

Answers

Module 1: Electric Charges, Coulomb's Law

A.1.1.1 (C)

Statement (1) is incorrect. The charge on any given object can only be increased/decreased by amounts that are integral multiples of the charge of the electron.

Statement (3) is incorrect. We need to find the algebraic sum of the different charges present as charges can be positive as well as negative.

Statements (2) and (4) are correct statements. Statement B implies that the total charge of the universe is always conserved. Statement D tells us about our understanding of the concept of charge.

A.1.1.2 (D)

Any charged object can be regarded as a point charge if its effects are observed at points that are far off from it. The usual (reasonable) meaning of far off points is points, whose distance from the charged object, is 100 (or more) times the dimensions of the object.

A.1.1.3 (A)

The concept of an infinite charged object is, in a way, the reverse of the concept of a point charge. We can (reasonably) think of a charged object as an infinite charged object when the distance of the point of interest, from the charged object, is equal to or less than $(\frac{1}{100})$ of the smallest dimensions of the object.

A.1.1.4 (D)

The charge, on the electron, is $-1.6 \times 10^{-19}\text{C}$. Thus even if the charge on a (macroscopic) object changes by 1 pC (10^{-12}C), it equals the charge of n electrons where n is between 10^6 to 10^7 . This number is clearly much more than 1; hence the granular (or quantized) nature of charge gets masked when we talk about the changes in charge of a macroscopic object.

[Option (B) is incorrect because 'quarks', by themselves, do not have an independent physical existence. The basic elementary unit of charge is still the charge of the electron.]



A.1.1.5 (A)

This is the process of charging by induction. When the object (to be charged by induction) is earthed, the same kind of charge (the kind of charge on the charging object) passes on to earth; the opposite kind of charge is retained by the object being charged (by induction)

A.1.1.6 (B)

As per Coulomb's law,

$$\mathbf{F}_{21} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \hat{\mathbf{r}}$$

where $r = OP$ and $\hat{\mathbf{r}}$ is a unit vector along the direction of OP .

$$\text{Here } r = [(x - 0)^2 + (y - 0)^2 + (z - 0)^2]^{1/2} = \sqrt{x^2 + y^2 + z^2}$$

$$\text{Also } \hat{\mathbf{r}} = \frac{x\hat{\mathbf{i}} + y\hat{\mathbf{j}} + z\hat{\mathbf{k}}}{\sqrt{x^2 + y^2 + z^2}}$$

$$\frac{\hat{\mathbf{r}}}{r^2} = \frac{x\hat{\mathbf{i}} + y\hat{\mathbf{j}} + z\hat{\mathbf{k}}}{\sqrt{x^2 + y^2 + z^2}} \cdot \frac{1}{(\sqrt{x^2 + y^2 + z^2})^2} = \frac{x\hat{\mathbf{i}} + y\hat{\mathbf{j}} + z\hat{\mathbf{k}}}{(x^2 + y^2 + z^2)^{3/2}}$$

$$\therefore \mathbf{F}_{21} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{(x^2 + y^2 + z^2)^{3/2}} \cdot (x\hat{\mathbf{i}} + y\hat{\mathbf{j}} + z\hat{\mathbf{k}})$$

A.1.1.7 (D)

As per the principle of superposition, the total force, on a given charge, equals the vector sum of the forces exerted on it, individually, by the different charges. We would, therefore, have

$$\mathbf{F} = \mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3$$

A.1.1.8 (B)

Refer Fig.A.1.1.1, The force, on q , due to q_1 is $\mathbf{F}_1 = \frac{1}{4\pi\epsilon_0} \frac{q_1 q}{r^2}$ along AP and that, due to q_2 , is

$$\mathbf{F}_2 = \frac{1}{4\pi\epsilon_0} \frac{q_2 q}{r^2}$$

along PB

$$\text{Here } |\mathbf{F}_1| = |\mathbf{F}_2| = 9 \times 10^9 \times \frac{10 \times 10^{-6} \times 1 \times 10^{-3}}{(10 \times 10^{-2})^2} = 9 \times 10^3 \text{ N}$$

