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Course in PHYSICS 4

Electrostatics and Current Electricity



S. C. Pandey

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Electrostatics and Current Electricity

(Volume 4)

S.C. Pandey

PEARSON

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Preface

For a science student, physics is the most important subject as it requires logical reasoning and high imagination. Without improving the level of physics, it is difficult to achieve a goal with the kind of competition that exists today. This five part volume covers all parts of general physics—Mechanics, Heat, Wave, Light, Electromagnetism and Modern Physics—which is written in accordance with the latest syllabus of the IIT-JEE and AIEEE. There is no single book that is available in the market that contains a large amount of solved examples.

SALIENT FEATURES

- Entire syllabus is covered in five volumes.
- Content of each chapter is well defined and builds new concepts from the scratch.
- Each chapter describes the theory in a simple and lucid style.
- Covers a wide spectrum of questions to enable the student to develop enough expertise to tackle any problem.
- Helps students in building analytical and quantitative skills, which, in turn, develop confidence in problem solving.
- Practice exercises are given at the end of each chapter.
- Numerous diagrams in every chapter.

After studying the entire chapter, students will be able to learn different tricks and techniques of problem solving with suitable level of analytical ability.

Suggestions for improving the book are always welcome.

All the best!

S. C. PANDEY

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CHAPTER

1

Electrostatics

1.1 INTRODUCTION

It is that branch of physics in which we study properties of charge at rest.

Benjamin Franklin (1706-1790) was the first *"American Scientist"* who proved that charge is of two types:

"Conventionally he assumed that charge appears on glass rod is (+ve) positive, while that on the rubber rod is (–ve) negative."

Now with the comparison of these two charges an unknown charge can be labelled at either (+*ve*) positive or negative (–*ve*).

CONCEPT

(i) The excess or deficiency of electrons in a body gives concept of charge.

If body has a excess of electrons then it will be negatively charge and if it has deficiency of electrons then it will be positively charged.

(ii) If n is the number of electrons transferred, then the charge acquired by the body will be

$$Q = ne$$

(iii) If a physical quantity does not vary continuously rather it can have only discrete value, then such physical quantity is said to be quantized. Therefore charge is quantized.

(iv) During the process of charging, mass of body changes.

Can a body have charge of 7 Coulomb?

Since, $Q = ne$

therefore, $7 = n \times 1.6 \times 10^{-19}$ C

or $$n = \frac{7}{1.6\times10^{-19}} = \frac{70}{16\times10^{-19}} = \frac{70}{16}\times10^{19}$$

$n = 4.375 \times 10^{19} = 4375 \times 10^{16}$

$n = 4.375 \times 10^{19} = 4375 \times 10^{16}$

Yes, a body can have charge of 7 C.

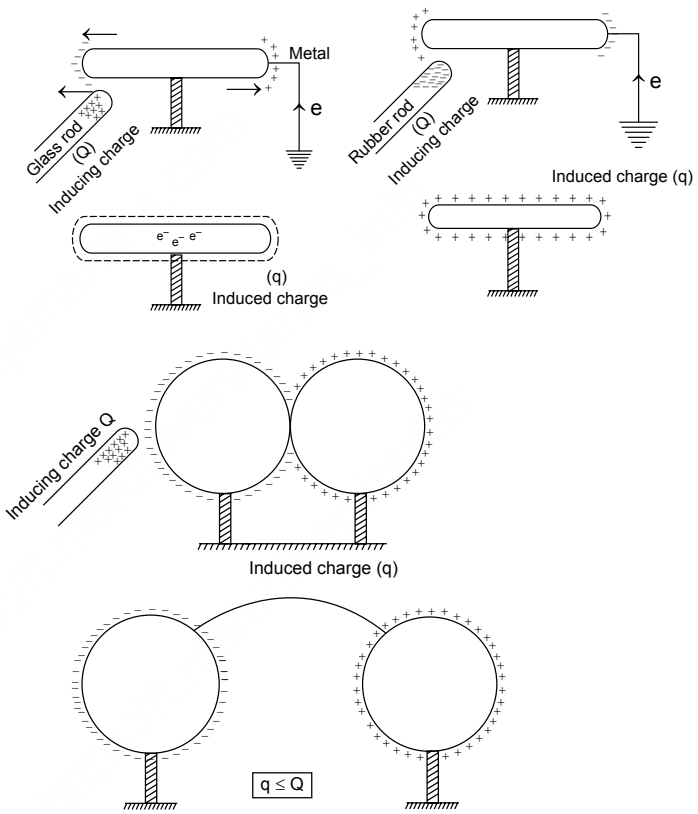
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CONCEPT

(v) Total charge of an isolated system is conserved. Charge can be created or destroyed but net charge cannot be changed.
(vi) Charge is an invariant with speed of charged body while mass and length are variant with speed.
(vii) If a particle is massless, then it will be chargeless too. But if it is chargeless then it can have mass.

Method of Charging:
A body can be charged via

(i) Rubbing
(ii) Conduction
(iii) Induction



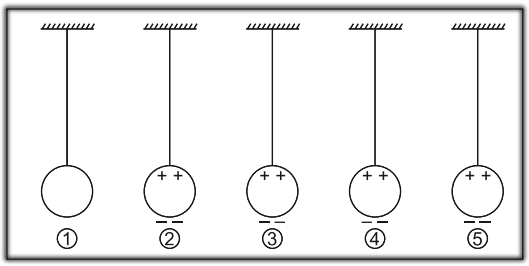
CONCEPT

(i) After induction, attraction takes place.
(ii) Therefore, attraction is not a sure test of electrification.
(iii) The sure test of electrification is repulsion.
(iv) If a charged body and uncharge body are connected through a wire, then charge flows from charged body to the neutral body till the potential becomes same.
(v) The amount of induced charge is always less than or equal to the amount of inducing charge.

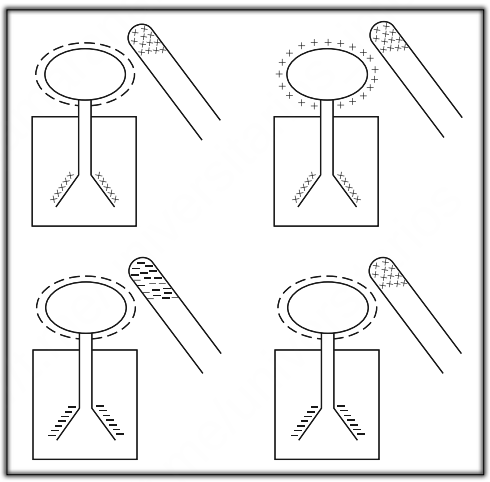
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Example

Five balls, numbered one to five are suspended as shown. Pairs (1,2), (2,4) (4,1) show electrostatic attraction, while pairs (2,3) and (4,5) show repulsion. Therefore, ball 1 must be neutral.



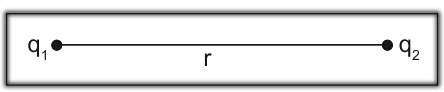
Testing of Charge of Gold Leaf Electroscope



1.2 COULOMB'S LAW

According to Coulomb, the force that operates between two point charges is directly proportional to

(i) the product of the magnitude of two charges, and
(ii) inverly proportional to square of distance between them.



Let q_1 and q_2 are the two point charges separated by distance r.
According to Coulomb,
If r be kept constant, then $F \propto q_1 q_2$

$\Rightarrow \quad F \propto \frac{q_1 q_2}{r^2}$; $F = \frac{kq_1 q_2}{r^2}$ in vacuum

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Here, $k = 9\times10^{9}\,\frac{\mathrm{N}-m^2}{e^2}$

Here, q_1 and q_2 denotes magnitude of charges.

CONCEPT

(i) In C.G.S., unit of charge is **Stat-Coulomb (e.s.u).**

$1\mathrm{C} = 3 \times 10^9$ esu

In C.G.S., $k = 1$

and $\mathrm{F} = \frac{q_1 q_2}{r^2}$

(ii) Coulombian force always operates between two charges along the line joining the centres of the particles. Therefore, it is a central force.

$$\mathrm{F} = f(r)$$

(iii) Coulombian force is of a long range. It operates upto ∞ (infinity)

(iv) Coulombian force is much stronger than the gravitational force.

$$\mathrm{F} = \frac{\mathrm{G}\,m_1 m_2}{r^2} = 6.67\times10^{-11}$$

Since $\mathrm{F} = \frac{kq_1q_2}{r^2}$

k is also written as, $k = \frac{1}{4\pi \in 0}$

$$\varepsilon_0 = \frac{1}{4\pi k} = 8.85\times10^{-12}\,\frac{\mathrm{C}^2}{\mathrm{N}-m^2}$$

$$= 8.85 \times 10^{-12}\ \mathrm{F/m}$$

Here, ε_0 is known as **Absolute permitivity of vacuum.**

$$\mathrm{F}_{\mathrm{Vacuum}} = \frac{1}{4\pi\varepsilon_0}\,\frac{q_1q_2}{r^2}$$

For a medium,

$$\mathrm{F}_{\mathrm{medium}} = \frac{1}{4\pi\varepsilon}\,\frac{q_1q_2}{r^2}$$

Here, ε is known as **Absolute permitivity of medium.**

$$\frac{\mathrm{F}_{vacuum}}{\mathrm{F}_{medium}} = \frac{\frac{1}{4\pi\varepsilon_0}\,\frac{q_1q_2}{r^2}}{\frac{1}{4\pi\varepsilon}\,\frac{q_1q_2}{r_2}} = \frac{\varepsilon}{\varepsilon_0} \quad \therefore \quad \varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

or $\varepsilon = \varepsilon_0\varepsilon_r$

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Here, $\varepsilon_r = \frac{F_{vacuum}}{F_{medium}} =$ Relative permitivity,

or Dielectric Constant of medium.

Relative permitivity is the ratio of force between two charges in vacuum to the force between same two charges at same distance in medium.

$$F_{medium} = \frac{1}{4\pi\varepsilon_0\varepsilon_r}\frac{q_1q_2}{r^2}$$

ε_r has no unit and ε_r different for different medium

For Water, $\varepsilon_r = 80$

For Air, $\varepsilon_r \approx 1.0001$ (approximately).

For Metals $\varepsilon_r = \infty$ (infinity).

CONCEPT

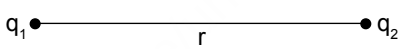
ε_r is greater than 1 for all medium except for plasma.

For plasma ε_r is less than 1

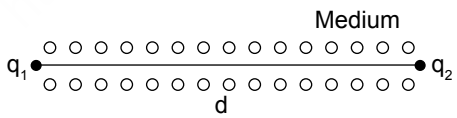
Coulombs Law in Isotropic Media

$$F = \frac{1}{4\pi\varepsilon_0\varepsilon_r}\frac{q_1q_2}{r^2}$$

Coulombs Law in an Isotropic Media



$$F_{vacuum} = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2}$$



$$F_{medium} = \frac{1}{4\pi\varepsilon_0\varepsilon_r}\frac{q_1q_2}{d^2}$$

Since $F_{vacuum} = F_{medium.}$

$$\therefore \quad \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2} = \frac{1}{4\pi\varepsilon_0\varepsilon_r}\frac{q_1q_2}{d^2}$$

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or $\frac{1}{r^2} = \frac{1}{d^2 \varepsilon_r}$

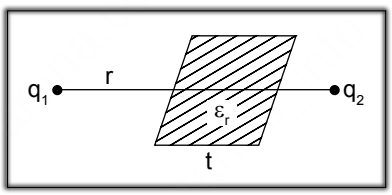
or $d^2 \varepsilon_r = r^2$

or $d = \frac{r}{\sqrt{\varepsilon_r}}$

$\therefore \quad r = d\sqrt{\varepsilon_r}$

where, d distance of a medium is equivalent to r distance of air.

Example

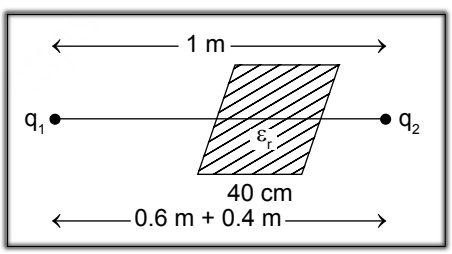


t distance of medium $= t\sqrt{\varepsilon_r}$ distance in air.

$$F = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{[(r-t) + t\sqrt{\varepsilon_r}]^2}$$

Example

Initially, two charges are separated by a distance of 1m. When a dielectric slab of thickness 40 cm is introduced between them, then force becomes half of its previous value. Find dielectric constant of medium.



☞ **Solution** $F_{vacuum} = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{(1)^2}$

$$F_{medium} = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{(0.6 + 0.4\sqrt{\varepsilon_r})^2}$$

But $F_m = \frac{F_v}{2}$.

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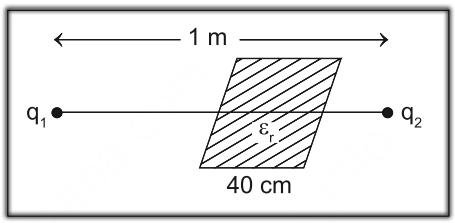
$$\therefore \quad \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{(0.6+0.4\sqrt{\varepsilon_r})^2}=\frac{q_1q_2}{4\pi\varepsilon_0(1)^2}\times\frac{1}{2}$$

or $(0.6+0.4\sqrt{\varepsilon_r})^2=2$

or $0.4\sqrt{\varepsilon_r}=1.4-0.6=0.8$

or $\sqrt{\varepsilon_r}=\frac{0.8}{0.4}=2$

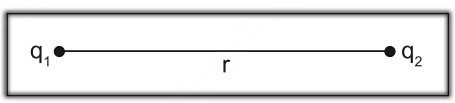
$\therefore \quad \varepsilon_r = \mathbf{4}$



Example

Two charges are separated by a distance of 1m. Find minimum force between the two charges.

☞ **Solution** $F=\frac{kq_1q_2}{r^2}$



Since, minimum possible charge is electronic charge.

$$F^{min}=\frac{kq_1^{\ min}\times q_2^{\ min.}}{r^2}$$

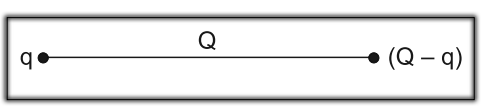
$$=\frac{9\times10^9\times(1.6\times10^{-19})^2}{1}$$

$$=9\times2.56\times10^{-29}\ \text{N.}$$

Example

How should a point charge *Q* be divided into two parts, so that force between them becomes maximum for a given separation?

☞ **Solution** Let the two parts be q and (Q – *q*)



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$$F = \frac{kq(Q-q)}{r^2} = \frac{k}{r^2}(Qq - q^2)$$

For F to be max^m. $\frac{dF}{dq} = 0$

or $\frac{k}{r^2}(Q - 2q) = 0$

or $Q - 2q = 0$

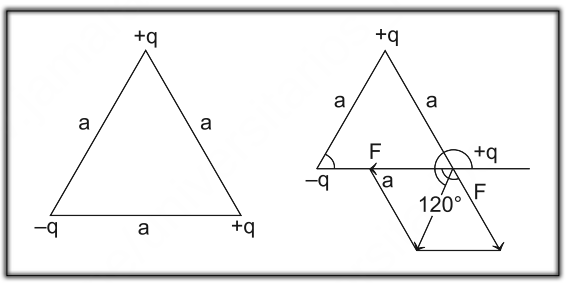
or $Q = 2q$

or $q = \frac{Q}{2}$

Hence, for force to be maximum, charge should be divided into two equal parts.

Example

In the figure shown, find force experienced by the charge at lower right corner.



☞ **Solution** Here, $F = \frac{kq^2}{a^2}$

Resultant force $= \sqrt{F^2 + F^2 + 2FF\cos 120°}$

$= \sqrt{2F^2 + 2F^2(-1/2)} = F$

$= \frac{kq^2}{a^2}$ at an angle 240° anti-clockwise direction.

Example

Find the force experienced by the charge $2q$, shown in the figure.

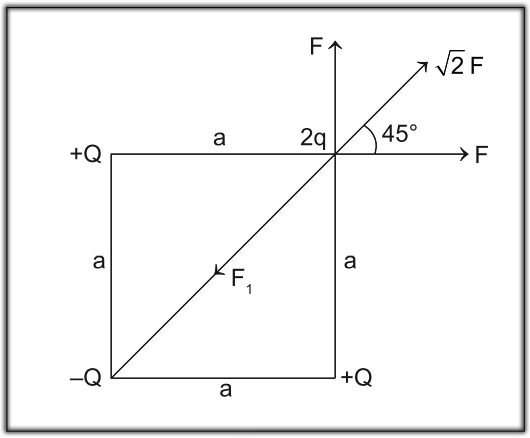
☞ **Solution** $F = \frac{k \times Q \times 2q}{a^2} = \frac{2kqQ}{a^2}$

$F_1 = \frac{k \times 2q \times Q}{2a^2} = \frac{kqQ}{a^2}$

Net Force $= \sqrt{2}\ F - F_1 = \sqrt{2} \times \frac{2kqQ}{a^2} - \frac{kqQ}{a^2}$

$F = \frac{kQq}{a^2}(2\sqrt{2} - 1)$

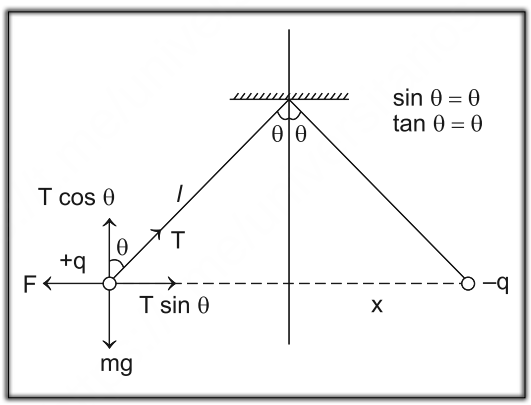
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Example

Two similar balls of mass m are hung from silk thread of length *l* and carry similar charge *q* as shown in the figure. Assuming θ to be very small, prove that

$$x = \left(\frac{q^2 l}{2\pi\varepsilon_0 mg} \right)^{1/3}$$



☞ **Solution** Here, T cos θ = *mg*

and T sin θ = F

$$\therefore \quad \tan\theta = \frac{F}{mg}$$

or $F = mg \tan\theta$

or $$\frac{1}{4\pi\varepsilon_0}\frac{q^2}{x^2} = mg \times \frac{x}{2l}$$

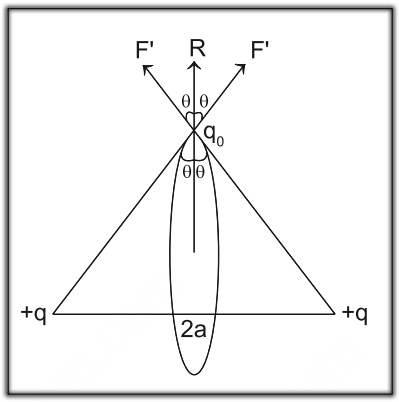
[∵ sin θ = tan θ, θ being very small.]

or $$x^3 = \frac{q^2 l}{2\pi\varepsilon_0 mg}$$

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Example

A test charge q_0 is kept on the perpendicular bisector of a line joining the two charges separated by a distance 2a. Find radius of symmetry r for which force (F) on the test charge will be maximum.



Net force, F = 2 F' cos θ

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

$$F = \frac{1}{2\pi\varepsilon_0} q^2 r \, (r^2 + a^2)^{-3/2}$$

For F to be maximum,

$$\frac{dF}{dr} = \frac{q^2}{2\pi\varepsilon_0}$$

$$\left[r \times \left(\frac{-3}{2} \right) \left(r^2 + a^2 \right)^{\frac{-5}{2}} \times 2r + (r^2 + a^2)^{\frac{-3}{2}} \right] = 0$$

or $(r^2 + a^2)^{-3/2} [-3r^2(r^2 + a^2)^{-1} + 1] = 0$

or $$\left(\frac{-3r^2}{r^2 + a^2} + 1 \right) = 0$$

or $$\left(\frac{-3r^2 + r^2 + a^2}{r^2 + a^2} \right) = 0$$

or $$\frac{a^2 - 2r^2}{r^2 + a^2} = 0$$

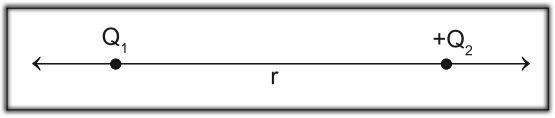
or $a^2 - 2r^2 = 0$

$\therefore$ $$r = \frac{a}{\sqrt{2}}$$

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1.3 ELECTRIC FIELD AND ELECTRIC INTENSITY

Electric Field and Electric Intensity

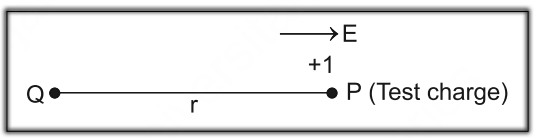


According to the modern concept, the force between two charges is not a single step process, but it is two step process:

(i) First of all, a charge creates a field around it and when another charge comes into contact with this field, it then experiences force.
(ii) Also, field due to a charge propagates (travel) with speed of light.

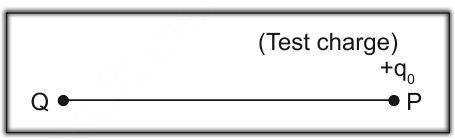
Electric Intensity

To study the behaviour of electric field we introduce a parameter, which is known as electric intensity. It is defined as the force experienced by unit test charge at required point.



$$F = \frac{1}{4\pi\varepsilon_0}\frac{Q\times 1}{r^2} = \frac{Q}{4\pi\varepsilon_0 r^2} \quad E_P = \frac{Q}{4\pi\varepsilon_0 r^2}$$

Note:

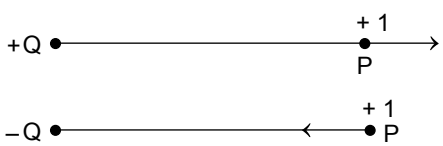


$$F = \frac{kQq_0}{r^2} \qquad \therefore \quad E = \frac{F}{q_0} = \frac{kQ}{r^2}$$

CONCEPT

(i) If Q charge lies in electric field E, then it experiences force.

$$F = qE$$



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(ii) Positive charge experiences force in direction of electric field while negative charge experiences force opposite to the field.

(iii) In vector notation,

$$\vec{F} = q\vec{E}$$

where, sign of charge should be taken.



$$E_2 = \frac{kQ_2}{r^2} \qquad E_1 = \frac{kQ_1}{r^2}$$

F_{12} = Force on 1 due to 2

F_{21} = Force on 2 due to 1

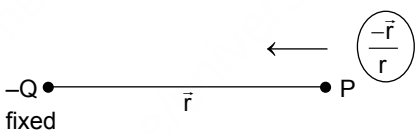
E_2 Q_1 E_1 Q_2

$$F_{12} = \frac{kQ_1Q_2}{r^2} \quad F_{21} = \frac{kQ_1Q_2}{r^2}$$

$E = 0$

(iv) Field due to a monopole (single pole) charge is spread upto ∞.

(v) If there are several charges, then electric intensity at a point will be sum of indivisible intensity.



$$E = \frac{kQ}{r^2}$$

(i) $\vec{E} = \frac{-kQ}{r^3}\ \hat{r}$

(ii) $\hat{E} = \frac{-kQ}{r^3}\hat{r}\ \vec{E} = \frac{kQ}{r^2}\left(-\frac{\vec{r}}{r}\right) = -\frac{kQ}{r^3}\vec{r}$

(iii) $\vec{E} = \frac{-kQ}{r^3}\vec{r}$

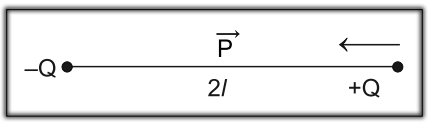
Electric Field due to Dipole

When two equal and opposite charges are separated by a very small distance then the system is known as **dipole** and the line joining the two charges is known as dipole axis.

Dipole moment (p) = Q × 2*l*

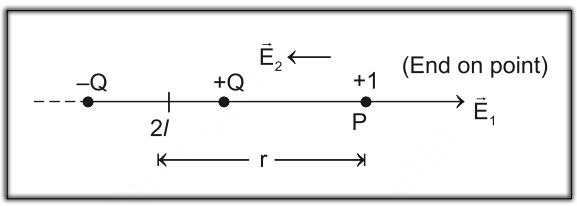
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Dipole moment is defined as product of magnitude of a charge and separation between the two charges.



It is vector quantity and is directed from (–ve) negative to (+ve) positive charge.

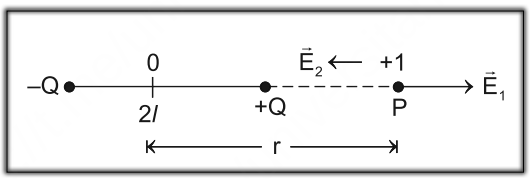
Electric Intensity on the Axis of Dipole



We have to find electric intensity at point P at a distance r from the centre of dipole.

$$\vec{E} = \vec{E}_1 + \vec{E}_2$$

$$E = E_1 - E_2$$



$$E_1 = \frac{kQ}{(r-l)^2}$$

$$\vec{E}_1 = \frac{kQ}{(r+l)^2}\,\hat{n}$$

$$\vec{E}_2 = \frac{kQ}{(r+l)^2}\,(-\hat{n})$$

Net electric intensity, $\vec{E} = \vec{E}_1 + \vec{E}_2$

$$= \frac{kQ}{(r-l)^2}\,\hat{n} + \frac{kQ}{(r+l)^2}\,(-\hat{n})$$

$$= kQ\hat{n}\left[\frac{1}{(r-l)^2} - \frac{1}{(r+l)^2}\right]$$

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$$= kQ\hat{n}\left[\frac{(r+l)^2-(r-l)^2}{(r-l)^2(r+l)^2}\right]$$

$$= kQ\hat{n}\left[\frac{2\times r\times 2l}{(r^2-l^2)^2}\right]$$

or $\vec{E} = kQ\hat{n}\dfrac{4rl}{(r-l^2)^2}$

If $r >> l$, then

$$\vec{E} = \frac{kQ\hat{n}\times 4l}{r^3} = \frac{2k(Q\times 2l)\hat{n}}{r^3}$$

$$\vec{E} = \frac{2k(p\hat{n})}{r^3}$$

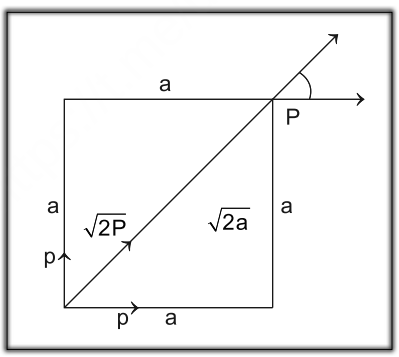
or $\vec{E} = \dfrac{2k\vec{p}}{r^3}$

$\therefore \quad \vec{p} = p\hat{n}$

On the axis of dipole, electric intensity at each point is in direction of dipole moment.

Example

In the figure shown, two dipoles each of dipole moment p are kept at square of side a as shown in the figure. Find resultant intensity at point *P*.



☞ **Solution** $E_P = \dfrac{2kp\sqrt{2}}{(\sqrt{2}a)^3}$

$$= \frac{2kp\sqrt{2}}{2\sqrt{2}\,a^3} = \frac{kp}{a^3}$$ at an angle 45º from the +ve –axis

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Example

For what value of θ electric intensity E will be perpendicular to dipole axis?

☞ **Solution** Here,

$$90 = \theta + \alpha$$

$$\therefore \quad \alpha = (90 - \theta)$$

or $\tan \alpha = \tan (90 - \theta)$

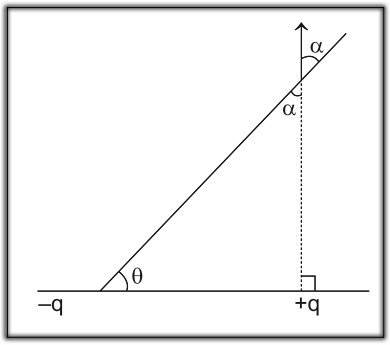
$$= \cot \theta$$

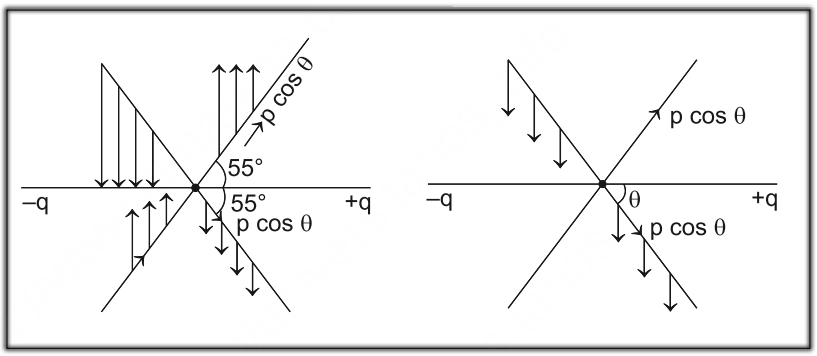
$$\therefore \quad \frac{1}{2}\tan\theta = \frac{1}{\tan\theta}$$

or $\tan^2 \theta = 2$

or $\tan\theta = \pm\sqrt{2}$

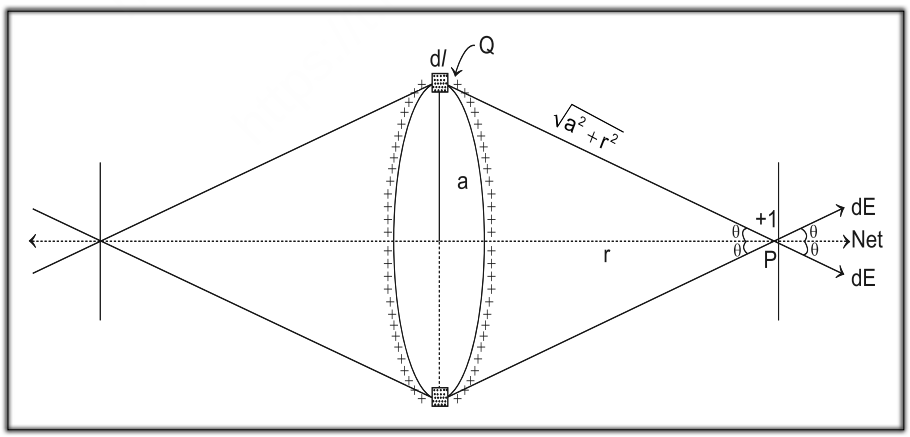
$$\therefore \quad \theta = \pm 55^\circ$$





Electric Intensity due to Continuous Charge Distribution

Uniformally charge per unit length same.



Here, Q = charge on ring.

a = radius of ring.

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Charge per unit length $(\lambda) = \dfrac{Q}{2\pi a}$

Charge on element = $dq = \lambda dl$

Electric intensity at point P due to small element

$$dE = \frac{kdq}{(a^2 + r^2)}$$

$$= \text{Net electric intensity} = \int dE\cos\theta$$

Integrating,

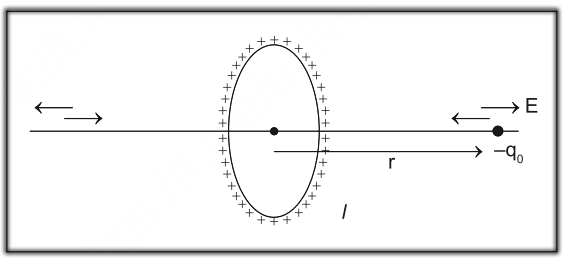
$$E = \int \frac{k\lambda dl}{a^2 + r^2}\frac{r}{\sqrt{a^2 + r^2}}$$

$$= \frac{k\lambda r}{(a^2 + r^2)^{3/2}}\int dl$$

$$= \frac{k\lambda r}{(a^2 + r^2)^{3/2}} \times 2\pi a$$

$$\therefore \quad E = \frac{kQr}{(a^2 + r^2)^{3/2}}$$

In case of positively charged ring, electric intensity on both sides of ring will be away from the centre of the ring and along the axis. While in case of negatively charged ring, electric intensity is towards the centre of the ring.



Note: Since, electric field at the centre of the ring is zero, therefore, there will be no force on the charge kept at the centre of ring.

If $r >> a$, then

$$E = \frac{kQr}{(a^2 + r^2)^{3/2}} = \frac{kQr}{r^3}$$

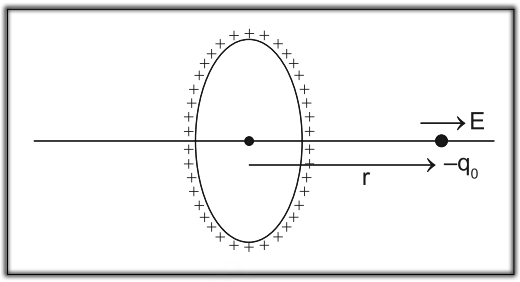
or $$E = \frac{kQ}{r^2}$$

For large distance ring behaves like a point charge.

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Example

A negative charge – q_0 is kept at very small distance from the centre of the ring. If radius of ring is a and total charge on the ring is Q, prove that motion of the charge will be simple harmonic. Mass = m



☞ **Solution** Force on negative charge

$$F = q_0 E$$

$$= \frac{q_0 kQr}{(a^2 + r^2)^{3/2}}$$

$$\text{Acceleration} = -\frac{kq_0 Qr}{m(a^2 + r^2)^{3/2}}$$

If $r << a$, then

$$\text{Acceleration} = -\left(\frac{kQq_0}{ma^3}\right) r$$

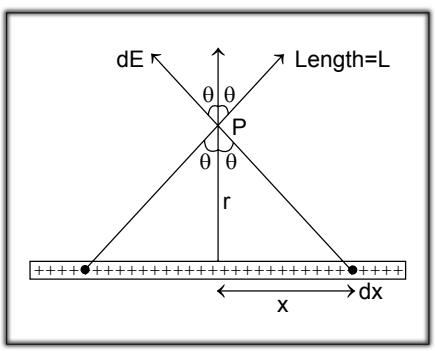
Acceleration, $a = \alpha\ \alpha\ r$

Hence, motion is simple harmonic.

Electric intensity at perpendicular bisector of uniformally charged rod of finite length

Let, λ = charge per unit length on the rod

Then, charge on element = $\lambda\ dx$



$$\text{Net intensity} = \int dE \cos\theta$$

$$= \int \frac{k\lambda dx}{(r^2 + x^2)} \cos\theta$$

From figure, $\tan\theta = \frac{x}{r}$

or $x = r \tan\theta$

Differentiating, $dx = r \sec^2\theta\ d\theta$

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$$\therefore \quad \text{Net intensity} = \int \frac{k\lambda}{r^2 \sec^2\theta} \times r \sec^2\theta \, d\theta \times \cos\theta$$

$$= \frac{k\lambda}{r} \int_{-\theta_2}^{\theta_1} \cos\theta \, d\theta$$

$$E = \frac{k\lambda}{r} \left[\sin\theta\right]_{-\theta_2}^{\theta_1}$$

or $$E = \frac{k\lambda}{r}$$

Finite rod. If both the ends tend to infinite,

then $\theta_1 = \theta_2 = \frac{\pi}{2}$ and $E = \frac{2k\lambda}{r}$

Example

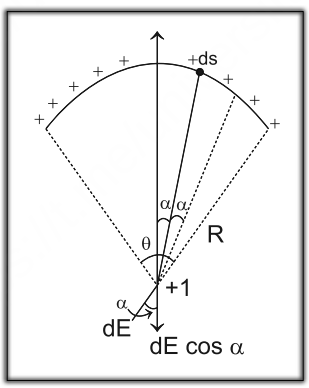
Find electric intensity at the centre of a charged circular sector (portion) making an angle θ at centre of the ring.

☞ **Solution** λ = charge per unit length.

Charge on element *ds*,

$$\lambda ds = \lambda R d\alpha$$

Electric intensity, $dE = \frac{k\lambda d\alpha}{R^2} dE \sin\alpha = \left(\frac{k\lambda d\alpha}{R}\right)$



Net intensity at the centre

$$E_y = \int dE \cos\alpha$$

$$= \int \frac{k\lambda}{R_{\theta/2}} d\alpha \cos\alpha$$

$$= \int \frac{k\lambda d\alpha}{R} \cos\alpha$$

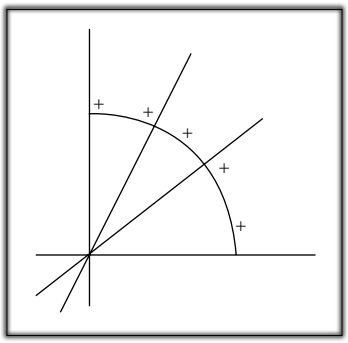
$$= \frac{k\lambda}{R} \int_{-\theta/2}^{\theta/2} \cos\alpha \, d\alpha = \frac{k\lambda}{R} \left[\sin\alpha\right]_{-\theta/2}^{\theta/2}$$

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$$= \frac{d\lambda}{R}\left[\sin\frac{\theta}{2} - \sin\left(\frac{-\theta}{2}\right)\right]$$

$$= \frac{k\lambda}{R}\left[2\sin\frac{\theta}{2}\right]$$

$$E_y = \left[\frac{2k\lambda}{R}\sin\frac{\theta}{2}\right]$$



*In case of semi-ring

$$\theta = \pi$$

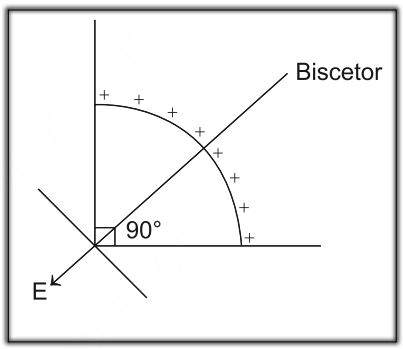
$$E_y = \frac{2k\lambda}{R}$$

*In case of ring in the form of a quadrant.

$$E = \frac{2k\lambda}{R}\sin\frac{\theta}{2}$$

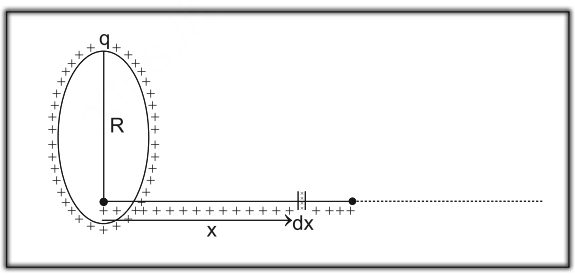
$$= \frac{2k\lambda}{R}\sin 45°$$

$$E = \frac{\sqrt{2}k\lambda}{R}$$



Example

A charge *q* is distributed uniformally on a circular ring of radius *R*. A rod having charge per unit length λ is kept along the axis of ring with its one end at the centre of ring. Find interaction force between rod and the ring.



☞ **Solution** Charge on element = λdx

force on element = $(\lambda dx)\, dE$

$$= \frac{\lambda dx k q x}{(x^2 + R^2)^{3/2}}$$

Net force on rod $= kq\lambda \int \frac{x dx}{(x^2 + R^2)^{3/2}}$

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$$F = kq\lambda \int_0^\infty \frac{x\,dx}{(x^2 + R^2)^{3/2}}$$

$$= \frac{kq\lambda}{2} \int_0^\infty 2x(x^2 + R^2)^{-3/2}\,dx$$

$$F = \frac{kq\lambda}{2}\left[\frac{(x^2 + R^2)^{-1/2}}{(-1/2)}\right]_0^\infty$$

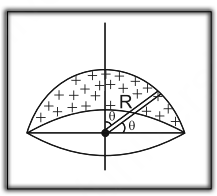
$$= \frac{kq\lambda}{2}\left[\frac{-2}{\sqrt{x^2 + R^2}}\right]_0^\infty$$

$\therefore \quad F = \frac{kq\lambda}{2} \times \frac{2}{R}$

or $\quad F = \frac{kq\lambda}{R}$

Example

Find electric intensity at the centre of a heavy sphere having charge per unit area, σ.



☞ **Solution** Charge on ring

$= \sigma \times 2\pi r \times R d\theta$

$= 2\pi R\sigma \times R \sin\theta\, d\theta$

$= 2\pi R^2 \sigma \sin\theta\, d\theta$

Electric intensity due to ring

$$E = \frac{k \times 2\pi R^2 \sigma \sin\theta d\theta \times R\cos\theta}{(R^2 \sin^2\theta + R^2\cos^2\theta)^{3/2}}$$

$$= \frac{k^2 \pi R^2 \sigma \sin\theta d\theta \times R\cos\theta}{R^3}$$

$= \pi k\, \sigma \sin 2\theta\, d\theta$

Net intensity $= k\pi\sigma \int_0^{\pi/2} \sin 2\theta d\theta$

$$= k\pi\sigma\left[\frac{-\cos 2\theta}{2}\right]_0^{\pi/2}$$

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$$= k\pi\sigma\left[-\cos\frac{\pi}{2}+\cos\theta\right]$$

$$= k\,\pi\,\sigma$$

$$= \frac{1}{4\pi\varepsilon_0}\times\pi\sigma$$

$\therefore$ Net intensity $= \dfrac{\sigma}{4\in_0}$

Electric Field Intensity on the Axis of Disc

Charge per unit area = σ

Radius of disc = R

Charge on ring = $(2\pi\, xdx)\,\sigma$

Electric intensity due to ring

$$= \frac{k\,(2p\;x\;dx\sigma)r}{(x^2+r^2)^{3/2}}$$

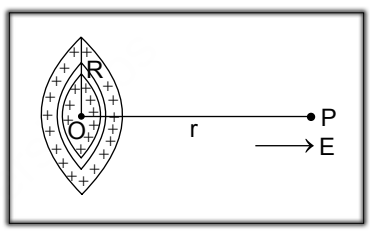
Electric intensity due to disc

$$= \pi k\sigma r\int 2x(x^2+r^2)^{-3/2}\,dx$$

$$= \pi k\sigma r\left[\frac{-2}{\sqrt{x^2+r^2}}\right]_0^R$$

$$= \pi k\sigma r\left[\frac{-2}{\sqrt{R^2+r^2}}+\frac{2}{r}\right]$$

$$= 2\pi k\sigma\left[1-\frac{r}{\sqrt{R^2+r^2}}\right]$$



$\therefore$ $\mathrm{E} = \dfrac{\sigma}{2\varepsilon_0}\left[1-\dfrac{r}{\sqrt{R^2+r^2}}\right]$

If R tends to infinity then disc will become a sheet intensity due to infinite sheet

$$= \frac{\sigma}{2\varepsilon_0}$$

$$\mathrm{E} = \frac{\sigma}{2\varepsilon_0}$$

Field set up by infinite sheet is uniform.

Torque due to Electric Diploe

$$\tau = p\ \mathrm{E}\sin\theta$$

and $\mathrm{I}\,\alpha = p\mathrm{E}\sin\theta$

$\therefore$ $\alpha = \dfrac{p\mathrm{E}\sin\theta}{\mathrm{I}}$

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Since, θ is very small, therefore

$$\alpha = \frac{pE}{I}\theta$$

Also, α is opposite to θ.

$$\therefore \quad \alpha = \frac{-pE}{I}\theta$$

$$\alpha \propto -\theta$$

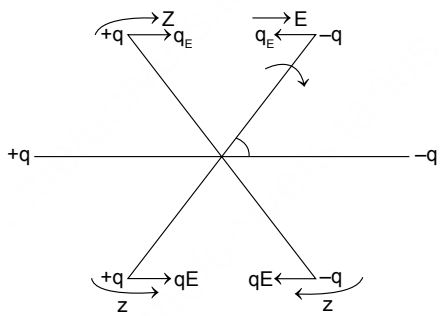
Hence, motion is angular simple harmonic

$$\omega^2 = \frac{pE}{I}$$

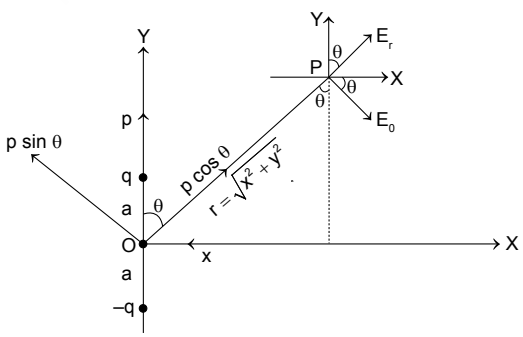
$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{I}{pE}}$$

CONCEPT

θ = 180° position of dipole is the case of unstable rotational equilibrium.



Example



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Prove that E_x at point P $E_x = \dfrac{3pxy}{4\pi\varepsilon_0\left(x^2+y^2\right)^{5/2}}$

Where, p = dipole moment

☞ **Solution**

$$E_r = \frac{2kp\cos\theta}{r^3};\ \text{and}\ E_\theta = \frac{kp\sin\theta}{r^3}$$

$$\therefore \quad E_x = E_q\cos q + E_r\sin q$$

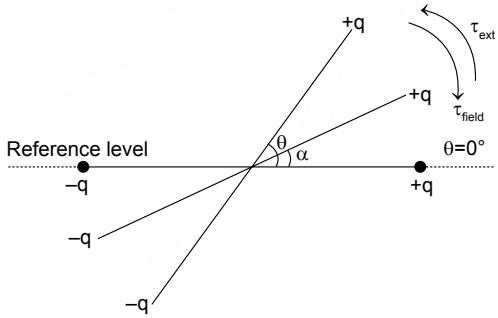
$$= \frac{kp\sin\theta}{r^3}\cos q + \frac{2kp\cos\theta.\sin\theta}{r^3}$$

$$= \frac{kp}{r^3}\left[\frac{x}{r}\times\frac{y}{r}+\frac{2y}{r}\times\frac{x}{r}\right]$$

$$= \frac{3kpxy}{r^5} = \frac{k3kpy}{\left(x^2+y^2\right)^{5/2}}$$

Potential Energy of dipole in uniform the electric field

Case (i) When θ = 0º is taken as reference level.



Let at any instant, dipole is at an angle α.

Torque on dipole due to external agent

$$\tau_{Ext} = pE\sin\alpha\ \text{(anti-clockwise)}$$

Work done by external agent during small rotation $d\alpha$,

$$dW = \vec{\tau}\cdot d\vec{\theta}$$

$$= \tau\, d\,\theta$$

$$= p\,E\sin\alpha\, d\,\alpha$$

$$\therefore \quad W_{Total} = pE\int_0^{\theta}\sin\alpha\, d\alpha$$

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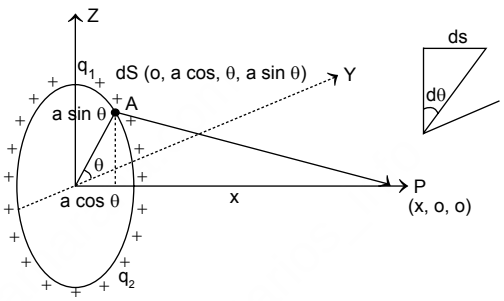
$$\text{P.E. } (U) = pE[-\cos\alpha]_0^{\theta}$$

$$= pE[-\cos\theta + \cos 0]$$

$$U = pE[1 - \cos\theta]$$

U is maximum at unstable ($\theta = 180^\circ$) rotational equilibrium and is minimum for stable equilibrium ($\theta = 0$).

Example



The charges q_1 and q_2 are spread on the first half and the second half of a non-conducting ring. Find components of electric intensity at point p along x-axis, y-axis and z-axis respectively.

$$\vec{AP} = (x-0)\,\hat{i} + (0 - a\cos\theta)\,\hat{j} + (0 - a\sin\theta)\,\hat{k}$$

$$x\hat{i} - a\cos\theta\,\hat{j} - a\sin\theta\,\hat{k}$$

$$\therefore \quad \hat{AP} = \frac{\vec{AP}}{|AP|} = \frac{x\hat{i} - a\cos\theta\hat{j} - a\sin\theta\hat{k}}{\sqrt{x^2 + a^2}}$$

$$\therefore \quad \text{Charge on element} = \lambda_1\, ds = \frac{q_1}{\pi a}\, ds$$

Electric intensity due to charge element

$$dE = \frac{kq_1 ds}{\pi a(x^2 + a^2)} \quad \vec{dE} = (dE)\,\hat{AP}$$

$$= \frac{kq_1 ds}{\pi a(x^2 + a^2)} \frac{(x\hat{i} - a\cos\theta\,\hat{j} - a\sin\theta\,\hat{k})}{\sqrt{x^2 + a^2}}$$

$$dE_x = \frac{kq_1 dsx}{\pi a(x^2 + a^2)^{3/2}}$$

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$$\therefore \quad E_x = \frac{kx}{\pi a(x^2+a^2)^{3/2}} \int q_1 ds$$

$$= \frac{kx}{\pi a(x^2+a^2)^{3/2}} \left[\int q_1 ds + \int q_2 ds \right]$$

$$= (q_1+q_2)\pi a \times \frac{kx}{\pi a(x^2+a^2)^{3/2}}$$

$$= \frac{kx(q_1+q_2)}{(x^2+a^2)^{3/2}}$$

$$dE_y = \frac{-kq_1 ds\, a\cos\theta}{\pi a(x^2+a^2)^{3/2}}$$

Since, $ds = ad\theta$, there fore

$$dE_y = \frac{-kq_1 a^2 \cos\theta d\theta}{\pi a(x^2+a^2)^{3/2}}$$

$$\therefore \quad E_y = \frac{ka^2}{\pi a(x^2+a^2)^{3/2}} \int q_1 \cos\theta\, d\theta$$

$$= \frac{ka}{\pi(x^2+a^2)^{3/2}} \left[q_1 \int_0^{\pi} \cos\theta\, d\theta + q_2 \int_{\pi}^{2\pi} \cos\theta\, d\theta \right]$$

$$\therefore \quad E_y = 0$$

Again, $$dE_z = \frac{kq_1 ds\, a\sin\theta}{\pi a(x^2+a^2)^{3/2}}$$

Since, $ds = ad\theta$, therefore

$$\therefore \quad dE_z = \frac{kq_1 a^2 \sin\theta\, d\theta}{\pi a(x^2+a^2)^{3/2}}$$

Integrating,

$$E_z = \frac{ka^2}{\pi a(x^2+a^2)^{3/2}} \int q_1 \sin\theta\, d\theta$$

$$= \frac{ka}{\pi(x^2+a^2)^{3/2}} \left[q_1 \int_0^{\pi} \sin\theta\, d\theta + q_2 \int_{\pi}^{2\pi} \sin\theta\, d\theta \right]$$

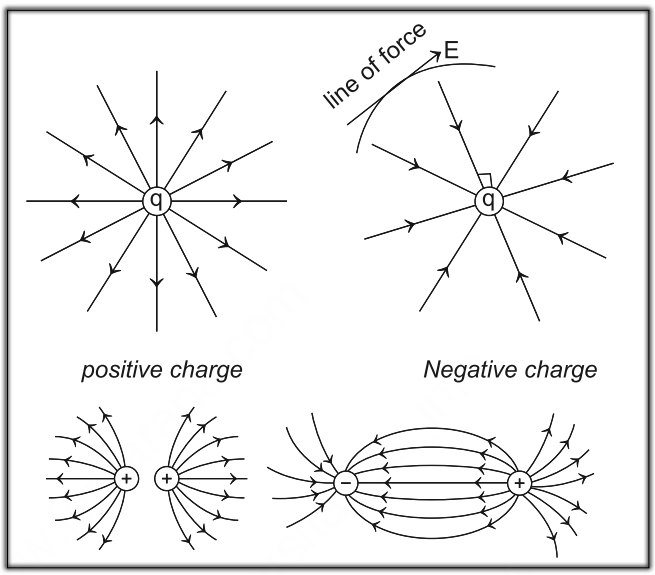
$$= \frac{ka}{\pi a(x^2+a^2)^{3/2}} \left[q_1 \left[-\cos\theta \right]_0^{\pi} + q_2 \left[-\cos\theta \right]_{\pi}^{2\pi} \right]$$

$$= \frac{ka^2}{\pi a(x^2+a^2)^{3/2}} [q_1(1+1) + q_2(-1+-1)] = \frac{2ka^2}{\pi a(x^2+a^2)^{3/2}} (q_1 - q_2)$$

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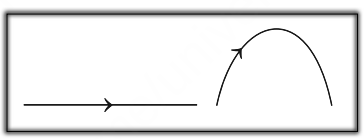
Line of Force of Geometrical Interaction

A line of force of $\vec{E}$ in a electric field is an imaginary curve, the tangent to which at end point on each represent the direction of $\vec{E}$ at that point.



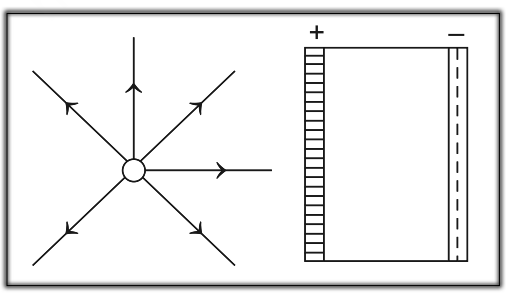
Important properties of lines of forces of $\vec{E}$

(i) Lines of force $\vec{E}$ are always in the state of **tence**



(ii) Lines of force are always originate from a positive charge and terminate of charge.

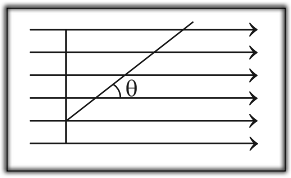
(iii) Lines of force need not be continuous.



(iv) Lines of $\vec{E}$ is drawn such that the density, that is the number of lines per unit area normal to the lines is proportional to the magnitude of $\vec{E}$

$$F = \frac{N}{ds\cos\theta}$$

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(v) Lines of force never intersect each other.

(vi) Any configuration at line of $\vec{E}$ at a static field should obey the property of rational field *i.e.,*

$$\vec{E}.dr = 0$$

$$\oint E.\ dr = 0$$

(vii) Along a line of force, the magnitude $\vec{E}$ decreases (except the case of uniform electric field).

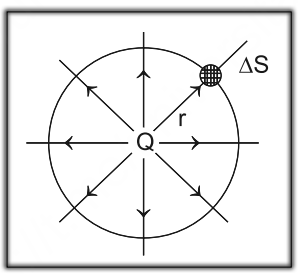
(viii) If there is no negative charge, then line of force goes up to infinity.

(ix) Number of lines of force imenates or terminates is directly proportional to the magnitude of charge.

Consider a point charge Q from each. Let N lines of force are originating and these lines of force passes through a hollow sphere of radius *r*.

$$\text{Number of lines per unit area} = \frac{N}{4\pi r^2}$$

Number of lines of force through area Δs



$$\Delta N = \frac{N}{4\pi r^2}\Delta S$$

But $N \propto Q$

$$N = C\,Q$$

$$\Delta N = \frac{CQ}{4\pi r^2}\,\Delta S$$

$$\frac{\Delta N}{\Delta S} = \frac{CQ}{4\pi r^2} \qquad ...(i)$$

But $$E = \frac{kQ}{r^2} \qquad ...(ii)$$

Dividing equation (i) by equation (ii), we

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$$\frac{\frac{\Delta N}{\Delta S}}{E} = \frac{CQ}{4\pi r^2} \times \frac{r^2}{kQ} = \frac{CQ}{r\pi}$$

$$\therefore \quad \frac{\Delta N}{\Delta S} = (\text{constant})\, E$$

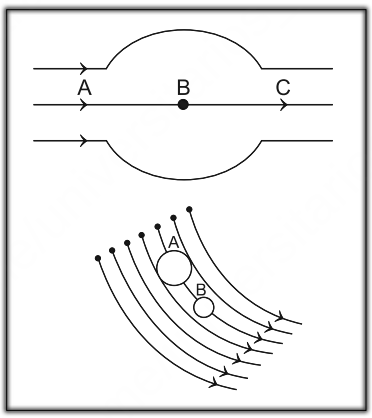
No density, $\frac{\Delta N}{\Delta S} \propto E$

If ΔS = constant, then $\Delta N \propto E$

(x) It means electric intensity is large where electric lines of force are crowded together.

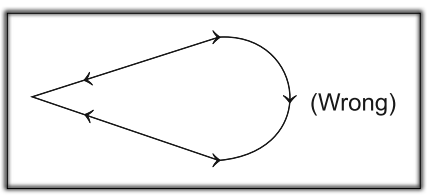
Example

Where electric density is large?



$E_C > E_A > E_B$ $\quad$ $E_A > E_B > E_C$

(xi) Electric lines of force are never closed looped because if it will be a closed loop, then work done on a charge during round trip will be zero by the field. Therefore, field will not remain conservative, but it is conservative in not ture.



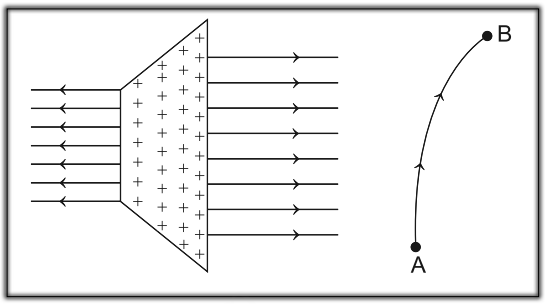
(xii) It is general misconception that electric lines of force are the path of charged particle followed in electric field.

If electric lines of force is a curve then a charged particle cannot follow this path because there will be no centripetal force. The only force will be in tangential direction.

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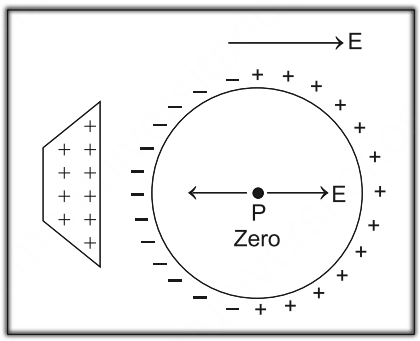
Example

If a (positive) charge is released at point A whether it will reach at point B?
Ans: No.

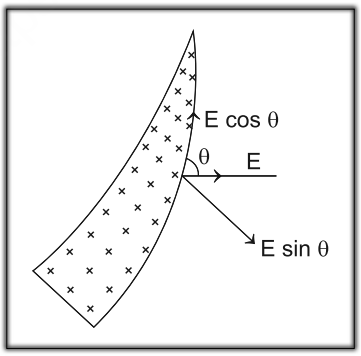


(xiii) When a conductor is kept in external field, then due to redistribution of charge electric intensity inside the conductor becomes zero.

As there is no flow of current in electrostatic condition. Hence, electric lines of force never enter inside the metallic conductor.



(xiv) Electric lines of force always Emenate or terminates on a surface of conductor normally.



Suppose a line of force emenates from surface of a positively charged conductor at an angle θ as shown, then due to the component E cos θ, charge will flow along the surface of conductor and hence current will flow but electrostatic condition current does not flow.

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Hence E cos θ must vary

$E \cos \theta = 0$

$\cos \theta = 0$

$\theta = \frac{\pi}{2}$

(xv) Electric Lines of force cannot be a continuous curve.

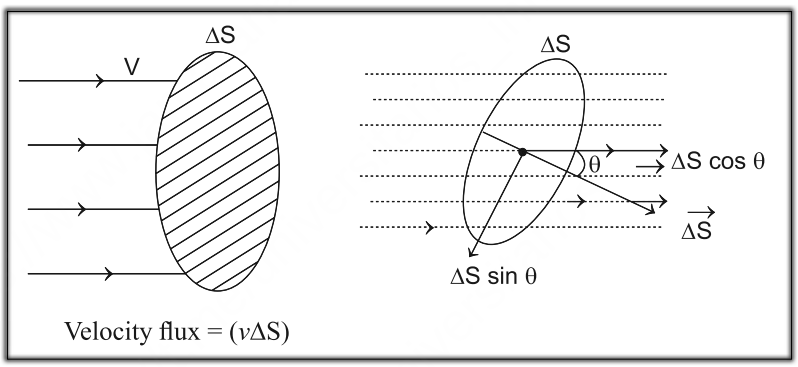
1.4 ELECTRIC FLUX

Flux: The general meaning of flux is flow.

Velocity flux: The amount of liquid flown through a given area in 1 second is known as velocity flux.

Let a liquid is flowing with velocity *v* is through on area Δs.

In 1 sec, liquid up to length *v* will cross the given area Amount of liquid flown = *v*ΔS



Here, B = angel between $\vec{\Delta S}$ and $\vec{v}$

area = *v*S cos θ

Amount of liquid flown = $v\ \Delta S \cos \theta$

Velocity flux = $v\Delta S \cos \theta$

$= \vec{v}\,\vec{\Delta S}$

CONCEPT

Area vector is that vector whose magnitude is equal to area of the body and its direction is perpendicular to the surface.

In case of closed body, area vector is always taken perpendicular to the surface and always in outward direction.

The dot product of any vector with area vector is known as flux of that vector. Therefore,

$$\text{Electric Flux } (\phi_E) = \vec{E} \cdot \vec{\Delta S} = E\,\Delta S \cos\theta$$

Flux is always defined for a vector quantity.

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The physical meaning of electric flux is the number of lines of force passing through a given area.

Example

A ring of radius *R* is kept at the perpendicular bisector of a dipole as shown in the figure. Find electric flux due to the dipole through the ring.

Consider a ring of radius x and width dx.

Electric flux through the ring.

$$d\phi = 2\,E\cos\theta \times 2\pi x\,dx$$

$$= 2\times\frac{kq}{l^2+x^2}\times\frac{l}{\sqrt{l^2+x^2}}\times 2\pi x\,dx$$

$$= 4kql\pi\frac{xdx}{\left(l^2+x^2\right)^{\frac{3}{2}}}$$

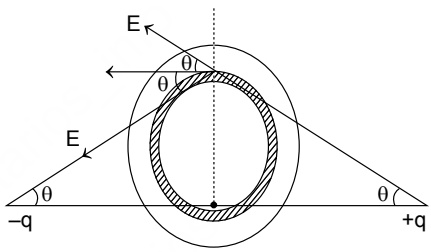
$$\therefore \quad \phi = \frac{ql}{2\varepsilon_0}\int_0^R \frac{2\pi dx}{\left(l^2+x^2\right)^{\frac{3}{2}}}$$

$$= \frac{ql}{2\varepsilon_0}\int_0^R \left(l^2+x^2\right)^{-3/2}\times 2x\,dx$$

$$= \frac{ql}{2\varepsilon_0}\left[-2\left(l^2+x^2\right)^{-1/2}\right]_0^R$$

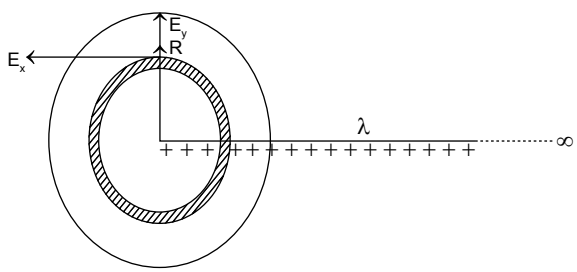
$$\phi = \frac{ql}{2\varepsilon_0}\left[-\frac{2}{\sqrt{l^2+x^2}}+\frac{2}{l}\right]$$

$$\phi = \frac{q}{\varepsilon_0}\left[1-\frac{l}{\sqrt{l^2+R^2}}\right]$$



Example

A semi infinite rod lies along the axis of a ring with its one end coincinding with the centre of the ring. Find electric flux through the ring if charge per unit length on the rod is λ.



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Here, $E_x = E_y = \frac{k\lambda}{x}$

Flux due to the rod through the ring

$$d\phi = \vec{E}.\vec{dS}$$

$$= E_x \times 2\pi x\, dx \cos 0°$$

$$= \frac{k\lambda}{x} \times 2\pi x\, dx$$

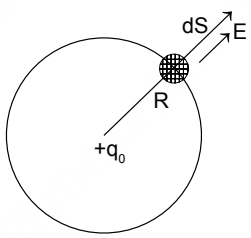
$$= \frac{1}{4\pi\varepsilon_0} \times \lambda \times 2\pi dx = \frac{\lambda}{2\varepsilon_0} dx$$

$\therefore$ Total flux, $\phi = \frac{\lambda}{2\varepsilon_0}\int_0^R dx = \frac{\lambda}{2\varepsilon_0}[x]_0^R = \frac{\lambda}{2\varepsilon_0}[R-0]$

$$\phi = \frac{\lambda R}{2\varepsilon_0}$$

Example

A point charge $+q_0$ is kept at the centre of a spherical shell of radius R. Find the electric flux due to point charge through the hollow sphere.



☞ **Solution** Electric flux through the small area $\vec{dS}$

Electric flux, $d\phi = \vec{E}\,.\,\vec{dS}$

$$= E\, dS$$

$$= \frac{kq_0}{R^2} dS$$

Total flux, $\phi = \int \frac{kq_0}{R^2} dS = \frac{kq_0}{R^2}\int dS$

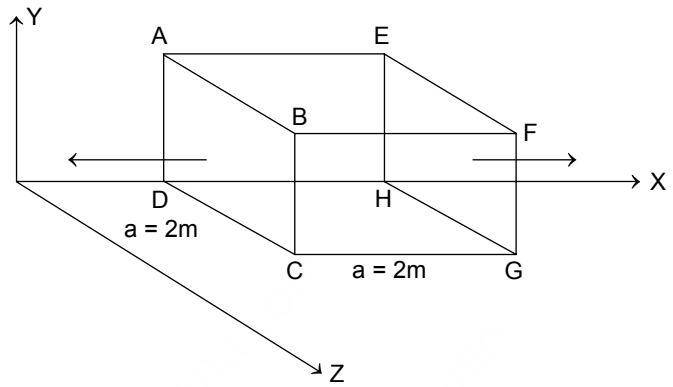
$$= \frac{kq_0}{R^2} \times 4\pi R^2 = \frac{1}{4\pi\varepsilon_0} \times q_0 \times 4\pi$$

$$\phi = \frac{q_0}{\varepsilon_0}$$

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Example

A tube of side 2 m is kept as shown in the figure. If the intensity E_x depends on co-ordinate X as $E_x = 2x^2$, find electric flux through the cube shown in the figure.

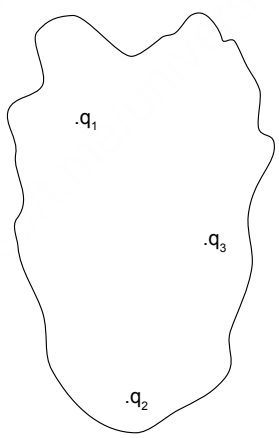


☞ **Solution** Since, Electric intensity on the surface ABCD is constant

$$\therefore \quad \phi_{ABCD} = \vec{E}.\vec{A} = E\,A\cos\theta$$

$$= 2a^2 \times a^2 \cos\pi = -2\,a^4$$

$$= -2 \times 16 = -32\ \text{Nm}^2/\text{C}$$



$$\phi_{EFGH} = \vec{E}.\vec{A} = E\,A\cos\theta$$

$$= 2\,(2a^2)\,a^2\cos\theta$$

$$= 8a^4 = 128\ \text{Nm}^2/\text{C}$$

$\therefore$ Total flux = 128 – 32

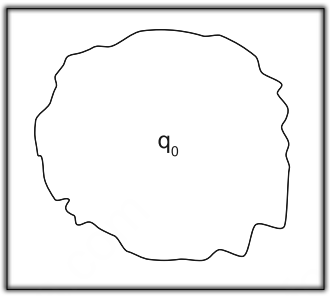
= 96 Nm²/C

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Gauss's Law

According to this theorem, the total electric flux through a closed body enclosing a charge q is equal to $\frac{q_o}{\varepsilon_o}$; where, q is equal to net charge enclosed by the body.

If there are so many charges inside a closed body, for example $q_1, -q_2$ and q_3, then the electric flux through the closed body due to these charges will be



$$\phi = \frac{q_{net}}{\varepsilon_0}$$

$$\phi = \frac{q_1 - q_2 + q_3}{\in_0}$$

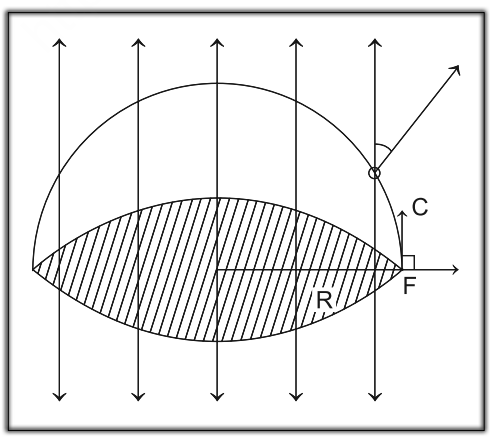
(i) If a body does not enclose any charge, then the electric flux through the body will be zero.

(ii) Electric flux is independent from the position of charge inside the closed body.

(iii) The total electric flux through a closed body is independent from the shape of body.

Example

A heavy spherical ball of radius R is kept as shown in the figure in uniform electric field E. Find electric flux through the curve surface.



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As there is no charge inside the bowl, hence from Gauss's Law,

$$\phi = \frac{q}{\varepsilon_0} = 0$$

$$\phi_F + \phi_C = 0$$

$$\phi_C = -\phi_F$$

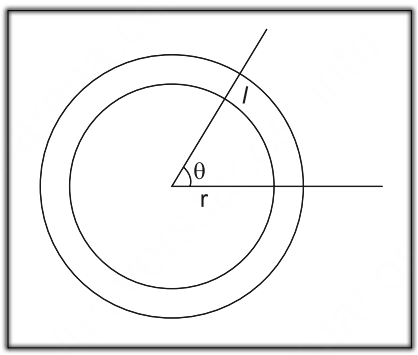
$$= -E A \cos\theta$$

$$= -E \pi R^2 \cos 180^\circ$$

or $$\phi_C = E \times \pi R^2$$

Plane Angle

$$\theta = \frac{l}{r}$$



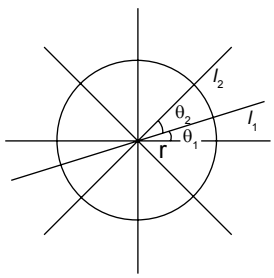
If $r = 1, \theta = l$

Plane angle is nothing but the length of the circle of unit radius intercepted between the two lines.

CONCEPT

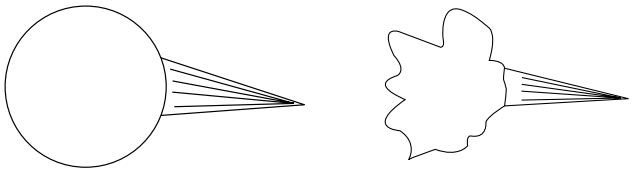
(i) Plane angle around a point at an interval point of a close curve is always equal to 2π.

$$\theta = \Sigma\theta_i = \frac{l_1}{r} + \frac{l_2}{r} + \ldots\ldots + \frac{l_n}{r} = \frac{2\pi r}{r} = 2\pi$$

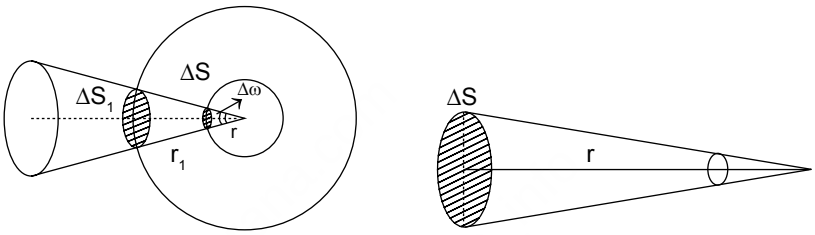


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(ii) If plane angle at an external point due to closed curve is equal to zero.



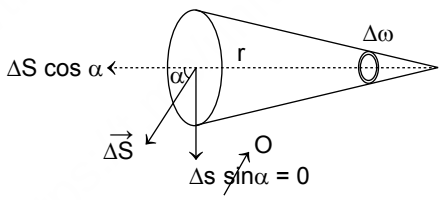
Solid Angle



$$\Delta\Omega = \frac{\Delta S}{r^2}$$

If $r = 1$, then $\Delta\Omega = \Delta S$

Solid angle is nothing but the area of sphere of unit radius intercepted by the cone.



$$\Delta\Omega = \frac{\Delta S\cos\alpha}{r^2}$$

Note:

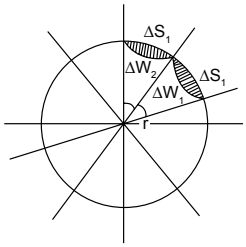
$$\Omega = \Sigma\,\Delta\,\Omega_i$$

$$= \frac{\Delta S_1}{r^2} + \frac{\Delta S_2}{r^2} + \ldots\ldots + \frac{\Delta S_n}{r^2}$$

$$= \frac{\Sigma\,\Delta S_i}{r^2} = \frac{4\pi r^2}{r^2} = 4\pi$$

$$\Omega = 4\pi$$

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Note:

(i) The total solid angle formed by a closed body as an internal point is equal to 4π.
(ii) Solid angle at external point due to a closed body is equal to zero.

The Most General Proof of Gauss's Law

Let us consider a charge q_0 inside a closed body of an arbitrary shape.
Electric flux due to point charge q_0 through the small area $\vec{dS}$

$$d\phi = \vec{E}.\vec{dS}$$

$$= E\, dS \cos\alpha$$

$$= \frac{kq_0}{r^2} dS\cos\alpha$$

$$= \frac{kq_0}{r^2}(dS\cos\propto)$$

$$= kq_0\left(\frac{dS\cos\alpha}{r^2}\right)$$

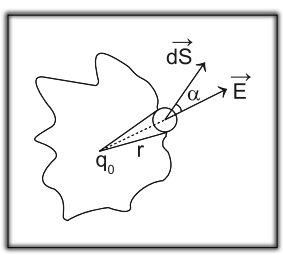
$$d\phi = kq_0\, d\Omega$$

$$\phi_{total} = kq_0 \int d\Omega$$

$$= kq_0 \times 4\pi$$

$$= \frac{1}{4\pi\in_0} \times q_0 \times 4\pi$$

Hence $\phi_{total} = \frac{q_0}{\varepsilon_0}$



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CONCEPT

Electric flux due to a charge lies outside the closed body is equal to zero.

Electric flux through small area $\vec{dS}$

$$\Delta\phi = \vec{E}.\vec{dS}$$

$$= E\,\Delta S \cos(180° - \alpha)$$

$$= -E\,\Delta S \cos\alpha$$

$$= \frac{-kq_0}{r^2}\Delta S\cos\alpha$$

$$= -kq_0\left(\frac{\Delta S\cos\alpha}{r^2}\right)$$

$$\Delta\phi = -kq_0\,\Delta\Omega$$

$$\therefore \quad \phi_{total} = \Sigma\,\Delta\phi$$

$$= \Sigma\,(-kq_0\,\Delta\Omega)$$

$$= -kq_0\,\Sigma\,\Delta\Omega = 0$$

Applications Based on Gauss's Law

Let, λ = charge per unit length on rod.

Electric flux through small area $\vec{dS}$ on the Gaussian surface.

$$d\phi = \vec{E}.\vec{dS} = E\,dS$$

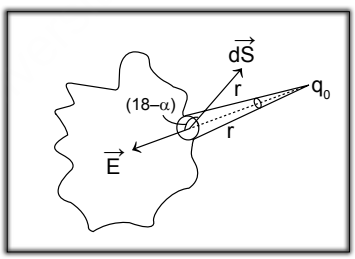
$$\phi_{\text{curved portion}} = \int E\,dS$$

$$= E\int dS$$

$$= E \times 2\pi rl$$

ϕ_{total} through closed surface.

$$\phi = E \times 2\pi rl + 0 + 0 = E \times 2\pi rl$$



Also, $$\phi = \frac{q}{\varepsilon_0} = \frac{l\lambda}{\varepsilon_0}$$

$$E \times 2\pi rl = \frac{l\lambda}{\varepsilon_0}$$

or $$E = \frac{\lambda}{2\pi \in_0 r}$$

Example

Using Gauss law, find electric intensity due to a point charge at distance *r* from it.

☞ **Solution** Let us draw a Gaussain surface of radius *r*.

$$\therefore \quad \oint \vec{E}.\vec{dS} = \frac{q}{\varepsilon_0}$$

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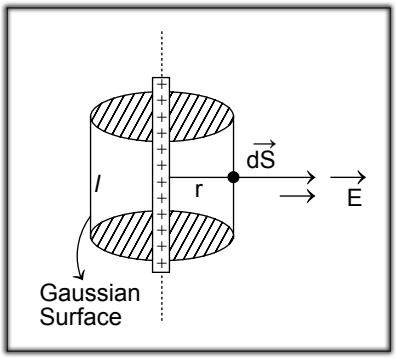
$$\phi_{total} = \oint \vec{E}.\vec{dS} = \oint E dS$$

$$= E \oint dS$$

$$= (E \times 4\pi r^2)$$

$$\therefore \quad E \times 4\pi r^2 = \frac{q}{\varepsilon_0}$$

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



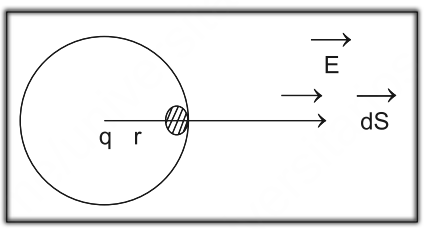
Electric intensity due to hollow sphere at external point.

Case A: Draw a Gaussian sphere of radius *r*.

$$\phi_{total} = \oint \vec{E}.\vec{dS}$$

$$= E \oint dS$$

$$= E \times 4\pi r^2$$



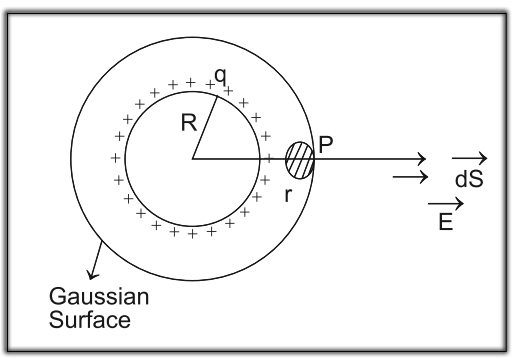
According to Gaussian Law,

$$\phi_{Total} = \frac{q}{\varepsilon_0}$$

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

or $$E = \frac{q}{4\pi \in_0 r^2}$$

or $$E = \frac{kq}{r^2}$$

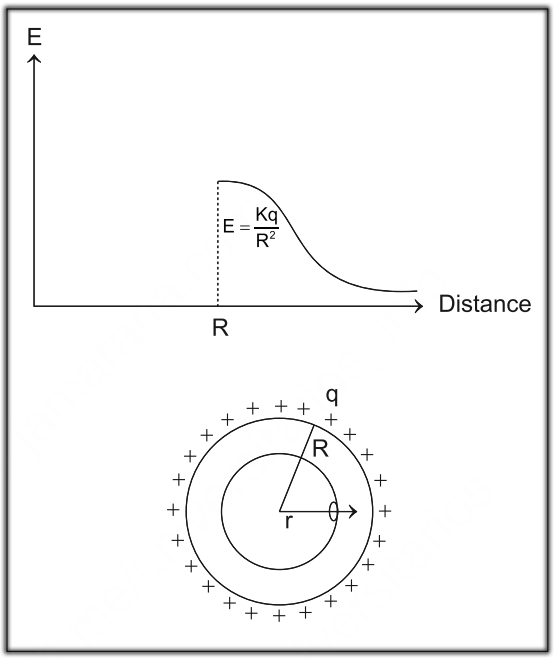


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For external point, hollow sphere behaves like a point charge where total charge may be supposed to be concentrated at the centre.

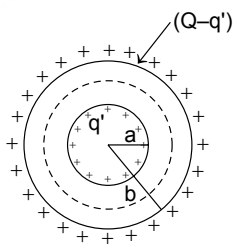
Case B: Electric intensity at an internal point.

As there is no charge inside the Gaussian surface, therefore, total electric flux through the Gaussian surface is zero, which is only possible when electric intensity is zero, inside the sphere.



CONCEPT

If a conductor is given charge, then the total charge appears on the outer surface of the conductor.



As there is no electric intensity inside the metal is zero, therefore, total flux through the Gaussain surface is zero.

But According to Gauss's Law,

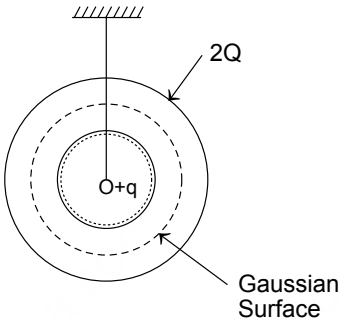
$$\phi = \frac{q'}{\varepsilon_0} \quad \text{or} \quad 0 = \frac{q'}{\varepsilon_0} \quad \text{or} \quad q' = 0$$

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Example

In the figure shown, if the outer sphere is given charge $2Q$, then what will be the charge on inner and outer surface?

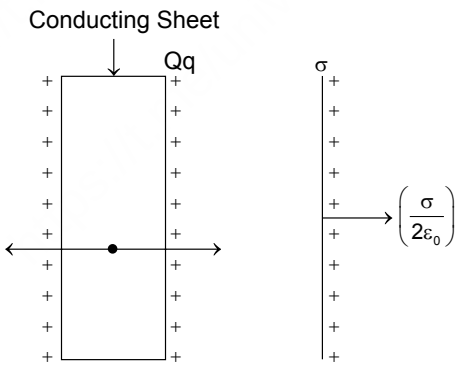
Ans. $-q$ and $(Q + q)$



CONCEPT

(i) If a conducting plate is given a charge Q, then the charge is equally distributed in the two parts, so that electric intensity inside the metal becomes zero.

(ii) If a conducting solid sphere is given charge, then there will be no charge inside the sphere. Therefore, the electric flux through the Gaussain surface inside the sphere will be zero. Therefore, electric intensity inside metallic solid sphere is zero, while for outside point same as hollow sphere.



Electric intensity due to non-conducting solid sphere

Draw a Gaussian surface of radius r. Electric flux through small area $\vec{dS}$ on Gaussian surface

$$d\phi = \vec{E}.\vec{dS} = E\,dS$$

$$\phi = \oint E dS = E \oint dS$$

$$\phi = E \times 4\pi r^2$$

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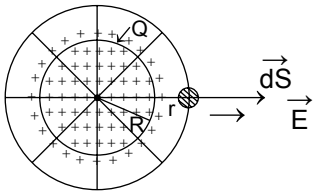
But, according to Gauss's Law,

$$\phi_{total} = \frac{Q}{\varepsilon_0}$$

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

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

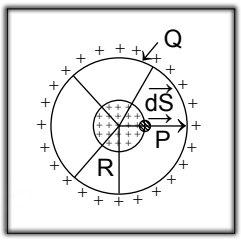
$$\therefore \quad E = \frac{kQ}{r^2}$$



For outside point, solid sphere behaves like a point charge.

Electric Intensity Inside the Solid Sphere

Draw a gaussian sphere of radius *r*.



Flux through the gaussian sphere,

$$= \oint \vec{E}.\vec{dS}$$

$$= \oint E dS$$

$$= E \times 4\pi r^2$$

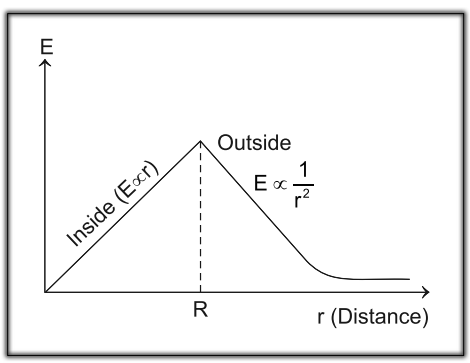
Charge inside the gaussian sphere

$$q_{inclosed} = \frac{Q}{\frac{4}{3}\pi R^3 \varepsilon} \times \frac{4}{3}\pi r^3 = \frac{Q r^3}{R^3} \qquad \therefore \quad \phi = q_{inclosed}/\varepsilon_o$$

But, $$E \times 4\pi r^2 = \frac{Q r^3}{R^3 \varepsilon_0}$$

$$\therefore \quad E = \frac{Qr}{4\pi\varepsilon_0 R^3} = \frac{Qr}{\frac{4}{3}\pi R^3} \times \frac{r}{3\varepsilon_0} = \frac{\rho_r}{3\varepsilon_0}$$

or $$E = \frac{kQr}{R^3}$$



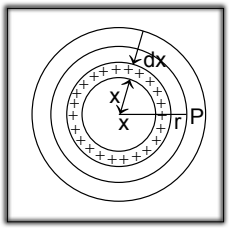
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Alternative Methods

Charge on spherical shell volume

$$= \rho \times (4 \pi x^2 dx)$$

Electric intensity at point ρ due to spherical shell



$$E = \frac{k\rho \times 4\pi x^2 dx}{r^2}$$

$$E_{net} = \frac{k\rho \times 4\pi}{r^2} \int_0^r x^2 dx$$

$$= \frac{k\rho \times 4\pi}{r^2} \times \frac{r^3}{3} = \frac{\rho r}{3\varepsilon_0}$$

Electric Intensity due to Infinite Sheet

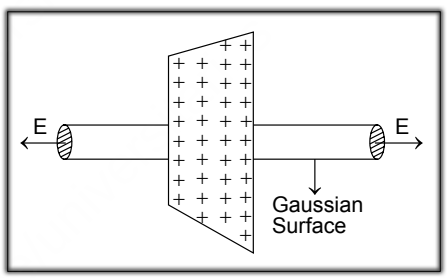
σ = Charge per unit area

Electric flux through the gaussain surface.

$\phi = E A + E A + 0 = 2 E A$

$q_{enclosed} = \sigma A$

According to Gauss's Law,



$$\phi_{Total} = \frac{q_{enclosed}}{\varepsilon_0}$$

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

or $$E = \frac{\sigma}{2\varepsilon_0}$$

In case of conducting sheet,

$$q_{enclosed} = 2 \sigma A$$

$$\therefore \quad \varepsilon = \frac{\sigma}{\varepsilon_0}$$

– *(ve)* Towards the plates.

+ *(ve)* Away from the plates.

Electric intensity near the surface of charge conductor is always equal to $\frac{\sigma}{\varepsilon_0}$.

