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PREFACE

" The woods are lovely, dark and deep. "

But I have promises to keep, and
miles to go before I sleep

- Robert Frost

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From the bottom of our heart, we at SURA Publications sincerely thank you for the support and patronage that you have extended to us for more than a decade.

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With due respect to Teachers, I would like to mention that this guide will serve as a teaching companion to qualified teachers. Also, this guide will be an excellent learning companion to students with exhaustive exercises and in-text questions in addition to precise answers for textual questions.

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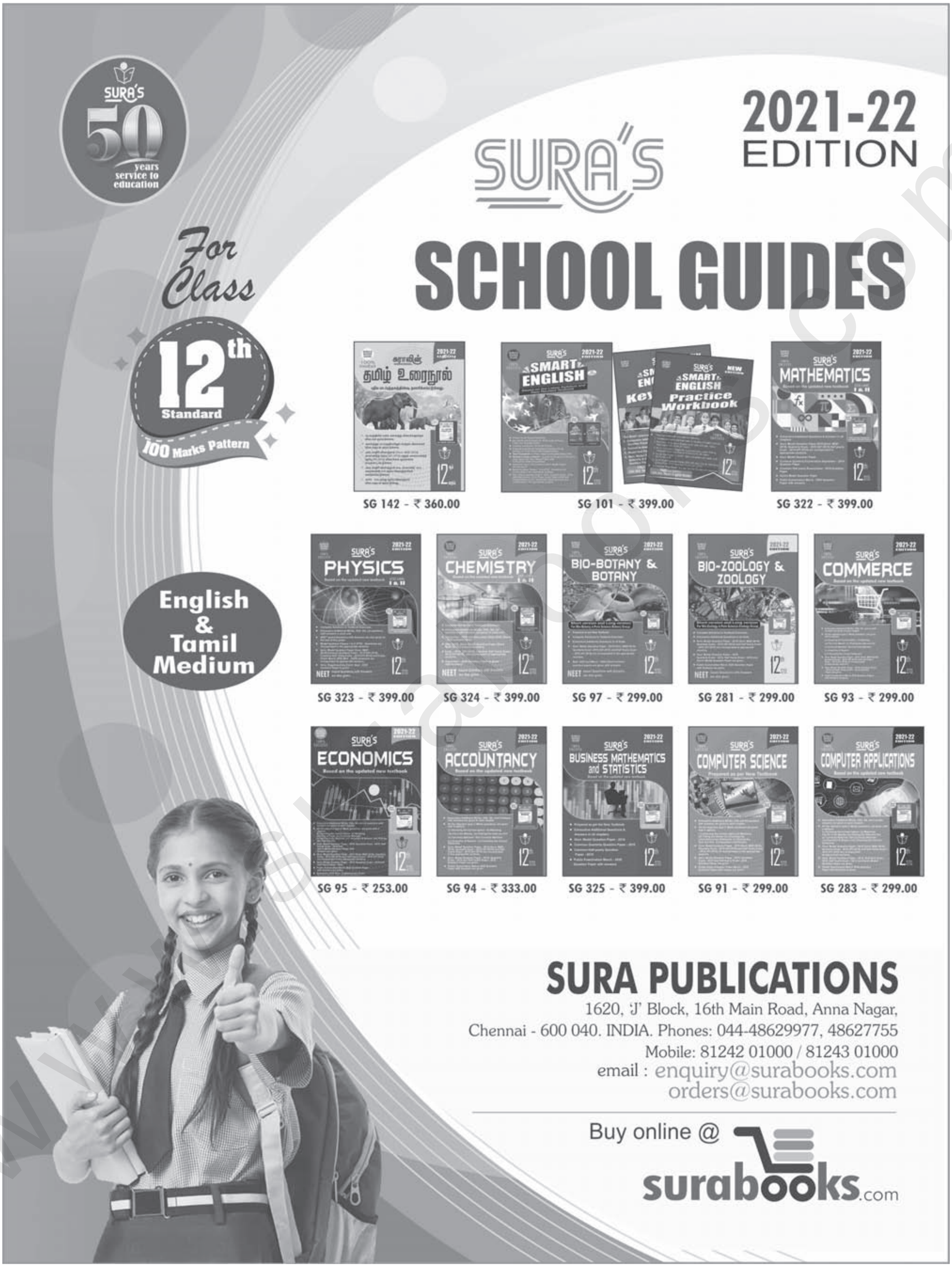
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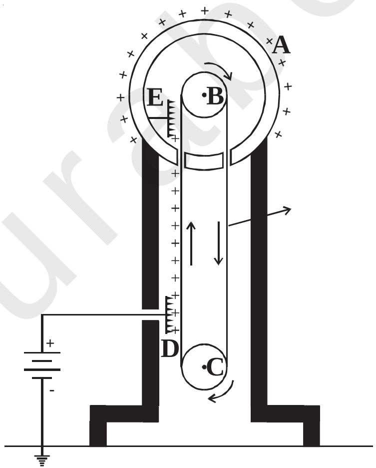

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UNIT 1 ELECTROSTATICS

CHAPTER SNAPSHOT

1.1 Introduction
1.1.1 Historical background of electric charges
1.1.2 Basic properties of charges
1.2 Coulomb's law
1.2.1 Superposition principle
1.3 Electric field and Electric Field Lines
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1.3.2 Electric field due to the system of point charges
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1.8 Capacitors and Capacitance
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1.9.3 Lightning arrester or lightning conductor
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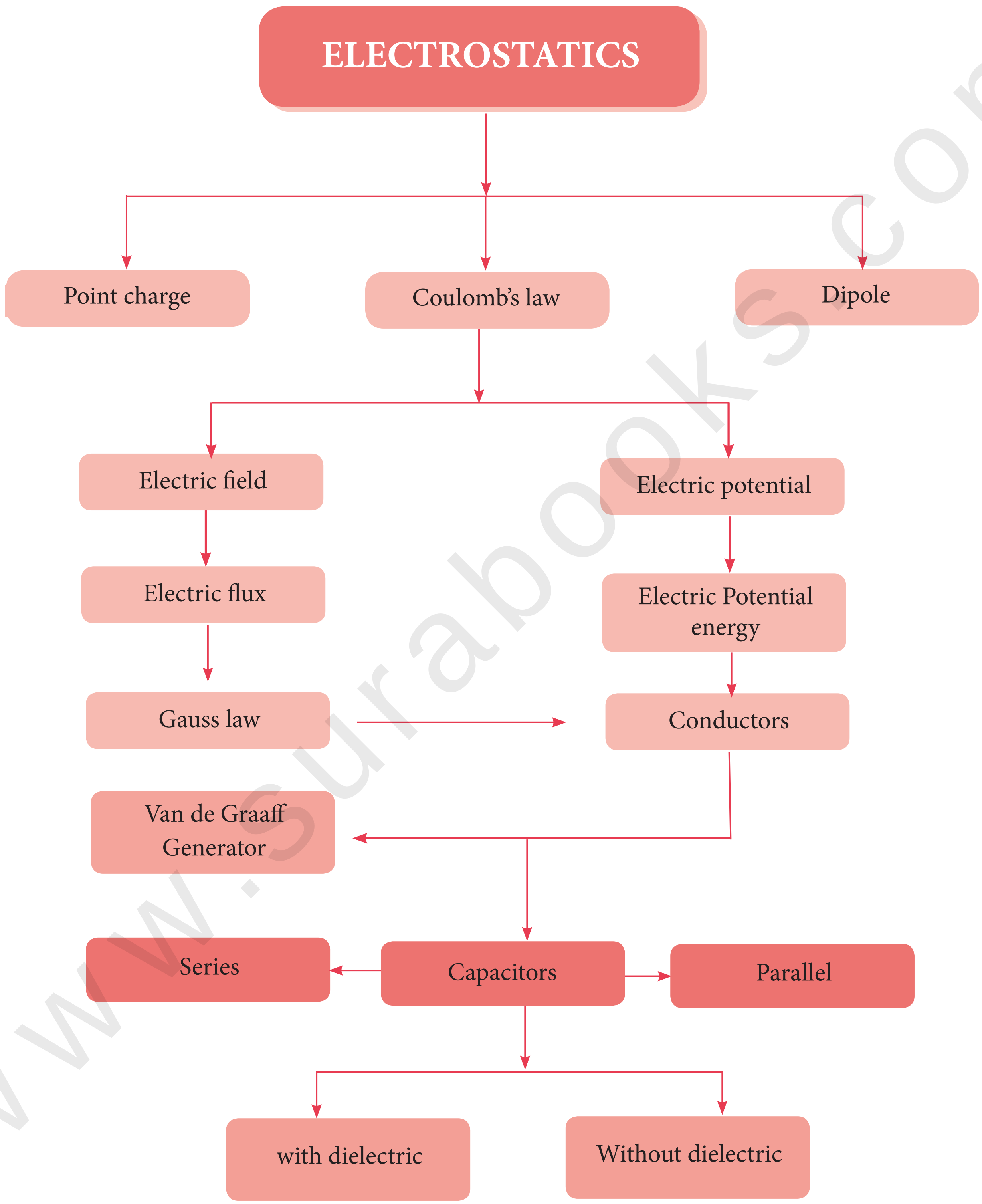
CONCEPT MAP


ELECTROSTATICS
Point charge
Coulomb's law
Dipole
Electric field
Electric potential
Electric flux
Electric Potential energy
Gauss law
Conductors
Van de Graaff Generator
Series
Capacitors
Parallel
with dielectric
Without dielectric

MUST KNOW DEFINITIONS

Electrostatics : Study of electric charges at rest or stationary charged bodies.

Electric charge : A basic property of some substances due to which they can exert a force of electrostatic attraction or repulsion on other charged bodies at a distance.

Frictional electricity :
- **600 B.C.** Thales, a Greek Philosopher - amber with fur - electrification
- **17th century** William Gilbert - glass, ebonite exhibit charging by rubbing.
- **Elektron** (Greek word) - means amber

Positive charge	Negative charge
Glass rod	Silk cloth
Fur cap	Ebonite rod
Woollen cloth	Plastic object

Superposition principle : In an isolated system, the total force on a given charge is the vector sum of the individual forces exerted on it by all other charges, each individual force calculated by Coulomb's law.

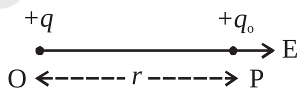
$$\vec{F}_1^{tot} = k\left[\frac{q_1 q_2}{r_{21}^2}\hat{r}_{21} + \frac{q_1 q_3}{r_{31}^2}\hat{r}_{31} + \ldots\ldots + \frac{q_1 q_n}{r_{n1}^2}\hat{r}_{nl}\right]$$

Properties of charges :

Quantisation of charge	$q = ne$ [n = 0, ±1, ±2, ±3,....]
Charges are additive	$Q = \Sigma Q_n$
Conservation of charges	Q = Constant

A point charge : The dimension of the charged object is very small and neglected in comparison with the distances involved.

Electric field due to a point charge :



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

Direction of E is along line joining OP : Points outward for $+q$ at O
Points inward for $-q$ at O

Definition of Coulomb : It is defined as the quantity of charge which when placed at a distance of 1 metre in air or vacuum from an equal and similar charge experiences a repulsive force of 9×10^9 N.

Test charge : A charge which, on introduction in an existing field, does not alter the field.

Electric field : It is the space or the region around the source charge in which the effect of the charge can be felt.

Electric field intensity : Force experienced by a unit positive charge kept at that point in the field.

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Electric lines of force	:	Imaginary straight or curved line along which a unit positive charge tends to move in an electric field. Each unit positive charge gives rise to $\frac{1}{\varepsilon_o}$ lines of force in free space.
Electric dipole	:	Two equal and opposite charges separated by a very small vector distance.
Importance of dipole	:	Any complicated array of a complex arrangement of charges, can be simplified as a number dipoles and analysed.
Potential difference	:	It is defined as the amount of work done in moving a unit positive charge from one point to the other in an electric field.
Volt	:	If 1 joule of work is done in moving 1 coulomb of charge from one point to another in an electric field.
Electric potential	:	It is defined as the amount of work done in moving a unit positive charge from infinity to that point.
Equipotential surface	:	If the potential at all points on a surface is the same, it is said to be an equipotential surface.
Electric flux	:	The total number of electric lines of force crossing a given area. $d\phi = \vec{E}.\vec{ds} = Eds\cos\theta$
Gauss' law	:	It states that the total flux of the electric field E over any closed surface is equal to $\frac{1}{\varepsilon_o}$ times the net charge enclosed by the surface, $\phi = \frac{q}{\varepsilon_o}$.
Gaussian surface	:	The closed imaginary surface over an enclosed net charge.
Electrostatic shielding	:	Process of isolating a certain region of space from external field. It is based on the fact that electric field inside a conductor is zero.
Electrostatic induction	:	It is the method of obtaining charges without any contact with another charge. They are called induced charges and the phenomenon of producing induced charges is called electrostatic induction. It is used in electrostatic machines like Van de Graaff generators and capacitors.
Capacitance	:	It is defined as the ratio of charge given to the conductor to the potential developed in the conductor. Its unit is farad (F). A conductor has a capacitance of one farad if a charge of 1 coulomb given to it raises its potential by 1 volt.
Dielectric	:	A dielectric is an insulating material in which all electrons are tightly bound to the nucleus of the atom. The electrons are not free to move under the influence of an external field. Hence, there are no free electrons to carry current.
Polar molecule	:	It is one in which the centre of gravity (mass) of the positive charges is separated from the centre of gravity of the negative charges by a finite distance. **e.g :** N_2O, H_2O, HCl, NH_3. These molecules have a permanent dipole moment.

Non-polar molecules	:	A non-polar molecule is one in which centers of positive and negative charges coincide. It has no permanent dipole moment, e.g: H_2, O_2, CO_2 etc.
Electric polarisation	:	The alignment of electric dipole moments of the permanent or induced dipoles in the direction of the external applied field.
Corona discharge	:	The leakage of electric charges from the sharp points on the charged conductor is called action of points or corona discharge. It is used in machines like Van de Graaff generators and lightning arrestors (conductors).

