Polar and Non-polar Dielectric molecules.

Polar and Non-polar

- The molecules of dielectrics may be classified as "polar" and "non-polar" molecules.
- The dielectrics having polar molecules are known as "polar substances or dielectrics"
- The dielectrics having non-polar molecules are known as "Non-polar Substances or dielectrics"

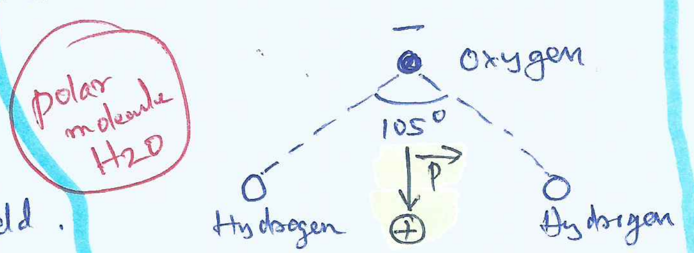
(a) Polar Substances or ~~Dielectrics~~ polar dielectrics:

A molecule in which the centre of mass of positive charges does not coincide with the centre of mass of negative charges is called polar ~~molecule~~ ~~or~~ molecule (even when there is no external electric field)

→ A substance made of polar molecules is known as a "polar substance"

→ Examples: HCl, H_2O, NH_3, CO_2, alcohol.

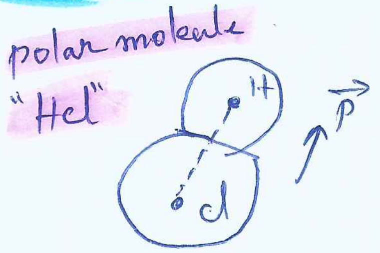
A H_2O molecule is shown below



→ Polar molecules donot have symmetrical shape.

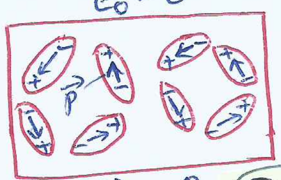
→ A polar molecule has permanent electric dipole moment ($\vec{p}$) even when there is no external electric field.

→ Therefore, polar molecules acts as an electric dipole.



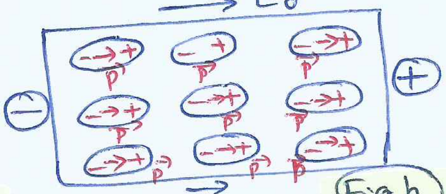
- Effect of external electric field on the polar Substance

$\vec{E_0} = 0$



$\vec{p} = 0$ (Fig a)

$\vec{E_0}$



$\vec{p}$ (Fig b)

- In the absence of external electric field $\vec{E_0}$, the molecules of the polar dielectric are randomly oriented due to thermal agitation. These molecules align themselves in the form of closed chains (fig (a)). Hence, net dipole moment of the polar dielectric is zero in the absence of external field.

- When external field $\vec{E_0}$ is applied across the polar dielectric, each molecule (or dipole) experiences a torque. This torque tends to align the molecules in the direction of external applied field $\vec{E_0}$.

→ If the thermal agitation or the temp^r of the dielectric is very small, all the molecules of the polar dielectric completely align themselves in the direction $\vec{E_0}$. The dipole moments of all the molecules get added and hence the polar dielectric has finite net dipole moment in the presence of the externally applied electric field. The dielectric is polarized. The extent of polarization depends on dipole PE tending to align with external field and also thermal energy to disrupt the alignment.

→ P.T.O

(b) Non-polar substances or dielectrics:

A molecule in which the centre of mass of +ve charges coincides with the centre of mass of −ve charges is called non-polar molecule.

