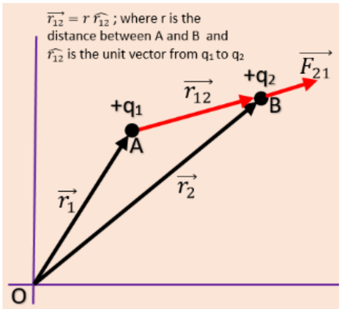
Coulomb's Force between charges in terms of their "Position Vectors"

- Let O be the origin of a co-ordinate frame of reference
- Suppose two point charges q_1 and q_2 (consider same polarity) are placed in vacuum at points A and B whose position vectors relative to origin are $\vec{r_1}$ *and* $\vec{r_2}$ respectively.
- Consider force on q_1 due to q_2, then the direction of the force $\vec{F_{12}}$ is given in the figure and the displacement vector $\vec{r_{21}}$ will be from q_2 to q_1 (as shown in the figure)
- In terms of expressing coulomb's law using displacement vector, $\vec{F_{12}}$ *is given by*
- $\vec{F_{12}} = \left(\frac{1}{4\pi\epsilon_0}\right)\frac{q_1q_2}{r^3}\,\vec{r_{21}}$ ------------------------ (1)
- We need to express the displacement vector $\vec{r_{21}}$ in terms of position vectors in order to specify the vector location in space. So, "r" to be expressed as position vectors.
- From figure, as per the law of triangle of vectors, we have
- $\vec{r_2} + \vec{r_{21}} = \vec{r_1}$
- $\vec{r_{21}} = (\vec{r_1} - \vec{r_2})$ −−−−−−− −−−−(2).
- The magnitude of $\vec{r_{21}}$ = $|\vec{r_{21}}| = r = |\vec{r_1} - \vec{r_2}|$ −−−−−−−− (3) ; Plug (2) and (3) in (1), we get
- $\vec{F_{12}} = \left(\frac{1}{4\pi\epsilon_0}\right)\frac{q_1q_2}{|\vec{r_1}-\vec{r_2}|^3}\,(\vec{r_1} - \vec{r_2})$



Derivation of $\vec{F_{21}}$ in terms of position vecors is given below

- Let O be the origin of a co-ordinate frame of reference
- Suppose two point charges q_1 and q_2 (consider same polarity) are placed in vacuum at points A and B whose position vectors relative to origin are $\vec{r_1}$ *and* $\vec{r_2}$ respectively.
- Consider force on q_2 due to q_1, then the direction of the force $\vec{F_{21}}$ is given in the figure and the displacement vector $\vec{r_{12}}$ will be from q_1 to q_2 (as shown in the figure)
- In terms of expressing coulomb's law using displacement vector, $\vec{F_{21}}$ *is given by*
- $\vec{F_{21}} = \left(\frac{1}{4\pi\epsilon_0}\right)\frac{q_1q_2}{r^3}\,\vec{r_{12}}$ ------------------------------ (1)
- We need to express the displacement vector $\vec{r_{12}}$ in terms of position vectors in order to specify the vector location in space. So, "r" to be expressed as position vectors.
- From figure, as per the law of triangle of vectors, we have
- $\vec{r_1} + \vec{r_{12}} = \vec{r_2}$
- $\vec{r_{12}} = (\vec{r_2} - \vec{r_1})$ −−−−−−− −−−−−−(2).
- The magnitude of $\vec{r_{12}}$ = $|\vec{r_{12}}| = r = |\vec{r_2} - \vec{r_1}|$ −−−−−−−− (3) ; Plug (2) and (3) in (1), we get
- $\vec{F_{21}} = \left(\frac{1}{4\pi\epsilon_0}\right)\frac{q_1q_2}{|\vec{r_2}-\vec{r_1}|^3}\,(\vec{r_2} - \vec{r_1})$



Since, $(\vec{r_1} - \vec{r_2})$ *and* $(\vec{r_2} - \vec{r_1})$ *are equal vectors* in magnitude but opposite in direction, we have $\vec{F_{21}} = -\vec{F_{12}}$. $\vec{F_{12}}$ and $\vec{F_{21}}$ acts (oppositely) along the line joining the two charges q_1 and q_2. That is, electrostatic force is a "central force".