12th Physics - Chapter 1

Derivations

Electric field

$$E = \frac{F}{q_0} \Rightarrow F = q_0 E \rightarrow \text{Force due to Electric field}$$

$$\cancel{E = \frac{F}{q_0}} \text{ or } \cancel{F = \frac{1}{4\pi\varepsilon_0}}$$

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q q_0}{r^2} \quad \text{Force between two point Charges}$$

$$E = \frac{\frac{1}{4\pi\varepsilon_0}\frac{q q_0}{r^2}}{q_0} = \frac{1}{4\pi\varepsilon_0}\frac{q \cancel{q_0}}{\cancel{q_0} r^2}$$

$$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$$

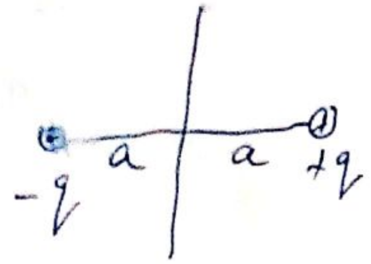
$$E_1 = \frac{1}{4\pi\varepsilon_0}\frac{q_1}{r_{1p}^2}$$

$$E_2 = \frac{1}{4\pi\varepsilon_0}\frac{q_2}{r_{2p}^2}$$

$$E = E_1 + E_2 + \cdots + E_n$$

$$E = \frac{1}{4\pi\varepsilon_0}\left[\frac{q_1}{r_{1p}^2} + \frac{q_2}{r_{2p}^2} + \cdots + \frac{q_n}{r_{np}^2}\right]$$

Dipole moment



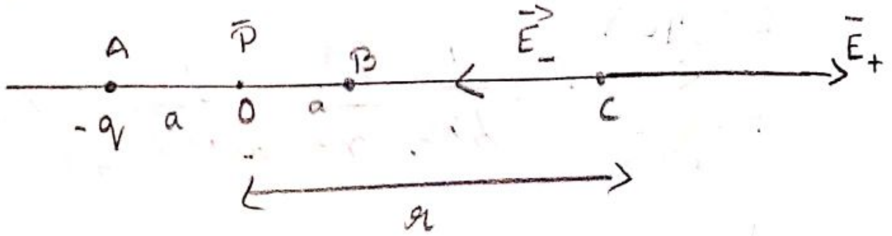
p = magnitude of charge $\times$ distance between 2 charge

$= q \times 2a$

$p = 2aq$

Electric field due to a dipole

case(i) Electric field due to an electric dipole at points on the axial line



Consider an electric dipole placed on the x-axis as shown in the diagram. A point B is located at a distance of r from the midpoint O of the dipole along ③ the axial line.

electric field at a point C due to +q is $(a^2-b^2)^2 = (a-b)^2 * (a+b)^2$

$$E_+ = \frac{1}{4\pi\varepsilon_0}\frac{q}{(r-a)^2}$$ along BC

$$E_+ = \frac{1}{4\pi\varepsilon_0}\frac{q}{(r-a)^2}\hat{p}$$

The electric field at a point C due to -q

$$E = -\frac{1}{4\pi\varepsilon_0}\frac{q}{(r+a)^2}\hat{p}$$

Total electric field at a point B is calculated by superposition principle of the electric field

$$\bar{E}_{tot} = \bar{E}_+ + \vec{E}_-$$

$$= \frac{1}{4\pi\varepsilon_0}\frac{q}{(r-a)^2}\hat{p} - \frac{1}{4\pi\varepsilon_0}\frac{q}{(r+a)^2}\hat{p}$$

$$\bar{E}_{tot} = \frac{q}{4\pi\varepsilon_0}\left[\frac{1}{(r-a)^2} - \frac{1}{(r+a)^2}\right]\hat{p}$$

$$\bar{E}_{tot} = \frac{1}{4\pi\varepsilon_0}q\left[\frac{(r+a)^2-(r-a)^2}{(r^2-a^2)^2}\right]\hat{p}$$

$$= \frac{q}{4\pi\varepsilon_0}\left[\frac{r^2+2ra+a^2-r^2-a^2+2ar}{(r^2-a^2)^2}\right]$$

$$= \frac{q}{4\pi\varepsilon_0}\left(\frac{4ar}{(r^2-a^2)^2}\right) = \frac{1}{4\pi\varepsilon_0} 2 \times 2ra$$