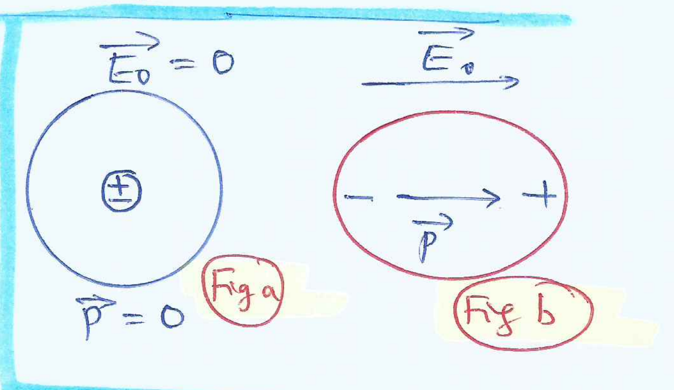
→ A ~~substan~~ substance made of non-polar molecules is known as "non-polar substance" or "non-polar dielectric".

→ Ex: → N_2, O_2, H_2, CO_2, methane, benzene etc...

→ A non-polar molecule has symmetrical shape.

→ Since, the centre of masses of +ve and −ve charges coincide, the molecule is not a ~~of~~ electric dipole and hence has no permanent (or intrinsic) dipole moment.

- **Effect of electric field on the non-polar molecule:**



→ In the absence of external electric field ($\vec{E_0}$), the non-polar molecule has zero dipole moment ($\vec{p} = 0$). (Fig (a))

→ When $\vec{E_0}$ is applied, the +ve charge is pulled in the direction of $\vec{E_0}$ and −ve charge is pulled in the direction opposite to $\vec{E_0}$.

→ The separation betⁿ the charges continues till the forces acting on them due to applied field ($\vec{E_0}$) are balanced by the internal restoring forces.

→ Thus, a non-polar molecule is stretched and becomes a polar molecule and is called "induced electric dipole" and its dipole moment ~~disappears~~ is called "induced electric dipole moment ($\vec{p}$)". The dielectric is said to be polarized by the external field.

→ Induced $\vec{p}$ disappears as soon as the external field $\vec{E_0}$ is removed.

⇒ non-polar molecule remains a polar molecule as long as electric field is applied across it.

IMP Thus, in either case, whether polar or non-polar dielectrics, a dielectric material develops a net dipole moment in the presence of an external electric field.

→ The dipole moment per unit volume is called polarisation and is denoted by P.

→ For linear isotropic dielectrics (χ_e is pronounced as "chi")

$$\vec{P} = \chi_e \vec{E} \longrightarrow (1)$$

where χ_e is a constant characteristic of the dielectric and is known as the "electric susceptibility" of the dielectric medium. For vacuum, $\chi_e = 0$.

It is possible to relate χ_e to the molecular properties of the substance, but NCERT syllabus will not pursue that further.

Info **polarizability**: (what is atomic or molecule polarizability)

For a simple molecule, induced electric dipole moment ($\vec{p}$) is directly $\propto$ to the applied external electric field ($\vec{E}$)

$$\vec{p} \propto \epsilon_0 \vec{E}$$

$$\boxed{\vec{p} = \epsilon_0 \alpha \vec{E}}$$

where α is a constant called "atomic" or "molecule" polarizability and is given by $\boxed{\alpha = \dfrac{\vec{p}}{\epsilon_0 \vec{E}}}$

$$\text{SI unit of } \alpha = \frac{\text{unit of } \vec{p}}{\text{unit of } \epsilon_0 \times \text{unit of } \vec{E}} = \frac{\cancel{C}\, m}{(\cancel{C^2} \cancel{N^{-1}} m^{-2})(\cancel{N} \cancel{C^{-1}})} = m^3$$

Thus, unit of atomic polarizability α is m^3 (same as unit of Volume)