Force - Displacing vector

Torque - Rotating vectors; it is the moment of force

Hint:

1. In a uniform electric field when equal and opposite forces act at the ends of the dipole, the net force is zero.
2. The forces act at different points. Hence, the moment of the force is non-zero and the torque is non-zero.
3. The non-zero torque, always tends to align the dipole in the direction of the field.
4. The direction of torque vector is along the axis of rotation.
5. Charges outside the Gaussian surface will not contribute to the flux inside.
6. Field outside the charged parallel sheets is zero.

Conduction	Induction
Charges are obtained in contact with other charged body.	Charges are obtained without any contact with other charged body.
Produces similar or one type of charge.	Both positive and negative charges are produced.
Only limited amount of charges are obtained.	Large quantity of charges can be induced.

	Capacitors in series	Capacitors in parallel
Total Charge	q is same for C_1 and C_2 and C_3	$q = q_1 + q_2 + q_3$ $q_1 = C_1V$; $q_2 = C_2V$ $q_3 = C_3V$
Total potential	$V = V_1 + V_2 + V_3$ $V_1 = \frac{q}{C_1}$; $V_2 = \frac{q}{C_2}$; $V_3 = \frac{q}{C_3}$	V is same for C_1, C_2 and C_3
Expression for equivalent capacitance	$\frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$	$C_p = C_1 + C_2 + C_3$

Charge (q)	Mass(m)
Can be zero, +ve or –ve	Can never be zero, only +ve
Force between two charges can be positive or negative	Force between any two masses is always attractive in nature
Value of constant depends upon $\varepsilon, \varepsilon_r, \varepsilon_0$	Value of constant G is always fixed.

FORMULAE

(1) Electrostatic force between charges q_1 and q_2, $F = \vec{F}_{12} = \frac{1}{4\pi\varepsilon_o}\frac{q_1 q_2}{r_{21}^2}\hat{r}_{21}$

(2) Value of $k = \frac{1}{4\pi\varepsilon_o} = 9 \times 10^9 \, Nm^2C^{-2}$

(3) Value of $\varepsilon = 8.854 \times 10^{-12} \, C^2N^{-1}m^{-2}$

(5) Total charge $q = n \times e$; Number of electrons × Charge of an electron

(6) Components of force F, $F_1 = F\cos\theta$; $F_2 = F\sin\theta$; $|F| = \sqrt{F_1^2 + F_2^2}$

(7) Relative permittivity or Dielectric constant $\varepsilon_r = \frac{\varepsilon}{\varepsilon_o}$

(8) Force between charges in medium $F_m = \frac{F_{air}}{\varepsilon_r}$

(9) Electrostatic field, $E = \frac{\text{force}}{\text{charge}} = \frac{F}{q} \Rightarrow F = qE$

(10) Electric field due to a point charge $E = \frac{1}{4\pi\varepsilon_o}\frac{q}{r^2}$

(11) Electric dipole moment, $\vec{p} = q \times 2a\hat{i}$

(12) (i) Electric field due to a dipole at a point on the axial line, $\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{2\vec{p}}{r^3}$ $(r >> a)$

(ii) Electric field due to a dipole at a point on the equatorial line $E = \vec{E}_{tot} = \frac{-1}{4\pi\varepsilon_0}\frac{\vec{p}}{r^3}$ $(r >> a)$

(13) Magnitude of torque $\tau = \vec{p} \times \vec{E} = pE\sin\theta$ $(p = q\,2a)$

(14) Electric potential at a point due to a point charge, $V = \frac{1}{4\pi\varepsilon_o}\frac{q}{r}$

(15) Electric potential energy of dipole $U = -pE\cos\theta = -\vec{p}.\vec{E}$

(16) Electric potential at a point due to an electric dipole $V = \frac{p}{4\pi\varepsilon_o}\frac{\cos\theta}{r^2}$

(17) Electric flux $= \frac{q}{\varepsilon_o} \Rightarrow \phi_E = \vec{E}.\vec{A} = EA\cos\theta$

(18) Electric field due to infinite long straight charged wire, $E = \frac{\lambda}{2\pi\varepsilon_o r}$

(19) Electric field due to plane sheet of charge $E = \frac{\sigma}{2\varepsilon_o} = \frac{q}{A}\frac{1}{2\varepsilon_o}$ Vector form, $\vec{E} = \frac{\sigma}{2\varepsilon_0}\hat{n}$

(20) Electric field at a point between two parallel sheets of charge $E = \frac{\sigma}{\varepsilon_o}$

(21) Electric field due to a uniformly charged sphere -

(i) at a point on the surface of the sphere, $E = \frac{1}{4\pi\varepsilon_o}\frac{Q}{R^2}\hat{r}$ $\quad \because [r = R]$

(ii) at a point outside the sphere $E = \frac{1}{4\pi\varepsilon_o}\frac{Q}{r^2}\hat{r}$

(iii) at a point inside the sphere $E = 0$ $\quad [r < R]$

(22) Capacitance of a conductor $C = \frac{q}{V}$

(23) Work done by a charge $W = qV$

(24) Charge density, $\sigma = \frac{q}{A}$

(25) Capacitance of a parallel plate capacitor $C = \frac{\varepsilon_o A}{d}$

(i) With a dielectric slab, $C = \frac{\varepsilon_o A}{\left[(d-t)+\frac{t}{\varepsilon_r}\right]}$

(ii) With the dielectric completely filled capacitor $C^1 = \frac{\varepsilon_o\varepsilon_r A}{d} = C \times \varepsilon_r$

(26) Energy stored in a capacitor $E = \frac{1}{2}CV^2$

(27) Capacitance of a spherical capacitor, $C = 4\pi\varepsilon_0 A$ or $C = \frac{A}{9\times 10^9}$

(28) Equivalent capacitance

(i) C_1 and C_2 in series $C_s = \frac{C_1C_2}{C_1+C_2}$; $C_s = \frac{1}{C_S} = \frac{1}{C_1} + \frac{1}{C_2}$

(ii) C_1 and C_2 in parallel $C_P = C_1 + C_2$

(29) Polarisation, $\vec{p} = \chi_e \vec{E}_{ext}$ (χ_e - electric susceptibility)

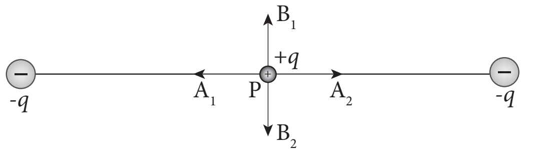
Values And Units

(1)	Permittivity of free space ε_o	=	$8.854\times10^{-12}\ C^2N^{-1}m^{-2}$
(2)	$\frac{1}{4\pi\varepsilon_o}$	=	$9\times10^9\ Nm^2C^{-2}$
(3)	Charge of an electron, e	=	1.6×10^{-19} C
(4)	1 micro farad	=	10^{-6} farad
(5)	1 pico farad	=	10^{-12} farad
(6)	Permittivity of medium, ε	=	$C^2N^{-1}m^{-2}$
(7)	Electric charge (q)	=	Coulomb (C)
(8)	Electric field (E)	=	NC^{-1} or $V\ m^{-1}$
(9)	Electric potential (V)	=	JC^{-1} or volt
(10)	Electric dipole moment (p)	=	Coulomb metre
(11)	Electric potential energy (U)	=	Joule
(12)	Capacitance (C)	=	farad
(13)	Electric flux	=	Nm^2C^{-1}
(14)	Torque	=	Nm
(15)	Relative permittivity of air	=	1 (no unit)

Evaluation

I. Multiple choice questions :

1. Two identical point charges of magnitude $-q$ are fixed as shown in the figure below. A third charge $+q$ is placed midway between the two charges at the point P. Suppose this charge $+q$ is displaced a small distance from the point P in the directions indicated by the arrows, in which direction(s) will $+q$ be stable with respect to the displacement?



(a) A_1 and A_2 (b) B_1 and B_2
(c) both directions (d) No stable

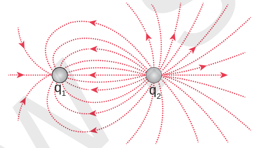
[Ans. (b) B_1 and B_2]

2. Which charge configuration produces a uniform electric field? *[HY-2019]*

(a) point Charge
(b) uniformly charged infinite line
(c) uniformly charged infinite plane
(d) uniformly charged spherical shell

[Ans. (c) uniformly charged infinite plane]

3. What is the ratio of the charges $\left|\frac{q_1}{q_2}\right|$ for the following electric field line pattern?



(a) $\frac{1}{5}$ (b) $\frac{25}{11}$ (c) 5 (d) $\frac{11}{25}$

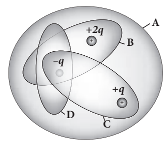
[Ans. (d) $\frac{11}{25}$]

4. An electric dipole is placed at an alignment angle of 30° with an electric field of 2×10^5 N C^{-1}. It experiences a torque equal to 8 N m. The charge on the dipole if the dipole length is 1 cm is *[QY-2019]*

(a) 4 mC (b) 8 mC
(c) 5 mC (d) 7 mC

[Ans. (b) 8 mC]

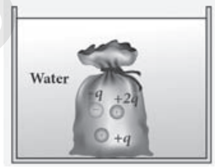
5. Four Gaussian surfaces are given below with charges inside each Gaussian surface. Rank the electric flux through each Gaussian surface in increasing order.



(a) D < C < B < A (b) A < B = C < D
(c) C < A = B < D (d) D > C > B > A

[Ans. (a) D < C < B <A]

6. The total electric flux for the following closed surface which is kept inside water



(a) $\frac{80q}{\varepsilon_o}$ (b) $\frac{q}{40\varepsilon_o}$
(c) $\frac{q}{80\varepsilon_o}$ (d) $\frac{q}{160\varepsilon_o}$

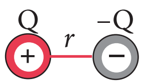
[Ans. (b) $\frac{q}{40\varepsilon_o}$]

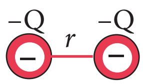
7. Two identical conducting balls having positive charges q_1 and q_2 are separated by a center to center distance r. If they are made to touch each other and then separated to the same distance, the force between them will be *(NSEP 04-05[Sep.-2020]*

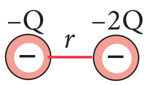
(a) less than before (b) same as before
(c) more than before (d) zero

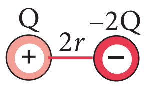
[Ans. (c) more than before]

8. Rank the electrostatic potential energies for the given system of charges in increasing order. *[PTA-4]*

(a) 

(b) 

(c) 

(d) 

(a) 1 = 4 < 2 < 3 (b) 2 = 4 < 3 < 1
(c) 2 = 3 < 1 < 4 (d) 3 < 1 < 2 < 4

[Ans. (a) 1 = 4 < 2 < 3]

Unit 1

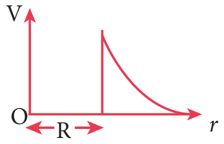
9. **An electric field $\vec{E} = 10x\hat{i}$ exists in a certain region of space. Then the potential difference $V = V_0 - V_A$, where V_0 is the potential at the origin and V_A is the potential at $x = 2$ m is:**

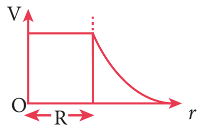
(a) 10 V (b) – 20 V

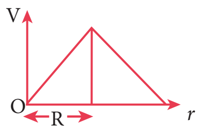
(c) +20 V (d) -10 V

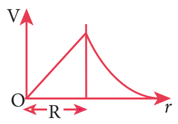
[*Ans.* (c) +20 V]

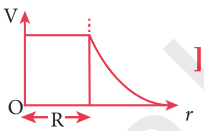
10. **A thin conducting spherical shell of radius R has a charge Q which is uniformly distributed on its surface. The correct plot for electrostatic potential due to this spherical shell is** *[PTA-1]*

(a)


(b)


(c)


(d)


[*Ans.* (b)


]

11. **Two points A and B are maintained at a potential of 7 V and –4 V respectively. The work done in moving 50 electrons from A to B is**

(a) 8.80×10^{-17} J (b) -8.80×10^{-17} J

(c) 4.40×10^{-17} J (d) 5.80×10^{-17} J

[*Ans.* (a) 8.80×10^{-17} J]

12. **If voltage applied on a capacitor is increased from V to 2V, choose the correct conclusion.** *[Govt. MQP-2019; Mar.-2020]*

(a) Q remains the same, C is doubled

(b) Q is doubled, C doubled

(c) C remains same, Q doubled

(d) Both Q and C remain same

[*Ans.* (c) C remains same, Q doubled]

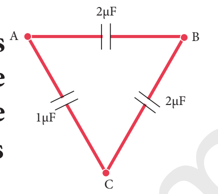
13. **A parallel plate capacitor stores a charge Q at a voltage V. Suppose the area of the parallel plate capacitor and the distance between the plates are each doubled then which is the quantity that will change?** *[Sep.-2020; QY-2019]*

(a) Capacitance (b) Charge

(c) Voltage (d) Energy density

[*Ans.* (d) Energy density]

14. **Three capacitors are connected in triangle as shown in the figure. The equivalent capacitance between the points A and C is**



(a) 1μF

(b) 2 μF

(c) 3 μF

(d) $\frac{1}{4}$μF [*Ans.* (b) 2 μF]

15. **Two metallic spheres of radii 1 cm and 3 cm are given charges of -1×10^{-2} C and 5×10^{-2} C respectively. If these are connected by a conducting wire, the final charge on the bigger sphere is** *(AIIPMT -2012)*

(a) 3×10^{-2} C (b) 4×10^{-2} C

(c) 1×10^{-2} C (d) 2×10^{-2} C

[*Ans.* (a) 3×10^{-2} C]

II. Short Answer Questions :

1. **What is meant by quantisation of charges?**

Ans. (i) The charge q on any object is equal to an integral multiple of the fundamental unit of charge e.

$$q = ne$$

(ii) Where n is any integer (0, ±1, ±2, ±3, ±4………..). this is called Quantisation of electric charge.

2. **Write down Coulomb's law in vector form and mention what each term represents.**

Ans. (i) According to Coulomb, the force on the point charge q_2 exerted by another point charge q_1 is

$$\vec{F}_{21} = k\frac{q_1 q_2}{r^2}\hat{r}_{12}$$

where $\hat{r}_{12}$ is the unit vector directed from charge q_1 to charge q_2 and k is the proportionality constant.

