ELECTROSTATICS
2. POTENTIAL

POINTS TO REMEMBER

1. Electric potential: Electric potential gives the electric condition of a body which determines the flow of charge. Electrons flow from a body at lower potential to a body at a higher potential.

2. Relation between Electric Intensity and potential: $E = \frac{V}{d}$

Also the electric intensity is defined as the negative rate of charge potential with distance. $E = -\frac{dv}{dr}$

3. **Potential difference :**Potential difference between two points in an electric field is defined as the work done in moving a unit positive charge from one point to another against the electric field. It is expressed in volt. It is a scalar quantity.

4. Electric potential energy : (EPE) Consider two charges q_1 and q_2 which are separated by a distance r_{12}. PE of the system is given by $PE = \frac{1}{4\pi \in_o} \frac{q_1 q_2}{r_{12}}$

5. Electrical potential is analogous to liquid level in hydrostatics and temperature in heat.
6. The potential at a point at infinite distance from a charged conductor in zero.
7. The potential of the earth is taken as zero since any loss(or) gain of charge by it does not alter its potential by any appreciable extent, due to its largeness.
8. Electron volt (ev) : The work done is charging a charge +e (charge of electron in coulomb) through a potential difference of (volt is called are ev.)
   1ev = $1.602 \times 10^{-19} C \times 1V = 1.602 \times 10^{-19}$ Joule.
9. **Equi- potential surface:** Equi -potential surface is the surface when the potential at all points are the surface is same. Work done to move a test charge on the equi-potential surface is zero.

LONG ANSWER QUESTIONS

1. Define electric potential and potential difference. Define a 'Volt'. Derive an expression for the electrostatic potential of a system of charged particles?

A. Electric potential:

Electric potential gives the electric condition of a body which determines the flow of charge. Electrons flow from a body at lower potential to a body at a higher potential.

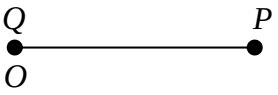
Definition: The potential at a point inside the electric field is the work done to bring a unit positive charge from infinity to that point in the electric field.

$V = \frac{1}{4\pi \in_o} \frac{q}{d}$ This is a scalar quantity.

The work done in bringing a charge q from infinity to a point in the electric field is given by $W = Vq$ Joule.

Explanation:

Consider a positive charge Q at a point O in free space. Let P be a point at a distance x from O. Let E be the intensity of the electric field at P.



Let a unit positive charge is moved through a distance dx from 'P' towards O. The work done in doing so is given by $dw = -Edx$. The negative sign indicates that E and dx are opposite.

The total work done in moving the unit positive charge from infinity to a point at a distance r from 'Q' is given by

$$W = \int_{\infty}^{r} dw = \int_{\infty}^{r} -Edx.$$

But $$E = \frac{1}{4\pi \in_o} \frac{Q}{x^2}$$

$$W = -\int_{\infty}^{r} \frac{1}{4\pi \in_o} \frac{Q}{x^2} \; dx = \frac{1}{4\pi \in_o} \frac{Q}{r}$$

This work done gives the potential at P due to the charge Q.

$$\therefore V = \frac{1}{4\pi \in_o} \frac{Q}{r}$$

Unit: Joule/col (or) volt

Definition: $\left[ML^2 \, T^{-3} \, I^{-1} \right]$

Potential difference :

Potential difference between two points in an electric field is defined as the work done in moving a unit positive charge from one point to another against the electric field. It is expressed in volt. It is a scalar quantity.

2. Define electric field, strength, potential and potential difference. Derive the relation between the field strength E and potential difference V between two points. (March2011)

A. **Electric field:** The space surrounding a charge over which the effect of a charge can be detected is defined as electric field.

Electric field strength $\left(\vec{\mathbf{E}}\right)$: The force experienced by a unit positive charge kept in an electric field is called the intensity of the electric field (E). It is a vector quantity.

Potential difference : Potential difference between two points is defined as the amount of work done to move a unit positive charge between these two points.

Relation between Electric Intensity and potential:

Consider two points A and B in a uniform electric field of intensity E separated by a distance d Let V be the potential difference between A and B. The work done in moving a charge Q between the points A and B is given by

$$W = VQ \qquad \ldots(1)$$

But the force acting are the charge is $F = EQ$.