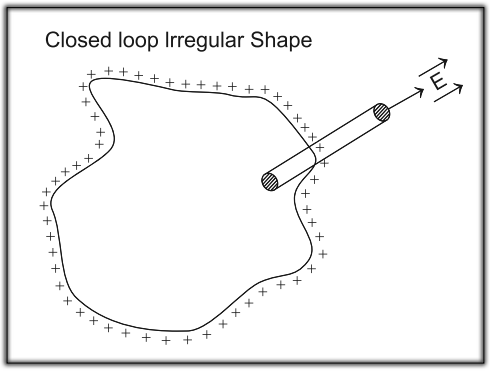
Total flux through the gaussian surface,

$$\phi = E A + 0 + 0$$

$$\phi = \frac{q_{enclosed}}{\varepsilon_0} = \frac{\sigma A}{\varepsilon_0}$$

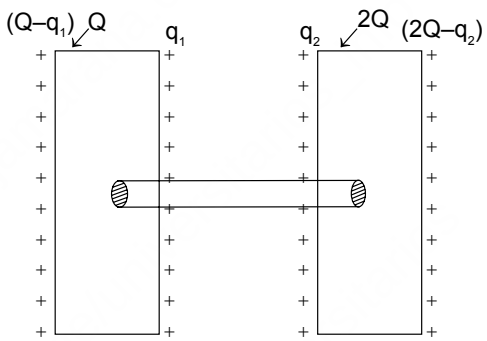
$$EA = \frac{\sigma A}{\varepsilon_0} \quad E = \frac{\sigma}{\varepsilon_0}$$

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CONCEPT

Identical Plates:



As ϕ through the Gaussian surface = 0, therefore

$$q_{\text{enclosed}} = 0$$

$$\Rightarrow \quad \frac{\sigma}{\varepsilon_0} = 0$$

$$\therefore \quad \sigma_1 A + \sigma_2 A = 0$$

or $\quad \sigma_1 A = -\sigma_2 A$

or $\quad \sigma_1 = -\sigma_2$

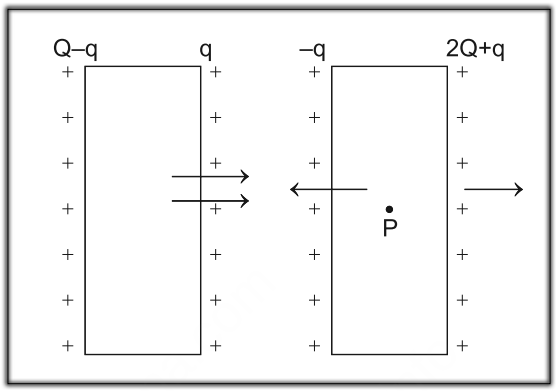
or $\quad \frac{q_1}{A} = \frac{-q_2}{A}$

or $\quad q_1 = -q_2$

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Example

Two identical metallic plates are given charges Q and $2Q$ as shown in the figure. Find the charge that will appear on the inner and outer surface of two plates.



☞ **Solution**

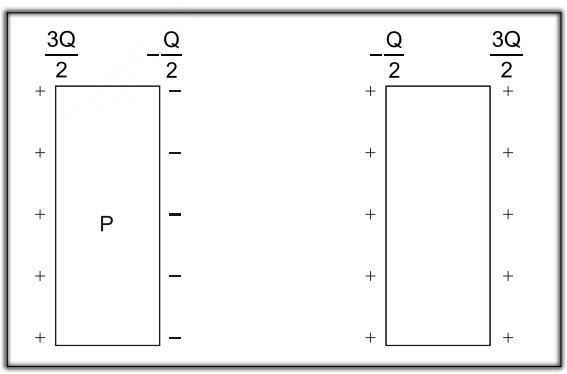
$$\vec{E}_P = \frac{Q-q}{2A\varepsilon_0} i + \frac{q}{2A\varepsilon_0} i + \frac{q}{2A\varepsilon_0}(-i) + \frac{2Q+q}{2A\varepsilon_0}(-i)$$

$$= \frac{i}{2A\varepsilon_0}(Q - q + q - q - 2Q - q)$$

$$\vec{E}_P = \frac{i}{2A \in_0}(-Q - 2q) = 0$$

$\Rightarrow \quad Q + 2q = 0$

$\Rightarrow \quad q = \frac{-Q}{2}$



Final distribution of charge on two plates.

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Example

There is a solid sphere of radius R having volume charge density $\rho = \rho_0(1-\frac{r}{R})$, where ρ_0 is any constant and r is the distance from the centre of sphere. Assuming permittivity of medium to equal to 1, find

(i) **Electric intensity E inside the sphere and outside the sphere at distance r.**
(ii) **Also find where will this intensity be maximum.**

☞ **Solution** Consider a Gaussian surface of radius r.

(i) (a) When r^o R Electric flux through small area,

$$d\phi = \vec{E}.\vec{dS} = E\ dS$$

$$\therefore \quad \phi = \oint E dS = E \oint dS = E \times 4\ \pi\ r^2$$

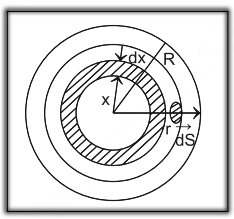
But according to Gauss's Law,

$$\phi = \frac{q_{enclosed}}{\varepsilon_0}$$

Charge q contained between radius x to $x + dx$.

$$dq = 4\pi x^2 \rho_0 (1-\frac{x}{R})$$

$$\therefore \quad \phi q = 4\pi\rho_0 \left(x^2 - \frac{x^3}{R} \right) dx$$



Charge enclosed inside the Gaussian surface,

$$q_{enclosed} = 4\pi\rho_0 \int_0^r \left(x^2 - \frac{x^3}{R} \right) dx$$

$$= 4\pi\rho_0 \left(\frac{x^3}{3} - \frac{x^4}{R} \right)_0^r$$

$$= 4\pi\rho_0 \left(\frac{r^3}{3} - \frac{r^4}{4R} \right)$$

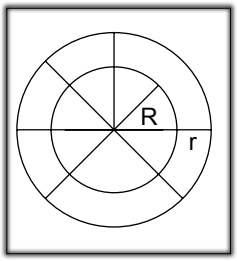
But $$E \times 4\pi r^2 = \frac{4\pi\rho_0}{\varepsilon_0} \left(\frac{r^3}{3} - \frac{r^4}{4R} \right)$$

$$\therefore \quad E = \frac{\rho_0 r}{\varepsilon_0} \left(\frac{1}{3} - \frac{r}{4R} \right)$$

$$\therefore \quad E = \frac{\rho_0 r}{3\in_0} \left(1 - \frac{3r}{4R} \right), \text{ when } r \le R.$$

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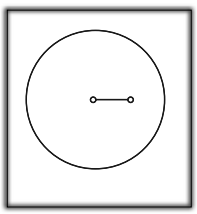
(b) When $r \geq R$, then



$$q_{enclosed} = 4\pi\rho_0\left[\frac{x^3}{3} - \frac{x^4}{4R}\right]_0^R$$

$$= 4\pi\rho_0\left[\frac{r^3}{3} - \frac{r^4}{4R}\right]_0^R$$

$$\therefore \quad E = \frac{\rho_0 R^3}{12\varepsilon_0 r^2}$$



(ii) For E to be maximum, $\frac{dE}{dr} = 0$

$$\therefore \quad \frac{dE}{dr} = \frac{\rho_0}{3\in_0}\left(1 - \frac{3}{4}R \times 2r\right) = 0$$

or $$1 - \frac{3r}{2R} = 0$$

or $$1 = \frac{3r}{2R}$$

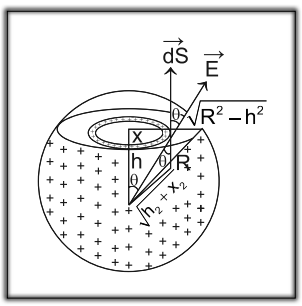
$$\therefore \quad v\ r = \frac{2R}{3}$$

Electric Flux through the ring of radius r.

Here, $d\phi = \vec{E}.\vec{dS}$

$$= E\,dS\cos\theta$$

$$= \frac{\rho}{3\varepsilon_0}\sqrt{h^2 + x^2} \times 2\pi x dx \times \frac{h}{\sqrt{h^2 + x^2}}$$



Integrating $\int d\phi = \frac{2\pi\rho h}{3\varepsilon_0}\int \frac{x\,dx}{\sqrt{R^2 - h^2}}$

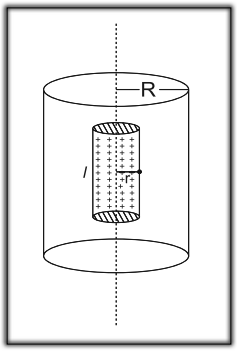
$$\therefore \quad \phi = \frac{2\pi\rho h}{3\varepsilon_0}\int_0^{\sqrt{R^2 - h^2}} x\,dx$$

$$= \frac{2\pi\rho h}{3\varepsilon_0}\left[\frac{x^2}{2}\right]_0^{\sqrt{R^2 - h^2}}$$

$$\phi = \frac{\pi\rho h}{3\varepsilon_0}\left[R^2 - h^2\right]$$

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Electric intensity inside an infinite solid cylinder



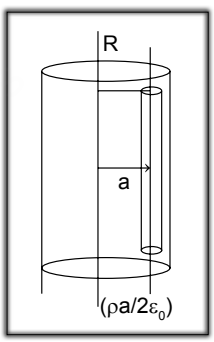
ρ = volume change density

Case A. When r < R

From symmetry, electric intensity on the Gaussian surface will be perpendicular to the Gaussian surface.

Electric flux through Gaussian surface

$$\phi = \oint \vec{E}.\vec{dS} = \oint E.dS = E\oint dS = E \times 2\pi rl$$



From Gauss's law,

$$\phi_{total} = q_{enclosed}$$

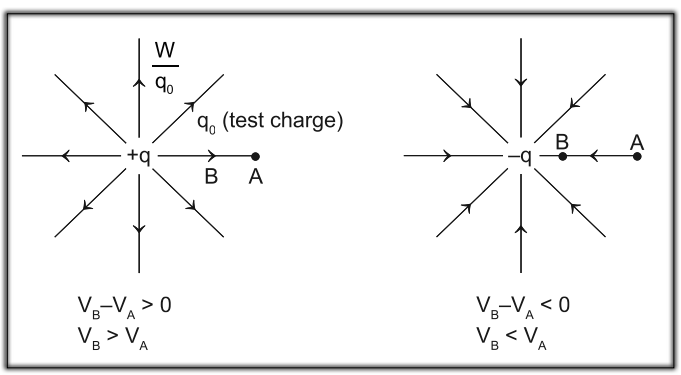
or $$E \times 2\pi rl = \rho \times \frac{\pi r^2 l}{\varepsilon_0}$$

or $$E = \frac{\rho r}{2\varepsilon_0}$$

Case B. When point lies outside the cylinder

$$E \times 2\pi rl = \rho \times \frac{\pi R^2 l}{\varepsilon_0};\ E = \frac{\rho R^2}{2\varepsilon_0}$$

Electric potential difference and Electric potential

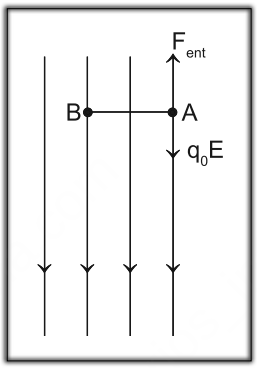


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Electric potential difference in a electric field between two points is defined as work done by external agent is moving unit positive charge from one point to another point keeping it to be in dynamic equilibrium.

If W be the amount of work done in moving a test charge q_0 from point A to B, then electric potential difference (PD)

$$V_B - V_A = \frac{W}{q_0}$$



Equi potential vector quantity

Since, electric potential difference depends on workdone, therefore, electric potential difference between two points may be *+ve*, *–ve* or zero.

CONCEPT

(i) If points A and B lie in the field of positive point charge, then in this case, work (W) will be (*+ve*) positive.

i.e., $V_B - V_A > 0$

$V_B > V_A$ (Higher potential)

On the other hand, if the two points lie in the field of (*–ve*) points charge, then work (W) will be (*–ve*) negative,

i.e., $V_B - V_A < 0$

or $V_B < V_A$

*S.I. unit of electric potential difference is "Joulel per Coulomb", also known as "volt"

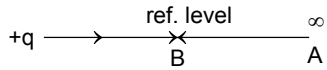
(ii) To find electric potential at a particular point, we choose a reference level where, electric potential is arbitrarily taken zero and in general reference level is taken as ∞ (infinity). You may assume electric potential at reference level to be 100 V or 200 V etc.

If V = electric potential of final point and reference level is taken at A, then

$$V_A = 0$$

$$V = \frac{W}{q_0}$$ x

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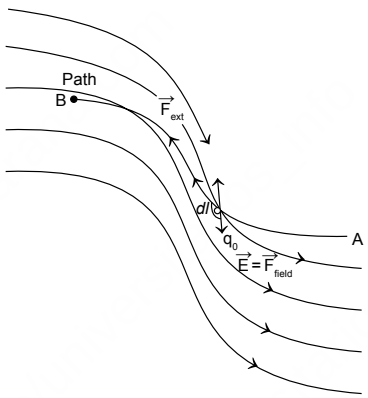


$$V_A - V_B = \frac{w}{q_0}$$

$$V_A = \frac{w}{q_0} = (-\text{ve})$$

Therefore, electric potential at a point due to a charge is defined as workdone by external agent in bringing unit (*+ve*) charge slowly from reference level to that point.

Relation between electric intensity and potential difference.



Consider two points A and B in non-uniform electric field. A test charge q_0 moves from point A to B.

Since, here field E is variable, therefore, force due to external agent will be also variable.

Here, Force due to external agent

$$\overrightarrow{F_{ext}} = -q_0 \vec{E}$$

Work done by external agent during small displacement $\vec{dl}$

$$dW = \overrightarrow{F_{ext}} \cdot \vec{dl}$$

$$= -q_0 \vec{E} \cdot \vec{dl}$$

$$W_{ext} = \int -q_0 \vec{E} \cdot \vec{dl}$$

$$W_{ext} = -q_0 \int \vec{E} \cdot \vec{dl}$$

Now, electric potential difference,

$$V_B - V_A = \frac{W_{ext}}{q_0}$$

$$V_B - V_A = -\int \vec{E} \cdot \vec{dl}$$

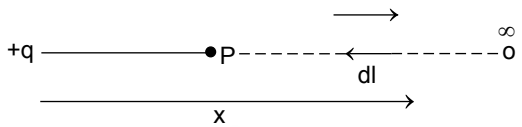
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If point A is taken as reference level, then

$$V_A = 0$$

$$V = -\int_{\infty} \vec{E}.\vec{dl}$$

*Electric potential near a point charge at distance r from it.



Electric potential difference,

$$V_p - V_\infty = -\int \vec{E}.\vec{dl}$$

or $$V_p = -\int E dl \cos 180°$$

$$= \int E dl = \int \frac{kq}{x^2} \, dl = \int -\frac{kq}{x^2} \, dx$$

$$= -kq \int_{\infty}^{r} \frac{dx}{x^2} = -kq \left[\frac{-1}{x}\right]_{\infty}^{r} = -kq \left[-\frac{1}{r} + \frac{1}{\infty}\right]$$

$$\therefore \quad V_p = \frac{kq}{r}$$

Note: If point charge q will be ($-ve$) then $V_p = -\frac{kq}{r}$. Therefore, we write the equation only as $V = \frac{kq}{r}$ and here, we remember that sign of charge q should be taken.

CONCEPT

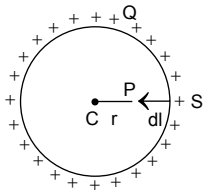
The same formula is applicable for the outside point due to spherical shell or solid sphere. Electric potential at the surface of spherical shell

$$V_S = \frac{kQ}{R}$$

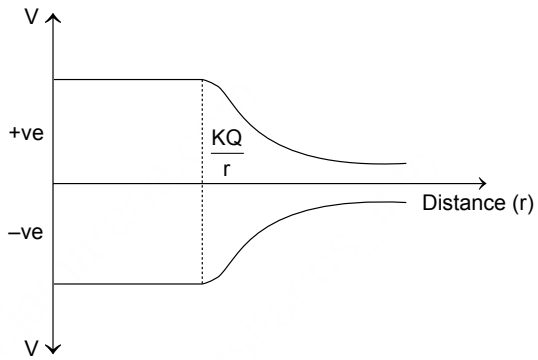
Now, $$V_p - V_S = -\int \vec{E}.\vec{dl}$$

$$V_p - V_S = 0; \quad V_p = V_S; \quad V_p = \frac{kQ}{R}$$

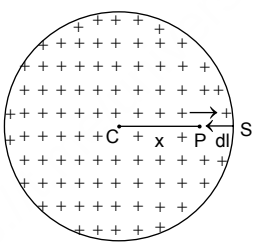
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All points inside spherical shell are equipotential.



Electric potential due to solid sphere



If ρ is volume charge density inside the solid sphere, then electric intensity inside the solid sphere is given by

$$E = \frac{\rho r}{3\varepsilon_0}$$

$$V_p - V_s = -\int \vec{E} \cdot \vec{dl}$$

$$= \int E dl \cos 180° = \int E dl$$

$$= -\int \frac{\rho}{3\varepsilon_0} (x)\,(-dx)$$

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$$= -\frac{\rho r}{3\varepsilon_0}\int_{R}^{r} x\,dx$$

$$= \frac{-\rho}{3\varepsilon_0}\left[\frac{x^2}{2}\right]_{R}^{r}$$

$$= \frac{-\rho}{3\in_0}\left[\frac{r^2}{2}-\frac{R^2}{2}\right]$$

$$\therefore \quad V_p - V_s = \frac{-\rho}{6\varepsilon_0}\left[r^2 - R^2\right]$$

Again $$V_p = \frac{kQ}{R} - \frac{Q}{\frac{4}{3}\pi R^3 \times 6\varepsilon_0}(r^2 - R^2)$$

$$= \frac{kQ}{R}\left[1 - \frac{(r^2 - R^2)}{2R^2}\right]$$

$$= \frac{kQ}{R}\left[\frac{2R^2 - r^2 + R^2}{2R^2}\right]$$

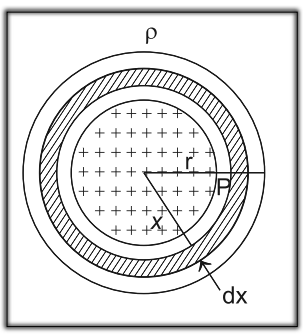
$$= \frac{kQ}{R}\left[\frac{3R^2 - r^2}{2R^2}\right]$$

$$= \frac{kQ}{2R^3}\left[3R^2 - r^2\right]$$

At the centre, r = 0 therefore, electric intensity at the centre of sphere will be zero, while electric potential at centre of sphere will not be zero.

Inside the solid sphere, electric potential V varies parabolically with distance.

Alternative Methods



A solid sphere may be thought or taken as combination of small solids sphere of radius *r* and a thick hollow sphere.

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Charge on small solid sphere $= \rho \times \frac{4}{3}\pi r^3$

$$= \frac{Q}{\frac{4}{3}\pi R^3} \times \frac{4}{3}\pi r^3 = \left(\frac{Qr^3}{R^3}\right)$$

Electric potential at point. P due to small solid sphere,

$$V_1 = \frac{kq}{r} = \frac{kQr^3}{rR^3} = \frac{kQ}{R^3} r^2$$

Charge on spherical shell,

$$q' = \rho \times 4\pi x^2 dx$$

$$= \frac{Q}{\frac{4}{3}\pi R^3} \times 4\pi x^2 dx = \left(\frac{3Qx^2 dx}{R^3}\right)$$

Electric potential at P due to spherical shell

$$= \frac{kq'}{x} = \frac{k}{x} \times \frac{3Q}{R^3} x^2 dx$$

$$= \frac{3kQ}{R^3} xdx$$

Due to thick hollow sphere

$$V' = \frac{3kQ}{R^3} \int_r^R xdx$$

$$= \frac{3kQ}{R^3} \left[\frac{x^2}{2}\right]_r^R$$

$$= \frac{3kQ}{R^3} \left[\frac{R^2}{2} - \frac{r^2}{2}\right]$$

$$= \frac{3kQ}{2R^3} [R^2 - r^2]$$

$$V_{net} = V_1 + v'$$

$$= \frac{kQr^2}{R^3} + \frac{3kQ}{2R^3} [R^2 - r^2]$$

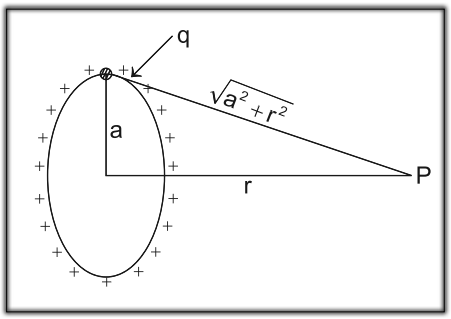
$$= \frac{kQ}{R^3} \left(r^2 + \frac{3}{2}[R^2 - r^2]\right)$$

$$= \frac{kQ}{R^3} \left(\frac{r^2 + 3R^2 - 3r^2}{2}\right)$$

$$= \frac{kQ}{2R^3} (3R^2 - 2r^2)$$

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Electric potential due to a ring in X-axis



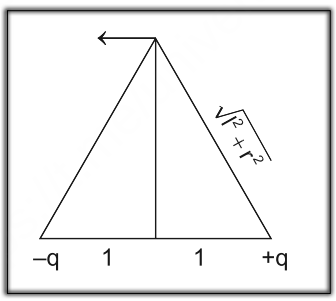
If λ = charge per unit length on ring, then charge on element = λ *dl*
Electric potential due to charged element

$$= \frac{k\lambda dl}{\sqrt{a^2+r^2}}$$

Net electric potential, $V = \frac{k\lambda}{\sqrt{a^2+r^2}} \int dl$

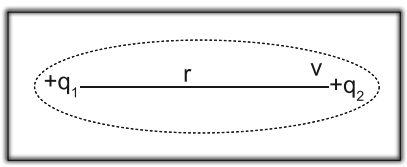
$$= \frac{k}{\sqrt{a^2+r^2}} \times \frac{q}{2\pi a} \times 2\pi a$$

$$\therefore \quad V = \frac{kq}{\sqrt{a^2+r^2}}$$



Electric Potential Energy

Electric potential energy of a system is defined as work done by external agent to assemble the system.



$$V = \frac{kq_1 q_2}{r}$$

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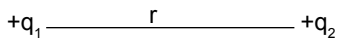
CONCEPT

Initially, it is assumed that the charges of the system considered is separated by (∞) infinite distance.

If q_1 and q_2 are the two point charges separated by a distance r, then we have to find electric potential energy of this system.

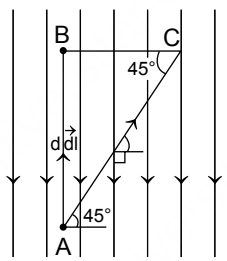
Electric PE (U) = Vq_2

$$= \frac{kq_1 q_2}{r}$$



Example

Two points A and B are separated by a distance d in uniform field. Find electric potential difference between points A and B, and also prove that potential difference between two points is independent from the path follow.



$$V_B - V_A = -\int \vec{E}.\vec{dl} = -\int E dl \cos 180°$$

$$= \int E dl = E\int dl$$

$\therefore \quad V_B - V_A = Ed$

Now, $V_c - V_A = -\int \vec{E}.\vec{dl}$

$$= -\int E dl \cos 135°$$

$$= -\int E dl\left(\frac{1}{\sqrt{2}}\right)$$

$$= \frac{E}{\sqrt{2}}\int dl$$

$$= \frac{E}{\sqrt{2}}(AC)$$

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$$= \frac{E}{\sqrt{2}} \times \sqrt{2}d \qquad [\because \sin 45° = d/AC]$$

$$= Ed \qquad \ldots(i)$$

$$V_B - V_C = -\int \vec{E}.\vec{dl}$$

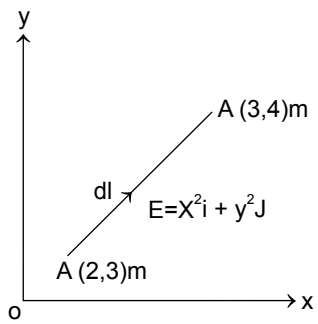
$$V_B - V_C = 0$$

Adding equations (i) and (ii), we get

$$V_B - V_A = Ed$$

Example

If two points A and B lie in electric field $\vec{E} = x^2\, i + y^2\, j$, find electric potential difference between B and A. If electric potential at origin is zero, find electric potential of point B.



Note: A small displacement $\vec{dl}$ can be written as

$$\vec{dl} = dl \cos\theta i + dl \sin\theta\, j$$

$$\vec{dl} = dxi + dyj$$

☞ **Solution** $V_B - V_A = -\int \vec{E}.\vec{dl}$

$$= -\left[\int (x^2 i + y^2 j)(dxi + dyj)\right] = -\left[\int_2^3 x^2 dx + \int_3^4 y^2 dy\right]$$

or $$V_B - V_A = -\left[\left(\frac{x^3}{3}\right)_2^3 + \left(\frac{y^3}{3}\right)_3^4\right]$$

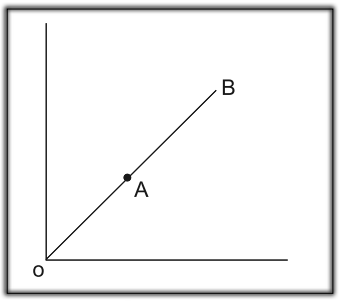
$$V_B - V_0 = -\int \vec{E}.\vec{dl} = -\int_0^3 x^2 dx + \int_0^4 y^2 dy$$

$$= -\left[\left(\frac{x^3}{3}\right)_0^3 + \left(\frac{y^3}{3}\right)_0^4\right]$$

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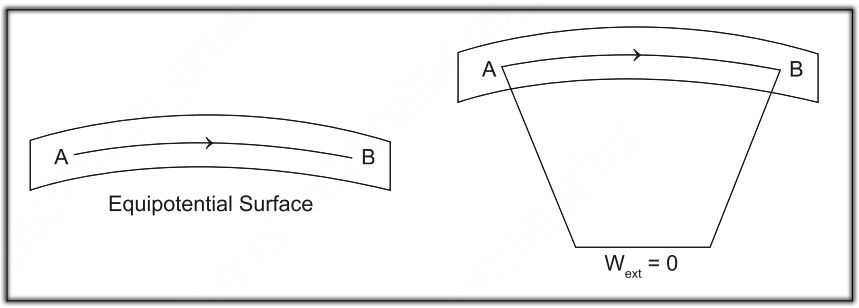
Solving, we get

$$V_B - V_A = \frac{91}{3} \quad \text{or} \quad V_B = \frac{91}{3} volts$$



Equipotential Surface

It is the locus of all the points whose potential is same or, it is that surface at which potential is same at each point.



$$V_B - V_A = \frac{W_{ext.}}{q_0}$$

But $V_A = V_B$

$W_{Ext.} = 0$

CONCEPT

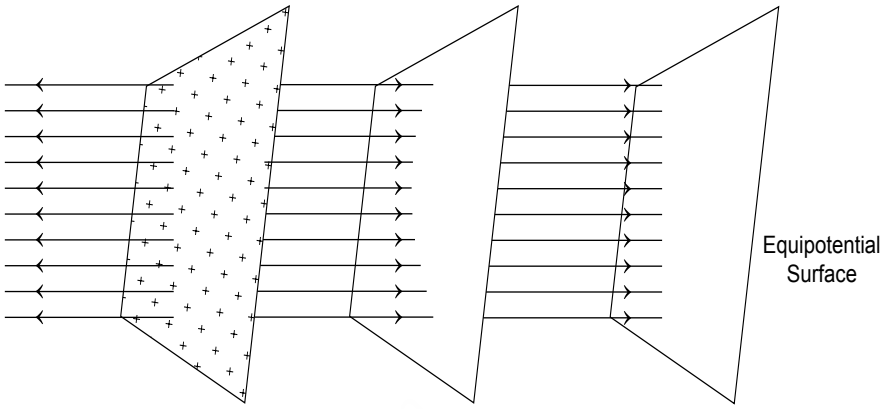
(i) Since, work done by external agent is zero, it means force due to external agent is perpendicular to equipotential surface. Such test charge is to move slowly. It means electric intensity is also perpendicular to equipotential surface. Therefore, Line of force also meets from the equipotential surface normally.

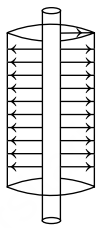
Or, if line of force meets from a surface normally, then the surface will be equipotential.

(ii) Since line of force always meets from surface of a conductor normally, therefore, each and every point of a conductor, is equipotential.

(iii) Shape of equipotential surface depends on system of charge. For example, Shape of equipotential surface for infinitely charge rod is cylinder. For sheet is sheet and for a point charge and hollow sphere shape will be sphere.

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(iv) To find shape of equipotential surface equate the given equation of potential with constant.

Example

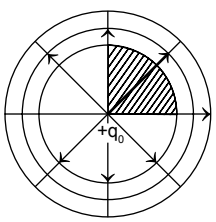
If $V = 2x^2 + y^2$, what will be the shape of equipotential surface?

☞ **Solution** $V = 2x^2 + y^2 = \text{Constant (C)}$

$$2x^2 + y^2 = C$$

or $$\frac{2x^2}{C} + \frac{y^2}{C} = 1$$

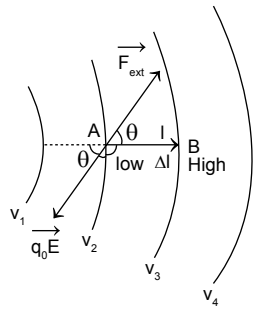
or $$\frac{x^2}{\frac{C}{2}} + \frac{y^2}{C} = 1$$



Hence, equipotential surface is ellipse.

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Relation between electric intensity and electric potential



Consider a family of equipotential surfaces having potentials V_1, V_2, V_3, ... so on. A test charge q_0 moves from point A to point B slowly.

Since, $V_B - V_A = \frac{W_{ext.}}{q_0}$

and $V_B - V_2 = \frac{W_{ext.}}{q_0}$

$\therefore \quad W_{ext} = q_0 (V_3 - V_2)$

or $\quad W_{ext} = q_0 \Delta V$

where ΔV = potential difference.

Also, Work (W) = $\vec{F} \cdot \vec{S}$

$= - q_0 \vec{E} \cdot \vec{\Delta l}$

$= - q_0 E \Delta l \cos (180 - \theta)$

$\therefore \quad W_{ext.} = q_0 E \Delta l \cos \theta$

But, $= q_0 E \Delta l \cos \theta = q_0 \Delta V$

$$E \cos \theta = \frac{\Delta V}{\Delta l}$$

But, E cos θ is the component of intensity in $-\Delta x$, therefore

$$-E = \frac{\Delta V}{\Delta l}$$

or $\quad E = -\frac{\Delta V}{\Delta l} \quad \ldots(\because E = \text{constant})$

If $= \Delta l \to 0$, then

$$E = -\frac{dV}{dl}$$

From here, it is clear that directional derivative of electric potential gives component of electric intensity in that direction.

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$$E_x = -\frac{\partial V}{\partial x}, E_y = -\frac{\partial V}{\partial y}, E_z = -\frac{\partial V}{\partial z}$$

Net $\vec{E} = E_x i + E_y j + E_z \hat{k}$

$$\vec{E} = -\frac{\partial V}{dx} i - \frac{\partial V}{dy} j - \frac{\partial V}{dz} \hat{k}$$

$$= -\left(\frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} \hat{k}\right) V$$

$$\vec{E} = -\overrightarrow{\Delta V}$$

Anti-gradient of potential gives electric intensity.

CONCEPT

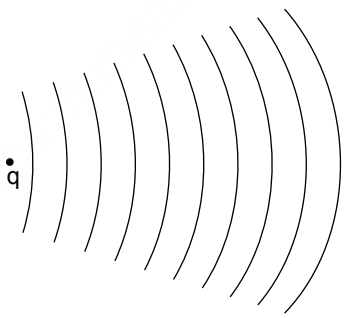
(i) $\vec{E} = -\frac{\Delta V}{\Delta l}$

From the equation, it is clear that electric intensity is always directed from high potential to low potential.

i.e., If $\Delta V < 0$, then E. > 0 (+*ve*)

(ii) If electric potential difference between two surfaces is constant.

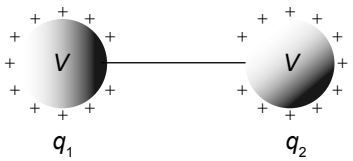
i.e., If ΔV = constant, then $\uparrow E \propto \frac{1}{\Delta l} \downarrow$



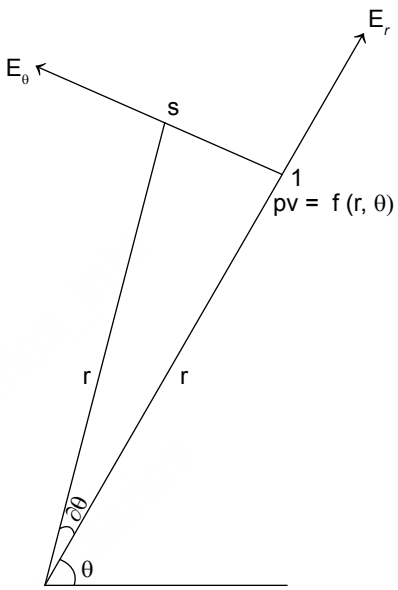
It means electric intensity is large, where, equipotential surfaces are close together and is less where they are far apart.

(iii) Since, tangent at a point to the line of force gives direction of electric intensity and electric intensity is directed from high potential to low potential, it means no two points on a line of force will be at same potential.

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If V is in the form of polar co-ordinate.



$$E_r = -\frac{\partial V}{V}$$

$$E_\theta = -\frac{\partial V}{\partial s}$$

But $\partial s = r\partial\theta$

$$E_\theta = -\frac{\partial V}{r\partial\theta}$$

$$E_\theta = \frac{-1}{r}\frac{\partial V}{\partial\theta}$$

$$\vec{E} = E_r\,\hat{r} + E_\theta\,\hat{\theta}$$

Net Electric intensity

$$E = \sqrt{E_r^{\,2} + E_\theta^{\,2}}$$

Electric potential at point P due to an electric dipole is given by

$$V = \frac{kP\cos\theta}{r^2}$$

$$E_r = -\frac{\partial V}{\partial r}$$

$$= -\frac{\partial}{\partial r}\left(\frac{kP\cos\theta}{r^2}\right)$$

$$= -kP\cos\theta\frac{\partial}{\partial r}(r^{-2})$$

$$\therefore \quad E_r = \frac{2kP\cos\theta}{r^3}$$

And $$E_\theta = -\frac{1}{r}\frac{\partial V}{\partial\theta} = -\frac{1}{r}\frac{\partial}{\partial\theta}\frac{kP\cos\theta}{r^2}$$

$$= \frac{kP}{r^3}\frac{\partial}{\partial\theta}(\cos\theta)$$

$$\therefore \quad E_\theta = \frac{kP}{r^3}\sin\theta$$

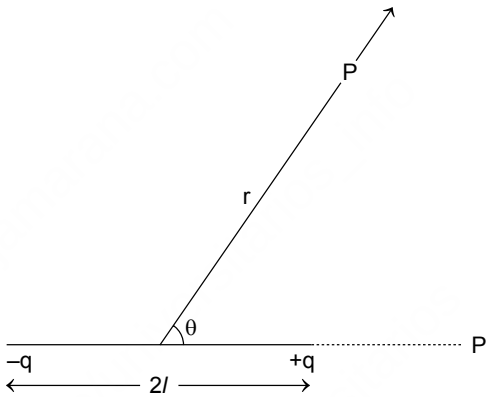
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Net Electric intensity, $E = \sqrt{E_\theta^2 + E_r^2}$

$$= \sqrt{\left(\frac{kP}{r^3}\right)^2 \sin^2\theta + \left(\frac{kP}{r^3}\right)^2 4\cos^2\theta}$$

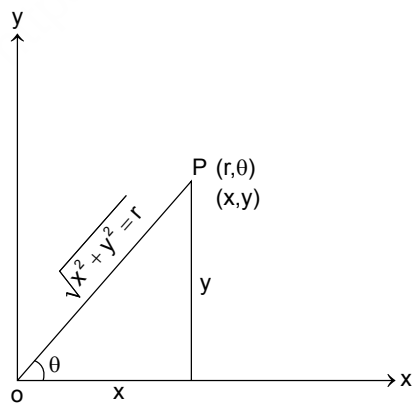
$$= \frac{kP}{r^3}\sqrt{\sin^2\theta + 4\cos^2\theta}$$

$\therefore$ $$E = \frac{kP}{r^3}\sqrt{1 + 3\cos^2\theta}$$



Example

If electric potential of dipole is $\frac{kP\cos\theta}{r^2}$, find cartensian equation for electric intensity at this point.



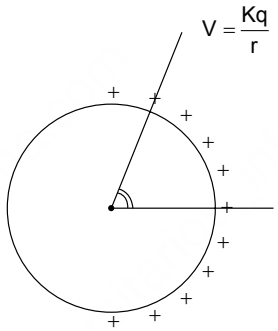
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☞ **Solution** $V = \frac{k\mathrm{P}}{(x^1 + y^1)} \times \frac{x}{\sqrt{x^1 + y^1}} = \frac{k\mathrm{P}x}{(x^2 + y^2)^{3/2}}$

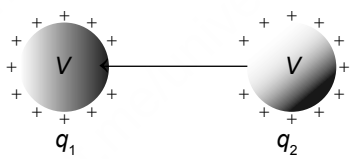
$\therefore \quad \mathrm{E}_x = -\frac{\partial \mathrm{V}}{\partial x}, \mathrm{E}_y = -\frac{\partial \mathrm{V}}{\partial y}$

$$\mathrm{E}_r = -\frac{d\mathrm{V}}{\partial r} = -\frac{\partial}{\partial r}\frac{k\mathrm{Q}}{r}$$

$$\mathrm{E} = \frac{+k\mathrm{Q}}{r^2}$$



Sharing of Charges:



Let, charge per unit area = σ_1

Two conducting spheres initially having charges Q_1 and Q_2 are connected through a wire in electrostatic equilibrium (no charge flow) let the charges on them become q_1 and q_2.

$\therefore \quad \frac{kq_1}{r_1} = \frac{kq_2}{r_2}$

or $q_1 r_2 = q_2 r_1$ .....(i)

Also, $q_1 + q_2 = \mathrm{Q}_1 + \mathrm{Q}_2$ …(ii)

From equations (i) and (ii),

$$q_1 = \frac{(\mathrm{Q}_1 + \mathrm{Q}_2) r_1}{r_1 + r_2} \text{ and } q_2 = \frac{(\mathrm{Q}_1 + \mathrm{Q}_2) r_2}{r_1 + r_2}$$

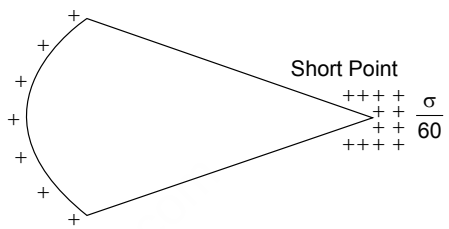
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If σ_1 and σ_2 are the surface charge density on the two spheres then from equation (i)

$$\sigma_1 \times 4\pi r_1^2 r_2 = \sigma_2 \times 4\pi r_2^2 r_1$$

$$\sigma_1 r_1 = \sigma_2 r_2$$

or $\sigma r = \text{constant} \quad \therefore \quad \sigma \propto \frac{1}{r}$



When a conductor is given charge, then at sharp σ becomes very large and electrons present in the atmosphere due to cosmic rays (sun) starts moving towards the conductor and therefore, in this way, conductor loses charge and medium gains charge. (+ve) charge i.e., leckage of charge takes place from the conductor. This is known as *Corona discharge*.

Example

In the figure shown find

(i) **Potentials of shell A, B and C,**

(ii) **If shell A and C are at same potential find relation between A, B and C.**

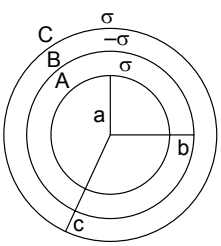
$q_A = (\sigma \times 4\pi a^2)$

$q_B = -(\sigma \times 4\pi b^2)$

and $q_C = (\sigma \times 4\pi c^2)$

☞ **Solution** Net potential of shell *A*

$$V_A + V_B + V_C = \frac{kq_A}{a} + \frac{kq_B}{b} + \frac{kq_C}{c}$$



$$= k\left(\frac{4\pi a^2\sigma}{a} - \frac{4\pi b^2\sigma}{b} + \frac{4\pi c^2\sigma}{c}\right) = k \times 4\pi\,\sigma\,(a - b + c)$$

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$$V_A = \frac{\sigma}{\varepsilon_0}(a - b + c)$$

$$V_B = \frac{kq_A}{b} + \frac{kq_B}{b} + \frac{kq_C}{c} = k\left(\frac{4\pi a^2 \times \sigma}{b} - \frac{4\pi b^2 \times \sigma}{b} + \frac{4\pi c^2 \sigma}{c}\right)$$

$$= k \times 4\pi\sigma\left[\frac{a^2 - b^2}{b} + c\right] = \frac{\sigma}{\varepsilon_0}\left[\frac{a^2 - b^2}{b} + c\right]$$

$$V_C = \frac{kq_A}{c} + \frac{kq_B}{c} + \frac{kq_C}{c} = k\left[\frac{4\pi a^2 \sigma}{c} - \frac{4\pi b^2 \sigma}{c} + \frac{4\pi c^2 \sigma}{c}\right]$$

$$= \frac{1}{4\pi \in_0} \times \frac{4\pi\sigma}{c}(a^2 - b^2 + c^2) = \frac{\sigma}{c\varepsilon_0}(a^2 - b^2 + c^2)$$

Since, $V_A = V_C$

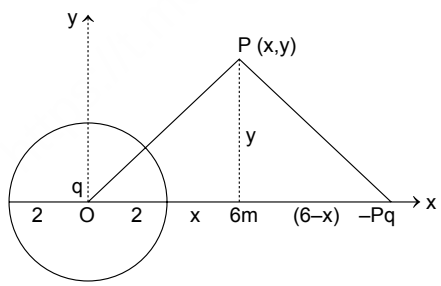
$$\therefore \quad \frac{\sigma}{\varepsilon_0}(a - b + c) = \frac{\sigma}{c\varepsilon_0}(a^2 - b^2 + c^2)$$

or $(a - b)\, c + c^2 = a^2 - b^2 + c^2$

or $c = a + b$

Example

Two electric charges q and – 2q are placed at a distance 6 m apart on a horizontal plane. Find the focus of the point of this plane where the potential has a zero value.



☞ **Solution** Electric potential at point P

$$\frac{kq}{\sqrt{x^2 + y^2}} - \frac{k \times 2q}{\sqrt{(6 - x)^2 + y^2}} = 0 \qquad \text{or} \qquad \frac{kq}{\sqrt{x^2 + y^2}} = \frac{2kq}{\sqrt{(6 - x)^2 + y^2}}$$

or $\sqrt{(6 - x)^2 + y^2} = 2\sqrt{x^2 + y^2}$

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or $(6 - x)^2 + y^2 = 4\,(x^2 + y^2)$

or $36 + x^2 - 12\,x + y^2 = 4\,(x^2 + 4y^2)$

or $3\,x^2 + 3y^2 + 12\,x - 36 = 0$

or $x^2 + y^2 + 2\,g\,x + 2\,fy + c = 0$

or $x^2 + y^2 + 4\,x - 12 = 0$

or $2g = 4$, or $g = 2$

$\therefore$ $2f = 0, f = 0$

Centre = $(-2, 0)$

and Radius, $r = \sqrt{g^2 + f^2 - c} = \sqrt{4 + 0 - (-12)} = \mathbf{4}$

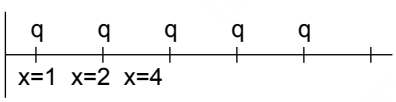
WORKED OUT EXAMPLES

1. An infinite number of charges each equal to q are placed along the x-axis at x = 1, x = 2, x = 4, x = 8 ... and so on. Find the potential and electric field at the point x = 0 due to this set of charges. What will be the potential and electric field if the above set up the consecutive charges have opposite sign?

☞ **Solution**

(i) Electric Potential at $x = 0$

$$V = \frac{1}{4\pi\varepsilon_0}\left[\frac{q}{1} + \frac{q}{2} + \frac{q}{4} + \frac{q}{8} + \ldots.\right]$$



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

$$= \frac{q}{4\pi\varepsilon_0}\left[\frac{1}{1 - \frac{1}{2}}\right] = \frac{q}{2\pi\varepsilon_0}$$

Intensity at $x = 0$

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

$$= \frac{q}{4\pi\varepsilon_0}\frac{1}{1 - \frac{1}{4}} = \frac{q}{3\pi\,\varepsilon_0}$$

(ii) When the charges are opposite

$$V = \frac{q}{4\pi\varepsilon_0}\left[1 - \frac{1}{2} + \frac{1}{4} - \frac{1}{8} + \ldots.\right]$$

$$= \frac{q}{4\pi\varepsilon_0}\left\{\left[1 + \frac{1}{4} + \frac{1}{16} + \ldots.\right]\right.$$

$$\left. - \left[\frac{1}{2} + \frac{1}{8} + \frac{1}{32} + \ldots.\right]\right\}$$

$$= \frac{q}{4\pi\varepsilon_0}\left[\frac{1}{1 - \frac{1}{4}}\right] - \frac{q}{4\pi\varepsilon_0}\left[\frac{\frac{1}{2}}{1 - \frac{1}{4}}\right]$$

$$= \frac{q}{\pi\varepsilon_0} - \frac{q}{2\pi\varepsilon_0} = \frac{q}{2\pi\,\varepsilon_0}$$

$$E = \frac{q}{4\pi\,\varepsilon_0}\left[1 - \frac{1}{2^2} + \frac{1}{4^2} - \frac{1}{8^2} + \frac{1}{16^2} - \ldots.\right]$$

$$= \frac{q}{4\pi\,\varepsilon_0}$$

$$\left[\left(1 + \frac{1}{16} + \frac{1}{256} + \ldots.\right) - \left(\frac{1}{4} + \frac{1}{64} + \ldots.\right)\right]$$

$$= \frac{q}{4\pi\,\varepsilon_0}\left[\left(\frac{1}{1 - \frac{1}{16}}\right) - \left(\frac{\frac{1}{4}}{1 - \frac{1}{16}}\right)\right]$$

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$$= \frac{q}{4\pi\varepsilon_0}\left[\frac{16}{15} - \frac{16}{4\times 15}\right]$$

$$= \frac{q}{4\pi\varepsilon_0}\times 16\left[\frac{1}{15} - \frac{1}{4\times 15}\right]$$

$$= \frac{4q}{\pi\varepsilon_0}\frac{3}{4\times 15} = \frac{q}{5p\varepsilon_0}$$

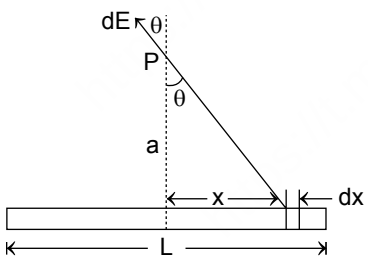
2. Find the electric field at a point P on the perpendicular bisector of a uniformly charged rod. The length of the rod is L, the charge on it is Q and the distance of P from the centre of the rod is a.

☞ **Solution** Charge per unit length $= \frac{Q}{L}$

Charge of length $dx = \frac{Q}{L}\,dx$

The electric field at the point P

$$dE = \frac{1}{4\pi\varepsilon_0}\frac{\frac{Q}{L}dx}{a^2 + x^2}$$



By the symmetry of result.

$$dE\cos\theta = \frac{1}{4\pi\varepsilon_0}\cdot\frac{Q dx}{L(a^2+x^2)}\cdot\frac{a}{(a^2+x^2)^{\frac{1}{2}}}$$

$$= \frac{Qa}{4\pi\varepsilon_0}\frac{dx}{(a^2+x^2)^{\frac{3}{2}}}$$

$$E = \int dE\cos\theta = \int_{-\frac{L}{2}}^{\frac{L}{2}} \frac{Qa}{4\pi\varepsilon_0}\frac{dx}{(a^2+x^2)^{\frac{3}{2}}}$$

Let, $x = a\tan\theta$, then $dx = a\sec^2\theta\, d\theta$

$$E = \frac{Qa}{4\pi\varepsilon_0}\int\frac{a\sec^2\theta d\theta}{a^3\sec^3\theta}$$

$$= \frac{Qa^2}{4\pi\varepsilon_0 a^3}\int\cos\theta d\theta$$

$$= \frac{Q}{4\pi\varepsilon_0 a^2}[\sin\theta] = \frac{Q}{4\pi\varepsilon_0 a}\left[\frac{x}{(a^2+x^2)^{1/2}}\right]_{-\frac{L}{2}}^{\frac{L}{2}}$$

$$= \frac{aQ}{4\pi\varepsilon_0 a^2}\left[\frac{2L}{(L^2+4a^2)^{\frac{1}{2}}}\right]$$

$$= \frac{Q}{2\pi\varepsilon_0 a\sqrt{L^2+4a^2}}$$

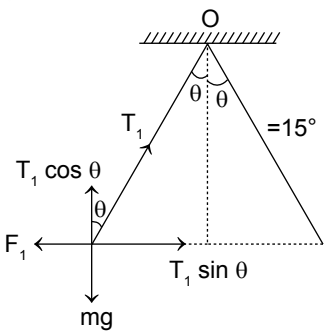
3. Two identically charged spheres are suspended by strings of equal lengths. The strings make an angle of 30° with each other. When suspended in a liquid of density 0.8 g cm^{-3}, the angle remains the same. What is the dielectric constant of the liquid? The density of the material of the sphere is 1.6 g cm^{-3}.

☞ **Solution** When the spheres are in air,

For equilibrium

$$mg = T_1\cos\theta \quad ...(i)$$

$$F_1 = T_1\sin\theta \quad ...(ii)$$



From the equations, (i) and (ii), we get

$$F_1 = mg\tan\theta$$

$$\frac{1}{4\pi\varepsilon_0}\frac{q^2}{r^2} = Vd\,g\tan\theta \quad ...(iii)$$

where, V = volume of each sphere

When spheres are in liquids, an upthrust given

$U = Vd_1g$

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where, $d_1 = 0.8\ g\ cm^{-3}$

$$\therefore \quad F_2 = \frac{1}{4\pi\varepsilon_0 k}\frac{q^2}{r^2}$$

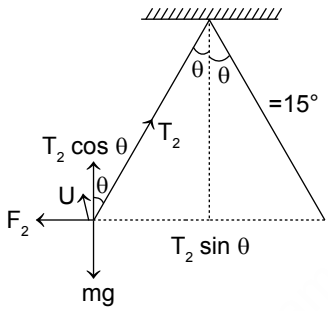
where, k = dielectric constant

For equilibrium

$$T_2 \cos\theta + U = mg$$

or $$T_2 \cos\theta = mg - U \quad ...(iv)$$

$$T_2 \sin\theta = F_2 \quad ...(v)$$



Dividing equation (v) by equation (iv), we get

$$\tan\theta = \frac{F_2}{mg - Vd_1 g}$$

or $F_2 = (mg - Vd_1\, g)\tan\theta$

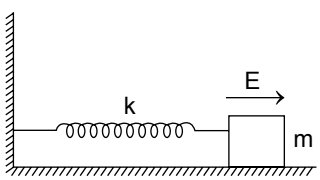
$$\therefore \quad \frac{1}{4\pi\varepsilon_0 k}\cdot\frac{q^2}{r^2} = (Vdg - Vd_1 g)\tan\theta \quad ...(vi)$$

From equations (iii) and (vi) we get

$$k = \frac{Vdg}{Vdg - Vd_1 g}$$

$$= \frac{d}{d - d_1} = \frac{1.6}{1.6 - 0.8} = 2$$

4. A block of mass m and having a charge q is placed on a smooth horizontal table and is connected to the wall through an unstressed spring of spring constant k as shown in the figure.



A horizontal electric field E parallel to the spring is switched on. Find the amplitude of the resulting SHM of the block.

☞ **Solution** Electric force of the block in forward direction = qE ...(i)

Spring force = $-kx$ ...(ii)

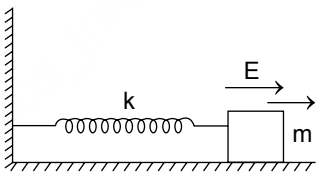
Here, $qE - kx = ma$ ...(iii)

Maximum x is equal to amplitude where acceleration is zero.

Let the amplitude be A

$$\therefore \quad qE = kA$$

or $$A = \frac{qE}{k}$$



Particle is in SHM because increased acceleration decreases displacement. Displacement always opposes the acceleration.

5. Two particles A and B each having a charge Q, are placed a distance d apart. Where should a particle of charge q be placed on the perpendicular bisector of AB so that it experience maximum force? What is the magnitude of this maximum force?

☞ **Solution** Let the distance x from the particle A, the third charge q is placed.

Net force on charge q is

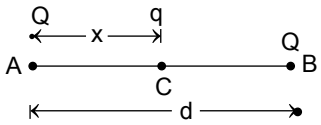
$$F = \frac{1}{4\pi\varepsilon_0}\left[\frac{qQ}{x^2} - \frac{qQ}{(d-x)^2}\right]$$

$$= \frac{qQ}{4\pi\varepsilon_0}\left[\frac{1}{x^2} - \frac{1}{(d-x)^2}\right]$$

For maximum value of F, $\frac{dF}{dx} = 0$

$$\therefore \quad \frac{dF}{dx} = \frac{qQ}{4\pi\varepsilon_0}\left[-\frac{2}{x^3} + \frac{2(d-x)}{(d-x)^4}\right] = 0$$

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or $x^3 - (d-x)^3 = 0$

or $x = d - x$

or $x = \mathbf{d/2}$.

6. Point charges q and–q are located at the vertices of a square with diagonals of length 2l. Find the electric field intensity at a point located symmetrically with respect to the vertices of the square at a distance *x* from it centre.

☞ **Solution** Let the centre is O (0, 0, 0)

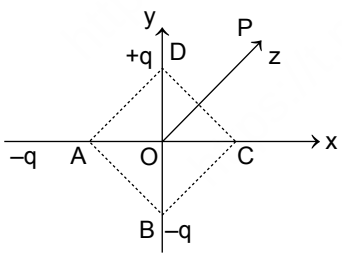
A = (–*l*, 0, 0), B = (0, –*l*, 0)

C = (*l*, 0, 0), D = (0, *l*, 0)

P = (0, 0, *x*),

The diagonals are *x*-axis and *y*-axis.

The distance from the vertices to the point P is equal.



$$\vec{E}_A = \frac{1}{4\pi\varepsilon_0}\frac{-q}{(l^2+x^2)^{\frac{3}{2}}}\left(x\vec{k}+l\vec{i}\right)$$

$$\vec{E}_A = \frac{1}{4\pi\varepsilon_0}\frac{-q}{(l^2-x^2)^{\frac{3}{2}}}.\left(x\vec{k}+l\vec{j}\right)$$

Similarly, $E_C = \frac{1}{4\pi\varepsilon_0}\frac{q}{(l^2+x^2)^{\frac{3}{2}}}.\left(x\vec{k}-l\vec{i}\right)$

$$E_D = \frac{1}{4\pi\varepsilon_0}\frac{q}{(l^2+x^2)^{\frac{3}{2}}}\left(x\vec{k}-l\vec{j}\right)$$

Now, $E = E_A + E_B + E_C + E_D$

$$= \frac{q}{4\pi\varepsilon_0}\frac{1}{(l^2+x^2)^{\frac{3}{2}}}$$

$$\left[-x\vec{k}-l\vec{i}-x\vec{k}-l\vec{j}+x\vec{k}-l\vec{i}+x\vec{k}-l\vec{j}\right]$$

$$= \frac{-q}{4\pi\varepsilon_0(l^2+x^2)^{\frac{3}{2}}}\left[2i\left(\vec{i}+\vec{j}\right)\right]$$

$$= \frac{ql}{\sqrt{2}\pi\varepsilon_0(l^2+x2)^{\frac{3}{2}}}.$$

7. A charge q is uniformly distributed over an arc angle θ_0. Find the electric field intensity at the centre of arc. The radius of arc is a.

☞ **Solution** The charge of *ds* element

$$dq = q\frac{ds}{s}$$

$$dq = q\frac{a\,d\theta}{a\,\theta_0} = \frac{q\,d\theta}{\theta_0}$$

The field at the centre

$$dE = \frac{dq}{4\pi\varepsilon_0 a^2} = \frac{qd\theta}{4\pi\varepsilon_0 a^2\theta_0}$$

For the symmetry

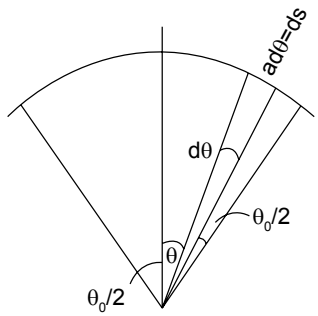
$$E = \int dE_y = \int dE\cos\theta$$

$$= \frac{q}{4\pi\varepsilon_0 a^2\theta_0}\int_{-\frac{\theta_0}{2}}^{\frac{\theta_0}{2}}\cos\theta d\theta$$

$$= \frac{2q}{4\pi\varepsilon_0 a^2\theta_0}\left[\sin\frac{\theta_0}{2}\right]$$

$$= \frac{q}{2\pi\varepsilon_0\theta_0 a^2}\sin\frac{\theta_0}{2}$$

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8. A thin non-conducting ring of radius R has linear charge density $\lambda = \lambda_0 \cos \varphi$, where λ_0 is constants and φ is the azimuthal angle. Find the magnitude of the electric field strength

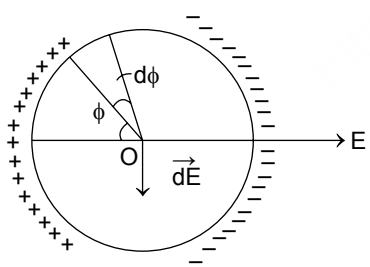
(i) **at the centre of ring.**

(ii) **on the axis of the ring as a function of the distance x from its centre.**

Investigate the obtained function at x >> R.

☞ **Solution**

(i) The given charge distribution is shown in the figure. The symmetry of this distribution implies that vector $\vec{E}$ at the point O is directed to the right and its magnitude is equal to the sum of the projection onto the direction of $\vec{E}$ vectors dE from elementary charges $T dq$.



The projection of vector $\vec{dE}$ on to the vector $\vec{E}$ is

$$dE\cos\phi = \frac{1}{4\pi\varepsilon_0}\frac{dq}{R^2}.\cos\phi. \qquad \ldots(i)$$

where, $dq = \lambda R\, d\phi = \lambda_0 R \cos\phi\, d\phi$

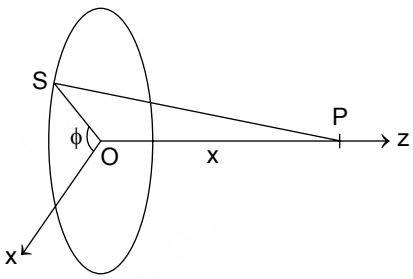
Integrating equation (i) over ϕ between 0 and 2π, we find the magnitude of the vector E.

$$E = \frac{\lambda_0}{4\pi\varepsilon_0 R}\int_0^{2\pi}\cos^2\theta\, d\theta$$

$$= \frac{\lambda_0}{4\pi\varepsilon_0 R}$$

$$\left[\because \int_0^{2\pi}\cos^2\phi = \int_0^{2\pi}\frac{1+\cos^2\phi d\phi}{2} = \pi\right]$$

(ii) Take an element S at an azimuthal angle ϕ from the x-axis subtending an angle $d\phi$ at the centre.



The elementary field at P due to the element

$$= \frac{\lambda_0 \cos\phi d\phi R}{4\pi\varepsilon_0(x^2+R^2)}$$

along SP with component.

$$\frac{\lambda_0 \cos\phi d\phi R}{4\pi\varepsilon_0(x^2+R^2)} \times \{\cos\theta \text{ along OP, } \sin\theta \text{ along OS}\}$$

where, $\cos\theta = \dfrac{x}{(x^2+R^2)^{\frac{1}{2}}}$

The component along OP vanishes on integration as $\int_0^{2\pi}\cos\phi d\phi = 0$. The component OS can be broken into the parts along OX and OY with

$$\frac{\lambda_0 R^2 \cos\phi d\phi}{4\pi\varepsilon_0(x^2+R^2)^{\frac{3}{2}}} \times (\cos\phi \text{ along OX, } \sin\phi \text{ along OY})$$

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On integration, the part along OY vanishes. Finally,

$$E = E_x = \frac{\lambda_0 R^2}{4\varepsilon_0 (x^2 + R^2)^{\frac{3}{2}}}$$

$$E_x = \frac{P}{4\pi\varepsilon_0 x^3}, \qquad \text{where } P = \lambda_0 \pi R^2$$

9. A ball of radius R carries a positive charge whose volume density depends only on the separation r from the ball's centres as $\rho = \rho_0\left(1 - \frac{r}{R}\right)$, where ρ_0 is constant. Assuming the permittivities of the ball and the environment to be equal to unity, Calculate:

(i) magnitude of the electric field strength as a function of distance r both inside and outside the ball.

(ii) maximum E_{max} and the corresponding distance r_{max}.

☞ **Solution** Electric field inside the ball

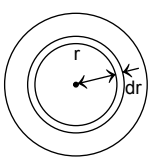
$$dE = \frac{1}{4\pi\varepsilon_0} \cdot \frac{dq}{R^2}$$

$$E = \int dE = \frac{1}{4\pi\varepsilon_0 r_2^2} \int_0^r \rho_0\left(1 - \frac{r}{R}\right).4\pi r^2 dr$$

where, $dq = \rho\, dV = \rho_0\left(1 - \frac{r}{R}\right).4\pi r^2 dr$

$$E = \frac{\rho_0}{\varepsilon_0 r^2}\left[\frac{r^3}{3} - \frac{r^4}{4}\right]_0^r$$

$$= \frac{\rho_0 r}{3\varepsilon_0}\left[1 - \frac{3r}{4R}\right] \text{ for } r < R$$



Electric field outside the ball

$$E = \frac{1}{4\pi\varepsilon_0 r^2} \int_0^R \rho_0\left(1 - \frac{r}{R}\right) 4\pi r^2 dr$$

$$= \frac{\rho_0}{\varepsilon_0 r^2}\left[\frac{r^3}{3} - \frac{r^4}{4R}\right]_0^R = \frac{\rho_0 R^3}{12\varepsilon_0 r^2}$$

(ii) For maximum value of E, $\frac{dE}{dr} = 0$

$$\therefore \quad \frac{dE}{dr} = \frac{\rho_0}{3\varepsilon_0}\left[1 - \frac{6r}{4R}\right] = 0$$

or $$\frac{\rho_0 r}{3\varepsilon_0}\left(1 - \frac{3r}{4R}\right) = 0$$

or $$1 - \frac{3r}{2R} = 0$$

or $$r = \frac{2}{3}R$$

$$\therefore \quad E = \frac{\rho_0 \frac{2}{3}R}{3\varepsilon_0}\left[1 - \frac{3 \times \frac{2}{3}R}{4R}\right]$$

$$= \frac{\rho_0 R}{9\varepsilon_0}$$

10. Calculate the electrostatic potential of a charged sphere of radius 'a' and having a charge density distribution as

$$\rho = \rho_0\left(1 - \frac{r}{a}\right); \text{ where } r \le a$$

$$= 0; \text{ where } r > a$$

(i) at the centre

(ii) inside and outside at a distance r_1 from the centre.

☞ **Solution**

(i) $$dV = \frac{1}{4\pi\varepsilon_0}\frac{dq}{r}$$

Here, $$dq = \rho\, dv = \rho_0\left(1 - \frac{r}{a}\right)4\pi r^2 dr$$

Integrating, we get

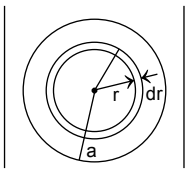
$$V = \int dV = \int_0^a \frac{1}{4\pi\varepsilon_0} \cdot \frac{\rho_0\left(1 - \frac{r}{a}\right)4\pi r^2 \cdot dr}{r}$$

$$= \frac{\rho_0}{\varepsilon_0}\int_0^a \left(r - \frac{r^2}{a}\right) dr$$

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$$= \frac{\rho_0}{\varepsilon_0}\left[\frac{r^2}{2} - \frac{r^3}{3a}\right]_0^a$$

$$= \frac{\rho_0 a^2}{6\varepsilon_0}$$



(ii) Potential at any point outside the sphere

$$V = \int \frac{dq}{4\pi\varepsilon_0 r_1}$$

$$= \frac{1}{4\pi\varepsilon_0 r_1}\int_0^a \rho_0\left(1 - \frac{r}{a}\right)4\pi r^2 dr$$

$$= \frac{\rho_0}{\varepsilon_0 r_1}\int_0^a \left(r^2 - \frac{r^3}{a}\right)dr$$

$$= \frac{\rho_0}{\varepsilon_0 r_1}\left[\frac{r^3}{3} - \frac{r^4}{4a}\right]_0^a = \frac{\rho_0 a^3}{12\varepsilon_0 r_1}$$

V_i = Potential due to the portion of sphere of radii 0 to r_1 + potential due to portion of the sphere between the radii r_1 to a.

$$= \frac{1}{4\pi\varepsilon_0}\frac{1}{r^1}\int_0^{r_1} 4\pi r^2 \rho_0\left(1 - \frac{r}{a}\right)dr$$

$$+ \frac{1}{4\pi\varepsilon_0}\int_{r_1}^a \frac{4\pi r^2}{r}\rho\left(1 - \frac{r}{a}\right)dr$$

$$= \frac{\rho_0}{\varepsilon_0 r_1}\left[\frac{r^3}{3} - \frac{r^4}{4a}\right]_0^{r_1} + \frac{\rho_0}{\varepsilon_0}\left[\frac{r^2}{2} - \frac{r^3}{2a}\right]_{r_1}^9$$

$$= \frac{\rho_0}{\varepsilon_0}\left[\frac{r_1^2}{3} - \frac{r_1^3}{4a} + \frac{a^2}{6} - \frac{r_1^2}{2} + \frac{r_1^3}{3a}\right]$$

$$= \frac{\rho_0}{6\varepsilon_0}\left[a^2 - r_1^2 + \frac{r_1^3}{2a}\right]$$

11. A non-conducting disc of radius 'a' and uniform positive surface charge density σ is placed on the ground with it axis vertical. A particle of mass 'm' and positive charge 'q' is dropped, along the axis of the disc, from a height 'H' with zero initial velocity. The particle has $\frac{q}{m} = \frac{4\varepsilon_0 g}{\sigma}$. Find the value of 'H' if the particale just reach the disc.

☞ **Solution** Let a ring is of radius x. Then

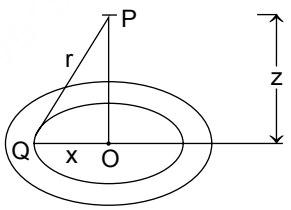
$dq = \sigma\, ds = \sigma .\, 2\pi x .\, dx$

$$dV = \frac{dq}{4\pi\varepsilon_0}.\frac{1}{r}$$

Integrating, we get

$$V = \int_0^a dV = \frac{\sigma.2\pi}{4\pi\varepsilon_0}\int_0^a \frac{x dx}{(x^2 + z^2)^{\frac{1}{2}}}$$

$$= \frac{\sigma}{2\varepsilon_0}\int_0^a \frac{x dx}{(x^2 + z^2)^{\frac{1}{2}}}$$



Put $x = z \tan\theta$

$\therefore \quad dx = z \sec^2\theta\, d\theta$

$$\therefore \quad V = \frac{\sigma}{2\varepsilon_0}\int \frac{z.\tan\theta.\sec^2\theta\, d\theta.z}{z.\sec\theta}$$

$$= \frac{\sigma}{2\varepsilon_0}\int z\tan\theta.\sec\theta.d\theta$$

$$= \frac{\sigma}{2\varepsilon_0}[z\sec\theta]$$

$$= \frac{\sigma}{2\varepsilon_0}\left[\left(a^2 + z^2\right)^{\frac{1}{2}} - z\right]$$

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The potential energy of the charge q at the point P is

U = (electrostatic + gravitational) potential energy

$$= \frac{q\sigma}{2\varepsilon_0}\left[(a^2+z^2)^{\frac{1}{2}} - z\right] + mgz$$

A particle of mass m and charge q is released with velocity v equal to zero along with axis of the disc at a distance H from the disc. It has just reach the disc (i.e., U = 0). This implies that

U (z = H) = U (z = 0)

i.e.,

$$\frac{q\sigma}{2\varepsilon_0}\left[(a^2+\mathrm{H}^2)^{\frac{1}{2}} - \mathrm{H}\right] + mg\mathrm{H} = \left(\frac{q\sigma}{2\varepsilon_0}\right)a \quad \ldots(\mathrm{i})$$

Given, $\frac{q}{m} = \frac{4\varepsilon_0 g}{\sigma}$

From equation (i), we have

$$\frac{q\sigma}{2\varepsilon_0}\left[(a^2+\mathrm{H}^2)^{\frac{1}{2}} - \mathrm{H}\right] + \frac{q\sigma}{4\varepsilon_0}\mathrm{H} = \left(\frac{q\sigma}{2\varepsilon_0}\right)a$$

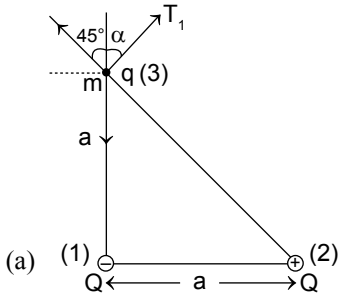
or $$(a^2+\mathrm{H}^2)^{1/2} - \mathrm{H} + \frac{\mathrm{H}}{2} = a$$

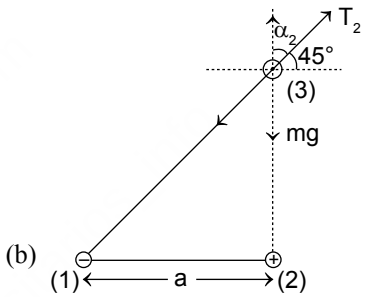
or $$a^2 + \mathrm{H}^2 = \left(a + \frac{\mathrm{H}}{2}\right)^2$$

or $$\mathrm{H} = \frac{4a}{3} \text{ and } \mathrm{H} = 0$$

12. Two small balls with equal but opposite charges are placed in a horizontal plane at a distance 'a' from each other. A third positively charged ball is suspended on a string. The point of suspension is first moved such that the third ball when in a state of equilibrium is above the first ball at a distance 'a' from it and then it moved such that the third ball is at a distance 'a' from the second one. Find the angle through which the string is deflected from the vertical, if angle of deflection above one of the balls is twice that above the other.

☞ **Solution**





When third ball is above the first ball at equilibrium,

Horizontal component

$$\mathrm{T}_1 \sin\alpha_1 = \frac{1}{4\pi\varepsilon_0}\frac{q\mathrm{Q}}{2a^2}\cdot\frac{1}{\sqrt{3}} \quad \ldots(\mathrm{i})$$

Vertical component

$$\mathrm{T}_1\cos\alpha_1 + \frac{1}{4\pi\varepsilon_0}\frac{q\mathrm{Q}}{2a^2}\cdot\frac{1}{\sqrt{2}}$$

$$= mg + \frac{1}{4\pi\varepsilon_0}\frac{q\mathrm{Q}}{a^2} \quad \ldots(\mathrm{ii})$$

From the figure (b)

$$\mathrm{T}_2\sin\alpha_2 = \frac{1}{4\pi\varepsilon_0}\frac{q\mathrm{Q}}{2a^2}\cdot\frac{1}{\sqrt{2}} \quad \ldots(\mathrm{iii})$$

For vertical component

$$\mathrm{T}_2\cos\alpha_2 + \frac{1}{4\pi\varepsilon_0}\cdot\frac{q\mathrm{Q}}{a^2}$$

$$= \mathrm{mg} + \frac{1}{4\pi\omega_0}\cdot\frac{q\mathrm{Q}}{2a^2}\cdot\frac{1}{\sqrt{2}} \quad \ldots(\mathrm{iv})$$

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Using equations (i), (ii), (iii) and (iv), we get

$\cot\alpha_1 - \cot\alpha_2 = 2(2\sqrt{2} - 1)$

But $\alpha_2 = 2\alpha_1$

$$\therefore \quad \frac{\sin 2\alpha_1 \cos\alpha_1 - \sin\alpha_1 \cos 2\alpha_1}{\sin\alpha_1 \sin 2\alpha_1} = 4\sqrt{2} - 2$$

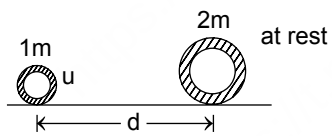
or $$\sin 2\alpha_2 = \frac{1}{4\sqrt{2} - 2}$$

$$\therefore \quad \alpha_2 = \frac{1}{2}\sin^{-1}\left(\frac{1}{4\sqrt{2} - 2}\right)$$

and $$\frac{1}{2}\left[\pi - \sin^{-1}\frac{1}{4\sqrt{2} - 2}\right]$$

13. Two particles of mass 'm' and '2m' carry a charge 'q' each. Initially, the heavier particle is at rest on a smooth horizontal plane and other is projected along the plane directly towards the first from a distance 'd' with speed 'u'. Find the closest distance of approach.

☞ **Solution**



For the closest approach because since the particle of mass 2 *m* is not fixed, hence, the second particle is also moving with velocity after the release.

Let for closest approach, $v_1 = v_2$.

Let the distance between them is *x*

From conservation of momentum,

From $mu = mv_1 + 2\,mv_2$

or $$v_1 = v_2 = \frac{u}{3}$$

By conservation of energy, loss in kinetic energy = gain in potential energy

$$\text{or} \quad \frac{1}{2}mu^2 - \left(\frac{1}{2}mv_2^1 + \frac{1}{2}2mv_2^2\right) = \frac{q^2}{4\pi\varepsilon_0}\left(\frac{1}{x} - \frac{1}{d}\right)$$

$$\text{or} \quad \frac{1}{2}mu^2 - \frac{1}{2}\frac{mu^2}{9}(1+2) = \frac{q^2}{4\pi\varepsilon_0}\left(\frac{1}{x} - \frac{1}{d}\right)$$

$$\text{or} \quad \frac{1}{3}mu^2 = \frac{q^2}{4\pi\varepsilon_0}\left(\frac{1}{x} - \frac{1}{d}\right)$$

$$\therefore \quad \frac{1}{x} = \frac{1}{d} + \frac{4\pi\varepsilon_0 mu^2}{3q^2}$$

$$\therefore \quad x = \frac{\boldsymbol{3q^2 d}}{\boldsymbol{3q^2 + 4\pi\varepsilon_0 mu^2 d}}$$

14. A charge 'q' is distributecd uniformly over the volume of a ball of radius R. Calculate:

(i) the energy stored in the ball

(ii) the energy in the surrounding space

(iii) Hence or otherwise, find the total energy of the system.

☞ **Solution**

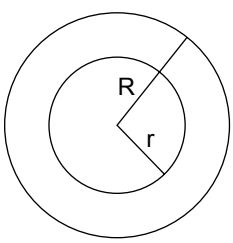
(i) When $r < R$

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

where, $$q = Q\cdot\frac{\frac{4}{3}\pi r^3}{\frac{4}{3}\pi R^3} = Q\left(\frac{r}{R}\right)^3$$

$$\therefore \quad E = \frac{1}{4\pi\varepsilon_0}\cdot\frac{Q\cdot r^3}{r^2 R^3} = \frac{1}{4\pi\varepsilon_0}\frac{Qr}{R^3}$$

Energy per unit volume $= \frac{1}{2}\varepsilon_0 E^2$



Energy, $U_1 = \int \frac{1}{2}\varepsilon_0 E^2 dv$

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$$= \int_0^R \frac{1}{2}\varepsilon_0 \left(\frac{Q}{4\pi\varepsilon_o}\right)^2 \frac{r^2}{R^6}.4\pi r^2.dr$$

$$= \frac{1}{2}\,\varepsilon_0 \left(\frac{Q}{4\pi\varepsilon_o}\right)^2 \cdot \frac{4\pi}{R^6}\int_0^R r^4.dr$$

$$= \frac{Q^2}{40\pi\varepsilon_0 R}$$

(ii) When $r > R$

Electric field intensity $= \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$

Energy of outside the ball

$$U_2 = \int_R^\infty \frac{1}{2}\varepsilon_0 E^2.dV$$

$$= \frac{1}{2}\varepsilon_0.\frac{Q^2}{(4\pi\varepsilon_0)^2}\cdot\int_R^\infty \frac{4\pi r^2.dr}{r^4}$$

$$= \frac{Q^2}{8\pi\varepsilon_0}\int_R^\infty \frac{dr}{r^2}$$

$$= \frac{Q^2}{8\pi\varepsilon_0 R}.$$

(iii) Total energy $= U_1 + U_2$

$$= \frac{Q^2}{40\pi\varepsilon_0 R} + \frac{Q^2}{8\pi\varepsilon_0 R}$$

$$= \frac{3Q^2}{20\pi\varepsilon_0 R}.$$

15. A charge 'q' uniformly distributed in a hemispherical surface of radius 'a'. Find the electric field intensity at the centre of the hemisphere.

☞ **Solution** From the figure

$$ds = 2\pi\,(a \sin\theta)\,(a\,d\theta)$$

The radius of strip is $a \sin\theta$ and its width is $(a\,d\theta)$

Area of the hemisphere,

$$A = 2\pi a^2$$

$$\therefore \quad dq = q\frac{ds}{A}$$

$$= \frac{q(2\pi a^2 \sin\theta\, d\theta)}{2\pi a^2}$$

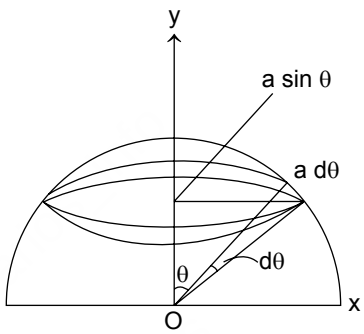
$$= q \sin\theta\, d\theta$$

$$dE = \frac{dp}{4\pi\varepsilon_0 a^2} = \frac{q\sin\theta\, d\theta}{2\pi a^2}$$

$$E = \int dE_y = \frac{q}{4\pi\varepsilon_0 a^2}\int_0^{\pi/2} \sin\theta\cos\theta\, d\theta$$

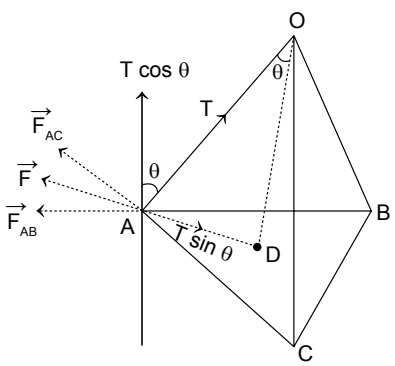
$$= \frac{1}{2}\times\frac{q}{4\pi\varepsilon_0 a^2}\left[\frac{-\cos 2\theta}{2}\right]_0^{\pi/2}$$

$$= \frac{q}{8\pi\varepsilon_0 a^2}.$$



16. Three particles, each of mass 1 gm and carrying a charge q, are suspended from a common point by insulated massless string, each 100 cm long. If the particles are in equilibrium and are located at the corners of an equilateral triangle of side length 3 cm, calculate the charge *q* on each particle. (Take g = 10 ms^{-2}).

☞ **Solution**



From the figure, O is the common point and D is the centre of equilibrium triangle.

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Resultant electric force,

$$\vec{F}_e = \vec{F}_{AB} + \vec{F}_{AC}$$

$$= 2 \cdot \frac{1}{4\pi\varepsilon_0} \cdot \frac{q^2}{a^2} \cos 30°$$

where, a is side of triangle.

$$\vec{F}_e = 2\left(\frac{1}{4\pi\varepsilon_0} \cdot \frac{q^2}{a^2}\right) \cdot \frac{\sqrt{3}}{2} \qquad \ldots(i)$$

In the direction of DA.

$$T \cos\theta = mg \qquad \ldots(ii)$$

$$T \sin\theta = F_e \qquad \ldots(iii)$$

From equations (ii) and (iii), we get

$$\tan\theta = \frac{F_e}{mg} = \left[9 \times 10^9 \times \frac{q^2}{(.03)^2}\sqrt{3}\right] \frac{1}{(10^{-3})(10)}$$

But $$AD = \frac{2}{3}\left(a^2 - \frac{a^2}{4}\right)^{\frac{1}{2}} = \frac{2}{3}\left(\frac{\sqrt{3}}{2}\right)(3\text{ cm})$$

$$= \sqrt{3}(10^{-2})\text{ m}$$

$$\sin\theta = \frac{AD}{AO} = \frac{\sqrt{3} \times 10^{-2}}{1} (AO = 1\text{m})$$

$\therefore$ $\tan\theta = .01732$ ($\cong \sin\theta$)

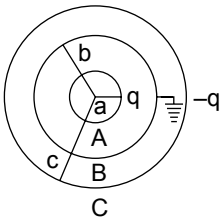
i.e., $$1.732 \times 10^{-2} = \frac{9 \times 10^9}{9 \times 10^{-4}} q^2 \left(\sqrt{3}\right) \frac{1}{(10^{-3})(10)}$$

or $$q^2 = \frac{10^{-8}}{10^9} = 10^{-17}$$

$\therefore$ $$q = \sqrt{10} \times 10^{-9}\text{ C}$$

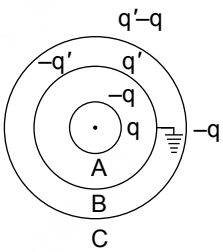
$$= \mathbf{3.16 \times 10^{-9}\ C.}$$

17. Figure shows three concentric thin spherical shells A, B and C of radii a, b and c respectively. The shells A and C are given charges q and –q respectively and the shell B is earthed. Find the charges appearing on the surfaces of B and C.



☞ **Solution**

The inner surface of B must have a charge $-q$ from the Gauss's law. Suppose, the outer surface of B has a charge q'. The inner surface of C must have charge $-q'$ from the Gauss's law. As the net charge on C must be $-q$, its outer surface should have a charge $q' - q$. The charge distribution is shown in the figure. The potential at B due to the charge q on A



$$= \frac{q}{4\pi\varepsilon_0 b}$$

Due to the charge $-q$ on the inner surface of B

$$= \frac{-q}{4\pi\varepsilon_0 b}$$

Due to the charge q' on the outer surface of B

$$= \frac{q'}{4\pi\varepsilon_0 b}$$

Due to the charge $-q'$, on the inner surface of C

$$= \frac{-q'}{4\pi\varepsilon_0 c}$$

And due to the charge $q' - q$ on the outer surface of C

$$= \frac{q' - q}{4\pi\varepsilon_0 c}$$

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The net potential is

$$V_B = \frac{q'}{4\pi\varepsilon_0 b} - \frac{q}{4\pi\varepsilon_0 c}$$

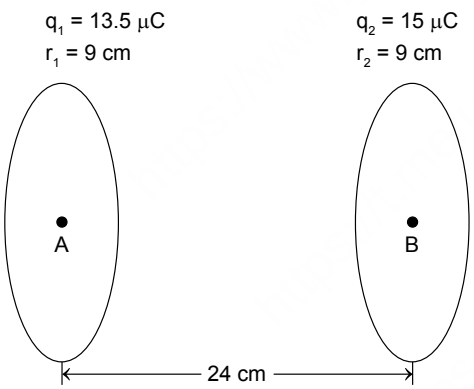
This should be zero as the shell B is earthed. Thus,

$$o = \frac{b}{c}q$$

18. Two parallel identical thin metallic rings, each of radius 9 cm, are mounted co-axially in free space at a distance of 24 cm from each other. One ring is given 13 μC and other 15 μC. Find the workdone in transporting 10 μC from the centre of one ring to the centre of the other ring.

☞ **Solution** Potential at the centre of the ring A due to charge q_1

$$V_1 = \frac{q_1}{4\pi\varepsilon_0}\cdot\frac{1}{r_1}$$



Potential at the centre of the ring A due to charge q_2

$$V_2 = \frac{q_2}{4\pi\varepsilon_0}\left(\frac{1}{\sqrt{r_2^2 + d^2}}\right)$$

Net potential at the centre of the ring A,
$V = V_1 + V_2$

$$= \frac{1}{4\pi\varepsilon_0}\left[\frac{q_1}{r_1} + \frac{q_2}{\sqrt{r_2^2 + d^2}}\right]$$

$$= 9\times10^9\left[\frac{13.5\times10^{-6}}{9\times10^{-2}} + \frac{15\times10^{-6}}{\sqrt{(9^2+24^2)\times10^{-4}}}\right]$$

$= 9 \times 10^9\,[1.5 \times 10^{-4} + 0.59 \times 10^{-4}]$

$= 18.81 \times 10^5$ V

Similarly,

Net potential at the centre of the ring B

$$V' = \frac{1}{4\pi\varepsilon_0}\left[\frac{q_2}{r_2} + \frac{q_1}{\sqrt{r_1^2 + d^2}}\right]$$

$$= 9\times10^9\left[\frac{15\times10^{-6}}{9\times10^{-2}} + \frac{13.5\times10^{-6}}{\sqrt{(9^2+24^2)\times10^{-4}}}\right]$$

$= 9 \times 10^9\,[1.67 \times 10^{-4} + 0.53 \times 10^{-4}]$

$= 19.8 \times 10^5$ V

Work done in transporting 10 μC

= (charge transported) × (potential difference)

$= (10 \times 10^{-6})\,(V' - V)$

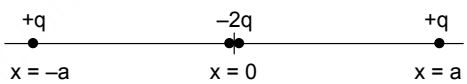
$= (10 \times 10^{-6})\,(19.8 \times 10^5 - 18.81 \times 10^5)$

$=$ **0.99 J.**

19. Two dipoles that are back to back from a linear electric quadrupole.

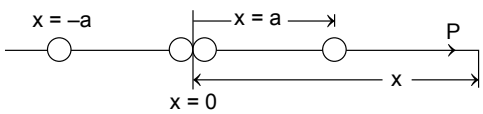
(i) **Calculate E_x for points on the x-axis, x >> a.**

(ii) **Calculate E_y for points on the y-axis, y >> a.**



☞ **Solution**

(i) Let at the point P, where the electric field are calculated. Distance from the point $x = 0$ to be x.



$$E_x = \frac{q}{4\pi\varepsilon_0}\frac{1}{(x-a)^2} + \frac{q}{4\pi\varepsilon_0(x+a)^2} - \frac{2q}{x^2}$$

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

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[For the expansion $(1 + x)^n = {}^nC_0 + {}^nC_1 x + {}^nC_2x^2 + \ldots$]

$$= \frac{q}{4\pi\varepsilon_0 x^2}\left[1 - \frac{2a}{x} + \frac{3a^2}{x^2} + \ldots + 1 + \frac{2a}{x} + \frac{3a^2}{x^2} + \ldots - 2\right]$$

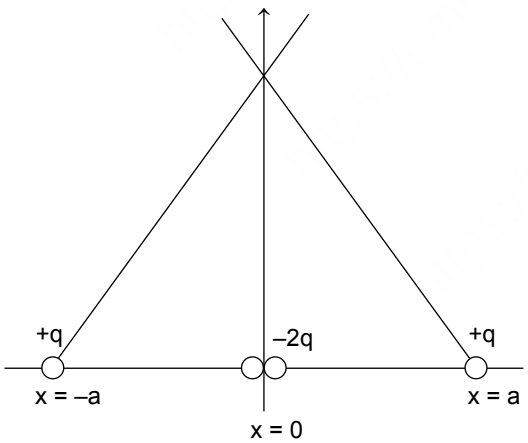
$$= \frac{q}{4\pi\varepsilon_0 x^2}\left[\frac{6a^2}{x^2}\right]$$

$$= \frac{6a^2 q}{4\pi\varepsilon_0 x^4}$$

(ii) $$E_y = \frac{1}{4\pi\varepsilon_0}\left[\frac{2qy}{(y^2 + a^2)^{\frac{3}{2}}} - \frac{2q}{y^2}\right]$$

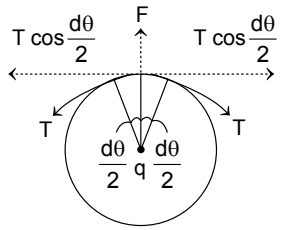
$$= \frac{2q}{4\pi\varepsilon_0 y^2}[y(y^2 + a^2)^{-3/2} - 2]$$

$$= \left(\frac{3qa^2}{4\pi\varepsilon_0 y^4}\right)$$



20. A thin conducting ring of radius r has an electric charge + Q. Find the increase in the tension of wire, if a charge + q is placed at the centre of ring.