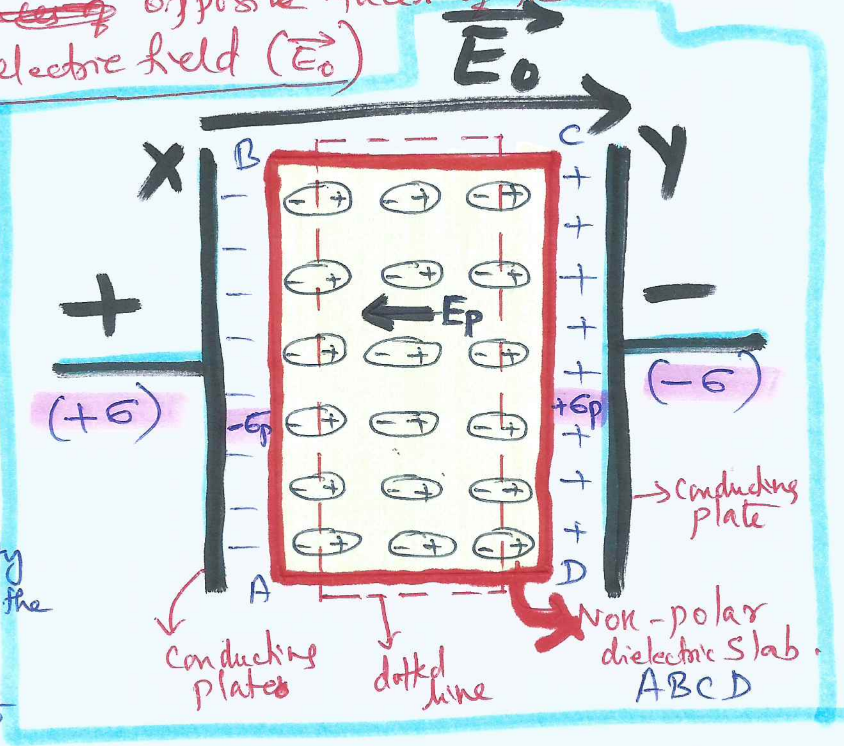
IMP

- ✗. Atomic polarizability (α) has the dimensions of volume.
- ✗. For most of the atoms, $\alpha \simeq 10^{-29}\, m^3$ to $10^{-30}\, m^3$, which is the order of atomic volume.

※ Polarization of Dielectric

(How does the polarized dielectric modify the original external electric field inside it) (page 72 of NCERT book)

Defn: Polarization of a dielectric is the process of inducing equal and opposite charges on the two ~~faces of~~ opposite faces of the dielectric on the application of external electric field ($\vec{E_0}$)



- Let XY be two parallel conducting plates (equally and oppositely charged) separated by some distance and having vacuum/air betn the plates.
- Then $\vec{E_0}$ is the electric field intensity betn X and Y (See fig)
- If $+\sigma$ is the surface charge density of positive plate and $-\sigma$ be the surface charge density of −Ve plate, then magnitude of electric field betn plates XY is

$$\boxed{E_0 = \frac{\sigma}{\epsilon_0} \longrightarrow (1)}$$

- Let us introduce a "non-polar dielectric slab" ABCD betn the plates. Under the influence of external field $\vec{E_0}$, each atom is elongated due to the displacement of the charges (See fig) and hence become a polar atom. Suppose all atoms of dielectric slab are uniformly polarized in the direction of $\vec{E_0}$. If 'x' is the displacement betn centres of ± charges in the atom, dipole moment of each atom = $p = qx$

If N is the ~~no~~ number of atoms per unit volume, then dipole moment per unit volume = total dipole moment density $P = Np$ or $\boxed{P = Nqx}$. This total dipole moment density P is called "electric polarization", which represents σ_p (SI unit = Cm^{-2})

(Each atom/molecule of the dielectric having dipole moment experiences a torque to get ~~a~~ aligned in the direction of $\vec{E_0}$ and hence all dipoles get aligned in the direction of applied electric field $\vec{E_0}$). The interior charges shown in the dotted rectangle cancel the effect of one another. Therefore, the net effect is that the opposite faces of the dielectric will have equal and opposite charges. These charges are called "induced charges" and the process is called "polarization of the dielectric". Induced charges are bound charges and ~~the fre~~ not the free charges.