$\therefore$ Work done in moving the charge through a distance d is given by $W = F \times d$

$$W = EQd \qquad \ldots(2)$$

From equations (1) and (2), VQ = EQd

(or) $$E = \frac{V}{d}$$

Also the electric intensity is defined as the negative rate of charge potential with distance. $E = -\frac{dv}{dr}$

SHORT ANSWER QUESTIONS

1. Define a) Intensity of electric field b) Potential difference between two points. Derive the relation between them.

A. **Intensity of electric field :**

The force experienced by a unit positive charge kept in an electric field is called the intensity of the electric field (E). It is a vector quantity.

$$E = \frac{1}{4\pi \in_o} \frac{q}{r^2} \mathrm{N / c}$$

The force acting on a charge q placed in a uniform electric field of intensity E is given by

$\bar{F} = \bar{E}q$ *Newton*

Electric potential:

Electric potential gives the electric condition of a body which determines the flow of charge. Electrons flow from a body at lower potential to a body at a higher potential.

Definition: The potential at a point inside the electric field is the work done to bring a unit positive charge from infinity to that point in the electric field.

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2. **Explain dielectric constant of a material. Derive an expression for the potential at a distance from a point charge.**

A. **Relative permittivity (ε_r) Or Dielectric constant of the medium K** :

The ratio of permittivity of a medium ε to the permittivity of free space ε_0 is termed as relative permittivity ε_r.

The ratio of force between two charges in vaccum to the force between those two charges kept at the same distance in the medium is termed as relative permittivity ε_r or dielectric constant (K) of the medium.

Relative permittivity, $\varepsilon_r = \dfrac{Force\ in\ vaccum}{Force\ in\ medium} = \dfrac{F_{voccum}}{F_{midium}}$

$$K = \frac{\varepsilon}{\varepsilon_0}$$

For all substances K > 1 ; for air or vaccum K = 1 ; for a perfect conductor K = ∞

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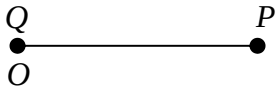
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unit positive charge is moved through a distance dx from 'P' towards O. The work done in doing so is given by

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But $E = \dfrac{1}{4\pi \in_o} \dfrac{Q}{x^2}$

$$W = -\int_{\infty}^{r} \frac{1}{4\pi \in_o} \frac{Q}{x^2} \quad dx = \frac{1}{4\pi \in_o} \frac{Q}{r}$$

This work done gives the potential at P due to the charge Q.

$$V = \frac{1}{4\pi \in_o} \frac{q}{d}$$

Unit: Joule/col (or) volt

VERY SHORT ANSWER QUESTIONS

1. Can there be electric potential at a point with zero electric intensity?

A. Yes. The electric potential is a scalar but intensity of electric field is a vector. So between two charges of same polarity we can get a point with zero intensity. But electric potential at that point is not zero.

2. Can there be electric intensity at a point with zero electric potential?

A. Yes. When two charges +q and –q are separated by a distance d in vaccum, at the mid point potential is zero. But electric field strength is $E = \frac{1}{4\pi\varepsilon_0}\frac{8q}{d^2}$

3. The potential of earth is taken as zero. Explain. (March2011)

A. The potential of the earth is zero. Earth is a huge conductor. Hence an addition or removal of a small amount of charge can not change its electrical conduction .

UNSOLVED PROBLEMS

1. Three charges +q, –q and –q are kept at the vertices of an equilateral triangle of 10 cm side. Calculate the potential at mid point in between –q, -q if q = 5 μC .