Their resultant has a magnitude $2 \times 9 \times 10^3 \times \cos\theta$, (where $\cos\theta = \frac{8}{10}$)

$$\therefore \text{ Magnitude of the resultant force } 2 \times 9 \times 10^3 \times 0.8 \text{ N} = 14400 \text{ N}$$

Its direction is parallel to the X-axis.

$$\text{Hence } \mathbf{F} = 14400 \hat{\mathbf{i}} \text{ N}$$

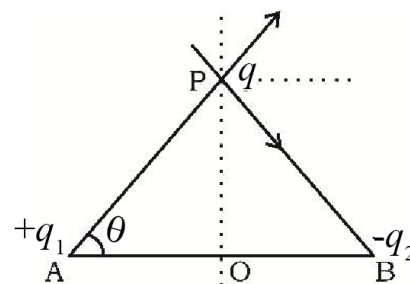


Fig.A.1.1.1

A.1.1.9 (C)

$$AG = BG = CG = \frac{2}{3} (2a \sin 60^\circ) = \frac{2}{3} \times 2a \times \frac{\sqrt{3}}{2} \text{ i.e. } r = \frac{2a}{\sqrt{3}}$$

Force on the charge at G, due to the charges at B and C, are

$$\mathbf{F}_B = \frac{1}{4\pi\epsilon_0} \frac{q^2}{r^2} \text{ along GB and } \mathbf{F}_C = \frac{1}{4\pi\epsilon_0} \frac{q^2}{r^2} \text{ along GC}$$

They are along directions inclined at 120° to each other.

$\therefore$ Their resultant has a magnitude

$$\mathbf{F}_{BC} = \left[2 \left(\frac{1}{4\pi\epsilon_0} \frac{q^2}{r^2} \right)^2 + 2 \left(\frac{1}{4\pi\epsilon_0} \frac{q^2}{r^2} \right)^2 \cos 120^\circ \right]^{1/2} = \frac{1}{4\pi\epsilon_0} \frac{q^2}{r^2}$$

It is directed along GO, i.e., along $-\hat{\mathbf{j}}$

$$\text{Also force, on the charge at G, due to the charge at A, is } \mathbf{F}_A = \frac{1}{4\pi\epsilon_0} \frac{q^2}{r^2} (-\hat{\mathbf{j}})$$

The total force, on the charge at G, is, therefore,

$$\mathbf{F} = \mathbf{F}_{BC} + \mathbf{F}_A = 2 \cdot \frac{1}{4\pi\epsilon_0} \frac{q^2}{r^2} (-\hat{\mathbf{j}})$$

$$= 2 \cdot \frac{q^2}{4\pi\epsilon_0} \frac{3}{4a^2} (-\hat{\mathbf{j}}) = \frac{3q^2}{8\pi\epsilon_0 a^2} (-\hat{\mathbf{j}})$$

A.1.1.10 (A)

Distance $AP=BP=CP=DP= a\sqrt{2}$ (Fig.A.1.1.2)

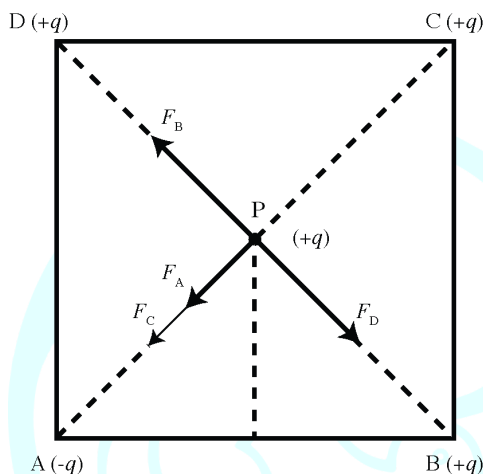


Fig.A.1.1.2

$$|\mathbf{F}_A| = |\mathbf{F}_B| = |\mathbf{F}_C| = |\mathbf{F}_D| = \frac{1}{4\pi\epsilon_0} \frac{q^2}{(a\sqrt{2})^2} = \frac{q^2}{8\pi\epsilon_0 a^2}$$

Force due the charge at B and charge at D are equal and opposite to each other, so they will cancel out each other.