P.T.O →

Contd. from pre. page

→ These induced charges set-up an electric field, which is known as "Induced electric field" $\vec{E_p}$

→ If σ_p and $-\sigma_p$ be the "surface charge densities" of the opposite faces of the dielectric, then the magnitude of "electric field" due to the polarization is given by

$$E_p = \frac{\sigma_p}{\epsilon_0}$$ directed opposite to external electric field $\vec{E_0}$

→ ∴ Net Electric field inside the dielectric is given by

$$E = E_0 - E_p \quad \text{or} \quad \boxed{E = \frac{\sigma - \sigma_p}{\epsilon_0}}$$

where $E_p = \frac{\sigma_p}{\epsilon_0}$

Thus, on placing a dielectric slab betn two parallel plates the electric field intensity inside the parallel plates gets reduced

∴ net electric field (E) inside the "dielectric" is known as "reduced value of electric field".

Dielectric constant : The ratio of applied external electric field ($\vec{E_0}$) to the reduced value of electric field intensity (E) on placing a dielectric betn two oppositely charged plates is called "dielectric constant (K)". It is given by

$$K = \frac{\text{Externally applied Electric field } (E_0) \text{ intensity}}{\text{reduced electric field intensity}}$$

$$\boxed{K = \frac{E_0}{E}} \quad \text{or} \quad K = \frac{\sigma}{\cancel{\epsilon_0}} \times \frac{\cancel{\epsilon_0}}{(\sigma - \sigma_p)}$$

$$\text{or} \quad \boxed{K = \frac{\sigma}{(\sigma - \sigma_p)}}$$

$E_0 = \frac{\sigma}{\epsilon_0}$

$E_p = \frac{\sigma_p}{\epsilon_0}$

$E = \frac{\sigma - \sigma_p}{\epsilon_0}$

Since $E_0 > E$ always, K is always > 1

※ Dielectric constant is a pure number (no units)

51

※ Relation betⁿ Surface charge density (σ) and Induced surface charge density (σ_p)

We know that the reduced value of electric field in the gap between two oppositely charged plates, when filled with a dielectric of "dielectric const" K is given by

$$\boxed{E = E_0 - E_p} \rightarrow (i)$$

where $E_0 = \frac{\sigma}{\epsilon_0}$; $E_p = \frac{\sigma_p}{\epsilon_0}$

We also know that "dielectric constant" $K = \frac{E_0}{E}$ (since $E_0 = \frac{\sigma}{\epsilon_0}$)

$$K = \frac{\sigma}{\epsilon_0 E}$$

$$\therefore \boxed{E = \frac{\sigma}{\epsilon_0 K}} \rightarrow (2)$$

plugging eqⁿ (2) in eqⁿ (i) and using $E_0 = \frac{\sigma}{\epsilon_0}$; $E_p = \frac{\sigma_p}{\epsilon_0}$

$$E = E_0 - E_p$$

$$\frac{\sigma}{\cancel{\epsilon_0} K} = \frac{\sigma}{\cancel{\epsilon_0}} - \frac{\sigma_p}{\cancel{\epsilon_0}} \implies \frac{\sigma}{K} = \sigma - \sigma_p$$

$$\left.\begin{aligned} &\implies \boxed{\sigma_p = \sigma\left(1 - \frac{1}{K}\right)} \\ &\therefore \boxed{\sigma_p = \left(\frac{K-1}{K}\right)\sigma} \end{aligned}\right\} (3)$$

From (3) Since $K > 1$ always, $\sigma_p < \sigma$ ⟶ IMP

※ If gap is filled with a "conductor" instead of "dielectric" material, then ~~reduced~~ net Electric field $E = 0$

$$E = E_0 - E_p = 0 \quad \therefore E_0 = E_p \quad \text{or} \quad \boxed{\sigma_p = \sigma}$$

Thus, induced surface charge density on a conductor is equal to the surface charge density (σ)

※ Polarization Vector: is defined as the dipole moment per unit volume of the polarized dielectric. The polarization vector measures the degree of polarization of the dielectric.