(ii) Also $k = \frac{1}{4\pi\varepsilon_0}$ and its value is $k = 9 \times 10^9$ Nm^2C^{-2}. Here ε_0 is the permittivity of free space or vacuum and the value of $\frac{1}{4\pi k} = 8.85 \times 10^{-12}\ C^2 N^{-1} m^{-2}$

3. What are the differences between Coulomb force and gravitational force? *[QY; HY - 2019]*

Ans.

	Coulomb	Gravitational
i)	It may be attractive or repulsive.	It is always attractive in nature.
ii)	It depends upon medium	It does not depend upon the medium
iii)	It is always greater in magnitude because of high value of $K = 9 \times 10^9$ Nm^2 C^{-2}	It is lesser than coulomb force because value of G is 6.62×10^{-11} Nm^2 kg^{-2}
iv)	The force between the charges will not be same during motion or rest.	It is always same whether the two masses are rest or motion

4. Write a short note on superposition principle.

Ans. When a number of charges are interacting the total force of a given charge is the vector sum of the individual forces exerted on the given charge by all the other charges.

5. Define 'electric field'.

Ans. (i) The electric field at the point P at a distance r from the point charge q is the force experienced by a unit charge and is given by

$$\vec{E} = \frac{\vec{F}}{q_0} = \frac{kq}{r^2}\hat{r} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}\hat{r}$$

(ii) Here $\hat{r}$ is the unit vector pointing from q to the point of interest P.

(iii) Vector quantity

(iv) SI unit is Newton per Coulomb (NC^{-1}).

6. What is meant by 'electric field lines'?

Ans. Electric field vectors are visualized by the concept of electric field lines. They form a set of continuous lines which represent the electric field in some region of space visually.

7. The electric field lines never intersect. Justify. *[PTA-4]*

Ans. If some charge is placed in the intersection point, then it has to move in two different directions at the same time, which is physically impossible. Hence, electric field lines do not intersect.

8. Define 'electric dipole'. Give the expression for the magnitude of its electric dipole moment and the direction.

Ans. (i) Two equal and opposite charges separated by a small distance, constitute an electric dipole.

(ii) The magnitude of the electric dipole moment is equal to the product of magnitude of one of the charges and the distance between them.

$|\vec{p}| = 2qa$

and it is directed from $-q$ to $+q$

9. Write the general definition of electric dipole moment for a collection of point charge.

Ans. The electric dipole moment for a collection of 'n' point charges is given by, $\vec{P} = \sum_{i=1}^{n} q_i \vec{r}_i$

where $\vec{r}_i$ is the position vector of charge q_i from the origin.

10. Define 'electrostatic potential'.

Ans. Work done by an external force to bring a unit positive charge with constant velocity from infinity to ones point in E scalar.

11. What is an equipotential surface?

Ans. A surface on which all the points are at the same potential.

12. What are the properties of an equipotential surface?

Ans. (i) The work done to move a charge q between any two points A and B, $W = q(V_B - V_A)$.

(ii) If the points A and B lie on the same equipotential surface, work done is zero because $V_B = V_A$.

(iii) The electric field is always normal to an equipotential surface.

13. Give the relation between electric field and electric potential. *[PTA-6]*

Ans. Consider a positive charge q kept fixed at the origin. To move a unit positive charge by a small distance dx in the electric field E, the work done is given by $dW = -E\,dx$. The minus sign implies that work is done against the electric field. This work done is equal to electric potential difference. Therefore,

$$dW = dV$$
$$\text{(or)} \quad dV = -E\,dx$$
$$\text{Hence } E = -\frac{dV}{dx}$$

The electric field is the negative gradient of the electric potential.

14. Define 'electrostatic potential energy'.

Ans. Electric potential energy is defined as the work done in bringing the various charges to their respective positions from infinitely large mutual separation.

15. Define 'electric flux'

Ans. (i) The number of electric field lines crossing a given area kept normal to the electric field lines is called electric flux.

(ii) Scalar quantity

(iii) SI $\Rightarrow$ Nm^2c^{-1}

16. What is meant by electrostatic energy density?

Ans. The energy stored per unit volume of space is defined as energy density $u_E = \frac{U}{Volume} = \frac{1}{2}\varepsilon_0 E^2$.

17. Write a short note on 'electrostatic shielding'.

Ans. (i) The phenomenon of protecting a region of space from any external electric field is called electrostatic shielding.

(ii) Consider a cavity inside the conductor. Whatever the charges at the surfaces and whatever the electrical disturbances outside, the electric field inside the cavity is zero.

18. What is Polarisation?

Ans. (i) Total dipole moment per unit volume of the dielectric.

$$\vec{p} = \chi_e \vec{E}_{ext}$$

(ii) χ_e electric susceptibility.

19. What is dielectric strength?

Ans. The maximum electric field the dielectric can withstand before it gets breakdown is called dielectric strength.

20. Define 'capacitance'. Give its unit.

Ans. Ratio of the magnitude of charge to the potential difference between the conductors. $C = \frac{Q}{V}$

21. What is Corona discharge? *[Mar. - 2020]*

Ans. (i) The electric field near the edge of conductor is very high and it ionizes the surrounding air.

(ii) The positive ions are repelled at the sharp edge.

(iii) Negative ions are attracted towards the sharper edge.

(iv) This reduces the total charge of the conductor near the sharp edge. This is called action at points or corona discharge.

III. Long Answer Questions :

1. Discuss the basic properties of electric charges.

Ans. (i) **Electric charge :** The electric charge is fundamental property of particles having mass and its unit is coulomb.

(ii) **Conservation of charges :** Charges are neither be created nor be destroyed but can only be transferred from one object to the other. This is called conservation of total charges.

(iii) **Quantisation of charges :** The charge q on any object is equal to an integral multiple of the fundamental unit of charge e. $q = ne$. Here n is any integer (0, ±1, ±2, ±3, ±4..........). This is called Quantisation of electric charge.

2. Explain in detail Coulomb's law and its various aspects. *[PTA-3]*

Ans. Various aspects of Coulomb's law :

(i) Coulomb's law states that electrostatic force between 2 stationary point charges is directly proportional to the product of the magnitude of the charges and is inversely proportional to the square of the distance between them.

(ii) The force on the charge q_2 exerted by the q_1 always lies along the line joining the two charges. $\hat{r}_{12}$ is the unit vector from charge q_1 to q_2. $\vec{F}_{21} = k\frac{q_1q_2}{r^2}\vec{r}_{12}$. The force on the charge q_1 exerted by q_2 is along $-\hat{r}_{12}$ (i.e., in opposite direction).

$$\vec{F}_{12} = k.\frac{q_1q_2}{r^2}.\hat{r}_{21} \text{ i.e. } \vec{F}_{12} = -\vec{F}_{21}$$

(iii) $k = \frac{1}{4\pi\varepsilon_0} = 9 \times 10^9\ Nm^2C^{-2}$in SI units.

ε_0-permittivity of free space or vacuum $\varepsilon_0 = 8.85 \times 10^{-12}\ C^2 N^{-1} m^{-2}$

(iv) If $q_1 = q_2 = 1C$; $r = 1m$, then

$$|F| = \frac{9\times10^9\times1\times1}{1^2} = 9\times10^9\ N$$

(v) In vacuum $\vec{F}_{21} = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2}\hat{r}_{12}$.

Electrostatics

In a medium $\vec{F}_{21} = \frac{1}{4\pi\varepsilon}\frac{q_1 q_2}{r^2}\hat{r}_{12}$ $\varepsilon > \varepsilon_0$

$\therefore \varepsilon = \varepsilon_0 . \varepsilon_r$ (ε_r -relative permittivity)

For air or vacuum $\varepsilon_r = 1$ and for all other media $\varepsilon_r > 1$.

(vi) It has same structure as Newton's law of gravitation, where $F = G\frac{M_1M_2}{r^2}$ and $G = 6.626 \times 10^{11}$ Nm² kg^{-2}

(vii) The expression for Coulomb force is true only for point charges.

(viii) Gravitational force is between 2 masses is independence of the medium but Coulomb force between 2 charges depends on the nature of the medium.

3. Define 'Electric field' and discuss its various aspects.

Ans. **Electric Field :** Electric Field at the point P at a distance r from the point charge q is the force experienced by a unit charge. $\vec{E} = \frac{\vec{F}}{q_0}$ i.e.

$$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}\hat{r} \quad ...(1)$$

Important aspects of the Electric field :

(i) If q is positive, electric field points away from source charge q. If q is negative, electric field points towards the source charge q.

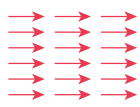
(ii) Force experienced by the test charge q_0 at P $\vec{F} = q_0\vec{E}$

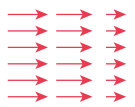
(iii) From equation (1) electric field is independent of q_0 (test charge) and depends on q (source charge).

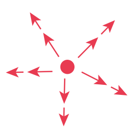
(iv) It is a vector quantity, which has unique direction and magnitude, and electric field decreases, when distance increases

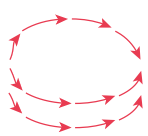
(v) Test charge is very small. So that field value of source charge is unaltered.

(vi) Equation (1) is only for point charges.


Uniform Electric field


Non uniform electric field


Non uniform electric field


Non uniform electric field

(vii) There are uniform and non-uniform electric fields.

Uniform electric field : It has same direction and constant magnitude at all points.

Non-uniform electric field : Different directions or different magnitudes or both at different points.

4. Calculate the electric field due to a dipole on its axial line and equatorial plane. *[PTA-5]*

Ans. **Electric field due to an electric dipole at points on the axial line :**

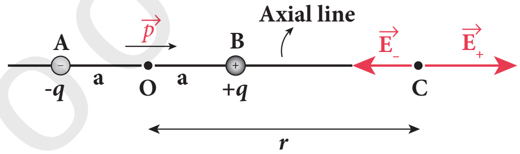
AB - Electric dipole; 2a -dipole distance.

C - point along axial line.

r - Distance from mid point 'O' to point C.

E at 'C' due to $+q$

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



E at 'C' due to $-q$

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

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

at 'C' using superpostion principle

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

$$\vec{E}_{tot} = \frac{1}{4\pi\varepsilon_0}q\left(\frac{4ra}{(r^2-a^2)^2}\right)\hat{p} \text{ along BC}$$

But r >> a when 'C' is for away from the dipole and $2aq\hat{p} = \vec{p}$

$$\vec{E}_{tot} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{2\vec{p}}{r^3}$$

$\vec{E}$ acts along $\vec{p}$

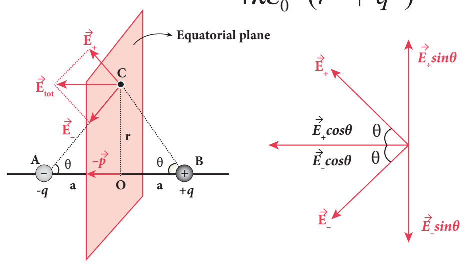
Electric field to dipole at a point on equatorial line :

AB - dipole ; $2a$ - dipole distance.

P - dipole moment

r - distance. E due to $+q = |E_+| = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{(r^2+q^2)}$
along BC along CA

E due to $-q = |E_-| = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{(r^2+q^2)}$



Electric field due to a dipole at a point on the equatorial plane

resolving into components, the perpendicular components are equal and opposite so they cancel each other. Total Electric Field at C is sum of parallel components.

$$\vec{E}_{tot} = -\left|\vec{E}_+\right|\cos\theta\,\hat{p} - \left|\vec{E}_-\right|\cos\theta\,\hat{p} \qquad ...(1)$$

$|E_+| = |E_-|$

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

$$\vec{E}_{tot} = -\frac{1}{4\pi\varepsilon_0} \cdot \frac{2qa}{(r^2+a^2)^{\frac{3}{2}}}\hat{p}$$

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

$r >> a$ and $\vec{p} = 2qa\,\hat{p}$

$$\vec{E}_{tot} = -\frac{1}{4\pi\varepsilon_0}\frac{\vec{p}}{r^3} \qquad (r >> a)$$

$\vec{E}$ is opposite to $\vec{p}$

5. Derive an expression for the torque experienced by a dipole due to a uniform electric field. *[PTA-3]*

Ans. Electric dipole in uniform electric field :

AB - an electrical dipole ; $\vec{p}$ dipole moment.

$\vec{E}$ - uniform electric filed : θ-angle made by $\vec{p}$ with $\vec{E}$ τ - Torque

$qE \rightarrow$ force experienced by $+q$; $-qE \rightarrow$ force experienced by - q. Total force acting on dipole is zero.

Two unlike force acting at different points produces torque. Torque tends to set dipole in the direction of $\vec{E}$.

Total torque on dipole

$$\vec{\tau} = \vec{OA} \times \left|-q\vec{E}\right| + \vec{OB} \times q\vec{E}$$

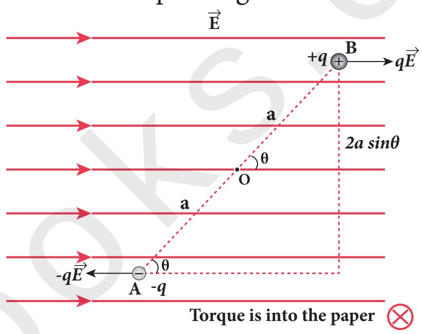
$\tau = qE \cdot 2a\sin\theta$; $\tau = p\,E\sin\theta$

$p = 2aq$

$\vec{\tau} = \vec{p} \times \vec{E}$, in terms of vector product

When $\theta = 90^o$ τ is maximum. i.e. $\tau = PE$

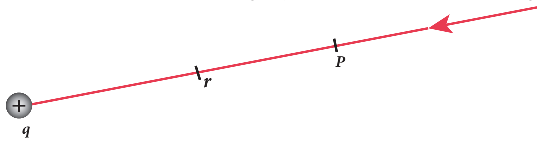
$\theta = 0^o$ $\tau = 0$ i.e. dipole align with the electric field E.



Torque on dipole

6. Derive an expression for electrostatic potential due to a point charge.

Ans. (i) Consider a positive charge q kept fixed at the origin. Let P be a point at distance r from the charge q. This is shown in Figure.