☞ **Solution** Horizontal force is balanced and the vertical component.



$$F = 2T\sin\frac{d\theta}{2}$$

Since, $d\theta$ is small, therefore $\sin\frac{d\theta}{2} = \frac{d\theta}{2}$

$$F = 2T\frac{d\theta}{2} = T \cdot d\theta$$

$$\frac{1}{4\pi\varepsilon_0}\frac{dQq}{r^2} = T \cdot d\theta$$

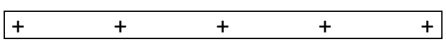
Here, $dQ = \frac{Q \cdot r\, d\theta}{2\pi r}$

Substituting this value in equation (i), we get

$$\frac{1}{4\pi\varepsilon_0}\frac{Q \cdot r\, d\theta}{r^2 \cdot 2\pi r} = T \cdot d\theta$$

or $$T = \frac{\boldsymbol{qQ}}{\boldsymbol{8\pi^2\varepsilon_0 r^2}}$$

21. A particle of mass 5×10^{-6} gm is kept over a large horizontal sheet of charge of density 4.0×10^{-6} C/m² as shown in the figure. What charge should be given to this particle so that if released, it does not fall down? How many electrons are to be removed to give this charge? How much mass is decreased due to removal of these electrons?



☞ **Solution** The electric field in front of the sheet is

$$E = \frac{\sigma}{2\varepsilon_0} = \frac{4.0\times10^{-6}\,C/m^2}{2\times8.85\times10^{-12}\,C^2/N\cdot m^2}$$

$$= 2.26 \times 10^5\ N/C$$

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If a charge q is given to the particle, the electric force qE acts in the upward direction. It will balance the weight of the particle if
$q \times 2.26 \times 10^5$ N/C $= 5 \times 10^{-9}$ kg $\times$ 9.8 m/s^2

or $$q = \frac{4.9\times10^{-8}}{2.26\times10^{5}}\text{C}$$
$$= 2.21 \times 10^{-13}\text{ C}$$

The charge on the electron is 1.6×10^{-19} *C*.
The number of electrons to be removed

$$= \frac{2.21\times10^{-13}}{1.6\times10^{-19}} = \mathbf{1.4\times10^{6}}$$

Mass decreased due to the removal of these electrons
$= 1.4 \times 10^6 \times 9.1 \times 10^{-31}$ kg
$= \mathbf{1.3 \times 10^{-24}\ kg}$

22. A soap bubble of radius r is given a charge of Q. Find out the change in the radius of bubble due to this charge. Atmospheric pressure is p.

☞ **Solution** According to Boyle's law

$$p\ \alpha \frac{1}{\text{V}}$$

or $$p = \frac{k}{\text{V}} = \frac{3k}{4\pi r^3}$$
$$= \frac{k'}{r^3}$$

where k' is a constant

$$\therefore \quad \frac{dp}{dr} = \frac{-3k'}{r^4} = \frac{-3pr^3}{r^4}$$
$$= \frac{-3p}{r}$$

$$\therefore \quad dr = \frac{-r}{3p}dp$$

Since, the change in pressure is due to charge given to drop, we have

$$dp = \frac{-\sigma^2}{2\varepsilon_0}$$

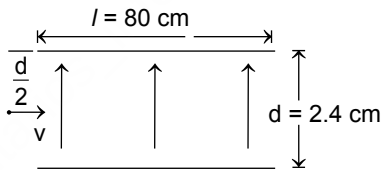
where, σ is surface density of charge.

$$\therefore \quad dp = -\left(\frac{\text{Q}}{4\pi r^2}\right)^2 \times \frac{1}{2\varepsilon_0} = -\frac{\text{Q}^2}{32\pi^2\varepsilon_0 r^4}$$

The radius will change by on amount

$$dr = -\frac{r}{3p}\left(\frac{\text{Q}^2}{32\pi^2\varepsilon_0 r^4}\right)$$
$$= \frac{Q^2}{96\pi^2\varepsilon_0 pr^3}$$

23. A particle with positive charge q = 5.5 × 10^{-5} C and mass m = 3.3 × 10^{-6} kg, initially travelling with speed v_0 = 4 × 10^2 ms^{-1} enters the region between two parallel plates, as shown in the figure. A uniform electric field E = 900 NC^{-1}, perpendicular to initial velocity exist between the plates.



(i) **Does the particle strike the upper plate? If it does where does it strike?**
(ii) **What is the minimum initial speed v_{min} the particle must have to get through the plates without striking them?**
(iii) **If the particle has minimum speed v_{min}, what is its velocity as it leaves the region between the plates?**

☞ **Solution**

(i) $\vec{\text{E}} = 900\,\text{NC}^{-1}$

At $t = 0$, $\vec{v} = v_0\vec{i}$
$v_0 = 4 \times 10^2\ ms^{-1}$
$q = 5.5 \times 10^{-5}$C, $m = 3.3 \times 10^{-6}$ kg,
$d = 2.4 \times 10^{-2}$m, $l = 80 \times 10^{-2}$m

Along y-direction:

Acceleration of the particle, $a_y = \frac{q\text{E}}{m}$

$\therefore \quad v_y = a_y t$ and $y = \frac{1}{2}a_y t^2$

When particle hits the plate, $y = \frac{d}{2}$

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$$\therefore \quad \frac{d}{2}=\frac{1}{2}\left(\frac{qE}{m}\right)t^2$$

or $$\frac{md}{qE}=t^2$$

or $$t^2=\frac{(3.3\times10^{-6})(2.4\times10^{-2})}{(5.5\times10^{-5})(900)}$$

$$\therefore \quad t=\sqrt{160}\times10^{-4}=4\sqrt{10}\times10^{-4}s$$

Along x-direction:

$$v_x=v_0 \text{ and } x=v_0t$$

$$\therefore \quad x=(4\times10^2)(4\sqrt{10}\times10^{-4})$$

$$=16\sqrt{16}\times10^{-2}m=16\sqrt{10}\,\text{cm}$$

Hence, particle strikes the plate at $x = 16\sqrt{10}$ cm, $y=\frac{d}{2}=\mathbf{1.2\,cm}$

(ii) For minimum speed, $x = l$

$$\therefore \quad 80\times10^{-2}=v\left(4\sqrt{10}\times10^{-4}\right)$$

$$\Rightarrow \quad v=\frac{20}{\sqrt{10}}\times10^2=\mathbf{2\sqrt{10}\times10^2\,ms^{-1}}$$

(iii) $$v_x=2\sqrt{10}\times10^2\,\text{ms}^{-1}$$

$$v_y=a_yt=\left(\frac{dE}{m}\right)t$$

[where, $t=4\sqrt{10}\times10^{-4}$ sec]

$$=\frac{(5.5\times10^{-5})(900)(4\sqrt{10}\times10^{-4})}{3.3\times10^{-6}}$$

$$=6\sqrt{10}\ \text{ms}^{-1}$$

$$\therefore \quad \vec{v}=\mathbf{2\sqrt{10}\times10^2\,\vec{i}+6\sqrt{10}\,\vec{j}\,(ms^{-1})}$$

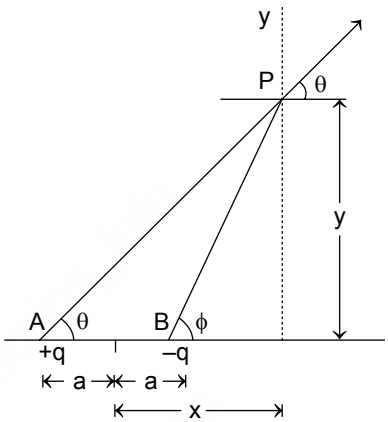
Since, no force acts on the particle after it leaves the region between the plates, it continues with velocity $\vec{v}$.

24. Show that the components E due to a dipole on the x-axis with its centre coinciding with the origin are given, at a distant point by

$$|E_x|=\frac{1}{4\pi\varepsilon_0}\frac{p(2x^2-y^2)}{(x^2+y^2)^{\frac{5}{2}}}$$

and $$|E_y|=\frac{1}{4\pi\varepsilon_0}\frac{3pxy}{(x^2+y^2)^{\frac{5}{2}}}$$

☞ **Solution**



From the figure

$$E_1=\frac{q}{4\pi\varepsilon_0}\frac{1}{y^2+(x-a)^2}$$

and $$E_2=\frac{-q}{4\pi\varepsilon_0}\frac{1}{y^2+(x+a)^2}$$

The expression of E_x is

$E_x = E_1 \cos\theta - E_2 \cos\phi$

$$=\frac{q}{4\pi\varepsilon_0}\frac{1}{y^2+(x+a)^2}\frac{x+a}{\sqrt{y^2+(x+a)^2}}$$

$$-\frac{q}{4\pi\varepsilon_0}\frac{1}{y^2+(x-a)^2}\frac{x-a}{\sqrt{y^2+(x-a)^2}}$$

Neglecting a^2 in the denominator, we get

$$E_x=\frac{q}{4\pi\varepsilon_0}$$

$$\left[\frac{x+a}{(x^2+y^2+2ax)^{\frac{3}{2}}}-\frac{x-a}{(x^2-y^2-2ax)^{\frac{3}{2}}}\right]$$

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$$= \frac{q}{4\pi\varepsilon_0}\frac{1}{(x^2+y^2)^{\frac{3}{2}}}\left[(x+a)\left(1-\frac{2ax}{x^2+y^2}\right)^{-\frac{3}{2}}\right.$$

$$\left.-(x-a)\left(1-\frac{2ax}{x^2+y^2}\right)^{-\frac{3}{2}}\right]$$

$$= \frac{q}{4\pi\varepsilon_0}\frac{1}{(x^2+y^2)^{\frac{3}{2}}}\left[(x+a)\left(1-\frac{3ax}{x^2+y^2}\right)\right.$$

$$\left.-(x-a)\left(1-\frac{3ax}{x^2+y^2}\right)\right]$$

$$= \frac{q}{4\pi\varepsilon_0}\frac{1}{(x^2+y^2)^{\frac{5}{2}}}[(x+a)\,(x^2+y^2-3ax)$$

$$-(x-a)\,(x^2+y^2+3ax)]$$

$$= \frac{q}{4\pi\varepsilon_0}\frac{1}{(x^2+y^2)^{\frac{5}{2}}}[-4ax^2+2ay^2]$$

$$= \frac{q(2a)(y^2-2x^2)}{(4\pi\varepsilon_0)(x^2+y^2)^{\frac{5}{2}}} = \frac{P(y^2-2x^2)}{4\pi\in_0(x^2+y^2)^{\frac{5}{2}}}$$

Working similarly for E_y, we get

$$E_y = E_1 \sin\theta - E_2 \sin\phi$$

$$= \frac{q}{4\pi\varepsilon_0}\frac{1}{y^2+(x+a)^2}\cdot\frac{y}{\sqrt{y^2+(x+a)^2}}$$

$$-\frac{q}{4\pi\varepsilon_0}\frac{1}{y^2+(x-a)^2}\cdot\frac{y}{\sqrt{y^2+(x-a)^2}}$$

$$= \frac{qy}{4\pi\varepsilon_0}\left[\frac{1}{\{y^2+(x+a)^2\}^{\frac{3}{2}}}-\frac{1}{\{y^2+(x-a)^2\}^{\frac{3}{2}}}\right]$$

Neglecting a^2 in the denominator, we get

$$E_y = \frac{qy}{4\pi\varepsilon_0}$$

$$\left[\frac{1}{(x^2+y^2+2ax)^{\frac{3}{2}}}-\frac{1}{(x^2+y^2-2ax)^{\frac{3}{2}}}\right]$$

$$= \frac{qy}{4\pi\varepsilon_0}\frac{1}{(x^2+y^2)^{\frac{3}{2}}}$$

$$\left[\left(1+\frac{2ax}{x^2+y^2}\right)^{-\frac{3}{2}}-\left(1-\frac{2ax}{x^2+y^2}\right)^{-\frac{3}{2}}\right]$$

$$= \frac{qy}{4\pi\varepsilon_0}\frac{1}{(x^2+y^2)^{\frac{3}{2}}}$$

$$\left[\left(1-\frac{3ax}{x^2+y^2}\right)-\left(1+\frac{3ax}{x^2+y^2}\right)\right]$$

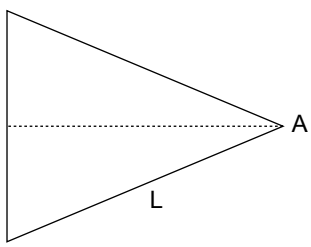
$$= \frac{qy}{4\pi\varepsilon_0}\frac{1}{(x^2+y^2)^{\frac{5}{2}}}$$

$$[x^2+y^2-3ax-x^2-y^2-3ax]$$

$$= \frac{-3pxy}{(4\pi\varepsilon_0)(x^2+y^2)^{\frac{5}{2}}}$$

Note: Had we taken the point P in the figure on the left side, we would have got the value $-E_x$ and $-E_y$.

25. A cone made of insulating material has a total charge Q spread uniformly over its sloping surface. Calculate the energy required to bring up a small test charge q from infinity to the apex A of the cone. The cone has a slope length L.

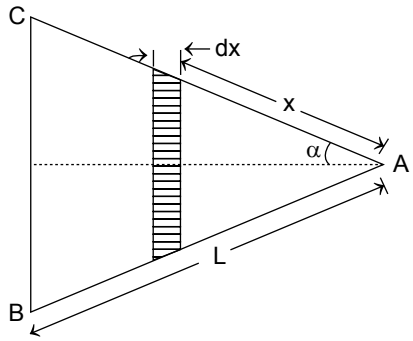


☞ **Solution** The total charge Q on the cone is uniformly spread over its sloping surface.

Let, σ be the surface charge density. The charge on an elementary area of the cone of side width dx at a distance x from the apex A is given by

$dq = 2\pi r\,(dx)\,\sigma = 2\pi\,(x\sin\alpha)\,dx\,\sigma$

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The potential at the apex due to this element area is given by

$$dV = \frac{1}{4\pi\varepsilon_0 x} dq$$

$$= \frac{2\pi(x\sin\alpha)\sigma\, dx}{4\pi\varepsilon_0 x} = \frac{\sigma\sin x}{2\varepsilon_0} dx$$

The potential due to the cone at A is then given by

$$V = \frac{\sigma\sin\alpha}{2\varepsilon_0}\int_0^L dx$$

$$= \frac{\sigma\sin\alpha\, L}{2\varepsilon_0}$$

Total charge on the cone is given by

$$Q = \text{curved surface area} \times \sigma$$

$$= \pi L^2 \sin\alpha\, \sigma$$

$$\therefore \quad V = \frac{Q}{2\pi\varepsilon_0 L}$$

The workdone in bringing up a charge $+q$ from infinity to A, then $\frac{Qq}{2\pi\varepsilon_0 L}$.

SOLVED OBJECTIVE TYPE QUESTONS

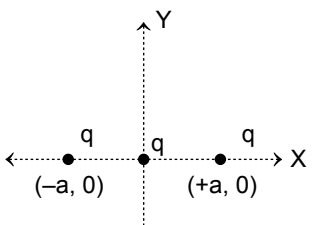
1. Two point charges each of charge +q are fixed at (+a, 0) and (–a, 0). Another positive point charge q placed at the origin is free to move along x-axis. The charge q at origin in equilibrium will have

(a) maximum force and minimum potential energy

(b) minimum force and maximum potential energy

(c) maximum force and maximum potential energy

(d) minimum force and minimum potential energy



☞ **Explanation** Net force on q at origin,

$$\vec{F} = \vec{F}_1 + \vec{F}_2$$

$$= \frac{1}{4\pi\varepsilon_0}\cdot\frac{q^2}{r^2}\hat{i} + \frac{1}{4\pi\varepsilon_0}\cdot\frac{q^2}{r^2}(-\hat{i}) = 0$$

Potential energy of the charge q in between the extreme charges at a distance x from the origin along +ve x axis is

$$U = \frac{1}{4\pi\varepsilon_0}\cdot\frac{q^2}{(a-x)} + \frac{1}{4\pi\varepsilon_0}\cdot\frac{q^2}{(a+x)}$$

$$= \frac{1}{4\pi\varepsilon_0}\cdot q^2\left[\frac{1}{a-x} + \frac{1}{a+x}\right]$$

$$\therefore \quad \frac{dU}{dx} = \frac{q^2}{4\pi\varepsilon_0}\left[-\frac{1}{(a-x)^2} + \frac{1}{(a+x)^2}\right]$$

For U to be minimum, $\frac{dU}{dx} = 0$, $\frac{d^2U}{dx^2} > 0$,

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$\Rightarrow \quad (a-x)^2 = (a+x)^2$

$\Rightarrow \quad a + x = \pm (a - x)$

$\Rightarrow \quad x = 0$, because other solution is relevent.

Thus the charged particle at the origin will have minimum force and minimum potential energy.

2. In a uniform electric field,

(a) all points are at the same potential

(b) pairs of points separated by the same distance must have the same potential difference

(c) no two points can have the same potential

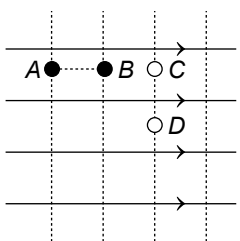
(d) none of the above

☞ **Explanation** If all points are at same potential, there cannot exist an electric field, as

$$E = \frac{dV}{dr}$$

Hence, (a) is not correct.

In a uniform electric field, the line of force are parallel and equidistant (solid lines). The equipotentials (dotted lines), being perpendicular to lines of force, are also equidistant and parallel. The distance between A and B is same as that between C and D. But, A and B will have some potential difference, whereas C and D being on the same equipotential, will have no potential difference.



Hence, (b) is not correct.

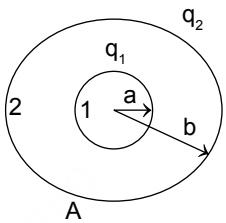
Points on an equipotential are at the same potential. Hence, (c) is not correct.

Hence, (d) is the correct answer.

3. Two conducting spheres having radii a and b are charged to q_1 and q_2 respectively. The potential difference between 1 and 2 will be

(a) $\frac{q_1}{4\pi\varepsilon_0 a} - \frac{q_2}{4\pi\varepsilon_0 b}$ (b) $\frac{q_2}{4\pi\varepsilon_0}\left(\frac{1}{a} - \frac{1}{b}\right)$

(c) $\frac{q_1}{4\pi_0}\left(\frac{1}{a} - \frac{1}{b}\right)$ (d) none of these



☞ **Explanation** Potential on the surface of the sphere 1 is given by

$$v_1 = \frac{1}{4\pi\varepsilon_0}\frac{q_1}{a} + \frac{1}{4\pi\varepsilon_0}\frac{q_2}{b}$$

Potential on the surface of the sphere 2 is given by,

$$v = v_1 - v_2$$

where, $v_2 = \frac{1}{4\pi\varepsilon_0}\frac{q_1}{b} + \frac{1}{4\pi\varepsilon_0}\frac{q_2}{b}$

$$\therefore \quad v = \frac{1}{4\pi\varepsilon_0}\frac{q_1}{a} + \frac{1}{4\pi\varepsilon_0}\frac{q_1}{b} = \frac{q_1}{4\pi\varepsilon_0}\left(\frac{1}{a} - \frac{1}{b}\right)$$

4. A quantity is given by $\varepsilon_0 L\frac{\Delta V}{\Delta t}$, where ε_0 is the permittivity of the free space, L is length, Δ is a potential difference and Δt is a time interval. The dimensional formula for X is same as that of

(a) resistance (b) charge

(c) voltage (d) current

☞ **Explanation** From the relation, $E = \frac{\sigma}{\varepsilon_0}$ and $\Delta V = E.L$, we get

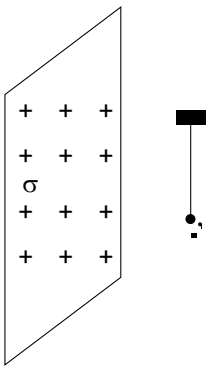
$$X = \frac{\sigma}{E}.L.\frac{EL}{\Delta t} = \frac{q}{L^2}\frac{L^2}{\Delta t} = \frac{q}{\Delta t}$$

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5. A small charged particle of mass m and charge q is suspended by an insulated thread in front of a very large sheet of charge density σ. The angle made by the thread with the vertical in equilibrium is

(a) $\tan^{-1}\left(\frac{\sigma q}{2\varepsilon_0 mg}\right)$ (b) $\tan^{-1}\left(\frac{\sigma q}{\varepsilon_0 mg}\right)$

(c) $\tan^{-1}\left(\frac{2\sigma q}{\varepsilon_0 mg}\right)$ (d) zero



☞ **Explanation** In equilibrium along x-axis,

$T \sin\theta = qE$

$\Rightarrow \quad T\sin\theta = q\frac{\sigma}{2\varepsilon_0}$ …(i)

where T is the tension in the string.

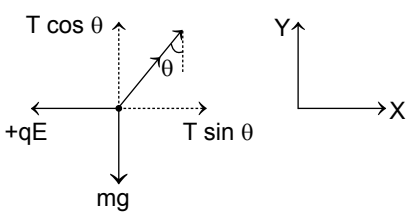
Along y-axis inequilibrium,

$T\cos\theta = mg$ ...(ii)

From equations (i) and (ii), we get

$$\tan\theta = \frac{q_\sigma}{2\varepsilon_{omg}}$$

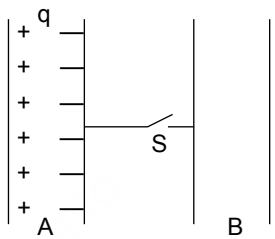
$\Rightarrow \quad \theta = \tan^{-1}\left(\frac{\sigma q}{2\varepsilon_0 mg}\right)$



6. Consider the situation shown in the figure. The capacitor A has a charge q on it whereas B is uncharged. The charge appearing on the capacitor B a long time after the switch is closed is

(a) zero (b) $\frac{q}{2}$

(c) q (d) $2q$



☞ **Explanation** As the negative charge on the plate of capacitor A is bound, it will not move upon closing thes switch.

Hence (a) is the correct answer.

7. A uniform electric field pointing in positive x-direction exists in a region. Let A be the origin, B be the point on the x-axis at x = +1 cm and C be the point on the y-axis at y = + 1 cm. Then the potentials at the points A, B and C statisfy

(a) $V_A < V_B$

(b) $V_A > V_B$

(c) $V_A < V_C$

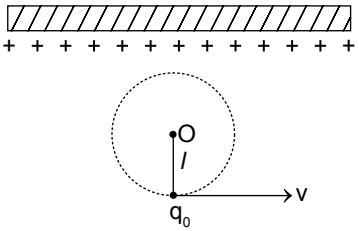
(d) $V_A > V_C$

☞ **Explanation** Since the potential decreases in the direction of electric field.

Hence (b) is the correct answer.

8. In the given figure, a large conducting ceiling having uniform charge density σ, below which a charge particle of charge q_0 and mass m is hanged from point O, through small string of length l. The minimum horizontal velocity required for the string to become horizontal, is

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(a) $\sqrt{2gl}$ (b) $\sqrt{5\left(gl+\frac{\sigma q_0}{\varepsilon_0}\right)}$

(c) $\sqrt{2l\left(g+\frac{\sigma q_0}{\varepsilon_0 m}\right)}$ (d) $\sqrt{g+\frac{\sigma q_0}{\varepsilon_0 m}}$

☞ **Explanation** Using work-energy theorem

$$\frac{1}{2}mv^2=\left(mg+\frac{\sigma q_0}{\varepsilon_0}\right)l$$

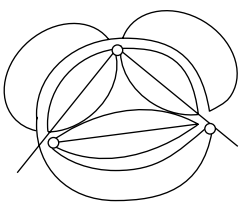
As for the tension to be zero in the horizontal position, V at that point must be zero.

$$\therefore \quad v^2=\frac{2l}{m}\left(mg+\frac{\sigma q_0}{\varepsilon_0}\right)$$

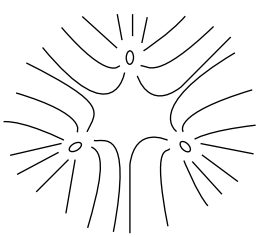
$$\Rightarrow \quad v=\sqrt{2l\left(g+\frac{\sigma q_0}{m\varepsilon_0}\right)}$$

9. Three positive charges of equal value q are placed at the vertices of an equilateral triangle. The resulting lines of force should be drawn as shown in

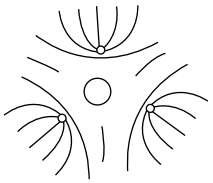
(a)



(b)



(c)



(d)



☞ **Explanation** Lines of force always emanate from positive charge and terminate at negative charge (or else go to infinity) and they never form closed curves.

Hence (c) is the correct answer.

10. Two equal point charges are fixed at x = –a and x = +a on the x-axis. Another point charge Q is placed at the origin. The change in the electrical potential energy of Q, when it is displaced by a small distance x along the x axis, is approximately proportional to

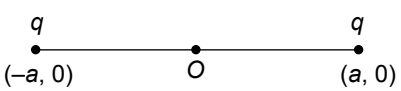
(a) x (b) x^2

(c) x^3 (d) $\frac{1}{x}$

☞ **Explanation** $U_i=\frac{2KQq}{a}$

$$U_f=\frac{KQq}{a+x}+\frac{KQq}{a-x}=\frac{2KQqa}{(a^2-x^2)}$$

$$\therefore \quad \Delta U=U_f-U_i$$



$$=2KQq\left[\frac{a}{a^2-x^2}-\frac{1}{a}\right]=2KQqa\left[\frac{x^2}{a(a^2-x^2)}\right]$$

$$=\frac{2KQqax^2}{a^3} \qquad (\text{since } a^2-x^2=a^2)$$

$$=\Delta U \mu x^2$$

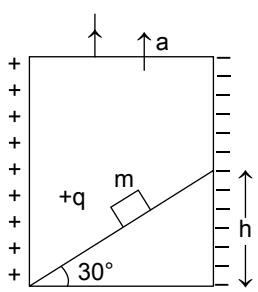
Hence (b) is the correct answer.

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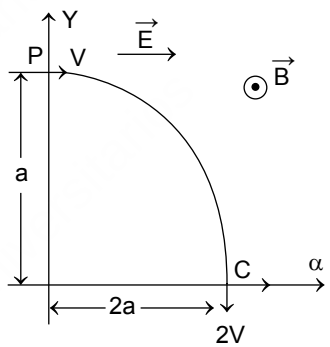
UNSOLVED OBJECTIVE TYPE QUESTIONS

1. **Three point charges are placed at the corners of an equilateral triangle. Assuming that only electrostatic are acting, the system**
   (a) will be in equilibrium if the charges have the same magnitude but not all have the same sign.
   (b) will be in equilibrium if the charges have different magnitudes but not all have the same sign.
   (c) will be in equilibrium if the charges rotate about the centre of the triangle.
   (d) can never be in equilibrium.

2. **A small block of mass 'm' is kept on a smooth inclined plane of angle 30° placed in an elevator going upward with acceleration 'a'. Electric field E exists between the vertical sides of the wall of the elevator. The charge on the block is +q. The time taken by the block to come to the lowest point of inclined plane is (take the surface to be smooth)**
   (a) $\sqrt{\frac{2h}{g}}$
   (b) $\sqrt{\frac{2h}{(g-a)+\frac{gE}{m}}}$
   (c) $\sqrt{\frac{2h}{(g+a)^2-\frac{qE}{m}\sqrt{3}}}$
   (d) $\sqrt{\frac{2h}{(g+a)^2-\left(\frac{qE}{m}\right)}}$



3. **A particle of charge +q and mass m moving under the influence of a uniform electric field $E\hat{i}$ and a uniform magnetic field $B\hat{k}$ follows trajectory from P to Q as a shown in the figure. The velocities at P and Q are $V\hat{i}$ and $-2V\hat{j}$ respectively.**
   (a) $E=\frac{3}{4}\frac{mv^2}{qa}$
   (b) Rate of work done by electric field at P is $\frac{3}{4}\frac{mv^3}{a}$
   (c) Rate of work done by electric field at P is not zero
   (d) All of these



4. **A positively charged disc is placed on a horizontal plane. A charged particle is released from a certain height on its axis. The particle just reaches the center of the disc. Then**
   (a) particle has negative charge on it
   (b) total potential energy (gravitational + electrostatic) of the particle first increases then decreases
   (c) total potential energy of the particle first decreases then increases
   (d) total potential energy of the particle continuously decreases

5. **Four charges of 6 μC, 2 μC, –12 μC and 4μC are placed at the corners of a square**

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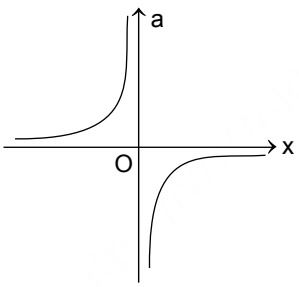
of side 1 m. The square is in x-y plane and its center at its origin. Electric potential due to these charges is zero everywhere on the line. Then

(a) $x = y, z = 0$ (b) $x = 0 = z$

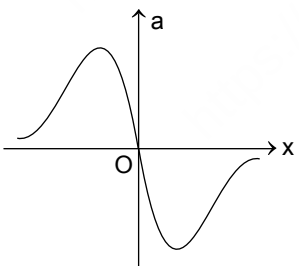
(c) $x = 0 = y$ (d) $x = z, y = 0$

6. Two identical positive charges are fixed on the y-axis, at equal distances from the origin O. A particle with negative charge starts on the x-axis at a large distance from O, moves along the x-axis, passes through O and moves for away from O. Its acceleration a is taken as positive along its direction of motion. The particle acceleration a is plotted against its x-coordinate. Which of the following best represents the plot?

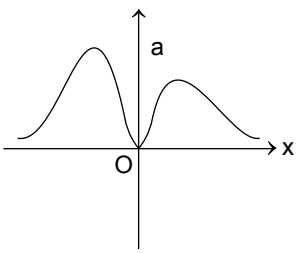
(a)



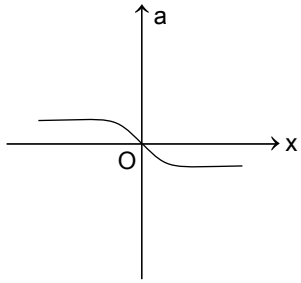
(b)



(c)



(d)



7. A rod of length L has a total charge q distributed uniformly along its length. It is bent in the shape of a semicircle. The electric potential at the center of the semicircle is

(a) $\frac{1}{4\pi\varepsilon_0}\frac{q}{L}$ (b) $\frac{q}{4\varepsilon_0 L}$

(c) $\frac{q}{2\varepsilon_0 L}$ (d) $\frac{1}{\pi\varepsilon_0}\frac{q}{L}$

8. A spherical volume contains a uniformly distributed charge of density ρ. The electric field inside the sphere at a distance r from center is

(a) $\frac{\rho}{3\varepsilon_0}r$ (b) $\frac{\rho}{4\pi\varepsilon_0}r$

(c) $\frac{\rho}{\varepsilon_0 r}$ (d) $\frac{1}{4\pi\varepsilon_0}r$

9. Two identical pendulums *A* and *B*, are suspended from the same point. The bobs are given positive charges, A having more charge than *B*. They diverge and reach equilibrium with *A* and *B* making angles θ_1 and θ_2 with the vertical respectively. Then

(a) $\theta_1 > \theta_2$

(b) $\theta_1 < \theta_2$

(c) $\theta_1 = \theta_2$

(d) The tension in A is greater than tension in B.

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10. Two fixed charges –2Q and + Q are located at points (–3a, 0) and (+3a, 0) respectively. Then

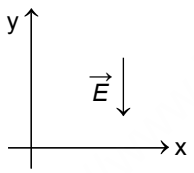
(a) points where the electric potential due to the two charges is zero, lie on a circle of radius 4a and center (5a, 0)

(b) potential is zero at $x = a$ and $x = 9a$

(c) If a particle of charge +q is released from the center of the circle obtained in part (a), it will eventually cross the circle

(d) All of these

11. A particle of mass m and charge –q is projected from the origin with a horizontal speed v into an electric field of intensity E directed downward. Then



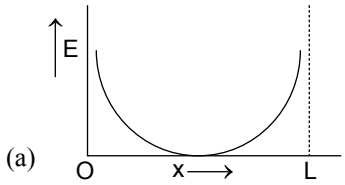
(a) The horizontal and vertical components of acceleration are $a_x = 0$, and $a_y = \frac{q\mathrm{E}}{m}$

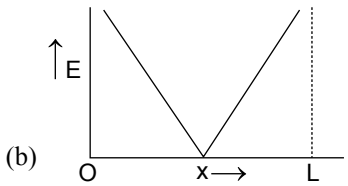
(b) equation of trajectory is, $y = \frac{1}{2}\left(\frac{q\mathrm{E}x^2}{mv^2}\right)$

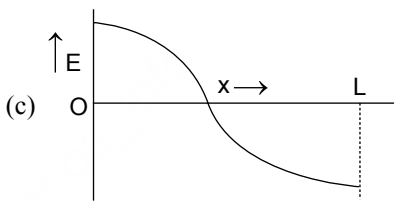
(c) horizontal and vertical displacements x and y after a time t are $x = vt$ and $y = \frac{1}{2}a_y t^2$

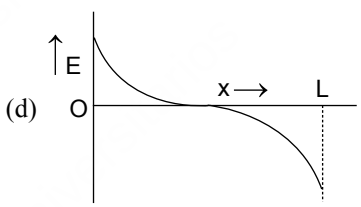
(d) all of these

12. Two identical point charges are placed at a separation of l. P is a point on the line joining the charges, at a distance x from any one charge. The field at P is E. E is plotted against x for values of x from close to zero to slightly less than l. Which of the following best represent the resulting curve?

(a)


(b)


(c)


(d)


13. A small ball of mass m and charge +q tied with a string of length l, is rotating in a vertical circle under gravity and a uniform horizontal electric field E as shown. The tension in the string will be minimum for

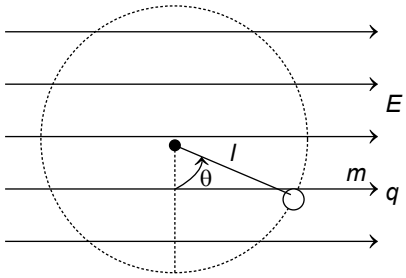
(a) $\theta = \tan^{-1}\left(\frac{q\mathrm{E}}{mg}\right)$

(b) $\theta = \pi$

(c) $\theta = \pi - \tan^{-1}\left(\frac{q\mathrm{E}}{mg}\right)$

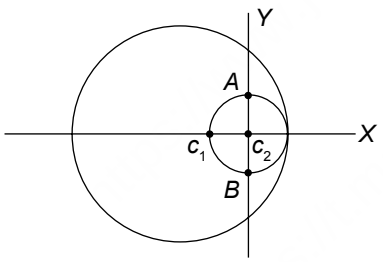
(d) $\theta = \pi + \tan^{-1}\left(\frac{q\mathrm{E}}{mg}\right)$

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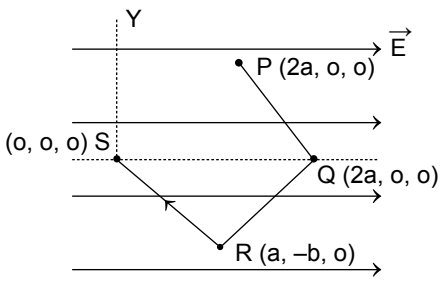


14. A uniformly charged sphere of radius R = 2 m and volume charge density ρ has a spherical cavity as shown. A point object of mass m = 1 g and charge q = 2 × 10⁻⁴ C is thrown, from point A. The minimum velocity required at A for it to reach point B is
(ρ = 3 ε₀ × 10⁻³ C/m³)

(a) 0.02 m/s (b) 0.g m/s
(c) 0.4 m/s (d) 0.04 m/s



15. A point charge q moves from point p to point S along the path PQRS in a uniform electric field $\vec{E}$ pointing parallel to the positive direction of the x-axis. The coordinate of points P, Q, R and S are (a, b, 0), (2a, 0, 0), (a, –b, 0) and (0, 0, 0) respectively. The work done by the field in the above process is given by the expression



(a) qaE
(b) $-qa$E
(c) $q(\sqrt{a^2+b^2})$E
(b) $3q$E$\sqrt{a^2+b^2}$

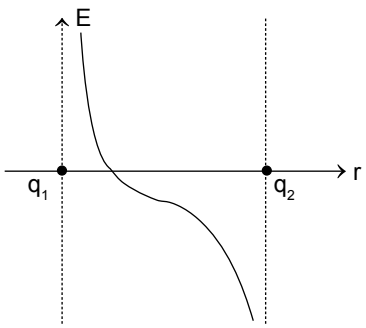
16. Five point charge (+q each) are placed at the five vertices of a regular hexagon of side 2a. What is the magnitude of the net electric field at the centre of the haxagon?

(a) $\frac{1}{4\pi\varepsilon_0}\frac{2}{a^2}$ (b) $\frac{q}{16\pi\varepsilon_0 a^2}$

(c) $\frac{\sqrt{2}\,q}{4\pi\varepsilon_0 a^2}$ (d) $\frac{5q}{16\pi\varepsilon_0 a^2}$

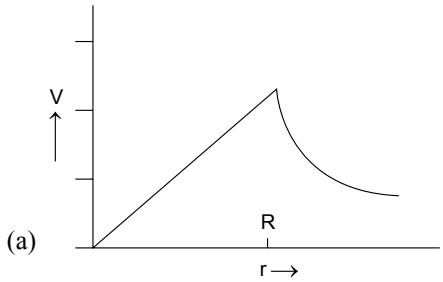
17. The variation of electric field between the two charges q_1 and q_2 along the line joining the charges is plotted against distance from q_1 (taking rightward direction of electric field as positive) as shown in the figure. Then

(a) q_1 and q_2 are positive and $q_1 < q_2$
(b) q_1 and q_2 are positive and $q_1 > q_2$
(c) q_1 is positive and q_2 is negative and $q_1 < q_2$
(d) q_1 and q_2 are negative and $q_1 < q_2$

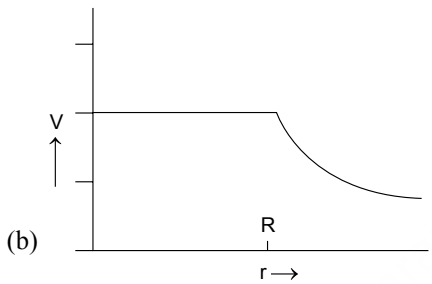


18. A solid sphere of radius R is charged uniformly. The electrostatic potential V is plotted as a function of distance r from the centre of the sphere. Which of the following best represents the resulting curve?

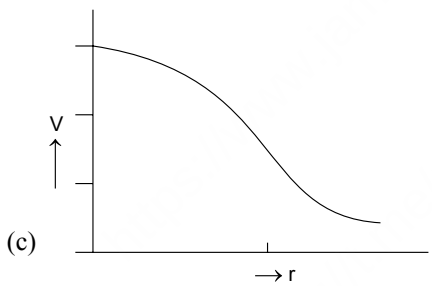
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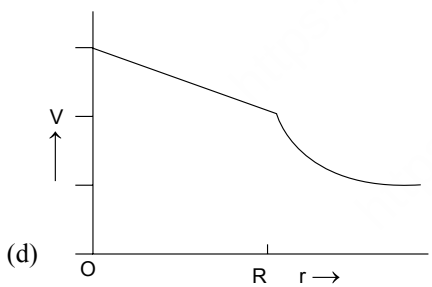
(a)



(b)

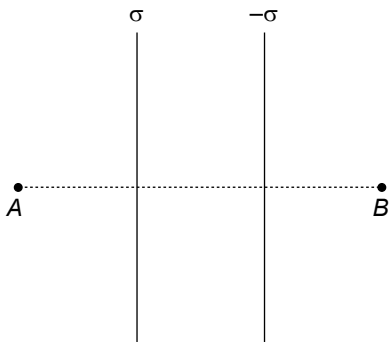


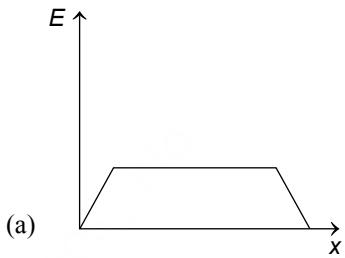
(c)



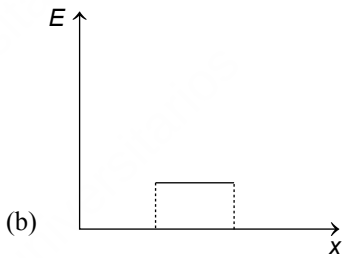
(d)

19. Two large parallel planes charged uniformly with surface charge density σ and –σ are located as shown in the figure. Which one of the following graphs shows the variation of electric field along a line perpendicular to the planes as one moves from A to B?

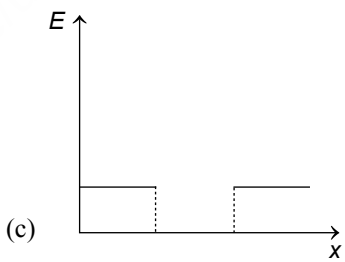




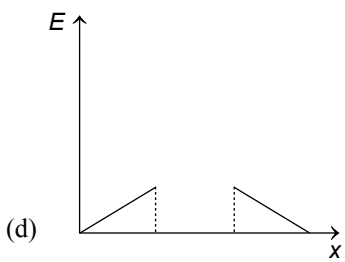
(a)



(b)



(c)

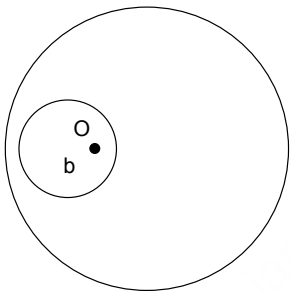


(d)

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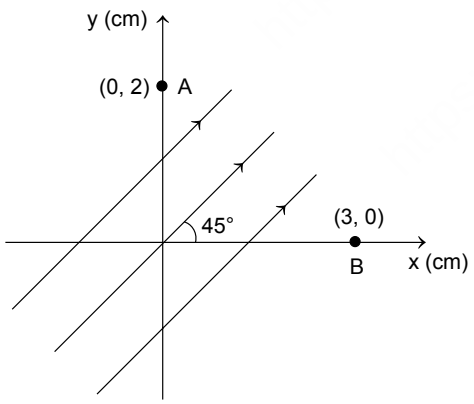
20. A charge q is placed at O in the cavity in a spherical uncharged conductor. Point S is outside the conductor. If the charge is displaced from O towards S still remaining within the cavity.

(a) electric field at S will increase
(b) electric field at S will decrease
(c) electric field at S will first increase and then decrease
(d) electric field at S will not change



21. A uniform electric field of 400 V/m is directed at 45° above the x-axis as shown in the figure. The potential difference $V_A - V_B$ is given by

(a) 0 (b) 1.8 V
(c) 2.8 V (d) 2.8 V



22. A large solid sphere with uniformly distributed positive charge has a smooth narrow tunnel through its centre. A small particle with negative charge, initially at rest for the sphere, approaches it along the line of the tunnel, reaches its surface with a speed v, and passes through the tunnel. Its speed at the centre of the sphere will be

(a) 0 (b) v
(c) $\sqrt{2}v$ (d) $\sqrt{1.5v}$

23. A point charge Q is placed outside a hollow spherical conductor of radius R, at a distance r (r > R) from its centre C. The field at C due to the induced charges on the conductor is

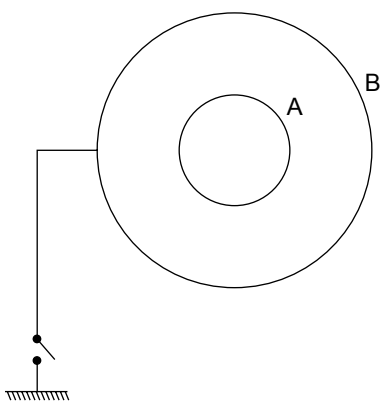
(a) zero
(b) $K\frac{Q}{(r-R)^1}$
(c) $K\frac{Q}{r^2}$, directed towards Q
(d) $K\frac{Q}{r^2}$, directed away from Q

24. A long string with a charge of λ per unit length passes through an imaginary cube of edge a. The maximum flux of the electric field through the cube will be

(a) $\frac{\lambda a}{q_0}$ (b) $\frac{\sqrt{2}\lambda a}{q_0}$
(c) $\frac{6\lambda a^2}{q_0}$ (d) $\frac{\sqrt{3}\lambda a}{q_0}$

25. Initially, the spheres A and B are at potentials V_A and V_B respectively. Now sphere B is earthed by closing the switch. The potential of A becomes

(a) 0 (b) V_A
(c) $V_A - V_B$ (d) V_B



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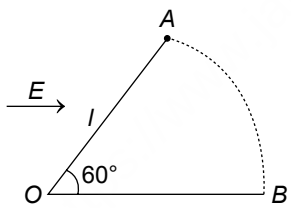
26. A particle of mass m and charge q is fastened to one end of a string of length *l*. The other end of the string is fixed to the point O. The whole system lies on a frictionless horizontal plane. Initially, the mass is at rest at A. A uniform electric field in the direction shown is then switched on. Then

(a) speed of the particle when it reaches B is $\sqrt{\frac{2qEl}{m}}$

(b) speed of the particle when it reaches B is $\sqrt{\frac{qEl}{m}}$

(c) tension in the string when particles reaches at B is qE

(d) tension in the string when the particle reaches at B is $2qE$



27. A charged particle of mass m and charge q is released from rest from position (x_0, 0) in a uniform electric field $E_0\hat{j}$. The angular momentum of the particle about origin

(a) is zero

(b) is constant

(c) increases with time

(d) decreases with time

28. A spherical conductor A of radius r is placed concentrically inside a conducting shell B of radius R (R > r). A charge Q is given to A, and then A is joined to B by a metal wire. The charge flowing from A to B will be

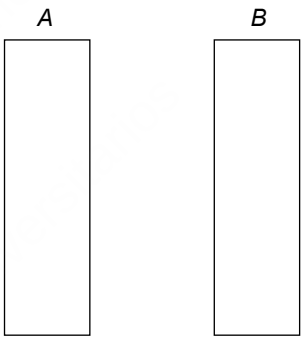
(a) $Q\left(\frac{R}{R+r}\right)$ (b) $Q\left(\frac{r}{R+r}\right)$

(c) Q (d) zero

29. Two conducting plates A and B each having large surface area S (on one side) are placed parallel to each other. The plate A is given a charge q, while the plate B is neutral. Then the electric field at a point in between the plates is

(a) $\frac{q}{2S\varepsilon_0}$ (b) $\frac{q}{S\varepsilon_0}$

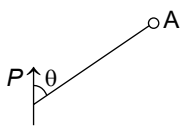
(c) $\frac{2q}{S\varepsilon_0}$ (d) $\frac{3}{2}\frac{q}{S\varepsilon_0}$



30. The electric field at A due to dipole p is perpendicular to p. The angle θ is

(a) 0º (b) 90º

(c) $\tan^{-1}2$ (d) $\tan^{-1}\sqrt{2}$



ANSWERS

1. (d)	**2.** (c)	**3.** (d)	**4.** (c)	**5.** (c)	**6.** (b)	**7.** (b)	**8.** (a)
9. (c)	**10.** (d)	**11.** (d)	**12.** (d)	**13.** (d)	**14.** (a)	**15.** (b)	**16.** (b)
17. (a)	**18.** (c)	**19.** (b)	**20.** (d)	**21.** (d)	**22.** (d)	**23.** (c)	**24.** (d)
25. (c)	**26.** (b,d)	**27.** (c)	**28.** (c)	**29.** (a)	**30.** (d)		

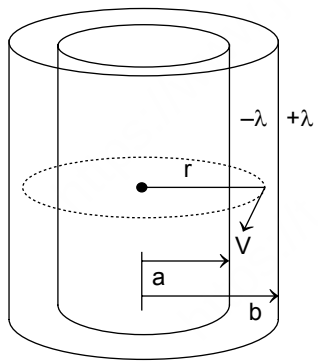
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PRACTICE EXERCISE 1

1. A uniform electric field having a magnitude E_0 and direction along positive X-axis exists. If the electric potential V is zero at x = 0, then its value at x = +x will be:

(a) $V_x = xE_0$ (b) $V_x = -xE_0$
(c) $V_x = x^2E_0$ (d) $V_x = -x^2E_0$

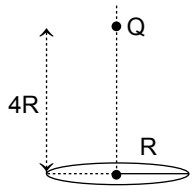
2. Figure shows two large cylindrical shells having uniform linear charge densities +λ and –λ. radius of inner cylinder is 'a' and that of outer cylinder is 'b'. A charged particle of mass m, charge q revolves in a circle of radius r. Then its speed 'v' is: (neglect gravity and assume the radii of both the cylinders to be very small in comparison to their length.)



(a) $\sqrt{\frac{\lambda q}{2\pi\varepsilon_0 m}}$ (b) $\sqrt{\frac{2\lambda q}{\pi\varepsilon_0 m}}$

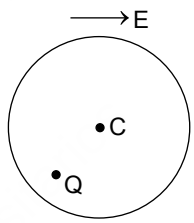
(c) $\sqrt{\frac{\lambda q}{\pi\varepsilon_0 m}}$ (d) $\sqrt{\frac{\lambda q}{4\pi\varepsilon_0 m}}$

3. A charge Q is placed at a distance of 4R above the centre of a dise of radius R. The magnitude of flux through the disc is φ. Now a hemispherical shell of radius R is placed over the disc such that it forms a closed surface. The flux through the curved surface taking direction of area vector along outward normal as positive, is



(a) zero (b) ϕ
(c) $-\phi$ (d) 2ϕ

4. A positive point charge Q is kept (as shown in the figure) inside a neutral conducting shell whose centre is at C. An external uniform electric field E is applied, then



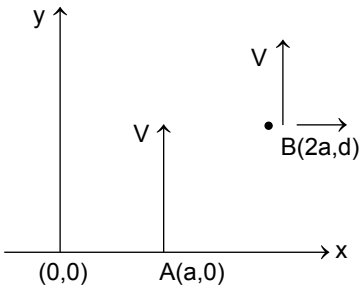
(a) force on Q due to E is zero
(b) net force on Q is zero
(c) net force acting on Q and conducting shell considered as a system is zero
(d) net force acting on the shell due to E is zero

5. A solid sphere of radius R has a volume charge density $\rho = \rho_0 r^2$ (where ρ_0 is a constant and r is the distance from centre). At a distance x from its centre for x < R. The electric field is directly proportional to:

(a) $1/x^2$ (b) $1/x$
(c) x^3 (d) x^2

6. Auniform electric field of strength exists in a region. An electron (charge –e, mass m) enters a point A with velocity $V\hat{j}$. It moves through the electric field and exits at point B. Then:

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(a) $\vec{E} = \frac{2amv^2}{ed^2}\hat{i}$

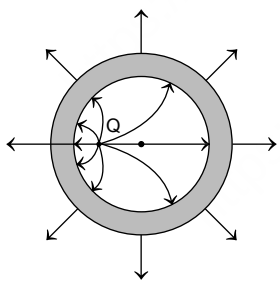
(b) Rate of work done by the electric field at is $\frac{4ma^2v^3}{d^3}$

(c) Rate of work by the electric field at A is zero

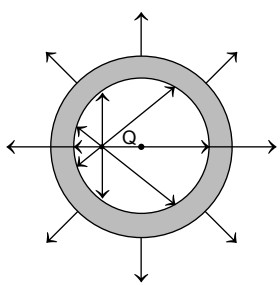
(d) Velocity at B is $\frac{2av}{d}\hat{i} + v\hat{j}$

7. A point charge 'q' is placed at a point inside a hollow conducting sphere. Which of the following electric force pattern is correct?

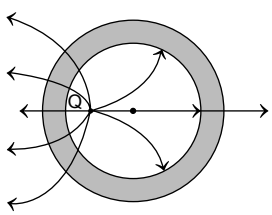
(a)



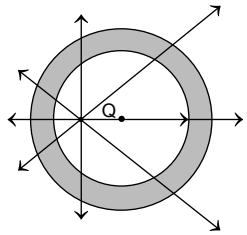
(b)



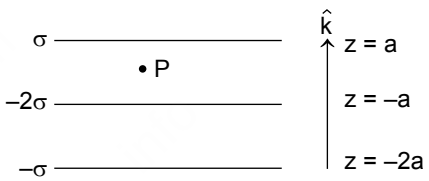
(c)



(d)



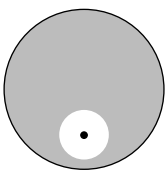
8. Three large parallel plates have uniform surface charge densities as shown in the figure. Find out electric field intensity at point P.



(a) $-\frac{4\sigma}{\varepsilon_0}\hat{k}$ (b) $\frac{4\sigma}{\varepsilon_0}\hat{k}$

(c) $-\frac{2\sigma}{\varepsilon_0}\hat{k}$ (d) $\frac{2\sigma}{\varepsilon_0}\hat{k}$

9. A spherical portion has been removed from a solid sphere having a charge distributed uniformly in its volume as shown in the figure. The electric field inside the emptied space is:



(a) zero everywhere
(b) non-zero and uniform
(c) non-uniform
(d) zero only at its center

10. Condider a system of three charges $\frac{q}{3}, \frac{q}{3}$ and $-\frac{2q}{3}$ placed at points *A, b,* and *c*, respectively, as shown in the figure, Take *O* to be the centre of the circle of radius *R* and angle *CAB* = 60º

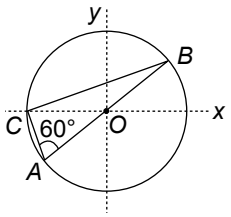
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(a) the electric field at point O is $\frac{q}{8\pi\varepsilon_0 R^2}$ directed

(b) the potential energy of the system is zero

(c) the magnitude of the force between the charges at C and B is $\frac{q^2}{54\pi\varepsilon_0 R^2}$

(d) the potential at point *O* is $\frac{q}{12\pi\varepsilon_0 R}$



11. The minimum strength of a uniform electric field which can tear a conducting uncharged thin-walled sphere into two parts is known to be E_0. Determine the minimum electric field strength E_1 required to tear the sphere of twice as large radius if the thickness of its walls is the same as in the former case.

(a) $\frac{E_0}{\sqrt{3}}$ (b) $\frac{E_0}{\sqrt{2}}$

(c) $\frac{E_0}{\sqrt{1}}$ (d) $\frac{E}{\sqrt{2}}$

12. A long, hollow conducting cylinder is kept coaxially inside another long, hollow conducting cylinder of larger radius. Both the cylinders are initially electrically neutral.

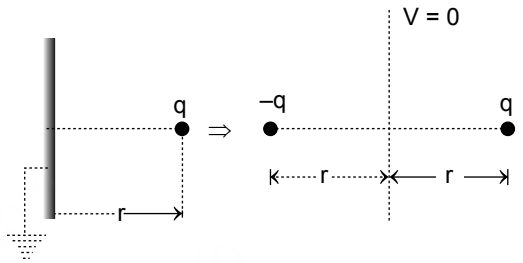
(a) P potential difference appears between the two cylinders when a charge density is given to the inner cylinder.

(b) A potential difference appears between two cylinders when a charge density is given to the outer cylinder.

(c) No potential difference appears between the two cylinders when a uniform line charge is kept along the axis of the cylinders

(d) No potential difference appears between the two cylinders when same charge density is given to both the cylinders

13. A point charge q is at a distance r from an infinite extend earthed conductor. Find force between them.



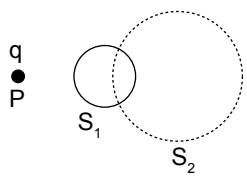
(a) $\frac{q^2}{12\pi\varepsilon_0 r}$ (b) $\frac{q^2}{18\pi\varepsilon_0 r}$

(c) $\frac{q^2}{16\pi\varepsilon_0 r}$ (d) $\frac{q^2}{13\pi\varepsilon_0 r}$

14. A conducting sphere S_1 intersects a closed surface S_2 as shown in the figure. A positive charge q is placed at a point P. What is the value of electric flux through the surface S_2?

(a) 0^+ (b) $\frac{q}{\varepsilon_0}$

(c) $< \frac{q}{\varepsilon_0}$ (d) $> \frac{q}{\varepsilon_0}$



15. In Vande-Graff's generator, the difference in potential between the inner sphere and the outer shell is independent of:

(a) the radius of the inner sphere

(b) the radius of the outer shell

(c) the charge on the inner shell

(d) the charge on the outer shell

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16. A conducting spherical bubble of radius a and thickness t(t<<a) is charged to a potential V. Now it collapses to form a spherical droplet. Find the potential of the droplet.

(a) $\left(\frac{a}{5t}\right)^{1/3}$ V (b) $\left(\frac{a}{t}\right)^{1/3}$ V

(c) $\left(\frac{a}{3t}\right)$ V (d) $\left(\frac{a}{3t}\right)^{1/3}$ V

17. There are two large metallic plates S_1 and S_2 carrying surface charge densities σ_1 and σ_2 respectively ($\sigma_1 > \sigma_2$) placed at a distance d apart in vacuum. Find the work done by the electric field in moving a point charge q distant a (a < d) from S_1 towards S_2 along a line making an angle $\pi/4$ with the normal to the plates.

(a) $\frac{q}{\sqrt{2}}(\sigma_1 - \sigma_2)$ (b) $\frac{qa}{\sqrt{2}}(\sigma_1 - \sigma_2)$

(c) $\frac{qa}{\sqrt{2}}(\sigma_1 + \sigma_2)$ (d) $\frac{qa}{\sqrt{4}}(\sigma_1 - \sigma_2)$

ANSWERS

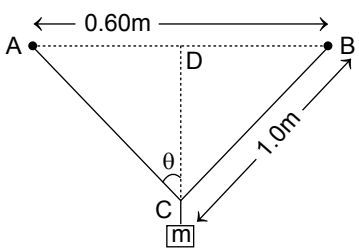
1. (b) **2.** (b) **3.** (c) **4.** (d) **5.** (c) **6.** (a,b,c,d) **7.** (a) **8.** (c)
9. (b) **10.** (c) **11.** (b) **12.** (a) **13.** (c) **14.** (c) **15.** (a) **16.** (d)
17. (b)

PRACTICE EXERCISE 2

1. Two similar helium filled spherical balloons tied to a 5 g weight with strings and each carrying an electric charge q, float in equilibrium as shown in the figure.

(a) Find the magnitude of q assuming that the charge on each balloon concentrated at its centre.

(b) Find the volume of each balloon (neglect the weight of the unfilled balloon and assume the density of air = 1.29 kg/m^3 and density of helium inside the balloon = 0.200 kg/m^3). **[IIT, 1967]**



[**Ans.** $q = \pm 0.55\ \mu C$, (b) 2.293×10^{-3} m^3]

2. An infinite number of charges each equal to q are placed along the x-axis at x = 1, x = 2, x = 4, x = 8, ... and so on. Find the potential and electric field at the point x = 0 due to this set of charges.

What will be the potential and electric field if in the above set up, the consecutive charges have opposite sign?

[IIT, 1974]

[**Ans.** At $x = 0, V = \frac{q}{2\pi\varepsilon_0}; E = \frac{q}{3\pi\varepsilon_0}$,

$V = \frac{q}{6\pi\varepsilon_0}; E = \frac{q}{5\pi\varepsilon_0}$]

3. Two point charges of value $(-20/3) \times 10^{-9}$ C and $(+ 20/3) \times 10^{-9}$ C are placed on the x-axis at x = –10 cm and x = 10 cm respectively.

(a) Calculate the potential and the electric fields at the points P (0, 10) and Q (20, 0).

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(b) Find the work done in carrying 1 C positive charge from P to Q along the straight-line joining P and Q.

(c) Is there any path along which the work done is less than the above value? Why. **[IIT, 1974]**

[**Ans.** (a) 400 volts; $E_Q = 5.33 \times 10^3$ N/C along the positive x-axis, (b) $W_{PQ} = 400$ joules, (c) There is no other path along which the work done is less than that calculated above, i.e., 400 joules.]

4. A positively charged oil droplet remains stationary in an electric field between two horizontal plates separated by a distance of 1 cm. If the charge on the drop is 3.2×10^{-19} C and the mass of the droplet is 10^{-14} kg, what is the potential difference between the plates? Now if the polarity of the plates is reversed what is the instantaneous acceleration of the droplet? [IIT, 1974]

[**Ans.** 3.063×10^3 volts; 19.6 m/s^2]

5. A particle of mass 40 mg and carrying a charge 5×10^{-9} C is moving directly towards a fixed positive charge of magnitude 10^{-8} C. When it is at a distance of 10 cm from the fixed positive charge it has a velocity of 0.5 m/s. At what distance from the fixed positive charge will the particle come momentarily at rest? Is the acceleration constant during motion? [IIT, 1975]

[**Ans.** 4.737×10^{-2}m; acceleration will not remain constant during motion]

6. Can a metal sphere of radius 1 cm hold a change of 1 coulomb? [IIT, 1975]

[**Ans.** No]

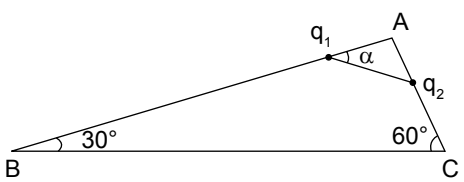
7. A particle having a charge of 1.6×10^{-19} C enters midway between the plates of a parallel plate condenser. The initial velocity of the particle is parallel to plates. A potential difference of 300 volt is applied to the capacitor plates. If the length of the capacitor plates is 10 cm and they are separated by 2 cm, calculate the greatest initial velocity for which the particle will not be able to come out of the plates. The mass of the particle is 12×10^{-24} kg. [IIT, 1976]

[**Ans.** 10^4 m/s]

8. Four charges +q, +q, – q and –q are placed respectively at the corners A, B, C and D of a square of side a, arranged in the given order. Calculate the potential and electric field at O, the centre of the square. If E and F are the mid pointsheet of the sides BC and CD respectively, what will be the work done in carrying a charge e from O to E and from O to F? [IIT, 1977]

$$\left[\text{Ans. } V_0 = 0; \frac{1}{4\pi\varepsilon_0} \cdot \frac{4\sqrt{2}\,q}{a^2}, -\frac{1}{4pe_0}\frac{4qe\left(\sqrt{5}-1\right)}{a\sqrt{5}}\right]$$

9. A rigid insulated wire frame in the form of a right angled triangle ABC is set in a vertical plane as shown in the Figure Two beads of equal masses m each and carrying charges q_1 and q_2 are connected by a chord of length l and can slide without friction on the wires. Considering the case when the beads are stationary, determine:



(a) the angle α

(b) the tension in the cord and

(c) the normal reactions on the beads.

If the cord is now cut, what are the value of the charges for which the beads continue to remain stationary. [IIT, 1978]

$$\left[\text{Ans. } (a)\,\alpha = 60°, (b)\frac{1}{4\pi\,\varepsilon_0} \cdot \frac{q_1 q_2}{l^2} + mg, (c)\,R_1 = \sqrt{3}mg, R_2 = mg\right]$$

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10. A pendulum bob of mass 80 mg and carrying a charge of 2×10^{-8} coulomb is at rest in a horizontal uniform electric field of strength 20,000 Vm^{-1}. Find the tension in the thread of the pendulum and angle it makes with the vertical. [IIT, 1979]

[**Ans.** 8.8×10^{-4} newton]

11. A copper atom consists of copper nucleus surrounded by 29 electrons. The atomic weight of copper is 63.5 g/mole. Let us now take two pieces of copper each weighing 10 g. Let us transfer one electron from one piece to another for every 1000 atoms in that piece. What will be the coulomb force between the two pieces after the transfer of electrons if they are 1 cm apart.

[Avogadro number = 6×10^{23} g/mole, Charge on one electron = -1.6×10^{-19} coulomb] [Roorkee, 1980]

[**Ans.** 2.057×10^{16}N]

12. Two equally charged identical metal spheres A and B repel each other with a force 2.0×10^{-5} newton. Another identical uncharged sphere C is touched to A and then placed at the mid point between A and B. What is the net electric force on C? [Roorkee, 1981]

[**Ans.** 2.0×10^{-5} N along $\vec{BA}$]

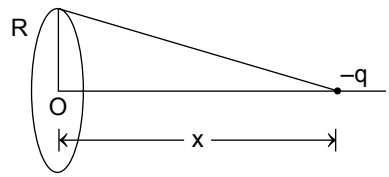
13. A charge Q is distributed over two concentric hollow spheres of radii r and R (where R > r) such that the surface densities are equal. Find the potential at the common centre. [IIT, 1981]

[**Ans.** Net potential at the centre,

$$\frac{1}{4\pi\varepsilon_0} \cdot \left(\frac{r+R}{r^2+R^2}\right) Q$$

]

14. A thin fixed ring of radius 1 m has a positive charge 1×10^{-5} coulomb uniformly distributed over it. A particle of mass 0.9 g and having a negative charge of 1×10^{-6} coulomb is placed on the axis at a distance of 1 cm from the centre of the ring. Show that the motion of the negatively charged particle is simple harmonic. Calculate the time of oscillation. [IIT, 1982]



[**Ans.** 0.628 sec]

15. Two identical particles of mass m carry a charge Q each. Initially one is at rest on a smooth horizontal plane and the other is projected along the plane directly towards the first particle from a large distance with the speed v. Find the closest distance of approach. [Roorkee, 1983]

$$\left[\textbf{Ans.}\ d = \frac{1}{4\pi\varepsilon_0} \cdot \frac{4Q^2}{mv^2}\right]$$

16. Two fixed equal positive charges, each of magnitude 5×10^{-5} coulomb are located at points A and B separated by a distance of 6 m. An equal and opposite charge moves towards them along the line COD, the perpendicular bisector of the line AB. The moving charge when it reaches the point C at a distance of 4 m from O, has a kinetic energy of 4 joule. Calculate the distance of the farthest point D which the negative charge will reach before returning towards C. [IIT, 1985]

[**Ans.** 8.5 m/s]

17. A drop of water of mass 18×10^{-3} g falls away from the bottom of charged conducting sphere of radius 20 cm carrying with it a charge of 10^{-9} coulomb and leaving on the sphere a uniformly distributed charge of 2.5×10^{-6} coulomb. What is the speed of the drop after it has fallen 30 cm?

[$(4\pi\varepsilon_0)^{-1} = 9 \times 10^9$ joule-meter/coulomb^2] [Roorkee, 1985]

[**Ans.** 3.658 m/s]

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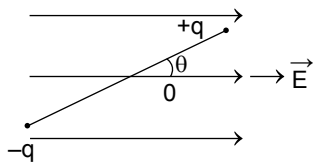
18. An inclined plane is making an angle of 30° with the horizontal electric field E of 100 V/m. A particle of mass 1 kg and charge 0.01 C is allowed to slide down from a height of 1 m. If the coefficient of friction is 0.2, find the time it will take the particle to reach the bottom.
[Roorkee, 1987]
[**Ans.** 1.34 second]

19. Three point charges q, 2q and 8q are to be placed on a 9 cm long straight-line. Find the position where the charges should be placed such that the potential energy of the system is minimum. In this situation, what is the electric field at the position of the charge q due to the other two charges? [IIT, 1987]
[**Ans.** 0]

20. Two identical charged spheres are suspended by strings of equal length. The strings make an angle 30° with each other. When suspended in a liquid of density 800 kg/m³, the angle remains the same. What is the dielectric constant of the liquid? The density of the material of the sphere is 1600 kg/m³.
[Roorkee, 1988; IIT, 1976]
[**Ans.** 2]

21. Three particles each of mass 1 gm and carrying a charge q are suspended from a common point by insulated massless strings, each 100 cm along. If the particles are in equilibrium and are located at the corners of an equilateral triangle of side length 3 cm, calculate the charge q on each particle.
(Take g = 10 m/s²) [IIT, 1988]
[**Ans.** 3.162×10^{-9} coulomb]

22. A point particle of mass M is attached to one end of a massless rigid non-conducting rod of length L. Another point particle of the same mass is attached to the other end of the rod. The two particles carry charges +q and –q respectively. This arrangement is held in a region of a uniform electric field E such that the rod makes a small angle θ (say of about 5 degrees) with the field direction. Find an expression for the minimum time needed for the rod to become parallel to the field after it is set free. [IIT, 1989]



$$\left[\textbf{Ans.}\ \frac{T}{4}=\frac{\pi}{2}\sqrt{\frac{ML}{2qE}}\right]$$

23. Two plane parallel conducting plates 1.5×10^{-2} m apart are held horizontally one above the other in air. The upper plate is maintained at positive potential of 1.5 kilovolt while the other plate is earthed. Calculate the number of electrons that must be attached to a small oil drop of mass 4.9×10^{-15} kg between the plates to maintain it at rest, assuming that the density of air is negligible in comparison with that of oil. If the potential of the above plate is suddenly changed to –1.5 kilovolt, what is the initial acceleration of the charged drop? Also obtain the terminal velocity of the drop if its radius is 5.0×10^{-6} m and the co-efficient of viscosity of air is 1.8×10^{-5} N-s/m².
[Roorkee, 1989]
[**Ans.** (a) $a = 19.6$ m/s² downward;
$v = 5.66 \times 10^{-5}$ m/s]

24. A charged dust particle of radius 5×10^{-7} m is located in a horizontal electric field having an intensity of 6.28×10^5 volt/m. The surrounding medium is air with co-efficient of viscosity $\eta = 1.6 \times 10^{-5}$ newton-sec/m². If this particle moves with a uniform horizontal speed 0.02 m/s, find the number of electrons on it.
[Roorkee, 1992]
[**Ans.** 30]

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25. Two circular wire loops of radii 0.05 m and 0.09 m respectively are put such that their axes coincide and their centre are 0.12 m apart. Charge of 10^{-6} C is spread uniformly on each loop. Find the potential difference between the centres of loops. [Roorkee, 1993]

[**Ans.** 7.08×10^4 volt]

26. A circular ring of radius R with uniform positive charge density λ per unit length is located in they y – z plane with its centre at the origin O. A particle of mass m and positive charge q is projected from the point P $\left(R\sqrt{3}, 0, 0\right)$ on the positive x-axis directly towards O, with an initial speed v. Find the smaller (non-zero) value of the speed v such that the particle does not return to P. [IIT, 1993]

$$\left[\textbf{Ans.}\ v = \sqrt{\frac{\lambda q}{2\varepsilon_0 m}}\right]$$

27. A charge of $+10^{-9}$ C is located at the origin in free space and another charge Q at (2, 0, 0). If the x-component of the electric field at (3, 1, 1) is zero, calculate the value of Q. Is the y-component zero at (3, 1, 1)?

[**Ans.** -4.27×10^{-10} C; *y*-component of electric field at P (3, 1, 1) is not zero]

28. A non-conducting disc of radius a and uniform positive surface charge density σ is placed on the ground, with its axis vertical. A particle of mass m and positive charge q is dropped, along the axis of the disc, from a height H, with zero initial velocity. The particle has

$$\frac{q}{m} = \frac{4\varepsilon_0 g}{\sigma}$$

Find the value of H if the particle just reaches the disc. [IIT, 1999]

$$\left[\textbf{Ans.}\ \mathrm{H} = \frac{4}{3}a\right]$$

29. Four point charges +8μC, –1 μC, –1μC and +8μC are fixed at point $-\sqrt{\frac{27}{2}}$ m, $-\sqrt{\frac{3}{2}}$ m, $+\sqrt{\frac{3}{2}}$ m and $+\sqrt{\frac{27}{2}}$ m respectively on the y-axis. A particle of mass 6×10^{-4} kg and of charge +0.1 μC moves along the – x direction. Its speed at x = + ∞ is v_0. Find the least value of v_0 for which the particle will cross the origin. Assume that the space is gravity free.

Given $\left(\frac{1}{4\pi\varepsilon_0}\right) = 9 \times 10^9$ Nm²/C². [IIT, 2000]

[**Ans.** 3 m/s]

30. A small ball of mass 2×10^{-3} kg having a charge of 1 μC is suspended by a string of length 0.8 m. Another identical ball having the same charge is kept at the point of suspension. Determine the minimum horizontal velocity which should be imparted to the lower ball so that it can make complete revolution. [IIT, 2001]

[**Ans.** 5.86 m/s]

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QUESTION BANK

CONCEPTUAL QUESTIONS

1. Two large conducting spheres carrying charges Q_1 and Q_2 are brought close to each other. Is the magnitude of electrostatic force between them exactly given by $Q_1Q_2/4\pi\varepsilon_0 r^2$, where r is the distance between their centres

2. If Coulomb's law involved $1/r^3$ dependence (instead of $1/r^2$), would Gauss's law be still true?

3. A small test charge is released at rest at a point in an electrostatic field configuration. Will it travel along the field line passing through that point?

4. What is the work done by the field of a nucleus in a complete circular orbit of the electron? What if the orbit is elliptical?

5. We know that electric field is discontinuous across the surface of a charged conductor. Is electric potential also discontinuous there?

6. What meaning would you give to the capacitance of a single conductor?

7. Guess a possible reason why water has a much greater dielectric constant (= 80) than say, mica (= 6)

8. The top of the atmosphere is at about 400 kV with respect to the surface of the earth, corresponding to an electric field that decreases with altitude. Near the surface of the earth, the field is about 100 Vm^{-1}. Why then do we not get an electric shock as we step out of our house into the open? (Assume the house to be a steel cage so there is no field inside.)

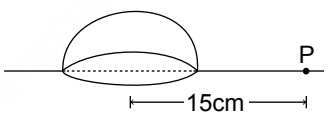
9. A man fixes outside his house one evening a two metre high insulating slab carrying on its top a large aluminium sheet of area 1 m^2. Will he get an electric shock if he touches the metal sheet next morning?

10. The discharging current in the atmosphere due to the small conductivity of air is known to be 1800 A on an average over the globe. Why then does the atmosphere not discharge itself completely in due course and become electrically neutral? In other words, what keeps the atmosphere charged?

11. What are the forms of energy into which the electrical energy of the atmosphere is dissipated during a lightning?

ONLY ONE OPTION IS CORRECT

1. Figure shows a solid hemisphere with a charge of 5nC distributed uniformly through its volume. The hemisphere lies on a plane and point P is located on the plane, along a radial line from the centre of curvature at distance 15 cm. The electric potential at point P due to the hemisphere, is



(a) 150 V (b) 300 V
(c) 450 V (d) 600 V

2. A point charge Q is placed at a distance d from the centre of an uncharged conducting sphere of radius R. The potential of the sphere is ($d > R$)

(a) $\frac{1}{4\pi\in_0}\cdot\frac{Q}{(d-R)}$ (b) $\frac{1}{4\pi\in_0}\cdot\frac{Q}{d}$

(c) $\frac{1}{4\pi\in_0}\cdot\frac{Q}{R}$ (d) zero

3. The plate of a parallel plate capacitor are separated by d cm. A plate of thickness t cm with dielectric constant k_1 is inserted and the remaining space is field with a plate of dielectric constant k_2. If Q is the charge on the capacitor and area of plates is A cm^2

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each, then potential difference between the plates is

(a) $\frac{Q}{\varepsilon_0 A}\left(\frac{t}{k_1}+\frac{d-t}{k_2}\right)$

(b) $\frac{4\pi Q}{A}\left(\frac{t}{k_1}+\frac{d-t}{k_2}\right)$

(c) $\frac{4\pi Q}{A}\left(\frac{k_1}{t}+\frac{k_2}{d-t}\right)$

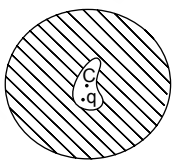
(d) $\frac{Q}{\varepsilon_0 A}\left(\frac{k_1}{t}+\frac{d-t}{k_2}\right)$

4. An electric field is given by $E_x = -2x^3$ kN/C. The potential of the point (1, –2), if potential of the point (2, 4) is taken as zero, is

(a) -7.5×10^3 V (b) 7.5×10^3 V

(c) -15×10^3 V (d) 15×10^3 V

5. The figure shows a charge q placed insider a cavity in an uncharged conductor. Now if an external electric field is switched on



(a) only induced charge on outer surface will redistribute

(b) only induced charge on inner surface will redistribute

(c) both induced charge on outer and inner surface will redistribute

(d) force on charge q placed inside the cavity will change

6. When a hydrogen atom is excited from ground state to first excited state then

(a) its kinetic energy increases by 10.2 eV

(b) its kinetic energy decreases by 10.2 eV

(c) its potential energy increases by 20.4 eV

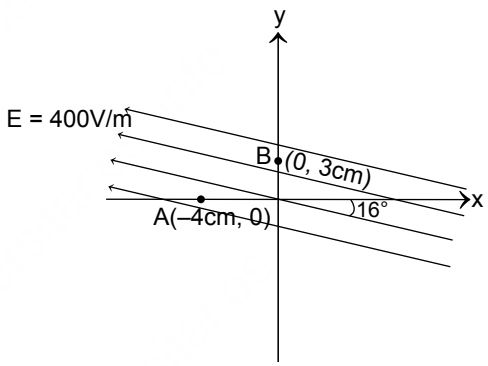
(d) its angular momentum increases by 1.05×10^{-34} J-s

7. A conducting disc of radius R about its axis with an angular velocity ω. Then the potential difference between the centre of the disc and its edge is (no magnetic field is present)

(a) zero (b) $\frac{m_e \omega^2 R^2}{2e}$

(c) $\frac{m_e \omega R^3}{3e}$ (d) $\frac{e m_e \omega R^2}{2}$

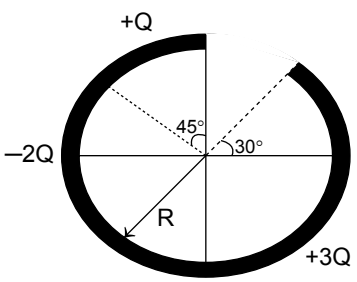
8. A uniform electric field of 400 V/m exists in space as shown in graph. Two points A and B are also shown with their co-ordinates. The potential difference $V_B - V_A$ in volts, is



(a) 18 V (b) 15 V

(c) 8 V (d) 12 V

9. Figure shows three circular arcs, each of radius R and total charge as indicated. The net electric potential at the centre of curvature is

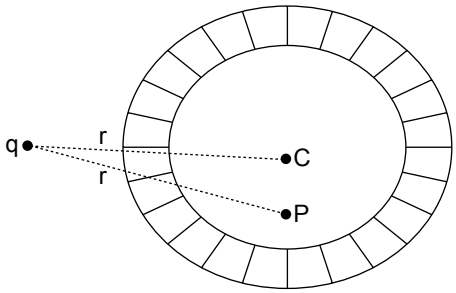


(a) $\frac{Q}{2\pi\varepsilon_0 R}$ (b) $\frac{Q}{4\pi\varepsilon_0 R}$

(c) $\frac{2Q}{\pi\varepsilon_0 R}$ (d) $\frac{Q}{\pi\varepsilon_0 R}$

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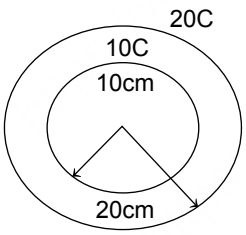
10. A neutral conducting spherical shell is kept near a charge q as shown. The potential at point p due to the induced charges is



(a) $\frac{kq}{r}$ (b) $\frac{kq}{r'}$

(c) $\frac{kq}{r}-\frac{kq}{r'}$ (d) $\frac{kq}{CP}$

11. Two concentric uniformly charged spheres of radius 10 cm and 20 cm are arranged as shown in figure. Potential difference between the sphere is



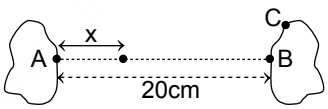
(a) 4.5×10^{11} V
(b) 2.7×10^{11} V
(c) 0
(d) None of these

12. The plates of a parallel plate capacitor are charged upto 100 volt. A 2 mm thick plate is inserted between the plates, then to maintain the same potential difference, the distance between the capacitor plates is increased by 1.6 mm. The dielectric constant of the plate is

(a) 5 (b) 1.25
(c) 4 (d) 2.5

13. In a uniform field
(a) all points are at the same potential
(b) pairs of points separated by the same distance must have the same potential difference
(c) no two points can have the same potential
(d) none of the above

14. Two metallic bodies separated by a distance 20 cm, are given equal and opposite charges of magnitude of $0.88\mu C$. The component of electric field along the line AB, between the plates, varies as $E_x = 3x^2 + 0.4$ N/C, where x (in meters) is the distance from one body towards the other body as shown.