Suppose all atoms are uniformly (homogeneously) polarized in the direction of external field $\vec{E_0}$, then each atom has same dipole moment $\vec{p}$. If there are N atoms per unit volume of the dielectric, then the polarization vector ($\vec{P}$) is given by $\vec{P} = N\vec{p}$

magnitude = $P = np$
unit = Cm^{-2}

Dimensional formula of polarization vector $[P] = \frac{[p]}{[V]} = \frac{[ql]}{[V]} = \frac{ATL}{L^3} = [M^0L^{-2}TA]$

* Relation betn Magnitude of polarization Vector and Surface charge Density of polarization Charges.

- Let magnitude of the polarization charge be q_p on the polarized dielectric.
- The polarized dielectric is assumed to be an "electric dipole"

Area of the dielectric slab = A

Thickness of dielectric = d [≡ distance betn polarization (induced) charges]

∴ dipole moment of ~~of~~ dielectric = one of the charges × dist betn charge

$= q_p d \longrightarrow (1)$

→ If σ_p = Surface charge density of the polarization charge, then polarization (induced) charge $q_p = \sigma_p A \longrightarrow (2)$ plug (2) in (1),

∴ dipole moment of dielectric $= \sigma_p A d$

$= \sigma_p V$

but $A \times d$ = volume of the dielectric

As per defn of "polarization Vector"

$$p = \frac{\text{Dipole moment}}{\text{Volume}} = \frac{\sigma_p \cancel{V}}{\cancel{V}} = \sigma_p$$

$$\therefore \boxed{\vec{p} = \sigma_p} \quad \text{or} \quad \boxed{\sigma_p = \vec{p}\cdot\hat{n}}$$

where $\hat{n}$ = unit vector ⊥r to surface of dielectric.

If $\vec{p}$ makes an ∠le with normal to the surface of ~~the~~ dielectric, then $\sigma_p = p\cos\theta$

If $\vec{p}$ is along the normal to the surface of dielectric, $\theta = 0°$

∴ ~~$\sigma_p \cos\theta$~~ $\sigma_p = \cancel{p} \, p\cos\theta = p$ ∴ $\boxed{\sigma_p = p}$

---

* Susceptibility and polarization Vector.

In most of the dielectrics, polarization Vector $\vec{p}$ is ∝' to the reduced electric field intensity $(\vec{E})$ in the dielectric

$$\Rightarrow \vec{p} \propto \epsilon_0 \vec{E}$$

$$\boxed{\vec{p} = \chi_e \epsilon_0 \vec{E}} \longrightarrow (1)$$

where χ_e is called ~~"dielectric Susceptibility"~~ "Electric Susceptibility", which is a natural measure of polarisability of a dielectric

chi ← $\boxed{\chi_e = \dfrac{p}{\epsilon_0 E}} \longrightarrow (2)$

unit of $\chi_e = \dfrac{\cancel{Cm^{-2}}}{\cancel{C^2N^{-1}m^{-2}} \times \cancel{NC^{-1}}}$ = No unit ∴ χ_e is dimensionless.

Relation betⁿ Electric Susceptibility (χ_e) and dielectric Constant K

We know that "reduced" electric field in a dielectric is given by

$$E = E_0 - E_p \qquad \Big|\; E_p = \frac{\sigma_p}{\epsilon_0}$$

$$\therefore E_0 = E + E_p = E + \frac{\sigma_p}{\epsilon_0} = E + \frac{P}{\epsilon_0} \qquad \Big|\; \vec{P} = \sigma_p$$

But the magnitude of polarization vector $P = \chi_e \epsilon_0 E$

$$\therefore E_0 = E + \frac{\chi_e \cancel{\epsilon_0} E}{\cancel{\epsilon_0}} = E(1+\chi_e)$$

or $\frac{E_0}{E} = 1 + \chi_e$ But $\frac{E_0}{E}$ = dielectric const K

$$\therefore \boxed{K = 1 + \chi_e} \longrightarrow \text{v. imp!}$$

Dielectric Strength.