Electrostatic potential at a point P

(ii) The electric potential at the point P is

$$V = \int_{\infty}^{r}\left(-\vec{E}\right) \cdot d\vec{r} = -\int_{\infty}^{r}\vec{E} \cdot d\vec{r} \qquad ...(1)$$

Electric field due to positive point charge q is

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

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

The infinitesimal displacement vector, $d\vec{r} = dr\hat{r}$ and using $\hat{r}.\hat{r} = 1$, we have

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

After the integration,

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

Hence the electric potential due to a point charge q at a distance r is

$$V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r} \qquad ...(2)$$

Important points :

(i) If the source charge q is positive, V > 0. If q is negative, then V is negative and equal to

$$V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$$

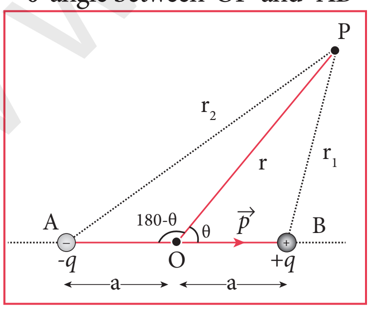
(ii) It is clear that the potential due to positive charge decreases as the distance increases, but for a negative charge the potential increases as the distance is increased. At infinity, ($r = \infty$) electrostatic potential is zero (V = 0).

(iii) A positive charge moves from a point of higher electrostatic potential to lower electrostatic potential, a negative charge moves from lower electrostatic potential to higher electrostatic potential.

(iv) The electric potential at a point P due to a collection of charges $q_1, q_2, q_3 .....q_n$ is equal to sum of the electric potentials due to individual charges.

7. Derive an expression for electrostatic potential due to an electric dipole. *[PTA-2,4 ; QY; HY-2019]*

***Ans.* (i)**
- ➢ AB - electric dipole.
- ➢ $2a$ dipole distance.
- ➢ 'r' be the distance between the point 'P' and mid point 'O' of AB.
- ➢ 'θ' angle between 'OP' and "AB'



Potential due to electric dipole

(ii) Let r_1 be the distance to P from $+q$ and r_2 be the distance of point P from $-q$.

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

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

Total potential at P,

$$\boxed{V = \frac{1}{4\pi\varepsilon_0} q\left(\frac{1}{r_1} - \frac{1}{r_2}\right)} \qquad ...(1)$$

(iii) By the cosine law for triangle BOP,

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

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

Since a<<r, Neglecting $\frac{a^2}{r^2}$

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

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

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

(iv) Using binomial theorem we get.

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

Similarly applying the cosine law for triangle AOP,

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

Since $\cos(180 - \theta) = -\cos\theta$ we get

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

Neglecting $\frac{a^2}{r^2}$ (because $r >> a$)

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

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

Using Binomial theorem, we get

$$\boxed{\frac{1}{r_2} = \frac{1}{r}\left(1 - a\frac{\cos\theta}{r}\right)} \qquad ...(3)$$

Substituting equation (3) and (2) in equation (1),

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

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

(v) $p = 2qa$,

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

Special cases

Case (i) If P lies on the axial line of $+q$ side, then $\theta = 0$, then

$$V=\frac{1}{4\pi\varepsilon_0}\frac{p}{r^2} \quad ...(4)$$

Case (ii) If P lies on $-q$ side then $\theta = 180°$, then

$$V=-\frac{1}{4\pi\varepsilon_0}\frac{p}{r^2} \quad ...(5)$$

Case (iii) P lies on the equatorial line, then $\theta = 90°$. Hence

$$V = 0 \quad ...(6)$$

8. Obtain an expression for potential energy due to a collection of three point charges which are separated by finite distances.

Ans. **(i)** The electric potential at a point at a distance r from point charge q_1 is given by

$$V=\frac{1}{4\pi\varepsilon_0}\frac{q_1}{r}$$

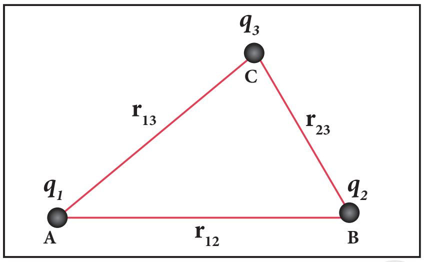
(ii) This potential V is the work done to bring a unit positive charge from infinity to the point. Now if the charge q_2 is brought from infinity to that point at distance r from q_1, the work done is the product of q_2 and the electric potential at that point. Thus we have

$$W = q_2 V$$

(iii) This work done is stored as the electrostatic potential energy U of a system of charges q_1 and q_2 separated by a distance r. Thus we have

$$U=q_2 V=\frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r} \quad ...(1)$$

(iv) Three charges are arranged in the following configuration as shown in Figure.



Electrostatic potential energy for Collection of point charges

(a) Bringing a charge q_1 from infinity to the point A requires no work, because there are no other charges already present in the vicinity of charge q_1.

(b) To bring the second charge q_2 to the point B, work must be done against the electric field at B created by the charge q_1. So the work done on the charge q_2 is $W = q_2 V_{1B}$. Here V_{1B} is the electrostatic potential due to the charge q_1 at point B.

$$U=\frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r_{12}} \quad ...(2)$$

(c) Similarly to bring the charge q_3 to the point C, work has to be done against the total electric field due to both the charges q_1 and q_2. So the work done to bring the charge q_3 is $= q_3 (V_{1C} + V_{2C})$. Here V_{1C} is the electrostatic potential due to charge q_1 at point C and V_{2C} is the electrostatic potential due to charge q_2 at point C.

The electrostatic potential is

$$U=\frac{1}{4\pi\varepsilon_0}\left(\frac{q_1q_3}{r_{13}}+\frac{q_2q_3}{r_{23}}\right) \quad ...(3)$$

(d) Adding equations (2) and (3), the total electrostatic potential energy for the system of three charges q_1, q_2 and q_3 is

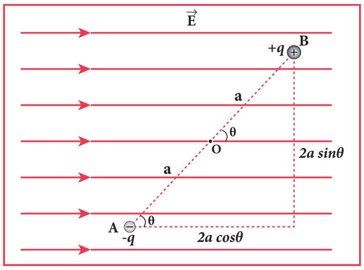
$$U=\frac{1}{4\pi\varepsilon_0}\left(\frac{q_1q_2}{r_{12}}+\frac{q_1q_3}{r_{13}}+\frac{q_2q_3}{r_{23}}\right) \quad ...(4)$$

This stored potential energy U is equal to the total external work done to assemble the three charges at the given locations.

(e) Electrostatic potential energy is independent of the configuration of charges since coulomb force is a conservative one.

9. Derive an expression for electrostatic potential energy of the dipole in a uniform electric field.

Ans. (i) Consider a dipole placed in the uniform electric field $\vec{E}$. This dipole experiences a torque which rotates the dipole to align it with the direction of the electric field. To rotate the dipole (at constant angular velocity) from its initial angle θ′ to another angle θ, an equal and opposite external torque must be applied on the dipole.



The dipole in a uniform electric field

(ii) The work done by the external torque to rotate the dipole at constant angular velocity is

$$W = \int_{\theta'}^{\theta} \tau_{ext}\, d\theta \qquad ...(1)$$

(iii) Since $\vec{\tau}_{ext}$ is equal and opposite to $\vec{\tau}_E = \vec{p} \times \vec{E}$

We have

$$\left|\vec{\tau}_{ext}\right| = \left|\vec{\tau}_E\right| = \left|\vec{p} \times \vec{E}\right| \qquad ...(2)$$

$\Rightarrow p_E \sin\theta = \tau_{ext}$

Substituting equation (2) in equation (1), we get

$$W = \int_{\theta'}^{\theta} pE\sin\theta\, d\theta$$

$$W = pE\,(\cos\theta' - \cos\theta)$$

(iv) This work done is equal to the potential energy difference. between n θ′ and θ.

$\Delta U = -\,pE\cos\theta + pE\cos\theta'$

If the initial angle is θ′ = 90°, then U (θ′) = pE cos 90° = 0 .

'U' also depends on the orientation ' θ' other than $\vec{p}$ and $\vec{E}$.

$$U = -\,pE\cos\theta = -\,\vec{p}\,.\,\vec{E} \qquad ...(3)$$

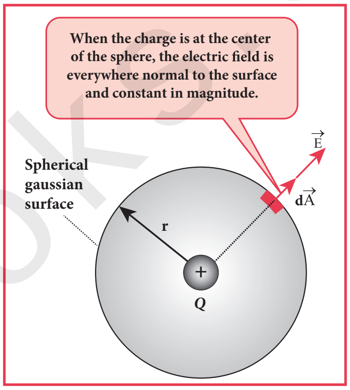
(v) The potential energy is maximum when the dipole is aligned anti-parallel (θ = π) and minimum when the dipole is aligned parallel (θ = 0) to the external field.

10. Obtain Gauss law from Coulomb's law. *[Sep.-2020]*

Ans. (i) A positive point charge Q is surrounded by an imaginary sphere of radius r electric flux through the closed surface of the sphere

$$\Phi_E = \oint \vec{E}.d\vec{A} = \oint E\,dA\cos\theta \qquad ...(1)$$

(ii) Since the electric field of the point charge is directed radially outward both $d\vec{A}$ and $\vec{E}$ are along the same direction therefore θ = 0°.



$$\therefore \Phi_E = \oint E\,dA \quad \text{since } \cos 0° = 1 \qquad ...(2)$$

E is uniform on the surface of the sphere,

$$\because \oint dA = 4\pi r^2$$

$$\therefore \varphi_E = 4\pi r^2 E \text{ and } E = \frac{1}{4\pi\varepsilon_0}\cdot\frac{Q}{r^2}$$

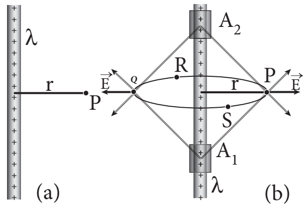
$$\Phi_E = \frac{1}{4\pi\varepsilon_0}\cdot\frac{Q}{r^2} \times 4\pi r^2 = 4\pi\frac{1}{4\pi\varepsilon_0}Q$$

$$\Phi_E = \frac{Q}{\varepsilon_0} \qquad ...(3)$$

The equation (3) is called as Gauss's law and is true fro any shaped surface that encloses 'Q' and total electric flux is same for all surfaces.

11. Obtain the expression for electric field due to an infinitely long charged wire. *[PTA-1]*

Ans. (i)
- ➢ λ - Linear charge density of an infinitily long, uniformly charged wire, r - distance between wire and point 'P'
- ➢ A_1, A_2 two charge elements.
- ➢ The resultant 'E' due to A_1 and A_2, act radially outward and is same at all points.
- ➢ r & L radius & length of cylindrical Gaussian surface of radius 'r'.



Electric field due to infinite long charged wire

(ii) The total electric flux

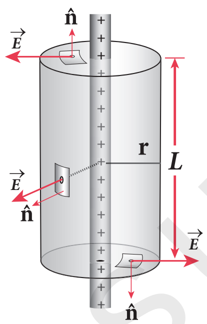
$$\Phi_E = \oint \vec{E} \cdot d\vec{A}$$

$$\oint_{\text{Curved surface}} \vec{E} \cdot d\vec{A} + \oint_{\text{top surface}} \vec{E} \cdot d\vec{A} + \oint_{\text{bottom surface}} \vec{E} \cdot d\vec{A} \quad ...(1)$$

(iii) for the curved surface, $\vec{E} \parallel \vec{A}$ and $\vec{E} \cdot d\vec{A}$ = E dA. For the top and bottom surfaces, $\vec{E} \perp r \ \vec{A}$ and $\vec{E} \cdot d\vec{A} = 0$

Applying Gauss law to the cylindrical surface,

$$\phi_E = \int_{\text{Curved surface}} E \cdot dA = \frac{Q_{encl}}{\varepsilon_0} \quad ...(2)$$



Cylindrical Gaussian surface

(vi) Since E is constant, $Q_{encl} = \lambda L$.

$$E \int_{\text{Curved surface}} dA = \frac{\lambda L}{\varepsilon_0} \quad ...(3)$$

But $\int dA$ = Total area of the curved surface = $2\pi rl$.

$$\therefore E \cdot 2\pi rL = \frac{\lambda L}{\varepsilon_0}$$

$$E = \frac{1}{2\pi\varepsilon_0} \frac{\lambda}{r} \quad \text{(or)}$$

In vector form $\vec{E} = \dfrac{1}{2\pi\varepsilon_0} \dfrac{\lambda}{r} \hat{r}$ and is true for an infinitely long wire.

12. Obtain the expression for electric field due to a charged infinite plane sheet.

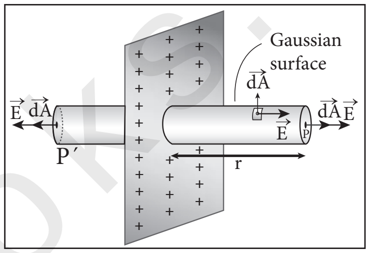
Ans. **Electric field due to charged infinite plane sheet :**

(i) $\sigma \rightarrow$ surface charge density of an infinite plane sheet.

(ii) 2r & A $\rightarrow$ length & area of cylindrical Gaussian surface,

$$\phi_E = \oint \vec{E} \cdot d\vec{A}$$

$$= \int_{\text{Curved surface}} \vec{E} \cdot d\vec{A} + \int_P \vec{E} \cdot d\vec{A} + \int_{P'} \vec{E} \cdot d\vec{A} = \frac{Q_{encl}}{\varepsilon_0} \quad ...(1)$$



Electric field due to charged infinite planar sheet

(iii) The E is perpendicular to the area element on the curved surface at all points

Then, E is parallel to $\vec{A}$ at P & P′.

$$\phi_E = \int_P E\, dA + \int_{P'} E\, dA = \frac{Q_{encl}}{\varepsilon_0} \quad ...(2)$$

(iv) $\therefore \ Q_{encl} = \sigma A$,

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

$$\int_P dA = A$$

$$\text{Hence } 2EA = \frac{\sigma A}{\varepsilon_0} \quad \text{or } E = \frac{\sigma}{2\varepsilon_0} \quad ...(3)$$

$$\text{or } \vec{E} = \frac{\sigma}{2\varepsilon_0} \hat{n} \quad ...(4)$$

$\hat{n}$ Unit vector normal to the plane.