(a) The capacitance of the system is $10\mu F$
(b) The capacitance of the system is $20\mu F$
(c) The potential difference between A and C is 0.088 volt
(d) The potential difference between A and C is cannot be determined from the given data

15. Electrical potential 'v' in space as a function of coordinates is given by, $V = \frac{1}{x}+\frac{1}{y}+\frac{1}{z}$. Then the electric field intensity at (1, 1, 1) is given by

(a) $-(\hat{i}+\hat{j}+\hat{k})$ (b) $\hat{i}+\hat{j}+\hat{k}$

(c) zero (d) $\frac{1}{\sqrt{3}}(\hat{i}+\hat{j}+\hat{k})$

16. Two concentric, thin metallic spheres of radii R_1 and R_2 ($R_1 > R_2$) bear changes Q_1 and Q_2 respectively. Then the potential at distance r between R_1 and R_2 will be $\left(k = \frac{1}{4\pi\varepsilon_0}\right)$

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(a) $k\left(\frac{Q_1+Q_2}{r}\right)$ (b) $k\left(\frac{Q_1}{r}+\frac{Q_2}{R_2}\right)$

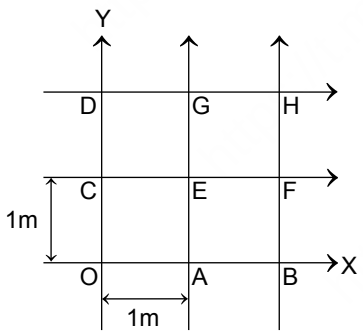
(c) $k\left(\frac{Q_2}{r}+\frac{Q_1}{R_1}\right)$ (d) $k\left(\frac{Q_1}{R_1}+\frac{Q_1}{R_2}\right)s$

17. A charge $+q$ is fixed at each of the points $x = x_0$, $x = 3x_0$, $x = 5x_0$, ... upto ∞ on X-axis and charge $-q$ is fixed on each of the points $x = 2x_0$, $x = 4x_0$, $x = 6x_0$, ... upto ∞. Here x_0 is a positive constant. Take the potential at a point due to a charge Q at a distance r from it to be $\frac{Q}{4\pi\varepsilon_0 r}$. Then the potential at the origin due to above system of charges will be

(a) zero (b) $\frac{q}{8\pi\varepsilon_0 x_0 \log_e 2}$

(c) ∞ (d) $\frac{q\log_e 2}{4\pi\varepsilon_0 x_0}$

18. The grid (each square of 1 m × 1 m), represents a region in space containing a uniform electric field.



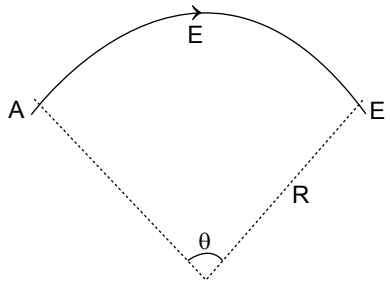
If potentials at points *O, A, B, C, D, E, F* and *G, H* are respectively 0, –1, –2, 1, 2, 0, –1, 1 and 0 volts, find the electric field intensity

(a) $(\hat{i}+\hat{j})$ V/m (b) $(\hat{i}-\hat{j})$ V/m

(c) $(-\hat{i}+\hat{j})$ V/m (d) $(-\hat{i}-\hat{j})$ V/m

19. Figure shows an electric line of force which curves along a circular arc.

The magnitude of electric field intensity is same at all points on this curve and is equal to E. If the potential at A is V, then the potential at B is



(a) $V - ER\theta$ (b) $V - E2R\ \sin\frac{\theta}{2}$

(c) $V + ER\theta$ (d) $V + 2ER\ \sin\frac{\theta}{2}$

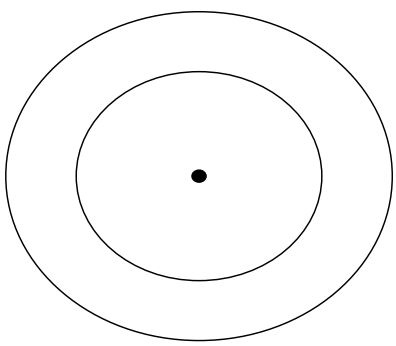
20. A parallel plate capacitor with air between the plates is charged to a potential difference of 500 V and then insulated. A plastic plate is inserted between the plates filling the whole gap. The potential difference between the plates now becomes 75 V. The dielectric constant of plastic is

(a) 10/3 (b) 5

(c) 20/3 (d) 10

21. In the figure, two conducting concentric spherical shells are shown.

If the electric potential at the centre is 20 V and the electric potential of the outer shell is 5 V, then the potential of the inner shell is

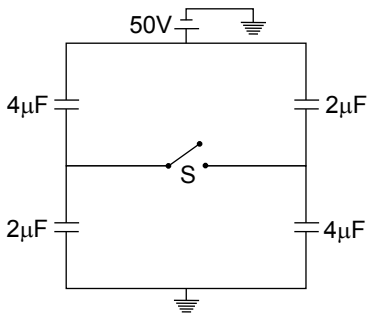


(a) 5 V (b) 15 V

(c) 20 V (d) 25 V

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22. The circuit was in the shown state for a long time. Now if the switch S is closed then the charge that flows through the switch S, will be



(a) $\frac{400}{3}\mu C$ (b) $100\mu C$

(c) $\frac{100}{3}\mu C$ (d) $50\mu C$

23. A capacitor of $1\mu F$ withstands a maximum voltage of 6 kilovolt while another capacitor of $2\mu F$ withstands a maximum voltage of 4 kilovolt. If the two capacitors are connected in series, the system will withstand a maximum voltage of

(a) 2 kV (b) 4 kV

(c) 6 kV (d) 9 kV

24. The potential at a certain point in an electric field is 200 V. The work done in carrying an electron upto that point will be

(a) 3.2×10^{-17} J (b) -3.2×10^{-17} J

(c) 200 J (d) –200 J

25. Two charged conducting spheres of radii r_1 and r_2 are at the same potential. The ratio of their surface charge densities will be

(a) r_1/r_2 (b) r_2/r_1

(c) $r_1^2/r_2^2 r_1^2/r_2^2$ (d) r_2^2/r_1^2

26. At the mid-point of a line joining an electron and a proton, the values of E and V will be

(a) $E = 0, V \neq 0$ (b) $E \neq 0, V = 0$

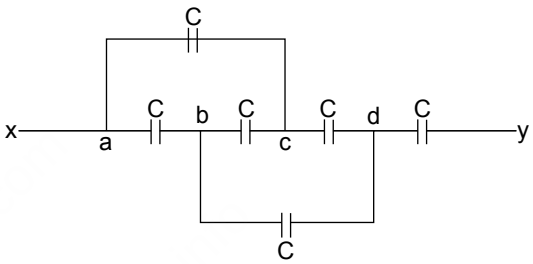
(c) $E \neq 0, V \neq 0$ (d) $E = 0, V = 0$

27. A charge of $10\mu C$ is kept at the origin of X–Y coordinate system. The potential difference in volts between two points $(a, 0)$ and $(a/\sqrt{2}, a/\sqrt{2})$ will be

(a) Zero (b) 9×10^4

(c) $\frac{9\times10^4}{a}$ (d) $\frac{9\times10^4}{\sqrt{2}}$

28. Find equivalent capacitance between X and Y if each capacitor is $4\mu F$.



(a) $4\mu F$ (b) $8\mu F$

(c) $12\mu F$ (d) $1\mu F$

29. Two point charge of $8\mu C$ and $12\mu C$ are kept in air at a distance of 10 cm from each other. The work required to change the distance between them to 6 cm will be

(a) 5.8 J (b) 4.8 J

(c) 3.8 J (d) 2.8 J

30. Two parallel plate capacitors of capacitances C and $2C$ are connected in parallel and charged to a potential difference V. The battery is then disconnected and the region between the plates of the capacitor C is completely filled with a material of dielectric constant K. The potential difference across the capacitors now becomes

(a) $\frac{3V}{K+2}$ (b) KV

(c) $\frac{V}{K}$ (d) $\frac{3}{KV}$

31. Maximum charge stored on a metal sphere of radius 15 cm may be $7.5\mu C$. The potential energy of the sphere in this case is

(a) 9.67 J

(b) 0.25 J

(c) 3.25 J

(d) 1.69 J

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32. Four identical particles each of mass m and charge q are kept at the four corners of a square of length L. The final velocity of these particles after setting them free will be

(a) $\left[\frac{Kq^2}{mL}(5.4)\right]^{1/2}$ (b) $\left[\frac{Kq^2}{mL}(1.35)\right]^{1/2}$

(c) $\left[\frac{Kq^2}{mL}(2.7)\right]^{1/2}$ (d) Zero

33. A parallel plate capacitor is charged to a certain potential difference A slab of thickness 3 mm is inserted between the plates and it becomes necessary to increase the distance between the plates by 2.4 mm to maintain the same potential difference. The dielectric constant of the slab is

(a) 3 (b) 5

(c) 2.5 (d) 2

34. A charge Q is distributed over two concentric hollow spheres of radii r and R ($R > r$) such that the surface densities are equal. The potential at the common centre is $\frac{1}{4\pi\varepsilon_0}$ times

(a) $Q\left[\frac{r+R}{r^2+R^2}\right]$ (b) $\frac{Q}{2}\left(\frac{r+R}{r^2+R^2}\right)$

(c) $2Q\left(\frac{r+R}{r^2+R^2}\right)$ (d) zero

35. A charge $+Q$ is uniformly distributed over a thin ring of radius R, velocity of an electron at the moment it passes through the centre O of the ring, if the electron was initially at rest at a point A which is very far away from the centre and on the axis of the ring is

(a) $\sqrt{\frac{2kQe}{mR}}$ (b) $\sqrt{\frac{kQe}{m}}$

(c) $\sqrt{\frac{kme}{QR}}$ (d) $\sqrt{\frac{kQe}{mR}}$

36. The electric potential V as a function of distance x (in metre) is given by: $V = (15x^2 + 10x - 9)$ V. The value of electric field of $x = 1$ m would be

(a) 20 V/m

(b) 6 V/m

(c) 11 V/m

(d) –23 V/m

37. In a region the electric field intensity E is given by $E = 100/x^2$ where x in metre. The potential difference between the points at $x = 10$ m and $x = 20$ m will be

(a) 1 V (b) 2 V

(c) 5 V (d) 10 V

38. An uncharged capacitor with a solid dielectric is connected to a similar air capacitor charged to a potential of V_0. If the common potential after sharing of charges becomes V, then the dielectric constant of the dielectric must be

(a) $\frac{V_0}{V}$ (b) $\frac{V}{V_0}$

(c) $\frac{V_0 - V}{V}$ (d) $\frac{V_0 + V}{V_0}$

39. Two parallel conducting plates 5 mm apart are held horizontally one above the other. The upper plate is maintained at a positive potential of 15 kV while the lower plate is earthed. If a small oil drop of relative density 0.92 and of radius 5μm remains stationary between the plates then the charge on the drop will be

(a) 10e (b) 8e

(c) 5e (d) 3e

40. An infinite number of charges (each of magnitude 1μc) are placed along the X-axis at $x = 1, 2, 4, 8....$ metre. If the charges are alternately of opposite sign, then the potential at the point $x = 0$ due to these charges will be

(a) 6×10^3 V (b) 9×10^3 V

(c) 1.8×10^4 V (d) 1.2×10^4 V

41. Two charged conducting sphere of radii R_1 and R_2, separated by a large distance, are

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connected by a long wire. The ratio of the charges on them is

(a) $\frac{R_1}{R_2}$ (b) $\frac{R_2}{R_1}$

(c) $\frac{R_1^2}{R_2^2}$ (d) $\frac{R_2^2}{R_1^2}$

42. Figure shows a ball having a charge q fixed at a point A. Two identical balls having charges $+q$ and $-q$ and mass 'm' each are attached to the ends of a light rod of length $2a$. The rod is free to rotate about a fixed axis perpendicular to the plane of the paper and passing through the mid-point of the rod. The system is released from the situation shown in figure. Find the angular velocity of the rod when the rod becomes horizontal.

(a) $\frac{\sqrt{2q}}{3\pi \in_0 ma^3}$ (b) $\frac{q}{\sqrt{3\pi \in_0 ma^3}}$

(c) $\frac{q}{\sqrt{6\pi \in_0 ma^3}}$ (d) $\frac{\sqrt{2q}}{4\pi \in_0 ma^3}$

43. A proton and an α-particle are at a distance r from each other. After letting them free if they move to infinity, the kinetic energy of the proton will be

(a) $8Ke^2/5r$ (b) $2Ke^2/5r$

(c) $8Ke^2/r$ (d) $Ke^2/5r$

44. 10^3 small water drops, each of radius r and each carrying charge q, combine to form one bigger drop. The potential of bigger drop as compared to that of smaller drop, will be

(a) 10^5 V (b) 10^3 V

(c) 10 V (d) 10^2 V

45. Infinite charges, each of q coulomb are lying on x-axis at x = 1 m, 2 m, 4 m, 8 m, ...The electric potential due to these at x = 0 will be

(a) Kq (b) $Kq/2$

(c) $2\,Kq$ (d) $Kq/3$

46. The plates of a parallel plate capacitor have an area of 90 cm^2 each and are separated by 2.5 mm. The capacitor is charged by a 400 volt supply. How much electrostatic energy is stored by the capacitor?

(a) 2.55×10^{-6} J (b) 1.55×10^{-6} J

(c) 8.15×10^{-6} J (d) 5.5×10^{-6} J

47. From a supply of identical capacitors rated 8 mF, 250 V, the minimum number of capacitors required to form a composite 16 mF, 1000 V is

(a) 2 (b) 4

(c) 16 (d) 32

48. Three charges $-q$, $+q$ and $+q$ are situated in X-Y plane at points $(0, -a)$, $(0, 0)$ and $(0, a)$ respectively. The potential at a point distant $r(r > a)$ in a direction making an angle θ from Y-axis will be

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

(b) $\frac{2kq\cos\theta}{r^2}$

(c) $\frac{Kq}{r}$

(d) $\frac{Kq}{r}\left(1+\frac{2a\cos\theta}{r}\right)$

49. A ball of mass 1 g and charge 10^{-7} C moves from a point A whose potential is 500 V to a point B whose potential is zero. If the speed of the ball at A is 0.51 m/s, its speed at point B will be

(a) 0.6 m/s (b) 6 m/s

(c) 2 m/s (d) 4 m/s

50. An alpha particle with kinetic energy 10 MeV is heading towards a stationary tin nucleus of atomic number 50. Calculate the distance of closest approach.

(a) 1.4×10^{-15} m (b) 4×10^{-15} m

(c) 14.4×10^{-15} m (d) 8×10^{-15} m

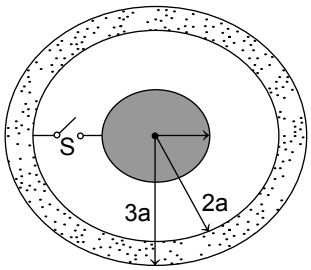
51. Calculate the area of the plates of a one farad parallel plate capacitor if separation between plates is 1 mm and plates are in vacuum.

(a) 18×10^8 m^2 (b) 0.3×10^8 m^2

(c) 1.3×10^8 m^2 (d) 1.13×10^8 m^2

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52. A solid conducting sphere of radius a having a charge q is surrounded by a concentric conducting spherical shell of inner radius $2a$ and outer radius $3a$ as shown in figure.

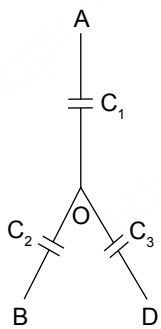


Find the amount of heat produced when switch is closed.

(a) $Kq^2/2a$ (b) $Kq^2/3a$

(c) $Kq^2/4a$ (d) $Kq^2/6a$

53. Three uncharged capacitors of capacities C_1, C_2 and C_3 are connected to one another as shown in the figure.



Points A, B and D are at potential V_1, V_2 and V_3 then the potential at O will be

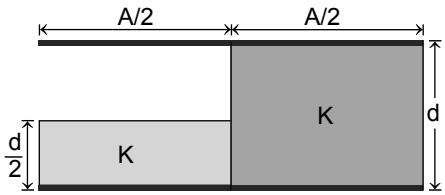
(a) $\dfrac{V_1C_1+V_2C_2+V_3C_3}{C_1+C_2+C_3}$

(b) $\dfrac{V_1+V_2+V_3}{C_1+C_2+C_3}$

(c) $\dfrac{V_1(V_2+V_3)}{C_1(C_2+C_3)}$

(d) $\dfrac{V_1V_2V_3}{C_1C_2C_3}$

54. A parallel plate capacitor of area 'A' plate separation 'd' is filled with two dielectrics as shown. What is the capacitance of the arrangement?



(a) $\dfrac{3K\varepsilon_0 A}{4d}$ (b) $\dfrac{4K\varepsilon_0 A}{3d}$

(c) $\dfrac{(k+1)\varepsilon_0 A}{2d}$ (d) $\dfrac{k(k+3)\varepsilon_0 A}{2(k+1)d}$

ONE OR MORE THAN ONE CHOICE MAY BE CORRECT

1. Two infinite, parallel, non-conducting sheets carry equal positive charge density σ. One is placed in the yz plane and the other at distance $x = a$. Take potential $V = 0$ at $x = 0$

(a) For $0 \le x \le a$, potential $V_x = 0$

(b) For $x \ge a$, potential $V_x = -\dfrac{\sigma}{\epsilon_0}(x-a)$

(c) For $x \ge a$, potential $V_x = \dfrac{\sigma}{\epsilon_0}(x-a)$

(d) For $x \le 0$ potential $V_x = \dfrac{\sigma}{\epsilon_0}x$

2. S_1 and S_2 are two equipotential surfaces on which the potentials are not equal.

(a) S_1 and S_2 cannot intersect.

(b) S_1 and S_2 both cannot be plane surfaces.

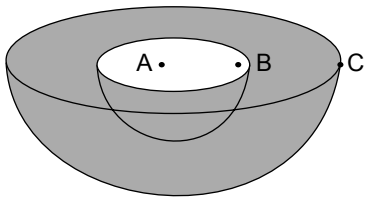
(c) in the region between S_1 and S_2, the field is maximum where they are closest to each other.

(d) A line of force from S_1 to S_2 must be perpendicular to both.

3. A uniformly charged hemisphere of radius $2a$ has a hemispherical depression of radius a, as shown in figure.

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Then,



(a) Potential at A is $\frac{3\rho a^2}{4\varepsilon_0}$

(b) Potential at B is $\frac{2\rho a^2}{3\varepsilon_0}$

(c) Potential at C is $\frac{3\rho a^2}{4\varepsilon_0}$

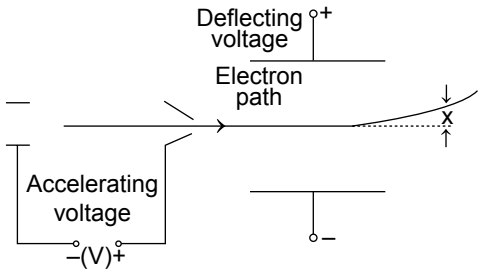
(d) Potential at A is $\frac{3\rho a^2}{2\varepsilon_0}$

4. A parallel plate capacitor is connected to a battery. The quantities charge, voltage, electric field and energy associated with this capacitor are given by Q_0, V_0, E_0 and U_0 respectively. A dielectric slab is now introduced to fill the space between the plates with the battery still in connection. The corresponding quantities now given by Q, V, E and U are related to the previous ones as

(a) $Q > Q_0$ (b) $V > V_0$
(c) $E > E_0$ (d) $U > U_0$

5. The diagram shows part of an evacuated tube in which a stream of electrons from an electron gun passes between a pair of parallel large deflecting plates. The vertical displacement of the electron beam as it leaves the parallel plates is x. (Do not consider gravity as the electron enters the deflecting region parallel to the plates)

Which one of A to D below will change the displacement x of the beam as it leaves the parallel plates?

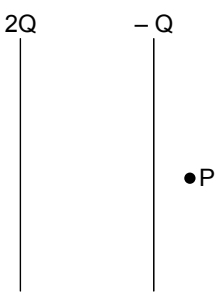


(a) increasing the accelerating voltage
(b) increasing the deflecting voltage
(c) increasing the distance between the electron gun and the deflecting plates
(d) increasing the distance between the two deflecting plates

6. A parallel-plate air capacitor of capacitance C_0 is connected to a cell of emf E and then disconnected from it. A dielectric slab of dielectric constant K, which can just fill the air gap of the capacitor, is now inserted in it.

(a) The potential difference between the plates decreases K times.
(b) The energy stored in the capacitor decreases K times.
(c) The change in energy is $\frac{1}{2}E^2C_0(K-1)$
(d) The change in energy is $\frac{1}{2}E^2C_0\left(1-\frac{1}{K}\right)$

7. In the figure shown the plates of a parallel plate capacitor have unequal charges. Its capacitance is C. P is a point outside the capacitor and close to the plate of charge $-Q$. The distance between the plates is 'd'.



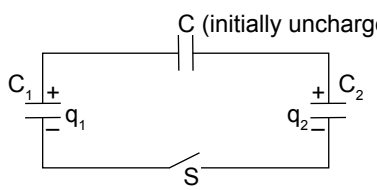
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(a) A point charge at point '*P*' will experience electric force due to capacitor
(b) The potential difference between the plates will be $3Q/2C$
(c) The energy stored in the electric field on the region between the plates is $9Q^2/8C$
(d) The force on one plate due to the other plate is $\frac{Q^2}{2\pi\varepsilon_0 d^2}$

8. A particle of mass 2 kg and charge 1 mC is projected vertically with a velocity 10 m/s. There is a uniform horizontal electric field of 10^4 N/C
(a) the horizontal range of the particle is 10 m
(b) the time of flight of the particle is 2s
(c) the maximum height reached is 5 m
(d) the horizontal range of the particle is 0

9. Potential at a point *A* is 3 volt and at point *B* is 7 volt, an electron is moving towards *A* from *B*.
(a) It must have some K.E. at *B* to reach *A*
(b) It need not have any K.E. at *B* to reach *A*
(c) To reach *A* it must have more than or equal to 4eV K.E. at *B*
(d) When it will reach *A*, it will have K.E. more than or at least equal to 4eV if it was released from rest at *B*.

10. Two capacitors C_1 and C_2 are charged to q_1 and q_2 and connected with capacitor *C* as shown in figure. As switch *S* is closed



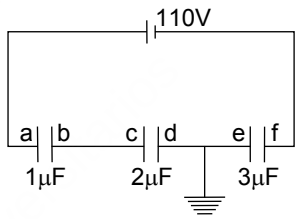
(a) *C* gets extra charge when $\frac{C_1}{q_1} > \frac{C_2}{q_2}$
(b) *C* gets extra charge when $\frac{C_1}{q_1} < \frac{C_2}{q_2}$
(c) *C* gets extra charge when $\frac{C_1}{q_1} = \frac{C_2}{q_2}$
(d) *C* does not gets extra charge for any value of q_1 and q_2.

11. Three equal point charges (*Q*) are kept at the three corners of an equilateral triangle *ABC* of side '*a*'. *P* is a point having equal distance '*a*' from *A*, *B* and *C*. If *E* is the magnitude of electric field and *V* is the potential at point *I* then

(a) $E = \frac{3Q}{4\pi\varepsilon_0 a^2}$ (b) $E = \frac{\sqrt{6}Q}{4\pi\varepsilon_0 a^2}$

(c) $V = \frac{3Q}{4\pi\varepsilon_0 a}$ (d) $E = \frac{3\sqrt{6Q}}{4\pi\varepsilon_0 a^2}$

12. For the given figure, choose the correct option



(a) $V_a - V_f = 110$ V
(b) $V_b - V_c = 0$
(c) $V_a - V_b = 60$ V
(d) $V_e = V_d = 0$

13. Capacitor C_1 of capacitance 1 microfarad and capacitor C_2 of capacitance 2 microfarad are separately charged fully by a common battery. The two capacitors are then separately allowed to discharge through equal resistors at time $t = 0$.
(a) The current in each of the two discharging circuits is zero at $t = 0$
(b) The currents in the two discharging circuits at $t = 0$ are equal but not zero.
(c) The currents in the two discharging circuits at $t = 0$ are unequal
(d) Capacitor C_1 loses 50% of its initial charge sooner than C_2 loses 50% of its initial charge.

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ASSERTION AND REASON QUESTIONS

Direction: Each question contains STATEMENT-1 (Assertion) and STATEMENT-2 (Reason). Each question has 4 choices (a), (b), (c) and (d) out of which ONLY ONE is correct.

(a) Statement-1 is True, Statement-2 is True; Statement-2 is a correct explanation for Statement-1.

(b) Statement-1 is True, Statement-2 is True; Statement-2 is NOT a correct explanation for Statement-1.

(c) Statement-1 is True, Statement-2 is False.

(d) Statement-1 is False, Statement-2 is True.

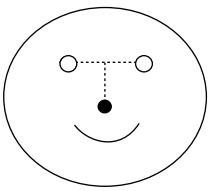
1. **Statement I:** A particle A of mass m and charge Q moves directly towards a fixed particle B, which has charge Q. The speed of A is v when it is far away from B. The minimum separation between the particles is proportional to Q^2.
   Statement II: Total energy remains conserved.

2. **Statement I:** Potential difference between two points lying in a uniform electric field may be equal to zero.
   Statement II: Points of line normal to electric field is equipotential line.

3. **Statement I:** At a distance r from a +ve charged particle potential is V and electric field strength E then graph between V^2 and E is straight line.
   Statement II: For a point charge
   $\frac{V^2}{E} = \frac{q}{4\pi \in_0}$

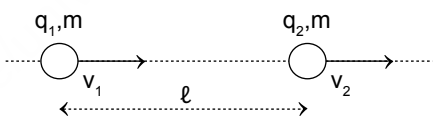
4. **Statement I:** Electrons move away from a region of lower potential to a region of higher potential.
   Statement II: Since an electron has a negative charge.

5. **Statement I:** The smiling face consists of three items a thin rod of charge $3\mu c$ that forms a full circle of radius 8 cm, a second thin rod of charge $2\mu c$ that forms a circular arc of radius 4 cm subtending an angle of 90º about the centre of the full circle, an electric dipole with a dipole moment that is perpendicular to a radial line and that has magnitude 1.28×10^{-21} C-m, electric potential at centre is zero.



   Statement II: Potential on equatorial point due to dipole is zero

6. **Statement I:** An isolated system consists of two particles of equal masses $m = 10$ gm and charges $q_1 = +1\mu C$ and $q_2 = -1\mu C$ as shown in figure. The initial separation of both charges is $\ell = 1$ m. Both the charges are given initial velocities $v_1 = 1$ m/s and $v_2 = 2$ m/s towards right. Then the maximum separation between the charges is infinite.



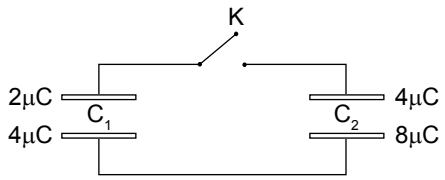
   Statement II: The total energy (Kinetic energy + electrostatic potential energy) of given two particle system is positive and initial velocity of separation is positive.

7. **Statement I:** Electric field E at a point P is zero if potential at that point is zero.
   Statement II: Potential difference between two points in space is zero if electric field at all points in space is zero.

8. **Statement I:** Charges are given to plates of two plane parallel plate capacitors C_1 and C_2 (such that $C_2 = 2C_1$) as shown in figure. Then the key K is pressed to complete the circuit. Finally, the net charge on upper plate and

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net charge on lower plate of capacitor C_1 is positive.



Statement II: In a parallel plate capacitor both plates always carry equal and opposite charge.

9. Statement I: Each of the plates of a parallel-plate capacitor is given equal positive charge Q. The charges on the facing surfaces will be same.
Statement II: A negative charge ($-Q$) will be induced on each of the facing surfaces.

10. Statement I: Electric potential is a property of an electric field, regardless of whether a charged object has been placed in that field.
Statement II: Potential depends on test charge.

11. Statement I: Electric potential and electric potential energy are different quantities.
Statement II: For a system of positive test charge and point charge electric potential energy = electric potential.

12. Statement I: The component of $\vec{E}$ in any direction is the negative of the rate of change of the electric potential with distance in that direction.
Statement II: Potential gradient in any direction at a point gives total electric field at that point.

13. Statement I: An excess charge placed on an isolated conductor will distribute itself on the surface of the conductor so that all points of the conductor, whether on the surface or inside, come to the same potential. This is true even if the conductor has an internal cavity and even if that cavity contains a net charge.
Statement II: It is not possible to maintain charge on inside surface of conductor.

14. Statement I: Two equipotential surfaces cannot cut each other.
Statement II: Two equipotential surfaces are parallel to each other.

MATCH THE COLUMN TYPE QUESTIONS

Each question contains statements given in two columns which have to be matched. Statements (A, B, C, D) in column I have to be matched with statements (p, q, r, s) in column II.

1. Column I gives certain situations in which capacitances of a capacitor is changed by different means. Column II gives resulting effect under different conditions. Match the statements in column I with the corresponding statements in column II.

	Column I		**Column II**
(a)	The plates of a plane parallel capacitors are slowly pulled apart. Then the magnitude of electric field intensity inside the capacitor.	(p)	Increases if the capacitor is maintained at constant charge.
(b)	The plates of a plane parallel plate capacitor are slowly pulled apart. Then the potential energy stored in the capacitor.	(q)	Decreases if the capacitor is maintained at constant charge.
(c)	The capacitance of an air filled plane parallel plate capacitor on insertion of dielectric.	(r)	Increases if the capacitor is maintained at constant potential difference.

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(d)	A dielectric slab is inserted inside an air filled plane parallel plate capacitor. The potential energy stored in the capacitor.	(s)	Decreases if the capacitor is maintained at constant potential difference.

2. Match the column:

	Column I		Column II
(a)	Solid non conducting sphere	(p)	Potential at centre = 3/2 at surface
(b)	Infinite non conducting sheet	(q)	Absolute potential not defined
(c)	Inside hollow non conducting sphere	(r)	$\vec{E}=\frac{\rho\vec{r}}{3\varepsilon_0}$ $r<R$
(d)	Inside solid conductor	(s)	$E=0$

3. Three concentric spherical metallic shells A, B and C of radii *a, b* and *c* ($a<b<c$) have charge densities of σ, $-\sigma$ and σ respectively, then

	Column I		Column II
(a)	The potential of *A*	(p)	$\frac{1}{\epsilon_0}\left(\frac{a^2}{c}-\frac{b^2}{c}+c\right)\sigma$
(b)	The potential of *B*	(q)	$\frac{1}{\epsilon_0}\left(\frac{a^2}{b}-b+c\right)\sigma$
(c)	The potential of *C*	(r)	$\frac{\sigma}{\epsilon_0}$
(d)	The electric field at surface of *A*.	(s)	$\frac{1}{\epsilon_0}(a-b+c)\sigma$

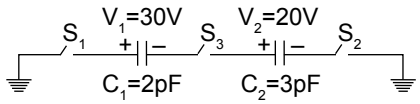
4. Two point charges Q and $-Q/4$ are separated by L

	Column I		Column II
(a)	Zero potential	(p)	$L/3$ on right side of charge $-Q/4$
(b)	Zero electric field	(q)	$L/5$ on left side of charge $-Q/5$
(c)	Infinite potential	(r)	L on right side of charge $-Q/4$
(d)	Infinite electric field	(s)	Near charge Q.

5. After charge a capacitor to a potential difference of 100 V, it is discharged through a resistor. After one second, the potential difference between the plates of capacitor becomes 80 volt. then

	Column I		Column II
(a)	Fraction of stored energy converted into heat during first one second.	(p)	16/25
(b)	Fraction of initial stored energy converted into heat after two seconds.	(q)	256/625
(c)	Fraction of energy retained after first one second.	(r)	9/25
(d)	Fraction initial stored energy retained after first two seconds.	(s)	369/625

6. For the circuit is shown

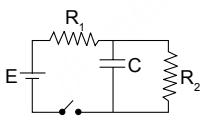


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Column I	Column II
(a) S_1 closed	(p) $V_1 = 0$
(b) S_3 closed	(q) $V_2 = 0$
(c) S_1 and S_2 closed	(r) $V_1 = 30$
(d) S_1, S_2, S_3 closed	(s) $V_2 = 20$ V

7. Column II gives the value of quantity described in Column I for the circuit

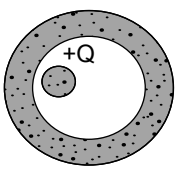
In the circuit shown in figure the switch is closed at $t = 0$. A long time after closing the switch

Column I	Column II
(a) voltage drop across the capacitor is	(p) zero
(b) current through the battery is	(q) $\frac{E}{R_1 + R_2}$
(c) energy stores in the capacitor is	(r) $\frac{1}{2}C\left(\frac{R_2 E}{R_1 + R_2}\right)^2$
(d) current through the capacitor b	(s) 

PASSAGE BASED QUESTIONS

PASSAGE–1

In the diagram shown, the outer conducting spherical shell (inner radius = b and the outer radius = c) is electrically neutral and the inner conducting sphere (radius = a) carries charge $+Q$.



1. What is the potential of the outer spherical shell?

(a) $Q/(4pe_0c)$

(b) $Q/(4pe_0c) - Q/(4pe_0a)$

(c) $Qbc/(4pe_0)(c - a)$

(d) none

2. If V_s is potential of inner sphere and V_c is the potential at the centre of spherical shell, then

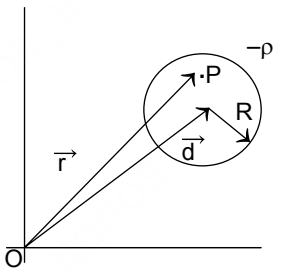
(a) $V_c > V_s$

(b) $V_c < V_s$

(c) $V_c = V_s$

(d) none of the conclusions can be drawn from the given information

3. A non-conducting sphere of radius R is filled with uniform volume charge density. The centre of this sphere is displaced from the origin by $\vec{d}$.



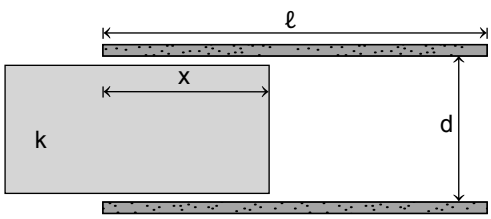
The electric field $\vec{E}$ at any point P having position vector, $\vec{r}$ inside the sphere is

(a) $\frac{\rho}{3\varepsilon_0}\vec{d}$ (b) $\frac{\rho}{3\varepsilon_0}(\vec{r} - \vec{d})$

(c) $\frac{\rho}{3\varepsilon_0}(\vec{d} - \vec{r})$ (d) $\frac{\rho}{3\varepsilon_0}(\vec{d} + \vec{r})$

PASSAGE–2

A capacitor is constructed from two square plates of sides ℓ and separation d, as suggested in figure. You may assume that d is much less than ℓ. The plates carry charges



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$+Q_0$ and $-Q_0$. A block of metal has width ℓ, length ℓ, and thickness slightly less than d. It is inserted a distance x into the capacitor. The charges on the plates are not disturbed as the block slides in. The plates having a thin insulation over it.

4. The stored energy as a function of x is

(a) $Q_0^2 d(\ell - x)/(2\ell^3 \in_0)$

(b) $Q_0^2 d(\ell - x)/(\ell^3 \in_0)$

(c) $Q_0^2 d/[2\ell \in_0 (\ell - x)]$

(d) $Q_0^2 d/[\ell \in_0 (\ell - x)]$

5. The direction and magnitude of the force that acts on the metallic block is

(a) $Q_0^2 d/(2\ell^3 \in_0)$ to the left

(b) $Q_0^2 d/(2\ell^3 \in_0)$ to the right

(c) $Q_0^2 d/(2\ell \in_0)$ to the left

(d) $Q_0^2 d/(2\ell \in_0)$ to the right

6. The area of the advancing front face of the block is essentially equal to ℓd. Considering the force on the block as acting on this face, then the stress (force per area) on it is

(a) $Q_0^2/(2\ell^4 \in_0)$ (b) $Q_0^2/(2\ell^2 \in_0)$

(c) $Q_0^2/(2\ell \in_0)$ (d) $2Q_0^2/(2\ell \in_0)$

7. If a metal block is released with its ℓ_0 length between the plates it starts oscillating. Its period of oscillation is (mass of block is m, there is no friction between plates)

(a) $4\sqrt{\dfrac{4(\ell - \ell_0)\ell^3 \in_0 m}{Q_0^2 d}}$

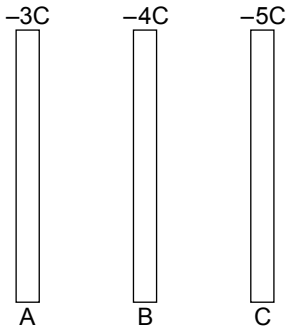
(b) $2\sqrt{\dfrac{4(\ell - \ell_0)\ell^3 \in_0 m}{Q_0^2 d}}$

(c) $\sqrt{\dfrac{4(\ell - \ell_0)\ell^3 \in_0 m}{Q_0^2 d}}$

(d) $\dfrac{1}{2}\sqrt{\dfrac{(\ell - \ell_0)\ell^3 \in_0 m}{Q_0^2 d}}$

PASSAGE–3

Three large plates A, B and C are placed parallel to each other and charges are given as shown.



8. The charge that appears on the left surface of plate B is

(a) $5C$

(b) $6C$

(c) $3C$

(d) $-3C$

9. The charge on inner surface of plate C, if plate B is earthed,

(a) $5C$ (b) $6C$

(c) $3C$ (d) $-3C$

10. The charge on left surface of B, if B and C both are earthed,

(a) $5C$ (b) $6C$

(c) $3C$ (d) $-3C$

PASSAGE–4

A non-conducting disc of radius 'a' and uniform surface charge density σ is placed on the ground, with its axis vertical. A particle of mass m and positive charge q is dropped, along the axis of the disc, from a height H with zero initial velocity. The particle has $q/m = 4\pi\varepsilon_0 g/\sigma$.

11. Find the value of H if the particle just reaches the disc.

(a) $a/3$ (b) $a/6$

(c) $2a/3$ (d) $4a/3$

12. Electrostatic potential at H is

(a) $\dfrac{\sigma}{\varepsilon_0}\left[(a^2 + H^2)^{1/2} - H\right]$

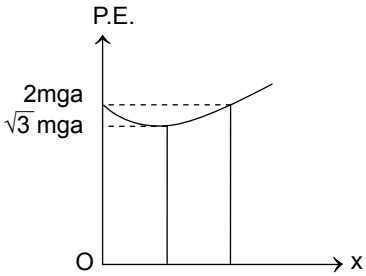
(b) $\dfrac{\sigma}{\varepsilon_0}\left[(a^2 + H^2)^{1/2} + H\right]$

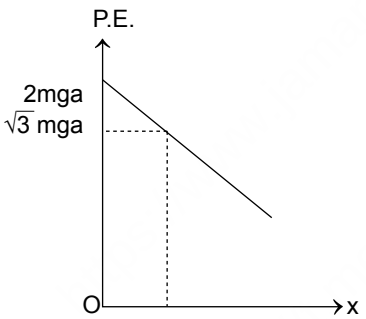
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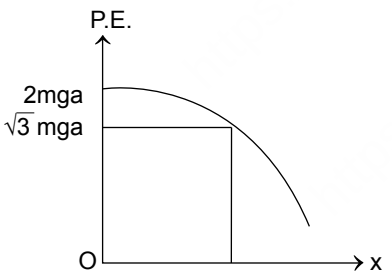
(c) $\frac{\sigma}{2\varepsilon_0}\left[(a^2+H^2)^{1/2}-H\right]$

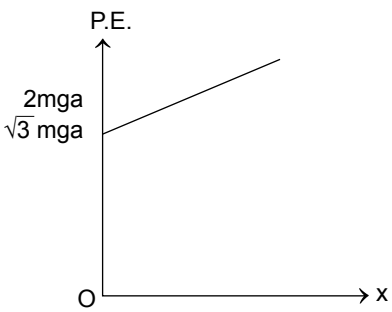
(d) $\frac{\sigma}{2\varepsilon_0}\left[(a^2+H^2)^{1/2}+H\right]$

13. Sketch the potential energy of the particle as a function of its height.

(a)


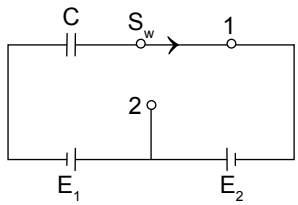
(b)


(c)


(d)


SUBJECTIVE QUESTIONS

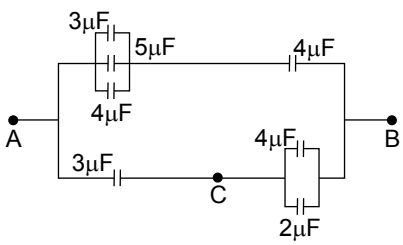
1. Amount of heat that will be generated in the circuit shown in the figure after the switch S_w is shifted from position 1 to position 2 is.



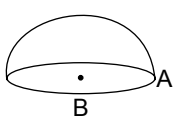
2. 12 J of work has to be done against an existing electric field to take a charge of 0.01 *C* from *A* to *B*. How much is the potential difference $V_B - V_A$?

3. The electric field in a region is given by $\vec{E} = (A/x)^3 \hat{i}$. Write a suitable SI unit for *A*. Write an expression for the potential in the region assuming the potential at infinity to be zero.

4. The capacitance of all the capacitors shown in figure are in micro farad.
What is the equivalent capacitance between *A* and *B*? If the charges on the 5μ*F* capacitors is 120μ*C*, what is the potential difference between *A* and *C*?



5. A spherical shell of radius *R* carries uniformly distributed charge of density σ on its surface.

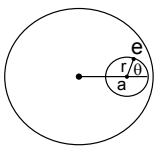


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The potential difference between point A on the edge and centre B; $V_A - V_B$ is.

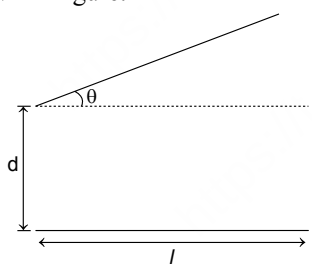
6. Two points charge q and $-2q$ are placed at a distance $6a$ apart. Find the locus of the point in the plane of charges where the field potential is zero.

7. A cavity of radius r is present inside a solid dielectric sphere of radius R, having a volume charge density of P.



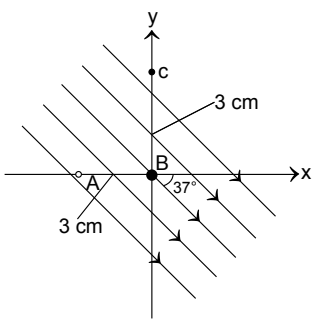
The distance between the centres of the sphere and the cavity is a. An electron e is kept inside the cavity at an angle $\theta = 45^\circ$ as shown. How long will it take to touch the sphere again?

8. A capacitor has square plates, each of side 'a' making an angle of θ with each other as shown in figure.



Calculate the capacitance of the arrangement for small θ.

9. A uniform electric field of 400 V/m is directed at 37º below the x axis, as shown in figure. Change in potential

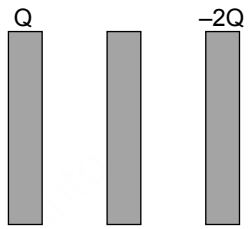


(a) $V_B - V_A$

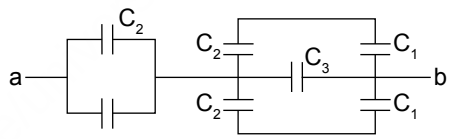
(b) $V_B - V_C$ [$AB = BC = 3$ cm]

10. Three identical metal plates with large surface area are kept parallel to each other as shown in figure.

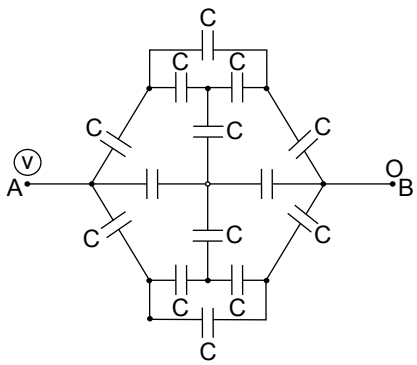
The leftmost plate is given a charge Q, the rightmost a charge $-2Q$ and the middle one remains neutral. Find the charge appearing on the outer surface of the rightmost plate.



11. The equivalent capacitance between points a and b in the circuit shown in figure. Here $C_1 = 3\mu F$, $C_2 = 6\mu F$, $C_3 = 2\mu F$. If a potential difference of 48 V is applied across a and b, find the charge stored in the capacitor C_3 at steady state.



12. The equivalent capacitance across A and B is

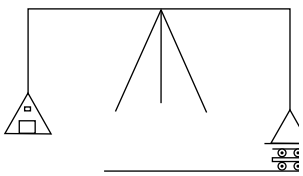


13. A dipole of dipole moment P lies in a uniform electric field E such that dipole

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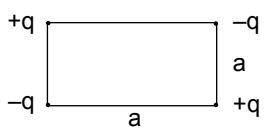
direction is along field. If dipole is rotated through 180º such that dipole direction becomes opposite to the field direction. Find the work done by the electrostatic field.

14. The lower plate of a parallel plate capacitor lies on an insulating plane. The upper plate is suspended from one end of a balance.



The two plates are joined together by a thin wire and subsequently disconnected. The balance is then counterpoised. A voltage $V = 5000$ volt is applied between the plates. The additional weight which should be placed to maintain balance is.
[The distance between the plates is d = 5 mm and the area of each plate is A = 100 cm^2]

15. What is work done by the electrostatic field when we put the four charges together, as shown in the figure? Each side of the square has a length a. Initially charges were at infinity.



16. Two parallel plate air capacitance C were connected in series to a battery with e.m.f. ε. Then one of the capacitors was filled up with uniform di-electric with relative permittivity k. (i) The electric field in the capacitor with dielectric is decreased n times where n = (ii) The amount of charge which flows through the battery during insertion of dielectric is.

17. The distance between the plates of a parallel plate condenser is 0.05 m. A field of 3×10^4 volt/m is established between the plates. It is then disconnected from the battery and an uncharged metal plates of thickness 0.01 m is inserted into the condenser parallel to its plates.

(i) The potential difference between the plates before the introduction of the metal plates is.
(ii) after its introduction is.
(iii) The potential difference, if a plate of di-electric constant $\in = 2$ is introduced in place of metal plate is.

PREVIOUS YEARS' IIT-JEE QUESTIONS

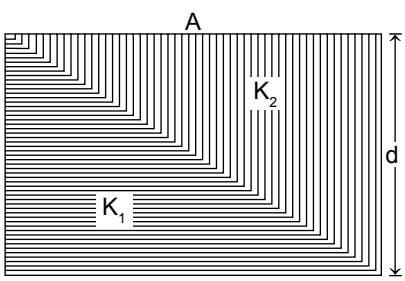
1. A parallel plate capacitor C is corrected to a battery and is charged to a potential difference V. Another capacitor of capacitance $2C$ is similarly charged to a potential difference 2 V volt. The charging battery is now disconnected and the capacitors are connected in parallel to each other in such a way that the positive terminal of one is connected to the negative terminal of other. The final energy of the configuration is

[**1995**]

(a) zero
(b) $(3/2)\ CV^2$
(c) $(25/6)\ CV^2$
(d) $(9/2)\ CV^2$

2. The capacitance of a parallel plate capacitor with plate area 'A' and separation d is C. The space between the plates is filled with two wedge of di-electric constant K_1 and K_2 respectively. Find the capacitance of the resulting capacitor.

[**1996**]



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ANSWERS

ONLY ONE OPTIONS IS CORRECT

1. (b)	**2.** (b)	**3.** (b)	**4.** (b)	**5.** (a)	**6.** (d)	**7.** (b)	**8.** (d)
9. (a)	**10.** (c)	**11.** (a)	**12.** (a)	**13.** (a)	**14.** (a)	**15.** (b)	**16.** (c)
17. (d)	**18.** (b)	**19.** (a)	**20.** (c)	**21.** (c)	**22.** (d)	**23.** (d)	**24.** (a)
25. (b)	**26.** (b)	**27.** (a)	**28.** (a)	**29.** (a)	**30.** (a)	**31.** (d)	**32.** (c)
33. (b)	**34.** (a)	**35.** (a)	**36.** (a)	**37.** (c)	**38.** (c)	**39.** (a)	**40.** (a)
41. (a)	**42.** (c)	**43.** (a)	**44.** (d)	**45.** (c)	**46.** (a)	**47.** (d)	**48.** (d)
49. (a)	**50.** (c)	**51.** (d)	**52.** (c)	**53.** (a)	**54.** (d)		

ONE OR MORE THAN ONE CHOICE MAY BE CORRECT

1. (a, b, d)	**2.** (a, c, d)	**3.** (a, b, c)	**4.** (a, b)	**5.** (a, b, d)	**6.** (a, b, d)	**7.** (a, b, c)
8. (a, b, c)	**9.** (a, c)	**10.** (a, b)	**11.** (b, c)	**12.** (a, c, d)	**13.** (b, d)	

ASSERTION AND REASON QUESTIONS

1. (a)	**2.** (a)	**3.** (a)	**4.** (a)	**5.** (d)	**6.** (a)	**7.** (d)	**8.** (c)
9. (c)	**10.** (c)	**11.** (c)	**12.** (c)	**13.** (c)	**14.** (c)		

MATCH THE COLUMN TYPE QUESTIONS

1. (a) $\rightarrow$ *p, q* (b) $\rightarrow$ *p, q* (c) $\rightarrow$ *p, q, s* (d) $\rightarrow$ *r, s*

2. (a) $\rightarrow$ *p, r*, (b) $\rightarrow$ *q*, (c) $\rightarrow$ *s*, (d) $\rightarrow$ *s*

3. (a) $\rightarrow$ *s*, (b) $\rightarrow$ *q*, (c) $\rightarrow$ *p* (d) $\rightarrow$ *r*

4. (a) $\rightarrow$ *p, q*, (b) $\rightarrow$ *r*, (c) $\rightarrow$ *s*, (d) $\rightarrow$ *s*

5. (a) $\rightarrow$ *r, q* (b) $\rightarrow$ *s*, (c) $\rightarrow$ *p*, (d) $\rightarrow$ *q*

6. (a) $\rightarrow$ *p, q* (b) $\rightarrow$ *p, q* (c) $\rightarrow$ *p, q* (d) $\rightarrow$ *r, s*

7. (a) $\rightarrow$ *s*, (b) $\rightarrow$ *q* (c) $\rightarrow$ *r*, (d) $\rightarrow$ *p*

PASSAGE BASED QUESTIONS

1. (a)	**2.** (c)	**3.** (c)	**4.** (a)	**5.** (d)	**6.** (a)	**7.** (a)	**8.** (b)
9. (a)	**10.** (c)	**11.** (d)	**12.** (c)	**13.** (a)			

HINTS AND SOLUTIONS

CONCEPTUAL QUESTIONS

1. No, because charge distribution will not be uniform.

2. No

3. Not necessarily. (True only if the field line is a straight line.) The field line gives the direction of acceleration, not that of velocity, in general.

4. Zero, no matter what the shape of the complete orbit is.

5. No, potential is continuous.

6. A single conductor is capacitor with one of the 'plates' at infinity.

7. A water molecule has permanent dipole moment. However, detailed explanation of the value of dielectric constant requires

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microscopic theory and is beyond the scope of the book.

8. Our body and the ground form an equipotential surface. As we step out into the open, the original equipotential surfaces of open air change, keeping our head and the ground at the same potential.

9. Yes. The steady discharging current in the atmosphere charges up the aluminium sheet gradually and raises its voltage to an extent depending on the capacitance of the capacitor (formed by the sheet, slab and the ground).

10. The atmosphere is continually being charged by thunderstorms and lightening all over the globe and discharged through regions of ordinary weather. The two opposing currents are, on an average, in equilibrium.

11. Light energy involving in lightening, heat and sound energy in the accompanying thunder.

MATCH THE COLUMN TYPE QUESTIONS

1. (a) At constant charge, the electric field within the capacitor remains same when plate separation is changed. The electric field in capacitor is $E = V/d$. Hence at constant potential difference the electric field decreases with increase in d.

(b) $U = \frac{1}{2}\frac{Q^2}{C}$. Hence at constant charge U increases with decrease in C.

$U = \frac{1}{2}CV^2$. Hence at constant potential difference U decreases with decrease in C.

(c) Capacitance increases on insertion of dielectric.

(d) As a result of insertion of dielectric the capacitance increases. $U = \frac{1}{2}\frac{Q^2}{C}$. Hence at constant charge U decreases with increase in C.

$U = (1/2)\, CV^2$. Hence at constant potential difference U increases with increase in C.

SUBJECTIVE QUESTIONS

1. $1/2\ CE_2^2$.

2. 1200 Volts

3. The SI unit of electric field is N/C or V/m. Thus,

The unit of A is $\frac{Nm^3}{C}$ or V–m^2.

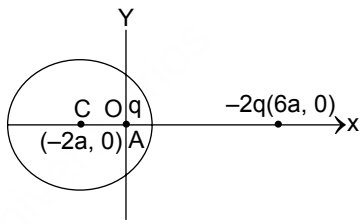
$V(x, y, z) = -\int_{\infty}^{(x,y,z)} \vec{E}.d\vec{r}$

$$= -\int_{x^3}^{(x,y,z)} \frac{A\,dx}{x^3} = \frac{A}{2x^2}$$

4. 5μF, 64 Volt

5. zero

6. Let us take the charge on X-axis; q at A (0, 0) and $-2q$ at $B(6a, 0)$ Potential at a point $P(x, y)$ is



$$V = \frac{q}{4\pi\varepsilon_0\sqrt{x^2+y^2}} + \frac{-2q}{4\pi\varepsilon_0\sqrt{(x-6a)^2+y^2}}$$

$\Rightarrow\ V = 0$

$$\Rightarrow \frac{q^2}{x^2+y^2} = \frac{4q^2}{(x-6a)^2+y^2}$$

$\Rightarrow$ the locus is $(x - 6a)^2 = 4x^2 + 3y^2$.

$3x^2 + 3y^2 + 2\,(6x) = 36a^2 \Rightarrow x^2 + y^2 + 4ax = 12a^2$

$(x + 2a)^2 + y^2 = 16a^2$

$\therefore$ Locus is a circle with centre $(-2a, 0)$ and radius $4a$.

7. $\sqrt{\frac{6\sqrt{2}\,mr\varepsilon_0}{\rho ea}}$

8. $\frac{\varepsilon_0 a^2}{d}\left(1 - \frac{a\theta}{2d}\right)$

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9. –9.57 V, –7.23 V

10. $-Q/2$

11. $4\mu F$, $64\mu F$

12. $5C/4$

13. $U_i = -\vec{P}.\vec{E} = -PE\cos O = -PE$

$U_f = -P.E.\cos(180^\circ) = PE$

work done by the field $= -\Delta U = U_i - U_f = -2PE$

14. 4.5 *g*

15. $U_i = 0$ [Where charges are separated by infinite distance]

$$U_f = \frac{1}{4\pi\varepsilon_0}\left(\frac{-4q^2}{a} + \frac{q^2}{\sqrt{2}a} + \frac{(-q)^2}{\sqrt{2}a}\right)$$ [for 6 pairs of charges]

Work done by field

$$-\Delta U = U_i - U_f = \frac{1}{4\pi\varepsilon_0}\frac{q^2}{a}\left(4 - \frac{\sqrt{2}}{a}\right)$$

16. (i) $(k+1)/2$,

(ii) $\frac{1}{2}C\varepsilon\frac{k-1}{k+1}$

17. (i) 1500 V,

(ii) 1200 V,

(iii) 1350 V

PREVIOUS YEARS' IIT-JEE QUESTIONS

1. (b)

2. $\frac{CK_1K_2}{K_1 - K_2}\ln\frac{K_1}{K_2}$

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CHAPTER

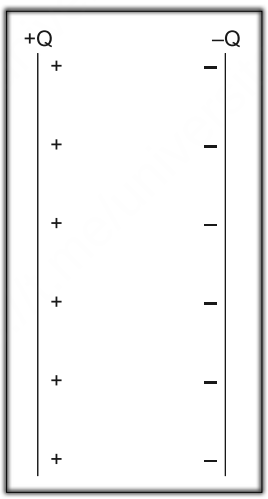
2

Capacitor

2.1 CAPACITORS

When two conductors carry equal and opposite charges then the arrangement of conductor is known as **capacitors.**

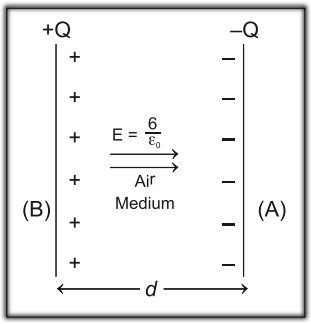
If the charge on the two conductors are not equal and opposite, then the arrangement will not be a capacitor it will still have capacity (C).



2.2 CAPACITY OF A CAPACITOR

Capacitance of a capacitor is defined as ratio of magnitude of charge given to the either plate and magnitude of potential difference between them.

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i.e., $C = \frac{Q}{V}$

where, Q = Charge on either plate magnitude

V = Potential difference between plates.

2.3 PARALLEL PLATE CAPACITORS

Let, A = Area of each plate.

d = Separation between plates.

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

$$V_B - V_A = -\int \vec{E} \cdot \vec{dl} = -\int E dl \cos 180°$$

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

$$= \frac{\sigma}{\varepsilon_0} \int dl = \frac{\sigma}{\varepsilon_0} d$$

Potential difference (PD) $= \frac{Qd}{A\varepsilon_0}$

Capacitance,

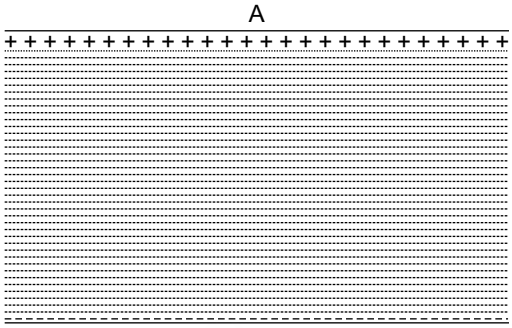
$$C = \frac{\text{Charge Supplied}}{\text{Potential difference developed between plates.}}$$

$C_{air} = \frac{Q}{\frac{Qd}{\varepsilon_0 A}} = \frac{\varepsilon_0 A}{d}$ (Homogeneous). $C_{medium} = \frac{\varepsilon_0 \varepsilon_r A}{d}$

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CONCEPT

How to find capacitance of a capacitor having non-homogeneous medium between two plates.



$$C_{medium} = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

Let the medium between the two plates is now removed and the capacitance remains uneffected or same.

$$C_{air} = \frac{\varepsilon_0 A}{r}$$

But $C_{medium} = C_{air}$



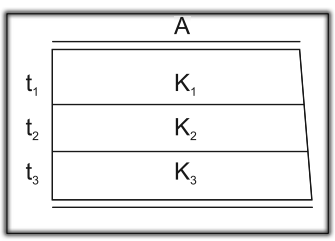
$$\therefore \quad \frac{\varepsilon_0 \varepsilon_r A}{d} = \frac{\varepsilon_0 A}{r}$$

or $$r = \frac{d}{\varepsilon_r}$$

Therefore, d distance of a medium is equivalent to $\frac{d}{\varepsilon_r}$ distance of air. For capacity to be same.

Example

Find the capacitance of capacitor shown in the figure below.

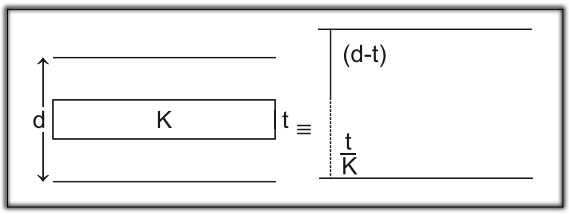


☞ **Solution** $C = \dfrac{\varepsilon_0 A}{\frac{t_1}{K_1} + \frac{t_2}{K_2} + \frac{t_3}{K_3}} = \dfrac{\varepsilon_0 A}{\sum \frac{t_i}{K_i}}$

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Example

Find capacitance of the arrangement shown.



$$C_{air} = \frac{\varepsilon_0 A}{d - t + \frac{t}{K}}$$

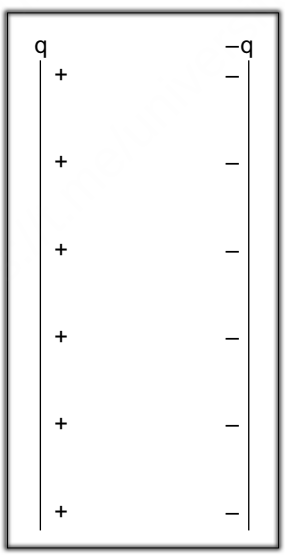
Capacitance of metal is greater.

2.4 ELECTRIC POTENTIAL ENERGY OF CAPACITOR

$$V_B - V_A = \frac{W_{ext.}}{q_0}$$

or $$W_{ext} = (V_B - V_A)\, q_0$$

$$V = Ed$$



Let, C = Capacitance of Capacitor.

At any instant charge on plate of capacitor be $+q$.

V = Potential difference between plates.

Let dq be the charge B further transferred from one plate to another plate.

Work done by external agent, $dW = V dg$.

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$$dW = \frac{q}{C} dq.$$

$$W_{Total} = \int \frac{q}{C} dq = \frac{1}{C} \int_0^Q q\, dq$$

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

$$W_{ext} = \frac{C^2V^2}{2}$$

$[\because Q = CV]$

$$W_{ext} = \frac{1}{2}CV^2 = \frac{1}{2}(CV)V = \frac{1}{2}QV$$

$$W_{ext} = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{Q^2}{2C}$$

Electric Potential energy of stored in the capacitor.

$$U = \frac{1}{2}CV^2 = \frac{1}{2}QV = \frac{Q^2}{2C}$$

CONCEPT

According to the modern view, it is assumed that electric field in the site of potential energy. Therefore, in case of parallel plate capacitor electric field exists in the volume A*d*.

Energy Density

$$\text{Energy per unit volume (energy density)} = \frac{\text{Energy}}{\text{Volume}}$$

$$\text{Energy density} = \frac{\frac{1}{2}CV^2}{Ad} = \frac{\frac{1}{2}\varepsilon_0 A \times V^2}{d \times Ad} = \frac{1}{2}\varepsilon_0 \frac{V}{d}$$

$$\text{Energy density} = \frac{1}{2}\varepsilon_0 E^2$$

Though, the result is derived for parallel plate capacitor still it is valid everywhere.

Example

If spherical shell of radius *R* is given charge *Q*, find self electrostatic potential energy of spherical shell.

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☞ **Solution** $U = \frac{1}{2} C V^2 = \frac{1}{2}(CV) V$

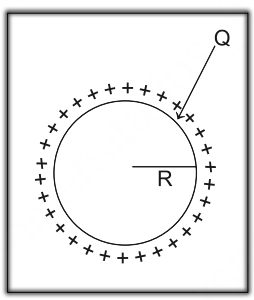
$$= \frac{1}{2} QV$$

$$= \frac{1}{2} Q \times \frac{kQ}{R}$$

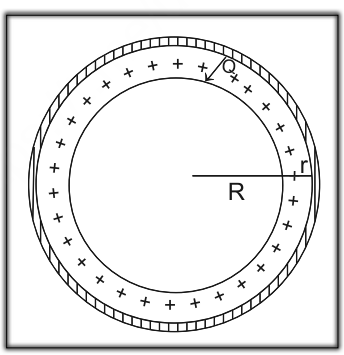
$$= \frac{1}{2} \frac{kQ^2}{R}$$

$$= \frac{1}{2} \times \frac{1}{4\pi\varepsilon_0} \frac{Q^2}{R}$$

$$U = \frac{1}{8\pi\varepsilon_0} \frac{Q^2}{R}$$



Alternative Method



Consider a spherical layer of radius R and thickness dr.
Volume of small layer = $(4 \pi r^2 dr)$
E can be assumed to be uniform in thickness *dr*.
Energy stored in *dr* thickness

$$dU = \frac{1}{2} \varepsilon_0 E^2 \times 4\pi r^2 dr$$

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$$= \frac{1}{2}\varepsilon_0 \times 4\pi\left(\frac{kQ}{r^2}\right)^2 \times r^2 dr$$

$$dU = \frac{Q^2}{8\pi\varepsilon_0}\frac{dr}{r^2}$$

Self electrostatic Potential energy (PE).

$$U = \frac{Q^2}{8\pi\varepsilon_0}\int_R^\infty \frac{dr}{r^2} = \frac{Q^2}{8\pi\varepsilon_0}\left[-\frac{1}{r}\right]_R^\infty$$

$$U = \frac{Q^2}{8\pi\varepsilon_0 R}$$

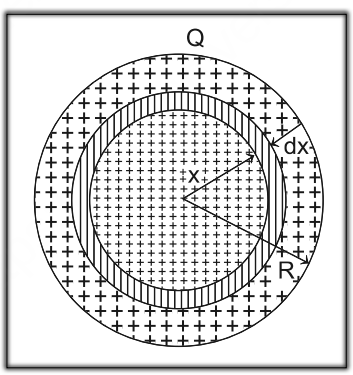
Example

A solid non-conducting sphere is charged uniformally having total charge *Q*, find:

(i) Total self electrostatic potential energy.
(ii) The ratio of self electrostatic potential energy outside and inside the solid sphere?

☞ **Solution**

$$E = \frac{\rho}{3\varepsilon_0}.r$$



Electric intensity at distance *x* from centre of sphere

$$E = \frac{\rho}{3\varepsilon_0}x$$

$$\therefore \quad dU = 4\pi x^2 dx\ \frac{1}{2}\varepsilon_0\left(\frac{\rho}{3\varepsilon_0}x\right)^2$$

$$= \frac{2\pi\rho^2 x^4}{9\varepsilon_0}dx$$

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Hence, $U = \frac{2\pi\rho^2}{9\varepsilon_0}\int_0^R x^4\, dx$

$$= \frac{2\pi}{9\varepsilon_0} \times \left(\frac{Q}{\frac{4}{3}\pi R^3} \right) \times \frac{R^5}{5}$$

$$= \frac{2\pi}{9\varepsilon_0} \times \frac{Q^2 \times 9}{16\pi^2 R^6} \times \frac{R^5}{5} = \frac{Q^2}{40\pi\varepsilon_0 R}$$

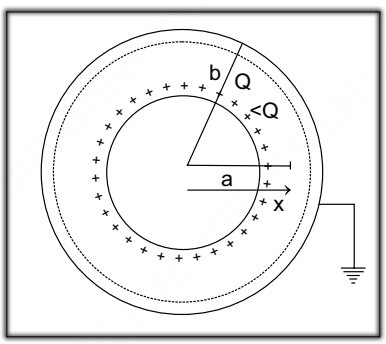
Total self electrostatic potential energy.

$PE = U_1 + U_2$

$$= \frac{Q^2}{8\pi\varepsilon_0 R} + \frac{Q^2}{40\pi\varepsilon_0 R} = \left(\frac{Q^2}{\pi\varepsilon_0 R} \times \frac{3}{20} \right)$$

Ratio = 5 : 1

2.5 SPHERICAL CAPACITOR



Case (A) When outer sphere is earthed and inner is given charge.

$$V_B - V_A = \int \vec{E}.\vec{dl} = -\int E dl$$

$$= -\int_a^b \frac{kQ}{x^2} dx$$

$$= -ks\left[\frac{-1}{x} \right]_a^b$$

$$= -kQ\left[-\frac{1}{b} + \frac{1}{a} \right]$$

$$= -kQ\frac{[b-a]}{ab}$$

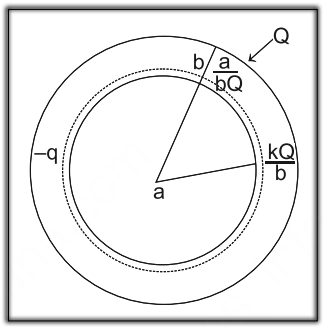
$$\text{Capacitance } C = \frac{\text{Charge supplied}}{\text{(PD) Potential difference developed}}$$

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$$= \frac{Q}{kQ\left(\frac{b-a}{ab}\right)}$$

$$C = \frac{4\pi\varepsilon_0 ab}{b-a}$$

Case (B) When inner sphere is earthed and outer is give charge.



When outer sphere is given charge, then the potential of inner sphere will be equal to the potential of outer sphere. Therefore, charge will flow from the earth at zero potential to smaller sphere till its potential becomes zero.

Let q = charge on smaller sphere in electrostatic equation.

$\therefore$ Potential of inner sphere $= \frac{-kq}{a} + \frac{kQ}{b} = 0$

$\Rightarrow \quad \frac{kQ}{b} = \frac{kq}{a}$

$\Rightarrow \quad q = \frac{a}{b}Q$

Electric potential of outer sphere $= \frac{-kq}{b} + \frac{kQ}{b}$

$$= \frac{k}{b}\left[-\frac{a}{b}Q + Q\right]$$

$$= \frac{kQ}{b}\left[\frac{b-a}{b}\right] = \frac{kQ(b-a)}{b^2}$$

Potential difference $= kQ\frac{(b-a)}{b^2}$

$\therefore \quad C = \frac{Q}{V} = k\frac{Q}{\frac{Q(b-a)}{b^2}}$

or $\quad C = \frac{4\pi\varepsilon_0 b^2}{b-a}$

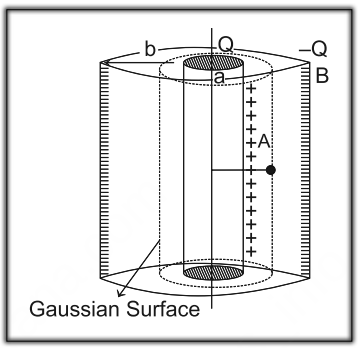
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2.6 CYLINDERICAL CAPACITOR

Consider two co-axial cylinders of inner radius *a* and *b*. Consider a Gaussian cylinder of radius *r*.

Electric flux through the Gaussian cylinder.

$$\phi = \oint \vec{E}.\vec{dS} = \oint E dS$$



$$= E \oint E dS$$

$$\therefore \quad \phi = (E \times 2\pi rl)$$

But according to Gauss law

Electric flux, $\phi = \dfrac{Q}{\varepsilon_0}$

$$\therefore \quad E \times 2\pi rl = \frac{Q}{\varepsilon_0}$$

or $$E = \frac{Q}{2\pi r \varepsilon_0 l}$$

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

$$V_B - V_A = \int \vec{E}.\vec{dl} = -\int E dl \cos 0°$$

$$= -\int \frac{\lambda}{2\pi \varepsilon_0 r} dr$$

$$= -\frac{\lambda}{2\pi \varepsilon_0} \int_a^b \frac{dr}{r} = \frac{\lambda}{2\pi \varepsilon_0} \left[(lnr) \right]_a^b$$

$$= \frac{\lambda}{-2\pi \varepsilon_0} ln \frac{b}{a}$$

Capacitance, $C = \dfrac{Q}{V}$

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$$= \frac{Q}{\frac{\lambda}{2\pi\varepsilon_0} ln\frac{b}{a}} = \frac{Q}{\frac{Q}{l \times 2\pi\varepsilon_0}} ln\frac{b}{a}$$

$$\therefore \quad C = \frac{2\pi\varepsilon_0 l}{ln(b/a)}$$

Capacitance per unit length $= \dfrac{2\pi\varepsilon_0}{ln(b/a)}$

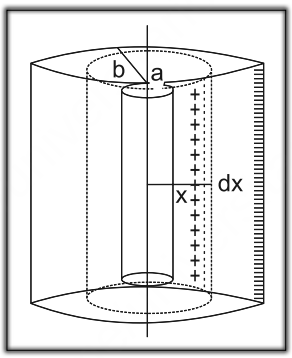
Example

Prove that half of the total energy stored in the case of cylindrical capacitor lies inside a cylinder whose radius is $r = \sqrt{ab}$.

☞ **Solution** Consider a cylinder of radius x and thickness dx.

Volume of cylindrical layer = Area × Thickness = $2\pi\, xl\, dx$

Energy stored in dx layer



$$= \frac{1}{2}\varepsilon_0 E^2 \times 2\pi x\, dx$$

$$= \frac{1}{2}\varepsilon_0 \left(\frac{\lambda}{2\pi\varepsilon_0 x}\right)^2 \times 2\pi x l\, dx$$

$$= \frac{\lambda^2 l}{4\pi\varepsilon_0}\frac{dx}{x}$$

Total stored energy $= \dfrac{\lambda^2 l}{4\pi\varepsilon_0}\int_a^b \frac{dx}{x}$

$$= \frac{\lambda^2 l}{4\pi\varepsilon_0}\left(ln\frac{b}{a}\right)$$

Energy stored in a cylinder of radius r.

$$U = \frac{\lambda^2 l}{4\pi\varepsilon_0}\left(ln\frac{r}{a}\right)$$

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But $\frac{\lambda^2 l}{4\pi\varepsilon_0} ln\frac{r}{a} = \frac{\lambda^2 l}{4\pi\varepsilon_0}\frac{ln\frac{b}{a}}{2}$

$\therefore \quad ln\frac{r}{a} = ln\left(\frac{b}{a}\right)^{1/2}$

or $\frac{r}{a} = \frac{\sqrt{b}}{\sqrt{a}}$

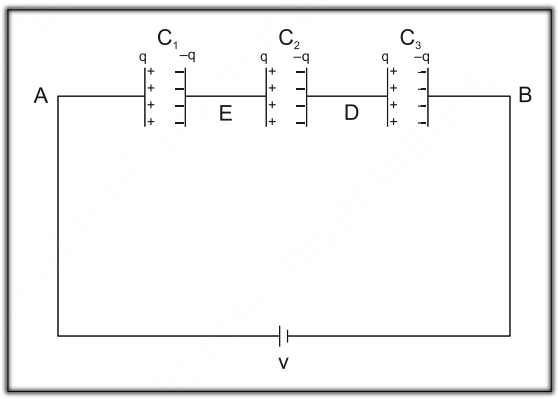
or $r = \sqrt{ab}$

2.7 COMBINATION OF CAPACITORS

Series Combination

In series combination, charge on each capacitors are same.

In general, in Series Combination, potential difference across capacitors are not same.



$V_1 + \frac{q}{C_1}$

$q = C_1 V_1$

$\therefore \quad q = C_2 V_2$

and $q = C_3 V_3$

or $C_1 V_1 = C_2 V_2 = C_3 V_3 = q$

$\therefore \quad C V = \text{Constant}$

$V \propto \frac{1}{C}$

$V_1 : V_2 : V_3 = \frac{1}{C_1} : \frac{1}{C_2} : \frac{1}{C_3}$

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Now, Potential difference, $V = V_1 + V_2 + V_3$

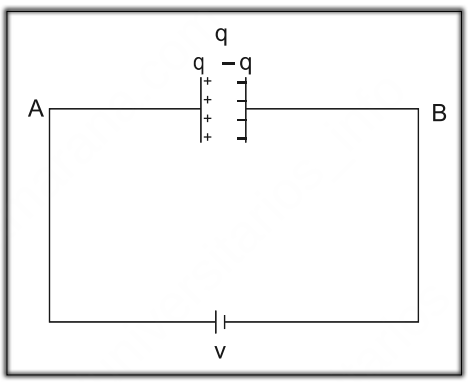
$$V = \frac{q}{C_1} + \frac{q}{C_2} + \frac{q}{C_3}$$

If = C Capacitance of equivalent capacitor.

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

$$\frac{q}{C} = \frac{q}{C_1} + \frac{q}{C_2} + \frac{q}{C_3}$$

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



CONCEPT

Equivalent of series combination means charge on equivalent capacitor will be equal to chrge on each capacitor while its P.D. will be equal to the sum of P.D. of each capacitor.

Here, $\frac{1}{C} > \frac{1}{C_i}$

or, $C_i > C$

$C < C_i$

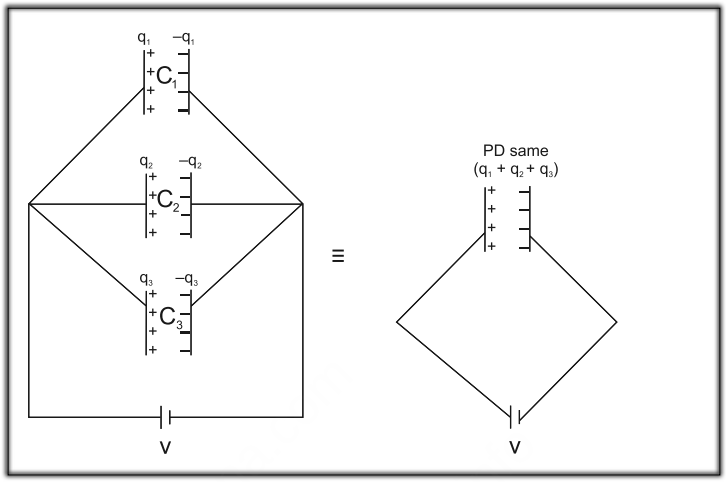
The value of equivalent capacitance in series combination is smaller than the smallest.

$C_{eq} = \frac{C}{n}$ if q is same for (V) all voltage.

$$C_{eq} = \frac{C_1 C_2}{C_i + C_2}$$

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Parallel Combination



Since, $q_1 = C_1V$

$q_2 = C_2V$

$q_3 = C_3V$

$\therefore \quad q_1 : q_2 : q_3 = C_1 : C_2 : C_3$

If C = Capacitance of equivalent capacitance, then

$$q_1 + q_2 + q_3 = CV$$

or $C_1V + C_2V + C_3V = CV$

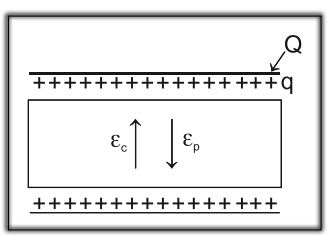
or $C = C_1 + C_2 + C_3$

Equivalent of parallel combination is greater than the greatest.

Charge on equivalent capacitor in parallel combination is sum of charge of all the capacitors while its P D will be equal to the P D of each and every capacitor.

2.8 POLARIZATION IN DIELECTRICS

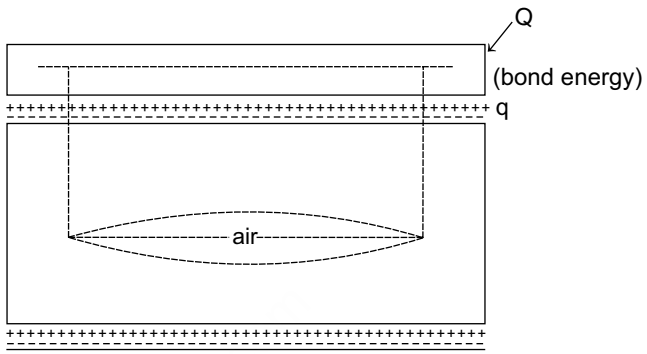
When a polar or a non-polar dielectric material is kept in a external field, then due to torque on dipoles, Dipole moment is aligned along the external field Due to this the surface of dielectric acquires charge, while inner volume is neutral. This phenomenon is known as **Polarization in dielectrics**.



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CONCEPT

When a dielectric lies in between plates of a capacitor then due to field produced by bond charge, net field inside the capacitor at any point decreases.



Consider a Gaussian surface as shown in the figure.

Electric flux through this gaussian surface,

$$\phi = \oint \vec{E}.\vec{dS} = \oint E dS$$

$$= E\int dS$$

$$= E_0 A,$$

where, A = Area of plate According to Gauss Law

$$\phi = \frac{q_{enclosed}}{\varepsilon_0} = \frac{Q+(-q)}{\varepsilon_0}$$

If dielectric is absent. Let field inside the capacitor is E_0.

$$\therefore \quad EA = \left(\frac{Q-q}{\varepsilon_0}\right) \qquad \ldots\ldots(i)$$

and $$E_0 A = \frac{Q}{\varepsilon_0} \qquad \ldots\ldots(ii)$$

From equations (i) and (ii), we have

$$\frac{E_0}{E} = \frac{Q}{\varepsilon_0} \times \frac{\varepsilon_0}{Q-q}$$

But $\frac{E_0}{E} = K$

$$\therefore \quad K = \frac{Q}{Q-q}$$

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or $K(Q - q) = Q$

or $KQ - Kq = Q$

or $q = \dfrac{Q(K-1)}{K}$

$\therefore \quad q = Q\left(1 - \dfrac{1}{k}\right)$

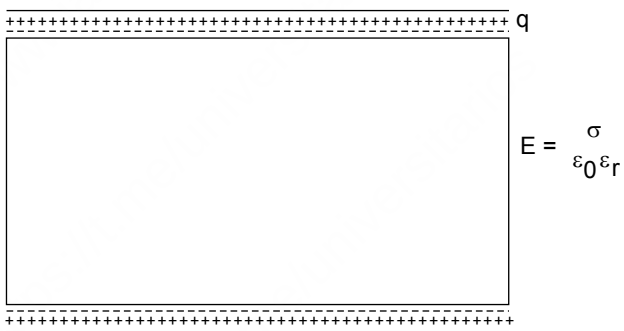
In this case, induced charge on the surface of dielectric is less than free charge. If the slab is of metal, then in this case

$K = \infty$ (infinite)

$q = Q$

CONCEPT

The result holds good for every type of dielectric material; though it is derived for special case of parallel plate capacitor.



$$q' = Q\left(1 - \frac{1}{K}\right)$$

$$\therefore \quad \sigma' = \frac{Q}{A}\left(1 - \frac{1}{K}\right)$$

$$\sigma' = \sigma\left(1 - \frac{1}{K}\right)$$

or $$\sigma' = \sigma - \frac{\sigma}{K}$$

$$\therefore \quad E_p = \frac{\sigma}{\varepsilon_0} - \frac{\sigma'}{\varepsilon_0} = \frac{1}{\varepsilon_0}(\sigma - \sigma')$$

$$= \frac{1}{\varepsilon_0}\left(\frac{\sigma}{K}\right) = \frac{\sigma}{\varepsilon_0 K}$$

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CONCEPT

How to write Gauss law in dielectrics:

$$\int \vec{E}.\vec{dS} = \left(\frac{Q-q}{\varepsilon_0}\right)$$

But $q = Q\left(1-\frac{1}{K}\right)$

$\therefore$ $q = Q - \frac{Q}{K}$

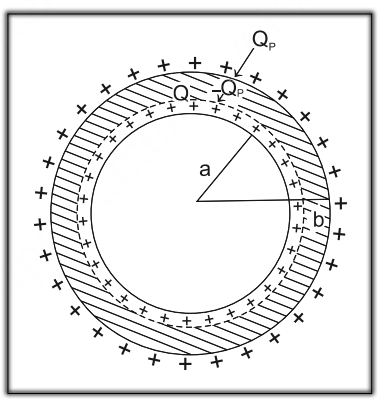
or $\frac{Q}{K} = (Q-q)$

From equation (i), $\int \vec{E}.\vec{dS} = \frac{Q}{K\varepsilon_0}$

or $K\int \vec{E}.\vec{dS} = \frac{Q}{\varepsilon_0}$ Free charge new form of Gauss's Law.

Example

A metallic sphere of radius q is surrounded by a homogeneous dielectric around it of outer radius *b*. Find capacitance of metallic sphere.



☞ **Solution** Bond charge, $Q_p = Q\left(1-\frac{1}{k'}\right)$

Electric potential of metallic sphere,

$$V = \frac{kQ}{a} - \frac{kQp}{a} + \frac{kQp}{b}$$

$$= \frac{kQ}{a} - \frac{kQ}{a}\left(1-\frac{1}{k_1}\right) + \frac{kQ}{b}\left(1-\frac{1}{k_1}\right)$$

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$$= \frac{kQ}{a}\left(1-1+\frac{1}{k_1}\right)+\frac{kQ}{b}\left(1-\frac{1}{k_1}\right)$$

$$= kQ\left[\frac{1}{k^1 a}+\frac{1}{b}-\frac{1}{k^1 b}\right] = kQ\left[\frac{1}{k_1}\left(\frac{1}{a}-\frac{1}{b}\right)+\frac{1}{b}\right]$$

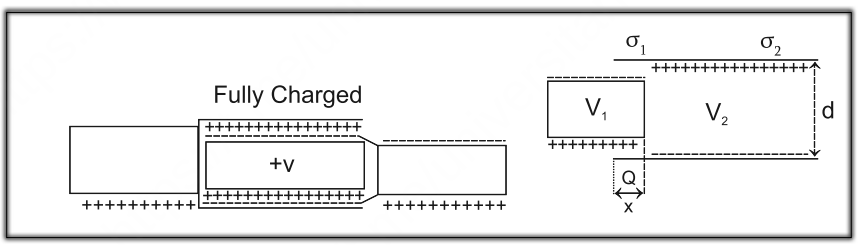
$$\therefore \quad C = \frac{Q}{V} = \frac{Q}{kQ\left[\frac{1}{k^1}\left(\frac{1}{a}-\frac{1}{b}\right)+\frac{1}{b}\right]}$$

or $$C = \frac{4\pi\varepsilon_0}{\frac{1}{k_1}\left(\frac{b-a}{ab}\right)+\frac{1}{b}}$$

Example

Two plates carry equal and opposite charges +*Q* and –*Q* separated by a distance d. A dielectric slab is introduced between the two plates as shown in the figure. Find

(i) Capacitance of this system.
(ii) Potential energy stored in the capacitor.
(iii) Force on dielectric by the plate.



☞ **Solution** $\sigma_1 = \sigma_2 \in_r$

$\sigma_1 > \sigma_2$

Capacitance of the system $C = C_1 + C_2$

$$= \frac{\varepsilon_0\left(x\frac{A}{l}\right)K}{d}+\frac{\varepsilon_0(l-x)\frac{A}{l}}{d}$$

$$= \frac{\varepsilon_0 A}{ld}\left[Kx+(l-x)\right]$$

$$= \frac{\varepsilon_0 A}{ld}\left[1+(K-1)x\right]$$

Energy stored in the capacitor, $U = \frac{Q^2}{2C}$

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$$U = \frac{Q}{\frac{2\varepsilon_0 A}{ld}[l + (K-1)x]} = \frac{Q^2 ld}{2\varepsilon_0 A[l + (K-1)x]}$$

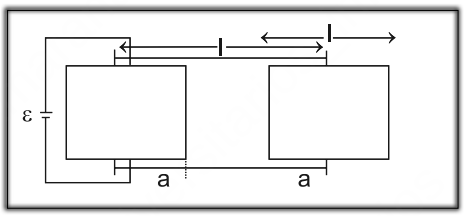
Force on dielectric due to the capacitor.

$$F = \frac{-dU}{dx} = \frac{-d}{dx}\left[\frac{Q^2 ld}{2\varepsilon_0 A}[l + (K-1)x]^{-1}\right]$$

$$= \frac{Q^2 ld}{2\varepsilon_0 A}\frac{(K-1)}{[l + (K-1)x]^2}$$

Example

If area of plate = A, width = $\frac{A}{l}$, find time period.



☞ **Solution** Let at any instant *x,* lengths of dielectric is interested in the capacitor.

$$C_{eq} = C_1 + C_2$$

$$= \frac{\varepsilon_0 (l-x)A}{ld} + \frac{\varepsilon_0 \varepsilon_r x A}{ld}$$

$$= \frac{\varepsilon_0 A}{ld}[l - x + \varepsilon_r x]$$

$$C = \frac{\varepsilon_0 A}{ld}[l + (\varepsilon_r - 1)x]$$

Energy stored in the capacitor.

$$U = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\varepsilon_0 A}{ld}[l + (\varepsilon_r - 1)x\,\varepsilon^2$$

$$F = \frac{-dU}{dx}$$

$$= -\frac{\varepsilon_0 A}{2ld}\varepsilon^2[\varepsilon_r - 1]$$

Acceleration of dielectric $a = \frac{\varepsilon_0 A\varepsilon^2}{2ldm}(\varepsilon_r - 1)$

Since, $s = ut + \frac{1}{2}a\,t^2$

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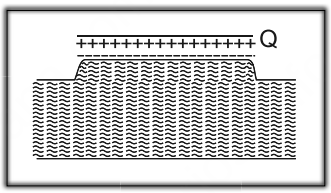
$$\therefore \quad (l-a)=\frac{1}{2}a\,t^2$$

or $$t=\sqrt{\frac{2(l-a)}{a^1}}$$

$$\text{Time period } T=2\left(\frac{2\sqrt{2(l-a)}}{a^1}\right)=\sqrt[4]{\frac{2(l-a)}{\varepsilon_0 A\varepsilon^2(\varepsilon_r-1)}{2ldm}}$$

Example

In the figure shown, find rise in the level of liquid inside the capacitor.



☞ **Solution** Net electric intensity at the upper surface.

$$E=\frac{\sigma(-j)}{\varepsilon_0}+\frac{\sigma'}{2\varepsilon}\hat{j}$$

$$=\frac{\hat{j}}{\varepsilon_0}\left[\frac{-Q}{A}+\frac{Q_p}{2A}\right]$$

$$E=\frac{\hat{j}}{\varepsilon_0}\left[-\frac{Q}{A}+\frac{Q\left(1-\frac{1}{K}\right)}{2A}\right]=\frac{\hat{j}Q}{A\varepsilon_0}\left[-1+\frac{\left(1-\frac{1}{K}\right)}{2}\right]$$

$$\vec{E}=\frac{-Q}{2A\varepsilon_0}\left(1+\frac{1}{K}\right)\hat{j}$$

For equilibrium, $QE = mg = Ah\rho g$

$$Q\left[\frac{-Q}{2A}\left(1+\frac{1}{K}\right)\right]=Ah\rho g$$

$$h=Q\left(1-\frac{1}{k}\right)\frac{-Q}{2A\varepsilon_0}\left(1+\frac{1}{k}\right)=\rho gAh$$

$$\therefore \quad h=\frac{Q\left(1-\frac{1}{k}\right)\frac{Q}{2A\varepsilon_0}\left(1+\frac{1}{k}\right)}{A\rho g}$$

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Example

A parallel plate condenser consists of two metal plates of area A and separation d. A slab of thickness 't' and dielectric constant k is inserted between the plates with its faces parallel to the plates and having the same surface area as that of the plates. Find the capacitance of the system. If $k = 2$, for what value of $\frac{t}{d}$, will the capacitance of the system be $\frac{3}{2}$ times that of the condenser with air filling the full space? Calculate the energy in the two cases and account for the energy charge.

☞ **Solution** In effect, the capacitor filled partly with the dielectric is a series combination of two capacitors of capacitances

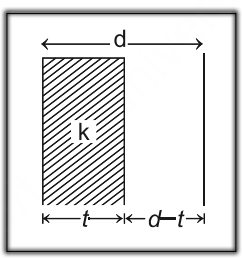
$$C_1 = \frac{\varepsilon_0 k A}{t}, \quad C_2 = \frac{\varepsilon_0 A}{d-t}$$

$\therefore$ Effective capacitance of the combination is

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} = \frac{t}{k\varepsilon_0 A} + \frac{d-t}{\varepsilon_0 A} = \frac{\frac{t}{k} + d - t}{\varepsilon_0 A}$$

$\therefore$ $$C = \frac{\varepsilon_0 A}{\frac{t}{k} + d - t} = \frac{\varepsilon_0 A}{d - \frac{t}{2}}$$

For the air condenser, $C_a = \frac{\varepsilon_0 A}{d}$



Now $$C = \frac{3}{2} C_a$$

$\therefore$ $$\frac{\varepsilon_0 A}{d - \frac{t}{2}} = \frac{3}{2} \times \frac{\varepsilon_0 A}{d}$$

$\therefore$ $$\frac{2}{3} = \frac{d - \frac{t}{2}}{d} = 1 - \frac{t}{2d}$$

$\therefore$ $$\frac{t}{2d} = 1 - \frac{2}{3} = \frac{1}{3}$$

$\therefore$ $$\frac{t}{d} = \mathbf{\frac{2}{3}}.$$

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If charge Q in the condenser remains unchanged, then

Energy of the air condenser, $W_i = \frac{1}{2}\frac{Q^2}{C_n}$

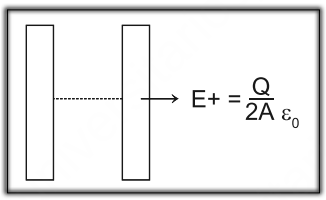
Energy after introducing the dielectric, $W_f = \frac{1}{2}\frac{Q^2}{C}$

$$\frac{W_i}{W_f} = \frac{C}{C_n} = \frac{3}{2}$$

The introduction of the dielectric reduces the potential energy of the condenser. This loss is used up to polorize the dielectric.