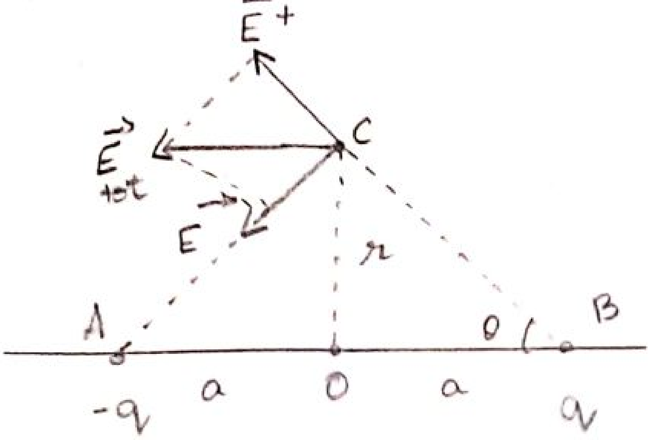
$$= \frac{1}{4\pi\varepsilon_0}\left(\frac{4qar}{(r^2)^2}\right)$$ (since a^2 ~~is smaller~~ is smaller)

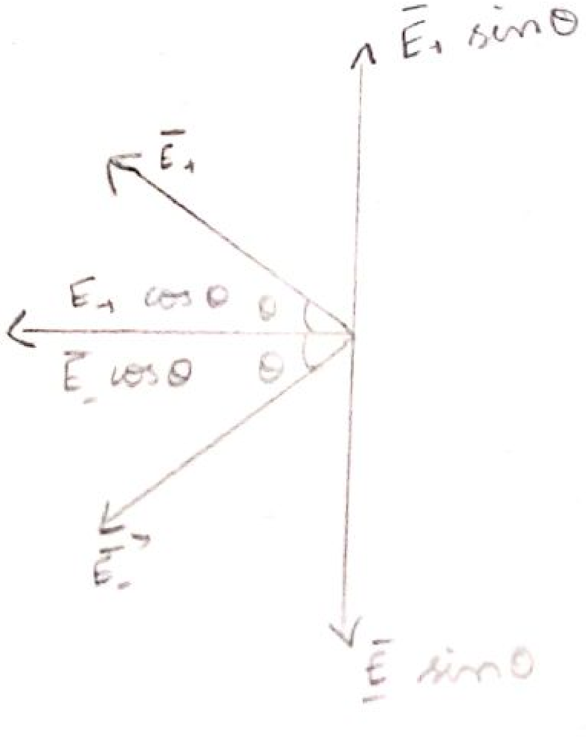
$2aq = P$

$= \frac{1}{4\pi\varepsilon_0} = \frac{2px}{r^3}$

$= \frac{1}{4\pi\varepsilon_0} \frac{2P}{r^3} \hat{p}$

Case (ii) Electric field due to an electric dipole at a point on the equatorial plane.





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$$E_{tot} = -|E_+| \cos\theta\, \hat{p} - |E_-| \cos\theta\, \hat{p}$$

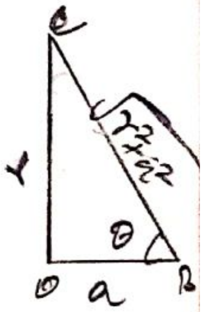
The magnitudes E_+ & E are the same and are given by

$$|\vec{E}_+| = |\vec{E}_-| = \frac{1}{4\pi\varepsilon_0} \frac{q}{(r^2+a^2)}$$

$$\cancel{\vec{E}_{tot} = -\frac{1}{4\pi\varepsilon_0} \frac{2q\cos\theta}{(r^2+a^2)} \hat{p}}$$

$$= -\frac{1}{4\pi\varepsilon_0(r^2+a^2)} q\cos\theta\, \hat{p} - \frac{1}{4\pi\varepsilon_0} \frac{q}{(r^2+a^2)} \cos\theta\, \hat{p}$$

$$= -\frac{1}{4\pi\varepsilon_0} \frac{2q\cos\theta\, \hat{p}}{(r^2+a^2)} \quad \text{— (1)}$$