If $\sigma > 0$, E – outward perpendicular to plane.

$\sigma < 0$, E – inward perpendicular to plane.

13. Obtain the expression for electric field due to a uniformly charged spherical shell. *[Govt. MQP-2019]*

Ans. **Electric field due to a uniformly charged spherical shell :**

Consider a uniformly charged spherical shell.

Radius - R

Total charge - Q

(a) At a point outside the shell (r > R) :

P is a point outside the shell at a distance r from the centre. The charge is uniformly distributed on the surface of the sphere.

(i) If Q > 0, field point radially outward.

If Q < 0, field point radially inward.

Applying Gauss law

$$\oint_{\text{Gaussian surface}} \vec{E}.\overrightarrow{dA} = \frac{Q}{\varepsilon_0} \qquad ...(1)$$

$\vec{E}$ and $\overrightarrow{dA}$ are in the same direction. at all point

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

But $\oint dA$ = total area of Gaussian surface $= 4\pi r^2$

Substituting in (1)

$$E.\,4\pi r^2 = \frac{Q}{\varepsilon_0} \text{ (or) } E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$$

In vector from $\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}.\hat{r}$

E at a point outside the shell will be the same and entire charge 'Q' is concentrated at the centre.

(b) At a point on the surface of the spherical shell (r = R). Electric field at points on the spherical shell, is r = R

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

(c) At a point inside the shell (r < R) :

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

$$\oint_{\text{Gaussian surface}} \vec{E}.\overrightarrow{dA} = \frac{Q}{\varepsilon_0}$$

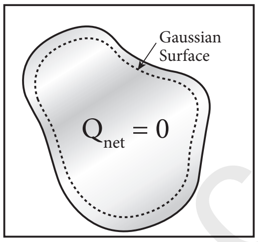
$$E\,.\,4\pi r^2 = \frac{Q}{\varepsilon_0}$$

Since Gaussian surface encloses no charge, so Q = 0.

$\therefore E = 0$

14. Discuss the various properties of conductors in electrostatic equilibrium.

Ans. (i) The Electric Field is zero everywhere inside the conductors whether the conductor is solid or hallow.



No net charge inside the conductor

(ii) There is no net charge inside the conductors. The charges must reside only on the surface of the conductors.

(iii) The Electric Field outside the conductor is perpendicular to the surface of the conductor and has a magnitude of $\frac{\sigma}{\varepsilon_0}$ where σ is the surface charge density at the point (i.e. $E \propto \sigma$)

(iv) The electrostatic potential has the same value on the surface and inside of the conductor. Potential is constant within and on the surface of a conductor.

15. Explain the process of electrostatic induction.

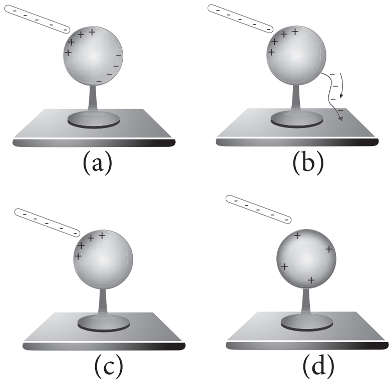
Ans. Charging without actual contact is called electrostatic induction.

(i) Consider an uncharged (neutral) conducting sphere at rest on an insulating stand. Suppose a negatively charged rod is brought near the conductor without touching it, as shown in Figure (a).

The negative charge of the rod repels the electrons in the conductor to the opposite side. As a result, positive charges are induced near the region of the charged rod while negative charges on the farther side.

Before introducing the charged rod, the free electrons were distributed uniformly on the surface of the conductor and the net charge is zero.

Once the charged rod is brought near the conductor, the distribution is no longer uniform with more electrons located on the farther side of the rod and positive charges are located closer to the rod. But the total charge is zero.



Various steps in electrostatic induction

(ii) Now the conducting sphere is connected to the ground through a conducting wire. This is called grounding. Since the ground can always receive any amount of electrons, grounding removes the electron from the conducting sphere.

Note that positive charges will not flow to the ground because they are attracted by the negative charges of the rod (Figure (b)).

(iii) When the grounding wire is removed from the conductor, the positive charges remain near the charged rod (Figure (c))

(iv) Now the charged rod is taken away from the conductor. As soon as the charged rod is removed, the positive charge gets distributed uniformly on the surface of the conductor (Figure (d)). By this process, the neutral conducting sphere becomes positively charged.

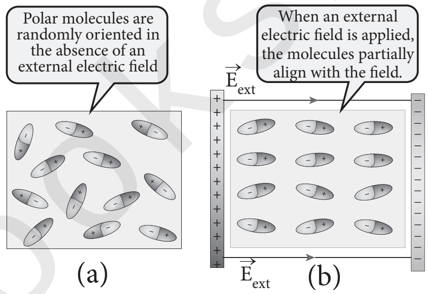
16. Explain dielectrics in detail and how an electric field is induced inside a dielectric.

Ans. (i) When an external electric field is applied on a conductor, the charges are aligned in such a way that an internal electric field is created which cancels the external electric field. But in the case of a dielectric, which has no free electrons, the external electric field only realigns the charges so that an internal electric field is produced.

(ii) The magnitude of the internal electric field is smaller than that of external electric field. Therefore the net electric field inside the dielectric is not zero but is parallel to an external electric field with magnitude less than that of the external electric field. Let us consider a rectangular dielectric slab placed between two oppositely charged plates (capacitor) as shown in the Figure (b).

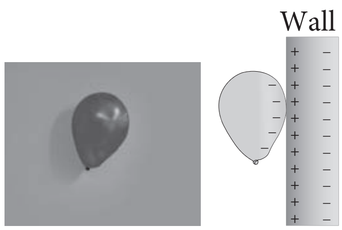
(iii) The uniform electric field between the plates acts as an external electric field $\vec{E}_{ext}$ which polarizes the dielectric placed between plates. The positive charges are induced on one side surface and negative charges are induced on the other side of surface.

(iv) But inside the dielectric, the net charge is zero even in a small volume. So the dielectric in the external field is equivalent to two oppositely charged sheets with the surface charge densities $+\sigma_b$ and $-\sigma_b$. These charges are called bound charges. They are not free to move like free electrons in conductors. This is shown in the Figure (b).



Induced electric field lines inside the dielectric

(v) For example, the charged balloon after rubbing sticks onto a wall. The reason is that the negatively charged balloon is brought near the wall, it polarizes (induces) opposite charges on the surface of the wall, which attracts the balloon.



(a) Balloon sticks to the wall

(b) Polarisation of wall due to the electric field due to the balloon

17. Obtain the expression for capacitance for a parallel plate capacitor. *[PTA-2]*

Ans. **Capacitance of a parallel plate capacitor**

Consider a capacitor with two parallel plates,

A - Area of each plate

d - Distance between the plates

σ - surface charge density on the plates $\sigma = \dfrac{Q}{A}$

The Electric Field between the plates is $E = \dfrac{Q}{A\varepsilon_0}$

Since the Electric Field is uniform, the electrical potential between the plates $V = Ed = \dfrac{Qd}{A\varepsilon_0}$

∴ Capacitance of the capacitor

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

18. Obtain the expression for energy stored in the parallel plate capacitor.

Ans. The capacitor stores not only charge but also it stores energy.

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

To transfer charge, work is done by the battery. This work done is stored as Electrostatic Potential energy in the capacitor.

dQ - Infinitesimal charge

V - potential difference

Work done $dW = V.dQ$

where $V = \dfrac{Q}{C}$

The total work done to charge the capacitor

$$W = \int_0^Q \frac{Q}{C}.dQ = \frac{Q^2}{2C}$$

This work done is stored as Electrostatic Potential Energy

$$U_E = \frac{Q^2}{2C} = \frac{1}{2}.CV^2 \qquad [\because Q = CV]$$

For parallel capacitor, capacitance $C = \dfrac{\varepsilon_0 A}{d}$ and $V = Ed$

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

Ad - volume of the space between the capacitor plates.

Energy density, $u_E = \dfrac{U}{\text{Volume}}$

$$u_E = \frac{1}{2}\varepsilon_0 E^2$$

19. Explain in detail the effect of a dielectric placed in a parallel plate capacitor. *[PTA-6; Sep.-2020]*

Ans. **Capacitance of a parallel plate capacitor with a dielectric medium:**

(i) X, Y - conducting plates ; A - area

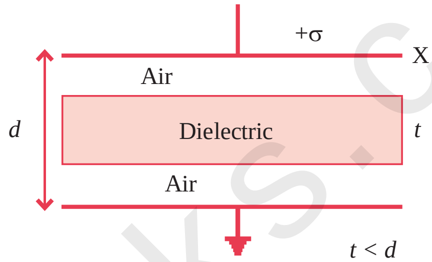
σ – charge density

t - Thickness of dielectric

ε_r - relative permittivity

(ii) Thickness of air gap = $(d - t)$. Electric field at any point in the air between the plates as shown in figure, $E' = \dfrac{\sigma}{\varepsilon_o}$

(iii) Electric field at any point, in the dielectric slab $E' = \dfrac{\sigma}{\varepsilon_o}$



Dielectric in capacitor

(v) $V = E(d - t) + E't$

$$V = \frac{\sigma}{\varepsilon_o}(d-t) + \frac{\sigma t}{\varepsilon_o \varepsilon_r} = \frac{\sigma}{\varepsilon_o}\left[(d-t) + \frac{t}{\varepsilon_r}\right]$$

(vi) The charge on the plate X, $q = \sigma A$

Hence the capacitance of the capacitor is,

$$C = \frac{q}{V} = \frac{\sigma A}{\frac{\sigma}{\varepsilon_o}\left[(d-t)+\frac{t}{\varepsilon_r}\right]} = \frac{\varepsilon_o A}{(d-t)+\frac{t}{\varepsilon_r}}$$

the capacitance increases, when dielectric is placed.

20. Derive the expression for resultant capacitance, when capacitors are connected in series and in parallel.

Ans. **Capacitors in series :**

C_1, C_2, C_3 - capacitances of capacitors connected in series.

V - battery voltage

Q - charge on each capacitor is same.

V_1, V_2, V_3 - potential difference across C_1, C_2, C_3.

$V = V_1 + V_2 + V_3$.

Since $Q = CV$; $V = \dfrac{Q}{C_1} + \dfrac{Q}{C_2} + \dfrac{Q}{C_3}$

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

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

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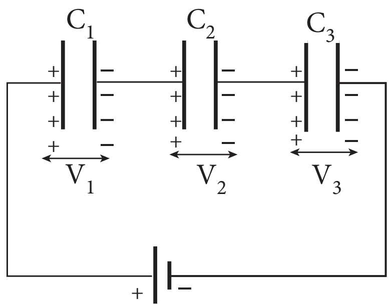
The inverse of the equivalent capacitance in series is equal to the sum of the inverses of each capacitance.

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



(a) Capacitors connected in series

Capacitor in parallel :

C_1. C_2, C_3 - capacitances of capacitors connected in parallel connection.

V - Applied parallel potential.

Potential difference across each capacitor is same. Q_1, Q_2, Q_3 - charge stored in C_1, C_2, C_3.

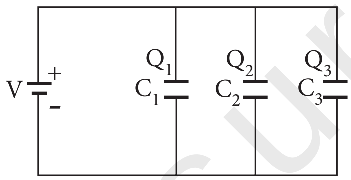
Total charge $Q = Q_1 + Q_2 + Q_3$

$Q = C_pV$;

$Q = C_1V + C_2V + C_3V$

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

$C_p \;\; = C_1 + C_2 + C_3$

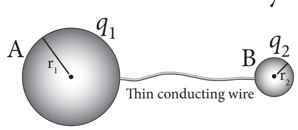


(a) Capacitors in parallel

The equivalent capacitance of capacitors connected in parallel is equal to the sum of the individual capacitance. C_p is always greater than the largest individual capacitance.

21. Explain in detail how charges are distributed in a conductor, and the principle behind the lightning conductor.

Ans. **(i)** The radius of conductor spheres A & B = r_1 & r_2. A & B are connected by thin wire.



Two conductors are connected through conducting wire

(ii) The distance between the spheres > radii of A & B. A- change given to A. This charge is redistributed into both A & B and Electrostatic potential becomes equal

q_1 - charge on A

q_2 - charge on B

$\therefore Q = q_1 + q_2$

The electrostatic potential at the surface of the sphere A is given by

$$V_A = \frac{1}{4\pi\varepsilon_0}\frac{q_1}{r_1} \qquad ...(1)$$

(iii) The electrostatic potential at the surface of the sphere B is given by

$$V_B = \frac{1}{4\pi\varepsilon_0}\frac{q_2}{r_2} \qquad ...(2)$$

(iv) The spheres are connected by the conducting wire, the surfaces of both the spheres together form an equipotential surface.

$V_A = V_B$

or $\dfrac{q_1}{r_1} = \dfrac{q_2}{r_2}$ ...(3)

(v) Let us take the charge density of A = σ_1

charge density of B = σ_2

$\therefore q_1 = 4\pi r_1^2\sigma_1$ and $q_2 = 4\pi r_2^2\sigma_2$ Substituting $\sigma \frac{q}{A} = 4\pi r_2^2$these values into equation (3), we get

$\sigma_1 r_1 = \sigma_2 r_2$ ...(4)

σr = constant ...(5)

$\sigma \propto \dfrac{1}{r}$

(vi) For a smaller radius, the charge density will be larger and vice versa.

22. Explain in detail the construction and working of a Van de Graaff generator. *[QY-2019]*

Ans. It is a machine which produces large electrostatic potential difference of the order of 10^7 V.

Principle:

Electrostatic induction and action at points.

Construction:

(i) It consists of a hollow metallic sphere (A) mounted on insulating pillars.

(ii) A pulley B is mounted at the centre of the sphere and another pulley C is mounted near the bottom.

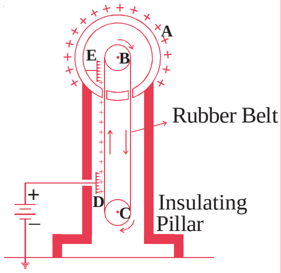
Electrostatics

(iii) A belt made of silk moves over the pulleys.

(iv) Two comb-shaped conductors D and E are mounted near the pulleys.