A. q = $5\mu C = 5\times10^{-6}$ Coulomb and $\frac{1}{4\pi\varepsilon_0} = 9\times10^9$

Potential at the required point is given by

$$V = V_1 + V_2 + V_3 \Rightarrow V = \frac{1}{4\pi\varepsilon_0}\left[\frac{-q}{5\times10^{-2}} - \frac{q}{5\times10^{-2}} + \frac{q}{5\sqrt{3}\times10^{-3}}\right]$$

$$V = \frac{9\times10^9\times5\times10^{-6}}{10^{-2}}\left[-\frac{1}{5} - \frac{1}{5} + \frac{1}{5\sqrt{3}}\right] = 12.8\times10^5 Volt$$

2. The potential at the origin is zero due to electric field $\vec{E} = 20\vec{i} + 30\vec{j}\ NC^{-1}$. Find the potential at point P (2m.2m). (May2009)

A. $\vec{E} = 20\vec{i} + 30\vec{i}$ position vector is $\vec{r} = 2\vec{i} + 2\vec{j}, V = ?$

But, $V = \vec{E}.\vec{r}$

$\Rightarrow \vec{V} = \left(20\vec{i} + 30\vec{j}\right).\left(2\vec{i} + 2\vec{j}\right)$

$\therefore V = -100\ Volt$

3. The electric field due to a point charge is 400 NC^{-1}. The electric potential at that point is 20 J C^{-1}.Calculate the magnitude of the charge.

A. Electric intensity $(E) = \frac{1}{4\pi\in_0}\frac{q}{r^2} = \frac{kq}{r^2}$

Electric potential (V) = $= \frac{1}{4\pi\in_0}\frac{q}{r} = \frac{kq}{r}$

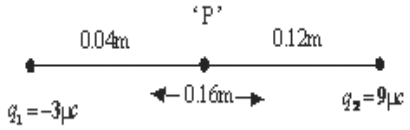
E = 400 N/C ; $V = 20\ J/C$

$$q = \frac{V^2}{EK} = \frac{20\times20}{400\times9\times10^9} \Rightarrow q = 0.11\times10^{-9} C$$

4. Two electric charges of 9 μC and - $3\mu C$ are placed 0.16 m apart in air. There are two points P and Q on the line joining the two charges at distances

of (i) 0.04 m from $-3\mu C$ and in between the charges and (ii) 0.08 m from $-3\mu C$ and outside the two charges. Find the potentials at P and Q.

A. (i) $r_1 = 0.04\,m$ and $r_2 = 0.12\,m$



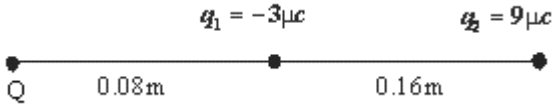
Potential at P,

$$V = V_1 + V_2 = \frac{1}{4\pi\varepsilon_0}\frac{q_1}{r_1} + \frac{1}{4\pi\varepsilon_0}\frac{q_2}{r_2}$$

$$= 9\times10^9\times10^{-4}\left[\frac{-3}{4}+\frac{3}{4}\right] = 0$$

ii) $r_1 = 0.08\ m$; $r_2 = 0.08 + 0.16 = 0.24\,m$

Potential at Q,



$$V = V_1 + V_2 = \frac{1}{4\pi\varepsilon_0}\frac{q_1}{r_1} + \frac{1}{4\pi\varepsilon_0} + \frac{q_2}{r_2}$$

$$= 9\times10^9\left[\frac{\left(-3\times10^{-6}\right)}{\left(8\times10^{-2}\right)} + \left(\frac{9\times10^{-6}}{24\times10^{-2}}\right)\right]$$

$$= 9\times10^9\times10^{-4}\left(\frac{-3}{8}+\frac{3}{8}\right) = 0$$

5. A body of mass one gram and carrying a charge $10^{-8}C$ passes through two points P and Q. The electrostatic potential at Q is O.V. The velocity of the body at Q is 0.2 ms^{-1} and at P is $\sqrt{0.028}\ ms^{-1}$. find the potential at point P. (Hint : As velocity of charged body decreases from Q to P it is evident that potential at P is greater than potential at Q. Now. $\frac{1}{2}m\left(v_Q^2 - v_p^2\right) = q\left(V_p - V_Q\right)$.