The resultant force on P is due to charge at A and charge at C.

$$\mathbf{F}_{net} = \mathbf{F}_A + \mathbf{F}_C = 2\mathbf{F} \hat{\mathbf{n}}$$

And $\hat{\mathbf{n}}$ is the unit vector along $\mathbf{PA}$

$$\text{So, } \hat{\mathbf{n}} = \cos 45^\circ (-\hat{\mathbf{i}}) + \sin 45^\circ (-\hat{\mathbf{j}}) = -\frac{1}{\sqrt{2}} (\hat{\mathbf{i}} + \hat{\mathbf{j}})$$

$$\text{Hence, } \mathbf{F}_{net} = -\frac{q^2}{8\sqrt{2}\pi\epsilon_0 a^2} (\hat{\mathbf{i}} + \hat{\mathbf{j}})$$

Module 2 : Electric Field; Gauss's Law

A.1.2.1 (C)

The presence of a unit charge (quite a large charge in SI units), or any other finite (small) charge, is likely to disturb the charge Q . This would make its electric effects (somewhat) different from what they were in the absence of this test charge. In practice, the test charge cannot have a magnitude less than the magnitude of the charge of the electron (the smallest charge that can be isolated in nature). We, therefore, find it best to define the electric field just in terms of the mathematical expression of Coulomb's law, corresponding to the force between the point charge Q and a unit charge.

A.1.2.2 (A)

Position vector of the origin, w.r.t., the first charge is

$$\mathbf{r}_1 = (-2\hat{\mathbf{i}} - 3\hat{\mathbf{j}} - 4\hat{\mathbf{k}})$$

$$\therefore |\mathbf{r}_1| = [(-2)^2 + (-3)^2 + (-4)^2]^{\frac{1}{2}} = \sqrt{29}$$

$$\therefore \mathbf{E}_1 = \frac{1}{4\pi\epsilon_0} \frac{10^{-6}}{29\sqrt{29}} (-2\hat{\mathbf{i}} - 3\hat{\mathbf{j}} - 4\hat{\mathbf{k}})$$

$$= \frac{9 \times 10^3}{29\sqrt{29}} (-2\hat{\mathbf{i}} - 3\hat{\mathbf{j}} - 4\hat{\mathbf{k}})$$

Similarly,

$$\mathbf{r}_2 = (-3\hat{\mathbf{i}} - 4\hat{\mathbf{j}} - 5\hat{\mathbf{k}})$$

$$|\mathbf{r}_2| = \sqrt{50}$$

$$\therefore \mathbf{E}_2 = \frac{9 \times 5 \times 10^3}{50\sqrt{50}} (-3\hat{\mathbf{i}} - 4\hat{\mathbf{j}} - 5\hat{\mathbf{k}})$$

$$\therefore \mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2$$

$$= -10^3 \left[\left(\frac{18}{29\sqrt{29}} + \frac{135}{50\sqrt{50}} \right) \hat{i} + \left(\frac{27}{29\sqrt{29}} + \frac{180}{50\sqrt{50}} \right) \hat{j} + \left(\frac{36}{29\sqrt{29}} + \frac{225}{50\sqrt{50}} \right) \hat{k} \right] \frac{N}{C}$$

A.1.2.3 (C)

The field, due to each of the three charges, has a magnitude $= \frac{1}{4\pi\epsilon_0} \frac{Q}{\left(\left(\frac{a\sqrt{3}}{2} \right)^2 + \left(\frac{2}{3} \right)^2 \right)} = \frac{1}{4\pi\epsilon_0} \frac{3Q}{a^2} = \mathbf{F}'$;

The situation has been depicted there schematically. The angle between any two fields is 120° . The resultant of the two ($\mathbf{F}'$)s along GE and GF is $2\mathbf{F}' \cos \frac{120^\circ}{2} = 2\mathbf{F}' \cos 60^\circ = \mathbf{F}'$, and it acts along GA, which is equal and opposite to $\mathbf{F}'$ along GD. So, the Net force is zero.