(v) The comb D is maintained at a positive potential of the order of 10^4 volt.

(vi) The upper comb E is connected to the inner side of the hollow metal sphere.



Van de Graaff Generator

Working:

(i) Because of the high electric field near the comb D, the air gets ionized.

(ii) The negative charges in air move towards the needles and positive charges are repelled towards the belt due to action of points.

(iii) The +ve charges stuck to the belt moves up end and reaches near the comb E.

(iv) E acquires negative charge and the sphere acquires positive charge due to electrostatic induction.

(v) The acquired +ve charge is distributed on the outer surface of the sphere.

(vi) Thus the machine, continuously transfers the positive charge to the sphere.

(vii) The leakage of charges from the sphere can be reduced by enclosing it in a gas filled steel chamber at a very high pressure.

(viii) The high voltage can be used to accelerate positive ions for the purpose of nuclear disintegration.

EXERCISES :

1. When two objects are rubbed with each other, approximately a charge of 50 nC can be produced in each object. Calculate the number of electrons that must be transferred to produce this charge. *[PTA-6]*

Ans. **Given:** Charge produced $q = 50$ nC $= 50 \times 10^{-9}$ C;

To find:

No. of electrons $n = ?$

$q = ne$ magnitude of electrons $= 1.6 \times 10^{-19}$ C

Solution:

$$n = \frac{q}{e} = \frac{50\times10^{-9}}{1.6\times10^{-19}} = 31.25 \times 10^{10} \text{ electrons.}$$

2. The total number of electrons in the human body is typically in the order of 10^{28}. Suppose, due to some reason, you and your friend lost 1% of this number of electrons. Calculate the electrostatic force between you and your friend separated at a distance of 1m. Compare this with your weight. Assume mass of each person is 60 kg and use point charge approximation.

Ans. **Given:**

Number of electrons in human body $= 10^{28}$

Charge appeared on my friend and me (ie)

C = 1% of charge on 10^{28} electrons

$$= \frac{1}{100} \times 10^{28} \times 1.6 \times 10^{-19} \text{ C}$$

$$= 1.6 \times 10^{7} \text{ C}$$

Electrostatic force between us $F_e = \dfrac{Kq^2}{r^2}$

$$= \frac{9\times10^9\times(1.6\times10^7)^2}{1^2} = 9\times2.56\times10^9\times10^{14}$$

$F_e = 23.04 \times 10^{23}$ N

Also mass of the person m $= 60$ kg

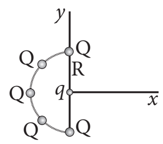
$\therefore$ weight $=$ mg

$= 60 \times 9.8$

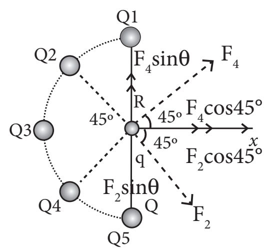
W $= 588$ N

$$\therefore \frac{F_e}{F_g} = \frac{F_e}{W} = \frac{23.04\times10^{23}}{588} = \mathbf{3.9183 \times 10^{21}}$$

3. Five identical charges Q are placed equidistant on a semicircle as shown in the figure. Another point charge *q* is kept at the centre of the circle of radius R. Calculate the electrostatic force experienced by the charge *q*.



Ans. The forces acting on q, due to Q_1 and Q_2 are F_1 and F_2.



These forces are equal and opposite.

Forces due to Q_2 and Q_4 on q is resolved into components.

$F_2 \sin\theta$ and $F_4 \sin\theta$ i.e $F_1 \sin45°$ and $F_2 \sin45°$ are equal and opposite. So they get cancel.

Unit 1

Total force acting on q is due to Q_3 (i.e F_3)

$F_4 \cos\theta$, $F_2 \cos\theta$ $F = F_3 + F_2 \cos\theta + F_4 \cos\theta$

$$\text{Total force F} = k.\frac{qQ}{R^2} + k.\frac{qQ}{R^2}.\cos45° + \frac{kqQ}{R^2}\cos45°$$

$$= \frac{kqQ}{R^2}\left[1+\frac{2}{\sqrt{2}}\right]$$

$$\text{Total F} = \frac{kqQ}{R^2}\left[1+\sqrt{2}\right]\hat{i}$$

$$= \frac{1}{4\pi\varepsilon_0}\frac{qQ}{R^2}\left[1+\sqrt{2}\right]\hat{i}$$

$$\left[\because k = \frac{1}{4\pi\varepsilon_0}\right]$$

4. Suppose a charge +*q* on Earth's surface and another +*q* charge is placed on the surface of the Moon. (a) Calculate the value of q required to balance the gravitational attraction between Earth and Moon (b) Suppose the distance between the Moon and Earth is halved, would the charge *q* change? (Take $m_E = 5.9 \times 10^{24}$ kg, $m_M = 7.9 \times 10^{22}$ kg)

***Ans.* Given:**

(a) Mass of the earth $m_E = 5.9 \times 10^{24}$ kg

Mass of the moon $m_M = 7.9 \times 10^{22}$ kg

Charge placed on earth and moon is q

To find: The amount of charge required to balance gravitational attraction between earth & moon = ?

If q is the charge placed on the moon & earth, then

Formula : $\frac{1}{4\pi\varepsilon_0}.\frac{q\times q}{r^2} = G.\frac{m_E \times m_M}{r^2}$

$$\frac{1}{4\pi\varepsilon_0} = 9 \times 10^9$$

$$G = 6.6 \times 10^{-11}\ Nm^{-2}\ kg^{-2}$$

$$4\pi\varepsilon_0 = 0.11 \times 10^{-9}$$

(or)

$$q = \sqrt{4\pi\varepsilon_0\, Gm_E.m_M}$$

$$= \sqrt{0.11\times10^{-9}\times6.6\times10^{-11}\times5.9\times10^{24}\times7.9\times10^{22}}$$

$$q = \sqrt{33.84\times10^{26}}$$

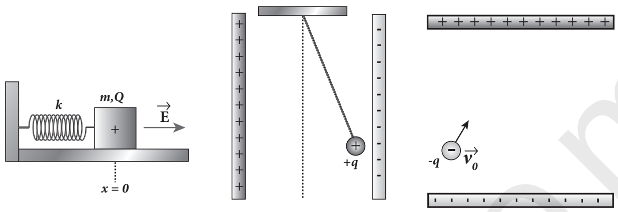
$q = 5.82 \times 10^{13}$ C.

(b) The distance between moon & earth is halved, the charge q = ?

$$\frac{1}{4\pi\varepsilon_0}.\frac{q_1q_2}{\left(\frac{r}{2}\right)^2} = G.\frac{m_E.m_M}{\left(\frac{r}{2}\right)^2}$$

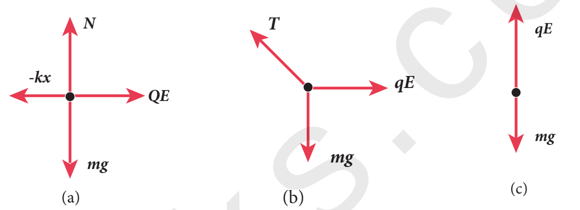
There will not be any change in the charge q.

5. Draw the free body diagram for the following charges as shown in the figure (a), (b) and (c).



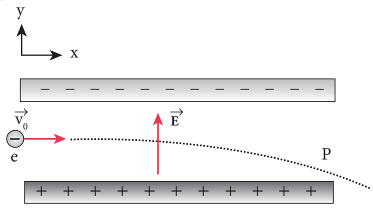
(a) (b) (c)

Ans.



(a) (b) (c)

6. Consider an electron travelling with a speed v_o and entering into a uniform electric field $\vec{E}$ which is perpendicular to $\vec{v}$ as shown in the Figure. Ignoring gravity, obtain the electron's acceleration, velocity and position as functions of time.



Ans. The speed of the electrons $= v_0$

Electric field strength $= \vec{E}$

Acceleration of the electrons a = ?

Velocity of the electrons v = ?

Position of the electrons r = ?

According to Newton's II law F = ma

The force on the electrons in an uniform electric field.

F = Ee

The e^- s acceleration due to electric field

$$a = \frac{F}{m} = \frac{Ee}{m}$$

The acceleration of the electrons $\left[a = \frac{Ee}{m}\right]$ is in the downward direction. The horizontal velocity remains v_0 as there is no acceleration in this direction.

Electrostatics

$$\vec{a} = -\frac{eE}{m}.\hat{j}$$

The downward component of the velocity of the electrons as it emerges from the field region is

$$v = v_x \hat{i} + v_y \hat{j}$$

The horizontal component of the velocity remains $v_x = v_0$. The vertical component (downward) velocity as it emerges from the field region is

$$v_y = \vec{a}\,t = -\frac{eE}{m}t.\hat{j}$$

The velocity of the electron, $\vec{\upsilon} = v_0\hat{i} - \frac{eE}{m}.t.\hat{j}$

The electrons starts with a velocity v_0.

From equation of motion, $s = ut + \frac{1}{2}at^2$

The position of the electrons $s = r = ?$

Initial velocity of the electrons $\vec{u} = v_0$

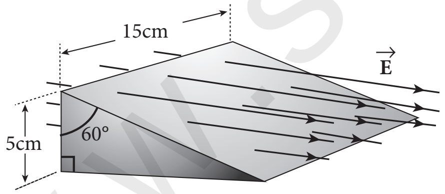
Acceleration of the electrons $\vec{a} = \left(-\frac{eE}{m}\right).\hat{j}$

$$\therefore \vec{r} = v_0 t\hat{i} + \frac{1}{2}.\left(-\frac{Ee}{m}t^2\right).\hat{j}$$

$$= v_0 t\hat{i} - \frac{1}{2}.\frac{Ee}{m}.t^2\hat{j}$$

$$\vec{r} = v_0 t\hat{i} - \frac{1}{2}.\frac{Ee}{m}.t^2\hat{j}$$

7. A closed triangular box is kept in an electric field of magnitude E = 2 × 10³ N C⁻¹ as shown in the figure.



Calculate the electric flux through the (a) vertical rectangular surface (b) slanted surface and (c) entire surface.

Ans. **Given:**

The magnitude of electric field $E = 2 \times 10^3$ NC⁻¹

Area of the surface $A = 0.15 \times 0.05$

[From the diagram l α = 15 cm = 0.15 m, b = 5 cm = 0.05m]

To find:

The electric flux through

a) Vertical rectangular surface $\phi_{vert} = ?$

Solution:

According to Gauss law $\phi = E A \cos\theta$

$\phi_{\text{vertical surface}} = 2 \times 10^3 \times 0.15 \times 0.05 \times \cos 0^\circ$

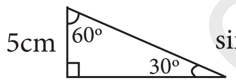
$= 0.015 \times 10^3 = 15$ Nm² C⁻¹

b) Electric flux through slanted surface

$\phi_{\text{slanted surface}} = ?$

$\phi_{\text{slanted surface}} = E A \cos\theta$

$\theta = 60^\circ \Rightarrow \cos 60^\circ = \frac{1}{2}$



$\sin 30 = \frac{\text{opposite}}{\text{hyp}}$

Opposite = 5 cm. $\text{hyp} = \frac{\text{opposite}}{\sin 30^\circ}$

$$\text{hyp.} = \frac{5 \times 10^{-2}}{\frac{1}{2}} = 2 \times .05$$

$= 0.10$ m

Area of the slanted surface

$A = (0.10 \times 0.15)$ m²

$\phi_{\text{slanted surface}} = EA\cos\theta$

$\phi_{\text{slanted surface}} = 2 \times 10^3 \times (0.10 \times 0.15) \times \cos 60^\circ$

$= 0.015 \times 10^3 = 15$ Nm² C⁻¹

c) Entire surface $\phi_{tot} = ?$

$\phi_{tot} = \phi_{vs} + \phi_{s.s} + \phi_{ends}$

$\phi_{ends} = EA\cos\theta$

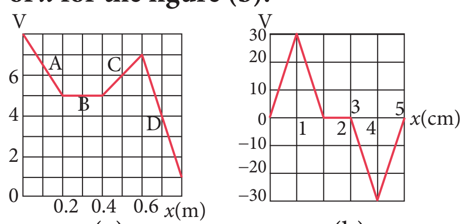
$\theta = 90^\circ$; $\cos 90^\circ = 0$

$\phi_{ends} = 0$

$= -15 + 15 + 0$

$\phi_{tot} = 0.$

8. The electrostatic potential is given as a function of *x* in figure (a) and (b). Calculate the corresponding electric fields in regions A, B, C and D. Plot the electric field as a function of *x* for the figure (b).



(a) (b)

Ans.

(a) $E = -\frac{dV}{dx}$

(i) Region A

$$\frac{dV}{dx} = \frac{-3}{0.2} = -15V_i,\ E = \frac{dV}{dx}$$

$\therefore E = -(-15) = 15$ Vm⁻¹

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(ii) Region B

$$\frac{dV}{dx} = \frac{0}{0.2} = 0$$

(iii) Region C

$$\frac{dV}{dx} = \frac{2}{0.2} = 10$$

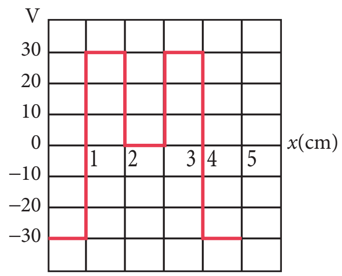
$$E = -\frac{dV}{dx} = (-10)Vm^{-1}$$

(iv) Region D

$$\frac{dV}{dx} = \frac{-6}{0.2} = -30$$

$$E = -\frac{dV}{dx} = -(-30) = 30Vm^{-1}.$$

(b)



9. A spark plug in a bike or a car is used to ignite the air-fuel mixture in the engine. It consists of two electrodes separated by a gap of around 0.6 mm gap as shown in the figure.

To create the spark, an electric field of magnitude 3 × 10⁶ Vm⁻¹ is required. (a) What potential difference must be applied to produce the spark? (b) If the gap is increased, does the potential difference increase, decrease or remains the same? (c) find the potential difference if the gap is 1 mm.

Ans. **Given:**

(a) The distance between two electrodes d = 0.6mm $= 0.6 \times 10^{-3}$ m

The magnitude of electric filed $E = 3 \times 10^6$ Vm^{-1}

To find:

Potential difference need to produce spark V = ?