2.9 FORCE BETWEEN THE PLATES OF CAPACITOR

Consider a parallel plate capacitor with plate area A. Suppose, a positive charge + Q is given to one plate and a negative charge – Q to the another plate. The electric field due to only the positive plate is



$$E_+ = \frac{\sigma}{2\varepsilon_0}$$

$$= \frac{Q}{2A\varepsilon_0}$$

at all points if charge is large. The negative charge – Q finds itself in the field of this positive charge. Therefore force on – Q is

$$F = -QE$$

$$= (-Q)\frac{Q}{2\varepsilon_0 A} = \frac{-Q^2}{2A\varepsilon_0}$$

The magnitude of force is

$$F = \frac{Q^2}{2A\varepsilon_0}$$

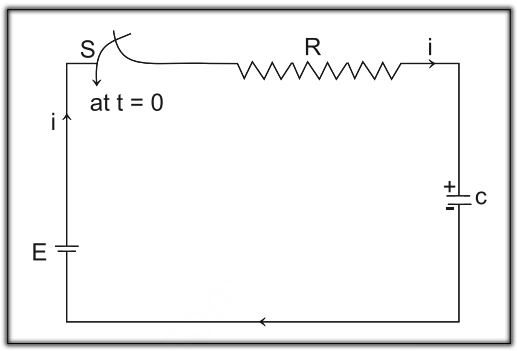
This is the force with which the positive plate attracts the negative plate. This is also the force of attraction on the positive plate by the negative plate. Thus, the plates of parallel plate capacitor attract each other with a force

$$F = \frac{Q^2}{2A\varepsilon_0}$$

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2.10 CHARGING OF A CAPACITOR

In the circuit an uncharged capacitor of capacitance C is connected to the resistance R. At the time $t = 0$, the switch S is closed and thus the current flow to the capacitor.



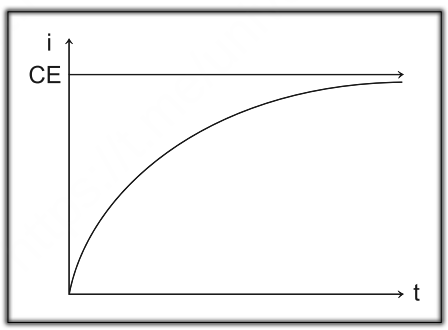
Let q, v_c be the charge and voltage of the capacitor at time t and i be the current. Then by Kirchoff's law

$$E - iR - v_c = 0$$

$$E - R\frac{dq}{dt} - \frac{q}{C} = 0 \qquad \left(\because i = \frac{dq}{dt}\right)$$

$$\Rightarrow \quad \frac{dq}{CE - q} = \frac{dt}{RC} \quad = \int_0^q \frac{-dq}{CE - q} = \int_0^t \frac{-dt}{RC}$$

$$q\,(t) = CE\,(1 - e^{-t/RC})$$



This equation gives the expression for charge on capacitor as a function of time. The charge grows on the plate exponentially as shown on the graph.

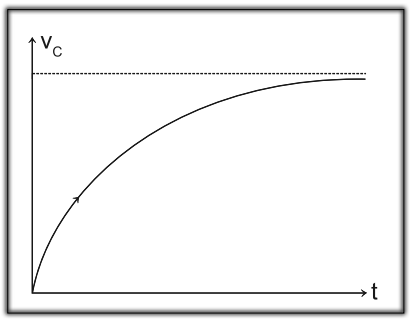
Note the Following Points

(i) In steady state: $t \to \infty$ and $q \to CE$

(ii) The voltage across capacitor also grows exponentially towards E

$$\upsilon_c = \frac{q}{C} = E\,(1 - e^{-t/RC})$$

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(iii) The time constant (τ) of the circuit is defined as the time after which the charge has grown upto

$\left(1-\frac{1}{e}\right)$ = 63% of its steady-state value.

$\tau = RC$

(iv) *From energy conservation, we can see that:*

Energy supplied by cell per sec. = energy stored in capacitor per sec. + heat dissipated in R per sec

or $Ei = iv_c + i^2R$

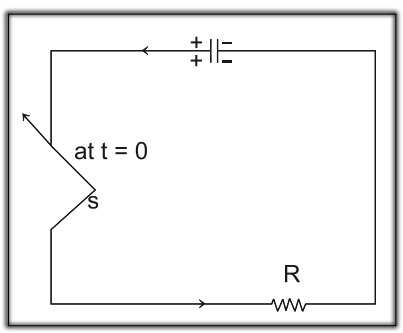
or $E = v_c + iR$

$$E = \frac{q}{C} + R\frac{dq}{dt}$$

(Note that $i = \frac{dq}{dt}$, as q is increasing and hence $\frac{dq}{dt}$ is positive).

2.11 DISCHARGING OF A CAPACITOR

If we connect a charge capacitor C across a resistance R, the capacitor begins to discharge through R. The excess positive charge on high potential plate flow through R to the negative plate and in steady-state, the capacitor plate become discharged.



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As the charge on plates decreases with time, $\frac{dq}{dt}$ is negative.

Hence $i = -\frac{dq}{dt}$

From Kirochoff's Law

$$\upsilon_c = iR$$

$$\Rightarrow \quad \frac{q}{C} = -R\frac{dq}{dt} \quad \Rightarrow \quad \int_{q_0}^{q} \frac{dq}{q} = \int_{0}^{t} -\frac{dt}{RC}$$

where, q_0 is the charge on capacitor at $t = 0$

$$\Rightarrow \quad q(t) = q_0\, e^{-t/RC}$$

Example

A capacitor of capacity 1 μF is connected in closed series circuit with a resistance of $10^7\ \Omega$, an open key and a cell of 2 V with negligible internal resistance:

(i) **When the key is switched on at time $t = 0$, find:**
  (a) time constant for the circuit.
  (b) charge on the capacitor at steady-state.
  (c) time taken to deposit charge equal to half of that at steady-state.

(ii) **If after fully charging the capacitor, the cell is shorted zero resistance at time $t = 0$, find the charge on the capacitor at t = 50 sec.**

☞ **Solution**

(i) (a) Time constant = RC

$= (10^7)\,(10^{-6}) =$ **10 sec.**

(b) Charge on the capacitor at steady-state,

$$Q_0 = V_0 C$$
$$= 2 \times 10^{-6}$$
$$= \mathbf{2\ \mu C}$$

(c) $q = \frac{1}{2}Q_0 = Q_0\left[1 - e^{-\frac{1}{CR}t}\right]$

$$\Rightarrow \quad e^{\frac{t}{10}} = 2$$

$$\Rightarrow \quad t = (10)\,(2.303)\,(\log_{10}^{2})$$
$$= \mathbf{6.94\ sec.}$$

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(ii) $q = Q_0 e^{-\frac{1}{CR}t} = (2\times10^{-6})e^{-\frac{50}{10}}$

$= 2\times10^{-6}\dfrac{1}{e^5}$ = **1.348 × 10⁻⁸ C** (since, $e = 2.718$)

Example

A 3 mega-ohm resister and 1 μF capacitor are connected in a single loop circuit with a source of constant 4 volts. At one second after the connection is made, what are the rates at which:

(i) **the charge on the capacitor is increasing.**
(ii) **energy is being stored in the capacitor.**
(iii) **joule heat is appearing in the resistor.**
(iv) **energy is being delivered by the source?**

☞ **Solution** Given: $R = 3\times10^6\ \Omega C = 1\times10^{-6}$ F

$v_0 = 4$ V, $t = 1$ sec

$q_0 = v_0 C = 4\times10^{-6} = 4\times10^{-6}\ C$

$q = q_0\left(1 - e^{-\frac{t}{CR}}\right)$

(i) $\dfrac{dq}{dt} = q_0\left(e^{-\frac{t}{CR}}\right).\dfrac{1}{CR}$

$= \dfrac{4\times10^{-6}}{3}\cdot e^{-\frac{1}{3}}$

= **0.96 ×10⁻⁶ Cs⁻¹**

(ii) Rate of energy stored $= \dfrac{d}{dt}\left(\dfrac{1}{2}\dfrac{q^2}{\mathrm{C}}\right)$

$= \dfrac{1}{2}.\dfrac{q}{\mathrm{C}}\dfrac{dq}{dt} = \dfrac{q_0}{\mathrm{C}}\left[1 - e^{-\frac{t}{RC}}\right]\dfrac{dq}{dt}$

$= \dfrac{4\times10^{-6}}{1\times10^{-6}}\left(1 - e^{-\frac{1}{3}}\right)(0.96\times10^{-6})$

= **1.09 × 10⁻⁶ *Js*⁻¹**

(iii) Rate of Joule heating = i^2R

$= (0.96\times10^{-6})^2\ (3\times10^6)$

$= 2.76\times10^{-6}\ J\mathrm{s}^{-1}$

(iv) Rate at which energy is drawn from the source

$= v_0\ i$

$= 4\times0.96\times10^{-6}$

= **3.84 × 10 ⁻⁶ Js⁻¹.**

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WORKED OUT EXAMPLES

1. The gap between the plates of a parallel-plate capacitor is filled with isotropic dielectric whose permittivity ε varies linearly from ε_1 to ε_2 ($\varepsilon_2 > \varepsilon_1$) in the direction perpendicular to the plates. The area of each plate equals S, the separation between the plates is equal to d. Calculate:

(i) capacitance of the capacitor.

(ii) space density of the bound charges as a function of ε if the charge of the capacitor is *q* and the field E in it directed toward the growing ε values.

☞ **Solution** The dielectric constant increasing linearly with distance.

Let $\varepsilon = \varepsilon_1 + bx$ and when $x = d$, $\varepsilon = \varepsilon_2$ When $x = 0$, $\varepsilon = \varepsilon_1$;

$$b = \frac{\varepsilon_2 - \varepsilon_1}{d}$$

$$\therefore \quad \varepsilon = \varepsilon_1 + \left(\frac{\varepsilon_2 - \varepsilon_1}{d}\right)x$$

$$V_+ - V_- = \int \vec{E}.dr = \int \frac{\sigma}{\varepsilon\,\varepsilon_0}dx$$

$$= \int_0^d \frac{dx}{\varepsilon_0\left[\varepsilon_1 + \left(\frac{\varepsilon_2 - \varepsilon_1}{d}\right)x\right]}$$

Put $\varepsilon_1 + \frac{(\varepsilon_2 - \varepsilon_1)}{d}x = z, \Rightarrow \frac{\varepsilon_2 - \varepsilon_1}{d}dx = dz$

or $x = 0, \quad z = \varepsilon_1$

and $x = d, \quad z = \varepsilon_2$

$$V_+ - V_- = \frac{\sigma}{\varepsilon_0}\int_{\varepsilon_1}^{\varepsilon_2} \frac{d}{\varepsilon_2 - \varepsilon_1}.\frac{dz}{z}$$

$$= \frac{\sigma}{\varepsilon_0(\varepsilon_2 - \varepsilon_1)}\ln\frac{\varepsilon_2}{\varepsilon_1}$$

Hence, the sought capacitance, $C = \frac{\sigma S}{V_+ - V_-}$

$$= \frac{(\varepsilon_2 - \varepsilon_1)\varepsilon_0 S}{\left(ln\frac{\varepsilon_2}{\varepsilon_1}\right)d}.$$

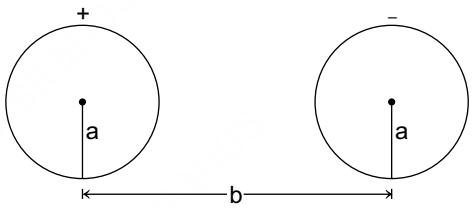
(ii) $D = \frac{q}{S}$ and $\rho = \frac{q}{S}\frac{q}{S\varepsilon(x)}$

And, the space density of bound charge is

$$\rho' = -div\,\rho = -\frac{\boldsymbol{q(\varepsilon_2 - \varepsilon_1)}}{\boldsymbol{Sd\varepsilon^2(x)}}.$$

2. Find the capacitance of a system of two identical metal balls of radius a if the distance between their centres is equal to b, with b >> a. The system is located in a uniform dielectric with permittivity ε.

☞ **Solution**



When, $b >> a$, the charge distribution on each spherical conductor is practically unatteched by the presence of the other conductor. Then, the potential ϕ_+ (ϕ_-) on the positive (respectively negative) charged conductor is

$$+\frac{q}{4\pi\varepsilon_0 a\varepsilon}\left(-\frac{q}{4\pi\varepsilon_0\varepsilon_a}\right)$$

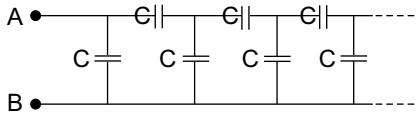
Thus, $\phi_+ - \phi_- = \frac{q}{2\pi\varepsilon\varepsilon_0 a}$

and $C = \frac{q}{\phi_+ - \phi_-} = 2\pi\varepsilon_0\varepsilon a$

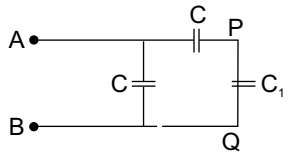
Note: If we require terms which depend on $\frac{a}{b}$, we have to take account of distribution of charge on the conductors.

3. Find the capacitance of infinite ladder shown in the figure.

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☞ **Solution** As the ladder is infinitely long, the capacitance of the ladder to the right of the points P and Q, is the same as that of the ladder to the right of the points A and B.



The equivalent capacitance between A and B.

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

or $C_1 C + C_1^2 = C^2 + 2C C_1$

or $C_1^2 - CC_1 + C^2 = 0$

Solving we get,

$$C_1 = \frac{C + \sqrt{C^2 + 4C^2}}{2} = \frac{1+\sqrt{5}}{2} C$$

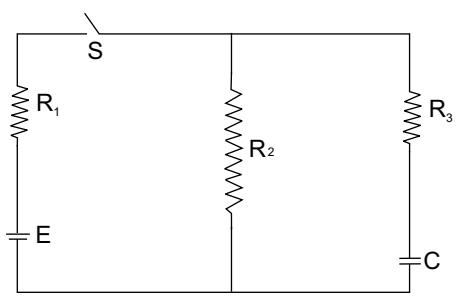
Negative value of C_1 is rejected.

4. In the circuit shown in the figure $R_1 = 2$, $R_2 = 6$, $R_3 = 300$ MΩ, $C = 0.1$ μF and $E = 10$ volt.

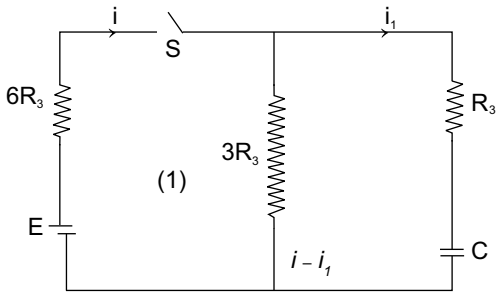
The switch 'S' is closed at t = 0. Calculate:

(i) **charge on the capacitance as a function of time.**

(ii) **energy of the capacitance at t = 15 sec.**



☞ **Solution**



Applying Kirchoff's law in loop I, we have

$$6R_3\, i + 3R_3\,(i - i_1) - E = 0$$

or $9R_3\, i - 3R_3\, i_1 - E = 0$ ...(i)

Again applying the Kirchoff's law, we have

$$6R_3 i + R_3 i_1 + \frac{q}{C} - E = 0 \quad \ldots(ii)$$

From equations (i) and (ii)

$$-6R_3 i_1 - 2E - 3R_3 i_1 - \frac{3q}{C} + 3E = 0$$

or $9R_3 i_1 + \frac{3q}{C} - E = 0$

But $i_1 = \frac{dq}{dt}$

$\therefore \quad 9R_3 \frac{dq}{dt} + \frac{3q}{C} - E = 0$

or $\frac{9R_3\, dq}{E - \frac{3q}{C}} = dt$

Let $E - \frac{3q}{C} = z$

or $-\frac{3}{C} dq = dz$

$\therefore \quad 9R_3(-)C\frac{dz}{3z} = dt$

or $-9R_3 C \ln\left(E - \frac{3q}{C}\right) = 3t$

or $E - \frac{3q}{C} = e^{-\frac{t}{9R_3C}}$

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or $E - e^{-\frac{t}{9R_3C}} = \frac{3q}{C}$

or $q = \frac{C}{3}\left(E - e^{-\frac{t}{9R_3C}}\right)$

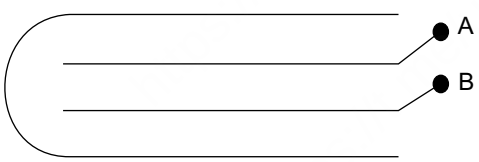
$= \frac{10^{-6}}{3}\left(1 - e^{-\frac{t}{15}}\right)C$

(ii) **Energy of capacitor** $= \frac{1}{2}\frac{q^2}{C}$

$= \frac{1}{2} \times \frac{\left[\frac{10^{-6}}{3}\left(1 - e^{-\frac{15}{15}}\right)\right]^2}{0.1 \times 10^{-6}}$

$= 0.22 \times 10^{-6}$ J

5. Four identical metal plates are located in air at equal distance d from one another. The area of each plate is equal to *S*. Find the capacitance of the system between points *A* and *B* if the plates are interconnected as shown.



☞ **Solution** The charge distribution is shown in the figure

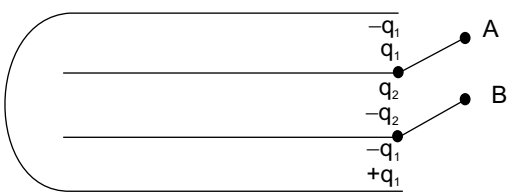
Applying the kirchoffs law

$$-\frac{-q_1}{C} + \frac{-q_2}{C} + \frac{(-q_1)}{C} = 0$$

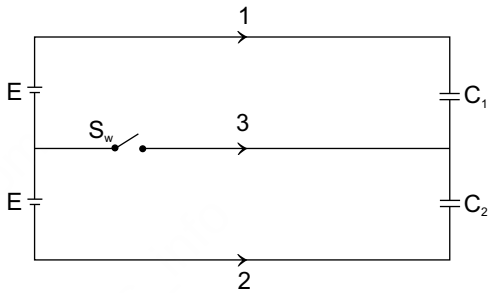
or $q_2 = 2\,q_1$ …(i)

Now $C_0 = \frac{q_1 + q_2}{\frac{q_1}{C}} = \frac{3}{2}C$

or $C_0 = \frac{3}{2}\frac{\varepsilon_0 S}{d}$.



6. In the circuit shown in the figure, electro magnetic field of each battery is equal to E = 60 V and the capacitor capacitances are equal to C_1 = 2.0 μF and C_2 = 3.0 μF. Find the charges which flow after the shorting of the switch S_w through section 1, 2 and 3 in the directions indicated by the arrow.

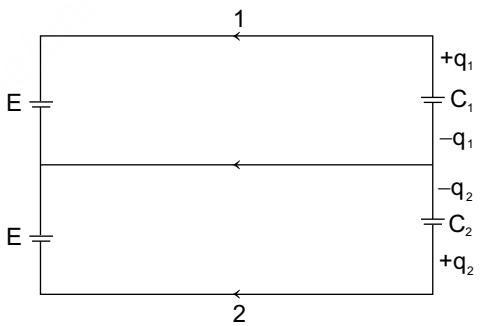


☞ **Solution** Applying the Kirchoff's law when the switch is closed.

$$E - \frac{q_1}{C_1} = 0$$

or $q_1 = EC_1$ …(i)

And $q_2 = E\,C_2$



When the switch is open, equivalent capacitance

$$C_0 = \frac{C_1 C_2}{C_1 + C_2}$$

$$\therefore \quad q_0 = \frac{2EC_1C_2}{C_1 + C_2}$$

Hence, the flow of charge due to the shorting of switch through section 1

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$= q_1 - q_0$

$= \mathrm{E}\, C_1 \left[\frac{C_1 - C_2}{C_1 + C_2}\right]$

$= \mathbf{-24\ \mu C}$

and through the section 2

$= -q_2 - (q_0)$

$= E C_2 \left[\frac{C_1 - C_2}{C_1 + C_2}\right]$

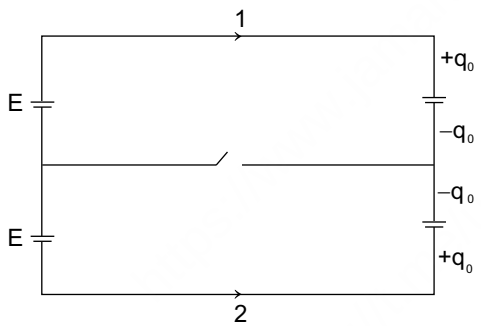
$= \mathbf{-36\ \mu C}$

and through the section 3

$= -q_2 - (q_1)$

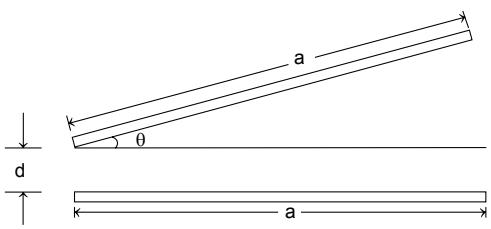
$= \mathrm{E}\,(C_2 - C_1)$

$= \mathbf{-60\ \mu C}$



7. A capacitor has square plates each of side a, making an angle of θ with each other as shown in the figure. Show that for small θ, the capacitance is given by

$$C = \frac{\varepsilon_0 a^2}{d}\left(1 - \frac{a\theta}{2d}\right)$$



☞ **Solution** Consider a strip of length dx at distance x. Then, the capacitance

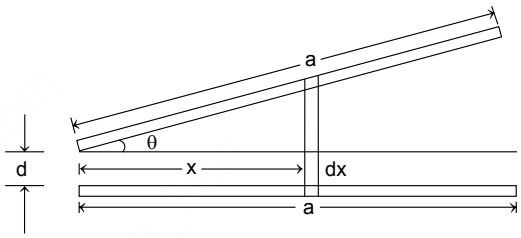
$$dC = \frac{\varepsilon_0 a\, dx}{d + y}$$

From the triangle $\tan\theta = \frac{y}{x}$

$\therefore \quad y = x \tan\theta$

For the small value of θ, $\tan\theta \approx \theta$

$$dC = \frac{\varepsilon_0 a\, dx}{d + x\theta}$$



Put $d + x\theta = z$ ....(i)

If $x = 0$, then $z = d$

If $x = a$ then $z = d + a\theta$

Differentiating equation (i), we get

$\theta\, dx = dz$

$\therefore \quad dx = \frac{dz}{\theta}$

$\therefore \quad dC = \frac{\varepsilon_0 a}{\theta} \cdot \frac{dz}{z}$

Thus, equivalent capacitance

$$C = \int dC = \int_d^{d+a\theta} \frac{\varepsilon_0 a}{\theta}\frac{dz}{z}$$

$$= \frac{\varepsilon_0 a}{\theta} \ln\frac{d + a\theta}{d}$$

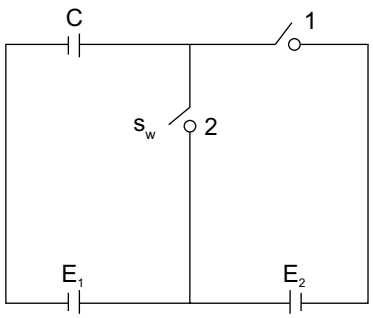
$$= \frac{\varepsilon_0 a}{\theta} \ln\left(1 + \frac{a\theta}{d}\right)$$

$$= \frac{\varepsilon_0 a}{\theta}\left[\frac{q\theta}{d} - \frac{a^2\theta^2}{2d^2} \ldots\right]$$

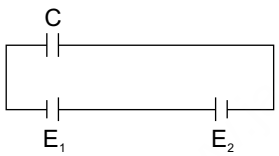
$$\Rightarrow \quad C = \frac{\varepsilon_0 \boldsymbol{a^2}}{\boldsymbol{d}}\left[\mathbf{1} - \frac{\boldsymbol{a}\theta}{\mathbf{2}\boldsymbol{d}}\right].$$

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8. What amount of heat will be generated in the circuit shown after the switch S_w is shifted from position 1 to position 2?



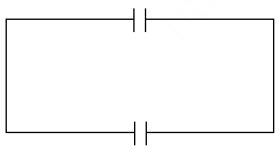
☞ **Solution**



Initially, the charge on the right plate of the capacitor

$$q = C(E_1 - E_2)$$

and finally when switched to the position 2, charge on the same plate of capacitor



$$q' = CE_1$$

$$\therefore \quad \Delta q = q' = CE_2$$

Now from energy conservation

$$\Delta U + \text{Heat liberated} = E_{cell}$$

where, ΔU is the electrical energy.

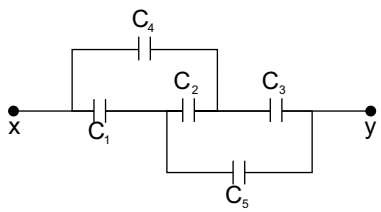
or $$\frac{1}{2}CE_1^2 - \frac{1}{2}C(E_1 - E_2) + \text{Heat liberated} = \Delta q\, E_1$$

As only the cell with electro magnetic field E_1 is responsible for redistribution of the charge, therefore

$$CE_1E_2 - \frac{1}{2}CE_2^2 + \text{Heat liberated} = CE_2E_1$$

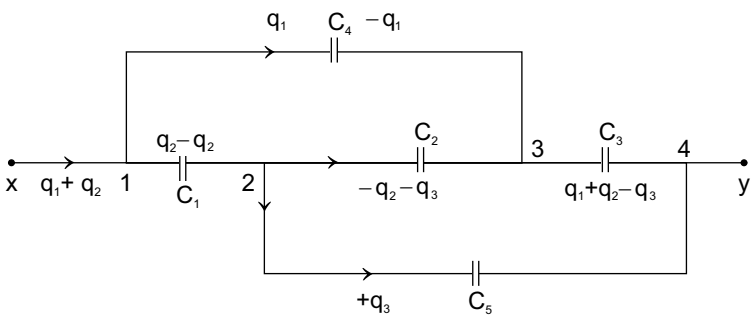
Hence heat liberated $= \frac{1}{2}\mathbf{CE_2^2}$.

9. Find the effective capacitance between points x and y shown in the figure.



(Hint: Apply a potential difference V between x and y and write down all the relationships that involve the charges and potential differences for the separate capacitors.)

☞ **Solution** The charge distribution is shown in the figure.



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Applying Kirchoff's law
Loop 1321:

$$\frac{q_1}{C^4}+\frac{q_2+q_3}{C_2}-\frac{q_2}{C_1}=0$$

or $\frac{q_1}{4}+\frac{q_2+q_3}{10}-\frac{q_2}{4}=0$

or $10\,q_1+4\,q_2+4\,q_3-10\,q_2=0$

or $10\,q_1-6\,q_2+4\,q_3=0$ …(i)

Loop 2342:

$$\frac{-q_2-q_3}{10}+\frac{q_1+q_2-q_3}{4}-\frac{q_3}{4}=0$$

or $-4\,q_2-4\,q_3\;10\,q_1+10\,q_2-10\,q_3-10\,q_3=0$

or $10\,q_1+6\,q_2-24\,q_3=0$ ..(ii)

Equivalent capacitance,

$$C_0=\frac{\text{Total charge}}{\text{Potential difference}}$$

$$=\frac{q_1+q_2}{\frac{q_1}{C^4}+\frac{q_1+q_2-q_3}{C_3}}$$

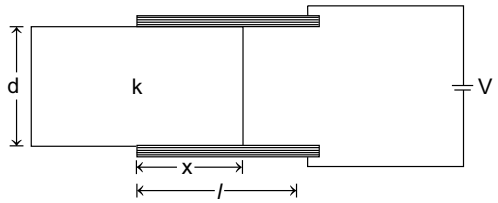
Putting the value of equation (i) and (ii), we get

$C_0 = \mathbf{4\ \mu F}$

10. Figure shows a parallel-plate capacitor with plates of width b and length l. The separation between the plates is d. The plates are rigidly clamped and connected to a battery of electro magnetic field V. A dielectric slab of thickness *d* and dielectric constant *k* is slowly inserted between the plates.

(i) **Calculate the energy of the system when a length x of the slab is introduced into the capacitor.**

(ii) **What force should be applied on the slab to ensure that it goes slowly into the capacitor? Neglect any effect of friction or gravity.**



☞ **Solution**

(i) The plate area of the part with the dielectric is *bx*. Its capacitance is

$$C_1=\frac{k\varepsilon_0 bx}{d}$$

Similarly the capacitance of the part without the dielectric is

$$C_2=\frac{\varepsilon_0 b(l-x)}{d}$$

These two parts are connected in parallel. The capacitance of the system is therefore,

$$C = C_1 + C_2$$

$$=\frac{\varepsilon_0 b}{d}[l+x(k-1)] \quad \text{…(i)}$$

Energy of the capacitor

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

$$=\frac{\varepsilon_0 bV^2}{2d}[l+x(k-1)]$$

(ii) Suppose, the electric field attracts the dielectric slab with a force *F*. An external force of equal magnitude F should be applied in opposite direction so that the plate moves slowly (no acceleration). Consider the part of motion in which the dielectric moves a distance *dx* further inside the capacitor. The capacitance increases to C + dC. As the potential difference remains constant at V, the battery has to supply a further charge

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$dQ = (dC)\,V$ to the capacitor.

The workdone by the battery is therefore,

$$dW_b = VdQ = dCV^2$$

The external force F does a work

$$dW_e = (-Fdx)$$

During the displacement.

The total workdone on the capacitor is

$$dW_b + dW_e = (dC)\,V^2 - Fdx$$

This should be equal to the increases dU in the stored energy. Thus,

$$\frac{1}{2}(dC)V^2 = (dC)V^2 - Fdx$$

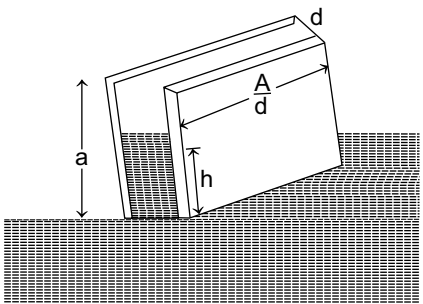
or $$F = \frac{1}{2}V^2\frac{dC}{dx}$$

Using equation (i), we get

$$F = \frac{\varepsilon_0 bV^2(k-1)}{2d}$$

Thus, the electric field attract the dielectric into the capacitor with a force $\frac{\varepsilon_0 bV^2(k-1)}{2d}$ and this much force should be applied in the opposite direction.

11. A parallel plate capacitor is charged by applying a potential difference V across its plates. The capacitor is now disconnected from the battery and is placed vertically on the surface of a liquid of density 1200 kgm^{-3}. If the liquid rises to a height of 2 mm inside the capacitor plates, calculate the potential difference V, initially applied across the plates. The capacitor plates are of length a = 10 cm and area A = 50 cm^2. They are separated by 1 mm. Dielectric constant of the liquid = 14.



☞ **Solution** When the charge capacitor placed on the liquid surface, the liquid gets polorized is drawn into the space between the plates. The charge on the capacitor is unchanged during this process while capacitance increase and potential and energy is decrease, so this decrease stored electrical energy is compensated to the potential energy of the liquid column held between the plates.

Therefore by the energy conservation principle.

Initial electric PE = Final electric potential energy + potential energy of liquid column.

If Q is the charge stored and C_1 and C_2 its capacitance before and after the introduction of the dielectric.

$$\frac{Q^2}{2C_1} = \frac{Q^2}{2C_2} + \text{mg}\left(\frac{h}{2}\right) \qquad \ldots(\text{i})$$

(The centre of gravity of the liquid column is at a height $\frac{h}{2}$ from the liquid surface).

For the parallel plate capacitor

$$C_1 = \frac{\varepsilon_0 A}{d}$$

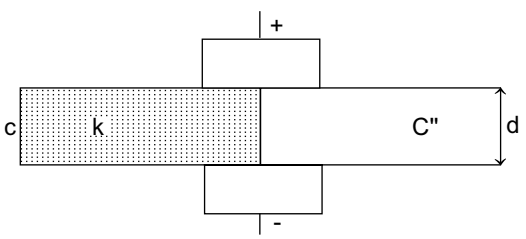
where, A is area of the plates and d is the distance between the plates.

When the capacitor is partly filled with dielectric, it can be assumed to consist of two capacitors connected in parallel.

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

$$C'' = \frac{\varepsilon_0(A - A')}{d}$$

$$\therefore \quad C_2 = \frac{k\varepsilon_0 A'}{d} + \frac{\varepsilon_0(A - A')}{d}$$



where, A′ = overlapping area covered by the dielectric.

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$= h \times$ breath of the plate

$= h \times \frac{A}{a}$

$\therefore \quad C_2 = \frac{k\varepsilon_0 hA}{da} + \frac{\varepsilon_0}{d}\left(A - \frac{hA}{a}\right)$

$= \frac{\varepsilon_0 A}{da}(kh + a - h)$

$= \frac{\varepsilon_0 A}{da}[a + (k-1)h]$

Mass of the liquid column, m = volume × density

$= h \times \frac{A}{a} \times d \times p$

$\therefore \quad m = 2\times10^{-3} \times \frac{5\times10^{-3}}{0.1} \times 1\times10^{-3} \times 1200$

$= 1.2 \times 10^{-4}$ kg

The charge stored in the capacitor,

$Q = C_1 V$

where, V = the potential applied.

Therefore from equation (i), we get

$$\frac{(C_1V)^2}{C_1} = \frac{(C_1V)^2}{C_2} + mgh$$

or $\quad C_1V^2 = \frac{C_1^2 V^2}{C_2} + mgh$

or $\quad V^2\left[C_1 - \frac{C_2^2}{C_1}\right] = mgh$

or $\quad \frac{V^2 C_1(C_2 - C_1)}{C^2} = mgh$

$\therefore \quad V = \left[\frac{mgh\, C_2}{C_1(C_2 - C_1)}\right]^{\frac{1}{2}}$ …(ii)

$C_1 = \frac{\varepsilon_0 A}{d}$

$= \frac{8.85\times10^{-12}\times5\times10^{-3}}{1\times10^{-3}}$

$= \mathbf{4.425 \times 10^{-11}\ F}$

$C_2 = \frac{\varepsilon_0 A}{da}[a + (k-1)h]$

$= \frac{8.85\times10^{-12}\times5\times10^{-3}}{1\times10^{-3}\times0.1}$

$[0.1 + (14-1)\times 2\times10^{-3}]$

$= 5.576 \times 10^{-11}$ F

From equation (ii)

$$V = \left[\frac{1.2\times10^{-4}\times9.81\times2\times10^{-3}\times5.576\times10^{11}}{4.425(5.576-4.425)}\right]^{\frac{1}{2}}$$

$= \mathbf{507.7\ V}$

12. A leaky parallel plate capacitor is filled completely with a material having dielectric constant k = 5 and electrical conductivity $\sigma = 7.4 \times 10^{-12}\ \Omega^{-1}\ m^{-1}$. If the charge on the plate at the instant t = 0 is q = 8.85 μC, then calculate the leakage current at the instant t = 12 sec.

☞ **Solution** The charge on the leaky capacitor decreases exponentially in time with a time constant RC i.e.,

$$\mathbf{Q = Q_0 e^{-\frac{t}{RC}}} \quad \text{…(i)}$$

where, R and C are given by the expression.

$R = \rho\left(\frac{d}{A}\right) = \frac{1}{\sigma}\left(\frac{d}{A}\right)$

$C = \varepsilon\left(\frac{A}{d}\right) = k\,\varepsilon_0\left(\frac{d}{A}\right)$

Thus $\quad RC = \frac{k\varepsilon_0}{\sigma}$

$= \frac{5\left[\frac{1}{41\times3.14\times9\times10^9\, Nm^2c^2}\right]}{7.4\times10^{-12}\,\Omega^{-1}m^{-1}}$

$= 5.98$ sec.

With this equation (i) becomes

$$Q = Q_0 \exp\left(-\frac{t}{RC}\right) = Q_0 \exp\left(-\frac{t}{5.98\,\text{sec.}}\right)$$

Now since, leakage current, $I = \left(\frac{dQ}{dt}\right)$

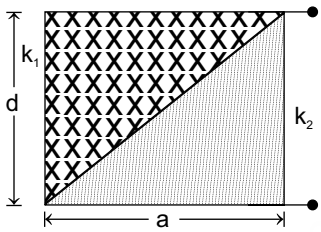
we have $I = -\frac{Q_0}{5.98}\exp\left(-\frac{t}{5.98}\right)$

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$$= -\frac{(8.85\,\mu C)}{5.98\,sec.}\exp\left(-\frac{12\,sec.}{5.98\,sec.}\right)$$

$$= -\frac{8.85}{5.98}\times 2.0076\,\mu A = \mathbf{2.98\ \mu A}$$

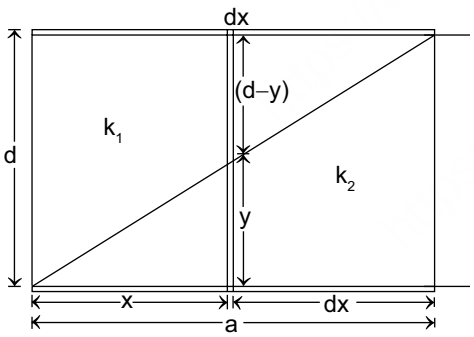
13. A capacitor is formed by two square metal-plates of edge a, separated by a distance d. Dielectrics of dielectric constant k_1 and k_2 are filled in the gap as shown in the figure. Find the capacitance.



☞ **Solution** Consider, a strip of thickness *dx* at a distance *x*

$$dC_1 = \frac{k_2\varepsilon_0 a\,dx}{y}$$

$$dC_2 = \frac{k_1\varepsilon_0 a\,dx}{(d-y)}$$



The capacitance are in parallel, so equivalent capacitance.

$$dC = \frac{dC_1 \times dC_2}{dC_1 + dC_2}$$

$$= \frac{\frac{k_1\varepsilon_0 a\,dx}{d-y}\times\frac{k_2\varepsilon_0 a\,dx}{y}}{\frac{k_1\varepsilon_0 a\,dx}{d-y}+\frac{k_2\varepsilon_0 a\,dx}{y}} = \frac{k_1k_2\varepsilon_0 dx}{yk_1 + k_2(d-y)}$$

$$dC = \frac{k_1\,k_2\,dx}{k_2\,d + (k_1 - k_2)y}$$

From the figure,

$$\frac{d}{a} = \frac{y}{x} \qquad \therefore \quad y = \frac{xd}{a}$$

$$dC = \frac{k_1k_2\varepsilon_0 a\,dx}{k_2 d + (k_1 - k_2)\frac{xd}{a}}$$

Let, $k_2\,d + (k_1 - k_2)\frac{xd}{a} = z$ ...(i)

If $x = 0$, then $z = k_2 d$

and if $x = a$, then $z = k_1 d$

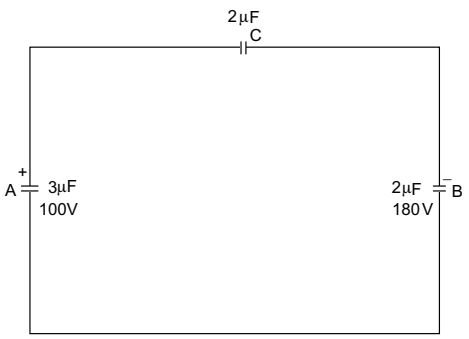
Differentiating equation (i), we get

$$dx = \frac{a\,dz}{d(k_1 - k_2)}$$

$$C = \frac{k_1k_2\varepsilon_0 a^2}{d(k_1 - k_2)}[\ln z]_{k_2 d}^{k_1 d}$$

$$= \frac{\varepsilon_0 k_1 k_2 a^2 ln\frac{k_1}{k_2}}{(k_1 - k_2)d}$$

14. Two capacitors A and B with capacities 3 μF and 2 μF are charged to a potential difference of 100 V and 180 V respectively. The plates of the capacitors are connected as shown in the figure with one wire from each capacitor free. The upper plate of A is positive and plate B is negative. An uncharged 2μF capacitor C with lead wires falls on the free ends to complete the circuit, calculate:

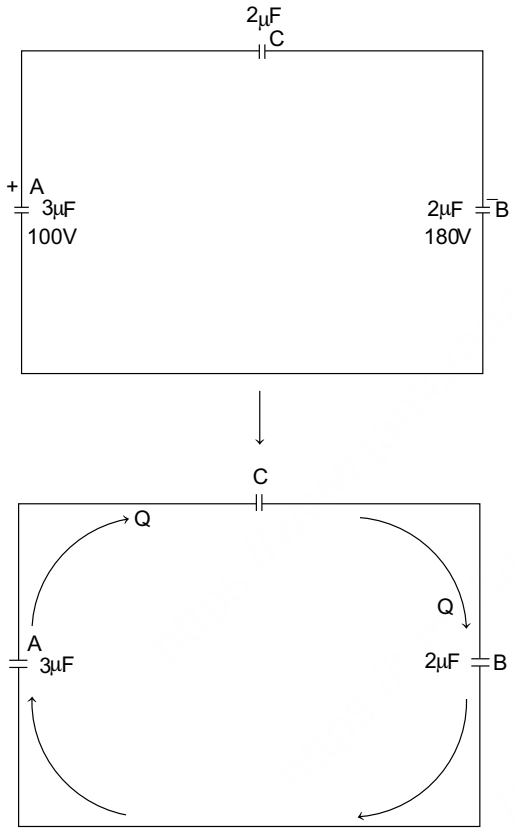


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(i) the final charge on the three capacitors.

(ii) the amount of electrostatic energy stored in the system before and after the completion of the circuit.

☞ **Solution**



Let, Q be the charge that flow in the circuit
From Kirchoff's voltage law, we can write

$$\Delta V_A + \Delta V_B = V_C$$

i.e., $$\left(100V - \frac{Q}{3\mu F}\right) + \left(180V - \frac{Q}{2\mu F}\right) = \frac{Q}{2\mu F}$$

This gives $$Q\left(\frac{1}{2\mu F} + \frac{1}{3\mu F} + \frac{1}{2\mu F}\right) = 280\,V$$

or $$Q = 280\,V\left(\frac{6\mu F}{8}\right) = 210\,\mu C$$

(i) **The final charge on the three capacitors are**

$Q_A = (V_A\, C_A)$ initial $- Q$
$= (100\ V)\ (3\mu F) - 210\ \mu C$
$= 300\ \mu C - 210\ \mu C$
$= 90\ \mu C$

$Q_B = (V_B\, C_B) - Q$
$= (180\ V)\ (2\mu F) - 210\ \mu C$
$= 360\ \mu C - 210\ \mu C$
$= 150\ \mu C$

$Q_C = Q =$ **210 μC**

(ii) **The electrostatic energy stored in the system before and after the completion of the circuit.**

$$U_{initial} = (U_A)_{initial} + (U_B)_{initial}$$

$$= \frac{1}{2}\frac{(Q_A)^2_{initial}}{C_A} + \frac{1}{2}\frac{(Q_B)^2_{initial}}{CB}$$

$$= \frac{1}{2}(V_A)^2_{initial} C_A + \frac{1}{2}(V_B)^2_{initial} C_B$$

$$= \frac{1}{2}(10^2\,V)^2(3\times 10_F^{-6})$$

$$+ \frac{1}{2}(180V)^2(2\times 10^{-6})$$

$$= 1.5 \times 10^{-2}J + 3.24 \times 10^{-2}J = 4.74 \times 10^{-2}J$$

$$U_{final} = \frac{1}{2}\frac{(Q_A)^2_{final}}{C_A}$$

$$+ \frac{(Q_B)^2_{final}}{2C_B} + \frac{1}{2}\frac{(Q_C)^2_{final}}{C_C}$$

$$= \frac{1}{2}\frac{(90\times 10^{-6}C)^2}{(3\times 10^{-6}C)} + \frac{1}{2}$$

$$\frac{(150\times 10^{-6}C)^2}{2\times 10^{-6}} + \frac{1}{2}\frac{(210\times 10^{-6})^2}{2\times 10^{-6}}$$

$= (0.1350 \times 10^{-2} + 0.5625 \times 10^{-2} + 1.1025 \times 10^{-6})\ J$

$= 1.8 \times 10^{-2}$ J = **18 mJ**

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SOLVED OBJECTIVE TYPE QUESTIONS

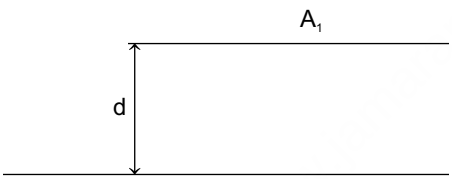
1. The capacitance of the system of parallel plates shown in the figure is

(a) $\frac{2\varepsilon_0 A_1 A_2}{(A_1 + A_2)d}$

(b) $\frac{2\varepsilon_0 A_1 A_2}{(A_2 - A_1)d}$

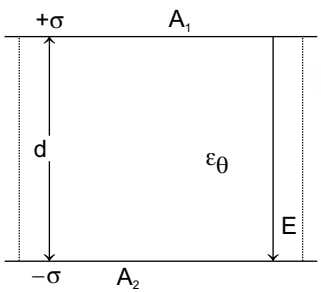
(c) $\frac{\varepsilon_0 A_1}{d}$

(d) $\frac{\varepsilon_0 A_2}{d}$

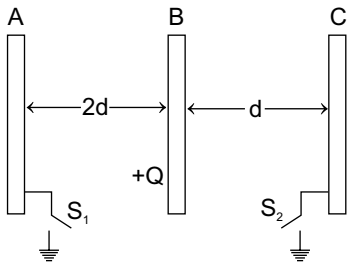


☞ **Explanation** Since the electric field between the parallel charge plates is uniform and independent of the distance, neglecting the fringe effect, the effective area of the plate of area A_2 is A_1. Thus the capacitance between the plates is

$$C = \frac{\varepsilon_0 A_1}{d}$$



2. Three identical, parallel conducting plates A, B and C are placed as shown. Switches S_1 and S_2 are open, and can connect A and C to earth when closed. + Q charge is given to B



(a) If S_1 is closed with S_2 open, a charge of amount Q will pass through S_1.

(b) If S_2 is closed with S_1 open, a charge of amount Q will pass through S_2.

(c) If S_1 and S_2 are closed together, a charge of amount $\frac{Q}{3}$ will pass through S_1, and a charge of amount $\frac{2Q}{3}$ will pass through S_2.

(d) All of above statement are incorrect.

☞ **Explanation** When either A or C is earthed (but not both together), a parallel-plate capacitor is formed with B, with ± Q charges on the inner surface. [The other plate, which is not earthed, plays no role]. Hence charge of amount + Q flows to earth.

When both are earthed together, A and C effectively become connected. The plates now from two capacitors in parallel, with capacitances in the ratio 1 : 2, and hence share charge Q in the same ratio.

3. The charge flowing across the circuit on closing the key K is equal to

(a) CV (b) $\frac{CV}{2}$

(c) 2CV (d) zero

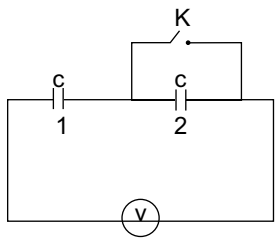
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☞ **Explanation** When the key K is kept open, the charge drawn from the source is

$$Q = C'V$$

where C′ = equivalent capacitance $\frac{C}{2}$

$$\therefore \quad Q = \left(\frac{C}{2}\right)V$$



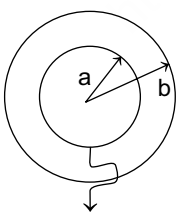
When the key K is closed, the capacitor 2 gets short circuit and thus the charge in that capacitor comes back to the source.

$\therefore$ Charge flowing is Q = (C/2) V

4. The figure shows a spherical capacitor with inner sphere earthed. The capacitance of the system is

(a) $\frac{4\pi\varepsilon_0 ab}{b-a}$ (b) $\frac{4\pi\varepsilon_0 b^2}{b-a}$

(c) $4\pi\varepsilon_0 (b + a)$ (d) none of these



☞ **Explanation** Let V be potential on the outer sphere. Thus we can consider two capacitors between the outer sphere and inner sphere (a) and other sphere and earth

Thus, $C_1 = 4\pi\varepsilon_0\left(\frac{ab}{b-a}\right)$ $C_2 = 4\pi\varepsilon_0 b$

$$C = 4\pi\varepsilon_0\left(\frac{ab}{b-a}\right) + 4\pi\varepsilon_0 b \quad C = \frac{4\pi\varepsilon_0 b^2}{b-a}$$

5. A conducting sphere of radius R, carrying charge Q, lies inside uncharged conducting shell of radius 2R. If they are joined by a metal wire,

(a) $\frac{Q}{3}$ amount of charge will flow from the sphere to the Q shell

(b) $\frac{2Q}{3}$ amount of charge will flow from the sphere to the shell

(c) Q amount of charge will flow from the sphere to the shell

(d) $k\frac{Q^2}{4R}$ amount of heat will be produced.

☞ **Explanation** Capacitances of the two are $C_1 = 4\pi\varepsilon_0 R$ and $C_2 = 4\pi\varepsilon_0 (2R)$

Initial energy, $E_1 = \frac{Q^2}{2C_1}$

Final energy, $E_f = \frac{Q^2}{C^2}$

$\therefore$ Heat produced $= E_i - E_f$

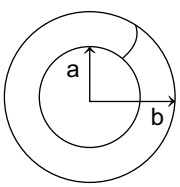
$$= \frac{Q^2}{2}\left[\frac{1}{4\pi\varepsilon_0 R} - \frac{1}{2\times 4\pi\varepsilon_0 R}\right]$$

$$= k\frac{Q^2}{2R}\left[1-\frac{1}{2}\right] = \frac{kQ^2}{4R}$$

6. The conducting spherical shells shown in the figure are connected by a conductor. The capacitance of the system is

(a) $4\pi\varepsilon_0\left(\frac{ab}{b-a}\right)$ (b) $4\pi\varepsilon_0 a$

(c) $4\pi\varepsilon_0 b$ (d) $4\pi\varepsilon_0\left(\frac{a^2}{b-a}\right)$



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☞ **Explanation** As there will be no charge on the inner sphere, therefore the capacitance only will exist due to outer sphere.

Hence the capacitance of the system is the capacitance due to outer sphere of radius b, therefore $C = 4\pi\varepsilon_0 b$.

7. Two identical capacitors, have the same capacitance C. One of them is charged to potential V_1 and the other to V_2. The negative ends of the capacitors are connect together. When the positive ends are also connected, the decrease in energy of the combined system is

(a) $\frac{1}{4}C\left(V_1^2 - V_2^2\right)$

(b) $\frac{1}{4}C\left(V_1^1 - V_1^1\right)$

(c) $\frac{1}{4}C(V_1 - V_2)^2$

(d) $= \frac{1}{2}C(V_1 + V_2)^2$

☞ **Explanation** Initial energy of combined system

$$U_1 = \frac{1}{2}CV_1^2 + \frac{1}{2}CV_2^2$$

Final common potential, $V = \frac{V_1 + V_2}{2}$

Final energy of system,

$$U_2 = 2 \times \frac{1}{2}C \times \left(\frac{V_1 + V_2}{2}\right)^2$$

Hence loss of energy

$$= U_1 - U_2 = \frac{1}{4}C(V_1 - V_2)^2$$

8. A capacitor of capacitance C is charged to a potential difference V from a cell and then disconnected from it. A charge + Q is now given to its positive plate. The potential difference across the capacitor is now

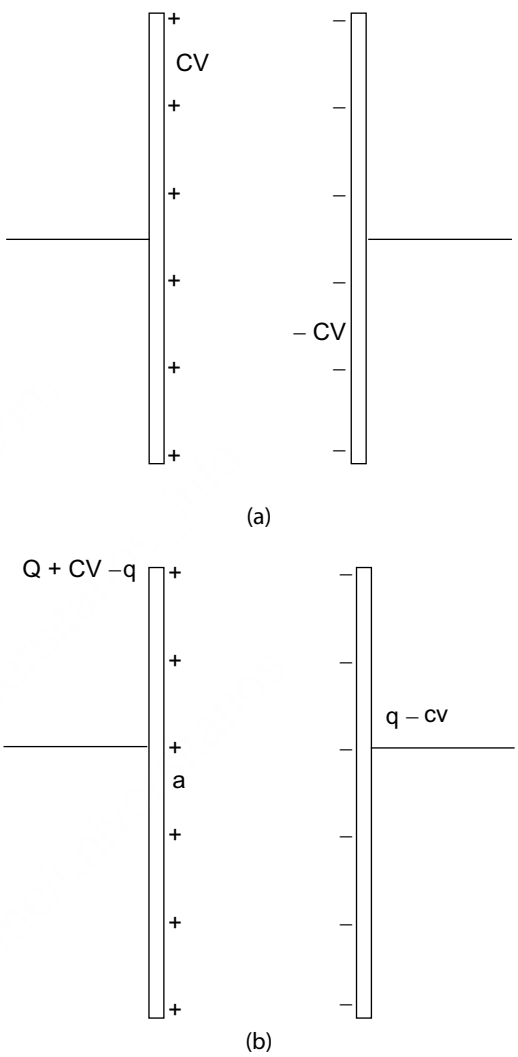
(a) V

(b) $V + \frac{Q}{C}$

(c) $V + \frac{Q}{2C}$

(d) $V - \frac{Q}{C}$ if $VQ < CV$

☞ **Explanation**



In the figure given below, let X and Y be positive and negative plates. After charging from the cell, the inner faces of X and Y have charges ± CV, as shown in Fig (a). The outer surfaces have no charge.

When charge Q is given to X, let the inner faces of X and Y have charges $\pm q$. Then, by the principle of charge conservation, the outer faces have charges $(Q + CV - q)$ for X and $(q - CV)$ for Y, as shown in Fig. (b).

Now, the outer faces must have equal charges.

$\therefore \quad Q + CV - q = q - CV$

or $\quad 2q = 2CV + Q$

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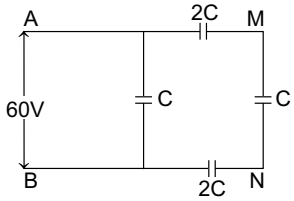
or $$q = CV + \frac{Q}{2}$$

Potential difference $= \frac{q}{C} = V + \frac{Q}{2C}$

9. In the circuit shown, a potential difference of 60V is applied across AB. The potential difference between the points M and N is

(a) 10 V (b) 15 V

(c) 20 V (d) 30 V



☞ **Explanation** Let Q amount of charge flow through the MN branch.

$$V = 60V = \frac{Q}{2C} + \frac{Q}{C} + \frac{Q}{2C} = 2\frac{Q}{C}$$

or $Q = 30\ CV$

Potential difference between M and N

$$= \frac{Q}{C} = \frac{30CV}{C} = 30\,V$$

10. In a parallel plate capacitor, the region between the plates is filled by a dielectric slab. The capacitor is charged from a cell and then disconnected from it. If the slab is now taken out

(a) the potential difference across the capacitor is reduced

(b) the potential difference across the capacitor is increased

(c) the energy stored in the capacitor is reduced

(d) no work is done by an external agent in taking the slab out.

☞ **Explanation** When a charged capacitor is disconnected from the cell to which it was connected, its charge remains constant. Any charge in the capacitor may change its capacitance, its stored energy and its potential difference.

UNSOLVED OBJECTIVE TYPE QUESTIONS

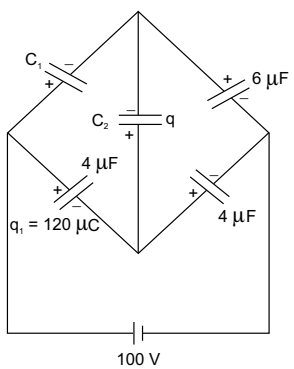
1. In the circuit shown

(a) $|q_2| = 280\ \mu C$

(b) $|q_3| = 160\ \mu C$

(c) $|q_2| = 120\ \mu C$, q_3 = zero

(d) It is impossible to find q_2 and q_3 unless C_1 and C_2 are known



2. A capacitor of capacity 2μF is charged to 100 V. What is the heat generated when the capacitance is connected in parallel to an another capacitor of same capacity?

(a) 2.5 mJ (b) 5.0 mJ

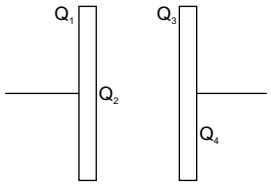
(c) 10 mJ (d) 4 mJ

3. In an isolated parallel–plate capacitor of capacitance C, the four surfaces carry net charge Q_1, Q_2, Q_3 and Q_4 as shown. The potential difference between the plates is

(a) $\frac{Q_1 + Q_2 + Q_3 + Q_4}{2C}$ (b) $\frac{Q_2 + Q_3}{C}$

(c) $\frac{Q_2 - Q_3}{2C}$ (d) $\frac{Q_1 + Q_4}{2C}$

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4. In a parallel plate capacitor, the region between the plates is filled by a dielectric slab. The capacitor is charged from a cell and then disconnected from it. The slab is now taken out

(a) the potential difference across the capacitor is reduced.

(b) the potential difference across the capacitor is increased.

(c) the energy stored in the capacitor is reduced.

(d) no work is done by an external agent in taking the slab out.

5. A charged capacitor is discharged through a resistance. The time constant of the circuit (i.e., CR) is η. Then the value of time constant for the power dissipated through the resistance will be

(a) η (b) 2η

(c) η/2 (d) zero

6. A capacitor is charged to potential E by a cell of emf E. If an identical capacitor inserted in the circuit in series with the previous capacitor, the potential difference across the new capacitor is

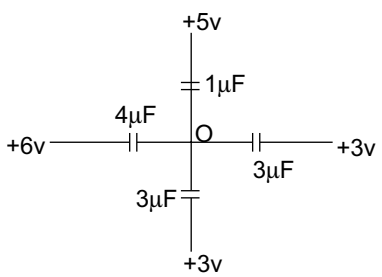
(a) 2E (b) E

(c) E/2 (d) zero

7. In the given figure the potential at point O is

(a) 4.27 V (b) 17 V

(c) zero (d) 34 V



8. A 2 μF capacitor is charged to 100 V and then its plates are connected by a wire. The heat produced will be

(a) 0.1 J (b) 0.1 J

(c) 0.01 J (d) 0.001 J

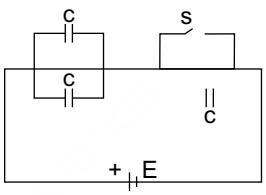
9. In the circuit shown, each capacitor has a capacitance C. The emf of the cell is ε. If the switch S is closed

(a) some charge will flow out of the positive terminal of the cell

(b) some charge will enter the positive terminal of the cell

(c) the amount of charge flowing through the cell will be Cε

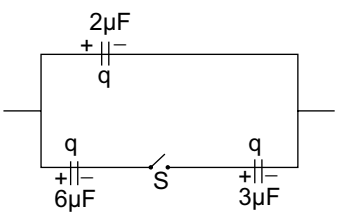
(d) the amount of charge flowing through the cell will be $\frac{4}{3}$ Cε.



10. The flow of charge through switch S when it is closed is

(a) zero (b) $\frac{q}{4}$

(c) $\frac{2q}{3}$ (d) $\frac{q}{3}$



11. A capacitor C is charged to a potential V by a battery. The emf of the battery is V. It is then disconnected from the battery and again connected with its polarity reversed to the battery.

(a) The work done by the battery is CV^2.

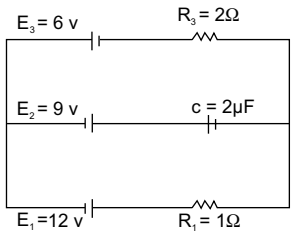
(b) The total charge that passes through battery is 2 CV.

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(c) The initial and final energy of the capacitor is same.
(d) All are correct.

12. In the given circuit, find charge across the capacitor C, when steady state is reached.

(a) 6 μ C (b) 9 μ C
(c) 18 μ C (d) zero



13. A parallel-plate air capacitor of capacitance C_0 is connected to a cell of emf ε and then disconnected from it. A dielectric slab of dielectric constant k, which can just fill the air gap of the capacitor, is now inserted in it. Then

(a) the potential difference between the plates decrease *k* times

(b) the change in energy is $\frac{1}{2}C_o\varepsilon^2(k-1)$

(c) the change in energy is $\frac{1}{2}C_o\varepsilon^2\left(1-\frac{1}{k}\right)$

(d) all of these

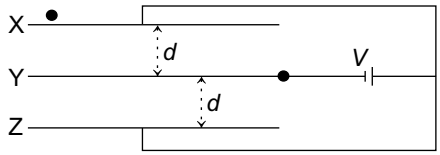
14. Consider the arrangement of three plates X, Y and Z each of the area A and separation d. The energy stored when the plates are fully charged is

(a) $\left[\sqrt{\frac{2\varepsilon_0 Mg}{A}}\left[d\frac{2V\varepsilon_0}{\sigma}\right]\right]$

(b) $\frac{\varepsilon_0 AV^2}{d}$

(c) $\frac{2\varepsilon_0 AV^2}{d}$

(d) $\frac{3\varepsilon_0 AV^2}{2d}$



15. Consider a capacitor-charging circuit. Let Q_1 be the charge given to the capacitor in a time interval of 10 ms and Q_2 be the charge given in the next time interval of 10ms. Let 10μC charge be deposited in a time interval t_1 and the next 10μC charge is deposited in the next time interval t_2. Then

(a) $Q_1 > Q_2, t_1 > t_2$ (b) $Q_1 > Q_2, t_1 < t_2$
(c) $Q_1 < Q_2, t_1 > t_2$ (d) $Q_1 < Q_2, t_1 < t_2$

16. There are three spherical conductors A, B and C having radius R, 3R and 4R. A and B were given a charge Q each and the 3rd one C was uncharged. If C is placed in between A and B such that it touches both A and B, then after sufficiently long time, how much charge will be on the conductor C?

(a) $\frac{Q}{2}$

(b) Q

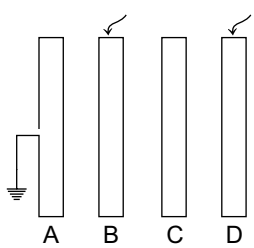
(c) $\frac{3}{4}Q$

(d) cannot be found out.

17. The charge on earthed side of plate A will be

(a) $\frac{\theta_1+\theta_2}{2}$ (b) $\frac{\theta_1-\theta_2}{2}$

(c) 0 (d) none of these

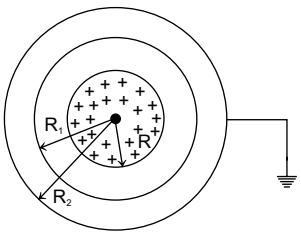


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18. q charge is distributed uniformly over the volume of a insulating solid sphere of radius R. It is enclosed by an earthed conducting spherical shell of inner radius R_1 and outer radius R_2. The charge on the outer surface of the sheel will be

(a) $+q$ (b) $\frac{R_2}{R_1}q$

(c) $\frac{R}{R_2}q$ (d) zero



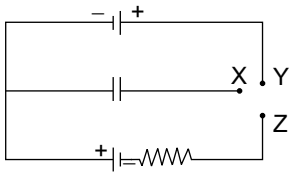
19. In the circuit shown, the cells are ideal and of equal emfs, the capacitance of the capacitor is C and resistance of the resistor is R. X is first joined to Y and then to Z. After a long time, the total heat produced in the resistor will be

(a) equal to the energy finally stored in the capacitor

(b) half of the energy finally stored in the capacitor

(c) twice the energy finally stored in the capacitor

(d) 4 times the energy finally stored in the capacitor.



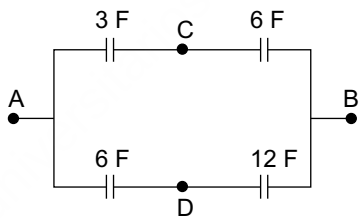
20. In the circuit shown, some potential difference is applied between A and B. If C is joined to D,

(a) no change will flow between C and D

(b) some charge will flow between C and D

(c) the equivalent capacitance between C and D will not change

(d) the equivalent capacitance between C and D will change



ANSWERS

1. (a, b)	**2.** (b)	**3.** (c)	**4.** (b)	**5.** (c)	**6.** (d)	**7.** (a)	**8.** (c)
9. (a, d)	**10.** (a)	**11.** (b, c)	**12.** (c)	**13.** (d)	**14.** (b)	**15.** (b)	**16.** (b)
17. (c)	**18.** (c)	**19.** (d)	**20.** (a, c)				

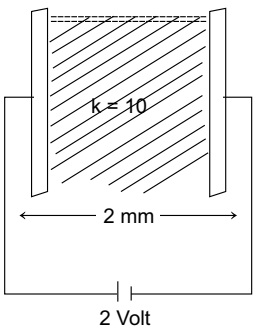
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PRACTICE EXERCISE 1

1. Leakage current is

(a) $\frac{2}{\varepsilon_0}\mu m$ (b) $\frac{4}{\varepsilon_0}\mu m$

(c) $\frac{6}{\varepsilon_0}\mu m$ (d) none



Resistivity of dielectric medium is 2Ω–m

2. The graph given below the variation of electric field E (in MV/m) with time t (in μs)

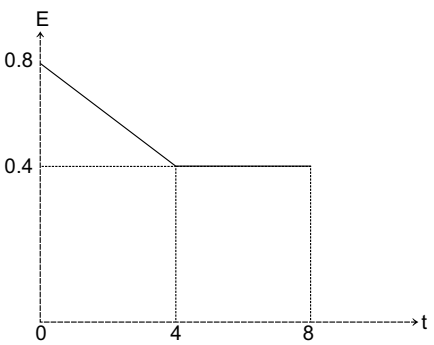
Consider the following statements:

1. The displacement current through a $1m^2$ region perpendicular to the field during the time interval t = 0 to t = 4μ is 0.885 A (given $\in_0 = 8.85 \times 10^{-12}$ SI unit)

2. The displacement current through 1 m^2 region perpendicular to the field during the time interval t = 4μs to 8μs is zero. Which of the statements given above is/are correct?

(a) 1 only (b) 2 only

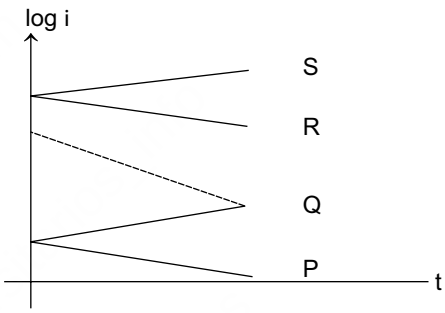
(c) both 1 and 2 (d) Neither 1 nor 2



3. In on RC circuit while charging, the graph of log i versus time is as shown by the dotted line in the figure, where i is the current. When the value of the resistance is doubled, which of the solid curve best represents the variation of log i versus time?

(a) P (b) Q

(c) R (d) S



4. A fully charged capacitor has a capacitance 'C'. It is discharged through a small coil of resistance wire embedded in a thermally insulated block of specific heat capacity 's' and mass 'm'. If the temperature of the block is raised by 'ΔT', the potential difference 'V' across the capacitance is

(a) $\frac{ms\Delta T}{C}$ (b) $\sqrt{\frac{2ms\Delta T}{C}}$

(c) $\sqrt{\frac{2mC\Delta T}{s}}$ (d) $\frac{2mC\Delta T}{s}$

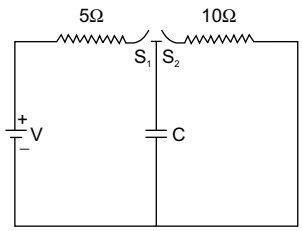
5. A parallel plate capacitor is charged and then isolated. On increasing the plate separation:

	Charge	potential	Capacity
(a)	remains constant	remains constant	decreases
(b)	remains constant	increases	decreases
(c)	remains constant	decreases	increases
(d)	increases	increases	decreases

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6. In the adjoining diagram, (assuming the battery to be ideal) the condenser C will be fully charged to potential V if

(a) S_1 and S_2 both are open
(b) S_1 and S_2 both are closed
(c) S_1 is closed and S_2 is open
(d) S_1 is open and S_2 is closed

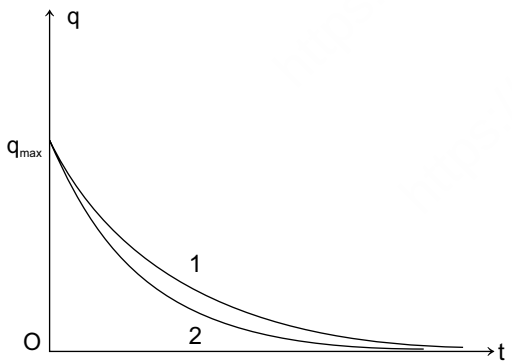


7. The instantaneous charge on a capacitor in two discharging RC circuits is plotted with respect to time in figure. Choose the correct statement(s) (where E_1 and E_2 are emf of two DC sources in two different charging circuits).

(a) $R_1C_1 > R_2C_2$

(b) $\frac{R_1}{R_2} < \frac{C_2}{C_1}$

(c) $R_1 > R_2$ if $E_1 = E_2$
(d) $C_2 > E_1$ if $E_1 = E_2$



8. An uncharged capacitor of capacitance C is connected to a battery of emf ε at t = 0 through a resistance R, then

(i) the maximum rate at which energy is stored in the capacitor is:

(a) $\frac{\varepsilon^2}{4R}$ (b) $\frac{\varepsilon^2}{2R}$

(c) $\frac{\varepsilon^2}{R}$ (d) $\frac{2\varepsilon^2}{R}$

(ii) time at which the rate has this maximum value is:

(a) 2CR In2 (b) $\frac{1}{2}$CR In2

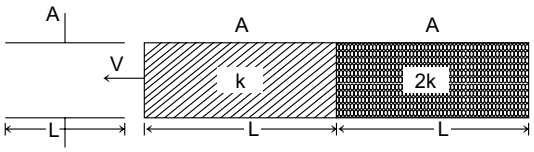
(c) CR In2 (d) 3CR In2

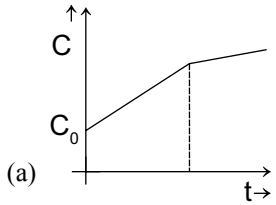
9. On placing a dielectric slab between the plates of an isolated charged condenser its

	Capacity	Charge	Difference
	Energy stored	Potential	
		Electric field	
(a)	decreases	remains	decreases
	increases	unchanged	
		increases	
(b)	increases	remains	increases
	increases	unchanged	
		decreases	
(c)	increased	remains	decreases
	decreases	unchanged	
		decreases	
(d)	decreases	remains	decreases
	increases	unchanged	
		remains unchanged	

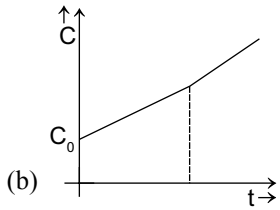
10. A parallel plate capacitor without any dielectric has capacitance C_0. A dielectric slab is made up of two dielectric slabs of dielectric constants K and 2K and is of same dimensions as that of capacitor plates and both the parts are of equal dimensions arranged serially as shown. If this dielectric slab is introduced (dielectric K enters first) in between the plates at constant speed, then variation of capacitance with time will be best represented by:

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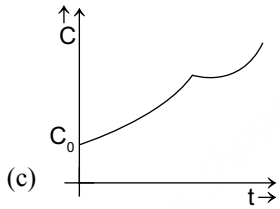




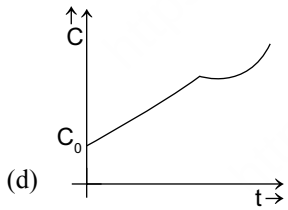
(a)



(b)

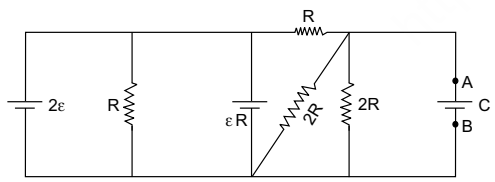


(c)



(d)

11. The time constant of the circuit shown is:



(a) $\frac{RC}{2}$ (b) $\frac{3RC}{5}$

(c) $\frac{RC}{3}$ (d) $\frac{RC}{4}$

12. A parallel plate capacitor of plate area A and plate separation d is charged to a potential difference V and then the battery disconnected. A slab of dielectric constant K is then inserted between the plates of the capacitor so as to fill the space between the plates, If Q, E and W denote respectively, the magnitude of the charge on each plate, the electric field between the plates (after the slab is inserted) and work done on the system, in the process of inserting the slab, then:

(a) $Q = \frac{\epsilon_0 AV}{d}$

(b) $Q = \frac{\epsilon_0 KAV}{d}$

(c) $E = \frac{V}{Kd}$

(d) $W = \frac{\epsilon_0 AV^2}{2d}\left(1 - \frac{1}{K}\right)$

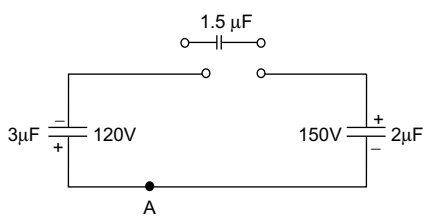
13. Two capacitors of 2μF and 3μF are charged to 150 volt and 120 volt respectively. The plates of a capacitor are connected as shown in the fig. A discharged capacitor of capacity 1.5 μF falls to the free ends of the wire. Then:

(a) charge on the 1.5 μF capacitor will become is 180 μC

(b) Charge on the 2 μF capacitor will become 120 μC

(c) +Ve charge flows through point A from left to right

(d) +Ve charge flows through point A from right to left



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14. The plates of a parallel plate condenser are being moved away with a constant speed v. If the plate separation at any instant of time is d then the rate of change of capacitance with time is proportional to-

(a) $\frac{1}{d}$ (b) $\frac{1}{d^2}$

(c) d^2 (d) d

15. A parallel plate air capacitor is connected to a battery. The quantities charge, electric field and energy associated with this capacitor are given by Q_0, V_0, E_0, and U_0 respectively. A dielectric slab is now introduced to fill the space between the plates with the battery still in connection. The corresponding quantities now given by Q, V, E and U are related to the previous one as:

(a) $Q > Q_0$
(b) $V > V_0$
(c) $E > E_0$
(d) $U > U_0$

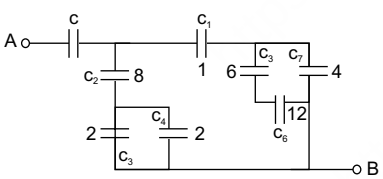
ANSWERS

1. (a)	**2.** (c)	**3.** (b)	**4.** (b)	**5.** (b)	**6.** (c)	**7.** (a, c),	**8.** (a)
9. (c)	**10.** (b)	**11.** (a)	**12.** (a, c, d)	**13.** (a, (b, c)	**14.** (b)	**15.** (a, d)	

PRACTICE EXERCISE 2

1. For the given figure find the value of the capacitance C if the equivalent capacitance between points A and B is to be 1 μF. All the capacitance are in μF.

[IIT, 1977]



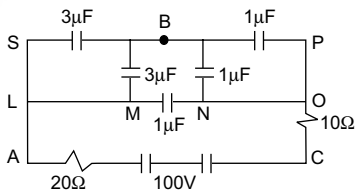
[**Ans.** $C = \frac{32}{23}\mu F$]

2. A parallel plate capacitor of a capacitance 100 μF is charged to a potential of 500 V. The plate separation is then reduced to half of its original value. Calculate the new potential on the capacitor and the change in stored energy.

[MNR, 1978]

[**Ans.** 250 volts, Change in energy stored, $\Delta U = 6.25 \times 10^{-6}$ J]

3. In the Figure, find the potential difference between the points A and B, and between the points B and C in the steady state. **[IIT, 1979]**



[**Ans.** V_{AB} = 250 volts, V_{BC} = 75 volts]

4. A charge Q is distributed over two concentric hollow spheres of radii r and R (R > r) such that the surface densities are equal. Find the potential at the common centre.

[IIT, 1981]

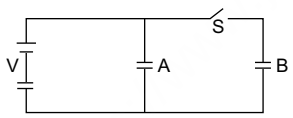
[**Ans.** $V = \frac{1}{4\pi\varepsilon_0} \cdot \frac{Q(r+R)}{R^2 + r^2}$]

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5. **A parallel plate condenser contains a mica sheet (thickness 10^{-3} m). The dielectric constant of mica is 8 and that of fibre is 2.5. Assuming that the fibre breaks down when subjected to an electric field of 6.4×10^6 V/m, find the maximum safe voltage that can be applied to the capacitor.** **[Roorkee, 1983]**

[**Ans.** 5200 volts]

6. **The given below shows two identical parallel plate capacitors connected to a battery with the switch 'S' closed. The switch is now opened and the free space between the plates of the capacitor is filled with a dielectric of dielectric constant (or relative permittivity) 3. Find the ratio of the total electrostatic energy stored in both capacitors before and after the introduction of the dielectric.** **[IIT, 1983]**



[**Ans.** 1.66 U_i]

7. **A capacitor is filled with two dielectrics of same dimensions but of dielectric constant $K_1 = 2$ and $K_2 = 3$ respectively. Find the ratio of the capacities in two possible arrangements.** **[MNR, 1985]**

$$\left[\textbf{Ans.}\ \frac{24}{25}\right]$$

8. **A parallel plate air capacitor is connected to a battery. The quantities charge, voltage, electric field and energy associated with this capacitor are given by Q_0, V_0, E_0 and U_0 respectively. A dielectric slab is now introduced to fill the space between the plates with battery still in connection. The corresponding quantities now given by Q, V, E and U. Find the relation between these and the previous ones.** **[IIT, 1985]**

[**Ans.** $U > U_0$]

9. **A capacitor of 20 μF and charged to 500 V is connected in parallel to another capacitor of 10 μF charged to 200 volt. Find the common potential.** **[Roorkee, 1986]**

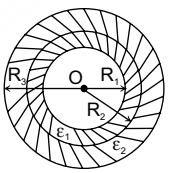
[**Ans.** 400 volts]

10. **Find the capacitance of a system of three parallel plates, each of area A m^2, separated by d_1 and d_2 metres. The space between them is filled with dielectric of relative dielectric constants ε_1 and ε_2. The dielectric constant of the free space is ε_0.** **[Roorkee, 1987]**

$$\left[\textbf{Ans.}\ C = \frac{\varepsilon_0\varepsilon_1\varepsilon_2 A}{d_1\varepsilon_2 + \varepsilon_1 d_2}\right]$$

11. **A double layer cylindrical capacitor with its parameter is shown in the figure. If the electric field strengths necessary to produce the break down of these dielectrics are equal to E_1 and E_2 respectively, then find the break down voltage of this capacitor if**

$$\varepsilon_1 R_1 E_1 < \varepsilon_2 R_2 E_2.$$



$$\left[\textbf{Ans.}\ E_1 R_1\left[\log_e\left(\frac{R_2}{R_1}\right) + \frac{\varepsilon_1}{\varepsilon_2}\log_e\left(\frac{R_3}{R_2}\right)\right]\right]$$

12. **The capacitance of a variable radio capacitor can be changed from 50 pF to 950 pF by tuning the dial from 0° to 180°. With the dial set at 180°, the capacitor is connected to a 400 V battery. After charging, the capacitor is disconnected from the battery and the dial is turned at 0°.**
    (a) What is the potential difference across the capacitor when the dial reads 0°?
    (b) How much work is required to turn the dial, if friction is neglected?
    [MNR, 1986]

[**Ans.** (a) 7600 V, (b) 1.3680×10^{-3} joule]

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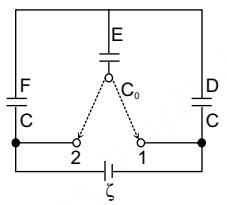
13. Calculate the heat generated when a condenser of 100 μF capacity and charged to 200 volt is discharged through a 2 ohm resistance. [Roorkee, 1989]

[**Ans.** 2 joule]

14. A radioactive source in the form of a metal sphere of diameter 10^{-3} m emits β particles at a constant rate of 6.25×10^{10} particles per second. If the source is electrically insulated, how long will it take for its potential to rise by 1.0 volt, assuming that 80% of emitted β particles escape from the surface.

[**Ans.** 6.95 μs]

15. Find the heat that will be generated in the circuit shown in the figure, if the switch S is shifted from position 1 to position 2?



$$\left[\text{Ans. } \varepsilon^2 \cdot \frac{CC_0}{2C + C_0}\right]$$

16. The distance between the plates of a parallel plate condenser is 0.05 m. A field of 3×10^4 volt/m is established between the plates. It is then disconnected from the battery and an uncharged metal plate of thickness 0.01 m is inserted into the condenser parallel to its plate. Find the potential difference between the plates

(a) before the introduction of the metal plate and

(b) after its introduction. What would be the potential difference if a plate of dielectric constant 2 is introduced in place of metal plate?

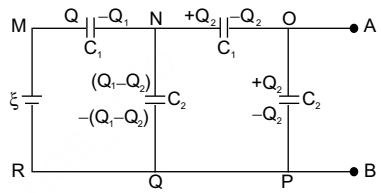
[Roorkee, 1991]

[**Ans.** (a) 1500 volts, (b) 1350 volts]

17. A capacitor of capacitance C_1 = 1.0 microfarad withstands the maximum voltage V_1 = 6.0 kilovolt while another capacitor of capacitance C_2 = 2.0 microfarad withstands the maximum voltage V_2 = 4.0 kilovolt. What maximum voltage will the system of these two capacitors withstand if they are connected in series? [MNR, 1992]

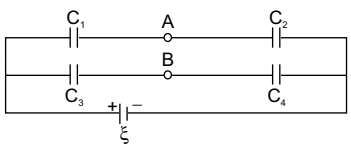
[**Ans.** 9.0 kV]

18. What is the potential difference between the points A and B of circuit shown in the figure, if the emf ε = 110 V and the capacitance ratio $\frac{C_2}{C_1} = \eta = 2.0$?



[**Ans.** 10 volts]

19. Find the potential difference between the points A and B shown in the figure. What is the condition for it to be zero?



$$\left[\text{Ans. } V_A - V_B = \varepsilon\left(\frac{C_1C_4 - C_2C_3}{(C_1 + C_2)(C_3 + C_4)}\right); \quad \frac{C_1}{C_2} = \frac{C_3}{C_4}\right]$$

20. Two parallel plate capacitors A and B have the same separation $d = 8.85 \times 10^{-4}$ m between the plates. The plate areas of A and B are 0.04 m^2 and 0.02 m^2 respectively. A slab of dielectric constant (relative permittivity) K = 9 has dimensions such that it can exactly fill the space between the plates of capacitor B.

(a) The dielectric slab is placed inside A as shown in Fig. (a). A is then charged to a potential difference of 110 V. Calculate

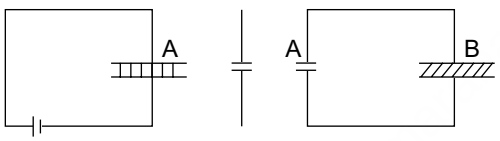
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the capacitance of A and the energy stored in it.

(b) The battery is disconnected and then the dielectric slab is removed from A. Find the work done by the external agency in removing the slab from A.

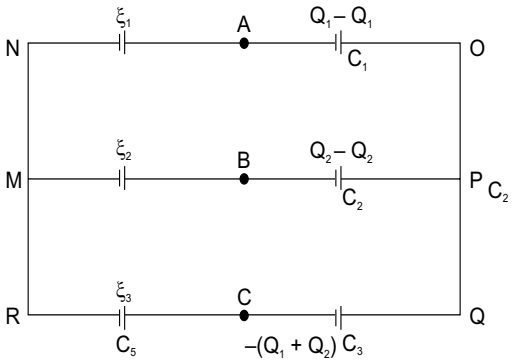
(c) The same dielectric slab is now placed inside B, filling it completely. The two capacitors A and B are then connected as shown in Fig. (b). Calculate the energy stored in the system.

[IIT, 1993]



[**Ans.** (a) $C_A = 2 \times 10^{-9}$ F, $U_A = 1.21 \times 10^{-5}$ J, (b) $W = 4.84 \times 10^{-5}$ J, (c) $U = 1.1 \times 10^{-5}$ J]

21. Find the potential at the point A of the circuit shown in the figure, if the potential at the point P is equal to zero.



$$\left[\textbf{Ans.}\ \frac{C_2\varepsilon_2 + C_3\varepsilon_3 - (C_2 + C_3)\varepsilon_1}{C_1 + C_2 + C_3}\right]$$

22. Two square metallic plates of 1 m side are kept 0.01 m apart, like a parallel plate capacitor, in air in such a way that one of their edges is perpendicular to an oil surface in a tank filled with an insulating oil. The plates are connected to a battery of emf 500 *V*. The plates are then lowered vertically into the oil at a speed of 0.001 m/s. Calculate the current drawn from the battery during the process. (dielectric constant of oil = 11, $\varepsilon_0 = 8.85 \times 10^{-12}$ $C^2N^2m^{-2}$). [IIT, 1994]

[**Ans.** 4.425×10^{-9} A]

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QUESTION BANK

CONCEPTUAL QUESTIONS

1. Under what conditions can a brass rod be charged?

2. An electric charge on a conducting sphere has to be divided into three equal parts. How can this be done?

3. Why is a metal chain that reaches the ground fixed to a lorry for transporting petrol?

4. Can a positive charged be obtained on the electroscope using a negatively charged ebonite rod?

5. What will happen to the surface charge density on a metal sheet rolled into a cylinder?

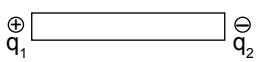
6. An elder ball is tied to a silk thread. What will happen when an electrostatically charged rod is brought close to it?

7. Do the electric field vector and the vector of the force exerted on a charge by an electric field always have the same directions?

8. Why is metal cap sometimes put on a vacuum tube?

9. Can electric charges be separated on
(a) conductor, (b) a dielectric?

10. A thin insulator rod is placed between two unlike point charges $+q_1$ and $-q_2$ (fig.). How will the force acting on the charges change?



11. A sphere carries a uniformly distributed electric charge. Prove that the field inside the sphere is zero.

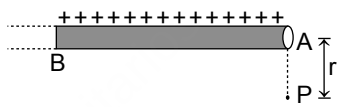
12. If only one charged body is available, can it be used to obtain a charge exceeding many times in absolute magnitude that which it itself has?

13. Can two likely-charged balls be attracted to each other?

14. A small metallic sphere is brought in contact in turn with points A, B, C of a charged body. Find the approximate charge on the sphere after each contact as would be indicated by bringing the sphere in contact with an electroscope. Do the leaves of the electroscope diverge at the same angle in all three cases?