From the diagram ~~cos θ~~ =

$$\cos\theta = \frac{a}{\sqrt{r^2+a^2}} \quad \text{— (2)}$$

$$BC^2 = OC^2 + OB^2$$
$$= r^2 + a^2$$
$$BC = \sqrt{r^2+a^2}$$

$$\cos\theta = \frac{a}{\sqrt{r^2+a^2}}$$

sub (2) in (1) $\Rightarrow$

$$= \frac{-1}{4\pi\varepsilon_0} \frac{2q\, a}{(r^2+a^2)\sqrt{r^2+a^2}}$$

$$= \frac{-1}{4\pi\varepsilon_0} \frac{2qa}{(r^2+a^2)^{3/2}}$$

$$2aq = p$$

$$= \frac{-\vec{p}}{4\pi\varepsilon_0(r^2+a^2)^{3/2}}$$

($r >> a$, Hence a neglected)

$$= -\frac{\vec{p}}{4\pi\varepsilon_0(r^2)^{3/2}}$$

$$= \frac{-\bar{p}}{4\pi\varepsilon_0\, r^3}$$

Electric potential due to a point charge.

Electric potential at a point P,

$$V = \int_{\infty}^{r} (-\bar{E}) \cdot d\bar{r} = -\int_{\infty}^{r} \bar{E} \cdot dr$$

Electric field due to positive point charge q is

$$\bar{E} = \frac{1}{4\pi\varepsilon_0} \frac{q}{r^2} \hat{r}$$

$$V = \frac{-1}{4\pi\varepsilon_0} \int_{\infty}^{r} \frac{q}{r^2} \hat{r} dr$$

~~The infinite~~

r^{-2}

$\frac{r^{-2+1}}{-2+1}$

$\frac{r^{-1}}{-1}$

$\frac{-1}{r}$

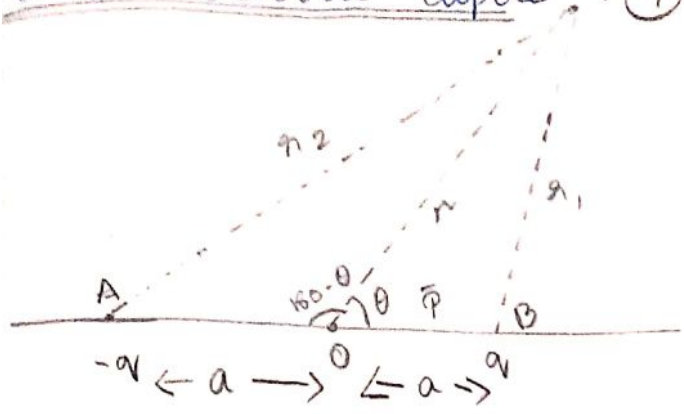
$$V = \frac{-q}{4\pi\varepsilon_0} \int_{\infty}^{r} \frac{1}{r^2}$$

$$V = \frac{-1}{r} \quad \frac{-q}{4\pi\varepsilon_0} \left[\frac{-1}{r}\right]_{\infty}^{r} \qquad \left[\frac{1}{r} - \frac{1}{\infty}\right]$$

$$V = \frac{q}{4\pi\varepsilon_0} \left[\frac{1}{r}\right]$$

$$V = \frac{1}{4\pi\varepsilon_0} \left[\frac{q}{r}\right]$$

Electrostatic potential at a point due to an electric dipole. (7)



Let r_1 be the distance of point P from +q and r_2 be the distance of point P from -q

Potential at P due to charge $+q = \frac{1}{4\pi\varepsilon_0}\frac{q}{r_1}$

Potential at P due to charge $-q = -\frac{1}{4\pi\varepsilon_0}\frac{q}{r_2}$

Total potential at the point P. (adding)

$$V = \frac{1}{4\pi\varepsilon} q\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \quad -(1)$$

By the cosine law ~~for~~ ~~triangle~~ triangle BOP,

$$r_1^2 = r^2 + a^2 - 2ra\cos\theta$$

$$r_1^2 = r^2\left(1 + \frac{a^2}{r^2} - \frac{2a}{r}\cos\theta\right)$$

$$r_1^2 = r^2\left(1 - 2a\frac{\cos\theta}{r}\right) \qquad \left(\frac{a^2}{r^2} \text{ very small}\right)$$