Defⁿ: The maximum value of the ~~dielectric~~ electric field intensity that can be applied to the dielectric without its electric break down is known as the dielectric strength of the dielectric.

$$\implies E_{break} = \frac{V_{break}}{d}$$

where V_{break} is the max. voltage a dielectric can withstand without electric breakdown. d = thickness of the dielectric.

→ When a dielectric is placed in an external electric field, it gets polarized. In a polarized dielectric, each atom gets stretched and some strain is produced in the atom.

→ As the electric field strength increases, the atoms are further stretched and strain on atoms also increases. When the electric field strength becomes too high, the strain becomes unbearable and the electrons get detached from the atom which in turn becomes a +ve ~~ione~~ ion.

→ This is known as the electric breakdown of the dielectric. The electrons drift towards the +ve plate of the capacitor and +ve ions drift towards the −ve plate of the capacitor. Now the dielectric no more remains an insulator.

P.T.O →

Contd...

→ SI unit of Dielectric strength of a material is Vm^{-1} (same as electric field) $\left(E = \frac{V}{d}\right)$

→ practical unit of dielectric strength is kV/mm

→ Dimensional formula of dielectric strength } $\frac{[\text{potential}]}{[\text{Distance}]} = \frac{[\text{work}]}{[\text{charge} \times \text{Distance}]}$

Since $V = \frac{U}{q}$, $V = \frac{\text{work}}{q}$

$= \frac{[\text{work}]}{[\text{current}][\text{time}][\text{Distance}]} = \frac{[ML^2T^{-2}]}{[ATL]} = [MLT^{-3}A^{-1}]$

Dielectric Const & Dielectric strength of some dielectrics.

Dielectric	Dielectric constant K	Dielectric strength kV/mm	
Vacuum	1.000	∞	
Air	1.006	0.8	
Natural rubber	2.7 - 5.0	18 - 24	
Mica	6 - 7	80	
polystyrene	2.55	20 - 28	
polythene	2 - 3	20 - 160	
Teflon/PTFE	2.1	16 - 20	
PVC	5 - 6	30	
Quartz Glass	3.78	—	
pyrex Glass	4.6	14	
paper	3.85	80	
Silicon	11.68		

Electric displacement Vector

The reduced value of electric field in a dielectric is given by

$$E = E_0 - E_p = \frac{\sigma}{\epsilon_0} - \frac{\sigma_p}{\epsilon_0}$$

$$\therefore E = \frac{(\sigma - \sigma_p)}{\epsilon_0} \longrightarrow (1)$$

$$\Rightarrow \vec{E}\cdot\hat{n} = \frac{\sigma - \sigma_p}{\epsilon_0}$$

$$\Rightarrow \vec{E}\cdot\hat{n} = \frac{\sigma - \vec{P}\cdot\hat{n}}{\epsilon_0} \qquad (\because \sigma_p = \vec{P}\cdot\hat{n})$$

$$\Rightarrow (\vec{E}\cdot\hat{n})\epsilon_0 = \sigma - \vec{P}\cdot\hat{n}$$

$$\boxed{(\epsilon_0\vec{E} + \vec{P})\cdot\hat{n} = \sigma} \quad \text{or} \quad \boxed{\vec{D}\cdot\hat{n} = \sigma}$$

and $\boxed{\vec{D} = \epsilon_0\vec{E} + \vec{P}}$ is known as "Electric Displacement Vector". $\longrightarrow (2)$