ONLY ONE OPTION IS CORRECT

1. A semi-infinite insulating rod has linear charge density λ. The electric field at the point P shown in figure is



(a) $\frac{2\lambda^2}{(4\pi\varepsilon_0 r)^2}$ at 45° with AB

(b) $\frac{\sqrt{2}\lambda^2}{4\pi\varepsilon_0 r^2}$ at 45° with AB

(c) $\frac{\sqrt{2}\lambda}{4\pi\varepsilon_0 r}$ at 45° with AB

(d) $\frac{\sqrt{2}\lambda}{4\pi\varepsilon_0 r}$ at perpendicular to AB

2. A certain charge Q is divided into two parts q and $(Q - q)$. For the maximum coulomb force between them, the ratio (q/Q) is
(a) 1/16 (b) 1/8
(c) 1/4 (d) 1/2

3. The force between two point charges $+Q$ and $-Q$ placed 'r' distance apart is f_1 and force between two spherical conductors, each of radius R placed with their centres

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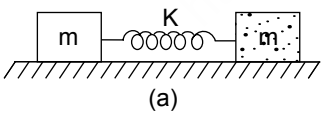
'r' distance apart charged with charge $+Q$ and $-Q$ is f_2. If the separation 'r' is not much larger than R, then

(a) $f_1 > f_2$
(b) $f_1 = f_2$
(c) $f_1 < f_2$
(d) $f_2 = (r/R) f_1$

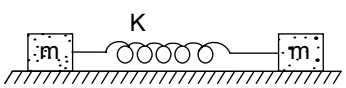
4. A point charge $+Q$ is placed at the centroid of an equilateral triangle. When a second charge $+Q$ is placed at a vertex of the triangle, the magnitude of the electrostatic force on the central charge is 8 N. The magnitude of the net force on the central charge when a third charge $+Q$ is placed at another vertex of the triangle is

(a) zero (b) 4 N
(c) $4\sqrt{2}$ N (d) 8 N

5. Two identical metallic blocks resting on a frictionless horizontal surface are connected by a light metallic spring having the spring constant 100 N/m and an unstretched length of 0.2 m, as shown in figure (a). A total charge Q is slowly placed on the system, causing the spring to stretch to an equilibrium length of 0.3 m, as shown in figure (b). The value of charge Q, assuming that all the charge resides on the blocks and that the blocks are like point charges, is



(a)



(b)

(a) 10 μC (b) 15 μC
(c) 20 μC (d) 30 μC

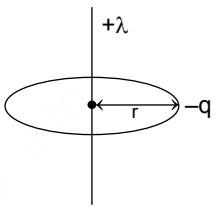
6. A particle of charge $-q$ and mass m moves in a circle of radius r around an infinitely long line charge on linear charge density $+\lambda$. Then time period will be $\left[\text{where } k = \frac{1}{4\pi \in_0}\right]$

(a) $T = 2\pi r\sqrt{\frac{m}{2k\lambda q}}$

(b) $T^2 = \frac{4\pi^2 m}{2k\lambda q} r^3$

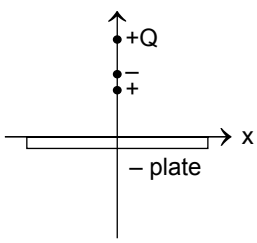
(c) $T = \frac{1}{2\pi r}\sqrt{\frac{2k\lambda q}{m}}$

(d) $T = \frac{1}{2\pi r}\sqrt{\frac{m}{2k\lambda q}}$



7. A large uniformly charged (negative) plate is placed in xz plane and a positive point charge is fixed on the y-axis. A dipole is positioned in between with its axis along y-axis, as shown. The dipole initially moves in

(a) negative y-direction
(b) negative x-direction
(c) positive x-direction
(d) positive y-direction



(c) positive x-direction

8. A ring of radius R is made out of a thin metallic wire of area of cross section A. The ring has a uniform charge Q distributed on it. A charge q_0 is placed at the centre of the ring. If Y is the young's modulus for the material of the ring and ΔR is the change in the radius of the ring, then

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(a) $\Delta R = \dfrac{q_0 Q}{4\pi\varepsilon_0 RAY}$

(b) $\Delta R = \dfrac{q_0 Q}{4\pi\varepsilon_0 RAY}$

(c) $\Delta R = \dfrac{q_0 Q}{8\pi\varepsilon_0^2 RAY}$

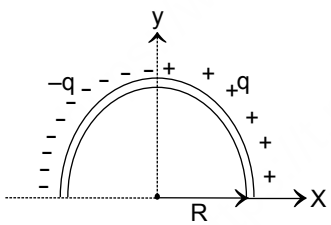
(d) $\Delta R = \dfrac{q_0 Q}{8\pi^2\varepsilon_0 RAY}$

9. A charge is situated at a certain distance from an electric dipole in the end-on position experiences a force F. If the distance of the charge is doubled, the force acting on the charge will be

(a) $F/4$ (b) $F/8$

(c) $2F$ (d) $F/2$

10. The dipole moment of the given charge distribution is



(a) $-\dfrac{4Rq}{\pi}\hat{i}$

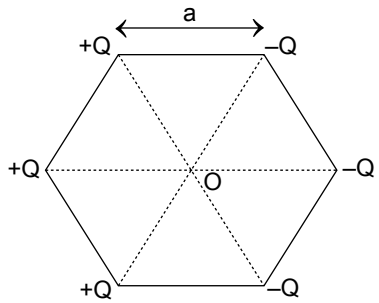
(b) $\dfrac{4Rq}{\pi}\hat{i}$

(c) $-\dfrac{2Rq}{\pi}\hat{i}$

(d) $\dfrac{2Rq}{\pi}\hat{i}$

11. Six charges are placed at the vertices of a regular hexagon as shown in the figure.

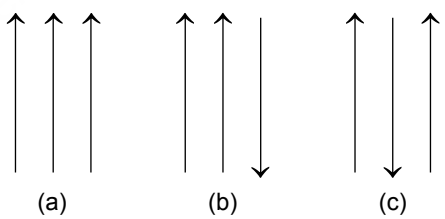
The electric field on the line passing through point O and perpendicular to the plane of the figure at a distance of x ($>>a$) from O is



(a) $\dfrac{Qa}{\pi\varepsilon_0 x^3}$ (b) $\dfrac{2Qa}{\pi\varepsilon_0 x^3}$

(c) $\dfrac{\sqrt{3Qa}}{\pi\varepsilon_0 x^3}$ (d) zero

12. When three electric dipoles are near each other, they each experience the electric field of the other two, and the three dipole system has a certain potential energy. Figure below shows three arrangements (a), (b) and (c) in which three electric dipoles are side by side. All three dipoles have the same electric dipole moment magnitude and the spacings between adjacent dipoles are identical. If U_1, U_2 and U_3 are potential energies of the arrangements (a), (b) and (c) respectively, then



(a) $U_1 > U_3 > U_2$
(b) $U_1 > U_2 > U_3$
(c) $U_1 > U_2 = U_3$
(d) $U_1 = U_2 = U_3$

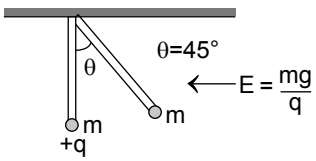
13. In a region of space, the electric field is given by $\vec{E} = 8\hat{i} + 4\hat{j} + 3\hat{k}$. The electric flux through a surface of area of 100 units in x-y plane is

(a) 800 units (b) 300 units

(c) 400 units (d) 1500 units

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14. A horizontal electric field ($E = (mg)/q$) exists in space as shown in figure and a mass m is attached at the end of a light rod. If mass m is released from the position shown in figure, find the angular velocity of the rod when it passes through the bottom most position.



(a) $\sqrt{\frac{g}{\ell}}$ (b) $\sqrt{\frac{2g}{\ell}}$

(c) $\sqrt{\frac{3g}{l}}$ (d) $\sqrt{\frac{5g}{l}}$

15. A dipole of dipole moment p is kept at the centre of radius R and charge Q. The dipole moment has direction along the axis of the ring. The resultant force on the ring due to the dipole is

(a) zero

(b) $\frac{kPQ}{R^3}$

(c) $\frac{2kPQ}{R^3}$

(d) $\frac{kPQ}{R^3}$ only if the charge is uniformly distributed on the ring

16. Two point charges $+q$ and $-q$ are held fixed at $(-d, 0)$ and $(d, 0)$ respectively of a (X, Y) co-ordinate system. Then

(a) The electric field $\vec{E}$ at all points on the X-axis has the same direction.

(b) $\vec{E}$ at all points on the Y-axis is along $\hat{i}$

(c) Work has to be done in bringing a test charge from infinity to the origin.

(d) The dipole moment is $2qd$ directed along $\hat{i}$

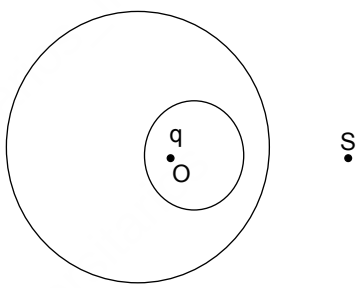
17. A particle of charge q and mass m moves rectilinearly under the action of electric field $E = A - Bx$, where A and B are positive constants and x is distance from the point where particle was initially at rest then the distance travelled by the particle before coming to rest and acceleration of particle at that moment are respectively

(a) $\frac{2A}{B}, 0$ (b) $0, \frac{qA}{m}$

(c) $\frac{2A}{B}, -\frac{qA}{m}$ (d) $\frac{-2A}{B}, -\frac{qA}{m}$

18. A charge q is placed at O in the cavity in a spherical uncharged conductor. Point S is outside the conductor.

If the charge is displaced from O towards S, still remaining within the cavity,



(a) electric field at S will increase

(b) electric field at S will decrease

(c) electric field at S will first increase and then decrease

(d) electric field at S will not change

19. Which of the following statements is true?

(a) The electric field due a point charge can be same at two points.

(b) The electric field increases continuously as one goes away from centre of a solid uniformly charged sphere

(c) The electric field of force of the electric field produced by the static charges from closed loops

(d) The magnetic lines of force of magnetic field produced by current carrying wire from closed loops

20. An electron of mass m_e initially at rest moves through a certain distance in a uniform electric field in time t_1. A proton

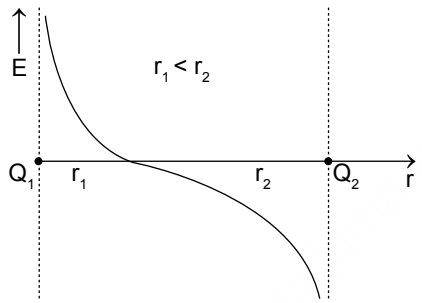
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of mass m_p also initially at rest takes time t_2 to move through an equal distance in this uniform electric field. Neglecting the effect of gravity the ratio of t_2/t_1 is nearly equal to

(a) 1 (b) $(m_p/m_e)^{1/2}$

(c) $(m_e/m_p)^{1/2}$ (d) 1836

21. The variation of electric field between two point charges along the line joining the charges is given in figure. Then which is/are correct?



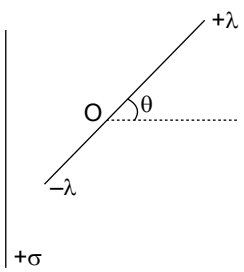
(a) Q_1 is +ve and Q_2 is –ve

(b) Q_1 is +ve and Q_2 is +ve

(c) $|Q_1| < |Q_2|$

(d) $|Q_1| > |Q_2|$

22. A largest sheet carries uniform surface charge density σ. A rod of length 2ℓ has a linear charge density λ on one half and –λ on the other half.

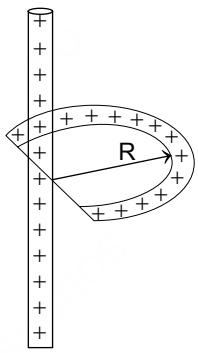


The rod is hinged at mid point *O* and makes angle θ with the normal to the sheet. The torque experienced by the rod is

(a) $\frac{\sigma\lambda\ell^2}{2\varepsilon_0}\cos\theta$ (b) $\frac{\sigma\lambda\ell}{\varepsilon_0}\cos^2\theta$

(c) $\frac{\sigma\lambda\ell^2}{2\varepsilon_0}\sin\theta$ (d) $\frac{\sigma\lambda\ell\sin^2\theta}{\varepsilon_0}$

23. Find the force experienced by the semi-circular wire charged with a charge q, placed as shown in figure. Radius of the wire is R and the line of charge with linear charge density λ is passing through its centre and perpendicular to the plane of wire.



(a) $\frac{\lambda q}{2\pi^2\varepsilon_0 R}$ (b) $\frac{\lambda q}{\pi^2\varepsilon_0 R}$

(c) $\frac{\lambda q}{4\pi^2\varepsilon_0 R}$ (d) $\frac{\lambda q}{4\pi\varepsilon_0 R}$

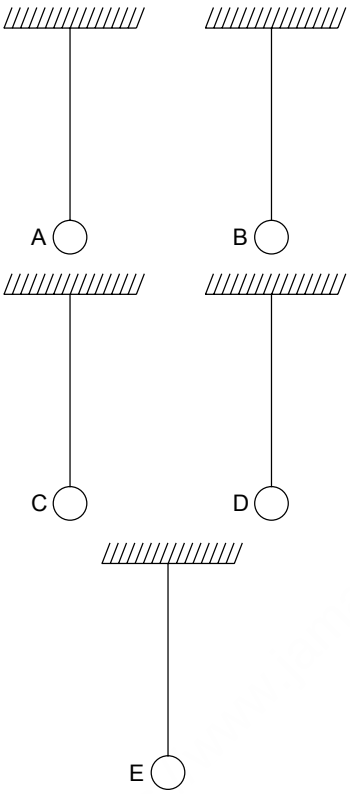
24. Five styrofoam balls are suspended from insulating threads. Several experiments are performed on the balls and the following observations are made

(i) Ball *A* repels *C* and attracts *B*

(ii) Ball *D* attracts *B* and has no effect on *E*

(iii) A negatively charged rod attracts both *A* and *E*. An electrically neutral styrofoam ball gets attracted if placed nearby a charged body due to negative charge. What are the charges, if any, on each ball?

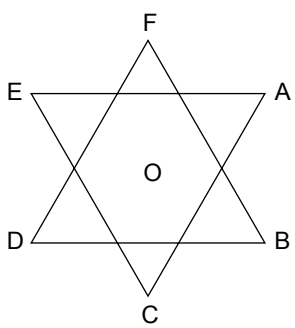
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	A	B	C	D	E
(a)	+	–	+	0	+
(b)	+	–	+	+	0
(c)	+	–	+	0	0
(d)	–	+	–	0	0

25. The electric force on $2\mu C$ charge placed at the centre O of two equilateral triangles each of side 10 cm, as shown in figure is F.

If charges A, B, C are each $2\mu C$ and charges D, E and F are each $-2\mu C$, then F is



(a) 21.6 N (b) 64.8 N
(c) 0 (d) 43.2 N

26. The electric field in a region of space is given by $\vec{E} = 5\hat{i} + 2\hat{j}N/C$. The electric flux due to this field through an area 2 m^2 lying in the YZ plane, in S.I. unit, is

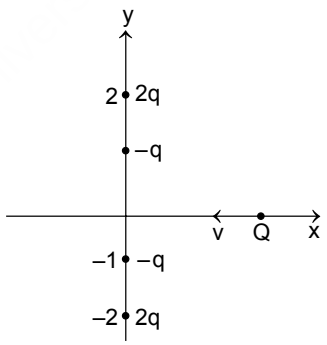
(a) 10 (b) 20
(c) $10\sqrt{2}$ (d) $2\sqrt{29}$

27. Two point dipoles $p\hat{k}$ and $\frac{p}{2}\hat{k}$ are located at (0, 0, 0) and (1 m, 0, 2 m) respectively. The resultant electric field due to the two dipoles at the point (1 m, 0, 0) is

(a) $\frac{9p}{32\pi\in_0}\hat{k}$ (b) $\frac{-7p}{32\pi\in_0}\hat{k}$

(c) $\frac{7p}{32\pi\in_0}\hat{k}$ (d) None of these

28. Four charges are rigidly fixed along the Y-axis as shown. A positive charge approaches the system along the X-axis with initial speed just enough to cross the origin. Then its total energy at the origin is



(a) zero
(b) positive
(c) negative
(d) data insufficient

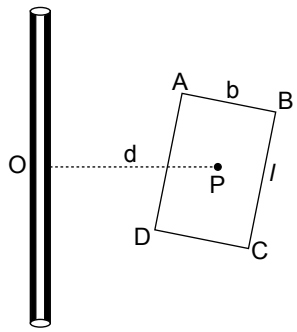
29. A circle of radius r has a linear charge density $\lambda = \lambda_0 \cos^2\theta$ along its circumference. Total charge on the circle is

(a) $\lambda_0(2\pi r)$ (b) $\lambda_0(\pi r)$

(c) $\lambda_0\left(\frac{\pi r}{2}\right)$ (d) $\lambda_0\left(\frac{\pi r}{4}\right)$

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30. Find the electric flux crossing the wire frame *ABCD* of length ℓ, width b and whose centre is at a distance $OP = d$ from an infinite line of charge with linear charge density λ. Consider that the plane of frame is perpendicular to the line *OP*.



(a) $\frac{\lambda\ell}{\pi\varepsilon_0}\tan^{-1}\left(\frac{b}{2d}\right)$

(b) $\frac{\lambda\ell}{2\pi\varepsilon_0}\tan^{-1}\left(\frac{b}{2d}\right)$

(c) $\frac{\lambda\ell}{\pi\varepsilon_0}\tan^{-1}\left(\frac{b}{4d}\right)$

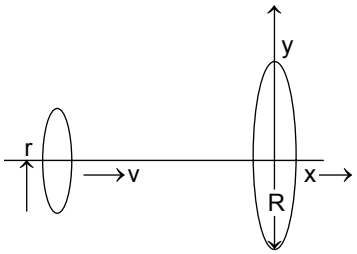
(d) $\frac{\lambda\ell}{2\pi\varepsilon_0}\tan^{-1}\left(\frac{b}{4d}\right)$

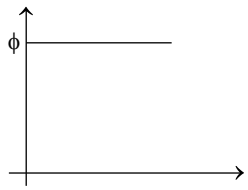
31. Two point charges exert on each other a force F when they are placed r distance apart in air. When they are placed R distance apart in a medium of dielectric constant K, they exert the same force. The distance R equals

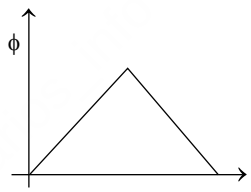
(a) $\frac{r}{\sqrt{K}}$ (b) $\frac{r}{\sqrt{K}}$

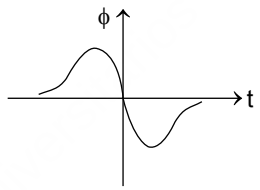
(c) rk (d) $r\sqrt{K}$

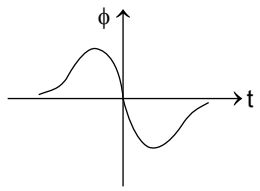
32. A ring of radius R is placed in the plane with its centre at origin and its axis along the x-axis and having uniformly distributed positive charge. A ring of radius $r(<< R)$ and coaxial with the ring is moving along the axis with constant velocity then the variation of electric flux (ϕ) passing through the smaller ring with position will be best represented by



(a)


(b)


(c)


(d)


33. A point charge q is placed at origin. Let $\vec{E}_A, \vec{E}_B$ and $\vec{E}_C$ be the electric field at three points $A(1, 2, 3)$, $B(1, 1, -1)$ and $C(2, 2, 2)$ due to charge q. Then

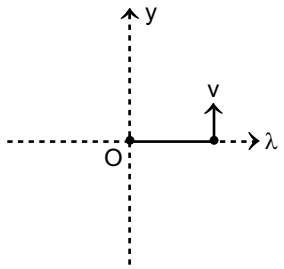
(a) $\vec{E}_A \perp \vec{E}_B$ (b) $|\vec{E}_B| = 4|\vec{E}_C|$

(c) $\vec{E}_A \| \vec{E}_B$ (d) $|\vec{E}_B| = 2|\vec{E}_C|$

34. A small sphere of mass m and carrying a charge q is attached to one end of an insulating thread of length 'a', the other end of which is fixed at (0, 0) as shown in the figure. There exists a uniform electric field $\vec{E} = -E_0\hat{j}$ in the region.

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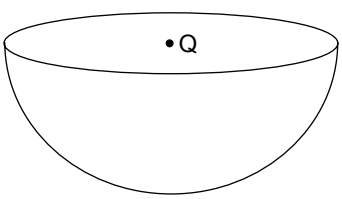
The minimum velocity which should be given to the sphere at (a, 0) in the direction shown so that it is able to complete the circle around the origin is (There is no gravity)



(a) $\sqrt{\frac{5qE_0a}{m}}$ (b) $\sqrt{\frac{3qE_0a}{m}}$

(c) $\sqrt{\frac{qE_0a}{m}}$ (d) $2\sqrt{\frac{qE_0a}{m}}$

35. A charge Q is placed at the centre of an imaginary hemispherical surface. Using symmetry arguments and the Gauss's law. The flux of the electric field due to this charge through the surface of the hemisphere (figure) is



(a) $\frac{Q}{2\varepsilon_0}$ (b) $\frac{Q}{\varepsilon_0}$

(c) $\frac{2Q}{\varepsilon_0}$ (d) $\frac{2Q}{3\varepsilon_0}$

36. A particle of mass m and charge Q is placed in an electric field E which varies with time t as $E = E_0 \sin wt$. It will undergo simple harmonic motion of amplitude

(a) $\frac{QE_0^2}{m\omega^2}$ (b) $\frac{QE_0}{m\omega^2}$

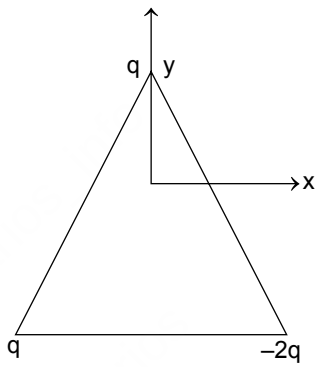
(c) $\sqrt{\frac{QE_0}{m\omega^2}}$ (d) $\frac{QE_0}{m\omega}$

37. An equivalent triangle wire frame of side L having 3 point charges at its vertices is kept in x-y plane as shown. Component of electric field due to the configuration in z direction at (0, 0, L) is [origin is centroid of triangle]

$F = qE_0 \sin wt$

$F = \frac{qE_0}{m} \sin wt$

$F = V = \frac{qE_0}{m} w \cos wt$



(a) $\frac{9\sqrt{3}\,kq}{8L^2}$ (b) zero

(c) $\frac{9\,kq}{8L^2}$ (d) None

38. A particle of mass m and charge q is placed at rest in a uniform electric field E and then released. The KE attained by the particle after moving a distance y is

(a) qEy^2 (b) qEy

(c) qE^2y (d) q^2Ey

39. If electric flux entering and leaving on enclosed surface is ϕ_1 and ϕ_2 respectively, the electric charge inside the enclosed surface will be

(a) $(\phi_1 - \phi_2)/\epsilon_0$ (b) $(\phi_2 - \phi_1)/\epsilon_0$

(c) $(\phi_1 + \phi_2)/\epsilon_0$ (d) $(\phi_2 - \phi_1)/2\,\epsilon_0$

40. Two particles A and B having equal charges are placed at a distance d apart. A third charged particle placed on the perpendicular bisector at a distance x will experience the maximum Coulomb's force when

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(a) $x = d/\sqrt{2}$ (b) $x = d/2$

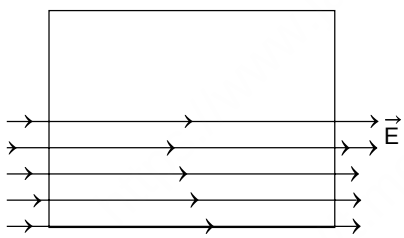
(c) $x = d/2\sqrt{2}$ (d) $x = d/3\sqrt{2}$

41. A charged particle of mass m and charge q initially at rest is released in an electric field of magnitude E. Its kinetic energy after time t will be

(a) $\frac{2E^2t^2}{mq}$ (b) $\frac{E^2q^2t^2}{2m}$

(c) $\frac{Eq^2m}{2t^2}$ (d) $\frac{Eqm}{t}$

42. A square surface of side L metres is in the plane of the paper. A uniform electric field $\vec{E}$ (volt/m), also in the plane of the paper, is limited only to lower half of the square surface, (see figure). The electric flux in SI units associated with the surface is



(a) $EL^2/2$ (b) zero

(c) EL^2 (d) $EL^2/(2\varepsilon_0)$

43. A mass particle (mass = m and charge = q) is placed between two point charge q. If these charge displaced $2L$. distance the frequency of oscillation of mass particle, if it is displaced for a small distance

(a) $\frac{q}{2\pi}\sqrt{\frac{1}{m\pi\varepsilon_0 L^3}}$

(b) $\frac{q}{2\pi}\sqrt{\frac{1}{2m\pi\varepsilon_0 L^3}}$

(c) $\frac{q}{2\pi}\sqrt{\frac{1}{4m\pi\varepsilon_0 L^3}}$

(d) $\frac{q}{2\pi}\sqrt{\frac{1}{16m\pi\varepsilon_0 L^3}}$

44. Two equal negative charges $-q$ are placed at point $(0, \pm a)$ on y-axis, one positive charge q is placed at $x = 2a$, this charge will

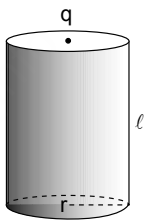
(a) Execute S.H.M. about the origin

(b) Oscillate but not execute S.H.M.

(c) Move towards origin and will become stationary

(d) S.H.M. along x-axis

45. An electric charge q is placed at the centre of the open end of a hollow cylindrical vessel of length l and radius r. Then the electric flux coming out of the surface of the cylinder is



(a) $\frac{q}{\epsilon_0}$ (b) $\frac{q}{\epsilon_0}(\pi r^2 + 2\pi r\ell)$

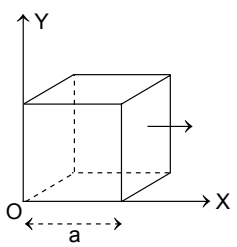
(c) $\frac{q}{2\epsilon_0}$ (d) Zero

46. The electrical breakdown of air occurs at E = 3000 volt/mm. Then the maximum charge that can be given to a sphere of diameter 5 metre will be nearly (in coulomb)

(a) 2.1×10^{-3} (b) 0.83×10^{-3}

(c) 4.6×10^{-2} (d) 2.1×10^{-6}

47. The electric field in the region shown here is given by $E = \sqrt{x}\hat{i}$ volt/m. Then the total electric flux through the cube of side 'a' is



(a) Zero (b) a^2

(c) $a^{5/2}$ (d) $a^{3/2}$

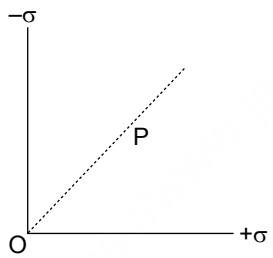
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48. Three identical spheres each having a charge q and radius R, are kept in such a way that each touches the other two. Find the magnitude of the electric force on any sphere due to other two.

(a) $\frac{1}{4\pi\varepsilon_0}\cdot\frac{\sqrt{3}}{4}\left[\frac{q}{R}\right]^2$ (b) $\frac{1}{4\pi\varepsilon_0}\frac{\sqrt{3}}{2}\left[\frac{q}{R}\right]^2$

(c) $\frac{1}{2\pi\varepsilon_0}\frac{\sqrt{3}}{4}\left[\frac{q}{R}\right]^2$ (d) None

49. If two infinite oppositely charged plates with surface charge density $|\sigma|$ on each plate are kept perpendicular to each other as shown in above figure, then a charge q at P will experience a force



(a) $\frac{\sigma q}{2\varepsilon_0}$ towards the

(b) $\frac{\sigma q}{2\varepsilon_0}$ away from horizontal plate

(c) $\frac{\sigma q}{\sqrt{2}\,\varepsilon_0}$ towards the origin O

(d) $\frac{\sigma q}{\sqrt{2}\,\varepsilon_0}$ making an angle 45° with respect to vertical

50. The electric dipole of moment $\vec{p} = p\hat{i}$ is kept at a point (x, y) in an electric field $\vec{E} = 4xy^2\hat{i} + 4x^2y\hat{j}$. The force on the dipole is

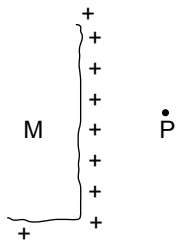
(a) zero

(b) $\frac{pyx}{\sqrt{x^2+y^2}}$

(c) $4py\sqrt{y^2+4x^2}$

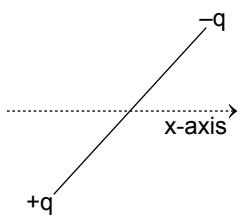
(d) cannot be calculated

51. Figure shows a metal body of mass M charged positively. P is a point in front of the body. The electric field at point P due to the body M is E_P. Now a negative change $-q$ is placed at point P and it experiences a force F. Then



(a) $E_P = F/q$
(b) $E_P < F/q$
(c) $E_P > F/q$
(d) None of these

52. There is a non-uniform electric field along x-axis as shown in figure. The field increases at a uniform rate along +ve x-axis. A dipole is kept inside the field as shown.
Which one of the following statements is correct for dipole?



(a) Dipole moves along positive x-axis and rotates clockwise
(b) Dipole moves along negative x-axis and rotates clockwise
(c) Dipole moves along positive x-axis and rotates anti-clockwise
(d) Dipole moves along negative x-axis and rotates anti-clockwise

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ONE OR MORE THAN ONE CHOICE MAY BE CORRECT

1. A thin walled spherical conducting shell S of radius R is given charge Q. The same amount of charge is also placed at its centre C. Which of the following are correct?

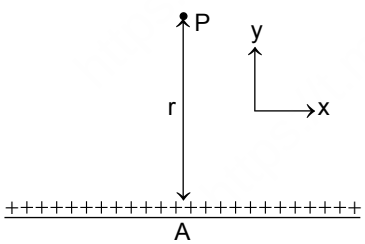
(a) On the outer surface of S charge density $= \frac{Q}{2\pi R^2}$.

(b) The electric field is zero at all points inside S.

(c) At a point just outside S, the electric field is double, the field at a point just inside S.

(d) At any point inside S, the electric field is inversely proportional to the square of distance from C.

2. Electric field, due to an infinite line of charge, as shown in figure at a point P at a distance r from the line is E. If one half of the line of charge is removed from either side of point A, then



(a) Electric field at P will have magnitude E/2.

(b) Electric field at P in x direction will be E/2.

(c) Electric field at P in y direction will be E/2.

(d) None of these

3. An electric dipole moment $\vec{p} = (2.0\hat{i} + 3.0\hat{j})$ $\mu C.m$ is placed in a uniform electric field $\vec{E} = (3.0\hat{i} + 2.0\hat{k}) \times 10^5 NC^{-1}$

(a) The torque that $\vec{E}$ exerts on $\vec{p}$ is $(0.6\hat{i} - 0.4\hat{j} - 0.9\hat{k})$ Nm

(b) The potential energy of the dipole is –0.6 J

(c) The potential energy of the dipole is 0.6 J

(d) If the dipole is rotated in the electric field, the maximum potential energy of the dipole is 1.3 J

4. Mark the correct options.

(a) Gauss's law is valid only for uniform charge distributions

(b) Gauss's law is valid only for charges placed in vacuum

(c) The electric field calculated by Gauss's law is the field due to all the charges.

(d) The flux of electric field through a closed surface due to all the charges is equal to the flux fue to the charges enclosed by the surface.

5. An electric field converges at the origin whose magnitude is given by the expression E = 100rNt/Coul., where r is the distance measured from the origin.

(a) Total charge contained in any spherical volume with its centre at origin is negative.

(b) Total charge contained at any spherical volume, irrespective of the location of its centre, is negative.

(c) Total charge contained in a spherical volume of radius 3 cm with its centre at the origin has magnitude $3 \times 10^{-13} C$.

(d) Total charge contained in a spherical volume of radius 3 cm with its centre at the origin has magnitude $3 \times 10^{-9} C$.

6. Select the correct alternative:

(a) The charge gained by the uncharged body from a charged body due to conduction is equal to half of the total charge initially present.

(b) The magnitude of charge increases with the increase in velocity of charge.

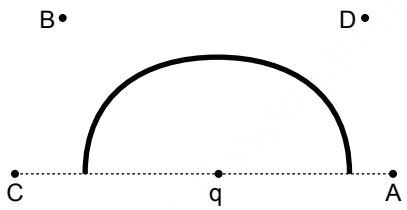
(c) Charge cannot exist without matter although matter can exist without charge

(d) Between two non-magnetic substances repulsion is the true test of electrification (electrification means body has net charge)

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7. The electric field intensity at a point in space is equal in magnitude to
(a) Magnitude of the potential gradient there
(b) The electric charge there
(c) The magnitude of the electric force, a unit charge would experience there
(d) The force, an electron would experience there

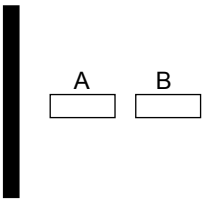
8. Figure shows a charge q placed at the centre of a hemisphere. A second charge Q is placed at one of the positions *A, B, C* and *D*.
In which position(s) of this second charge, the flux of the electric field through the hemisphere remains unchanged?



(a) *A*
(b) *B*
(c) *C*
(d) *D*

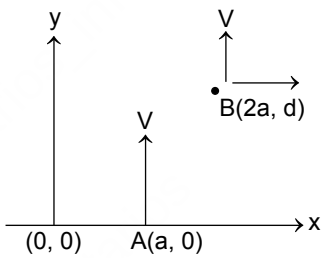
9. An electric dipole is placed at the centre of a sphere, mark the correct options
(a) The flux of the electric field through the surface is zero
(b) The electric field is zero at every point of the sphere
(c) The electric field is not zero anywhere on the sphere
(d) The electric field is zero an a circle on the sphere.

10. A large nonconducting sheet M is given a uniform charge density. Two uncharged small metal rods A and B are placed near the sheet as shown in figure.



(a) M attracts A (b) M attracts B
(c) A attracts B (d) B attracts A

11. A uniform electric field of strength $E\hat{j}$ exists in a region. An electron (charge $-e$, mass m) enters a point A with velocity $V\hat{j}$. It moves through the electric field and exists at point B. Then



(a) $E = -\dfrac{2amv^2}{ed^2}\hat{j}$

(b) Rate of work done by the electric field at B is $\dfrac{4ma^2v^3}{d^3}$

(c) Rate of work by the electric field at A is zero

(d) Velocity at B is $\dfrac{2av}{d}\hat{i} + v\hat{j}$

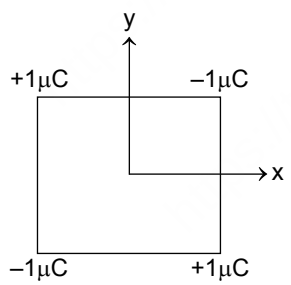
12. An oil drop has a charge $-9.6 \times 10^{-19}C$ and has a mass 1.6×10^{-15} gm. When allowed to fall, due to air resistance force it attains a constant velocity. Then if a uniform electric field is to be applied vertically to make the oil ascend up with the same constant speed, which of the following are correct. (g = 10 m/s) (Assume that the magnitude of resistance force is same in both the cases)

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(a) the electric field is directed upward
(b) the electric field is directed downward
(c) the intensity of electric field is $\frac{1}{3}\times 10^2\, NC^{-1}$
(d) the intensity of electric field is $\frac{1}{6}\times 10^5\, NC^{-1}$

13. An electric dipole is kept in the electric field produced by a point charge
(a) dipole will experience a force
(b) dipole can experience a torque
(c) dipole can be in stable equilibrium
(d) it is possible to find a path (not closed) in the field on which work required to move the dipole is zero.

14. Point charges are located on the corner of a square as shown.
Find the components of electric field at any point on the z-axis which is axis of symmetry of the square.



(a) $E_z = 0$ (b) $E_x = 0$
(c) $E_y = 0$ (d) None of these

ASSERTION AND REASON QUESTIONS

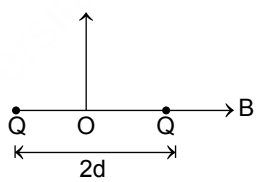
Direction: Each question contains STATEMENT-1 (Assertion) and STATEMENT-2 (Reason). Each question has 4 choices (a), (b), (c) and (d) out of which ONLY ONE is correct.

(a) Statement-1 is True, Statement-2 is True; Statement-2 is a correct explanation for Statement-1.
(b) Statement-1 is True, Statement-2 is True; Statement-2 is NOT a correct explanation for Statement-1.
(c) Statement-1 is True, Statement-2 is False.
(d) Statement-1 is False, Statement-2 is True.

1. **Statement 1:** A positive point charge is brought in an electric field, the electric field at nearby point will increase.
Statement 2: Electric field produce by charge may favour the existing electric field.

2. **Statement 1:** Flux through a closed surface is zero.
Statement 2: Total charge inside the surface must be zero.

3. **Statement 1:** Consider two identical charges placed distance $2d$ apart, along x-axis. The equilibrium of a positive test charge placed at the point O midway between them is stable for displacements along the x-axis.
Statement 2: Force on test charge is zero.



4. **Statement 1:** A parallel beam of electrons is shot into a uniform strong electric field initially parallel to and then against the field with a small initial speed. Then the beam tends to spread out at the beginning and narrows down later.
Statement 2: The total energy of the beam is conserved.

5. **Statement 1:** An ellipsoidal cavity is carved within a perfect conductor. A positive charge q is placed at the centre of the cavity. The points A and B are on the cavity surface. Potential at A = potential at B.
Statement 2: Surface of charge conductor is always equipotential.

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6. **Statement 1:** A deuteron and an α-particle are placed in an electric field. If F_1 and F_2 be the forces acting on them and a_1 and a_2 be their accelerations respectively then, $a_1 = a_2$.
Statement 2: Forces will be same in electric field.

7. **Statement 1:** Charges Q_1 and Q_2 are placed inside and outside respectively of an uncharged conducting shell, their separation is r. Then the force on Q_1 is zero.
Statement 2: Lines of force cannot enter conducting shell.

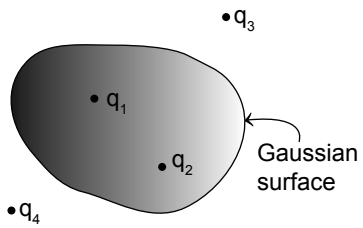
8. **Statement 1:** When a charged comb is brought near a small piece of paper, it attracts the piece.
Statement 2: Because the paper becomes charged.

9. **Statement 1:** A point charge is placed in a cavity in a metal block. If another charge is brought outside the metal, the charge in the cavity does not feel any electric force
Statement 2: There is no electric field line in the cavity of a metal block.

10. **Statement 1:** A small metal ball is suspended in a uniform electric field with an insulated thread. If high energy X-ray beam falls on the ball, the ball will be deflected in the electric field.
Statement 2: X-rays beam falls on the ball, the ball will be deflected in the magnetic field.

11. **Statement 1:** The tyres of aircrafts are slightly conducting.
Statement 2: If a conductor is connected to ground, the extra charge induced on conductor will flow to ground.

12. **Statement 1:** Four point charges q_1, q_2, q_3 and q_4 are as shown in figure. The flux over the shown Gaussian surface depends only on charges q_1 and q_2.



Statement 2: Electric field at all points on Gaussian surface depends only on charges q_1 and q_2.

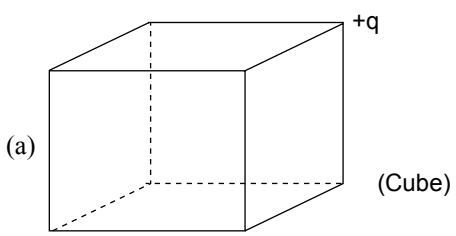
13. **Statement 1:** An insulator does not conduct electricity usually.
Statement 2: The number of electrons in an insulator is very small in comparison to that in a conductor.

14. **Statement 1:** The positive charge particle is placed in front of a spherical uncharged conductor. The number of lines of forces terminating on the sphere will be more than those emerging from it.
Statement 2: The surface charge density at a point on the sphere nearest to the point charge will be negative and maximum in magnitude compared to other points on the sphere.

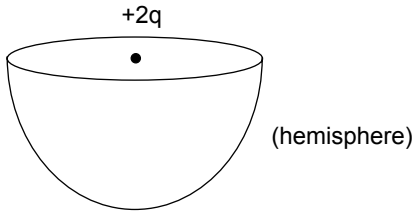
MATCH THE COLUMN TYPE QUESTIONS

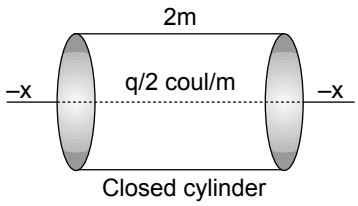
Each question contains statements given in two columns which have to be matched. Statements (A, B, C, D) in column I have to be matched with statements (p, q, r, s) in column II.

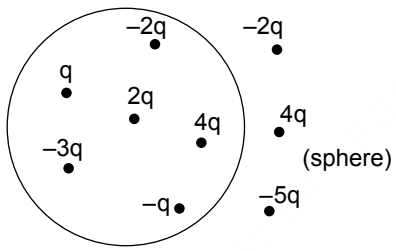
1. Match the column:
Column I
Arrangement



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(b)


(c)


(d)


Column II

Flux through the entire surface of the body.

(p) $\frac{q}{\varepsilon_0}$ (q) $\frac{q}{8\varepsilon_0}$

(r) $\frac{q}{4\varepsilon_0}$ (s) $\frac{3q}{\varepsilon_0}$

2. An electric dipole is placed in an electric field. The column I gives the description of electric field and the angle between the dipole moment $\vec{p}$ and the electric field intensity $\vec{E}$ and the column II gives the effect of the electric field on the dipole. Match the description in Column I with the statements in column II.

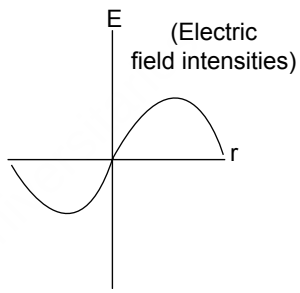
Column I	**Column II**
(a) Uniform electric field, $\theta = 0$	(p) force = 0
(b) Electric field due to a point charge, $\theta = 0$	(q) Torque = 0
(c) Electric field between the two oppositely charged large plates, $\theta = 90^\circ$	(r) $\vec{p}.\vec{E} = 0$
(d) Dipole moment parallel to uniformly charged long wire.	(s) Force $\neq 0$

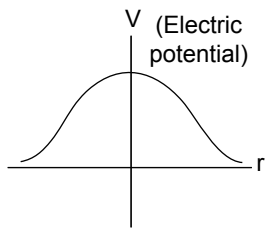
3. Column II describes graph for charge distribution given in column I. Match the description.

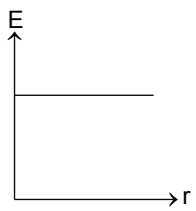
Column I

(a) Uniformly charged ring
(b) Infinitely large charge conducting sheet
(c) Infinite non conducting thin sheet.
(d) Hollow non conducting sphere.

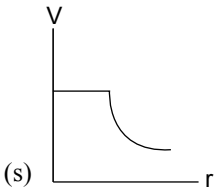
Column II

(p)


(q)


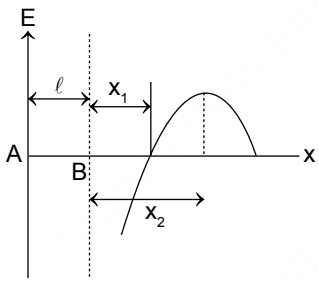
(r)


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(s)

4. Two points, like charges Q_A and Q_B are positioned at points A and B. The electric field strength to the right of charge Q_B on the line that passes through the two charges varies according to a law that is represented shematically in the figure accompanying the problem without employing a definite scale. Assume electric field to be positive if its direction coincides with the positive direction on the x-axis. Distance between the charges is l.



Column I	Column II
(a) Charge Q_A	(p) –ve
(b) Charge Q_B	(q) +ve
(c) $\lvert Q_A / Q_B \rvert$	(r) $\left(\frac{\ell + x_1}{x_1}\right)^2$
(d) x_2	(s) $\frac{\ell}{(Q_A/Q_B)^{1/3} - 1}$

5. Match the column:

Column I	Column II
(a) Like charges repels and unlike attracts.	(p) Dr William Gilbert
(b) Numerical value of force between two charges	(q) Thomos Brown
(c) Methods of charging	(r) Coulomb by (torsion balance)
(d) Amount of induced charge	(s) Faraday ice pail exp.

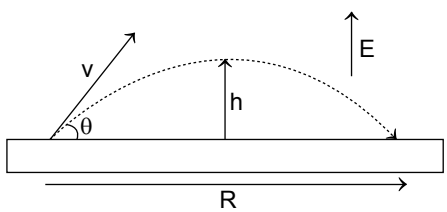
6. Match the column:

Column I	Column II
(a) e/m of electron	(p) J.J. Thomson
(b) Charge and mass (indirectly) of electron and quanta of charge.	(q) R.A. millikan (by oil drop exp.)
(c) Concept of line of force	(r) M. Faraday
(d) Highestcommon factor method	(s) Max Plank

PASSAGE BASED QUESTIONS

PASSAGE–1

A very large, charged plate floats in deep space. Due to the charge on the plate, a constant electric field E exists everywhere above the plate. An object with mass m and charge q is shot upward from the plate with a velocity v and an angle θ. It follows the path shown reaching a height h and a range R. Assume the effects of gravity to be negligible.



1. Which of the following must be true concerning the object?
(a) q must be positive
(b) q must be negative
(c) m must be large
(d) m must be small

2. Which of the following gives the vertical velocity of the object in terms of h just before colliding with the plate at the end of its flight?

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(a) $\sqrt{2gh}$ (b) $\sqrt{2Eqh}$

(c) $\sqrt{\frac{2mh}{Eq}}$ (d) $\sqrt{\frac{2qhE}{m}}$

3. Which of the following is true concerning all objects that follow the path shown when propelled with a velocity v at an angle θ?

(a) they must have the same mass

(b) they must have the same charge

(c) they must have the same mass and the same charge

(d) their mass to charge ratios must be the same

4. Suppose E is 10 N/C, m is 1 kg, q is –1 C, v is 100 m/s and θ is 30º. What is h?

(a) 25 m (b) 45 m

(c) 80 m (d) 125

5. Which of the following is true concerning the flight of the projectile shown?

(a) Increasing the mass m decreases the maximum height h

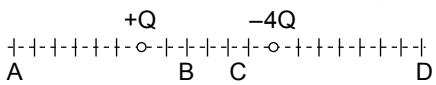
(b) Increasing the charge q increases the maximum height h

(c) Increasing the mass m decreases the downward acceleration

(d) Increasing the charge q decreases the downward acceleration

PASSAGE–2

Related to the following diagram of two charges, $+Q$ and $-4Q$



6. The net electric field is zero near which point?

(a) A (b) B

(c) C (d) D

7. At which point does the net electric field vector point to the left?

(a) A (b) B

(c) C (d) D

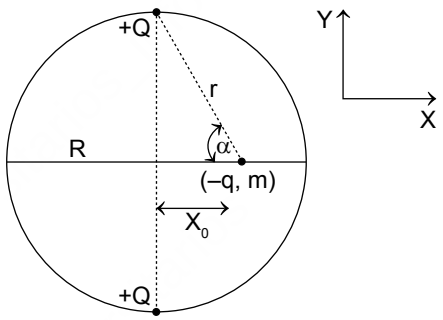
8. At which point would a small positive charge q feel the greatest force?

(a) A (b) B

(c) C (d) D

PASSAGE–3

A thin insulating wire is stretched along the diameter of an insulated circular loop of radius R. A small bead of mass m and charge $-q$ is threaded on to the wire. Two small identical charges are tied to the hoop at points opposite to each other, so that the diameter passing through them is perpendicular to the thread (see figure). The bead is released at a point which is a distance x_0 from the centre of the loop. Assume that $x_0 << R$.



9. The resultant force acting on the charged bead is

(a) $F = -\frac{k2Qq}{x_0^2 + R^2} \cdot \frac{x_0}{r}$

(b) $F = \frac{k2Qq}{x_0^2 + R^2} \cdot \frac{x_0}{r}$

(c) $F = -\frac{k2Qq}{x_0^2 - R^2} \cdot \frac{x_0}{r}$

(d) $F = \frac{k2Qq}{x_0^2 - R^2} \cdot \frac{x_0}{r}$

10. The exact equation of motion of the bead along the thread is

(a) $m\frac{d^2x}{dt^2} = -\frac{k2Qqx}{\left(x^2 + R^2\right)^{3/2}}$

(b) $m\frac{d^2x}{dt^2} = -\frac{kQqx}{\left(x^2 - R^2\right)^{3/2}}$

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(c) $m\frac{d^2x}{dt^2} = -\frac{k2Qqx}{\left(x^2 - R^2\right)^{3/2}}$

(d) $m\frac{d^2x}{dt^2} = -\frac{kQqx}{\left(x^2 - R^2\right)^{3/2}}$

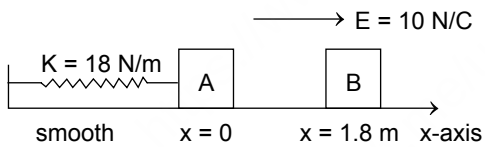
11. The time when will the velocity of the bead vanish for the first time is

(a) $\sqrt{\frac{\pi^2 mR^3}{k2Qq}}$ (b) $\sqrt{\frac{\pi^2 mR^3}{kQq}}$

(c) $\sqrt{\frac{\pi^2 mR^3}{k4Qq}}$ (d) $\sqrt{\frac{2\pi^2 mR^3}{kQq}}$

PASSAGE–4

In the figure shown $m_A = m_B = 1$ kg. Block A is neutral while $q_B = -1$ C. Sizes of A and B are negligible. B is released from rest at a distance 1.8 m from A. Initially, spring is neither compressed nor elongated.



12. If collision between A and B is perfectly inelastic, what is the velocity of combined mass just after collision?

(a) 6 m/s (b) 3 m/s

(c) 9 m/s (d) 12 m/s

13. Equilibrium position of the combined mass is at $x = \ldots . m$

(a) –2/9 (b) –1/3

(c) –5/9 (d) –7/9

14. The amplitude of oscillation of the combined mass will be

(a) $\frac{2}{3}m$ (b) $\sqrt{\frac{124}{3}}m$

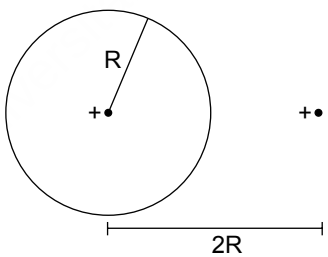
(c) $\frac{\sqrt{72}}{9}m$ (d) $\frac{\sqrt{106}}{9}m$

SUBJECTIVE QUESTIONS

1. Two identical conducting of spheres (of negligible radius), having charges of opposite sign, attract each other with a force of 0.108 N when separated by 0.5 metre. The spheres are connected by a conducting wire, which is then removed (when charge stops flowing) and therefore repel each other with a force of 0.036 N keeping the distance same. What were the initial charges on the spheres?

2. Two particles A and B having charges of $+2.00 \times 10^{-6}C$ and of $-4.00 \times 10^{-6}C$ respectively are held fixed at a separation of 20.0 cm. Locate the point(s) on the line AB where the electric field is zero.

3. Find the flux of the electric field through a spherical surface of radius R due to a charge of $18.85 \times 10^{-8}C$ at the centre and another equal charge at a point $2R$ away from the centre.



4. A clock face has negative charges $-q$, $-2q$, $-3q$, …… .., $-12q$ fixed at the position of the corresponding numerals on the dial. The clock hands do not disturb the net field due to point charges. At what time does the hour hand point in the same direction is electric field at the centre of the dial.

5. The electric field in a region is given by $\vec{E} = \frac{E_0 x}{\ell}\hat{i}$. Find the charge contained inside a cubical volume bounded by the surfaces $x = 0$, $y = 0$, $y = a$, $z = 0$ and

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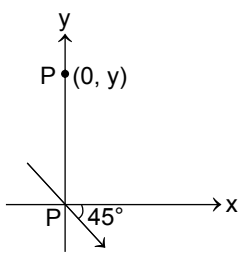
$z = a$. Take $E_0 = 5 \times 10^3$ N/C, $l = 2$ cm and $a = 1$ cm.

6. A solid non-conducting sphere of radius R has a non-uniform charge distribution of volume charge density, $\rho = \rho_0 \frac{r}{R}$; where ρ_0 is a constant and r is the distance from the centre of the sphere. Show that
(a) the total charge on the sphere is $Q = \pi\rho_0 R^3$ and
(b) the electric field inside the sphere has a magnitude given by, $E = \frac{KQr^2}{R^4}$

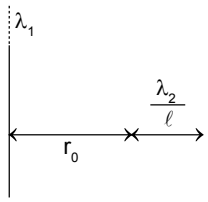
7. An electron beam after being accelerated from rest through a potential difference of 500 V in vacuum is allowed to impinge normally on a fixed surface. If the incident current is 100 μA, determine the force exerted on the surface assuming that it brings the electrons to rest.
($e = 1.6 \times 10^{-19} C$, $m = 9.0 \times 10^{-31}$ kg)

8. A charge Q is uniformly distributed over a rod of length l. Consider a hypothetical cube of edge l with the centre of the cube at one end of the rod. Find the minimum possible flux of the electric field through the entire surface of the cube.

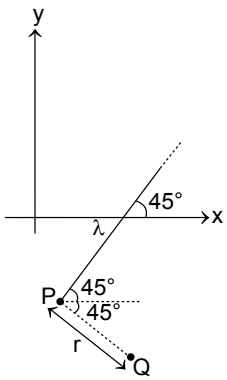
9. A dipole is placed at origin of coordinate system as shown in figure, find the electric field at point P $(0, y)$.



10. An infinitely long string uniformly charged with a linear density λ_1 and a segment of length l uniformly charged with linear density λ_2 lie in a plane at right angles to each other and separated by a distance r_0.
Determine the force with which these two interact.



11. A very long charged thread (lying in the xy plane) which is having a linear charge density λ is having one of its end at a point P as shown in figure. What is electric field intensity at point Q?



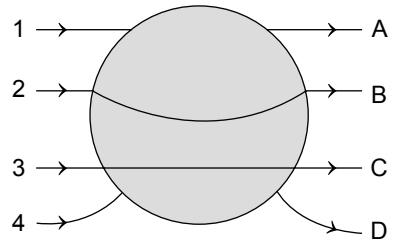
12. Two like charged, infinitely long rod with the same linear charge density of 3×10^{-8} C/cm are 2 cm apart. Find the electric force per unit length on each rod due to the other and the work done against that force per unit length to be done in bringing them closer by 1 cm.

PREVIOUS YEARS' IIT-JEE QUESTIONS

1. A metallic solid sphere is placed in a uniform electric field. The lines of force follow the path (s) shown in figure as

[1996]

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

2. A positively charged thin metal ring of radius R is fixed in the xy-plane with its centre at the O. A negatively charged particle P is released from rest at the point $(0, 0, z_0)$, where $z_0 > 0$. Then the motion of P is

[1998]

(a) Periodic for all values of z_0 satisfying $0 < z_0 < \infty$
(b) Simple harmonic for all values of satisfying $0 < z_0 < R$
(c) Approximately simple harmonic provided $z_0 << R$
(d) Such that P crosses O and continues to move along the negative z-axis towards $z = -\infty$

3. A non-conducting solid sphere of radius R is uniformly charged. The magnitude of the electric field due to the sphere at a distance r from its centre

[1998]

(a) Increases as r increases for $r < R$
(b) Decreases as r increases for $0 < r < \infty$
(c) Decreases as r increases for $R < r < \infty$
(d) Is discontinuous at $r = R$

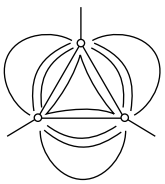
4. The dimension of $(1/2)\ \varepsilon_0 E^2$ (ε_0: permittivity of free space, E: electric field) is

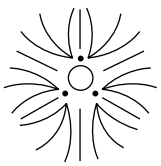
[2000]

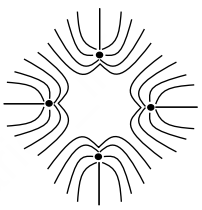
(a) MLT^{-1}
(b) ML^2T^{-2}
(c) $ML^{-1}T^{-2}$
(d) ML^2T^{-1}

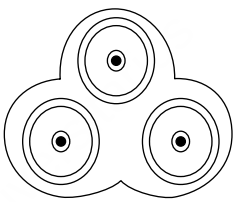
5. Three positive charges of equal value q are placed at the vertices of an equilateral triangle. The resulting lines of force should be sketched as in

[2001]

(a) 

(b) 

(c) 

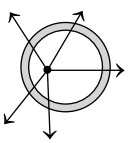
(d) 

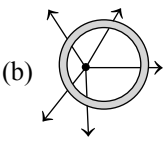
6. A small ball of mass 2×10^{-3} kg having a charge of 1 μC is suspended by a string of length 0.8 m. Another identical ball having the same charge is kept at the point of suspension. Determine the minimum horizontal velocity which should be imparted to the lower ball so that it can make complete revolution.

[2002]

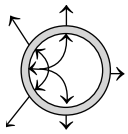
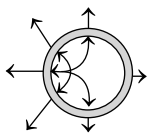
7. A metallic shell has a point charge q kept inside its cavity. Which one of the following diagrams correctly represents the electric lines of forces?

[2003]

(a) 

(b) 

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(c)  (d) 

8. A charge $+Q$ is fixed at the origin of the co-ordinate system while a small electric dipole of dipole-moment $\vec{p}$ pointing away from the charge along the x-axis is set free from a point far away from the origin.

[2003]

(a) Calculate the K.E. of the dipole when it reaches to a point $(d, 0)$.

(b) Calculate the force on the charge $+Q$ at this moment.

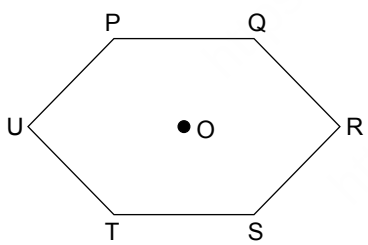
9. Six charges, three positive and three negative of equal magnitude are to be placed at the vertices of a regular hexagon such that the electric field at O is double the electric field when only one positive charge of same magnitude is placed at R. Which of the following arrangements of charges is possible for P, Q, R, S, T and U respectively?

(a) +, –, +, –, –, +

(b) +, –, +, –, +, –

(c) +, +, –, +, –, –

(d) –, +, +, –, +, –



10. Consider the charge configuration and spherical Gaussian surface as shown in the figure. When calculating the flux of the electric field over the spherical surface the electric field will be due to

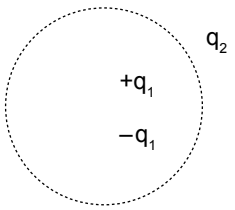
[2004]

(a) q_2

(b) only the positive charges

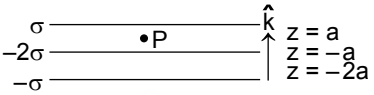
(c) all the charges

(d) $+q_1$ and $-q_1$



11. Three infinitely long charge sheets are placed as shown in figure. The electric field at point P is

[2005]



(a) $\frac{2\sigma}{\varepsilon_0}\hat{k}$ (b) $-\frac{2\sigma}{\varepsilon_0}\hat{k}$

(c) $\frac{4\sigma}{\varepsilon_0}\hat{k}$ (d) $-\frac{4\sigma}{\varepsilon_0}\hat{k}$

12. Consider a neutral conducting sphere. A positive point charge is placed outside the sphere. The net charge on the sphere is then

[2007]

(a) negative and distributed uniformly over the surface of the sphere

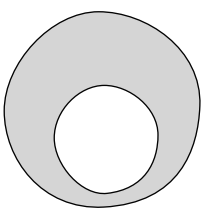
(b) negative and appears only at the point on the sphere closest to the point charge

(c) negative and distributed non-uniformly over the entire surface of the sphere

(d) zero

13. A spherical portion has been removed from a solid sphere having a charge distributed uniformly in its volume as shown in the figure. The electric field inside the emptied space is

[2007]



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(a) zero everywhere
(b) non-zero and uniform
(c) non-uniform
(d) zero only at its centre

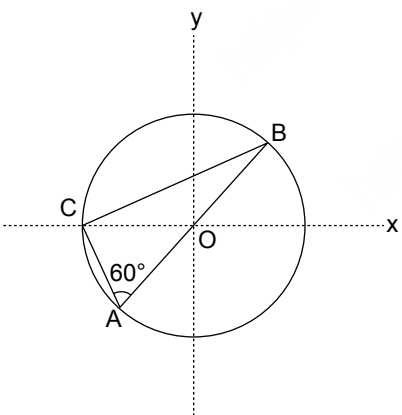
14. Positive and negative point charge of equal magnitude are kept at (0, 0, $a/2$) and (0, 0, $-a/2$) respectively. The work done by the electric field when another positive point charge is moved from ($-a$, 0, 0) to (0, a, 0) is

[2007]

(a) positive
(b) negative
(c) zero
(d) depends on the path connecting the initial and final positions

15. Consider a system of three charges $q/3$, $q/3$ and $2q/3$ placed at points *A, B* and *C*, respectively, as shown in the figure.
Take *O* to be the centre of the circle of radius *R* and angle $CAB = 60°$

[2008]

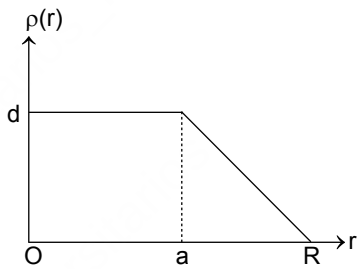


(a) The electric field at point *O* is $\frac{q}{8\pi\varepsilon_0 R^2}$ directed along the negative *x*-axis
(b) The potential energy of the system is zero
(c) The magnitude of the force between the charges at *C* and *B* is $\frac{q^2}{54\pi\varepsilon_0 R^2}$
(d) The potential at point *O* is $\frac{q}{12\pi\varepsilon_0 R}$

PASSAGE

Direction (Questions 16 to 18): The nuclear charge (Ze) is non-uniformly distributed within a nucleus of radius *R*. The charge density ρ (*r*) [charge per unit volume] is dependent only on the radial distance *r* from the centre of the nucleus as shown in figure. The electric field is only along the radial direction.

[2008]



16. The electric field at $r = R$ is
(a) independent of a
(b) directly proportional to a
(c) directly proportional to a^2
(d) inversely proportional to a

17. For $a = 0$, the value of d (maximum value of ñ as shown in the figure) is

(a) $\frac{3Ze}{4\pi R^3}$ (b) $\frac{3Ze}{\pi R^3}$
(c) $\frac{4Ze}{3\pi R^3}$ (d) $\frac{Ze}{3\pi R^3}$

18. The electric field within the nucleus is generally observed to be linearly dependent on *r*. This implies
(a) $a = 0$
(b) $a = R/2$
(c) $a = R$
(d) $a = 2R/3$

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ANSWERS

ONLY ONE CORRECT OPTION TYPE QUESTIONS

1. (c)	**2.** (d)	**3.** (c)	**4.** (d)	**5.** (c)	**6.** (a)	**7.** (d)	**8.** (d)
9. (b)	**10.** (b)	**11.** (a)	**12.** (b)	**13.** (b)	**14.** (b)	**15.** (b)	**16.** (b)
17. (c)	**18.** (d)	**19.** (d)	**20.** (b)	**21.** (c)	**22.** (c)	**23.** (b)	**24.** (c)
25. (d)	**26.** (a)	**27.** (b)	**28.** (b)	**29.** (b)	**30.** (a)	**31.** (d)	**32.** (c)
33. (b)	**34.** (b)	**35.** (a)	**36.** (b)	**37.** (b)	**38.** (b)	**39.** (b)	**40.** (c)
41. (b)	**42.** (b)	**43.** (a)	**44.** (b)	**45.** (c)	**46.** (a)	**47.** (c)	**48.** (a)
49. (d)	**50.** (c)	**51.** (b)	**52.** (d)				

ONE OR MORE THAN ONE CHOICE MAY BE CORRECT

1. (a, c, d)	**2.** (a, b, c)	**3.** (a, b, d)	**4.** (c, d)	**5.** (a, b, c)	**6.** (c, d)	**7.** (b, c)	**8.** (a, d)
9. (a, c)	**10.** (c, d)	**11.** (b, c, d)	**12.** (b, c)	**13.** (b, c, d)	**14.** (a, b, c)		

ASSERTION AND REASON QUESTIONS

1. (d)	**2.** (a)	**3.** (b)	**4.** (a)	**5.** (a)	**6.** (c)	**7.** (a)	**8.** (c)
9. (a)	**10.** (c)	**11.** (b)	**12.** (c)	**13.** (c)	**14.** (b)		

MATCH THE COLUMN TYPE QUESTIONS

1. (a) $\rightarrow q$, (b) $\rightarrow p$, (c) $\rightarrow p$, (d) $\rightarrow s$

2. (a) $\rightarrow p, q$, (b) $\rightarrow q, s$ (c) $\rightarrow p, r$, (d) $\rightarrow p, r$

3. (a) $\rightarrow p, q$, (b) $\rightarrow r$, (c) $\rightarrow r$, (d) $\rightarrow s$

4. (a) $\rightarrow q$, (b) $\rightarrow p$, (c) $\rightarrow r$, (d) $\rightarrow s$

5. (a) $\rightarrow p$, (b) $\rightarrow q$, (c) $\rightarrow r$, (d) $\rightarrow s$

6. (a) $\rightarrow p$, (b) $\rightarrow r$, (c) $\rightarrow q$, (d) $\rightarrow s$

PASSAGE BASED QUESTIONS

1. (b)	**2.** (d)	**3.** (d)	**4.** (d)	**5.** (c)	**6.** (a)	**7.** (d)	**8.** (c)
9. (a)	**10.** (a)	**11.** (a)	**12.** (b)	**13.** (c)	**14.** (d)		

PREVIOUS YEARS' IIT-JEE QUESTIONS

1. (d)	**2.** (a, c)	**3.** (a, c)	**4.** (c)	**5.** (c)	**6.** 5.86 m/s	**7.** (c)	**8.** (b)
9. (d)	**10.** (c)	**11.** (b)	**12.** (a, b, c, d)		**13.** (b)	**14.** (c)	**15.** (c)
16. (a)	**17.** (b)	**18.** (c)					

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HINTS AND EXPLANATIONS

SUBJECTIVE QUESTIONS

1. $\pm 1.0 \times 10^{-6}C$, $\because 3 \times 10^{-6}C$

2. $\frac{20}{\sqrt{2}-1} = 48.3$ cm from Allong BA

3. $10^4 \frac{N-m^2}{C}$

4. 9.39

5. $2.2 \times 10^{-12}C$

6. $0, \frac{2k\lambda}{r}, 0$

7. $7.5 \times 10^{-9}N$

8. $\frac{Q}{2\epsilon_0}$

9. $\frac{kp}{\sqrt{2}y^3}(-\hat{i}-2\hat{j})$

10. $F = \frac{\lambda_1\lambda_2}{2\pi\varepsilon_0}\ln\left(1+\frac{\ell}{r_0}\right)$

11. $|E| = \frac{\sqrt{2}k\lambda}{r}$, $\vec{E} = \frac{\sqrt{2}k\lambda}{r}(-\hat{j})$

12. $B = \frac{2k\lambda^2}{r}$ = 8.1 N/m, $2k\lambda^2$,

ln 2 = 0.1129 J/m

PREVIOUS YEARS' IIT-JEE QUESTIONS

8. $K.E. = \frac{P}{4\pi\varepsilon_0}\frac{Q}{d^2}$ (b) $\frac{QP}{2\pi\varepsilon_0 d^3}$ along positive x-axis

15. (c) Net electric field to both charges $q/3$, will get cancelled. Electric field due to $(-2q/3)$ will be directed in –ve axis.

$$E = \frac{k(2q/3)}{R^2} \Rightarrow E = \frac{q}{6\pi\varepsilon_0 R^2}$$

P.E. of system

$$= \frac{K(q/3)^2}{2R} + \frac{K\frac{q}{3}\left(-\frac{2q}{3}\right)}{2R\sin 60°} + \frac{K\frac{q}{3}\left(-\frac{2q}{3}\right)}{2R\cos 60°}$$

16. (a) $E = \frac{KQ}{R^2}$ (Q = Total charge within the nucleus = Ze)

So, $E = \frac{KZe}{R^2}$

So electric field is independent of a.

17. (b) $q = \int_0^R \frac{d}{R}(R-x)4\pi x^2 dx = Ze$

$$d = \frac{3Ze}{\pi R^3}$$

18. (c) If within a sphere ρ is constant $E \propto r$

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CHAPTER

3

Current Electricity

3.1 ELECTRIC CURRENT IN CONDUCTORS

If there is a continuous flow of something its constitute the current

For the electric current there must be a continuous flow of charge, in other words they are two essential things for constituting an electric current:

(i) charge carrier
(ii) its motion

The following can constitute the current:

(i) A fast beam of neutron
(ii) Nuclear charge
(iii) Orbital electron

Instantaneous Current

$$i = \pm\frac{dq}{dt}$$

where, q is the charge flow of conductor.

Average current through a cross-section medium during the time interval t.

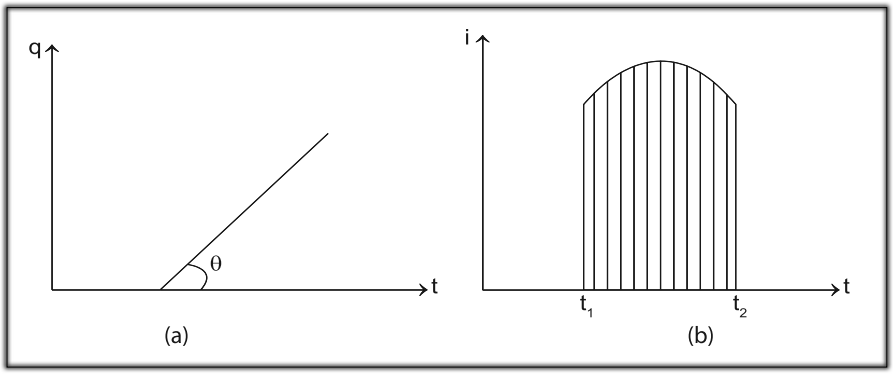
If $i = f(t),\ 0 \le t \le t$

Then $$< i >= \frac{\int_0^t i\,dt}{\int_0^t dt} = \frac{q}{t}$$

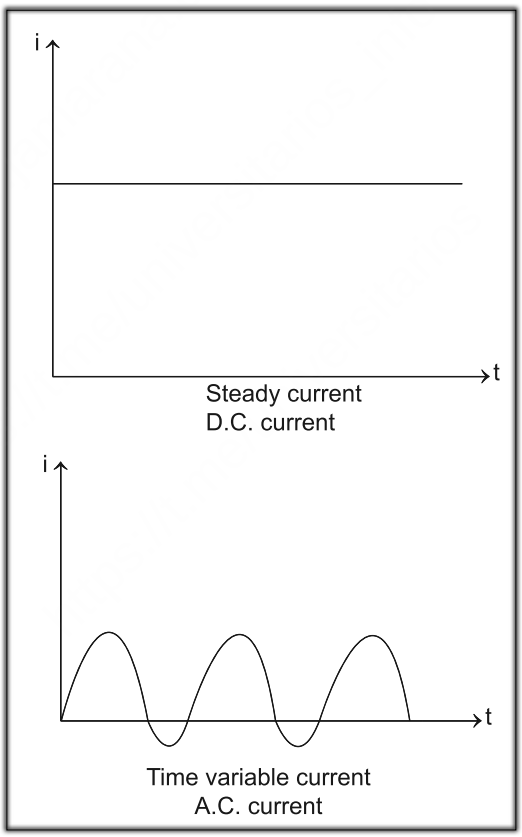
Note:

1. Current is independent of a cross-sectional area of the medium.
2. Current is essentially a positive charge.
3. The flow of negative charge carrier in any direction is equivalent to the flow of same amount of positive charge in opposite direction.
4. The direction of electric current is same as that of direction of flow of positive charge carriers.

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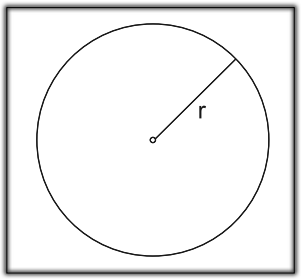
From figure (b) $\int_{t_1}^{t_2} i\,dt$ = Area under curve = net charge flow



(i) An electron circulates in a orbit of radius r with constant angular velocity ω. Its equivalent current is obtained as

$$T = \frac{2\pi}{\omega} \qquad i = \frac{e}{T} = \frac{e}{\frac{2\pi}{\omega}} = \frac{e\omega}{2\pi}$$

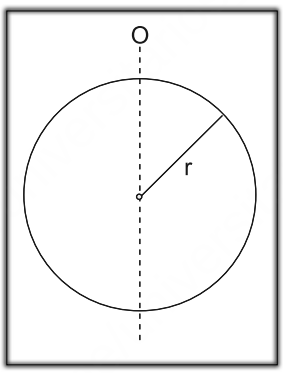
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(ii) An electron of sodium atom revolves in a orbit of a radius r with constant angular speed. Its equivalent current is obtained as

$$i = \frac{ze\omega}{2\pi}$$

(iii) A ring of radius r is non-uniformly charge q and rotates with angular velocity ω about fixed axis passing through the centre of the ring and perpendicular to its plane. Its equivalent current is given by



$$di = \frac{\omega}{2\pi} dq \quad i = \frac{\omega}{2\pi} q$$

Example

An air cylindrical capacitor with a *D.C.* voltage $V = 200$ V applied to it is being submerged vertically into a vessel filled with water at a velocity $\nu = 5.0$ mm/s. The electrodes of the capacitor are separated by a distance $d = 2.0$ mm, the mean curvature radius of the electrode is equal to $r = 50$ mm. Find the current flowing in this case along lead wires, if $d << r$.

☞ **Solution** Since, $d << r$, the capacitance of the given capacitor can be calculated using the formula for a parallel plate capacitor. Therefore, if the water (permittivity $\in$) is introduced up to an height x and the capacitor of length l, we have

$$C = \frac{\varepsilon \varepsilon_0 2\pi r x}{d} + \frac{\in_0 (l-x) 2\pi r}{d}$$

$$= \frac{\varepsilon_0 2\pi r}{d} (\varepsilon x + l - x)$$

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Hence, the charge on the plate at that instant,

$$q = CV$$

Again we know that the electric current intensity

$$I = \frac{dq}{dt} = \frac{d(CV)}{dt}$$

$$= V\varepsilon_0 2\pi r \frac{d(\varepsilon x + l - x)}{dt}$$

$$= \frac{V 2\pi r \varepsilon_0}{d}(\varepsilon - 1)\frac{dx}{dt}$$

But $\frac{dx}{dt} = v$

$$\therefore \quad I = \frac{2\pi r\ \varepsilon_0(\varepsilon - 1)V}{d} v$$

$$= \mathbf{0.11\ \mu A}$$

3.2 MECHANISM OF CONSTITUTING THE CURRENT IN A CONDUCTING MEDIUM (METALLIC WIRE)

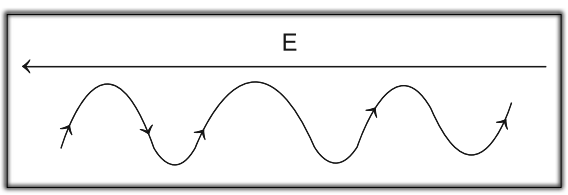
In an isolated conductor, the electric field inside, at any point is equal to zero. The mobile electron inside an isolated conductor are in random motion. Therefore, the velocity of free electron passing through any cross-section area of a conductor at any instant of time will be equal to zero.

Let, there are *n* number electrons passing through a certain cross-section area of a conductor with velocity $\vec{v}_1, \vec{v}_2 \ldots \vec{v}_n$ respectively. Then, the average velocity

$$< \vec{v} >= \frac{\vec{v}_1 + \vec{v}_2 + \ldots + \vec{v}_n}{n} = 0$$

When the potential difference is applied across the end of the conductor, an electric field is set up in the conductor. With no time an short ejecting electric force on the mobile electron throughout the conductor is setup and as a result we have a net flow of electron opposite to direction of field inside the conductor. Hence, we have the conventional current in the direction opposite to the direction of flow of electron.

In reality, the electrons do not move in straight line along the conductor. Instead of they undergo readilly collision with other atom with metallic wire which result in a zig-zag motion. The energy transferred from the electron to the atoms of the conductor due to electric collision increases vibration energy of atom and therefore corresponding increase in the temperature of the conductor.



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Average velocity of electrons during the time interval two equating collision. *(drift velocity)*

$$< \vec{v}' >= \left(\overline{v}_1 + \frac{e\overline{\mathrm{E}} t_1}{m_e} \right) + \left(\overline{v}'_2 + \frac{e\vec{\mathrm{E}} t_2}{m_e} \right) + ..$$

$$+ \left(\vec{v}'_n + \frac{e\vec{\mathrm{E}} t_n}{m_e} \right)$$

$$< \vec{v} >= \left(\frac{\overline{v}'_1 + \overline{v}'_2 + ... + \overline{v}'_n}{n} \right) n + \frac{e\vec{\mathrm{E}}'}{m_e}$$

$$\left(\frac{t_1 + t_2 + ... + t_n}{n} \right) = 0 + \frac{e\vec{\mathrm{E}} t}{m_e}$$

$$< \vec{\upsilon}_d > = \frac{e\vec{\mathrm{E}}}{m_e} t$$

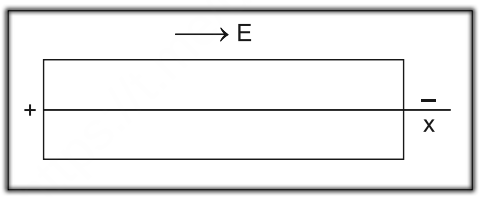
$$< v' > = \vec{\upsilon}_d = \frac{e\vec{\mathrm{E}}}{m_e} t \qquad ...(i)$$

$\upsilon_d \uparrow\uparrow \mathrm{E}$ if charge carrier is positive.

$\upsilon_d \uparrow\downarrow \mathrm{E}$ if charge carrier is negative.

Note: The drift velocity is the average velocity of the charge carried during the reaction time where as the current velocity in the velocity of the propagation of $\vec{\mathrm{E}}$ (electromagnetic wave) which is about $\frac{1}{10}$ velocity of light.

Let us consider a conducting wire element of cross-sectional area S_x and thickness *dx*. The amount of charge contain this wire element



$$dq = \rho \mathrm{S} dx$$

or $$\frac{dq}{dt} = \rho \mathrm{S} \frac{dx}{dt} = \rho \mathrm{S} \upsilon_d$$

$$\frac{i}{\mathrm{S}} = \vec{j} = \rho \upsilon_d \qquad [\text{Here, } \vec{j} = \text{current density}]$$

In vector form $\vec{j} = \rho \vec{\upsilon}_d$ …(ii)

In general $\vec{j} \uparrow\uparrow \tilde{o}_d$ if ρ is positive

$\vec{j} \uparrow\downarrow \tilde{o}_d$ if ρ is negative

or $i = \int \vec{j} \cdot d\vec{\mathrm{S}}$

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From equations (i) and (ii), we get

$$J = \sigma \vec{E}$$

Here, σ is a constant of a particular temperature for a medium and is known as the *conductivity of medium,* and

$\frac{1}{\sigma} = \rho$ is called the *resistivity of the medium* which is also a constant for a medium for a particular temperature.

Note: In the strict sense, $\vec{j}$ is the property of point (which is also obvious)

From equation (iii), $\frac{i}{S_x} = \frac{E}{\rho} = -\frac{dV}{\int dx}$

$$-dV = i\left(\frac{\int dx}{S_x}\right) = i dR$$

$$V_{higher} - V_{lower} = V = IR \qquad ...(iv)$$

Equation (iv) is not the Ohm's law but it is a general formula which also contain Ohm's law. It is valid even for pourly medium.

$$R = \int dR = \int \frac{\rho dx}{S_x} \qquad ...(v)$$

$$i = \sigma S_x \left(-\frac{dV}{dx}\right) \qquad ...(vi)$$

$$\frac{d\phi}{dt} = H = kS_x \left(-\frac{dT}{dr}\right) \qquad ...(vii)$$

Effect of Temperature on Resistance and Resistivity

The resistance and resistivity of all materials changes with temperature. In general:

(i) The resistance increases with the rise in temperature in case of metals (conductor).
(ii) The resisance decreases with temperature in case of insulator and semiconductor (e.g. carbon, silicon.)

Temperature Coefficient of Resistivity

If ρ_1 and ρ_2 are resistivities of a meterial at temperature t_1 and t_2 respectively, then

$$\rho_2 = \rho_1 (1 + \alpha_\rho \theta)$$

where, $\theta = t_2 - t_1$ is the temperature difference, and α_p is known as temperature coefficient of resistivity.

Temperature Coefficient of Resistance

If R_1 and R_2 are resistance of a materials at temperature t_1 and t_2 respectively, then

$$R_2 = R_1 (1 + \alpha_R \theta)$$

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where, $\theta = t_2 - t_1$ is the temperature difference, and α_R is known as *temperature coefficient of resistance.*

$$\alpha_R = \alpha_p - \alpha$$

where, α = coefficient of linear expansion

$\Rightarrow \quad \alpha_R = \alpha_p$ (as $\alpha << \alpha_p$)

Example

A certain electric conductor has a square cross-section 2.0 mm on a side and is 12 m long. The resistance between its ends is 0.072 Ω.

(i) What is the resistivity of the materials?

(ii) If the electric field magnitude in the conductor is 0.12 $\frac{V}{m}$, what is the total current?

(iii) If the material has 8×10^{28} free electron per cubic metre, find the average drift velocity under the condition of part (ii).

☞ **Solution**

(i) Here, $A = (2 \times 10^{-3})^2 = 4 \times 10^{-6}\ m^2$

$l = 12\ m$,

$R = 0.072\ \Omega$

$$R = \frac{\rho i}{A}$$

$$\therefore \quad \rho = \frac{RA}{l}$$

$$= \frac{0.072 \times 4 \times 10^{-6}}{12} = 2.4 \times 10^{-8}\ \Omega m$$

(ii) Electric field in the conductor

$$= \frac{V}{l} = 0.12$$

$\therefore \quad V = 0.12 \times 12 = 1.44$ volt

$$\therefore \quad i = \frac{V}{R} = \frac{1.44}{0.072} = 20\ A$$

(iii) Let drift velocity = υ_d

$n = 8 \times 10^{28}$ electron/m^3

Current, $i = enA\upsilon_d$

$$\therefore \quad \tilde{o}_d = \frac{i}{enA}$$

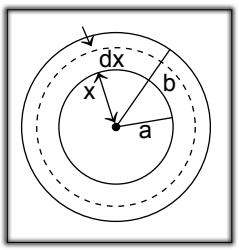
$$= \frac{20}{1.6 \times 10^{-19} \times 8 \times 10^{28} \times 4 \times 10^{-6}}$$

$$= \mathbf{3.9 \times 10^{-4}\ m/sec.}$$

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Example

A metal ball of radius a is surrounded by a thin concentric metal shell of radius *b*. The space between these electrodes is filled up with a pourly conducting homogeneous medium of resistivity ρ. Find the resistance of the inter electrode gap. Analyse the obtained solution at $b = \infty$.



☞ **Solution** Let a strip of length dx, then

$$dR = \rho\frac{dx}{A}$$

Here, $A = 4\pi x^2$

$$\therefore \quad dR = \frac{\rho dx}{4\pi x^2}$$

or $$R = \int dR = \int_a^b \frac{\rho dx}{4\pi x^2}$$

$$= \frac{\rho}{4\pi}\left[-\frac{1}{x}\right]_a^b = \frac{\rho}{4\pi}\left[\frac{1}{a} - \frac{1}{b}\right]$$

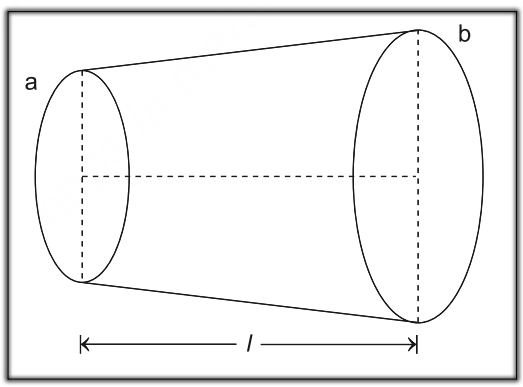
$$R = \frac{\rho}{4\pi}\frac{(b-a)}{ab}$$

If $b \to \infty$

$$R = \frac{\rho}{4\rho a}$$

Example

In the given figure, the resistivity is ρ and the radii are *a* and *b*. The length is *l*. Find the resistance of this figure.



☞ **Solution** Let at the distance x, the radius is r. Then,

$$r = a + \Delta r = a + \left(\frac{b-a}{l}\right)x$$

$$R = \int dR = \int \frac{\rho dx}{\pi r^2} = \int_0^l \frac{\rho dx}{\pi\left[a + \left(\frac{b-a}{l}\right)x\right]^2}$$

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Let, $a+\left(\frac{b-a}{l}\right)x = z \quad \therefore \quad \left(\frac{b-a}{l}\right)dx = dz$

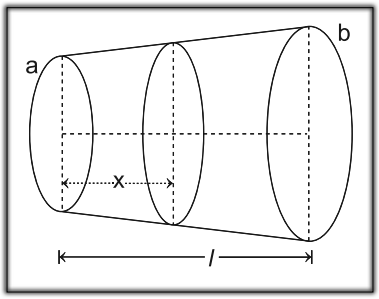
$z \to a$ to b

$$\therefore \quad \mathrm{R} = d\mathrm{R} = \int_a^b \frac{\rho l}{\pi(b-a)}\frac{dz}{z^2}$$

$$\therefore \quad \mathrm{R} = \int d\mathrm{R} = \frac{\rho l}{\pi(b-a)}\int_a^b \frac{dz}{z^2}$$

$$= \frac{\rho l}{\pi(b-a)}\left(\frac{1}{a}-\frac{1}{b}\right)$$

$$= \frac{\rho l}{\pi ab} \quad \therefore \quad \mathrm{R} = \frac{\rho l}{\pi ab}$$



Example

Two conductors of arbitrary shape are embedded into an infinite homogenous poorly conducting medium with resistivity ρ and permittivity ε. Find the value of product *RC* for this system, where *R* is the resistance of the medium between the conductors and *C* is the mutual capacitance of the wires in the presence of the medium.

☞ **Solution** Let us mentally import charge $+q$ and $-q$ to the conductor. As the medium is poorly conducting, the surface of conductors are equipotential and the field configuration is same as in the absence of the medium.