A. Potential at 'P' = V_p

Potential at 'Q' = $V_Q^p = 0$

Velocity at 'P' = $V_p = \sqrt{0.028}\,ms^{-1}$

Velocity at 'Q' = $V_Q = 0.2\,ms^{-1}$

Mass on body = 1 gm = $10^{-3}kg$

Charge of body = q = $10^{-8}C$

From conservation of energy,

$$\frac{1}{2}m\left(V_Q^2 - V_p^2\right) = q\left(V_p - V_Q\right) = \frac{1}{2}\left(10^{-3}\right)\left(0.04 - 0.028\right) = 10^{-8}\left[V_p - 0\right]$$

$$\Rightarrow V_p = \frac{1}{2}\times\frac{10^{-3}\times0.012}{10^{-8}} = \frac{1200}{2} = 600V$$

6. A charged sphere of radius 0.02 m has charge density of 1 cm^2. Find the work done when a charge of 40 nano coulomb is moved from infinity to a point that is at a distance of 0.04 m from the centre of the sphere. (1 nano coulomb = $10^{-9}C$)

A. Radius of sphere = R= 0.02m = 2×10^{-2}m = $2\times10^{-2}\,m$

Charge density $\sigma = \frac{Q}{A} = 1C\,m^{-2}$

$\Rightarrow Q = A\times 1 = 4\pi R^2 = 4\pi\left(4\times10^{-4}\right) = 16\pi\times10^{-4}C$

Charge to be moved = $Q_0 = 40nc = 40\times10^{-9}C$

Potential at distance d is $V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{d}$

$\Rightarrow V = 9\times10^9\times\frac{16\pi\times10^{-4}}{4\times10^{-2}} = 36\pi\times10V$

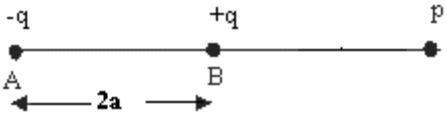
$\therefore$ Work done = VQ_0 = $36\pi\times10^7\times40\times10^{-9}$ = $144\pi\times10^{-2} = 14.4\pi J$

7. Find the potential due to the electric dipole at a distance r from the dipole on the axial line.

A. Consider a electric dipole of two equal and opposite charges +q and –q at distance '2a'. 'P' is a point on axial line at distance 'r' from centre of dipole.

Potential at 'P' ue to charge '+q'

$V_1 = \frac{1}{4\pi\varepsilon_0}\frac{q}{(r-a)}$



Potential due to charge '-q' at 'P'

$V_2 = \frac{1}{4\pi\varepsilon_0}\frac{(-q)}{(r+a)}$

Total Potential at 'P' = V = $V_1 + V_2$ = $\frac{1}{4\pi\varepsilon_0}\frac{q}{(r-a)} + \frac{1}{4\pi\varepsilon_0}\frac{(-q)}{(r+a)}$

$= \frac{q}{4\pi\varepsilon_0}\left[\frac{1}{r-a}+\frac{1}{r+a}\right] = \frac{q}{4\pi\varepsilon_0}\left[\frac{r+a-r+a}{(r-a)(r+a)}\right] = \frac{1}{4\pi\varepsilon_0}\frac{2lq}{(r^2-a^2)}$

$\Rightarrow V = \frac{1}{4\pi\varepsilon_0}\frac{p}{(r^2-a^2)}$

$\because (P = 2aq \rightarrow dipolemoment)$

If r>>a then a^2 can be neglected

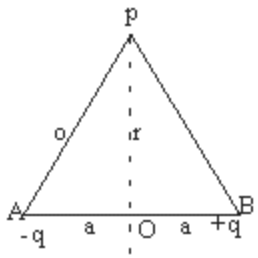
$\Rightarrow V_{axial} = \frac{1}{4\pi\in_0}\left(\frac{2qa}{r^2}\right)$

8. Find the potential due to the electric dipole at a distance r from the dipole on the equatorial line.

A. Consider electric dipole of two equal and opposite charges +q and –q at distance '2*l*' 'P' is a point on equatorial line of dipole at distance 'r' from centre of dipole.

Potential at 'p' due to charge $+q = V_1 = \frac{1}{4\pi\varepsilon_0}\frac{q}{r_1}$

Potential at 'P' due to charge - q = $V_2 = \frac{1}{4\pi\varepsilon_0}\frac{(-q)}{r_2}$



Total potential at 'P'

V = $V_1 + V_2 = \frac{1}{4\pi\varepsilon_0}\frac{q}{r_1} + \frac{1}{4\pi\varepsilon_0}\frac{(-q)}{r_2} = \frac{q}{4\pi\varepsilon_0}\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$

Where $r_1 = \sqrt{r^2 + a^2}$, $r_2 = \sqrt{r^2 + a^2}$

Since $r_1 = r_2 \Rightarrow V_{equator} = 0$.