Formula: $E = \dfrac{V}{d}$

Solution: $\therefore V = E.d = 0.6 \times 10^{-3} \times 3 \times 10^6 = 1800$ V.

(b) From the above, we come to know when the gap is increased. potential also increase.

(c) The distance, $d = 1 \text{ mm} = 1 \times 10^{-3}$ m

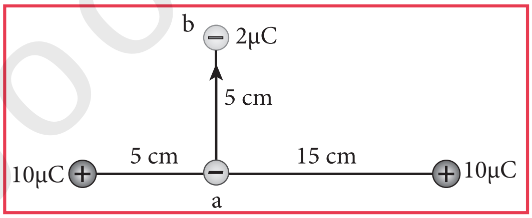
Electric field, $E = 3 \times 10^6$ Vm^{-1}

New potential difference due to increase in the gap.

$V = E.d = 3 \times 10^6 \times 1 \times 10^{-3}$

$= 3000$ V.

10. A point charge of +10 μC is placed at a distance of 20 cm from another identical point charge of +10 μC. A point charge of –2 μC is moved from point a to b as shown in the figure. Calculate the change in potential energy of the system? Interpret your result.



Ans. Given : $q_1 = 10 \times 10^{-6}$ C, $q_2 = -2 \times 10^{-6}$ C

$r = 5 \times 10^{-2}$ m

Solution: Change in potential energy

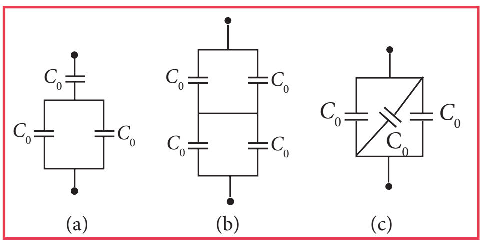
$$\Delta U = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r} = \frac{9\times10^9\times(10)(-2)\times10^{-12}}{5\times10^{-2}}$$

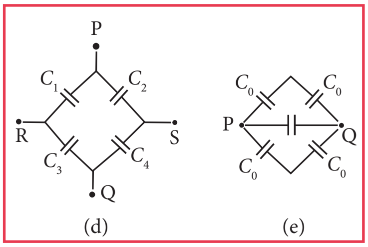
$$= \frac{-9\times10^9\times \overset{4}{\cancel{20}}\times10^{-12}\times10^2}{\cancel{5}}$$

$$= -36 \times 10^{-1} = -3.6 \text{ J}$$

ΔU = -3.6 J, negative sign implies that to move the charge -2μC no external work is required. System spends its stored energy to move the charge from point a to point b.

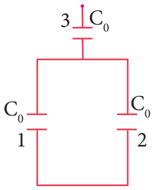
11. Calculate the resultant capacitances for each of the following combinations of capacitors.





Ans.

a.



Capacitor 1 & 2 are connected in parallel

$$C_p = C_0 + C_0 = 2C_0$$

Capacitor C_p and C_3 are in series.

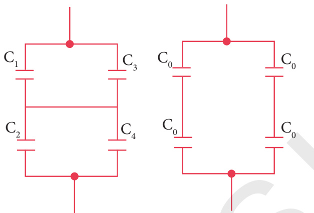
$$\frac{1}{C_s} = \frac{1}{C_p} + \frac{1}{C_3} \Rightarrow \frac{1}{C_s} = \frac{1}{2C_0} + \frac{1}{C_0}$$

$$= \frac{1+2}{2C_0} = \frac{3}{2C_0}$$

$$\therefore C_s = \frac{2}{3}.C_0$$

The resultant capacitance $= \frac{2}{3}C_0$

b.



C_1 & C_2 are in series $\frac{1}{Cs_1} = \frac{1}{C_0} + \frac{1}{C_0} = \frac{2}{C_0}$

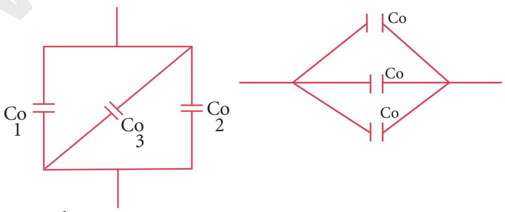
C_3 & C_4 are in series $\frac{1}{Cs_2} = \frac{2}{C_0}$

Cs_1 & Cs_2 are in parallel.

$$\therefore C_p = Cs_1 + Cs_2 = \frac{C_0}{2} + \frac{C_0}{2} = C_0$$

Resultant capacitance $= C_0$

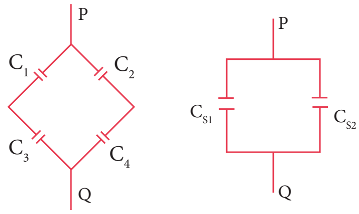
c.



Resultant capacitance $C_p = C_0 + C_0 + C_0$

$C_p = 3\,C_0$

d.



C_1 and C_3 are in series $\frac{1}{Cs_1} = \frac{1}{C_1} + \frac{1}{C_3} = \frac{C_1+C_3}{C_1C_3}$

$$Cs_1 = \frac{C_1C_3}{C_1+C_3}$$

C_2 and C_4 are in series

$$\frac{1}{Cs_2} = \frac{1}{C_2} + \frac{1}{C_4}$$

$$Cs_2 = \frac{C_2+C_4}{C_2C_4} = \frac{C_2C_4}{C_2+C_4}$$

Now Cs_1 and Cs_2 are parallel

$$Cp = Cs_1 + Cs_2$$

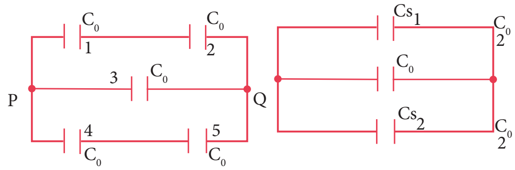
$$= \frac{C_1C_3}{C_1+C_3} + \frac{C_2C_4}{C_2+C_4}$$

$$= \frac{(C_1C_3)(C_2+C_4)+(C_2C_4)(C_1+C_3)}{(C_1+C_3)(C_2+C_4)}$$

The resultant capacitance

$$= \frac{C_1C_2C_3+C_1C_3C_4+C_1C_2C_4+C_3C_2C_4}{(C_1+C_3)(C_2+C_4)}$$

e.



Capacitors 1 and 2 are in series

$$\frac{1}{Cs_1} = \frac{1}{C_0} + \frac{1}{C_0} = \frac{2}{C_0}$$

$$Cs_1 = \frac{C_0}{2}$$

Parallerly 4 and 5 are in series

$$Cs_2 = \frac{C_0}{2}$$

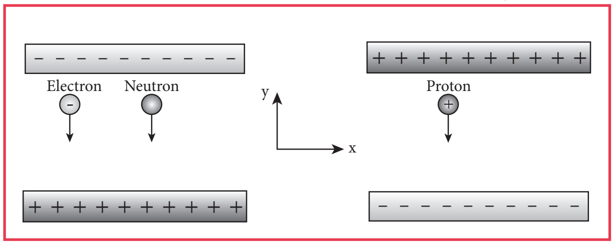
Cs_1, Cs_2, 3 are in parallel

$$\therefore C_p = \frac{C_0}{2} + \frac{C_0}{2} + C_0$$

$$= C_0 + C_0$$

Resultant capacitance $= 2C_0$.

12. An electron and a proton are allowed to fall through the separation between the plates of a parallel plate capacitor of voltage 5 V and separation distance h = 1 mm as shown in the figure.



(a) Calculate the time of flight for both electron and proton (b) Suppose if a neutron is allowed to fall, what is the time of flight? (c) Among the three, which one will reach the bottom first?

(Take $m_p = 1.6 \times 10^{-27}$ kg, $m_e = 9.1 \times 10^{-31}$ kg and $g = 10$ m s^{-2})

Ans. **Given:** Potential difference between the plates of Parallel plate capacitor = V = 5V

Distance between the plates of

$h = 1$ mm $= 1 \times 10^{-3}$ m

Mass of proton $m_p = 1.6 \times 10^{-27}$ kg

Mass of electron $m_e = 9.1 \times 10^{-31}$ kg

Charge of proton, $e = 1.6 \times 10^{-19}$ C

To find:

a. Time of flight of an electron t_e = ?

$$s = ut + \frac{1}{2}at^2, \text{ initial velocity } (u) = 0$$

Solution:

$$s = \frac{1}{2}at^2 \Rightarrow t = \sqrt{\frac{2s}{a}}$$

$a = \dfrac{F}{m}$ (according to Newton's II law) [F = ma]

F - force due to electric field

$$F = Ee, \; E = \frac{\Delta V}{\Delta d} = \frac{5}{10^{-3}}$$

$$\therefore a = \frac{Ee} {m} \qquad \therefore t = \sqrt{\frac{2sm}{Ee}}$$

s = h distance of separation $= 1 \times 10^{-3}$ m

$$\therefore t_e^2 = \frac{2hm_e}{\frac{\Delta V}{\Delta d}.e}$$

$$t_e^2 = \Delta dx \frac{2hm_e}{\Delta Ve} = \frac{2\times10^{-3}\times9.1\times10^{-31}\times10^{-3}}{5\times1.6\times10^{-19}}$$

$$t_e = \sqrt{\frac{2\times10^{-3}\times9.1\times10^{-31}\times10^{-3}}{5\times1.6\times10^{-19}}}$$

$$= \sqrt{2.275\times10^{-18}} = 1.5 \times 10^{-9} \text{ s (or) } 1.5 \text{ ns}$$

$$t_p = \sqrt{\frac{2\times10^{-3}\times\cancel{1.6}\times10^{-27}\times10^{-3}}{5\times\cancel{1.6}\times10^{-19}}}$$

$$= \sqrt{\frac{2}{5}\times10^{-33}\times10^{19}} = \sqrt{0.4\times10^{-14}}$$

$t_p = 0.63 \times 10^{-7}$ s (or) 63×10^{-9}s (or) 63 ns

b. If Neutron falls, it is a neutral charge so it does not experience any electric filed. (It is like a force fall)

$t^2 = \dfrac{2h}{g}$ [i.e. $t = \dfrac{2s}{a}$] $a = g, s = h$

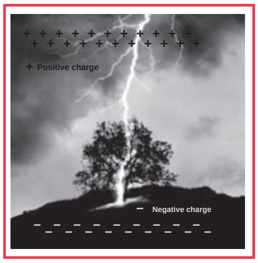
$$t = \sqrt{\frac{2\times10^{-3}}{10}} = \sqrt{2\times10^{-4}}$$

$t = 1.414 \times 10^{-2}$ sec.

c. Electron will reach first

∵ the time to reach the bottom first by electron is 1.5 ns.

13. During a thunder storm, the movement of water molecules within the clouds creates friction, partially causing the bottom part of the clouds to become negatively charged. This implies that the bottom of the cloud and the ground act as a parallel plate capacitor. If the electric field between the cloud and ground exceeds the dielectric breakdown of the air (3×10^6 Vm^{-1}), lightning will occur.



(a) If the bottom part of the cloud is 1000 m above the ground, determine the electric potential difference that exists between the cloud and ground.

(b) In a typical lightning phenomenon, around 25 C of electrons are transferred from cloud to ground. How much electrostatic potential energy is transferred to the ground?

Electrostatics

Ans. **Given:**

a. Electric field between ground and cloud

$E = 3 \times 10^6 \text{ Vm}^{-1}$

Distance between ground and the cloud

$d = 1000\text{m}$

To find: Electric potential between ground and the cloud V = ?

Formula: $E = \frac{V}{d} \Rightarrow V = E.d.$

$E = 3 \times 10^6 \times 10^3 = 3 \times 10^9$ V

b. The amount of electrons transfered from cloud to ground $q = 25$ C

Electrostatic P.E. transfered from cloud to ground U = ?

Solution:

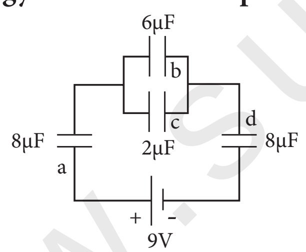
$$U = \frac{1}{2} CV^2$$

$$C = \frac{q}{V} \qquad \therefore U = \frac{1}{2} q.V$$

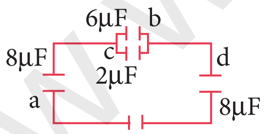
$$U = \frac{1}{2} \times 25 \times 3 \times 10^9 = \frac{75}{2} \times 10^9$$

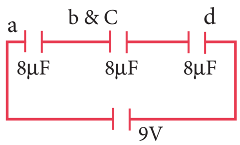
$$= 37.5 \times 10^9 \text{ J.}$$

14. For the given capacitor configuration *[QY-2019]*
(a) Find the charges on each capacitor
(b) potential difference across them
(c) energy stored in each capacitor



Ans.





B & C are parallel so C = (6 + 2) μF = 8μF

Now all a, b & c, d are in series.