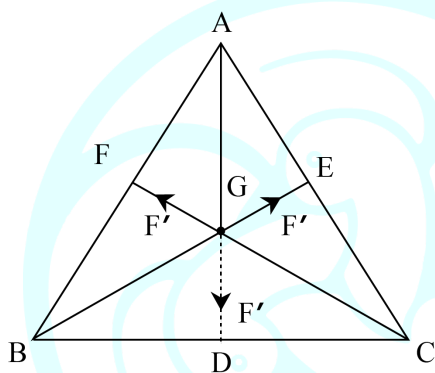


Fig.A.1.2.1

A.1.2.4 (C)

The charge, on an infinitesimal element of the wire, at the point $(x, 0)$

$$dq = (b|x|dx)$$

The field, due to this charge element, at the point $(0, a)$ is

$$d\mathbf{E}_1 = \frac{1}{4\pi\epsilon_0} \frac{b|x|dx}{(x^2 + a^2)^{3/2}} (-x\hat{i} + a\hat{j})$$

The field, due to another such element, located at the point $(-x, 0)$

$$d\mathbf{E}_2 = \frac{1}{4\pi\epsilon_0} \frac{b|x|dx}{(x^2 + a^2)^{3/2}} (x\hat{i} + a\hat{j})$$

The total field, due to these two (symmetrically located) elements, is $d\mathbf{E} = \frac{1}{4\pi\epsilon_0} \frac{2ab|x|dx}{(x^2+a^2)^{3/2}} \hat{\mathbf{j}}$

The total field, due to the whole wire, is $\mathbf{E} = \frac{2ab}{4\pi\epsilon_0} \int_{x=-L}^{x=+L} \frac{|x|}{(x^2+a^2)^{3/2}} dx$

$$\mathbf{E} = \frac{2ab\hat{\mathbf{j}}}{4\pi\epsilon_0} (2) \int_{x=0}^{x=L} \frac{x}{(x^2+a^2)^{3/2}} dx$$

$$\text{Put } (x^2 + a^2) = z^2$$

$$2x dx = 2z dz \text{ or } x dx = z dz$$

When $x = 0$, $z^2 = a^2$, $z = a$; when $x = L$, $z = \sqrt{x^2 + a^2}$

$$\begin{aligned} \mathbf{E} &= \frac{4ab\hat{\mathbf{j}}}{4\pi\epsilon_0} \int z^{-2} dz \\ &= \frac{-4ab\hat{\mathbf{j}}}{4\pi\epsilon_0} \left| \frac{1}{z} \right|_a^{\sqrt{L^2+a^2}} \\ &= \frac{ab}{\pi\epsilon_0} \left(\frac{1}{a} - \frac{1}{\sqrt{L^2+a^2}} \right) \hat{\mathbf{j}} \\ &= \frac{b}{\pi\epsilon_0} \left(\frac{\sqrt{L^2+a^2}-a}{\sqrt{L^2+a^2}} \right) \hat{\mathbf{j}} \end{aligned}$$

A.1.2.5 (D)

The Gaussian surface, for any charge distribution, is a surface that satisfies both the conditions listed in option (D). It is only such a surface that enables one to use Gauss's theorem for calculating the electric field due to a given charge distribution.

A.1.2.6 (B)

The flux of the given electric field is non-zero only through the faces ALPO and CBMN of the cube. Outward flux through the face ALPO

$$= (c + b \times 0) \hat{\mathbf{i}} \cdot (a^2(-\hat{\mathbf{i}})) \quad [\text{since, } x = 0 \text{ at the origin}]$$

$$= -ca^2$$

Outward flux through the face CBMN

$$= (c + b \times a) \hat{\mathbf{i}} \cdot (a^2 (+ \hat{\mathbf{i}}))$$

$$= (ca^2 + ba^3)$$

$\therefore$ Net flux through the cube

$$= (-ca^2) + (ca^2 + ba^3) = ba^3$$

A.1.2.7 (C)

The total charge enclosed by the concentric sphere of radius R_0 ($R_0 > R$), equals the total charge present on the charged solid sphere.