14. An infinite number of charges, 'q' each are placed along the X-axis x = 1, x = 2, x =4, x = 8 and so on. If the distances are in metres, calculate the electric potential at x = 0. What will be the potential if consecutive charges are of opposite sign?

Sol: 1) $V = \frac{1}{4\pi\varepsilon_0}\sum\frac{q_n}{r_n} = \frac{1}{4\pi\varepsilon_0}\left[\frac{q}{1} + \frac{q}{2} + \frac{q}{4} + \frac{q}{8} + ...\right] = \frac{q}{4\pi\varepsilon_0}\left[1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + ...\right]$

$= \frac{q}{4\pi\varepsilon_0}\left[1 + \frac{1}{2} + \frac{1}{2^2} + \frac{1}{2^3} + ...\right] = \frac{q}{2\pi\varepsilon_0}$.

2) $V = \frac{q}{4\pi\varepsilon_0}\left[1 - \frac{1}{2} + \frac{1}{2^2} - \frac{1}{2^3} + ...\right] = \frac{q}{6\pi\varepsilon_0}$

9. Calculate the electrostatic potential energy of an electron-proton system of hydrogen atom in joules. In the first Bohr orbit of hydrogen atom, the radius of the orbit is $5.3\times10^{-11} m$.

Sol: The charge of electron $q_1 = -1.6\times10^{-19} C$.

The charge of proton $q_2 = +1.6\times10^{-19} C$

The distance of separation $r_{12} = 5.3\times10^{-11} m$.

The potential energy of the system is given by

$U(\text{electron-proton}) = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r_{12}} = \frac{(9\times10^9)(-1.6\times10^{-19})(+1.6\times10^{-19})}{5.3\times10^{-11}}$

$U = -4.35\times10^{-18} J$

10. Two charges each Q are at a distance d apart. They are released. What is the velocity of each charged body of mass m when the distance between them is 2d?

Sol: Initial P.E $= \frac{Q_1 Q_2}{4\pi\varepsilon_0 r} = \frac{Q^2}{4\pi\varepsilon_0 d}$

Final P.E$= \frac{Q^2}{4\pi\varepsilon_0 (2d)}$.

$\therefore$ Loss of P.E $= \frac{Q^2}{4\pi\varepsilon_0 d} - \frac{Q^2}{8\pi\varepsilon_0 d} = \frac{Q^2}{8\pi\varepsilon_0 d}$.

Gain of K.E.$= \frac{1}{2}(mv^2)\times 2$

By the principle of conservation of energy, loss of P.E.= gain of K.E.

$\therefore \frac{Q^2}{8\pi\varepsilon_0 d} = mv^2$

$\Rightarrow v = \frac{Q}{\sqrt{8\pi\varepsilon_0 dm}}$.

11. A charge q is released with a velocity $1\times10^6 m/s$ from a large distance from a fixed positive charge Q. What is the closest distance of approach? The mass of the charge q is m.

Sol: Initially q has K.E.= $\frac{1}{2}mv^2 = \frac{1}{2}m\times10^{12}$.

Charge q momentarily comes to rest at a distance x from Q (and them goes back).

In that position its $P.E = \frac{Qq}{4\pi\varepsilon_0 x} = 9\times10^9 \times \frac{Qq}{x}$

At closest distance of approach P.E. = Initial K.E.

$$\frac{9\times10^9\times Qq}{x} = \frac{1}{2}m\times10^{12}$$

$$\therefore x = \frac{Qq\times9\times10^9\times2}{10^{12}m} = \frac{18Qq}{10^3 m}.$$

12. Find the distance from a charge of 10 μC where the potential is $3\times10^4 V$.

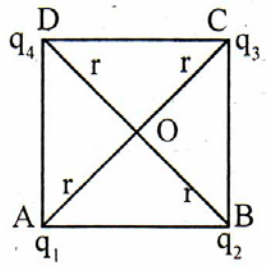
Sol: q = $10\mu C = 10\times10^{-6}C$, V = $3\times10^4 V$

Let the distance be r from the charge.

$$V = \left(\frac{1}{4\pi\varepsilon_0}\right)\frac{q}{r} \quad \Rightarrow \quad 3\times10^4 = \frac{9\times10^9\times\left(10\times10^{-6}\right)}{r} \quad \text{Or } r = \frac{9\times10^9\times10^{-5}}{3\times10^4} = 3m$$

13. Four charges $q_1 = -0.02\mu C$, $q_2 = 0.04\mu C$, $q_3 = 0.02\mu C$ and $q_4 = -0.04\mu C$ are at the four corners of a square of side 9 cm. Calculate the potential at the centre of the square.