Effective capacitance $\frac{1}{C_s} = \frac{1}{8} + \frac{1}{8} + \frac{1}{8} = \frac{3}{8} \quad \therefore C_s = \frac{8}{3}$

a. Charges on each capacitor :

Total charges on capacitor = $q = C_s$.

$$V = \frac{8}{3} \times 9 \times 10^{-6} = 24 \,\mu C$$

Charge on capacitor $a = q_a =$ C.V.

$$q_a = 24 \,\mu C$$

In case of capacitor in series the charge flowing through capacitor is same.

$$q_a = q_d = 24 \,\mu C$$

But across b & c, the charge is not same since they are in parallel.

$$\text{Charge on b} = q_b = \frac{6}{3} \times 9 \times 10^{-6}$$

$$= 18 \,\mu C$$

$$\text{Charge on c} = q_c = \frac{2}{3} \times 9 \times 10^{-6}$$

$$= 6 \,\mu C$$

b. Potential difference across capacitor *a*

$$V_a = \frac{q_a}{C_a} = \frac{24 \times 10^{-6}}{8 \times 10^{-6}} = 3V$$

Potential difference across capacitor *b*

$$V_b = \frac{q_b}{C_b} = \frac{18 \times 10^{-6}}{6 \times 10^{-6}} = 3V$$

Potential difference across capacitor *c*

$$V_c = \frac{q_c}{C_c} = \frac{6 \times 10^{-6}}{2 \times 10^{-6}} = 3V$$

Potential difference across capacitor *d*

$$V_d = \frac{q_d}{C_d} = \frac{24 \times 10^{-6}}{8 \times 10^{-6}} = 3V$$

c. Energy stored in *a* $U_a = \frac{1}{2} CV^2$

$$U_a = \frac{1}{2} \times 8 \times 10^{-6} \times 3 \times 3 = 36 \,\mu J$$

Energy stored in b

$$U_b = \frac{1}{2} \times 6 \times 3 \times 3 \times 10^{-6} = 27 \,\mu J$$

$[C_b = 6 \,\mu F]$

Energy stored in c

$$U_c = \frac{1}{2} \times 2 \times 3 \times 3 \times 10^{-6} = 9 \,\mu J$$

$[C_c = 2 \,\mu F]$

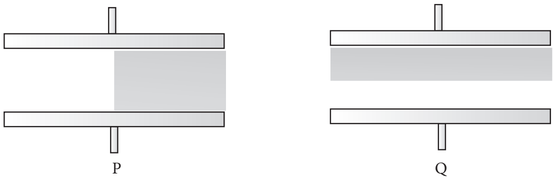
Energy stored in d

$$U_d = \frac{1}{2} \times 8 \times 10^{-6} \times 3 \times 3 = 36 \times 10^{-6} = 6 \text{ J}$$

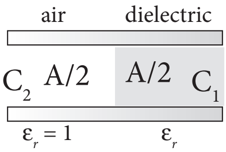
$= 36$ μj

15. Capacitors P and Q have identical cross sectional areas A and separation d. The space between the capacitors is filled with a dielectric of dielectric constant ε_r as shown in the figure.

Calculate the capacitance of capacitors P and Q. *[PTA-4]*



Ans. (i)



The given arrangement is equivalent to parallel combination of the capacitor each plate of

areas = $\dfrac{A}{2}$

Plate of separation = d

The medium of one dielectric constant = K_1, $\varepsilon_r = 1$ (air) $K_1 = 1$

The medium of other dielectric constant = K_2, i.e, $K_2 = \varepsilon_r$

The capacitance for $K_1 = C_1$

The capacitance for $K_2 = C_2$ $\quad\left[C = \dfrac{\varepsilon A}{d}\right]$

$$C_1 = \frac{\varepsilon_0 \frac{A}{2}.K_1}{d} = \frac{\varepsilon_0 K_1 A}{2d}$$

$$C_2 = \frac{\varepsilon_0 \frac{A}{2}.K_2}{d} = \frac{\varepsilon_0 K_2 A}{2d}$$

If C is the capacitance of the capacitor. then

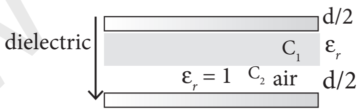
$$C = C_1 + C_2$$

$$= \frac{\varepsilon_0 K_1 A}{2d} + \frac{\varepsilon_0 K_2 A}{2d} = \frac{\varepsilon_0 (K_1 + K_2) A}{2d}$$

$$C = \frac{\varepsilon_0 (1+\varepsilon_r) A}{2d}$$

For capacitor Q.

(ii)



This is equivalent to a series combination of two capacitors

Plate of separation $\dfrac{d}{2}$

Dielectric constant for first medium = K_1 [air $K_1 = \varepsilon_r$]

Dielectric constant for second medium = K_2 [direction $K_2 = \varepsilon_r$]

$$\text{Capacitance of first} = C_1 = \frac{\varepsilon_0 K_1 A}{\frac{d}{2}} = \frac{2\varepsilon_0 K_1 A}{d}$$

$$\text{For second Capacitance} = C_2 = \frac{\varepsilon_0 K_2 A}{\frac{d}{2}} = \frac{2\varepsilon_0 K_2 A}{d}$$

If C is the capacitance of the capacitor

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

$$= \frac{d}{2\varepsilon_0 A}\left[\frac{1}{K_1} + \frac{1}{K_2}\right] = \frac{d}{2\varepsilon_0 A}.\left[\frac{K_1 + K_2}{K_1 K_2}\right]$$

$$\frac{1}{C} = \frac{d}{2\varepsilon_0 A}\left[\frac{1+\varepsilon_r}{\varepsilon_r}\right]$$

$$C_R = \frac{2\varepsilon_0 A}{d}\left[\frac{\varepsilon_r}{1+\varepsilon_r}\right].$$

PTA Model Questions & Answers

Choose the Correct Answer — 1 Mark

1. An air-core capacitor is charged by a battery. After disconnecting it from the battery, a dielectric slab is fully inserted in between its plates. Now, which of the following quantities remains constant? *[PTA-1]*

(a) Energy (b) Voltage
(c) Electric field (d) Charge

[Ans. (d) Charge]

2. The unit of permittivity is: *[PTA-2]*

(a) $C^2 N^{-1} m^{-2}$ (b) $N m^2 C^{-2}$
(c) $H m^{-1}$ (d) $N C^{-2} m^{-2}$

[Ans. (a) $C^2 N^{-1} m^{-2}$]

3. A coil of area of cross-section 0.5 m² with 10 turns is in a plane which is parallel to a uniform electric field of 100 N/C. The flux through the plane is: *[PTA-2]*

(a) 100 V.m (b) 500 V.m
(c) 20 V.m (d) zero

[Ans. (b) 500 V.m]

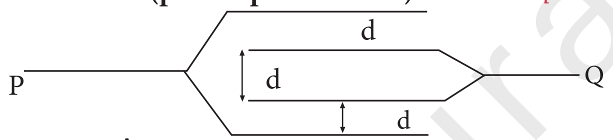
Electrostatics

4. **Dimension and unit of Electric flux is __________** *[PTA-3]*
   (a) $ML^2T^3A^{-2}$, Nm^2C^{-1}
   (b) $ML^3T^{-3}A^{-1}$, Nm^2C^{-1}
   (c) $ML^2T^{-1}A^{-2}$, Nm^2C^{-1}
   (d) $ML^{-4}T^{-3}A^{-2}$, Nm^2C^{-1}
   [*Ans.* (b) $ML^3T^{-3}A^{-1}$, Nm^2C^{-1}]

5. **At infinity, the electrostatic potential is** *[PTA-4]*
   (a) infinity
   (b) maximum
   (c) minimum
   (d) zero **[*Ans.* (d) zero]**

6. **Five balls marked 1, 2, 3, 4 and 5 are suspended by separate threads. The pairs (1, 2) (2, 4) and (4, 1) show mutual attraction and the pairs (2,3) and (4, 5) show repulsion. The number of ball marked as 1 is** *[PTA-5]*
   (a) positive
   (b) negative
   (c) neutral
   (d) can't determine **[*Ans.* (c) neutral]**

7. **The resultant capacitance of four plates, each is having an area A, arranged as shown above, will be (plate separation is d)** *[PTA-5]*



   (a) $\frac{A\varepsilon_0}{d}$ (b) $\frac{A\varepsilon_0}{2d}$
   (c) $\frac{2A\varepsilon_0}{d}$ (d) $\frac{3A\varepsilon_0}{d}$
   [*Ans.* (c) $\frac{2A\varepsilon_0}{d}$]

Hint: $C = C_1 + C_2 = 2C$

$\therefore C = \frac{2\varepsilon_0 A}{d}$

8. **An electric dipole is placed at an angle 30° with an electric field intensity of 2×10^5 N C^{-1}. It experiences a torque equal to 4 N m. The charge on the dipole if the dipole length is 2 cm is** *[PTA-6]*
   (a) 8 mC (b) 2 mC
   (c) 5 mC (d) 7 μC
   [*Ans.* (2 mC)]

Very Short Answer Questions — 2 Marks

1. **The electric field outside a conductor is perpendicular to its surface. Justify.** *[PTA-1]*

Ans. (i) The electric field outside the conductor is perpendicular to the surface of the conductor and has a magnitude of $\frac{\sigma}{\varepsilon_0}$ where σ is the surface charge density at that point.

(ii) If the electric field has components parallel to the surface of the conductor, then free electrons on the surface of the conductor would experience acceleration.

(iii) This means that the conductor is not in equilibrium. Therefore at electrostatic equilibrium, the electric field must be perpendicular to the surface of the conductor.

2. **State the law of conservation of electric charges.** *[PTA-2]*

Ans. The total electric charge in the universe is constant and charge can neither be created nor be destroyed. In any physical process, the net change in charge will always be zero.

3. **Define the physical quantity whose unit is Vm, and state whether it is scalar or vector.** *[PTA-3]*

Ans. Unit of Electric flux is Vm or Nm^2C^{-1}
It is a scalar quantity.

4. **Can two equipotential surfaces intersect? Give reason.** *[PTA-5]*

Ans. Since the electric field is normal to the equipotential surface and also the potential difference between any two points on the surface is nullified, the intersection is not possible.

5. **Define electric dipole.** *[PTA-5]*

Ans. Two equal and opposite charges separated by a very small vector distance.

6. **Define electric potential.** *[PTA-6]*

Ans. It is defined as the amount of work done in moving a unit positive charge from infinity to that point.

Short Answer Questions — 3 Marks

1. **Four point charges $+q$, $+q$, $-q$ and $-q$ are to be arranged respectively at the four corners of a square PQRS of side r. Find the work needed to assemble this arrangement.** *[PTA-1]*

Sol. The work done to arrange the charges in the corners of the square is independent of the way they are arranged. We can follow any order

(i) First, the charge $+q$ is brought to the corner P. This requires no work since no charge is already present, $W_P = 0$

(ii) Work required to bring the charge $-q$ to the corner Q = $(-q) \times$ potential at a point Q due to $+q$ located at a point P.

$$W_Q = -q \times \frac{1}{4\pi\varepsilon_0}\frac{q}{a} = \frac{1}{4\pi\varepsilon_0}\frac{q^2}{a}$$

(iii) Work required to bring the charge $+q$ to the corner R= $q \times$ potential at the point R due to charges at the point P and Q.

$$W_R = q \times \frac{1}{4\pi\varepsilon_0}\left(-\frac{q}{a}+\frac{q}{\sqrt{2}a}\right) = \frac{1}{4\pi\varepsilon_0}\frac{q^2}{a}\left(-1+\frac{1}{\sqrt{2}}\right)$$

(iv) Work required to bring the fourth charge $-q$ at the position S = $q \times$ potential at the point S due the all the three charges at the point P, Q and R

$$W_S = -q \times \frac{1}{4\pi\varepsilon_0}\left(\frac{q}{a}+\frac{q}{a}+\frac{q}{\sqrt{2}a}\right) = \frac{1}{4\pi\varepsilon_0}\frac{q}{a}\left(2-\frac{1}{\sqrt{2}}\right)$$

2. Two capacitors of unknown capacitances are connected in series and parallel. If net capacitances in two combinations are 6 μF and 25 μF respectively, find their capacitances. *[PTA-2]*

Sol. $$\frac{1}{C_s} = \frac{1}{C_1}+\frac{1}{C_2} = \frac{C_1+C_2}{C_1C_2}$$

$$\Rightarrow C_s = \frac{C_1C_2}{C_1+C_2} \quad \text{But } C_P = C_1 + C_2$$

$$\text{Hence } C_s = \frac{C_1C_2}{C_P} \Rightarrow 6 = \frac{C_1C_2}{25}$$

$$\therefore C_1 C_2 = 25 \times 6 = 150$$

$$\Rightarrow C_2 = \frac{150}{C_1};\ C_1 + C_2 = 25$$

$$C_1 = \frac{150}{C_1} = 25 \Rightarrow C_1^2 + 150 = 25\,C_1$$

(or)

$$\begin{aligned}
C_1^2 - 25\,C_1 + 150 &= 0\\
C_1^2 - 10\,C_1 - 15\,C_1 + 150 &= 0\\
C_1(C_1-10) - 15(C_1-10) &= 0\\
(C_1-10)(C_1-15) \text{ or } C_1 &= 10 \text{ or } 15\\
\text{if } C_1=10\mu F;\ C_2 &= 15\mu F\\
C_1=15\mu F;\ C_2 &= 10\mu F
\end{aligned}$$

3. Calculate the force between electron and proton in Hydrogen atom.($e = 1.6 \times 10^{-19}$ C and $r_0 = 0.53$Å) *[PTA-3]*

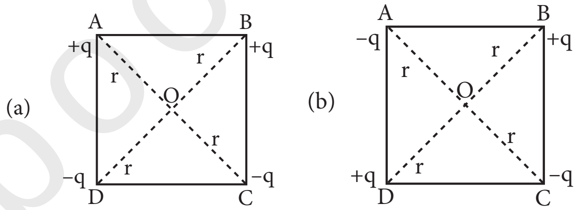
Sol. The proton and the electron attract each other. The magnitude of the electrostatic force between these two particles is given by

$$F_e = \frac{ke^2}{r^2} = \frac{9\times10^9\times(1.6\times10^{-19})^2}{(5.3\times10^{-11})^2}$$

$$= \frac{9 \times 2.56}{28.09} \times 10^{-7}$$

$$= 8.2 \times 10^{-8}\ N$$

4. Four point charges are placed at the four corners of a square in two ways (a) and (b) as shown in figure. Will the (i) electric potential and (ii) electric field, at the centre of the square be the same or different in the two configurations and why? *[PTA-5]*



Ans. (i) Electric field at the centre of fig (b) will be zero because same charges on the diagonally opposite corners of a square give zero electric field at the centre whereas it will be 'non zero' in fig (a).

(ii) Electric potential will be the same in case of fig(a) and (b) because there are two positive and two negative charges of same magnitude at equal distance from centres in both figures.

Government Exam Questions & Answers

Choose the Correct Answer — 1 Mark

1. When a point charge of 6mC is moved between two points in an electric field, the work done is 1.8×10^{-5} J. The potential difference between the two points is *[Govt. MQP-2019]*

(a) 1.08 V (b) 1.08 μV
(c) 3 V (d) 30 V **[Ans. (c) 3 V]**

Hint: $$V = \frac{W}{q} = \frac{1.8\times10^{-5}}{6\times10^{-6}} = 3\ V$$