$$r_1 = \sqrt{r^2\left(1 - 2a\frac{\cos\theta}{r}\right)}$$

$$r_1 = r\left(1 - 2a\frac{\cos\theta}{r}\right)^{1/2}$$

$$\frac{1}{r_1} = \frac{1}{r}\left(1 - \frac{2a}{r}\cos\theta\right)^{-1/2}$$

By using binomial expansion

$$\frac{1}{r_1} = \frac{1}{r}\left(1 - \left(-\frac{1}{2}\right)\frac{2a}{r}\cos\theta\right)$$

$$= \frac{1}{r}\left(1 + \frac{a\cos\theta}{r}\right) \quad - (2)$$

Applying cosine law for ΔAOP

$$r_2^2 = r^2 + a^2 - 2ra\cos\theta(180-\theta)$$

$\cos(180-\theta) = -\cos\theta$

we get

$$r_2^2 = r^2 + a^2 + 2ra\cos\theta$$

$$r_2^2 = r^2\left(1 + \frac{a^2}{r^2} + \frac{2a\cos\theta}{r}\right) \quad \left(\frac{a^2}{r^2} \text{ is very small}\right)$$

$$r_2 = \sqrt{r^2\left(1 + \frac{a^2}{r^2} + \frac{2a\cos\theta}{r}\right)}$$

$$r_2 = r\left(1 + \frac{2a\cos\theta}{r}\right)^{1/2}$$

$$\frac{1}{r_2} = \frac{1}{r}\left(1 + \frac{2a\cos\theta}{r}\right)^{-1/2} \quad - (3)$$

By binomial theorem

$$\frac{1}{r_2} = \frac{1}{r}\left(1 - \left(\frac{1}{2}\right)\frac{2a\cos\theta}{r}\right)$$

$$= \frac{1}{r}\left(1 - \frac{a\cos\theta}{r}\right)$$

Substituting 2 & 3 in 1

$$V = \frac{1}{4\pi\varepsilon_0} q \left(\frac{1}{r}\left(1 + \frac{a\cos\theta}{r}\right) - \frac{1}{r}\left(1 - \frac{a\cos\theta}{r}\right)\right)$$

$$V = \frac{q}{4\pi\varepsilon_0}\left(\frac{1}{r}\left(1 + \frac{a\cos\theta}{r}\right) - \left(1 - \frac{a\cos\theta}{r}\right)\right)$$

$$V = \frac{q}{4\pi\varepsilon_0}\left(\frac{1}{r}\left(\cancel{1} + \frac{a\cos\theta}{r} - \cancel{1} + \frac{a\cos\theta}{r}\right)\right)$$

$$V = \frac{q}{4\pi\varepsilon_0}\left(\frac{1}{r}\left(\frac{2a\cos\theta}{r}\right)\right)$$

$$V = \frac{q}{4\pi\varepsilon_0}\left(\frac{2a\cos\theta}{r^2}\right)$$

$$V = \frac{1}{4\pi\varepsilon_0}\frac{2aq\cos\theta}{r^2}$$

$2aq = p$

$$\boxed{V = \frac{1}{4\pi\varepsilon_0}\frac{p\cos\theta}{r^2}}$$

In vector form

$$V = \frac{1}{4\pi\varepsilon_0}\frac{p\cos\theta}{r^2}$$

$p\cos\theta = \bar{p}\cdot\hat{r}$

$$V = \frac{1}{4\pi\varepsilon_0}\frac{\bar{p}\cdot\hat{r}}{r^2}$$

Special cases

* If the point lies on the axial line of the dipole on the side of $+q$, $\theta = 0$

$\therefore \cos\theta = 1$

$$V = \frac{1}{4\pi\varepsilon_0}\frac{p}{r^2}$$

* If the point P lies on the axial line of the dipole on the side of -q, then $\theta = 180°$

then, $\cos\theta = \cos 180 = -1$

$$V = -\frac{1}{4\pi\varepsilon_0}\frac{P}{r^2}$$

* If the point P lies on the equatorial line of the dipole

then $\theta = 90°$.