Sol: Each charge is at a distance r from the centre and $r = \frac{9}{\sqrt{2}}cm = \frac{9}{\sqrt{2}}\times10^{-2}m$.



Potential at the centre is given by

$$V = \sum\frac{1}{4\pi\varepsilon_0}\frac{q}{r} = \frac{1}{4\pi\varepsilon_0}\left[\frac{-0.02+0.04+0.02-0.04}{r}\right]\times10^{-6} \quad = 0$$

14. Calculate the work done in eV while carrying an electron from one plate to another which are maintained at a potential difference of 200V

Sol: $q = 1.6\times10^{-19}C$; V = 200V

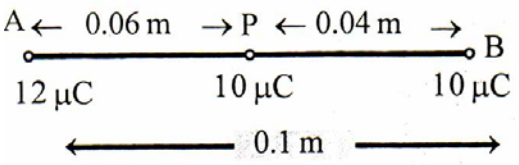
$\therefore$ Work done in carrying the electron from one plate to another is

$W = qV = \left(1.6\times10^{-19}\right)(200) = 32.0\times10^{-18}J = 200eV$

15. Two positive charges 12 μC and 10 μC, are initially separated by 10 cm. Calculate the work done in bringing the two charges 4 cm closer.

Sol: The charges are

$q_1 = 12\times10^{-6}C$ and $q_2 = 10\times10^{-6}C$.



Initially, the two charges are at A and B, at a distance of 0.1 m. Hence, initially the potential energy of the system is

$$U_1 = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r} = 9\times10^9 \times \frac{12\times10^{-6}\times10\times10^{-6}}{0.1}$$

Now the two charges are brought 0.04 m close. Now the distance of separation is 0.06 m

The potential energy of the system $U_2 = \frac{9\times10^9\times12\times10^{-6}\times10\times10^{-6}}{0.06} J$

Hence the work done is $W = U_2 - U_1 = 9\times10^9\times12\times10^{-6}\times10\times10^{-6}\left[\frac{1}{0.06}-\frac{1}{0.1}\right]$

$= 7.2J$

16. Two protons are at a distance of 01.53×10^{-10} m. Calculate the potential energy of the system in eV.

Sol: Potential energy of the system

$$U = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r_{12}} = \left(9\times10^9\right)\frac{\left(+1.6\times10^{-19}\right)\left(+1.6\times10^{-19}\right)}{0.53\times10^{-10}} \text{ J}$$

$$\therefore U = \frac{\left(9\times10^9\right)\left(+1.6\times10^{-19}\right)}{0.53\times10^{-10}} eV = +27.2 \text{ eV}$$

17. The potential difference between two points that are at 10 cm distance away is 350 V. Calculate the electric field strength produced assuming the electric field to be uniform.

Sol: $V = 350V$ and d = 10 cm = 0.1 m

Electric field strength $E = \frac{V}{d} = \frac{350V}{0.1m} = 3500Vm^{-1}$.

ASSESS YOURSELF

1. Electrostatic field lines of force do not form closed loops. If they form closed loops then the work done in moving a charge along a closed path will not be zero. From the above two statements can you guess the nature of electrostatic force?

Sol: It is a conservative force.

2. The electrostatic potential energy is independent of the manner in which the configuration is achieved. This is due to the path independence of work. From this what can you guess about the nature of electrostatic force?

Sol: It is a conservative force.

3. Inside a hollow conducting sphere of charge Q, the electric intensity (E) is zero. But, the potential (V) is not zero. How should be the potential inside the charged conducting sphere to satisfy the condition that E is zero inside?

Sol: The potential should be the same every where inside the sphere so that $\frac{dV}{dr} = 0$