Since $E = \frac{\sigma - \sigma_p}{\epsilon_0}$

and $P = \sigma_p$

$$\text{Now } \frac{D}{E} = \frac{\epsilon_0 E + P}{E} = \epsilon_0 + \frac{P}{E}$$

$$= \epsilon_0 + \frac{\sigma_p\,\epsilon_0}{\sigma - \sigma_p}$$

$$\frac{D}{E} = \frac{\epsilon_0\sigma - \cancel{\epsilon_0\sigma_p} + \cancel{\epsilon_0\sigma_p}}{\sigma - \sigma_p} = \frac{\sigma\,\epsilon_0}{\sigma - \sigma_p}$$

But $\frac{\sigma}{\sigma - \sigma_p} = K \quad \therefore \frac{D}{E} = K\epsilon_0$

Hence $\boxed{\vec{D} = \epsilon_0 K\vec{E}} \longrightarrow (3)$

From eqn (2), $\vec{D} = \epsilon_0\vec{E} + \vec{P} \quad \therefore \vec{P} = \vec{D} - \epsilon_0\vec{E}$

using eqn (3) $\quad \therefore \vec{P} = \epsilon_0 K\vec{E} - \epsilon_0\vec{E}$

$$\vec{P} = \epsilon_0(K-1)\vec{E}$$

But $\chi_e = (K-1) \quad \therefore \boxed{\vec{P} = \epsilon_0\chi_e\vec{E}}$ where χ_e is electric susceptibility

IMP ※ Electrical Capacitance :-

The measure of the ability of a conductor to store charge or energy is known as electrical capacitance or capacity of a conductor.

→ When some charge is given to a conductor, it gains some electrostatic potential. More is the charge on a conductor, higher is the potential on the conductor.

→ Let q be the charge on a conductor and V be its potential, then $q \propto V$ or $q = CV$

where C is a constant of proportionality and is called electrical capacitance or capacity of the conductor

$$\boxed{C = \frac{q}{V}}$$

If $V = 1$, $C = q$ ⟹ electrical capacitance of a conductor is defined as the charge required to raise its potential thro' ~~one~~ one unit.

→ Capacitance is a positive quantity.

→ Capacitance is a scalar quantity.

→ SI unit is ~~Farad~~ farad (F)

→ $C = \frac{q}{V}$ if $q = 1\,C$ and $V = 1\,V$, we get

$$1 \text{ farad } (F) = \frac{1 \text{ coulomb}}{1 \text{ Volt}} = 1\,CV^{-1}$$

Thus capacitance or capacity of a conductor is said to be 1 farad if 1 coulomb of charge is required to raise its potential through 1 volt.

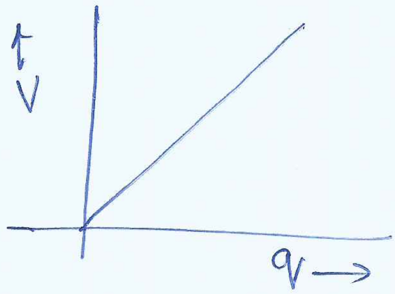
$1\,\mu F = 10^{-6} F$, $1\,nF = 10^{-9} F$, $1\,pF = 10^{-12} F$

→ Dimensional formula $C = \frac{q}{V} = \frac{q}{W/q} = \frac{q^2}{W} = \frac{(it)^2}{W}$

$$[C] = \frac{[A^2T^2]}{[ML^2T^{-2}]} = [M^{-1}L^{-2}T^4A^2].$$

P.T.O →

→ For a capacitor, $C = \frac{q}{V}$, But $V \propto q$ i.e. ~~p.d.~~ potential difference is $\propto$' to the charge, so changing 'q' means changing 'V' by the same factor, thus capacitance of the given capacitor does not change in this manner.



→ Capacitance of a capacitor is determined by the nature of dielectric in betⁿ plates of a capacitor, geometrical shape/size of plates and distance between the plates.