The charge, present in the spherical shell, contained within spheres of radius r and $(r + dr)$, is

$$dq = \rho(r) \cdot (4\pi r^2 dr) = kr^2 \cdot 4\pi r^2 dr = 4\pi kr^4 dr$$

$\therefore$ Total charge on the whole solid sphere is

$$Q = 4\pi k \int_0^R r^4 dr = \frac{4\pi k R^5}{5}$$

$\therefore$ Flux, through the concentric sphere of radius R_0 ($R_0 > R$) is given by

$$\phi = \frac{Q}{\epsilon_0} = \frac{4\pi k R^5}{5\epsilon_0}$$

A.1.2.8 (A)

The charge present on the elemental segment between x and $(x + dx)$, is

$$dq = [\lambda(x)]dx = \left[a \sin\left(\frac{2\pi x}{L}\right) \right] dx$$

$\therefore$ charge on the first half is

$$Q_{\frac{1}{2}} = \int_0^{\frac{L}{2}} a \sin\left(\frac{2\pi x}{L}\right) dx = \frac{-aL}{2\pi} \left[\cos\left(\frac{2\pi x}{L}\right) \right]_0^{\frac{L}{2}} = \frac{-aL}{2\pi} [\cos\pi - \cos 0] = \frac{aL}{\pi}$$

Also charge on the whole wire is

$$Q = \int_0^L a \sin\left(\frac{2\pi x}{L}\right) dx = \frac{-aL}{2\pi} \left[\cos\left(\frac{2\pi x}{L}\right) \right]_0^L = \frac{-aL}{2\pi} [\cos 2\pi - \cos 0] = 0$$

$$\therefore \phi_1 = \frac{La}{\pi\epsilon_0} \text{ and } \phi_2 = 0$$

A.1.2.9 (B)

The charge, within the elemental area, contained in the strip of width dy , located at a distance y from the base side is

$$dQ = [\sigma(y)][ady] = k a y dy$$

$\therefore$ Total charge on the square sheet is

$$Q = \int dQ = ka \int_0^a y dy = \frac{ka^3}{2}$$

$\therefore$ Flux of the electric field, due to this charged square sheet, through a sphere that completely encloses is $\phi = \frac{Q}{\epsilon_0} = \frac{ka^3}{2\epsilon_0}$ (It is independent of the value of R)

A.1.2.10 (B) The equilibrium position of corresponds to condition

$$\begin{aligned} \tan\theta &= \frac{F_e}{mg} \\ &= \frac{\frac{q^2}{4\pi\epsilon_0 4a^2}}{mg} = \frac{q^2}{16\pi\epsilon_0 a^2 mg} \end{aligned}$$

Thus (B) is correct.

Module 3: Electric Dipole

A.1.3.1 (B)

The electric field (E) and the potential (V), of a dipole, vary with distance (r), at a (much) faster rate than the corresponding quantities for a monopole (a point charge). This is because the dipole is made of two equal and opposite charges that are only a small distance apart from each other.

For a monopole (a point charge), it is known that $E(r) \propto \frac{1}{r^2}$ and $V(r) \propto \frac{1}{r}$

For a dipole, we have $E(r) \propto \frac{1}{r^3}$ and $V(r) \propto \frac{1}{r^2}$

A.1.3.2 (D)

While deriving the value of potential where neglected terms of power of $\frac{a}{r}$ higher than 1.

A.1.3.3 (B)

A dipole experiences a torque but no net force when kept in a uniform external electric field aligned at a certain angle with the dipole. However, it experiences a torque as well as a nonzero net force when kept in a (highly) non-uniform external field.