$\cos 90° = 0$

$V = 0$

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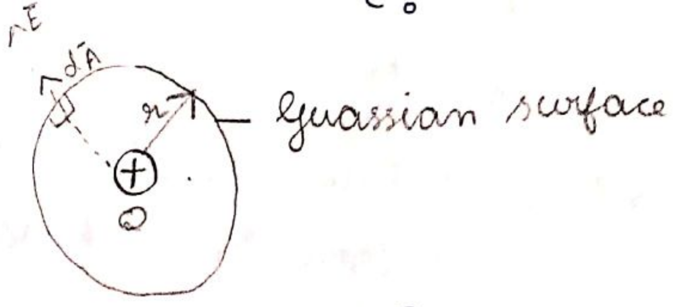
Gauss law

Gauss law states that if a charge Q is enclosed by an arbitrary closed surface, then the total electric flux Φ_E through the closed surface is

$$\Phi_E = \oint \bar{E} \cdot d\bar{A} = \frac{Q_{encl}}{\varepsilon_0}$$



$$\Phi_E = \oint E\,dA \quad (\text{since } \cos 0 = 1)$$

E is uniform on the surface of the sphere

$$\Phi_E = E \oint dA$$

Substituting $4\pi r^2$ in $\oint dA$ and

$$E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$$

$$\Phi_E = \cancel{4\pi}\,\cancel{r^2} \times \frac{1}{\cancel{4\pi}\varepsilon_0}\frac{Q}{\cancel{r^2}}$$

$$\Phi_E = \frac{Q}{\varepsilon_0}$$

$$\Phi_E = \oint \bar{E} \cdot d\bar{A} = \frac{Q_{encl}}{\varepsilon_0}$$

Here Q_{encl} denotes the charges inside the closed surface.

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Applications of gauss law:

(X) i) Electric field due to an infinitely long charged wire

(X) ii) Electric field due to charged infinite plane sheet

iii) Electric field due to two parallel charged infinite sheets

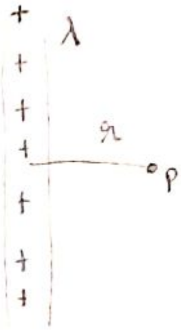
New iv) Electric field due to a uniformly charged spherical shell.

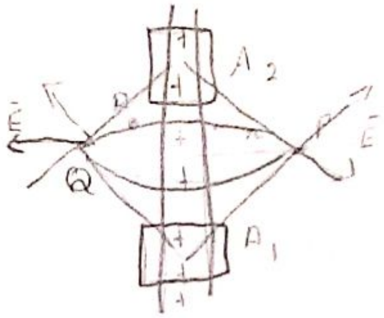
C-(a) At a point outside the shell $(r > R)$

C-(b) At a point on the surface of the spherical ~~&~~ shell $(r = R)$

C-(c) At a point inside the spherical shell $(r < R)$

Electric field due to an infinitely long charged wire :





$$\Phi_E = \oint \bar{E} \cdot d\bar{A}$$

$$= \underbrace{\int \bar{E} \cdot d\bar{A}}_{\text{curved surface}} + \underbrace{\int \bar{E} \cdot d\bar{A}}_{\text{top surface}} + \underbrace{\int \bar{E} \cdot d\bar{A}}_{\text{bottom surface}}$$

For curved surface $\bar{E}$, is parallel to $\bar{A}$

For top & bottom $\bar{E}$, is perpendicular to $\bar{A}$ and $\bar{E} \cdot d\bar{A} = 0$

$$\Phi_E = \underbrace{\int E \, dA}_{\text{curved surface}} = \frac{Q_{encl}}{\varepsilon}$$

$Q_{encl} = \lambda L$.

$\underbrace{E \int dA}_{\text{curved surface}}$ = total area of the curved surface $= 2\pi r L$.

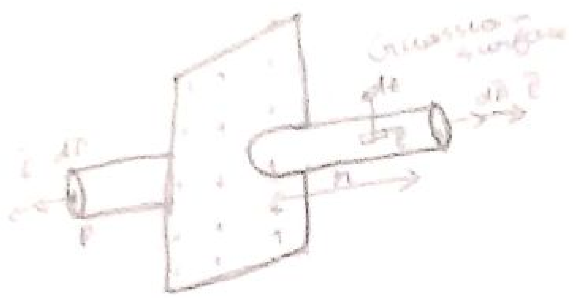
$$E \cdot 2\pi r L = \frac{\lambda L}{\varepsilon}$$

$$E = \frac{\lambda \cancel{L}}{\varepsilon} \cdot \frac{1}{2\pi r \cancel{L}}$$

$$= \frac{\lambda}{2\pi \varepsilon_0 r}$$

In Vector form $\bar{E} = \frac{1}{2\pi\varepsilon_0} \frac{\lambda}{r} \hat{r}$

Electric field due to charged infinite plane sheet



$\Phi_E = \oint \bar{E} \cdot d\bar{A}$

$= \int_{\text{curved surface}} \bar{E} \cdot d\bar{A} + \int \bar{E} \cdot d\bar{A} + \int_{P'} \bar{E} \cdot d\bar{A} = \frac{Q_{encl}}{\varepsilon_0}$