Let us surround, for example, the positively charged conductor by a closed surface *s*, just containing the conductor.

Then, $\mathrm{R} = \frac{\mathrm{V}}{\mathrm{I}} = \frac{\mathrm{V}}{\int \vec{j}\cdot d\vec{s}} = \frac{\mathrm{V}}{\int \sigma \mathrm{E}_n ds}$, as $\vec{j} \uparrow\uparrow \vec{\mathrm{E}}$

and, $\mathrm{C} = \frac{q}{v} = \frac{\varepsilon\varepsilon_0 \int \mathrm{E}_n ds}{\mathrm{V}}$

$\therefore \quad RC = \frac{\varepsilon\varepsilon_0}{\rho} = \rho\varepsilon\varepsilon_0. \quad \left(\because \rho = \frac{1}{\sigma}\right)$

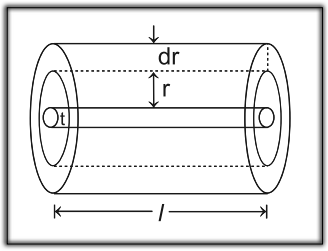
Example

A homogenous poorly conducting medium of resistivity ρ fill up the space between two thin coaxial ideally conductivity cylinders are equal to *a* and *b* with *a* < *b*. The length of each cylinder is *l*. Neglecting the edge effects, find the resistance of the medium between the cylinders.

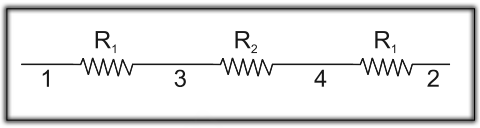
☞ **Solution** $d\mathrm{R} = \rho\frac{dr}{s(r)} = \rho\frac{dr}{2\pi rl}$

$$\therefore \quad \mathrm{R} = \int d\mathrm{R} = \int_a^b \frac{\rho dr}{2\pi rl} = \frac{\rho}{2\pi l}\ln\frac{b}{a}$$

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Series grouping of resistance



$$R_{equi} = \frac{V_1 - V_2}{I} \quad \text{...(i)}$$

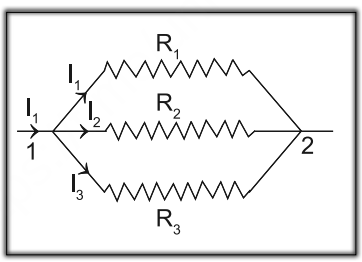
$$V_1 - V_2 = V_1 - V_3 + V_3 - V_4 + V_4 - V_2$$
$$= IR_1 + IR_2 + IR_3$$
$$= I(R_1 + R_2 + R_3)$$

$$\frac{V_1 - V_2}{I} = R_1 + R_2 + R_3 \quad \text{...(ii)}$$

From equations (i) and (ii), we get

$$R_{equi} = R_0 = R_1 + R_2 + R_3$$

Parallel grouping of resistance:



$$R_0 = \frac{V_1 - V_2}{I} \quad \text{...(i)}$$

$$I = I_1 + I_2 + I_3$$
$$= \frac{V_1 - V_2}{R_1} + \frac{V_1 - V_2}{R_2} + \frac{V_1 - V_2}{R_3} \quad \text{...(ii)}$$

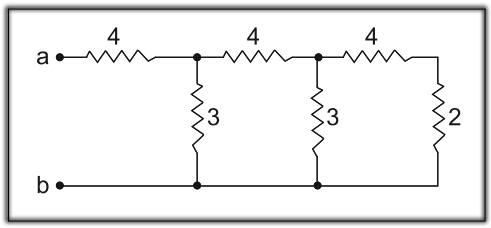
Compare equation (i) with the equation (ii), we get

$$\frac{1}{R_0} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

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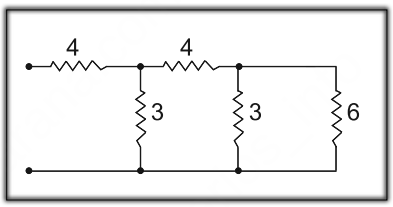
Example

Find the equivalent resistance between the points *a* and *b* of the network shown in the figure.

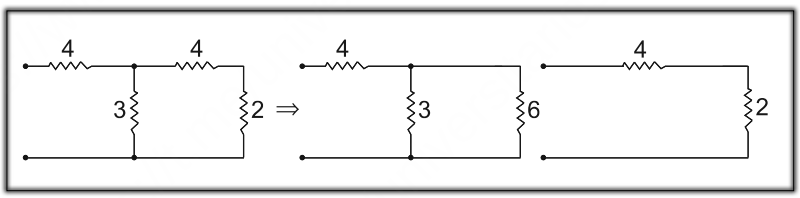


☞ **Solution** Since 2 Ω and 4 Ω resistances are series, therefore

$R_1 = (2 + 4)\ \Omega = 6\ \Omega$



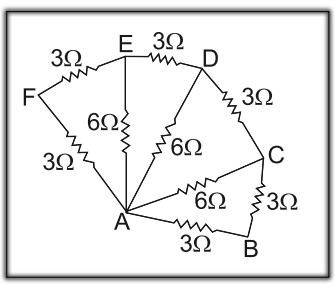
Since 3 Ω and 6 Ω are in parallel, therefore $R_2 = \frac{3 \times 6}{9} = 2\Omega$



Hence, equivalent resistance = **6** Ω

Example

Find the effective resistance between the points *A* and *B* in the figure given below.



☞ **Solution** In left side, 3 Ω and 3 Ω are the series

$$R_{AE} = \frac{6 \times 6}{6 + 6} = 3\Omega \qquad R_{AD} = \frac{6 \times 6}{6 + 6} = 3\Omega$$

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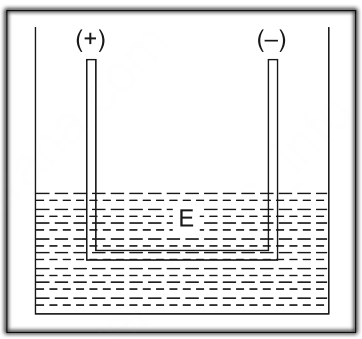
Similarly, $R_{AC} = \frac{6 \times 6}{6+6} = 3\Omega$

$$R_0 = \frac{6 \times 6}{6+3} = 2\Omega$$

3.3 SEAT OF ELECTOMAGNETIC FIELD

A device (or a arrangement) by which electric energy can be abored at expense of some other form of energy. A familiar example is simple cell.

If the small charge *dq* is transferred from the positive to negative terminal no matter in which way, there is a loss of electrical energy because in our case



$dW_{field} = dq\,(V_+ - V_-)$

$= dq \times V$ = positive

According to our requirement, we can utilize this electrical energy in some other form. For example, operating a motor.

For simplicity, if we connect a resistance (R) between the cell, then seat electromagnetic field

$dW = dqV = (idt)iR = i^2\,R dt = dH$

$H = \int i^2\,R dt = \int P dt$

$P = i^2R = \frac{V^2}{R} = Vi$

$P = i^2R = j^2S^2\left(\rho\frac{dx}{S}\right) = j^2S\rho dx$

$P = \rho j^2\,dv$

Power density, $P = \rho j^2$

Example

An electric tea kettle has two heating coils. When one of coil is switched on, the kettle begins to boil in 6 minutes and when the other is switched on the kettle begins to boil in 8 minutes. In what time will the boiling begin if both the coils are switched simultaneously?

(i) In series
(ii) Parallel

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☞ **Solution** Heat required to begin boiling is same for every case. Let this be H.
Let R_1 and R_2 be the resistances of the coils and V be the supply voltage.

$t_1 = 6$ min. and $t_2 = 8$ min.

Let t_s is the time when they are series and t_p is the time when they are in parallel.

H = power × time

$$H = \frac{V^2}{R_1}t_1 = \frac{V^2}{R_1}t_2 = \frac{V^2}{R_1 + R_2}t_8 = \frac{V^2(R_1 + R_2)}{R_1R_2}t_p$$

$$\Rightarrow \quad R_1 = \frac{V^2 t_1}{H} \text{ and } R_2 = \frac{V^2 t_2}{H}$$

Substituting, we get $H = \frac{V^2 t_8}{R_1 + R_2} = \frac{V^2 t_8}{V^2(t_1 + t_2)}$

$$\Rightarrow \quad t_8 = t_1 + t_2 = \mathbf{14 \text{ minutes}}$$

Substituting in H, we get

$$H = \frac{V^2}{R_1R_2}(R_1 + R_2)t_p$$

$$\Rightarrow \quad H = V^2 t_p\left(\frac{H}{V^2 t_1} + \frac{H}{V^2 t_2}\right)$$

$$\Rightarrow \quad t_p = \frac{t_1t_2}{t_1 + t_2} = \frac{6 \times 8}{6 + 8} = \frac{\mathbf{24}}{\mathbf{7}} \textbf{minutes.}$$

Example

A fuse made of lead wire has area of cross-sectional 0.2 mm^2. On short circuit, the current in the fuse reaches 30 *A*. How long after short circuit will the fuse begin to melt? Density = 11.34 g/cc, specific heat of lead = 0.032 cal/g/ºC, melting point 327ºC, resistivity = 22 × 10^{-6} Ω cm, initial temperature 20º.2.

☞ **Solution** The fuse begins to melt when temperature rises to 327ºC from 20ºC.

Heat required = $ms\theta = (Ald)\, s\theta$

where, l = length of wire

If t is the time, then total dissipation

$$= \frac{i^2Rt}{4.18} \text{ cal/sec}$$

$$\Rightarrow \quad (Ald)\, s\theta = \frac{i^2Rt}{4.18} = \frac{i^2\rho lt}{4.18A}$$

$$\Rightarrow \quad t = \frac{4.18A^2 ds\theta}{i^2\rho}$$

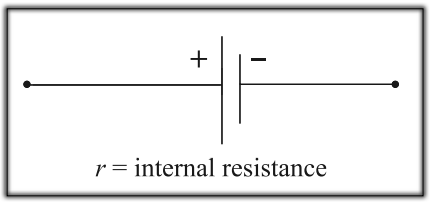
$$= \frac{4.18 \times (0.2 \times 10^{-2})^2 \times 11.34 \times 0.032(327 - 20)}{30 \times 30 \times 22 \times 10^{-6}}$$

$$= \mathbf{0.0945}$$

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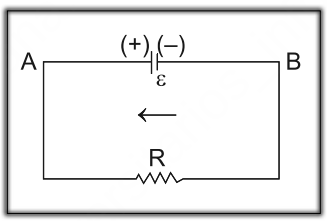
3.4 ELECTROMAGNETIC FIELD OF THE CELL

It is define as the workdone by the mechanism operating within the cell by unit positive charge to bring it from the negative to positive terminal of cell against the electric field set up inside it. The electro-magnetic field of the cell is denoted by ε.



Cell on Discharge

From energy conservation



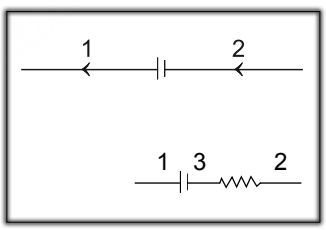
$$(idt)\ \varepsilon = i^2 R dt + i^2 r dt$$

$$\varepsilon = RI + r\,I$$

$$IR = \varepsilon - r\,I$$

$$V_A - V_B = \varepsilon - r\,I$$

or $$V = \varepsilon - r\,I$$



$$i \uparrow\uparrow \varepsilon$$

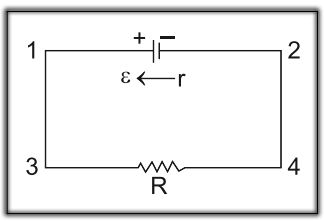
$$V_1 - V_2 = \varepsilon + (-Ir)$$

or $$V = \varepsilon - Ir$$

$$\varepsilon - ri - Ri = 0 \qquad \text{...(i)}$$

or $$-\nabla V = 0$$

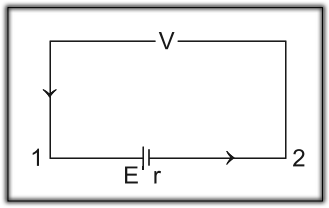
$$\int E dr = 0$$



This is nothing but energy conservation.

Hence from equation (i) $I = \dfrac{\varepsilon}{r+R} = \dfrac{net\ \text{EMF}}{R_0}$

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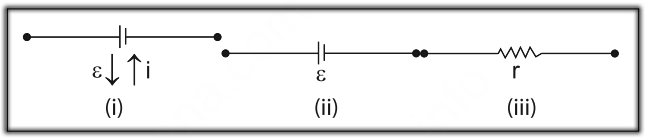
Cell on charge

From energy conservation

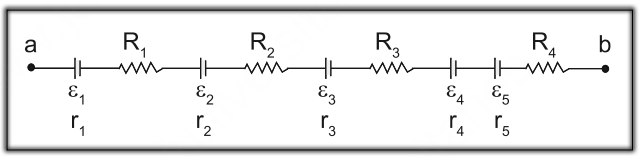
$$(idt)V = (idt)\,\varepsilon + ri^2dt$$

$$V = \varepsilon + ri$$

$$V_1 - V_2 = \varepsilon + ri$$



Example



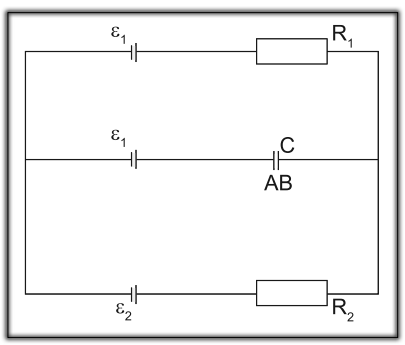
Find the potential difference of given figure between *a* and *b*.

☞ **Solution** $V_a - V_b = IR_1 + \varepsilon_1 + r_1I - \varepsilon_2 + IR_2 + Ir_2 - \varepsilon_3 + IR_3 + Ir_3 - \varepsilon_4 + IR_4 + r_4I + \varepsilon_5$

$= \varepsilon_1 + \varepsilon_5 - (\varepsilon_2 + \varepsilon_3 + \varepsilon_4) + I\,(r_1 + r_2 + r_3 + r_4 + r_5) + I\,(R_1 + R_2 + R_3 + R_4)$

Example

In the circuit shown in the figure, the source have emf's $\varepsilon_1 = 1.0\ V$ and $\varepsilon_2 = 2.5\ V$ and the resistance have the values $R_1 = 10\ \Omega$ and $R_2 = 20\ \Omega$. The internal resistance of the sources are negligible. Find a potential difference $V_A - V_B$ between the points *A* and *B* of the capacitor *C*.



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☞ **Solution** No current passes through the capacitor

$$I = \frac{\varepsilon_2 - \varepsilon_1}{R_1 + R_2}$$

$$V_A - V_B = \varepsilon_1 + \frac{(\varepsilon_2 - \varepsilon_1)R_2}{R_1 + R_2} - \varepsilon_2$$

$$= \varepsilon_1 R_1 + \varepsilon_1 R_2 + \varepsilon_2 R_2 - \varepsilon_1 R_2 - \varepsilon_2 R_1 - \varepsilon_2 R_2$$

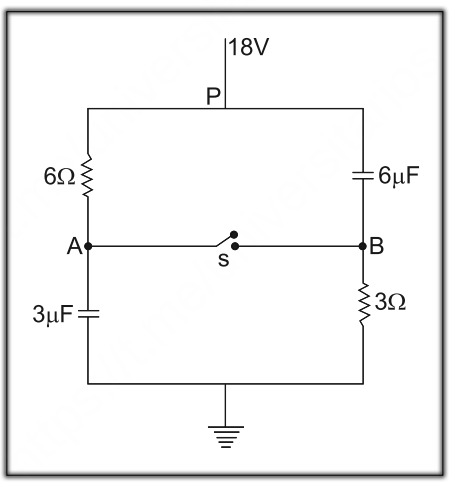
$$= \frac{(\varepsilon_1 - \varepsilon_2)R_1}{R_1 + R_2} = \mathbf{-0.5\ V.}$$

Example

Find

(i) $V_A - V_B$ **when switch S is open.**
(ii) **the flow of charge through the switch after closed it.**
(iii) **the change of charge on each capacitor.**

☞ **Solution**



(i) When switch is open

$$V_A - V_B = 18V$$

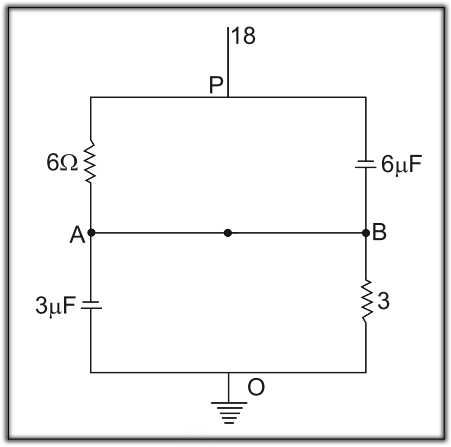
$$\frac{q}{C} = 18V$$

(ii) $q_1 = 18 \times 3\mu F$

$= 54\mu C$

(iii) When the switch is closed $I = \frac{18}{6+3} = 2\,A$

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Potential difference between 2μF is

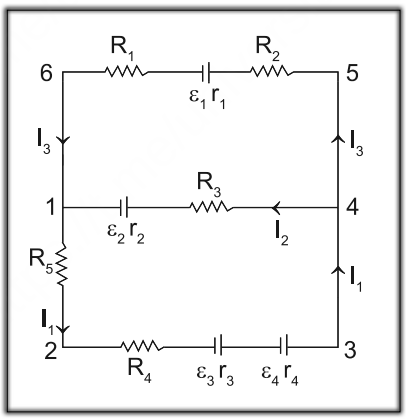
$$q'_1 - q_1 = q'_2 - q_2 = \mathbf{36\ C}$$

Junction Point

It is the point of a network where atleast three conducting paths meet.

Point Rule

The algebraic sum of the current meeting at a junction point is equal to zero. That is,



From $\Sigma I = 0$

At the junction 1 or 4,

$$I_2 + I_3 - I_1 = 0$$

In figure 1 and 4 are junction points.

The point rule is nothing but the conservative of charge. According to which the net charge reaching per second at any junction point 1 and 4 is equal to the net charge leaving per second.

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Loop Rule (Kirchhoff's Second Law)

In a loop at the network $\Sigma\varepsilon = \Sigma IR$

To apply this rule take clockwise or interclockwise sense as positive

In the loop 12341

$$\varepsilon_3 + \varepsilon_4 - \varepsilon_2 = I_1(R_5 + R_4 + r_4 + r_3) + I_2(R_3 + r_2) + \varepsilon_3 + \varepsilon_4 - \varepsilon_2 - I_1 (R_5 + R_4 + r_4 + r_3)$$
$$- I_2(R_3 + r_2) - (\varepsilon_3 + \varepsilon_4 - \varepsilon_2) + I_1 (R_5 + R_4 + r_4 + r_3) + I_2 (R_3 + r_2)$$

Some Important Points

(i) Before applying the point rule at a junction point, indicate the different currents meeting at the junction point. But one should not indicate all the currents leaving and reaching junction point. If there are *n*-junction points in our network, apply point rule at $(n - 1)$ of these junction point.

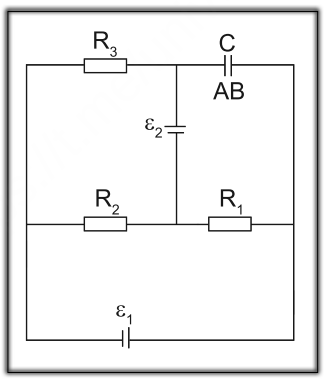
(ii) Before applying the loop rule, one should never consider such a loop which can be obtained by the super-position of the loop consider before.

(iii) For the application of loop rule, one should never consider such a loop which can be obtained by the super-position of the loop consider before.

(iv) Be sure that the number of equations obtain by charge of energy conservation are not less than the unknown involves in the problem. Hence, a problem of multiloop.

Example

Find the potential difference $V_A - V_B$ between the plates of a capacitor C in the circuit shown in the figure, if the sources have emf's $\varepsilon = 4.0\ V$ and $\varepsilon = 1.0\ V$ and the resistances are equal to $R_1 = 10\ \Omega$, $R_2 = 20\ \Omega$ and $R_3 = 30\ \Omega$. The internal resistance of the sources are negligible.



☞ **Solution**

$$I_1 = I_2 + I_3 \qquad ...(i)$$

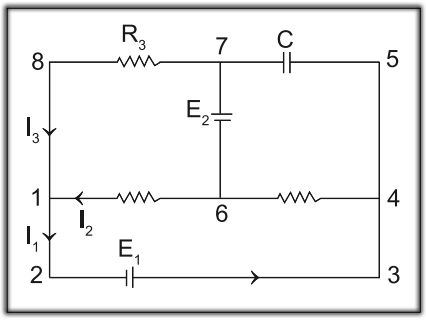
Applying the loop rule in 123461

$$\varepsilon_1 = I_1R_1 + R_2I_2 \qquad ...(ii)$$

In the loop 16781

$$\varepsilon_2 = I_3 R_3 - I_2 R_2 \qquad ...(iii)$$
$$\varepsilon_1 = R_1(I_2 + I_3) + R_2 I_2$$
$$\varepsilon_1 = (R_1 + R_2) I_2 + R_1 I_3 \qquad ...(iv)$$

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From equations (iii) and (iv), we get

$R_1 \varepsilon_2 - R_3 \varepsilon_1 = -[I_2 (R_2 R_1 + R_1 R_3 + R_2 R_3)]$

or $I_2 = \dfrac{\varepsilon_1 R_3 - R_1 \varepsilon_2}{R_1 R_2 + R_2 R_3 + R_1 R_3}$ ...(v)

From equation (ii) $\varepsilon_1 = I_1 R_1 + R_2 \cdot \left[\dfrac{\varepsilon R_3 - R_1 \varepsilon_2}{R_1 R_2 + R_2 R_3 + R_3 R_1}\right]$

or $\varepsilon_1 - R_2 \left[\dfrac{\varepsilon_1 R_3 - R_1 \varepsilon_2}{R_1 R_2 + R_2 R_3 + R_3 R_1}\right] = I_1 R_1$

$V_A - V_B = \varepsilon_2 - I_1 R_2$

$V_A - V_B = \varepsilon_2 - \left[\dfrac{\varepsilon_1 - R_2 (\varepsilon_1 R_3 - R_1 \varepsilon_2)}{R_1 R_2 + R_2 R_3 + R_3 R_1}\right]$

$= \mathbf{-1.0\ V}$

Example

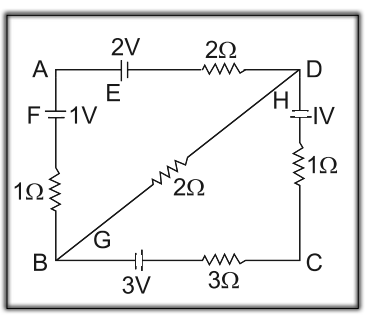
In the circuit shown in the figure, E, F, G, and H are cells of emft's 2, 1, 3 and 1*V* respectively. The 2, 1, 3 and 1 Ω are their respective internal resistances. Calculate:

(i) **the potential difference between B and D.**

(ii) **the potential differences across the terminals of each of the cells G and H.**

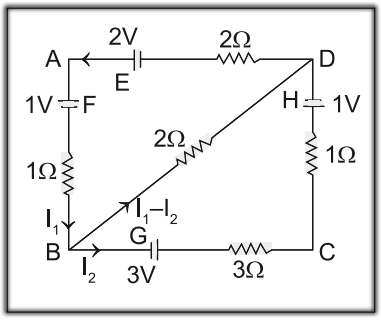
☞ **Solution** Arrow the current of the circuit.

Applying Kirchhoff's Law.



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Loop ABDA:



$$I_1 + 2(I_1 - I_2) + 2I_1 = (2 - 1)V$$

or $$5I_1 - 2I_2 = 1V \quad \text{...(i)}$$

Loop BCDB:

$$3I_2 + I_2 - 2(I_1 - I_2) = 2v$$

or $$-2I_1 + 6I_2 = 2\ V \quad \text{...(ii)}$$

From equation (i) and (ii)

$$I_1 = \frac{5}{13}A \text{ and } I_2 = \frac{6}{13}A$$

$$\therefore \quad I_1 - I_2 = \frac{-1}{13}A$$

(i) $$V_A - V_B = (2\Omega)\left(\frac{1}{13}\right) = \mathbf{\frac{2}{13}V}$$

(ii) The potential difference across the cell G is

$$V_C - V_D = -(3\Omega)\, i_2 + 3\ V$$

$$= \left(3V - \frac{18}{13}\right)V = \mathbf{\frac{21}{13}\ V}$$

The potential difference across the cell H is

$$V_C - V_B = (1\ \Omega)\, i_2 + 1\ V$$

$$= \mathbf{\frac{19}{13}\ V}$$

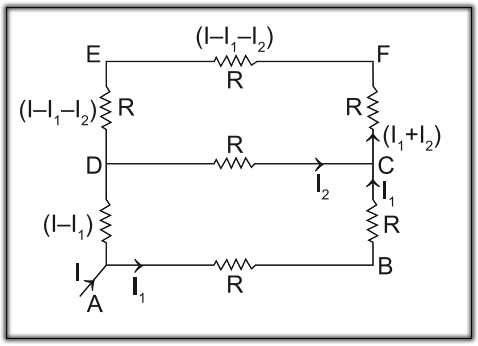
Equivalent Resistor or Mixed or Complex in Network

In the network the loop ABCDA:

$$2I_1R - RI_2 - (I - I_1)R = 0$$

or $$-I + 3I_1 - I_2 = 0 \quad \text{...(i)}$$

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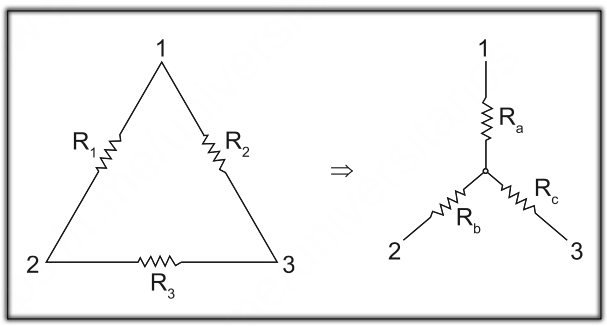
In the loop DCFED:

$$I_2R + (I_1 + I_2)\,R - 2R\,(I - I_1 - I_2) = 0 \qquad \text{...(ii)}$$

$$R_{equi} = R_0$$

$$= \frac{V_A - V_B}{I}$$

3.5 DELTA STAR TRANSFORMATION



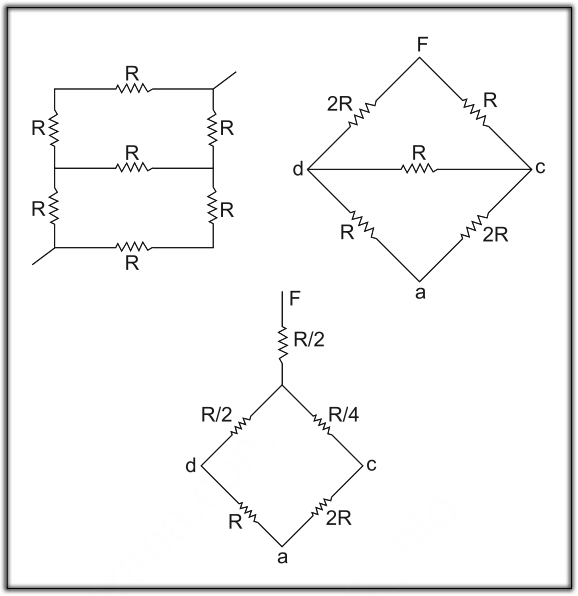
$$1^R2 = \frac{(R_2 + R_3)R_1}{R_1 + R_2 + R_3} = R_a + R_b \qquad \ldots(i)$$

$$2^R3 = \frac{(R_1 + R_2)R_3}{R_1 + R_2 + R_3} = R_b + R_c \qquad \ldots(ii)$$

$$1^R3 = \frac{(R_1 + R_3)R_2}{R_1 + R_2 + R_3} = R_a + R_c \qquad \ldots(iii)$$

Calculate the values of R_a, R_b and R_c from equations (i), (ii) and (iii). Similarly, calculate, R_1, R_2 and R_3. For example,

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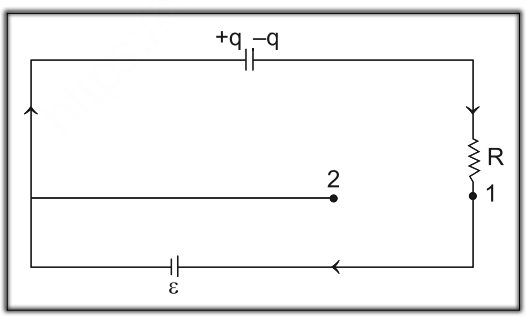
3.6 R.C. CIRCUIT

Charging of a capacitor

At $t = 0, q = 0$ $-\varepsilon + \frac{q}{C} + iR = 0$

$$-\varepsilon + \frac{q}{C} + \frac{dq}{dt}R = 0$$

$$\Rightarrow \quad \int_{q=0}^{q} \frac{dq}{C\varepsilon - q} = -\frac{1}{RC}\int_{0}^{t} dt$$



$$\ln\frac{C\varepsilon - q}{C\varepsilon} = -\frac{t}{RC}$$

$$C\varepsilon - q = C\varepsilon\, e^{-\frac{t}{RC}}$$

$$\Rightarrow \quad q = C\varepsilon\left(1 - e^{-\frac{t}{RC}}\right) \qquad \text{...(i)}$$

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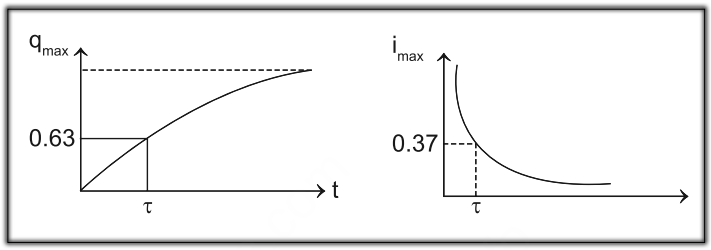
At $t = \infty$

$q = q_{max} = C\,\varepsilon$

Hence equation (i) becomes

$$q = q_{max}\left(1 - e^{-\frac{t}{RC}}\right)$$

where, $\tau = RC$ = Time constant,



Differentiating with respect to time of equation (i), we get

$$i = \frac{\varepsilon}{R} e^{-\frac{t}{RC}} \quad \ldots(ii)$$

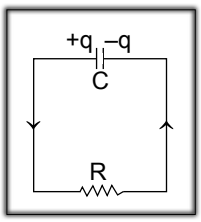
At $t = 0$

$$i = i_{max} = \frac{\varepsilon}{R}$$

Here, $i = i_{max} e^{\frac{-t}{\tau}}$

Discharging of Capacitor

After charging, the switch is the connected to point 2.



At $t = 0$, $q = q_{max}$ $iR - \frac{q}{C} = 0$

or $R\frac{dq}{dt} = \frac{q}{C}$

Integrating, $\int_{q_{max}}^{q} \frac{dq}{q} = -\frac{1}{RC}\int_{0}^{t} dt$

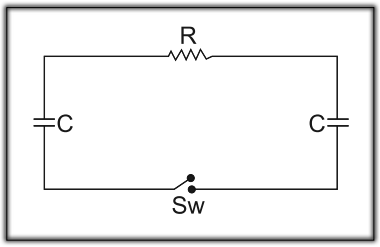
or $\ln\frac{q}{q_{max}} = -\frac{t}{RC}$

$\therefore \quad q = q_{max} e^{-\frac{t}{\tau}}$

Example

In a circuit shown in the figure the capacitance of each capacitor is equal to *C* and the resistance *R*. One of the capacitors connected to a voltage V_0 and then at the moment $t = 0$ was shorted by means of the switch Sw. Calculate

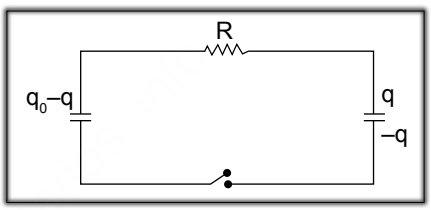
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(i) **a current I in the circuit as function of time *t*.**
(ii) **the amount of generated heat provided a dependence *I* (*t*) is known.**

☞ **Solution**

(i) At $t = 0$, the switch is open to 2



$$\frac{-d(q-q_0)}{dt} = \frac{dq}{dt} = i$$

$$\Rightarrow \quad \frac{q}{C} - \frac{q_0 - q}{C} + iR = 0$$

$$\Rightarrow \quad \frac{2q}{C} - \frac{q_0}{C} + \frac{dq}{dt}R = 0$$

$$\Rightarrow \quad \frac{dq}{dt}R = \frac{q_0 - 2q}{C}$$

$$\Rightarrow \quad \int \frac{dq}{q_0 - 2q} = \frac{1}{RC}\int dt \qquad \Rightarrow \quad \frac{1}{2}\ln\frac{q_0 - 2q}{q_0} = -\frac{t}{RC}$$

$$\Rightarrow \quad \ln\frac{q_0 - 2q}{q_0} = -\frac{2t}{RC} \qquad \Rightarrow \quad \frac{q_0 - 2q}{q_0} = e^{-\frac{2t}{RC}}$$

$$\Rightarrow \quad q_0 - 2q = q_0 e^{-\frac{2t}{RC}} \qquad \therefore \quad q = \frac{1}{2}q_0\left(1 - e^{-\frac{2t}{RC}}\right)$$

$$i = \frac{dq}{dt} = \frac{1}{2}\cdot q_0 \frac{2}{RC}e^{-\frac{2t}{RC}} = CV_0 \cdot \frac{2}{RC}e^{-\frac{2t}{RC}} = \frac{\mathbf{V_0}}{\mathbf{R}}\boldsymbol{e}^{-\frac{\mathbf{2t}}{\mathbf{RC}}}$$

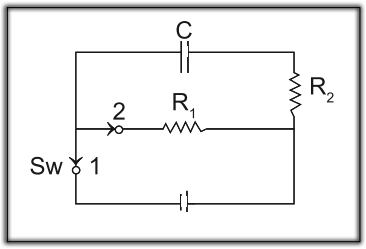
(ii) Heat, $H = \int i^2 dt$

$$= \int_0^t \left(\frac{V_0}{R}e^{-\frac{2t}{RC}}\right)^2 R\,dt = \int \frac{V_0^2}{R^2}e^{-\frac{4t}{RC}}R\,dt = \frac{V_0^2}{R}\left[\frac{e^{-\frac{4t}{RC}}}{\frac{4}{RC}}\right] = \frac{\mathbf{1}}{\mathbf{4}}\mathbf{CV_0^2}$$

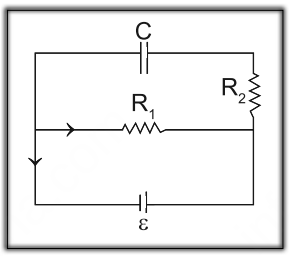
Example

A capacitor of capacitance $C = 5.0\ \mu F$ is connected to a source of constant emf = 200 V as shown in the figure. Then, the switch Sw was thrown over from contact 1 to contact 2. Find the amount of heat generated in resistance R_1 if $R_2 = 330\Omega$.

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☞ **Solution** *When connected to 1,*



Energy stored in capacitor $= \frac{1}{2} C \varepsilon^2$

When connected to 2

The energy stored is distributed of heat proportional to R_1 and R_2.

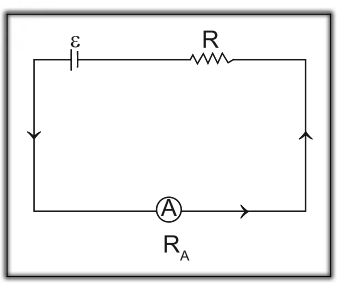
Heat liberated in $R_1 = \frac{1}{2} C \varepsilon^2 \frac{R_1}{R_1 + R_2} = \mathbf{60\ mJ.}$

3.7 ELECTRICAL INSTRUMENTS

Ammeter: Ammeter is connected in series in a circuit.

In the absence of ammeter

$$i_0 = \frac{\varepsilon}{R} \qquad \ldots(i)$$



In presence of ammeter

$$i = \frac{\varepsilon}{R + R_A} \qquad \ldots(ii)$$

For $i \approx i_0$

$R_A << R$

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Shunt:

From figure $i_s = \dfrac{iR_g}{R_g + R_s}$

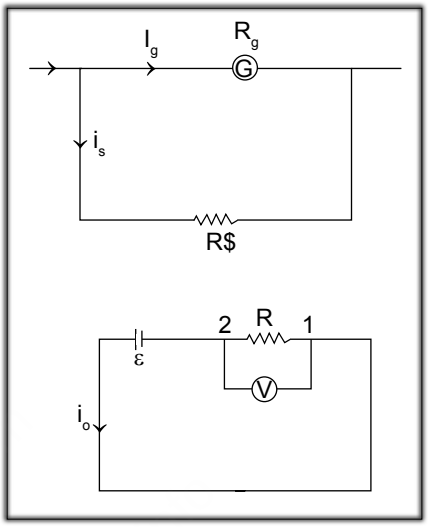
$$i_g = \frac{iR_s}{R_g + R_s}$$

$$\frac{i_s}{i_g} = \frac{R_g}{R_s}$$

$$\Rightarrow \quad \frac{i_s}{i_g} + 1 = \frac{R_g}{R_s} + 1$$

$$\Rightarrow \quad \frac{i}{i_g} = n = \frac{R_g + R_s}{R_s}$$

$$\therefore \quad R_s = \frac{R_g}{n-1}$$



When the shunt is connected in galvanometer, maximum current passes through the shunt, because shunt resistance is small. Thus, save the galvanometer for large current measurement.

Voltmeter: In the absence of voltmeter

$$i = \frac{\varepsilon}{R}$$

In the presence of voltmeter

$$i = \frac{\varepsilon}{\dfrac{RR_V}{R + R_V}}$$

$\therefore \quad V_1 - V_2 = i\,R$ at $iR \simeq i_o\,R$, so $i \simeq i_0$

$$\therefore \quad \frac{RR_V}{R + R_V} \simeq R$$

or $$\frac{R}{\dfrac{R}{R_V} + 1} = R$$

Since R_V is very large, therefore

$$\frac{R}{R_V} = 0$$

or $\quad R_V = \infty$

Hence voltmeters are connected parallel in the circuit.

Example

A battery of emf 1.4 *V* and internal resistance 2 Ω is connected to a resistor of 100 Ω resistance. In order to measure the current through the resistance and the potential difference across its ends, an ammeter is connected in series with it and a voltmeter is connected across its ends. The resistance of ammeter

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is 4/3 Ω and that of voltmeter is 200 Ω. What are the readings of the two instruments? What would be their reading if they were ideal instrument?

☞ **Solution** $i = \dfrac{\varepsilon}{r + R_A + \dfrac{RR_V}{R + R_V}}$

$$= \frac{1.4}{\dfrac{100 \times 200}{100 + 200} + \dfrac{4}{3} + 2}$$

$$= 0.02 \text{ A}$$

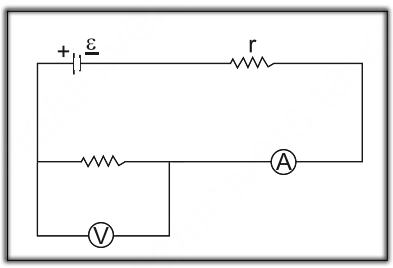
Hence the current through the ammeter is 0.02 A.

Reading of voltmeter = P·*d* across its terminals

$$= i\frac{RR_V}{R + R_V}$$

$$= 0.02\left(\frac{100 \times 200}{100 + 200}\right)$$

$$= \frac{4}{3}\text{volts}$$



If the ammeter and voltmeter would have been ideal, then

$R_A = 0$ and $R_V = \infty$

The reading of ammeter $= \dfrac{\varepsilon}{r + R} = \dfrac{1.4}{100 + 2} = \dfrac{\mathbf{1.4}}{\mathbf{102}}$ **A**

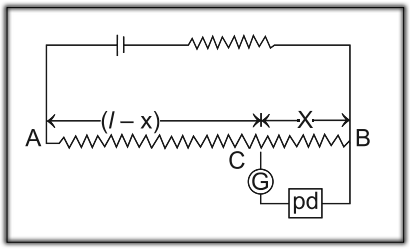
The reading of voltmeter = IR

$$= \frac{1.4}{102} \times 100 = \mathbf{1.37\ V.}$$

Potentiometer

We already know that, when a voltmeter is used to measure potential difference, its finite resistance causes it to draw a current from the circuit. Hence, the potential difference which is to be measured is changed due to the presence of the instrument itself. Potentiometer is an instrument which allows the measurement of potential difference without drawing current from the circuit being measured. Hence, it acts as an infinte resistance voltmeter.

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The resistance between A and B is of uniform wire of length l, with a sliding contact C at a distance x from B. The potential difference V is measured by a sliding contact until the galvanometer G reads zero. The no deflection condition of galvanometer ensures that there is no current through the branch containing G and potential difference is to be measured. The length x for no deflection is called as the *balancing length.*

V_{CB} = V P·d to be measured.

If λ is the resistance per unit length of AB, then

$$V = V_{CB} = \frac{R_{CB} V_{AB}}{R_{AB}} = \frac{\lambda x}{\lambda l} V_{AB}$$

$$V = \left(\frac{V_{AB}}{l} \right) x$$

$\therefore$ Potential to be measured = (potential gradient in wire AB) × (balancing length)

Example

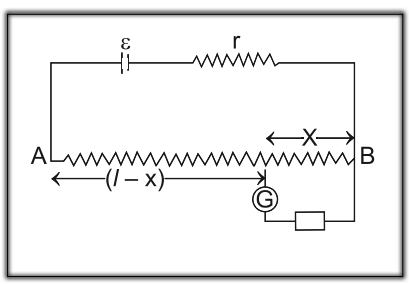
A battery of emf 4*V* is connected across a 10 m long potentiometer wire having a resistance per unit length 1.6 Ω m^{-1}. A cell of emf 2.4 *V* is connected so that its negative terminal is connected to the low potential end of potentiometer wire and the other end is connected through a galvanometer to a sliding contact along the wire. It is found that the no-deflection point occurs against the balancing length of 8 m. Calculate the internal resistance of the 4 *V* battery.

☞ **Solution** The *emf* of the cell is the potential difference to be measured.

emf of cell = (potential gradient) x

or $$2.4 = \frac{V_{AB}}{l} x = \frac{V_{AB}}{10} \times 8$$

$\therefore$ V_{AB} = 3 Volt



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But $V_{AB} = \frac{E}{r + R_{AB}} R_{AB}$

or $3 = \left(\frac{4}{r + 1.6 \times 10} \right) \times (1.6 \times 10)$

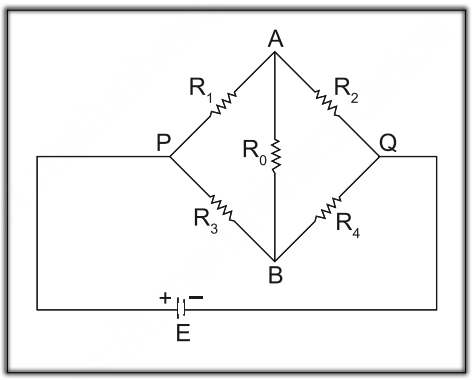
$\therefore \quad r = \frac{16}{3} \Omega.$

Note that as there is no deflection in the galvanometer, so that battery E, internal resistance *r* and potential wire AB are is series.

Wheatstone Bridge Network

The circuit shown in figure is called as *Wheatstone bridge network.* It can be shown by solving the circuit that the current through the resistance R_0 becomes zero if the following condition are satisfied:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$



In that condition, A and B are at the same potential and, hence a galvanometer connected in series with R_0 will not show any deflection. If the above condition is satisfied, the network is called a *balance network.*

Metre Bridge

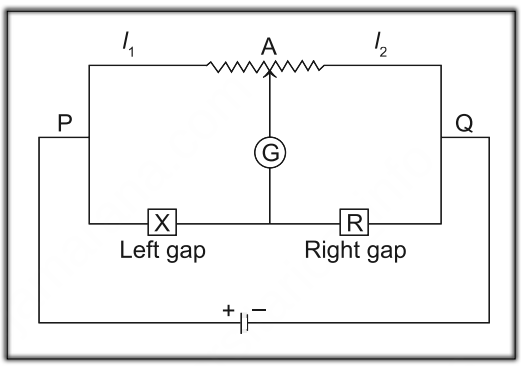
The Wheatstone network is used to determine unknown resistances. The metre bridge is an instrument based on the balancing condition of the wheatstone network. The resistances R_1 and R_2 are two parts of a long wire (usually 1 m long) PQ. The portion PA of the wire offers resistance R_1 and the portion QA offers resistance R_2. The sliding contact at A is adjusted so that galvanometer reads zero. In the no deflection condition,

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$$\frac{R_1}{R_2} = \frac{X}{R}$$

$$\Rightarrow \quad X = R\left(\frac{R_1}{R_2}\right)$$

$$\Rightarrow \quad X = R\left(\frac{l_1}{l_2}\right)$$

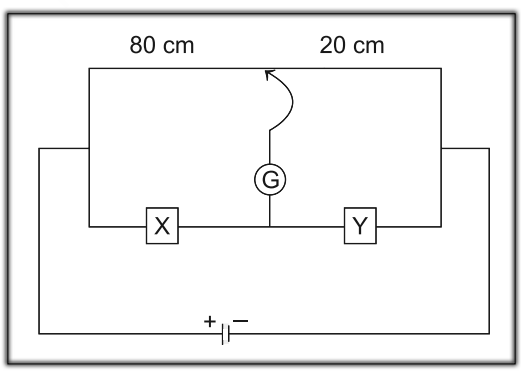


If R is a known resistance, then X can be measured by measuring the lengths l_1 and l_2.

Example

Two unknown resistances *X* and *Y* are placed in the left and right gaps of a metre bridge. The null point in galvanometer is obtained at a distance of 80 cm from left. A resistance of 100 Ω is now connected in parallel across *X*. The null point is then found by shifting sliding contact towards left by 20 cm. Calculate *X* and *Y*.

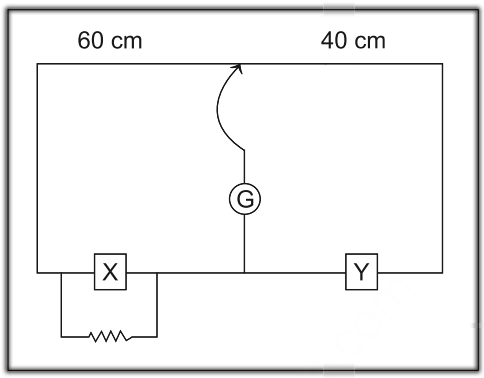
☞ **Solution**



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From first null point

$$\frac{X}{Y}=\frac{80}{20}$$



...(i)

From second null point

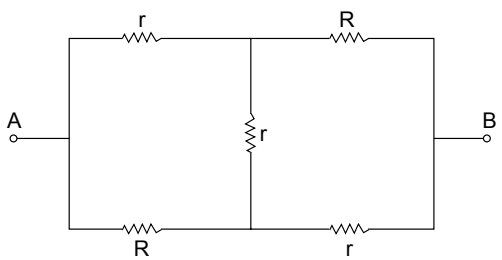
$$\frac{\left(\frac{100X}{100+X}\right)}{Y}=\frac{60}{40} \qquad \ldots(ii)$$

From equations (i) and (ii), we have

$$X=\frac{500}{3}\ \Omega \text{ and } Y=\frac{125}{3}\Omega$$

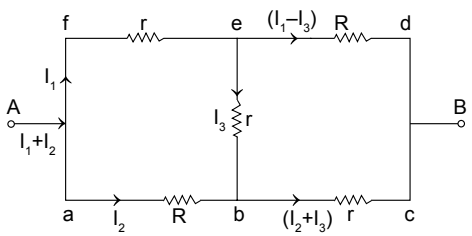
WORKED OUT EXAMPLES

1. Find the equivalent resistance between points *A* and *B* of the circuit shown in the figure.



☞ **Solution** From the figure the current distribution of each branch is as shown below.

Applying Kirchhoff's Law in *the loop abef and bcde:*



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$$I_2R - I_3r - I_1r = 0$$

or $$rI_1 - RI_2 + rI_3 = 0 \quad ...(i)$$

or $$(I_2 + I_3)\, r - (I_1 - I_3)\, R + I_3r = 0$$

or $$-RI_1 + I_2r + (2r + R)\, I_3 = 0 \quad ...(ii)$$

Then, the equivalent resistance

$$R_0 = \frac{V_A - V_B}{I_1 + I_2}$$

$$= \frac{rI_1 + (I_1 - I_3)R}{I_1 + I_2} \quad ...(iii)$$

From equations (i) and (ii), we have

$$rI_1 - RI_2 = -rI_3 \quad ...(iv)$$

$$-RI_1 + rI_2 = -(2r + R)\, I_3 \quad ...(v)$$

Multiplying equation (iv) by R, equation (v) by r and adding, we get

$$-R^2 I_2 + r^2 I_2 = (-rRI_3 - 2r^2 - rR)\, I_3$$

or $$I_2 = \frac{2r^2 + 2rR}{R^2 - r^2} I_3$$

$$= \frac{2r(r + R)}{(R + r)(R - r)} I_3 = \frac{2r}{R - r} I_3$$

From equation (v), we get

$$rI_1 - R\frac{2r}{R - r} I_3 = -rI_3$$

$$\therefore \quad I_1 = \left(\frac{2R}{R - r} - r\right) I_3$$

or $$I_1 = \left(\frac{R + r}{R - r}\right) I_3$$

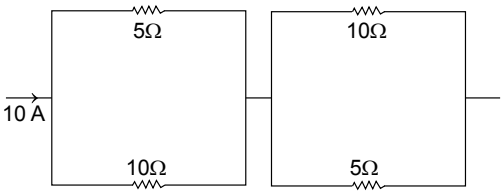
From equation (iii), we have

$$R_0 = \frac{r \cdot \left(\frac{R + r}{R - r}\right) I_3 + \left(\frac{R + r}{R - r} I_3 - I_3\right) R}{\left[\frac{R + r}{R - r} + \frac{2r}{R - r}\right] I_3}$$

$$= \frac{r(R + r) + 2rR}{R + 3r}$$

$$R_0 = \left[\frac{\boldsymbol{r(r + 3R)}}{\boldsymbol{R + 3r}}\right]$$

2. Four resistances carrying a current as shown in the figure are immersed in a box containing ice at 0°C. How much ice must be put in the box every 10 minutes to keep the average quantity of ice in box constant? Latent heat of ice is 80 cal g^{-1}.



☞ **Solution** The equivalent resistance

$$R_0 = \frac{5 \times 10}{5 + 10} + \frac{5 \times 10}{5 + 10} = \frac{100}{15}\ \Omega$$

Heat $= I^2 Rt$

$$= 10 \times 10 \times \frac{100}{15} \times 10 \times 60$$

$$= 4 \times 10^5 \quad ...(i)$$

Heat gain by ice = mL

$$= m \times 80 \times 4.2 \quad ...(ii)$$

From equations (i) and (ii), we get

$$m \times 80 \times 4.2 = 4 \times 10^5$$

$$\therefore \quad m = \frac{4 \times 10^5}{80 \times 4.2}$$

$$= \frac{10 \times 10 \times 10 \times 10 \times 10}{20 \times 4.2} = \mathbf{1190\ g.}$$

3. What amount of heat will be generated in coil of resistance R due to a charge q passing through it, if the current in the coil decreases down to zero uniformly during a time interval Δt?

☞ **Solution** It is very simple and basic problem from the point of view of Physics, but its mathematical analysis is interesting.

As the current decreases uniformly the current (i) should be the linear function of time *(t)* like

$$i = i_0 + kt \quad ...(i)$$

where, i_0 is the initial current and k is some constant.

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From the first condition of problem

$i = 0$ at $t = \Delta t$

Hence from equation (i),

$$k = \frac{i_0}{\Delta t}$$

$$\therefore \quad i = i_0\left(1 - \frac{t}{\Delta t}\right) \qquad \ldots(ii)$$

Similarly, from the second condition

$$q = \int_0^{\Delta t} i\,dt$$

$$= \int_0^{\Delta t} i_0\left(1 - \frac{t}{\Delta t}\right)dt = \frac{i_0 \Delta t}{2}$$

Hence, $i_0 = \dfrac{2q}{\Delta t}$

Putting it in equation (ii) we get the original linear equation of current varying with time as

$$i = \frac{2q}{\Delta t}\left(1 - \frac{t}{\Delta t}\right) \qquad \ldots(iii)$$

Hence, the sought amount of heat liberated through the coil of resistance R,

$$H = \int i^2 R\,dt$$

or $$H = \int_0^{\Delta t} \frac{2q}{\Delta t}\left(1 - \frac{t}{\Delta t}\right)^2 R\,dt$$

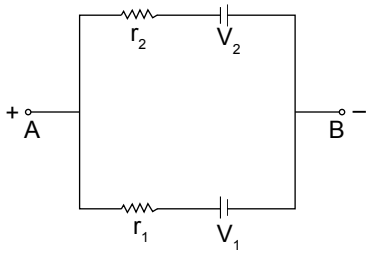
$$= \frac{4}{3}\frac{q^2 R}{\Delta t}$$

In the above problem the variation of current may be given in some another way, for example the current decreases down to zero having its value every Δt seconds.

In this case obviously the variation of current with time becomes

$$i = i_0\left(\frac{1}{2}\right)^{\frac{t}{\Delta t}}$$

4. Find the emf (V) and internal resistance (r) of a single battery which is equivalent to a parallel combination of two batteries of emf V_1 and V_2 and internal resistance r_1 and r_2 respectively, with polarities as shown in the figure.



☞ **Solution** *Applying Kirckhoff's loop rule to the loop abcda,*

we get

$$-Ir_2 + V_2 + V_1 - Ir_1 = 0$$

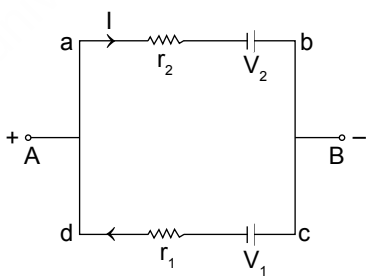
$\therefore$ potential

$$V_{AB} = -V_2 + I r_2 \text{ (or } V_{AB} = V_1 - I_1 r_1)$$

$$= -V_2 + \left(\frac{V_1 + V_2}{r_1 + r_2}\right) r_2$$

$$= \frac{V_2 r_1 - V_2 r_2 + V_1 r_2 + V_2 r_2}{r_1 + r_2}$$

$$= \frac{V_1 r_2 - V_2 r_1}{r_1 + r_2}$$



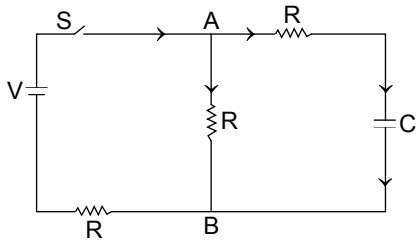
The emf V of a single equivalent cell will be equal to V_{AB}. Its internal resistance is given as

$$R = r_1 \,||\, r_2$$

$$= \frac{r_1 r_2}{r_1 + r_2}$$

5. In the circuit shown in the figure, the battery is an ideal one, with emf V. The capacitor is initially uncharged. The switch S is closed at time $t = 0$.

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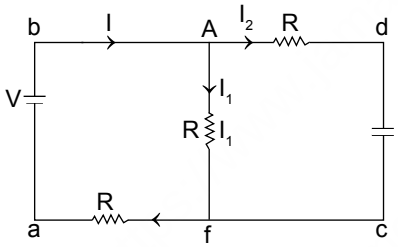
(i) Find the charge Q on the capacitor at time t.

(ii) Find the current in AB at time t. What is its limiting value as $t \to \infty$?

☞ **Solution**

(i) At $t \to 0$, switch is closed.

Applying Kirchhoff's law loop rule to the loop abdea:



$$V - I_2R - \frac{q}{C} - (I_1 + I_2)R = 0$$

or $2RI_2 + RI_1 + \frac{q}{C} = V$ …(i)

In loop cdefc:

$$I_2 R + \frac{q}{C} - I_1 R = 0 \quad \ldots(ii)$$

Eliminating I_1 from equations (i) and (ii), we have

$$3RI_2 + \frac{2q}{C} = V$$

or $$3R\frac{dq}{dt} = \left(V - \frac{2q}{C}\right)$$

$$\int_0^Q \frac{dq}{V - \frac{2q}{C}} = \frac{1}{3R}\int_0^t dt$$

Let, $V - \frac{2q}{C} = z$

or $$-\frac{2}{C}dq = dz$$

$$z \to V \text{ to } V - \frac{2Q}{C}$$

$$\therefore \quad \frac{C}{2}\int_V^{V-\frac{2Q}{C}} \frac{dz}{z} = -\frac{1}{3R}\int dt$$

or $$\ln\frac{V - 2Q/C}{V} = \frac{-2}{3RC}t$$

or $$\frac{V - \frac{2Q}{C}}{V} = e^{\frac{-2}{3RC}t}$$

or $$Q = \frac{VC}{2}\left(1 - e^{-\frac{2t}{3RC}}\right)$$

(ii) Current, $I_2 = \frac{dQ}{dt} = \frac{V}{3R}e^{-\frac{2t}{3RC}}$

From equation (ii),

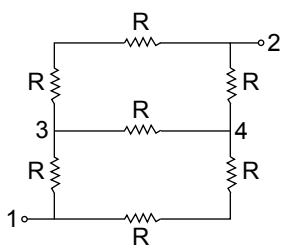
$$I_1 = I_2 + \frac{Q}{RC}$$

$$= \frac{V}{3R}e^{-\frac{2t}{3RC}} + \frac{V}{2R}\left(1 - e^{-\frac{2t}{3RC}}\right)$$

$$= \frac{V}{2R} - \frac{V}{6R}e^{-\frac{2t}{3RC}}$$

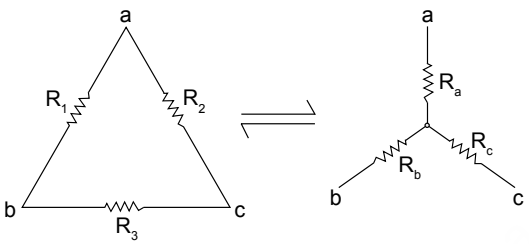
Finally, $\lim_{t\to\infty} I_1 = \frac{V}{2R}$ (This is to be expected as the capacitor is fully charged.)

6. Find the equivalent resistance of the network shown in the figure between the terminals 1 and 2.



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☞ **Solution** This is the familiar problem, which can be solved using Kirchhoff's rule. Here, the problem is going to be simplified using Delta-star Transformation. Before going through the solution, let us understand this Delta-Star Transformation. This figure (a) and (b) show the Delta and Star respectively.



(a) (b)

For obtaining the expression for equivalent we first derive expression for resistance between points of terminals and then equating the expression for resistance of the corresponding terminals of two circuits.

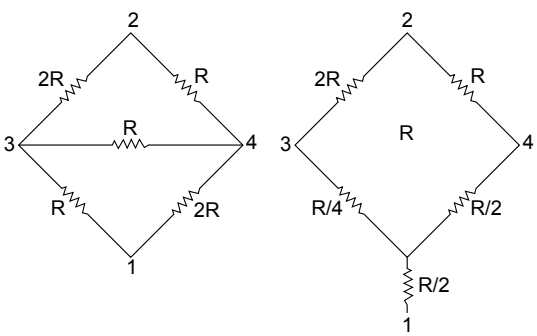
Now for Delta Configuration, the equivalent resistance between *a* and *c*,

$$R_a = \frac{R_1 R_2}{R_1 + R_2 + R_3}$$

$$R_b = \frac{R_1 R_3}{R_1 + R_2 + R_3}$$

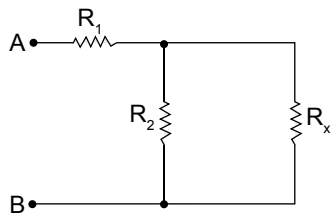
$$R_c = \frac{R_2 R_3}{R_1 + R_2 + R_3}$$

The given network can be reduced in the form as shown using series and parallel grouping.



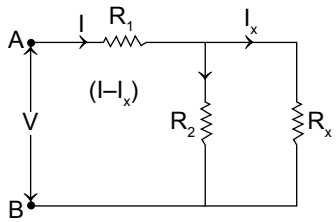
Using Delta-Star Transformation, the figure *(c)* can be reduced to figure *(d)*. Now the reduced network is very simple and using series and parallel grouping, the equivalent resistance between terminal 1 and 2 becomes $\frac{7}{5}$ R.

7. A circuit shown in the figure has resistances R_1 = 20Ω and R_2 = 30Ω. At what value of the resistance R_x will the thermal power generated in it be practically independent of small variations of that resistance *P*. The voltage between the points *A* and *B* is supposed to be constant in this case.



☞ **Solution** The equivalent resistance between the point

$$R_0 = R_1 + \frac{R_2 R_x}{R_2 + R_x}$$



Power generated by $R_x = I_x^2 R_x$

From the figure, $I = \frac{V}{R_1 + \frac{R_2 R_x}{R_2 + R_x}}$

$$\therefore \quad I_x = \left(\frac{V}{R_1 + \frac{R_2 R_x}{R_2 + R_x}} \right) \left(\frac{R_2}{R_2 + R_x} \right)$$

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$$\therefore \quad P_x = I_x^2 R_x = \left[\frac{VR_2}{R_1R_2 + R_1R_x + R_2R_x}\right]^2 R_x$$

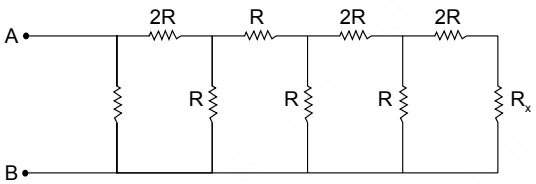
$$\therefore \quad \frac{dP_x}{dR_x} = (VR_2)^2 \; [R_1R_2 + R_1R_x + R_2R_x)^2 - 2(R_1R_2 + R_1R_x + R_2R_x)\,(R_1 + R_2)R_x]$$

For maximum value $\frac{dP_x}{dR_x} = 0$

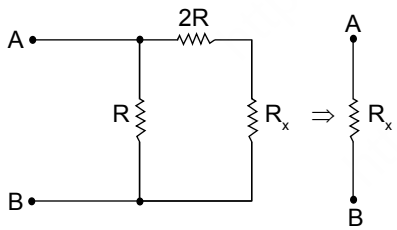
or $\quad R_1R_2 + R_1R_x\,R_2R_x = 2\,(R_1 + R_2)\,R_x$

or $\quad R_x = \frac{R_1R_2}{R_1 + R_2} = \frac{20 \times 30}{20 + 30} = \mathbf{20\ \Omega}$

8. At what value of resistance R_x in the circuit shown in the figure will the total resistance between points *A* and *B* be independent of the number of cells?



☞ **Solution** Total resistance of the circuit will be independent of the number of cells.



If $\quad R_x = \frac{(R_x + 2R)R}{R_x + 2R + R}$

or $\quad R_x^2 + 2RR_x - 2R^2 = 0$

On solving and rejecting the negative root of the quadratic equation, we have

$$R_x = R\left(\sqrt{3} - 1\right)$$

9. At the temperature 0°C, the electric resistance of the conductor 2 is *n* times that of conductor 1. Their temperature coefficients of resistance are equal to α_2 and α_1 respectively. Find the temperature coefficient of resistance of the circuit segment consisting of these two conductors when they are connected

(i) in series

(ii) in parallel

☞ **Solution**

(i) Let after time *t*, the resistances

and $\quad R_1 = R_{01}\,(1 + \alpha_1\,\Delta\,t)$

Now $R_2 = R_{02}\,(1 + \alpha_2\,\Delta\,t)$

$$R = R_1 + R_2$$

$$= R_{01}\,(1 + \alpha_1\,\Delta t) + R_{02}\,(1 + \alpha_2\,\Delta\,t)$$

$$= (R_{01} + R_{02})\,[1 + \alpha\,\Delta\,t] \qquad ...(i)$$

According to the problem $R_{02} = nR_{01}$ ...(ii)

From equations (i) and (ii)

$R_{01}\,(1 + \alpha_1\,\Delta t) + nR_{01}\,(1 + \alpha_2\,\Delta t) = (R_{01} + nR_{01})\,(1 + \alpha\,\Delta t)$

or $\quad 1 + \alpha_1\,\Delta\,t + n + n\,\alpha_2\,\Delta\,t = 1 + \alpha\,\Delta\,t + n + n\,\alpha\,\Delta\,t$

or $\quad \alpha = \frac{\alpha_1 + n\alpha_2}{1 + n}$

(ii) In parallel combination

$$R = \frac{R_{01}(1 + \alpha_1 t)\,nR_{01}(1 + \alpha_2 t)}{R_{01}(1 + \alpha_1 t) + nR_{01}(1 + \alpha_2 t)}$$

$$= R'\,(1 + \alpha' t)$$

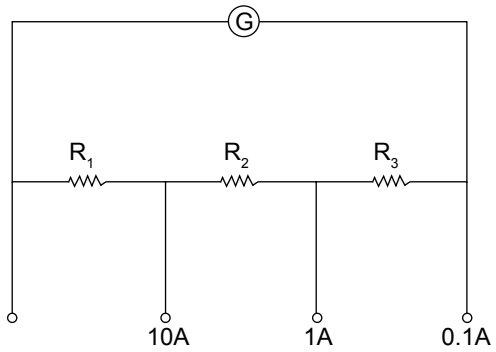
where, $\quad R' = \frac{nR_0}{1 + n}$

Now neglecting the terms proportional to the product of temperature coefficient, being very small, we get

$$\alpha' = \frac{n\alpha_1 + \alpha_2}{1 + n}$$

10. The resistance of a moving coil galvanometer *G* is 25 ohms and it deflects full scale with a current of 0.01 amperes. Find the magnitude of resistances R_1, R_2 and R_3 to convert the galvanometer into a multi-range ammeter deflecting full scale with currents 10 amp, 1 amp and 0.1 amp.

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☞ **Solution** In a galvanometer

$$\frac{I_g}{i} = \frac{S}{G+S}$$

or $$\frac{0.01}{0.1} = \frac{R_1+R_2+R_3}{G+R_1+R_2+R_3} = \frac{1}{10}$$

or $$G + R_1 + R_2 + R_3 = 10\,(R_1 + R_2 + R_3)$$

or $$G = 9\,(R_1 + R_2 + R_3) = 25$$

$$\therefore \quad R_1 + R_2 + R_3 = \frac{25}{9}$$

Similarly, $$\frac{i_g}{i} = \frac{R_1+R_2}{G+R_1+R_2+R_3}$$

$$= \frac{0.01}{1} = \frac{1}{100}$$

or $$100\,(R_1 + R_2) = G + R_1 + R_2 + R_3$$

$$= 25 + \frac{25}{9} = \frac{250}{9}$$

$$\therefore \quad R_1 + R_2 = \frac{250}{900}$$

Again $$\frac{i_g}{i} = \frac{R_1}{G+R_1+R_2+R_3}$$

$$= \frac{.01}{10} = \frac{1}{1000}$$

or $$1000\,R_1 = G + R_1 + R_2 + R_3$$

$$= 25 \times \frac{25}{9} = \frac{250}{9}$$

$$\therefore \quad R_1 = \frac{250}{9000} = \frac{1}{36}\ \Omega$$

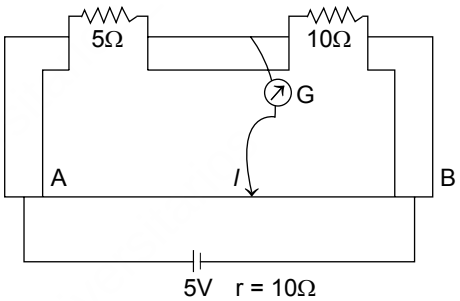
$$R_2 = \frac{250}{900} - R_1$$

$$= \frac{25}{90} - \frac{1}{36} = \frac{1}{4}\ \Omega$$

and $$R_3 = (R_1 + R_2 + R_3) - (R_1 + R_2)$$

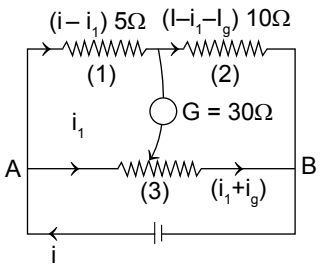
$$= \frac{25}{90} - \frac{25}{90} = \frac{225}{90} = \frac{5}{2}\ \Omega$$

11. An a meter bridge circuit, the two resistances in the gap are 5 ohms and 10 ohms. The wire resistance is 5 ohms. The emf of the cell connected at the ends of wire is 5 volts and its internal resistance is 10 ohm. What current will flow through the galvanometer of resistance 30 ohms if the contact is made at the mid-point of wire?



☞ **Solution**

The distribution of currents is shown in the figure. Applying Kirchhoff's law to closed mesh (1), (2) and (3), we have



$5\,(i - i_1) \times 30\,i_g - 2\,i_1$ or $5\,i - 7\,i_1 + 30\,i_g = 0$ ...(i)

or $$10\,(i - i_1 - i_g) - 2\,(i_1 + i_2) - 30\,i_g = 0$$

or $$10\,i - 19 i_1 - 42\,i_g = 0 \qquad \text{...(ii)}$$

$$2i_1 + 2\,(i_1 + i_2) + i = 5$$

or $$4i_1 + 2i_g + i = 5 \qquad \text{...(iii)}$$

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From equations (i) and (ii)

or $12i_1 + 42\, i_g = 14\, i_1 - 60\, i_g$

$102i_g = 2i_1$

or $i_1 = 51 i_g$ ...(iv)

From equations (ii) and (iii)

$10\, i - 42\, i_g = 15 - 3\, i - 6\, i_g$

or $13\, i = 36\, i_g + 15$ ...(v)

Substituting equations (iv) and (v) in equation (iii), we get

$$4(51\, i_g) + 2i_g + \frac{36i_g + 15}{13} = 0$$

or $$204 i_g + 2i_g + \frac{36i_g + 15}{13} = 5$$

or $2652\, i_g + 26\, i_g + 36\, i_g + 15 = 65$

or $2714\, i_g = 50$

$$\therefore \quad i_g = \frac{\mathbf{25}}{\mathbf{1357}}\ \mathbf{A}$$

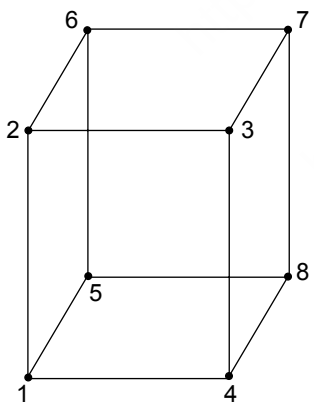
12. Find the resistance of wire frame shaped as a cube shown in the figure when measured between points

(i) **1 – 7**

(ii) **1 – 2**

(iii) **1 – 3**

The resistance of each edge of the frame is R.



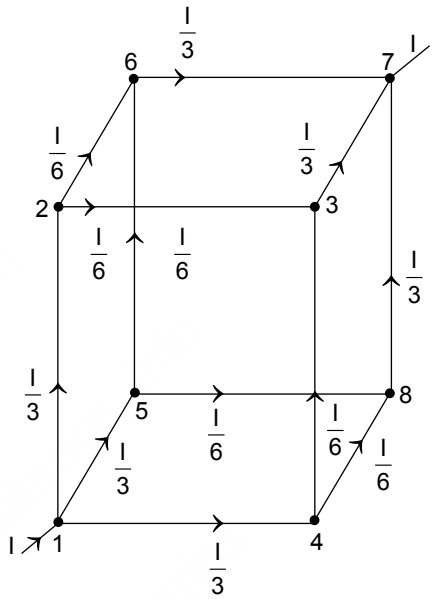
☞ **Solution**

(i) The current are as shown.

From Ohm's law applied between 1 and 7 via 1487 (say)

$$I R_{eq} = \frac{I}{3}R + \frac{I}{6}R + \frac{I}{3}R = \frac{5}{6}RI$$

Then, $$R_{eq} = \frac{\mathbf{5R}}{\mathbf{6}}$$



(ii) From Ohm's law applied between 1 and 2 from the loop 14321

$I_1 R = 2I_2 R + I_3 R$

or $I_1 = I_3 + 2\, I_2$ ...(i)

From the loop 48734

$(I_2 - I_3)\, R + 2\, (I_2 - I_3)\, R + (I_2 - I_3)\, R = I_3 R$

or $4\, (I_2 - I_3) = I_3$

or $$I_3 = \frac{4}{5} I_2$$

$$\therefore \quad I_1 = \frac{14}{5} I_2$$

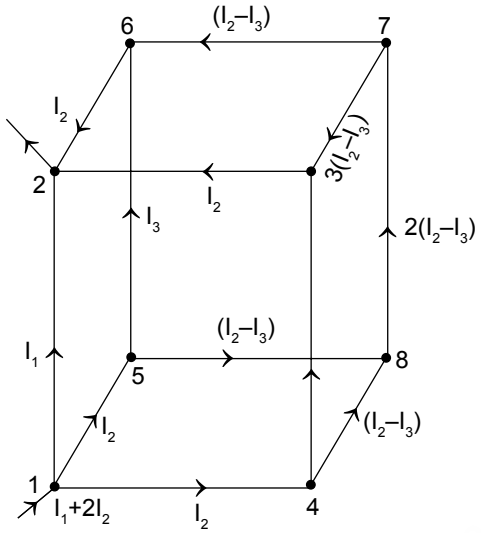
So, from equation (i),

$$(I_1 + 2R_2) R_{eq} = \frac{24}{5} I_2 R_{eq}$$

$$= I_1 R = \frac{14}{5} I_2 R$$

or $$R_{eq} = \frac{\mathbf{7}}{\mathbf{12}}\mathbf{R}$$

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(iii) From Ohm's law applied between 1 and 3 from the loop 15621

$$I_2R = I_1R + \frac{I_1}{2}R$$

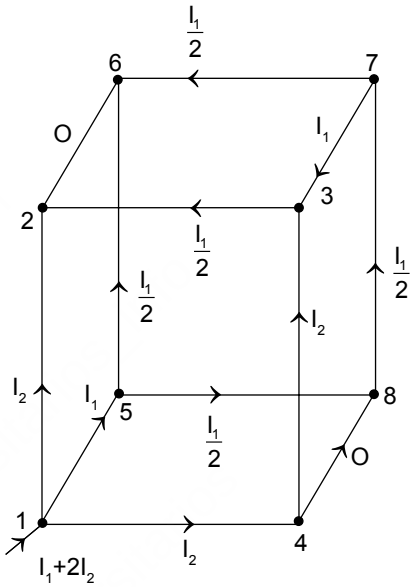
or $$I_2 = 3\frac{I_1}{2}$$

Then, $(I_1 + 2I_2)\, R_{eq} = 4I_1\, R_{eq}$

$= I_2R + I_2R$

$= 3I_1R$

Hence, $R_{eq} = \frac{3}{4}\mathbf{R}$



SOLVED OBJECTIVE TYPE QUESTIONS

1. In a gas discharge tube if 3×10^{18} electrons are flowing per sec from left to right and 2×10^{18} protons are flowing per second from right to left through a given cross section. The magnitude and direction of current through the cross section will be

(a) 0.48, left to right
(b) 0.48 A, right to left
(c) 0.80 A, left to right
(d) 0.80 A, right to left

☞ **Explanation** Since current is rate of flow of charge in the direction in which positive charge will move, then

current due to electron will be $i_e = \frac{n_e q_e}{t}$

$= 3 \times 10^{18} \times 1.6 \times 10^{-19} = 0.48$ A

(Opposite to the motion of electrons i.e., right to left)

Current due to protons, $i_p = \frac{n_p q_p}{t} = 2 \times 10^{18} \times 1.6 \times 10^{-19}$

$= 0.32$ A (Right to left)

$\therefore$ total $I = i_e + i_p$

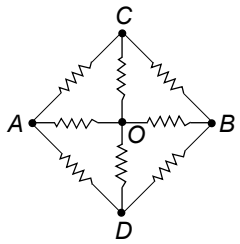
$= 0.48 + 0.32 = 0.80$ A (Right to left)

2. In the network shown, each resistance is equivalent to *R*. The equivalent resistance between points *A* and *B* is

(a) $\frac{R}{3}$ (b) $\frac{2R}{3}$

(c) R (d) $\frac{4R}{3}$

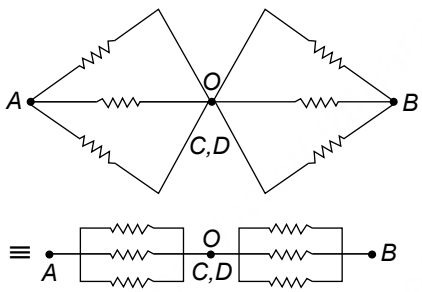
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☞ **Explanation** If a potential is applied across A and B, due to symmetry, the points C, O and D will have same potentials. We can therefore join all these points without affecting current in any branch. The network then reduces to

∴ Equivalent resistance,

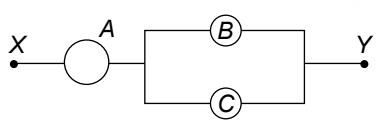
$$R_{eq} = \frac{R}{3} + \frac{R}{3} = \frac{2R}{3}$$



3. Three voltmeters *A*, *B* and *C*, having resistances *R*, 1.5 *R* and 3*R*, respectively, are connected as shown. When some potential difference is applied between *X* and *Y*, the voltmeter readings are V_A, V_B and V_C respectively. Then

(a) $V_A \neq V_B = V_C$ (b) $V_A = V_B \neq V_C$

(c) $V_B \neq V_A = V_C$ (d) $V_A = V_B = V_{Cs}$



☞ **Explanation** The division of current I into the two parallel branches will be as shown,

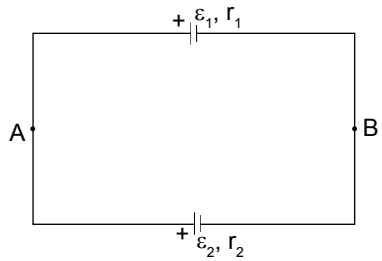
∴ $V_A = IR$

$$V_B = \left(\frac{2I}{3}\right)1.5R = IR$$

$$V_C = \left(\frac{I}{3}\right)3R = IR$$

∴ $V_A = V_B = V_C$

4. Two cells of unequal emfs ε_1 and ε_2, and internal resistances r_1 and r_2 are joined as shown. V_A and V_B are the potential at *A* and *B* respectively. Then



(a) One cell will continuously supply energy to the other.

(b) The potential difference across both the cells will be equal

(c) The potential difference across both the cell will be greater than its emf.

(d) All of these

☞ **Explanation** Let $e_1 < e_2$

Current in the circuit, $i = \frac{\varepsilon_1 - \varepsilon_2}{r_1 + r_2}$

$V_A - V_B = \varepsilon_2 + ir_2$ = potential difference across eachs cell.

Here $V_A - V_B > \varepsilon_2$.

Current flows in the cell of emf ε_2 from the positive plate to the negative plate inside the cell and hence it absorbs energy.

5. An electric bulb rated for 500 *W* at 100 *V* is used in a circuit having a 200 *V* supply. The resistance *R* that must be put in series with the bulb, so that the bulb draws 500 *W* is

(a) 100 Ω (b) 50 Ω

(c) 20 Ω (d) 10 Ω

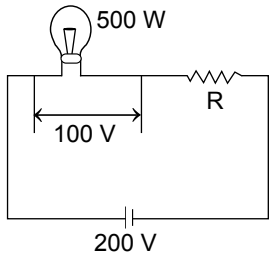
☞ **Explanation** For the bulb to draw 500 W, there should be 100 V applied across it. The remaining 100 V should be dropped in the series resistance R.

Now, the current in the bulb is given by

P = V.I

∴ $I = \frac{P}{V} = \frac{500}{100} = 5A$

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Since same current flows through R, therefore

$$R = \frac{V}{I} = \frac{100}{5} = 20\ \Omega$$

6. The magnitude of momentum of electrons in a straight wire of copper of length 1 meter carrying a current of 16 ampere will be

(a) 14.56×10^{-12} kg m sec^{-1}

(b) 29.12×10^{-12} kg m sec^{-1}

(c) 18.2×10^{-11} kg m sec^{-1}

(d) 91×10^{-12} kg m sec^{-1}

☞ **Explanation** If n is the number of electrons per unit volume, then total number of free electrons = nLA

Hence Total mass of the electrons = $n\text{LA}m_e$

Total momentum of electrons = $n\text{LAm}_e \times V_d$

$$= n\text{LAm}_e \times \frac{I}{e}$$

$$= \frac{1 \times 9.1 \times 10^{-31} \times 16}{1.6 \times 10^{-19}} = 91 \times 10^{-12} \text{kg sec}^{-1}$$

7. A wire of length L and 3 identical cells of negligible internal resistances are connected in series. Due to the current, the temperature of the wire is raised by ΔT in a time t. A number N of similar cells is now connected in series with a wire of the same material and cross-section but of length $2L$. The temperature of the wire is raised by the same amount ΔT in the same time t. The value of N is

(a) 4 (b) 6

(c) 8 (d) 9

☞ **Explanation** In the first case, $i = \frac{3E}{R}$

where E is the emf of each cells and R ($\propto$ L) is the resistance of the wire.

Also i^2 Rt = m.s.ΔT ...(i)

where m = mass of L length of wire and S is the specific heat of the material of the wire

In the second case, $i' = \frac{NE}{R'}$

where R′ $\propto$ 2L

and i'^2 R′t = m′.s.ΔT ...(ii)

Dividing equation (ii) by equation (i), we have

$$\left(\frac{i'}{i}\right) \cdot \left(\frac{R'}{R}\right) = \frac{m'}{m}$$

$$\Rightarrow \quad \frac{N^2}{9} \cdot \frac{R}{R'} = \frac{m'}{m}$$

$$\Rightarrow \quad \frac{N^2}{9} \cdot \frac{1}{2} = 2$$

$$\Rightarrow \quad N = \mathbf{6}$$

8. A electric current of 16 A exists in a metal wire of cross section 10^{-6} m^2 and length 1m. Assuming one free electrons per atom, the drift speed of the free electrons in the wire will be (Density of metal = 5×10^3 kg/m^3, atomic weight = 60)

(a) 5×10^{-3} m/s (b) 2×10^{-3} m/s

(c) 4×10^{-3} m/s (d) 7.5×10^{-3} m/s

☞ **Explanation** According to Avogadro's hypothesis

$$\frac{N}{N_A} = \frac{m}{M}$$

So, $$n = \frac{N}{V} = N_A \frac{m}{VM} = \frac{N_A}{M}$$

Hence total number of atoms,

$$n = \frac{6 \times 10^{23} \times 5 \times 10^3}{60 \times 10^{-3}} = 5 \times 10^{28}/\text{m}^3$$

As $I = n_e\, e A v_d$

Hence drift velocity,

$$V_d = \frac{1}{n_e e A}$$

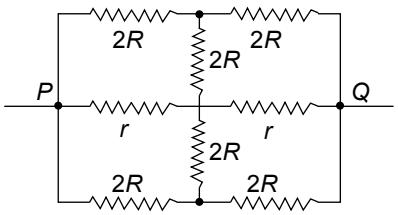
$$= \frac{16}{5 \times 10^{28} \times 1.6 \times 10^{-19} \times 10^{-6}} = \mathbf{2 \times 10^{-3}\ m/s}$$

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9. The effective resistance between points *P* and *Q* of the electrical circuit shown in the figure is

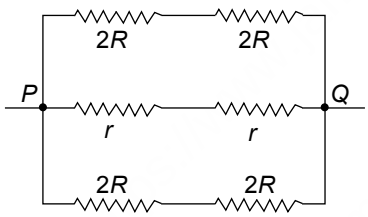
(a) $\frac{2Rr}{R+r}$ (b) $\frac{8R(R+r)}{3R+r}$

(c) $2r+4R$ (d) $\frac{5R}{2}+2r$

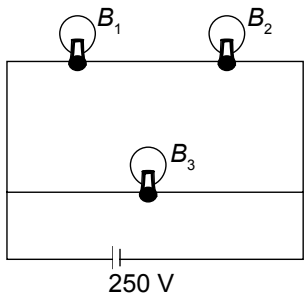


☞ **Explanation** From symmetry, the equivalent circuit reduces to as shown in the figure.

$\therefore \quad R_{eq} = \frac{2Rr}{(R+r)}$



10. A 100 *W* bulb B_1, and two 60 *W* bulbs B_2 are connected to a 250 *V* source, as shown in the figure. Now W_1, W_2 and W_3 are the output powers of the bulbs B_1, B_2 and B_3 respectively. Then



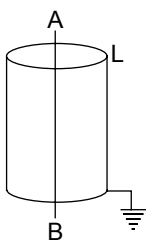
(a) $W_1 > W_2 = W_3$
(b) $W_1 > W_2 > W_3$
(c) $W_1 < W_2 = W_3$
(d) $W_1 < W_2 < W_3$

☞ **Explanation** Voltage across bulb B_2 will be less than that across B_3

$\therefore \quad W_1 < W_3$

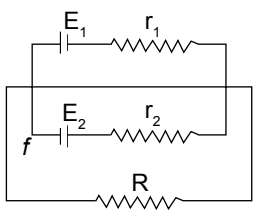
UNSOLVED OBJECTIVE TYPE QUESTIONS

1. A straight conductor *AB* lies along the axis of a hollow metal cylinder *L*, which is connected to earth through a conductor *C*. A quantity of charge will flow through *C*,



(a) if a current begins to flow through AB
(b) if the current through AB is reversed
(c) if AB is removed, and a beam of electrons flows in its place.
(d) if AB is removed, and a beam of protons flows in its place.

2. The current in the resistance *R* will be zero if



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(a) $E_1 r_1 = E_2 r_2$

(b) $\frac{E_1}{r_1} = \frac{E_2}{r_2}$

(c) $(E_1 + E_2) r_1 = E_1 r_2$

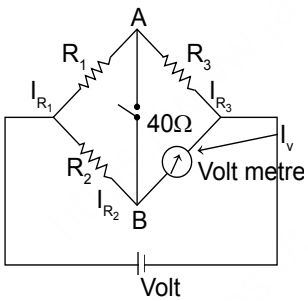
(d) $(E_1 - E_2) r_1 = E_2 r_1$

3. A battery of emf 10 *V* and internal resistance *r* = 1Ω, is connected to an external resistance *R* = 4 Ω. What should be the value of *R* so that the voltmetre reads half the value it reads in the previous case when connected across *R*?