Hence $\tau \neq 0$ and $F = 0$ in case (i)

and $\tau \neq 0$ and $F \neq 0$ in case (ii)

A.1.3.4 (B)

By its very definition, the monopole moment (net charge) has to be zero for all neutral atoms/molecules. Hence $q_0 = 0$ for all neutral atoms/molecules. However, p_0 can be non-zero for some of neutral atoms/molecules. These are the (asymmetrical) atoms/molecules in which the positions of the centres of their positive and (equal magnitude) negative charges do not quite coincide. Hence such atoms/molecules can be thought of as being equivalent to two equal and opposite charges having a slight separation between them. Hence their dipole moment is non-zero.

Thus $p_0 = 0$ for some (asymmetrical) atoms/molecules.

A.1.3.5 (B)

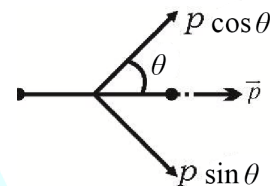
(i) the parallel orientation is a position of stable equilibrium. Hence, on a (slight) clockwise/(anticlockwise) rotation, the resulting torque is anticlockwise/(clockwise) and it tends to bring the dipole back to its position of stable equilibrium.

(ii) The antiparallel orientation is a position of unstable equilibrium. Hence, on a (slight) clockwise/(anticlockwise) rotation, the resulting torque is also clockwise/(anticlockwise) and it tends to take the dipole away from its position of unstable equilibrium forwards to its position of stable equilibrium.

A.1.3.6 (D)

We can resolve the dipole moment, $\vec{p}$, of the dipole, into an (axial) component $p \cos \theta$ and an (equatorial) component $p \sin \theta$. The contribution of the equatorial component ($p \sin \theta$) to the potential, at point P, is zero (Fig.A.1.3.1). The contribution of the axial component ($p \cos \theta$) at point P, is

$$V_a \cong \frac{1}{4\pi\epsilon_0} \frac{p \cos \theta}{r^2}$$



Hence the net potential, at point P, is $V = \frac{1}{4\pi\epsilon_0} \frac{p \cos \theta}{r^2}$

Fig.A.1.3.1

A.1.3.7 (A)

For $|\vec{p} \times \vec{E}| = pE$, we have $|pE \sin \theta| = pE$

$$\therefore |\sin \theta| = 1 \quad \text{Hence } \theta = \frac{\pi}{2} \quad (\text{for first orientation})$$

The work done in changing the orientation of the dipole from $(\theta = \theta_1)$ to $(\theta = \theta_2)$ is given by

$$W = \int_{\theta_1}^{\theta_2} (pE \sin \theta) d\theta = -pE [\cos \theta]_{\theta_1}^{\theta_2} = pE (\cos \theta_1 - \cos \theta_2)$$

The reference position is $\theta_1 = \frac{\pi}{2}$. Hence the P.E. of the dipole, of orientation θ , is given by

$$\text{PE} = pE \left(\cos \frac{\pi}{2} - \cos \theta \right) = -pE \cos \theta$$

$\therefore$ The graph between PE and (θ) is as shown below (Fig.1.3.2).

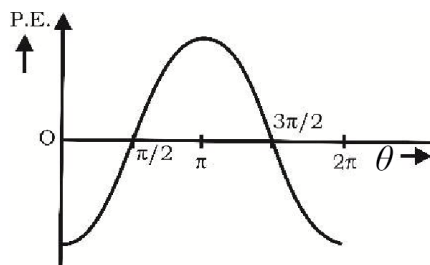


Fig.A.1.3.2

A.1.3.8 (A)

We can resolve the dipole moment p , of the dipole, into an (axial) component $p \cos \theta$ and an (equatorial) component $p \sin \theta$. The electric field, at P, due to the axial component, is given by

$$\mathbf{E}_a = \frac{2p \cos \theta}{4\pi\epsilon_0 r^3} \hat{n}_1 = \frac{2qa \cos \theta}{4\pi\epsilon_0 r^3} \hat{n}_1$$