The electric field is perpendicular to the area element at all points on the curved surface and is parallel to the surface areas at P & P'

$\Phi_E = \int E\,dA + \int E\,dA = \frac{Q_{encl}}{\varepsilon_0}$

Magnitude of the electric field at these two equal surfaces is uniform. Q_{encl} is given by σA.

$2E\int dA = \frac{\sigma A}{\varepsilon_0}$

$\int dA = A$

Hence $2EA = \frac{\sigma A}{\varepsilon_0}$ or $E = \frac{\sigma}{2\varepsilon_0}$

In vector form, $\bar{E} = \frac{\sigma}{2\varepsilon_0}\hat{n}$

iii) Electric field due to two parallel charged infinite sheets

Pg - 45, 46 theory

$$E_{inside} = \frac{\sigma}{2\varepsilon} + \frac{\sigma}{2\varepsilon} = \frac{\sigma}{\varepsilon}$$

iv) Electric field due to a uniformly charged spherical shell

Case (a) At a point outside the shell

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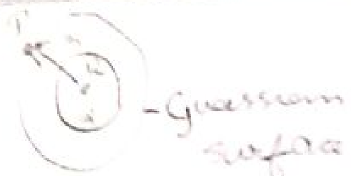


$$\oint \bar{E} \cdot d\bar{A} = \frac{Q}{\varepsilon_0}$$

$$E \oint dA = \frac{Q}{\varepsilon_0}$$

But $\oint dA$ = total area of gaussian ~~surface~~ surface

$= 4\pi r^2$

$$E \cdot 4\pi r^2 = \frac{Q}{\varepsilon}$$

$$E \cdot 4\pi r^2 = \frac{Q}{\varepsilon} \quad \text{or} \quad E = \frac{1}{4\pi\varepsilon_0} \frac{Q}{r^2}$$

In vector form

$$\bar{E} = \frac{1}{4\pi\varepsilon_0} \frac{Q}{r^2} \hat{r}$$

Case -(b)

At a point on the surface of the spherical shell ($r = R$)

$$E = \frac{Q}{4\pi\varepsilon_0 R^2}\hat{r}$$

Case (c) At a point inside the spherical shell ($r < R$)

Consider a point P inside the shell at a distance r from the center

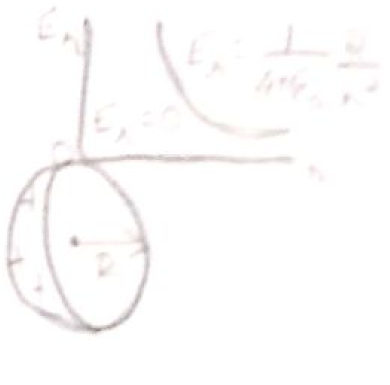
$$\oint E\, dA = \frac{Q}{\varepsilon_0}$$

$$E \cdot 4\pi r^2 = \frac{Q}{\varepsilon_0}$$

Since guassian surface encloses no charge.

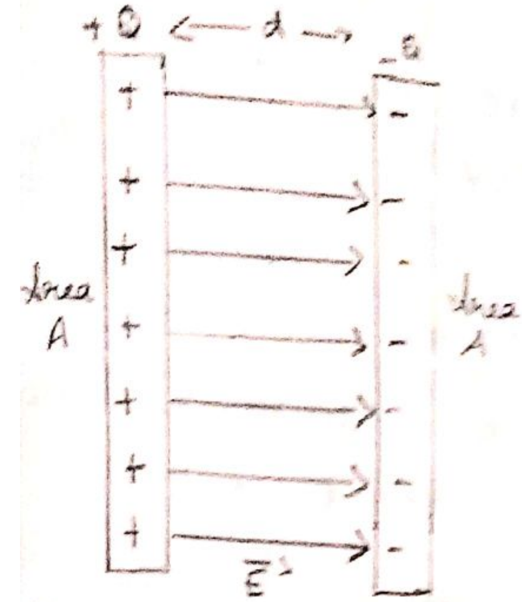
$Q = 0$, The equation becomes

$E = 0$



Capacitance of parallel plate capacitor

Consider a capacitor with two parallel plates each of cross-sectional area A and separated by a distance d.