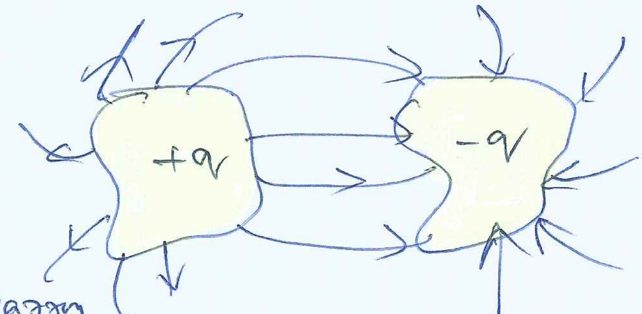
How much charge will appear on the plates of a capacitor has capacitance of 177 pF when p.d. ~~of~~ 100V is applied.

→ Given $C = 1.77 \times 10^{-12}$ F, $V = 100$ V

$q = CV = 1.77 \times 10^{-12} \times 100 = 17.7 \times 10^{-9}$ C $= \underline{17.7 \text{ nC}}$

*. Capacitor *' (or Condenser)

A capacitor consists of 2 conductors of any shape separated by a non-conducting medium such that it can store electric charge.



→ when a capacitor is charged by connecting the two uncharged conductors to the terminals of a battery, the two conductors carry ~~ces~~ charges of equal magnitude but of opposite sign.

→ when battery is disconnected, the charges on the conductors are retained. Hence C stores the charge

→ The p.d. $(V = V_1 - V_2)$ betⁿ 2 conductors is p.d. across the capacitor.

~~This p.d. charge on the capacitor is $\propto$' to~~

This p.d. (V) is $\propto$' to the charge (q) on the capacitor, ⇒

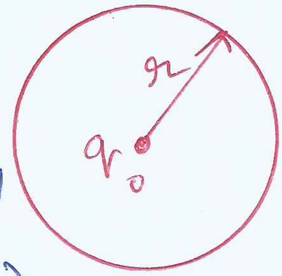
$q \propto V \Rightarrow q = CV$ C = Capacitance of the capacitor.

$$\boxed{C = \frac{q}{V}}$$

The net charge on the capacitor is zero because both conductors of a capacitor have equal and opposite charge, but the magnitude of charge on either conductor is referred to the charge on the capacitor.

*. Capacitance of an Isolated Spherical conductor *.

Consider an isolated spherical conductor of radius r in free space.
Let a charge q be given to the sphere which is assumed to be concentrated at the centre (O) of the sphere.



potential at any point on the surface of the sphere is given by

$$V = \frac{1}{4\pi\epsilon_0}\frac{q}{r}$$

We know that $C = \frac{q}{V} = q\left(\frac{1}{V}\right) = \cancel{q}\left(\frac{4\pi\epsilon_0 r}{\cancel{q}}\right)$

$$\boxed{C = 4\pi\epsilon_0 r} \Rightarrow \boxed{C \propto r} \qquad \boxed{\frac{1}{4\pi\epsilon_0} = 9\times10^{9}\ Nm^2C^{-2}}$$

* Capacitance of Earth.

Radius of earth $= r = 6400$ km $= 6.4\times10^{6}$ m

Capacitance of earth $= C = 4\pi\epsilon_0 r$

$$C = \frac{1}{9\times\cancel{10^{9}}\,{}_{3}}\times 6.4\times\cancel{10^{6}} = 0.711\times10^{-3}\,F = \underline{711\,\mu F}$$

Will a mechanic be able to use $1\mu F$ capacitor in a TV set? Here $C = 1\mu F = 10^{-6}$ F, $r = ?$

$$C = 4\pi\epsilon_0 r$$

$$r = \frac{1}{4\pi\epsilon_0}C = 10^{-6}\times9\times10^{9} = \underline{9\ Km}$$

Thus, such a huge capacitor cannot be used in a TV set.