The electric field, at P, due to the equatorial component is

$$\mathbf{E}_e = \frac{p \sin \theta}{4\pi\epsilon_0 r^3} (-\hat{n}_2) = \frac{2qa \sin \theta}{4\pi\epsilon_0 r^3} (-\hat{n}_2)$$

∴ Resultant field at P has a magnitude

$$E = \sqrt{E_a^2 + E_e^2} = \frac{p\sqrt{1+3\cos^2\theta}}{4\pi\epsilon_0 r^3}$$

Its direction is inclined at an angle α to the direction of E_a where $\tan \alpha = \frac{p \sin \theta}{2p \cos \theta} = \frac{1}{2} \tan \theta$

∴ The direction of $\mathbf{E}$ is inclined to the direction of $\mathbf{p}$ at an angle $\left[\theta + \tan^{-1} \left(\frac{1}{2} \tan \theta \right) \right]$

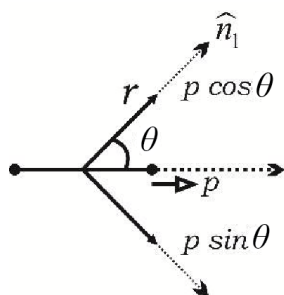


Fig.A.1.3.3

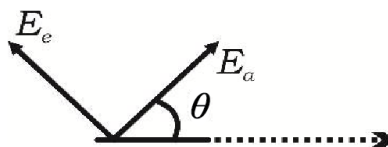


Fig.A.1.3.4

A.1.3.9 (C)

At an axial point, distant x from the centre, we have

$$V_a = \frac{1}{4\pi\epsilon_0} \left[\frac{-q}{x+2a} + \frac{2q}{x} + \frac{-q}{x-2a} \right] = \frac{q}{4\pi\epsilon_0} \left[\frac{2}{x} - \frac{x-2a+x+2a}{x^2-4a^2} \right]$$

$$= \frac{q}{4\pi\epsilon_0} \left[\frac{2(x^2-4a^2)-2x^2}{x(x^2-4a^2)} \right] = \frac{-4(2qa)a}{4\pi\epsilon_0 x(x^2-4a^2)} = \frac{-4pa}{4\pi\epsilon_0(x)(x^2-4a^2)} \approx \frac{pa}{\pi\epsilon_0 x^3}$$

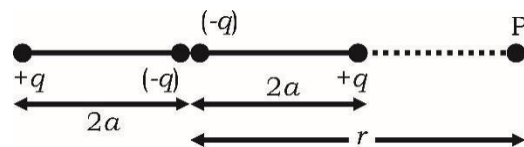


Fig.A.1.3.5

For an equatorial point distant y from the centre,

$$V_e = \frac{1}{4\pi\epsilon_0} \left[\frac{(-q)}{(4a^2+y^2)^{1/2}} + \frac{2q}{y} + \frac{(-q)}{(4a^2+y^2)^{1/2}} \right] = \frac{2q}{4\pi\epsilon_0} \left[\frac{1}{y} - \frac{1}{(4a^2+y^2)^{1/2}} \right] \approx \frac{2q}{4\pi\epsilon_0} \left[\left(\frac{2a^2}{y^3} \right) \right] = \frac{1}{2\pi\epsilon_0} \frac{pa}{y^3}$$

A.1.3.10 (D)

We have

$$V_P = \frac{1}{4\pi\epsilon_0} \left[\frac{q}{(r+2a)} + \frac{(-2q)}{r} + \frac{q}{(r-2a)} \right]$$

$$= \frac{q}{4\pi\epsilon_0} \left[\frac{r(r-2a)-2(r^2-4a^2)+r(r+2a)}{r(r^2-4a^2)} \right] = \frac{8qa^2}{r(r^2-4a^2)} \approx \frac{8qa^2}{r^3} \text{ (as } r \gg a, \text{ and so } \left(\frac{a}{r}\right)^2 \rightarrow 0)$$

$$\therefore V(r) \propto \left(\frac{1}{r^3} \right)$$



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