The electric field between two infinite parallel plates is uniform

$$E = \frac{\sigma}{\varepsilon_0}$$

where $\sigma = \frac{Q}{A}$ (surface charge density)

d is smaller than the size of plates

$d^2 \ll A \qquad E = \frac{Q}{A\varepsilon_0}$

Electric potential $V = Ed$

$$= \frac{Qd}{A\varepsilon_0}$$

Capacitance $C = \frac{Q}{V} = \frac{Q}{\frac{Qd}{A\varepsilon_0}}$

$$C = \frac{A\varepsilon_0}{d}$$

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Effect of dielectrics in capacitors

i) When the capacitor is disconnected from the battery:

Consider a capacitor with two parallel plates each of cross-sectional area A and are separated by a distance d.

The capacitor is charged by a battery of voltage V_0 and the charge stored is Q_0.

The capacitance of the capacitor without dielectric is

$$C_0 = \frac{Q_0}{V_0}$$

$$E = \frac{E_0}{\varepsilon_r}$$

ε_r is the relative permeability of the dielectric or simply it is dielectric constant.

$$V = Ed$$

$$E = \frac{\varepsilon_0}{\varepsilon_r}$$

$$V = \frac{\varepsilon_0}{\varepsilon_r} d = \frac{V_0}{\varepsilon_r}$$

The new capacitance in the presence of dielectric is

$$C = \frac{Q_0}{V}$$ (V-potential constant)

$$\cancel{C = \frac{Q_0}{\frac{\varepsilon_0 d}{\varepsilon_r}}}$$

$$V = \frac{V_0}{\varepsilon_r}$$

$$= \varepsilon_r \frac{Q_0}{V_0}$$

$$= \varepsilon_r C_0$$

Insertion of the dielectric constant ε_r increases the capacitance

$\left(\frac{\varepsilon_0 A}{d}\right)$ form [illegible]

$$C = \varepsilon_r \frac{\varepsilon_0 A}{d}$$

ii) When the battery remains connected to the capacitor

The potential difference V_0 across the plates remains constant. But charge stored in the capacitor is increased by a factor ε_r

$$Q = \varepsilon_r Q_0$$

Due to this increased charge, the capacitance is also increased. The new capacitance is

$$C = \frac{Q}{V_0}$$

$$= \frac{\varepsilon_r Q_0}{V_0}$$

$$= \varepsilon_r C_0$$

Now, $C_0 = \frac{\varepsilon_0 A}{d}$

$$C = \frac{\varepsilon A}{d}$$

The energy stored in the capacitor before the insertion of dielectric

$$U_0 = \frac{1}{2} C_0 V_0^2$$

where $U_0 = \frac{1}{2} \frac{Q_0^2}{C_0}$

After the dielectric is inserted, the capacitance is increased, hence stored energy is also increased

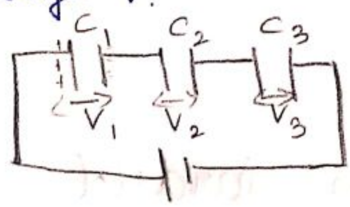
$$U = \frac{1}{2} C V_0^2$$
$$= \frac{1}{2} \varepsilon_r C_0 V_0^2 \quad (\varepsilon_r \text{ times increase})$$

Energy density is

$$u = \frac{1}{2} \varepsilon E_0^2$$

Capacitor in series

Consider the capacitors C_1, C_2, C_3 with a battery of voltage V.



$$V = V_1 + V_2 + V_3$$

$Q = CV$, we have $V = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3}$

$$= Q\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)$$

They are in series connection so they form an equivalent single capacitor C_s

$$V = \frac{Q}{C_s}$$

$$\frac{Q}{C_s} = Q\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)$$

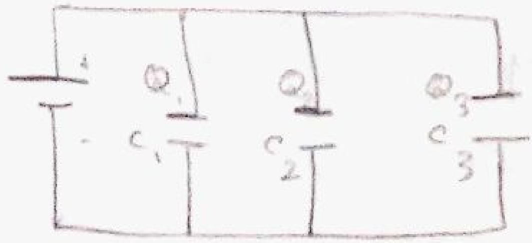
$$\frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Inverse of the equivalent capacitance C_s of three capacitors connected in series is equal to the sum of the inverses of each the capacitance.

This C_s is always less than the smallest individual capacitance in the series.

<u>Capacitance in parallel</u>

Consider three capacitors of capacitance C_1, C_2 & C_3 connected in parallel with a battery of voltage V



$$Q = Q_1 + Q_2 + Q_3$$

$$Q = CV$$

$$Q = C_1V + C_2V + C_3V$$

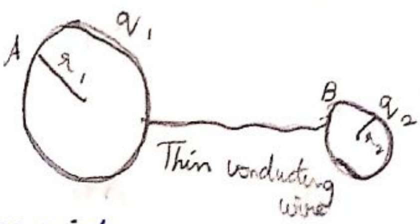
Three capacitors are considered to form a single capacitance C_p which stores the total charge Q.

$$C_pV = C_1V + C_2V + C_3V$$

$$C_pV = V(C_1 + C_2 + C_3)$$

$$C_p = C_1 + C_2 + C_3$$

Distribution of charges



Consider two conducting spheres A & B of radii r_1 & r_2 connected to each other by a thin conducting wire.

Distance between the spheres is much greater than the radii of either spheres.

If a charge Q is introduced into any one of the spheres this charge Q is redistributed into both the spheres such that the electrostatic potential is same in both the spheres. They are now uniformly charged and attain electrostatic equilibrium.

$$Q = q_1 + q_2$$

Charges are distributed only on the surface and there is no net charge inside the conductor

$$V_A = \frac{1}{4\pi\varepsilon_0} \frac{q_1}{r_1}$$

$$V_B = \frac{1}{4\pi\varepsilon_0} \frac{q_2}{r_2}$$

Since the spheres are connected by conducting wire the surfaces of both the spheres together form an equipotential surface.

$$V_A = V_B$$

$$\frac{1}{4\pi\varepsilon_0} \frac{q_1}{r_1} = \frac{1}{4\pi\varepsilon_0} \frac{q_2}{r_2}$$

$$\frac{q_1}{r_1} = \frac{q_2}{r_2}$$

Let us take the charge density on the surface of the sphere A is σ_1 and charge density on the surface of the sphere B is σ_2.

This implies that $q_1 = 4\pi r_1^2 \sigma$

$q_2 = 4\pi r_2^2 \sigma_2$

Substituting these values into equation

$$\sigma_1 r_1 = \sigma_2 r_2$$

$$\sigma r = \text{constant}$$

Energy stored in the capacitor

Capacitor not only stores the charge but also it stores energy.

When a battery is connected to the capacitor, electrons of total charge $-Q$ are transferred from one plate to the other plate.

To transfer charge work is done by battery.

To transfer infinitesimal charge dQ for a potential difference V, the work done is given by

$$dW = V dQ$$

$$V = \frac{Q}{C}$$

Total work done to charge a capacitor is

$$dW = V dQ$$

$$\int dW = \int_0^Q \frac{Q}{C}\, dQ$$

$$= \frac{1}{C}\left[\frac{Q^2}{2}\right]_0^Q$$

$$= \frac{1}{C}\,\frac{Q^2}{2}$$

$$= \frac{Q^2}{2C}$$

$U_E \Rightarrow$ potential energy in capacitor

$$U_E = \frac{Q^2}{2C} \qquad (Q = CV)$$

$$= \frac{C^2V^2}{2\cancel{C}}$$

$$= \frac{CV^2}{2}$$

$$= \frac{1}{2}CV^2$$

$$C = \frac{\varepsilon_0 A}{d}, \quad V = Ed$$

$$U_E = \frac{1}{2}\left(\frac{\varepsilon_0 A}{d}\right)(Ed)^2$$

$$= \frac{1}{2}\,\frac{\varepsilon_0 A}{\cancel{d}}\,E^2 d^{\cancel{2}}$$

$$= \frac{1}{2}\varepsilon_0 (Ad) E^2$$

Ad = Volume of the space between the capacitor plates.

$$u_E = \frac{U}{\text{Volume}}$$

$$u_E = \frac{\frac{1}{2}\varepsilon_0 (\cancel{Ad}) E^2}{\cancel{Ad}} = \frac{1}{2}\varepsilon_0 E^2$$

Prepared

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