(a) $\frac{4}{3}\Omega$ (b) 1 Ω

(c) 2 Ω (d) $\frac{2}{3}\Omega$

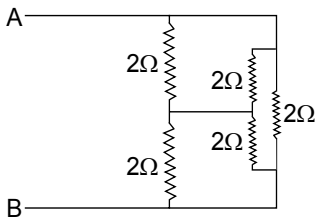
4. In a given circuit, $R_1 \neq R_2$ but the reading of the voltmetre is same with switch *S* open or close, then



(a) $I_{R_2} = I_V$ (b) $I_{R_1} = I_{R_2}$

(c) $I_{R_3} = I_V$ (d) none of these

5. Find the equivalent resistance between *A* and *B* of the given circuit.



(a) 2 Ω (b) 4 Ω

(c) 1 Ω (d) none of these

6. In an household electric circuit,

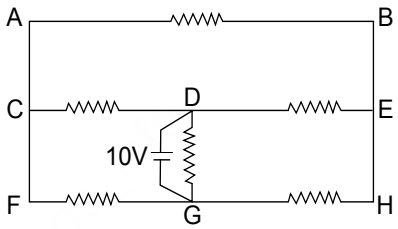
(a) all electric appliance drawing power are joined in parallel

(b) a switch may be either in series or in parallel with the appliance which it controls

(c) if a switch is in parallel with an appliance, it will draw power when the switch is in the 'off' position (open)

(d) if a switch is in parallel with an appliance, the fuse will blow (burn out) when the switch is put 'on' (closed)

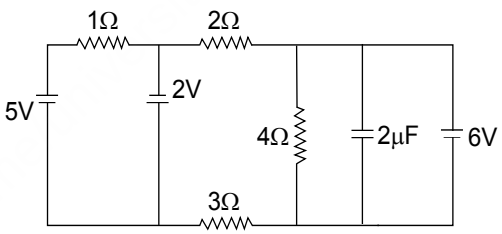
7. All resistance shown in circuit are 2 Ω each. The current in the resistance between *D* and *E* is



(a) 5 A (b) 2.5 A

(c) 1 A (d) 7.5 A

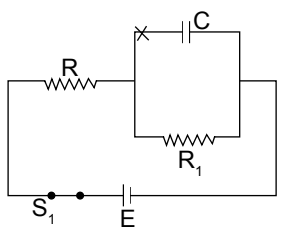
8. The current in 1 Ω resistance and charge stored in the capacitor are



(a) 5 A 10 μC (b) 7 A, 12 μC

(c) 4 A, 12 μC (d) 6 A, 6 μC

9. In the given, at time *t* = 0, switch S_1 is closed. When steady state is reached, switch S_1 is again opened. Find the current through resistance R_1 at the instant when switch S_1 is opened.

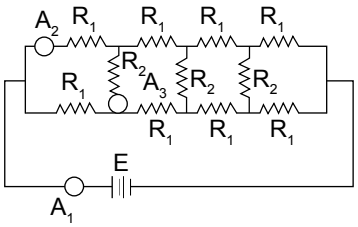


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(a) $\frac{E}{R}$ (b) $\frac{E}{R_1}$

(c) $\frac{E}{R+R_1}$ (d) $\frac{E\times R}{(R+R_1)R_1}$

10. In the given circuit, $R_1 = 10\ \Omega$, $R_2 = 6\ \Omega$ and $E = 10\ V$. Then



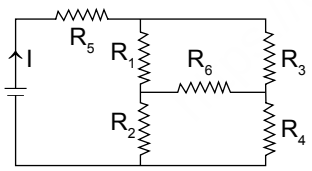
(a) Effective resistance of the circuit is 20 Ω

(b) Reading of A_1 is $\frac{1}{2}$ amp.

(c) Reading of A_2 is $\frac{1}{4}$ amp.

(d) All of these

11. In the given circuit, it is observed that the current I is independent of the value of the resistance R_6. Then the resistance values must satisfy



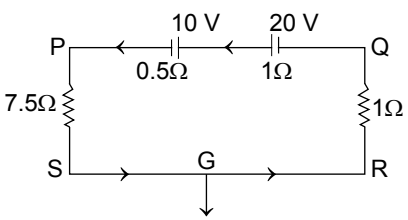
(a) $R_1R_2R_5 = R_3R_4R_6$

(b) $\frac{1}{R_5}+\frac{1}{R_6}+\frac{1}{R_1+R_2}+\frac{1}{R_3+R_4}$

(c) $R_1R_4 = R_2R_3$

(d) $R_1R_3 = R_2R_4 = R_5R_6$

12. In the circuit shown, the potential



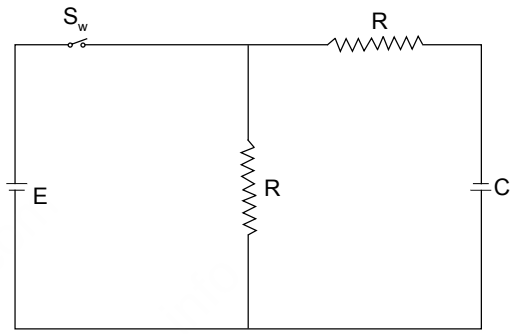
(a) at P is – 7.5 V

(b) at Q is – 1 V

(c) at s is zero

(d) all of these

13. A capacitor C is connected to two equal resistances as shown in the figure. Then



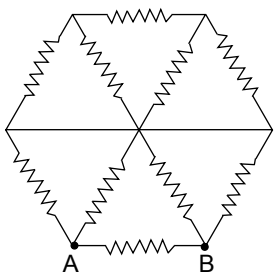
(a) at the time of charging of capacitor time constant of the circuit is 2 CR

(b) at the time of discharging of capacitor time constant of the circuit is CR

(c) at the time of discharging of the capacitor the time constant of the circuit is 2 CR.

(d) at the time of charging of capacitor, the time constant of the circuit is CR.

14. In the network shown in figure, each resistance is R. The equivalent resistance between A and B is

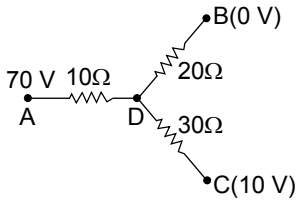


(a) $\frac{20}{11}R$ (b) $\frac{19}{20}R$

(c) $\frac{8}{15}R$ (d) $\frac{R}{2}$

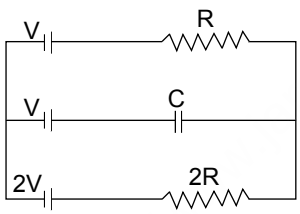
15. In the network shown, points A, B and C are at potential of 70 V, zero and 10 V respectively, Then

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(a) point D is at a potential of 40 V
(b) currents in the sections. AD, DB, DC are in the ratio 3 : 2 : 1
(c) network draws a total power of 200 W.
(d) all of these

16. In the given circuit, with steady current, the potential drop across the capacitor must be

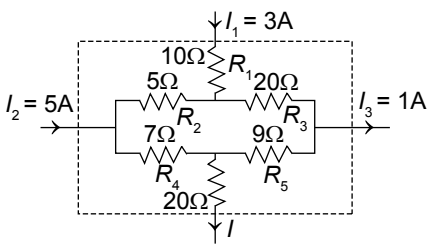


(a) V (b) $\frac{V}{2}$
(c) $\frac{V}{3}$ (d) $\frac{2V}{3}$

17. A capacitor charges from a cell through a series resistance. The time constant of the circuit is τ. The time taken by the capacitor to collect 10% of its final charge is

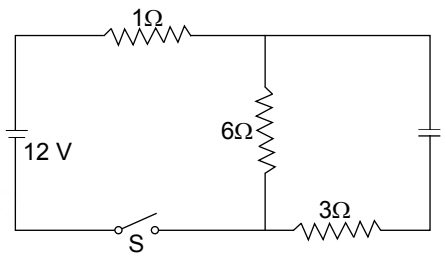
(a) $\tau l_n(0.1)$ (b) $\tau l_n\left(\frac{9}{10}\right)$
(c) $\tau l_n\left(\frac{10}{9}\right)$ (d) $\tau l_n\left(\frac{10}{11}\right)$

18. The given network is a part of a bigger network. Determine the value of current flowing in resistor R_6.



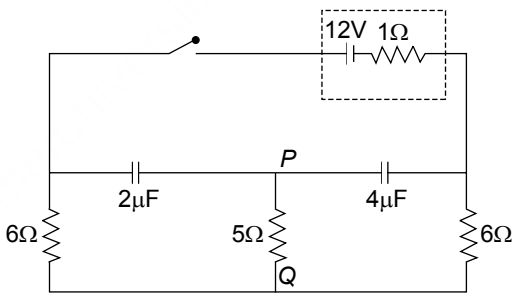
(a) 9 A
(b) 8 A
(c) 7 A
(d) 1 A

19. When the switch is closed, the initial current through the 1 Ω resistor is



(a) 12 A (b) 4 A
(c) 3 A (d) $\frac{10}{7}$A

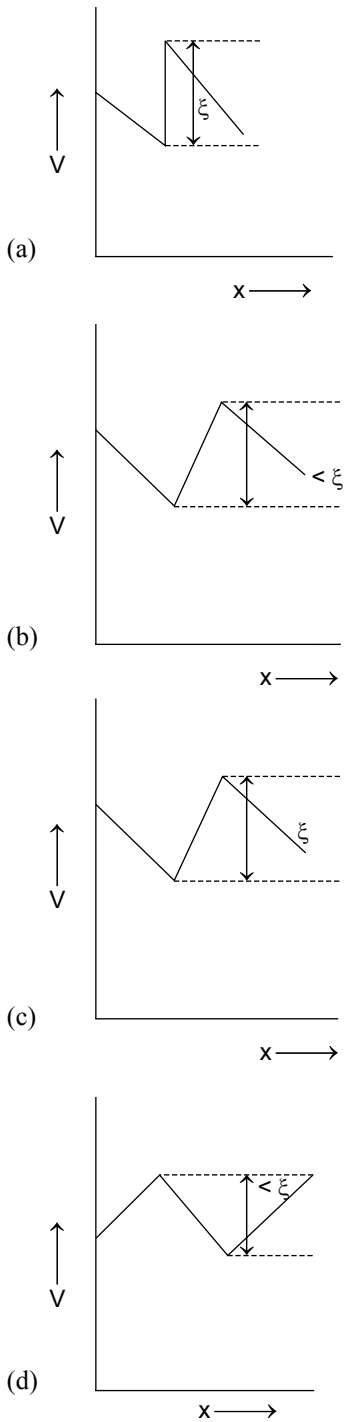
20. In the circuit shown in figure, the capacitors are initially uncharged. The current through resistor *PQ* just after closing the switch is



(a) 2 A from P to Q
(b) 2 A from *Q* to *P*
(c) 6 A from P to Q
(d) zero

21. The two ends of a uniform conductor are joined to a cell of emf ε and some internal resistance starting from the midpoint *P* of the conductor, we move in the direction of the current and return to *P*. The potential *V* at every point on the path is plotted against the distance covered (*x*). Which of the following best represent the resulting curve?

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22. The electron in a hydrogen atom moves in circular orbit of radius 5×10^{-11} m with a speed of $0.6\pi \times 10^6$ m/s, then

(a) frequency of the electron is 6×10^{15} rev/s

(b) electron carries 1.6×10^{-19} C around the loop

(c) current flows in the opposite direction to the direction of the motion of electron.

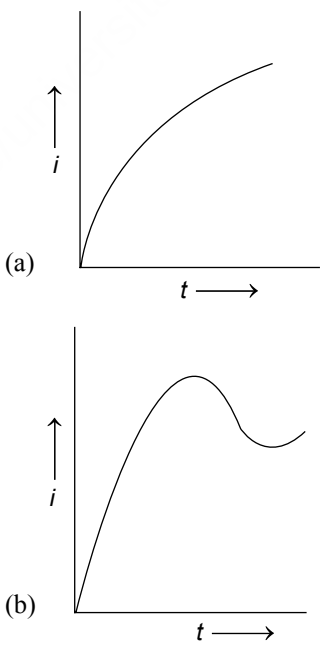
(d) all of these

23. If a copper wire is stretched to make it 0.1% longer, the percentage change in its resistance is

(a) 0.2% increase (b) 0.2% decrease

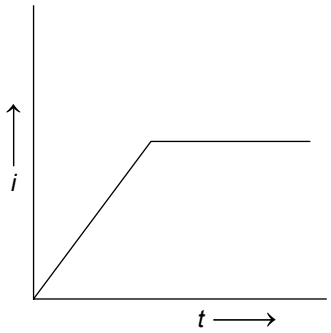
(c) 0.1% increase (d) 0.1% decrease

24. When an electric heater is switched on the current flowing through it (i) **is plotted against time (*t*). Taking into account the variation of resistance with temperature, which of the following best represents the resulting curve?**

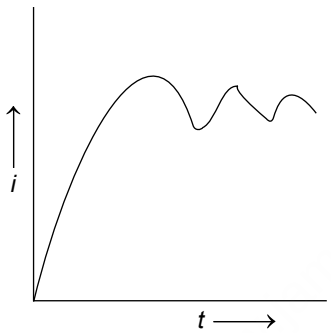


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(c)



(d)



25. The mass of the three wire of copper are in the ratio 1 : 3 : 5, and their lengths are in ratio 5 : 3 : 1. The ratio of their electrical resistances is

(a) 1 : 3 : 5

(b) 5 : 3 : 1

(c) 1 : 15 : 125

(d) 125 : 15 : 1

26. A battery of 10 volts is connected to a resistance of 20 ohm through a variable resistance *R*, the amount of charge which has passed in the circuit in 4 minutes, if the variable resistance *R* is increased at the rate of 5 ohm/min.

(a) 120 coulomb

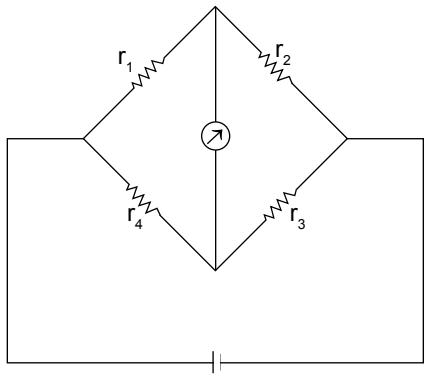
(b) 120 $\log_e 2$ coulomb

(c) $\frac{120}{\log_e 2}$ coulomb

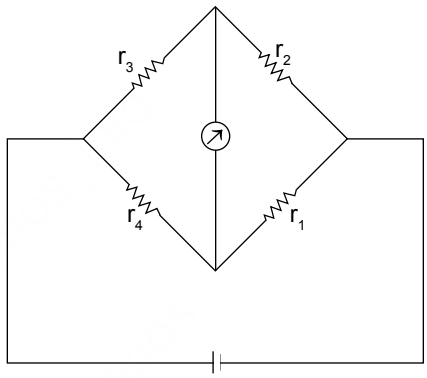
(d) $\frac{60}{\log_e 2}$ coulomb

27.

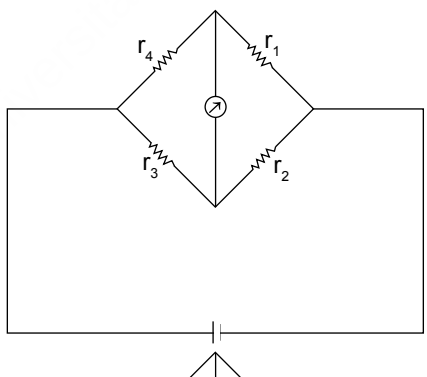
(a)



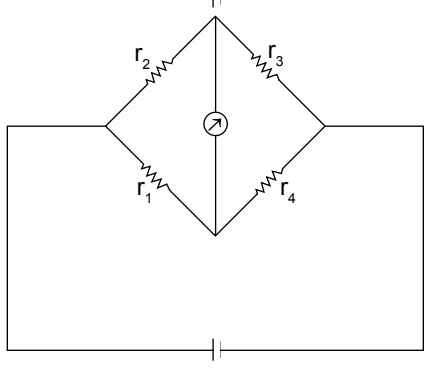
(b)



(c)



(d)



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In the circuit shown in *A*, the galvanometer shows zero deflection The resistance r_1, r_2, r_3 and r_4 are now rearranged in three different ways, shown in *B*, *C* and *D*. The golvanometer will show zero deflection in

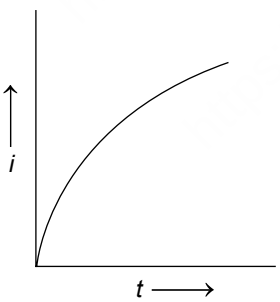
(a) B only
(b) C only
(c) B and D
(d) B, C and D

28. Two resistances, R_1 and R_2, are joined in parallel to a source of emf of negligible internal resistance. The power developed in R_2 is *P*. If R_1 is now removed, the power developed in R_2 will be

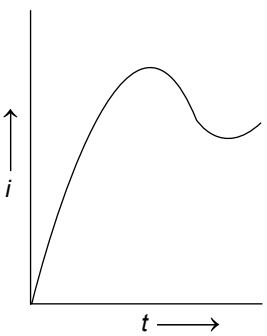
(a) greater than P for all values of R_1 and R_2
(b) less than P for all values of R_1 and R_2
(c) P for all values of R_1 and R_2
(d) P only if $R_1 = R_2$

29. An ideal cell is connected to a capacitor through a voltmeter. The reading *V* of the voltmeter is plotted against time. Which of the following best represents the resulting curve?

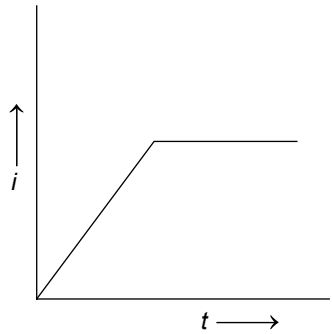
(a)



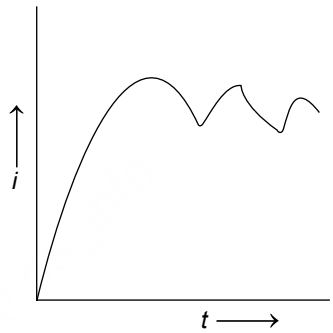
(b)



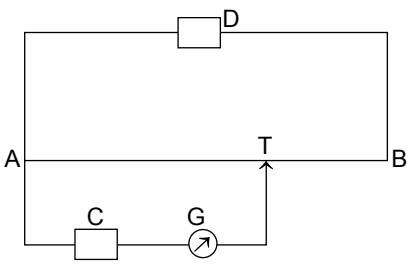
(c)



(d)



30. The figure shows a potentiometer arrangement. *D* is the driving cell. *C* is the cell whose emf is to be determined. *AB* is the potentiometer wire and *G* is a galvanometer. *J* is a sliding contact which can touch any point on *AB*. Which of the following are essential condition for obtaining balance?



(a) The emf of D must be greater than the emf of C.
(b) Either the positive terminals of both D and C or the negative terminals of both D and C must be joined to A.
(c) The positive terminal of D and C must be joined to A.
(d) The resistance of G must be less than the resistance of AB.

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ANSWERS

1. (c,d)	**2.** (b)	**3.** (d)	**4.** (a)	**5.** (c)	**6.** (c,d)	**7.** (b)	**8.** (b)
9. (c)	**10.** (d)	**11.** (c)	**12.** (d)	**13.** (c,d)	**14.** (d)	**15.** (d)	**16.** (c)
17. (c)	**18.** (c)	**19.** (b)	**20.** (d)	**21.** (b)	**22.** (c)	**23.** (a)	**24.** (b)
25. (d)	**26.** (b)	**27.** (d)	**28.** (c)	**29.** (b)	**30.** (a)		

PRACTICE EXERCISE 1

1. The walls of a closed cubical box of edge 50 cm are made of a material of thickness 1 mm and thermal conductivity 4×10^{-4} cal s^{-1} cm^{-1} $(°C)^{-1}$. The interior of the box is maintained 100°C above the outside temperature by a heater placed inside the box and connected across 400 *V* dc. Calculate the resistance of the heater. [IIT, 1971]
[**Ans.** 6.35 Ω]

2. Three equal resistors connected in series across a source of emf together dissipate 10 watt of power. What would be the power dissipated if the same resistors are connected in parallel across the same source of emf? [IIT, 1972]
[**Ans.** 90 watt]

3. (a) A galvanometer having a coil resistance of 100 ohm gives a full scale deflection when a current of one milliampere is passed through it. What is the value of resistance which can convert this galvanometer into ammeter giving a full scale of deflection for a current of 10 ampere?

(b) A resistance of the required value is available but it will get burnt if the energy dissipated in it is greater than one watt. Can it be used for the above described conversion of the galvanometer?

(c) When this modified galvanometer is connected across the terminals of battery, it shows a current 4 amp. The current drops to 1 amp. When a resistance of 1.5 ohm is connected in series with modified galvanometer. Find the emf and internal resistance of the battery. [IIT, 1972]
[**Ans.** (a) 0.01 Ω, (b) Yes, (c) 0.49 Ω]

4. A wire of resistance 0.1 ohm cm^{-1} is bent to form a square *ABCD* of side 10 cm. A similar wire is connected between the corners *B* and *D* to form the diagonal *BD*. Find the effective resistance of this combination between the corners *A* and *C*. If a 2*V* battery of negligible internal resistance is connected across *A* and *C*, calculate the total power dissipated. [IIT, 1971]
[**Ans.** 4 watts]

5. A galvanometer together with an unknown resistance in series is connected across two identical batteries each of 1.5 *V*. When the batteries are connected in series, the galvanometer records a current of 1*A*, and when the batteries are in parallel, the current is 0.6 *A*. What is the internal resistance of the battery? [IIT, 1973]

$\left[\text{Ans.}\frac{1}{3}\,\Omega\right]$

6. Two heater coils made of same material are connected in parallel across the mains. The length and diameter of the wire of one of coils are double that of the other. Which one of them will produce more heat? [IIT, 1973]
[**Ans.** More heat will be produced in the second coil.]

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7. An electric current of 5 amp. is divided in three branches forming a parallel combination. The length of the wire in the three branches are in the ratio 2, 3 and 4. Their diameters are in the ratio 3, 4 and 5. Find the current in each branch if the wires are of the same material. **[IIT, 1975]**

[**Ans.** i_1 = 1.40 amp, i_2 = 1.66 amp, i_3 = 1.94 amp]

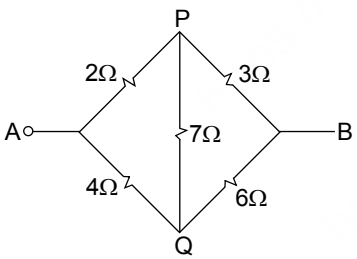
8. A battery of emf 1.4 *V* and internal resistance 2 ohm is connected to a resistance of 100 ohm through an ammeter. The resistance of ammeter is $\frac{4}{3}$ ohm. A voltmeter has also been connected to find the potential difference across the resistor.

(a) The ammeter reads 0.02 A. What is the resistance of the voltmeter?

(b) The voltmeter reads 1.10 V. What is the error in the reading? **[IIT, 1975]**

[**Ans.** (a) 200 Ω, (b) 0.23 V]

9. Five resistances are connected as shown in the figure. Find the effective resistance between the points *A* and *B*. **[IIT, 1976]**



[**Ans.** $\frac{10}{3}\Omega$]

10. A potentiometer wire of length 100 cm has a resistance of 10 ohm. It is connected in series with a resistance and an accumulator of emf 2*V* and of negligible internal resistance. A source of emf 10 *mV* is balanced against a length of 40 cm of the potentiometer wire. What is the value of external resistance? **[IIT, 1976]**

[**Ans.** 790 ohms]

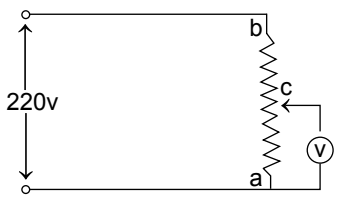
11. 12 cells each having the same emf are connected in series and are kept in a closed box. Some of the cells are wrongly connected. This battery is connected in series with an ammeter and the two cells identical with the others. The current is 3*A* when the cells and battery aid each other and is 2*A* when the cells and battery oppose each other. How many cells are wrongly connected? **[IIT, 1976]**

[**Ans.** 1]

12. A fuse of lead wire has an area of cross section 0.2 mm^2. On short circuiting, the current in the fuse wire reaches 30 A. How long after the short circuiting will fuse begin to melt? For lead, specific heat = 0.032 cal g^{-1} (°C)$^{-1}$, melting point = 327°C, density = 11.34 g-cm^{-3}, and resistivity = 22 × 10^{-6} Ω-cm. The initial temp. of wire is 20°C. Neglect heat losses. **[IIT, 1976]**

[**Ans.** 0.093 second]

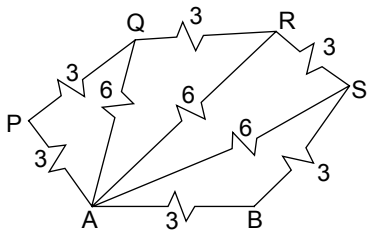
13. A potential difference of 220 volt is maintained across a 12000 Ω rheostat as shown in the figure. The voltmeter has a resistance of 6000 Ω and point *C* is at one-fourth of the distance from *a* to *b*. What is the reading of voltmeter? **[IIT, 1977]**



[**Ans.** 40 volts]

14. All the resistance in the figure are in ohms. Find the effective resistance between points *A* and *B*. **[IIT, 1977]**

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[**Ans.** 2 Ω]

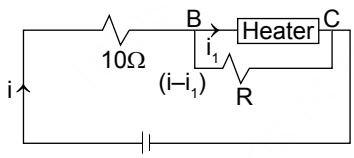
15. Two electric bulbs each designed to operate with a power of 500 watt in a 220 *V* line are put in series in 110 *V* line. What will be the power generated in each bulb?

[IIT, 1977]

[**Ans.** 31.23 watts]

16. A heater is designed to operate with a power of 1000 watt in a 100 *V* line. It is connected in combination with a resistance of 10 Ω and a resistance *R*, to 100 *V* mains, as shown in the figure. What will be the value of *R* so that the heater operates with a power of 62.5 watt?

[IIT, 1978]



[**Ans.** 5 Ω]

17. Two resistors R_1 and R_2 may be connected either in series or in parallel across a battery of zero internal resistance. It is required that the joule heating for the parallel combination be five times that for series combination. If R_1 is 100 Ω, find R_2.

[MNR, 1978]

[**Ans.** 261.8 Ω or 38.2 Ω]

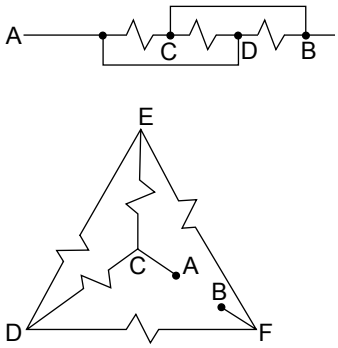
18. A copper wire is stretched to make it 0.1% longer. What is the percentage change in its resistance?

[IIT, 1978; MNR, 1990]

[**Ans.** 0.2%]

19. Each of the resistance in the network below is equal to *R*. What is the resistance between the terminal *A* and *B* for Fig. (a) and Fig. (b).

[IIT, 1978]



[**Ans.** $R_{AB} = R$]

20. A copper wire having cross-sectional area 0.5 mm² and a length of 0.1 m is initially at 25°C and is thermally insulated from the surroundings. If a current of 10 *A* is set up in the wire,

(a) find the time in which the wire will start melting. The change of resistance with temperature of the wire may be neglected.

(b) what will be the time taken if the length of the wire is doubled?

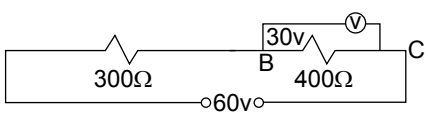
Given, density of copper = 9×10^3 kg/m³, specific heat = 9×10^{-2} kilo cal kg^{-1} $(°C)^{-1}$, melting point = 1075°C, specific resistance = 1.6×10^{-8} ohm meter.

[IIT, 1979]

[**Ans.** (a) 558.14 sec., (b) The time after which it melts remains unchanged.]

21. In the circuit shown in the figure, a voltmeter reads 30 *V* when it is connected across 400 ohm resistance. Calculate what the same voltmeter will read when it is connected across the 300 ohm resistance.

[IIT, 1980]



[**Ans.** 22.49 V]

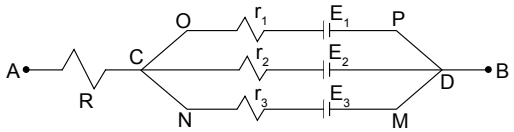
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22. In the circuit shown in the figure, $E_1 = 3$ volt, $E_2 = 2$ volt, $E_3 = 1$ volt and $R = r_1 = r_2 = r_3 = 1$ ohm.

(a) Find the potential difference between the points A and B and the current through each branch.

(b) If r_2 is short circuited and the point A is connected to point B, find the currents through E_1, E_2, E_3 and the resistor R.

[IIT, 1981]



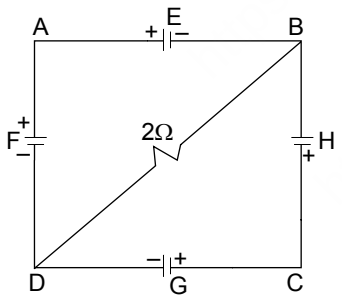
[**Ans.** (a) 2 volt, (b) 1 ampere, 2 ampere, –1 ampere]

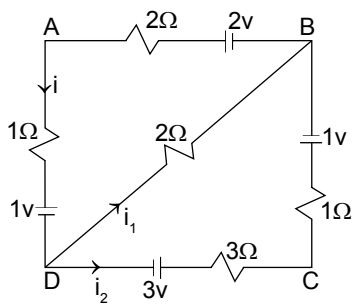
23. In the circuit shown in the figure, E, F, G, H are cells of emf 2, 1, 3 and 1 volt and their internal resistances are 2, 1, 3 and 1 ohm respectively. Calculate:

(a) the potential difference between B and D, and

(b) the potential difference across the terminals of each of the cells G and H.

[IIT, 1981]





[**Ans.** (a) $\frac{2}{13}$ volt, (b) Potential difference across the cell G = 1.61 V, Potential difference across the cell = 1.46 V]

24. A hollow copper tube of 5 m length has got external diameter equal to 10 cm and the walls are 5 mm thick.

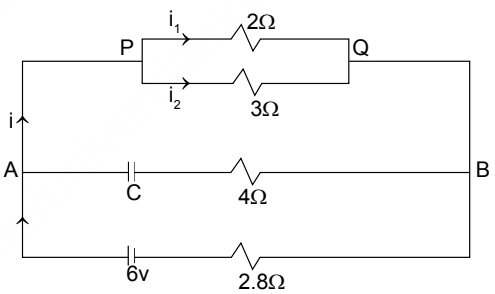
If specific resistance of copper is 1.7 × 10^{-8} ohm × meter, calculate the resistance of the tube.

[MNR, 1982]

[**Ans.** 5.69 × 10^{-5} Ω]

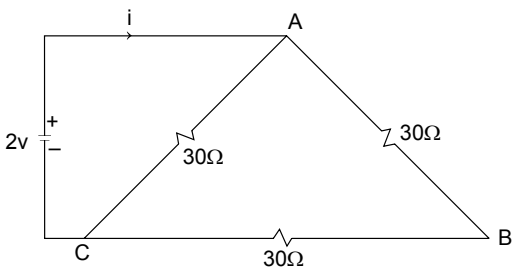
25. Calculate the steady state current in a 2 Ω resistor shown in the figure. The internal resistance of the battery is negligible and the capacitance of the condenser is 0.2 μ*F*.

[IIT, 1982]



[**Ans.** 0.9 A]

26. Find the curreAnt *I* in the circuit shown in the figure.

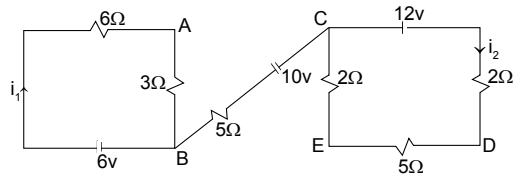


[IIT, 1983]

[**Ans.** 0.1 A]

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27. Find the potential difference between the points *A* and *D* of the circuit shown in the figure.

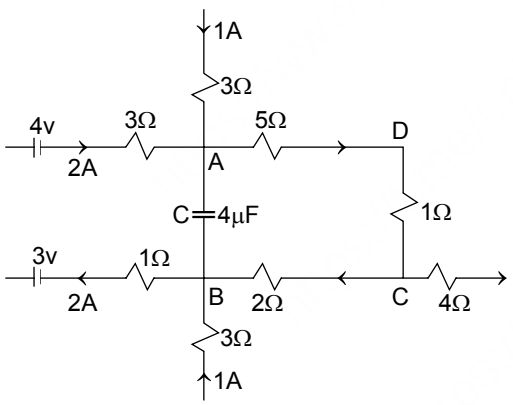


[**Ans.** 2.67 volts]

28. A 220 volt 100 watt bulb is connected to 110 volt source. Calculate the power consumed by the bulb. [Roorkee, 1986]

[**Ans.** 25 watts]

29. A part of the circuit in a steady state along with the currents flowing in the branches, the value of resistance etc. is shown in the figure. Calculate the energy stored in the capacitor *C* (4 μ*F*). [IIT, 1986]



[**Ans.** 0.8×10^{-3} joule]

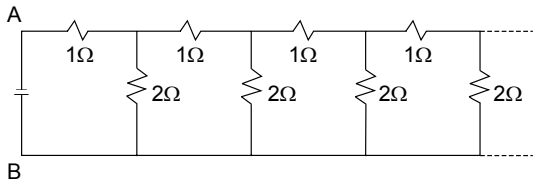
30. An electric bulb rated for 500 watt at 100 volt is used in a circuit having a 200 volt supply. Calculate the resistance *R* that one must put in series with the bulb, so that the bulb delivers 500 watt. [IIT, 1987]

[**Ans.** 20 ohms]

32. An infinite ladder network of resistance is constructed with 1 ohm and 2 ohm resistances as shown in the figure. The 6-volt battery between *A* and *B* has negligible resistance.

(a) **Show that the effective resistance between *A* and *B* is 2 ohm.**

(b) **What is the current that passes through the 2 ohm resistance nearest the battery. [IIT, 1987, Roorkee, 1989]**



[**Ans.** (a) 2 ohm or –1 ohm (b) 1.5 A]

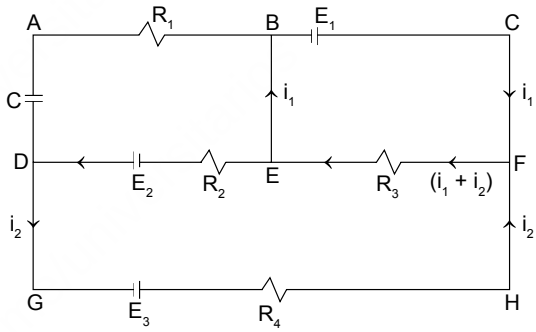
31. In the given circuit,

$$E_1 = 3E_2 = 2E_3 = 6 \text{ volts}$$

$$R_1 = 2R_4 = 6 \text{ ohm}$$

$$R_3 = 2R_2 = 4 \text{ ohm}$$

$$C = 5\mu F$$



Find the current in R_3 and the energy stored in the capacitor. [IIT, 1988]

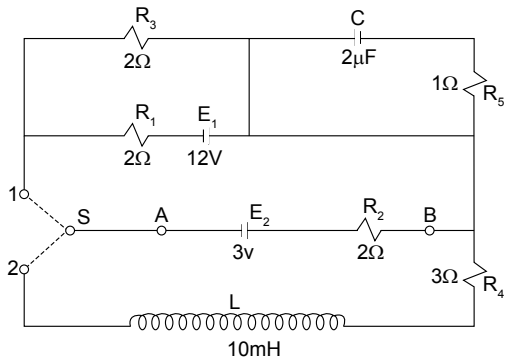
[**Ans.** (a) 1.5 A, from F to E. 14.4×10^{-6} joule]

32. A cell of emf 3.4 volt and internal resistance 3 Ω is connected to an ammeter having resistance 2 ohm and to an external resistance of 100 ohm. When a voltmeter is connected across the 100 ohm resistance the ammeter reading is 0.04 amp. Find the voltage read by the voltmeter and its resistance. Had the voltmeter been an ideal one, what would have been its reading? [Roorkee, 1990]

[**Ans.** Voltage read by the voltmeter 3.2 volts, 3.238 volts.]

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33. A circuit containing a two-position switch *S* is shown in the figure.



(a) **The switch is in position 1. Find the potential difference $V_A - V_B$ and the rate of production of Joule heat in R_1.**

(b) **If now the switch S is put in position 2 at $t = 0$, find**

(i) **steady current in R_4 and**

(ii) **the time when the current in R_2 is half the steady value. Also calculate the energy stored in the inductor *L* at that time.**

[IIT, 1991]

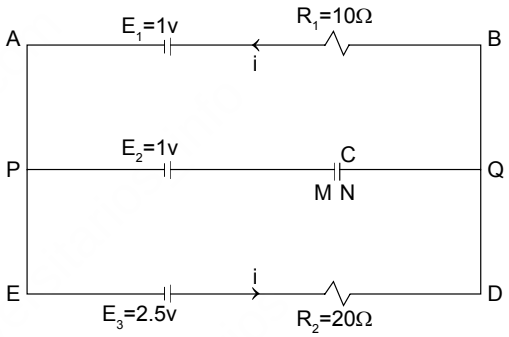
[**Ans.** (a) $V_A - V_B = -5$ volt, (b) (i) $i = 0.6$ A, (ii) $t = 0.0014$ second]

34. A thermocouple circuit consists of two thermal junctions and a low resistance galvanometer, all in series. The galvanometer has a resistance of 8 ohm and the rest of the circuit a resistance of 1.6 ohm. The thermocouple develops an emf of 10 microvolt per degree Celsius difference of temperature between the two junctions. When one junction is kept at 0°C and the other in a molten metal, the galvanometer reads 8 millivolt. What is the temperature of the molten metal? You may assume that the emf varies linearly with the temperature difference.

[MNR, 1992]

[**Ans.** $t = 960$°C]

35. Find the potential difference across the plates of capacitor *C* in the circuit shown in the figure.



[**Ans.** 0.5 volt]

36. The scale of a galvanometer is divided into 150 equal divisions. The galvanometer has the current sensitivity of 10 divisions per mA and the voltage sensitivity of 2 divisions per *mV*. How the galvanometer be designed to read

(a) **6 A per division, and**

(b) **1 V per division?** **[Roorkee, 1999]**

[**Ans.** (a) $S \approx 1.67 \times 10^{-5}$ R Ω,
(b) $R' = 2 \times 10^3$ R Ω]

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QUESTION BANK

CONCEPTUAL QUESTIONS

1. Ammeters often contains fuses that protect them from large currents, while voltmeters seldom do. Explain.

2. When batteries are connected in parallel, they should have the same emf. However, batteries connected in series need not have the same emf. Explain

3. Why do light bulbs usually burn out just after they are switched on and not when they have been on for a while?

4. When electrons drift in a metal from lower to higher potential, does it mean that all the 'free' electrons of the metal are moving in the same direction?

5. Think of a wire of length L as two wires of length $L/2$ in series. Construct an argument for why the resistance of a wire must be proportional to its length.

6. Why are electric stoves and clothes dyres supplied with 240V, but lights, radios and clocks are supplied with 120 V?

7. Is the electric field inside a conductor always zero? If not, when it is not zero? Explain.

8. Are the paths of electrons straight lines between successive collisions (with the positive ions of the metal) in the (i) absence of electric field, (ii) presence of electric field?

9. A friend says that electric current "follows the path of least resistance." Is that true? Explain.

10. The electron drift speed is estimated to be only a few mm s^{-1} for currents in the range of a few amperes? Then how is current established almost instant when a circuit is closed?

11. Some batteries can be "recharged". Does that mean that the battery has a supply of charge that is depleted as the battery is used? If "recharging" does not literally mean to put charge back into the battery, what does it mean?

12. The electron drift arises due to the force experienced by electrons in the electric field inside the conductor. But force should cause acceleration. Why then do the electrons acquire a steady average drift speed?

13. Why does the resistivity of a metallic conductor increase with increasing temperature?

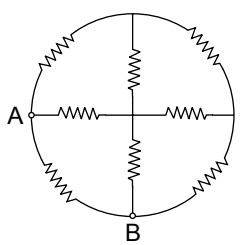
14. A 15-A circuit breaker trips repeatedly. Explain why it would be dangerous to replace it with a 20-A circuit breaker.

15. Why are ammeters connected in series with a circuit element in which the current is to be measured and voltmeters connected in parallel across the element for which the potential difference is to be measured?

16. If the electron drift speed is so small, and the electron's charge is small, how can we still obtain large amounts of current in a conductor?

ONLY ONE OPTION IS CORRECT

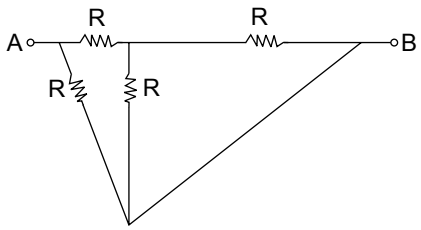
1. Eight resistances each of resistance 5 W are connected in the circuit shown in figure. The equivalent resistance between A and B is



(a) (8/3) Ω (b) (16/3) Ω
(c) (15/7) Ω (d) (19/2) Ω

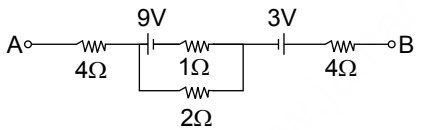
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2. The equivalent resistance between points A and B is



(a) $2R$ (b) $(3/4)R$
(c) $(4/3)R$ (d) $(3/5)R$

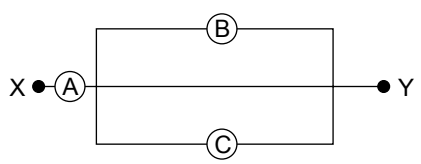
3. In the circuit shown in figure, potential difference between points A and B is 16 V. The current passing through 2Ω resistance will be



(a) $2.5A$ (b) $3.5A$
(c) $4.0A$ (d) zero

4. At what temperature would the resistance of a copper conductor be doubled of its value at 0ºC. Does this same temperature hold for all copper conductors regardless of shape and size? $\alpha_{Cu} = 4.0 \times 10^{-3}$/ºC.
(a) 250ºC (b) 50ºC
(c) 150ºC (d) 200ºC

5. Three voltmeters A, B and C having resistances R, 1.5 R and $3R$, respectively, are connected as shown. When come potential difference is applied between X and Y, the voltmeter readings are V_A, V_B and V_C respectively. Then

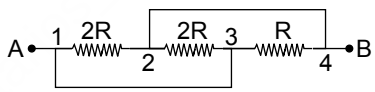


(a) $V_A \neq V_B = V_C$ (b) $V_A = V_B \neq V_C$
(c) $V_A \neq V_B = V_C$ (d) $V_A = V_B = V_C$

6. An electric bulb rated for 500 W at 100 V is used in a circuit having a 200 V supply. The resistance R that must be put in series with the bulb, so that the bulb draws 500 W is
(a) 100Ω (b) 50Ω
(c) 20Ω (d) 10Ω

7. The length of a potentiometer wire is ℓ. A cell of emf E is balanced at a length $\ell/3$ from the positive end of the wire. If the length of the wire is increased by $\ell/2$. At what distance will the same cell give a balance point?
(a) $2\ell/3$ (b) $\ell/2$
(c) $\ell/6$ (d) $4\ell/3$

8. Find equivalent resistance between the points A and B.



(a) $R/2$ (b) $R/4$
(c) R (d) $R/8$

9. Temperature of a resistance at temperature tºC is $R = R_0(1 + at + bt^2)$. Here R_0 is the temperature at 0ºC. the temperature coefficient of resistance at temperature t is

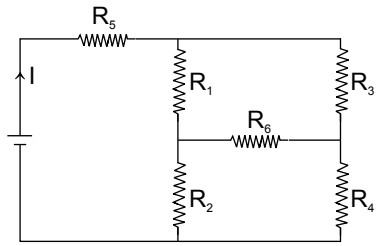
(a) $\dfrac{a+2bt}{1+at+bt^2}$ (b) $(a + 2bt)$

(c) $\dfrac{1+at+bt^2}{a+2bt}$ (d) constant

10. Calculate the drift velocity of electrons in silver wire with cross-sectional area 3.14×10^{-6}m^2 carrying a current of 20 A. Given atomic weight of $Ag = 108$, density of silver $= 10.5 \times 10^3$ kg/m^3
(a) 2.798×10^{-4}m/sec
(b) 67.98×10^{-4}m/sec
(c) 0.67×10^{-4}m/sec
(d) 6.798×10^{-4}m/sec

11. In the given circuit, it is observed that the current I is independent of the value of the resistance R_6. Then the resistance values must satisfy

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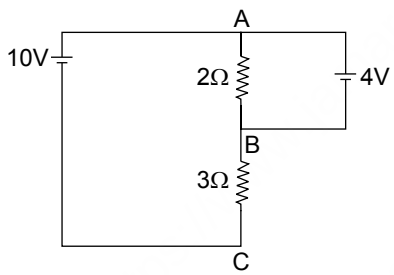
(a) $R_1R_2R_5 = R_3R_4R_6$

(b) $\frac{1}{R_5}+\frac{1}{R_6}=\frac{1}{R_1+R_2}+\frac{1}{R_3+R_4}$

(c) $R_1R_4 = R_2R_3$

(d) $R_1R_3 = R_2R_4 = R_5R_6$

12. Current passing through 3Ω resistance is



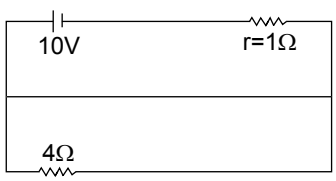
(a) (14/3) *A*

(b) 3 *A*

(c) 2 *A*

(d) (12/5) *A*

13. Potential difference across the terminals of the battery shown in figure is – (*r* = internal resistance of battery)



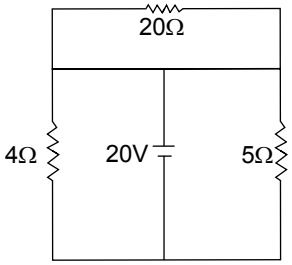
(a) 8 V

(b) 10 V

(c) 6 V

(d) zero

14. In the circuit shown in figure



(a) current passing through 2Ω resistance is zero

(b) current passing through 4Ω resistance is 5 *A*

(c) current passing through 5Ω resistance is 4 *A*

(d) all of the above

15. A voltmeter with resistance 500 W is used to measure the emf of a cell of internal resistance 4Ω. The percentage error in the reading of the voltmeter will be

(a) 0.2%

(b) 0.8%

(c) 1.4%

(d) 2.2%

16. Find the resistance of galvanometer in which maximum deflection of 50 div is reduced to 20 div when shunted by a 12 Ω resistance.

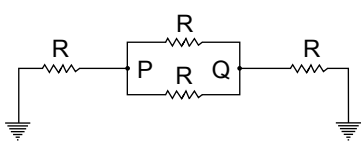
(a) 8Ω

(b) 18Ω

(c) 12Ω

(d) 10Ω

17. The net resistance between point *P* and *Q* in the circuit shown in figure is

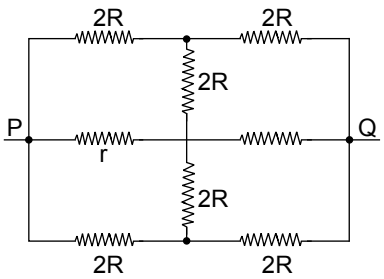


(a) *R*/2 (b) 2*R*/5

(c) 3*R*/5 (d) *R*/3

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18. The effective resistance between points P and Q of the electrical circuit shown in the figure is



(a) $\frac{2Rr}{R+r}$ (b) $\frac{8R(R+r)}{3R+r}$

(c) $2r + 4R$ (d) $\frac{5R}{2+2R}$

19. All the edges of a block with parallel faces are unequal. Its longest edge is twice its shortest edge. The ratio of the maximum to minimum resistance between parallel faces is

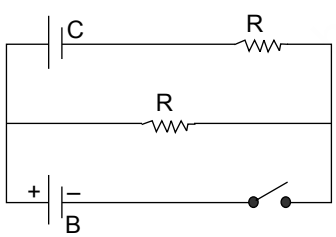
(a) 2

(b) 4

(c) 8

(d) indeterminate unless the length of the third edge is specified

20. In the circuit shown, when the switch is closed, the capacitor charges with a time constant



(a) RC (b) $2RC$

(c) $(1/2)RC$ (d) $RC \ln 2$

21. Calculate the relaxation time and mean free path in Cu at room temperature 300 K, if number density of free electrons is $8.5 \times 10^{28}/m^3$ and resistivity $\rho = 1.7 \times 10^{-8}$ mho-m. Given $k = 1.38 \times 10^{-23}$J/K.

(a) 25 Å (b) 20 Å

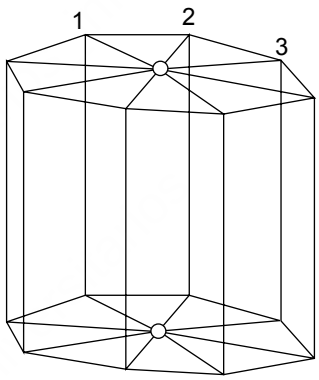
(c) 5 Å (d) 30 Å

22. A battery is suppling power to a tape-recorder by cable of resistance of 0.02 Ω. If the battery is generating 50 W power at 5 V, then power received by tape-recorder is

(a) 50 W (b) 45 W

(c) 30 W (d) 48 W

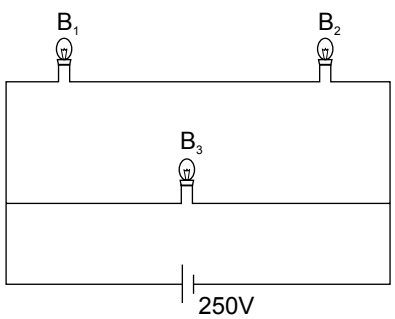
23. In the diagram shown, all the wires have resistance R. The equivalent resistance between the upper and lower dots shown in the diagram is



(a) $R/8$ (b) R

(c) $2R/5$ (d) $3R/8$

24. A 100 W bulb B_1 and two 60 W bulbs B_2 and B_3, are connected to a 250 V source, as shown in the figure. Now W_1, W_2 and W_3 are the output powers of the bulbs B_1, B_2 and B_3 respectively. Then



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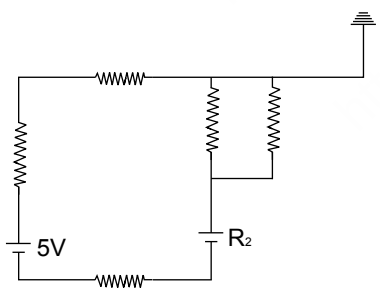
(a) $W_1 > W_2 = W_3$
(b) $W_1 > W_2 > W_3$
(c) $W_1 < W_2 = W_3$
(d) $W_1 < W_2 < W_3$

25. A capacitor is charged and then made to discharge through a resistance. The time constant is t. In what time will the potential difference across the capacitor decrease by 10%?
(a) $t \ln (0.1)$ (b) $t \ln (0.9)$
(c) $t \ln (10/9)$ (d) $t \ln (11/10)$

26. A uniform wire has electric resistance R. The wire is cut into n equal parts. All wires are put parallel to each other and joined at the ends. The resistance of the combination is
(a) R/n (b) R/n^2
(c) R (d) none of these

27. A galvanometer of resistance 12Ω shows full scale deflection for a current of 2.5 mA. How will you convert it to ammeter of range 7.5 A and voltmeter of range 10 volt. Resistance of metre is
(a) 2000Ω (b) 5000Ω
(c) 400Ω (d) 4000Ω

28. In the circuit shown, each resistances is 2Ω. The potential V_1 as indicated in the circuit, is equal to

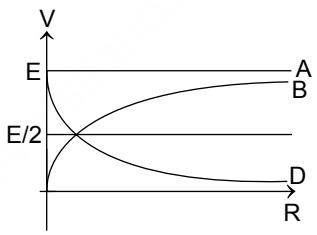


(a) 11 V (b) –11 V
(c) 9 V (d) –9 V

29. To get maximum current through a resistance of 2.5Ω, one can use 'm' rows of cells, each row having 'n' cells. The internal resistance of each cell is 0.5Ω. What are the values of n and m, if the total number of cells is 45?
(a) 3, 15 (b) 5, 9
(c) 9, 5 (d) 15, 3

30. A battery of internal resistance 2Ω is connected to a variable resistor whose value can vary from 4Ω to 10Ω. The resistance is initially set at 4Ω. If the resistance is now increased then
(a) power consumed by it will decrease
(b) power consumed by it will increase
(c) power consumed by it may increase or may decrease
(d) power consumed will first increase then decrease

31. A cell of emf E having an internal resistance 'r' is connected to an external resistance R. The potential difference 'v' across the resistance R varies with R as shown by the curve



(a) A (b) B
(c) C (d) D

32. 'n' identical light bulbs, each designed to draw P power from a certain voltage supply are joined in series and that combination is connected across that supply. The power consumed by one bulb will be
(a) nP (b) P
(c) P/n (d) P/n^2

33. Two long coaxial and conducting cylinders of radius a and bare separated by a material of conductivity σ and a constant potential difference V is maintained between them, by a battery. Then the current, per unit length of the cylinder flowing from one cylinder the other is

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(a) $\frac{4\pi\sigma}{\ln(b/a)}$V (b) $\frac{4\pi\sigma}{(b+a)}$V

(c) $\frac{2\pi\sigma}{\ln(b/a)}$V (d) $\frac{2\pi\sigma}{(b+a)}$V

34. How many electrons flow through the filament of a 120 volt, 60 W electric lamp in one second?

(a) 3.125×10^{18} (b) 31.25×10^{18}

(c) 0.3×10^{18} (d) 312.5×10^{18}

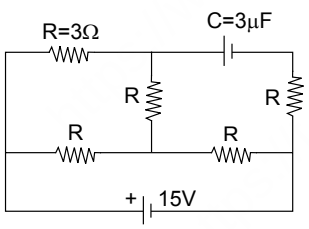
35. The charge on a capacitor decreases h times in time t, when it discharges through a circuit with a time constant t

(a) $t = ht$ (b) $t = h \ln t$

(c) $t = t(\ln h - l)$ (d) $t = \tau \ln\left(1 - \frac{1}{\eta}\right)$

36. In the circuit shown, the cell is ideal, with emf = 15 V. Each resistance is of 3 W.

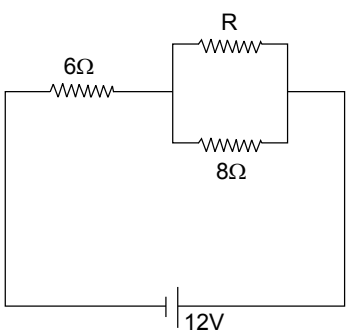
The potential difference across the capacitor is



(a) zero (b) 9 V

(c) 12 V (d) 15 V

37. In the circuit shown in figure, the power which is dissipated as heat in the 6Ω resistor is 6 W. What is the value of resistance R in the circuit?



(a) 6Ω

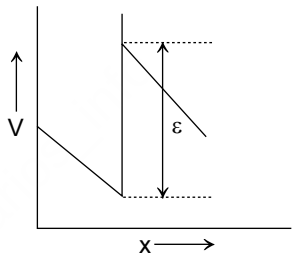
(b) 10Ω

(c) 13Ω

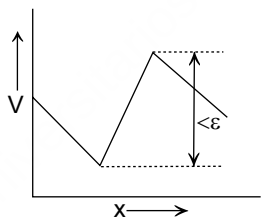
(d) 24Ω

38. The two ends of a uniform conductor are joined to a cell of emf e and some internal resistance. Starting from the midpoint P of the conductor, we move in the direction of the current and return to P. The potential V at every point on the path is plotted against the distance covered (x). Which of the following best represents the resulting curve?

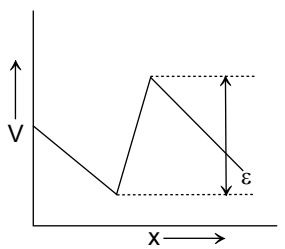
(a)



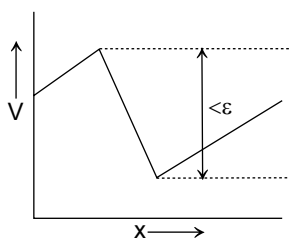
(b)



(c)

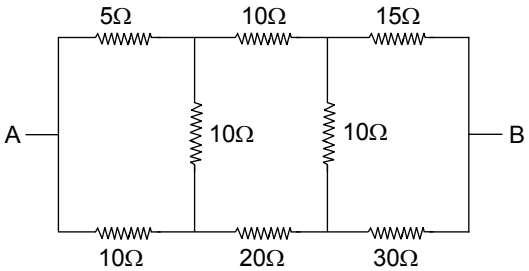


(d)



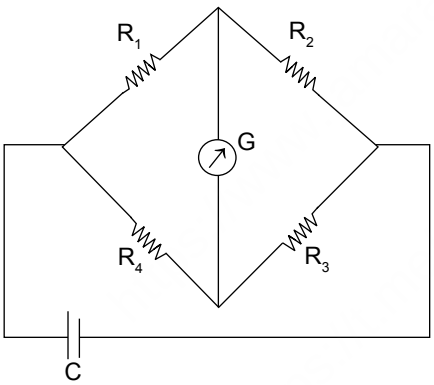
39. Calculate the effective resistance between A and B in following network.

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(a) 5Ω (b) 10Ω
(c) 20Ω (d) 30Ω

40. The Wheatstone bridge shown in the figure is balanced. If the positions of the cell C and the galvanometer G are now interchanged, G will show zero deflection



(a) in all cases
(b) only if all the resistances are equal
(c) only if $R_1 = R_3$ and $R_2 = R_4$
(d) only if $R_1/R_3/R_2/R_4$

41. A current of 0.5 A is passing through a $CuSO_4$ solution. How many Cu^{++} ions will be deposited on cathode in 10 second?
(a) 0.15×10^{19} (b) 4×10^{19}
(c) 15.625×10^{19} (d) 1.5625×10^{19}

42. In case of hydrogen atom an electron moves in an orbit of radius 5×10^{-11} m with a speed of 2.2×10^6 m/s. Calculate equivalent current.
(a) 1.12 mA (b) 0.12 mA
(c) 1.2 mA (d) 2 mA

43. Three resistances R, $2R$ and $3R$ are connected in parallel to a battery. Then
(a) The potential drop across $3R$ is maximum
(b) The current through each resistance is same
(c) The heat developed in $3R$ is maximum
(d) The heat developed in R is maximum.

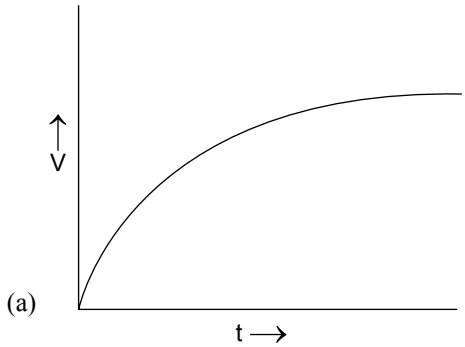
44. An ammeter and a voltmeter are joined in series to a cell. Their readings are A and V respectively. If a resistance is now joined in parallel with the voltmeter.
(a) both A and V will increase
(b) both A and V will decrease
(c) A will decrease, V will increase
(d) A will increase, V will decrease.

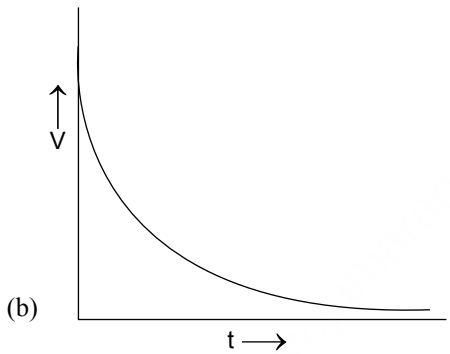
45. A wire of length L and 3 identical cells of negligible internal resistances are connected in series. Due to the current, the temperature of the wire is raised by ΔT in a time t. A number N of similar cells is now connected in series with a wire of the same material and cross-section but of length $2L$. the temperature of the wire is raised by the same amount ΔT in the same time t. The value of N is
(a) 4 (b) 3
(c) 8 (d) 9

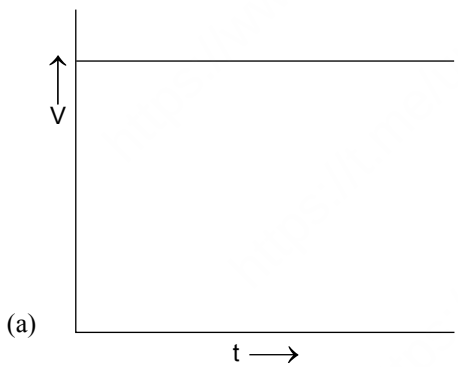
46. In the given circuit, it is observed that the current I is independent of the value of the resistance R_6. Then the resistance values must satisfy
(a) $R_1R_2R_5 = R_3R_4R_6$
(b) $\frac{1}{R_5} + \frac{1}{R_5} = \frac{1}{R_1 + R_2} + \frac{1}{R_3 + R_4}$
(c) $R_1R_4 = R_2R_3$
(d) $R_1R_3 = R_2R_4 = R_5R_6$

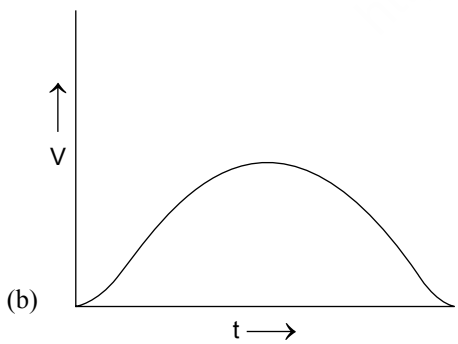
47. An ideal cell is connected to a capacitor and a voltmeter in series. The reading V of the voltmeter (added in parallel with resistor) is plotted against time. Which of the following best represents the resulting curve?

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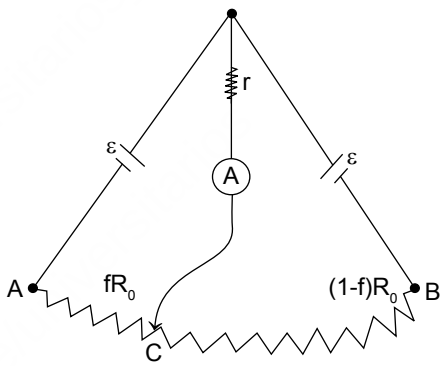


48. A wire of resistance 10Ω is bent to form a circle. P and Q are the points on the circumference of the circuit dividing it into a quadrant and are connected to a 3 V battery having internal resistance 1Ω as shown in the figure. The currents in the two parts of the circle are

(a) (5/26) A and (15/26) A
(b) (4/25) A and (12/25)A
(c) (3/35) A and (9/25) A
(d) (6/23) A and (18/23)A

49. Figure shows a wire of uniform resistance between A and B with a total resistance of R_0. The contact C can divide the wire into resistances fR_0 and $(1-f)R_0$.

The batteries are identical and have zero internal resistances. The value of f for which ammeter reads maximum is



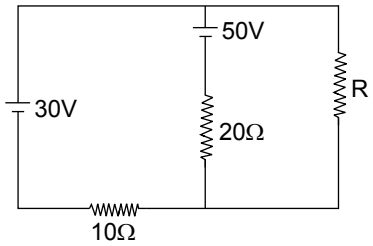
(a) 0
(b) 1
(c) 0 or 1
(d) Cannot be found

50. 50 V battery is supplying current of 10 amp when connected to a resistor. If the efficiency of battery at this current is 25%. Then internal resistance of battery is

(a) 2.5Ω
(b) 3.75Ω
(c) 1.25Ω
(d) 5Ω

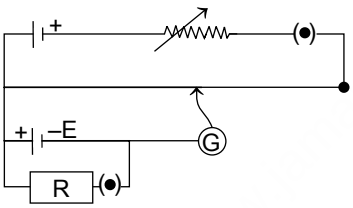
51. In the circuit shown, the value of R in ohm that will result in no current through the 30 V battery, is

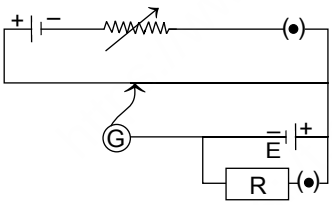
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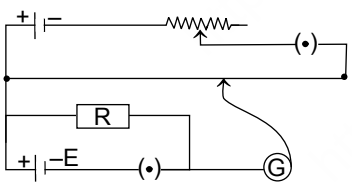


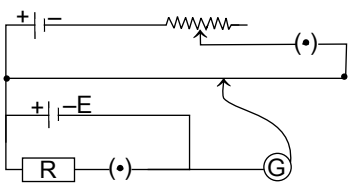
(a) 10Ω (b) 25Ω
(c) 30Ω (d) 40Ω

52. The correct circuit for the determination of internal resistance of a primary cell by using potentiometer is

(a)


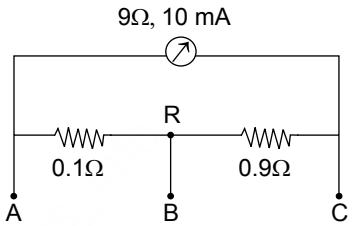
(b)


(c)


(d)


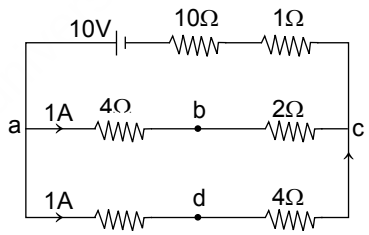
53. A piece of copper and another of germanium are cooled from room temperature to 80°K. The resistance of
(a) Each of them increases
(b) Each of them decreases
(c) Copper increases and germanium decreases
(d) Copper decreases and germanium increases

54. A milliammeter of range 10 mA and resistance 9Ω is joined in a circuit as shown. The metre gives full-scale deflection for current I when *A* and *B* are used as its terminals, i.e., current entres at *A* and leaves at *B* (*C* is left isolated). The value of I is



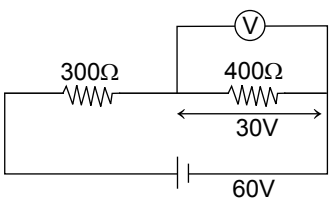
(a) 100 mA (b) 900 mA
(c) 1 A (d) 1.1 A

55. Calculate potential difference between points *d* and *b* in the circuit.



(a) 2 volt (b) 1 volt
(c) 5 volt (d) 8 volt

56. When a voltmeter is connected across a 400Ω resistance, it reads 30 V. When it is connected with 300Ω resistance, it will read

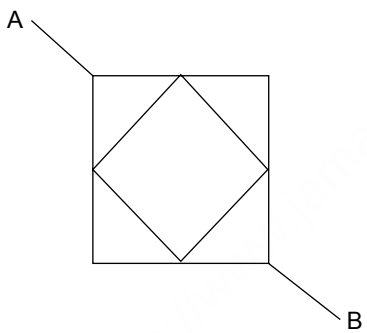


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(a) 30 V (b) 22.5 V
(c) 20 V (d) 25 V

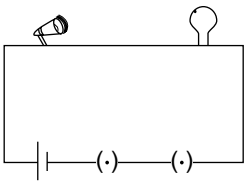
57. The charge flowing through a resistance R varies with time t as $Q = at - bt^2$. The total heat produced in R by the time current ceases is
(a) $a^3R/6b$ (b) $a^3R/3b$
(c) $\frac{a^3R}{2b}$ (d) $\frac{a^3R}{b}$

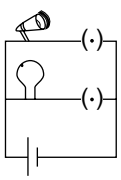
58. A wire has linear resistance ρ (in Ohm/m). Find the resistance R between points A and B if the side of the larger square is 'd'.

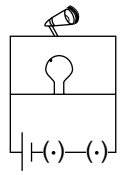


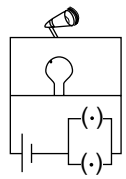
(a) $\rho d/\sqrt{2}$
(b) $\sqrt{2}\,\rho d$
(c) $2\,\rho d$
(d) None of these

59. In the house of a person who is weak of hearing, a light bulb is also lit when somebody rings the door bell. The ring can be operated both from the garden gate and from the door of the house. Select the correct possible circuit required.

(a)


(b)


(c)


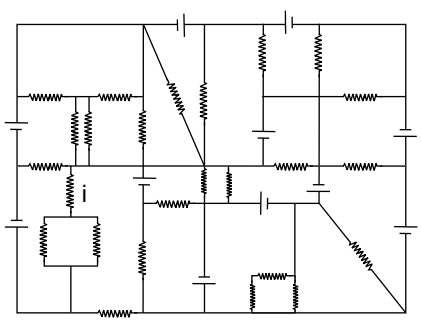
(d)


60. n identical cells, each of emf ε and internal resistance r, are joined in series to form a closed circuit. One cell (A) is joined with reversed polarity. The potential difference across each cell, except A, is
(a) $\frac{2\varepsilon}{n}$ (b) $\frac{n-1}{n}\varepsilon$
(c) $\frac{n-2}{n}\varepsilon$ (d) $\frac{n-2}{n}\varepsilon$

61. In the circuit, the heat produced in the 5 ohm resistor due to the current flowing through it is 10 calories per second. The heat generated in the 4 ohms resistor is
(a) 1 calorie/sec (b) 2 calories/sec
(c) 3 calories/sec (d) 4 calories/sec

62. The current i in the circuit (see figure) is
(a) (1/45) A (b) (1/15) A
(c) (1/10) A (d) (1/5) A

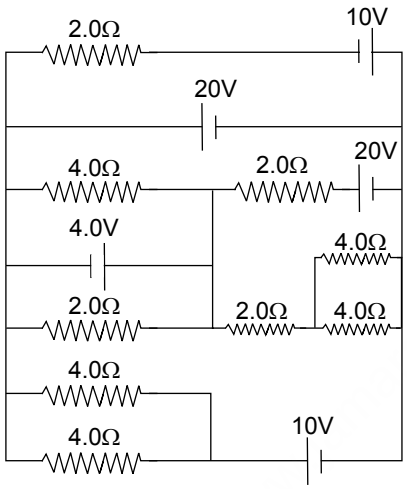
63. In the circuit shown, all resistances are of 4 Ω and all batteries have an emf 10 V. The current i is



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(a) 4 amp upward
(b) 4 amp downward
(c) 2 amp upward
(d) 2 amp downward

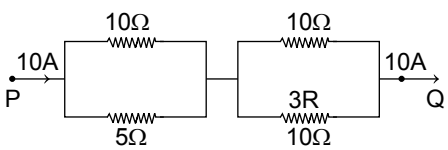
64. In the circuit shown, the current i_1 is



(a) 4 amp leftward
(b) 4 amp rightward
(c) 3 amp leftward
(d) 3 amp rightward

65. If two bulbs of power 25 W and 100 W respectively chrated at 220 V are connected in series with the supply of 440 V. Which bulb will fuse?
(a) 25 W bulb (b) 40 watts
(c) None of these (d) both 1 and 2

66. Four resistances carrying a current shown in the circuit diagram are immersed in a box containing ice at 0ºC. How much ice must be put in the box every 10 minutes to keep the average quantity of ice in the box constant?
(Latent heat of ice is 80 cal/gm)



(a) 5 kg (b) 1.19 kg
(c) 3 kg (d) 2.29 kg

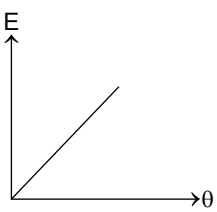
67. The thermo emf E (in volts) of a certain thermocouple is found to vary with θ (in ºC) according to equation $E = 20\theta - \theta^2/20$, where θ is temperature of the hot junction, the cold junction being kept at 0ºC. Then the neutral temperature of the thermocouple is
(a) 300ºC (b) 400ºC
(c) 100ºC (d) 200ºC

68. The thermo emf of a thermocouple is given by $E = 2164\ t - 6.2t^2$, where tºC is the temperature of hot junction and cold junction is at 0ºC. The values of neutral temperature and temperature of inversion will be
(a) 180ºC, 360ºC
(b) 170ºC, 340ºC
(c) 174.5ºC, 349ºC
(d) 166.4ºC, 332.8ºC

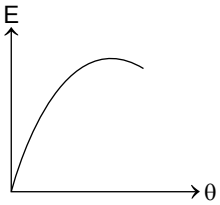
69. If 100 kwh of energy is consumed at 66 V in a copper voltmeter, then the mass of copper liberated will be (given e.c.e. of Cu = 0.33×10^{-6} kg C^{-1})
(a) 1.65 kg (b) 1.8 kg
(c) 3.3 kg (d) 3.6 kg

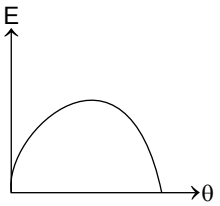
70. A heater with power rating 220 V, 1000 W heats a volume of water in 5 minute time. If the voltage drops to 110 V, then the time taken to heat the same amount of water will be
(a) 20 min. (b) 10 min.
(c) 5 min (d) 2.5 min.

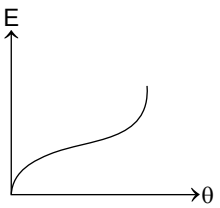
71. Which of the following graphs represent the variation of thermo emf(E) of a thermocouple with temperature θ of hot junction (the cold junction being kept at 0ºC)?

(a)


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(b)


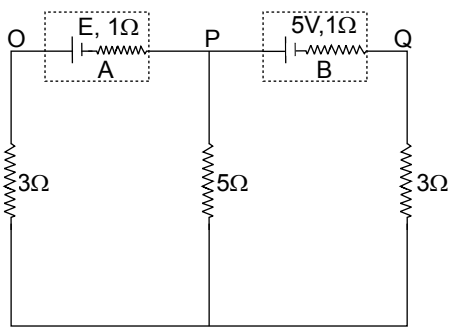
(c)


(d)


ONE OR MORE THAN ONE CHOICE MAY BE CORRECT

1. The charge flowing in a conductor varies with line as $Q = at - bt^2$. Then, the current
(a) decreases linearly with time
(b) reaches a maximum and then decreases
(c) fall to zero after time $t = a/2b$
(d) changes at a rate $-2b$

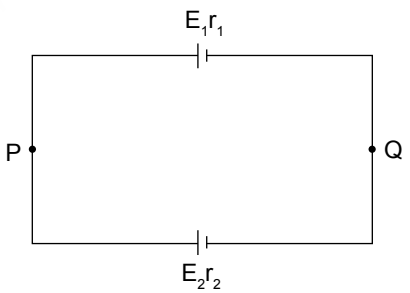
2. Two batteries A and B and three resistors are connected. Internal resistance of both batteries is 1Ω each as shown. EMF of battery B is 5 V, the potential difference between P and Q is zero. Which of the following is/are true?



(a) the current through 5Ω is 3A
(b) the current through the battery A is 8A
(c) the emf of the source A is 47A
(d) the *p.d.* between O and P is 8 V

3. In a potentiometer arrangement, E_1 is the cell establishing current in primary circuit, E_2 is the cell to be measured. AB is the potentiometer wire and G is a galvanometer. Which of the following is/are the essential condition/s for balance to be obtained.
(a) The emf of E_1 must be greater than the emf of E_2.
(b) Either the positive terminals of both E_1 and E_2 or the negative terminals of both E_1 and E_2 must be joined to one end of potentiometer wire.
(c) The positive terminals of E_1 and E_2 must be joined to one end of potentiometer wire.
(d) The resistance of G must be less than the resistance of AB

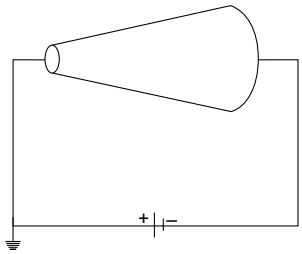
4. Two cells of unequal emfs E_1 and E_2 and internal resistances r_1 and r_2 are joined as shown in figure. V_p and V_Q are the potential at P and Q respectively.



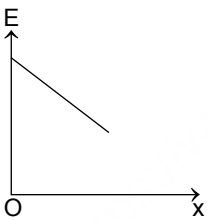
(a) The potential difference across both the cells will be equal.
(b) One of the cell, will supply energy to the other cell.
(c) The potential difference across one of the cells will be greater than its emf.
(d) $V_P - V_Q = \dfrac{E_1 r_2 + E_2 r_1}{r_1 + r_2}$

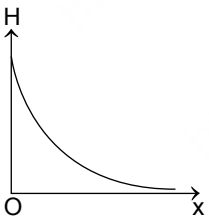
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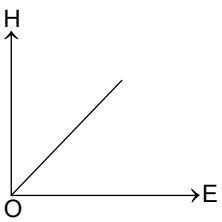
5. A conductor is made of an isotropic material and has shape of a truncated cone.

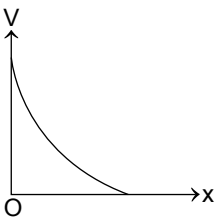


A battery of constant emf is connected across it and its left end is earthed as shown in figure. If at a section distance x from left end, electric field intensity, potential and the rate of generation of heat per unit length are E, V and H respectively, which of the following graphs is/are correct?

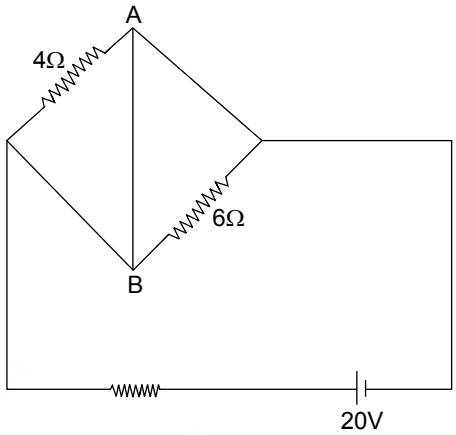
(a)


(b)


(c)


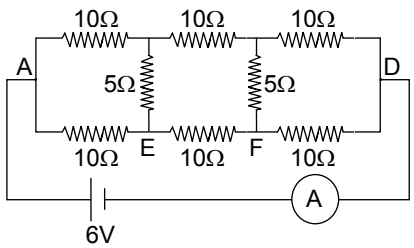
(d)


6. In the circuit shown in figure



(a) power supplied by the battery is 200 watt
(b) current flowing in the circuit is 5A
(c) potential difference across 4Ω resistance is equal to the potential difference across 6Ω resistance
(d) current in wire AB is zero

7. In the given circuit.



(a) Current measured by ammeter is 0.4 amp
(b) Potential of point C and F are equal
(c) Potential of point B and E are equal
(d) If 5 ohm resistances are replaced by 10 ohm resistance each, then current in all the 10 ohm resistance will be same.

8. Two heaters designed for the same voltage V have different power ratings. When connected individually across a source of voltage V, they produce H amount of heat

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each in times t_1 and t_2 respectively. When used together across the same source, they produce H amount of heat in time t

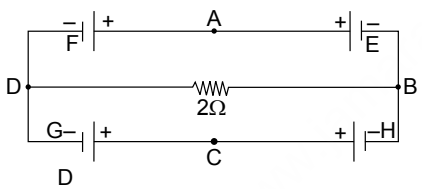
(a) if they are in series, $t = t_1 + t_2$

(b) if they are in series, $t = 2(t_1 + t_2)$

(c) if they are in parallel, $t = \dfrac{t_1 t_2}{(t_1 + t_2)}$

(d) if they are in parallel, $t = \dfrac{t_1 t_2}{2(t_1 + t_2)}$

9. In the circuit shown E, F, G and H are cells of e.m.f. 2 V, 1 V, 3 V and 1 V respectively and their internal resistance are 2Ω, 1Ω, 3Ω and 1Ω respectively.



(a) $V_D - V_B = -\dfrac{2}{13}V$

(b) $V_D - V_B = \dfrac{2}{13}V$

(c) $V_G = \dfrac{13}{21}V$ = Potential difference across

(d) $GV_H = \dfrac{19}{13}V$ = Potential difference across H.

10. Which of the following statements is/are correct?

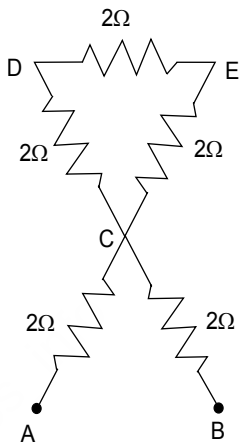
(a) Potential difference between terminals of a non-ideal battery can never be greater than its emf.

(b) If a non-ideal battery is short circuited by a wire, heat generated in the wire is less than electric energy developed in the battery.

(c) EMF of an ideal battery is, first, measured by a potentiometer and than by a voltmeter. Both the measurements are equally correct.

(d) The terminal potential difference of a battery can never be zero in any closed circuit containing other batteries.

11. For the circuit shown in the figure,



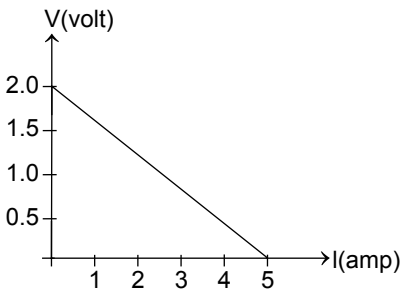
(a) $R_{AB} = 4\Omega$

(b) $R_{CD} = 4/3\Omega$

(c) $R_{CE} = 4/3\Omega$

(d) $R_{CD} = 1/3\Omega$

12. For a cell, a graph is plotted between the potential difference V across the terminals of the cell and the current I drawn from the cell. The e.m.f. and internal resistance of the cell is E and r respectively.



(a) $E = 2$ V, $r = 0.5\Omega$

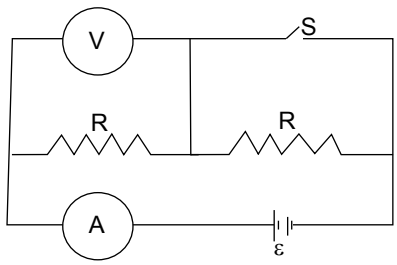
(b) $E = 2$ V, $r = 0.4\Omega$

(c) $r = 0.4\Omega$

(d) $r = 0.5\Omega$

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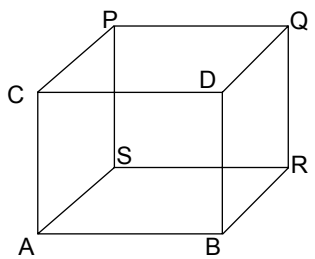
13. The diagram shows a circuit with two identical resistors. The battery has a negligible internal resistance. When switch *S* is closed



(a) Equivalent resistance of the circuit decreases
(b) Ammeter reading will increase
(c) Voltmeter reading will increase
(d) Power dissipated across *R* in right branch will become zero.

14. A uniform wire of resistance *R* is shaped into a regular *n*-sided polygon (*n* is even). The equivalent resistance between any two corners can have
(a) the maximum value *R*/4
(b) the maximum value *R/n*
(c) the minimum value $R\left(\frac{n-1}{n^2}\right)$
(d) the minimum value *R/n*

15. For the circuit shown in the figure, (each wire of resistance *r*). Then



(a) $R_{BP} = 5r/6$ (b) $R_{AR} = 3r/4$
(c) $R_{AQ} = 5r/6$ (d) $R_{AC} = 7r/12$

ASSERTION AND REASON QUESTIONS

Note: Each question contains STATEMENT-1 (Assertion) and STATEMENT-2 (Reason). Each question has 4 choices (a), (b), (c) and (d) out of which ONLY ONE is correct.

(a) Statement-1 is True, Statement-2 is True; Statement-2 is a correct explanation for Statement-1.
(b) Statement-1 is True, Statement-2 is True; Statement-2 is NOT a correct explanation for Statement-1.
(c) Statement-1 is True, Statement-2 is False.
(d) Statement-1 is False, Statement-2 is True.

1. **Statement 1:** When an electric current at the junction of two wires of same material is directed from the thick wire to the thin wire, the drift speed or electrons increases as they pass through this junction.
Statement 2: The drift speed of electrons is directly proportional to the electric field in the wire.

2. **Statement 1:** When a battery is short-circuited, the terminal voltage is zero.
Statement 2: In the situation of a short-circuit, the current is zero.

3. **Statement 1:** The equation $V = RI$ does not apply to those conducting devices which do not obey Ohm's law.
Statement 2: $V = RI$ is a statement of Ohm's law.

4. **Statement 1:** The emf of a battery equal the potential difference between its terminals when the terminals are not corrected externally.
Statement 2: Terminals potential difference can be greater than emf of cell.

5. **Statement 1:** A current flows in a conductor only when there is an electric field within the conductor.
Statement 2: The drift velocity of electron in presence of electric field decreases.

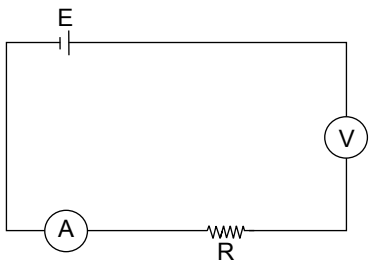
6. **Statement 1:** A resistor of resistance *R* is connected to an ideal battery. If the value of

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R is decreased, the power dissipated in the circuit will increase.

Statement 2: The power dissipated in the circuit is directly proportional to the resistance of the circuit.

7. **Statement 1:** All electric devices shown in the circuit are ideal. The reading of ammeter (A) is zero and that of voltmeter (V) is E.



Statement 2: An ideal voltmeter draws almost no current due to very large resistance, and hence (V) and (A) will read zero.

8. **Statement 1:** A potentiometer of longer wire is preferred to a potentiometer of shorter wire.

Statement 2: In case of longer wire, the potential gradient is small, and hence the measured value is more accurate.

9. **Statement 1:** The conductivity of molten electrolytes is smaller than the common metallic conductors.

Statement 2: Positive and negative ions flow in opposite directions.

10. **Statement 1:** The potential difference across a battery is always less than its emf.

Statement 2: Because $V = E \pm IR$

11. **Statement 1:** If ρ_1 and ρ_2 be the resistivities of the materials of two resistors of resistances R_1 and R_2 respectively and $R_1 > R_2$, then $\rho_1 > \rho_2$

Statement 2: The resistivity (ρ) doesn't depend on R.

12. **Statement 1:** The product of resistivity and conductivity of a conductor is constant.

Statement 2: Because each of resistivity and conductivity depends on the material of the conductor.

13. **Statement 1:** Voltmeter is much better than a potentiometer for measuring emf of cell.

Statement 2: A potentiometer draws no current while measuring emf of a cell.

14. **Statement 1:** A voltmeter and ammeter can be used together to measure resistance and power.

Statement 2: Resistance and power both are proportional to voltage and current.

15. **Statement 1:** A torch bulb give light if operated on AC of same voltage and current as DC.

Statement 2: Heating effect is common to both AC and DC.

16. **Statement 1:** Long distance power transmission is done at high voltage.

Statement 2: At high voltage supply power losses are less.

17. **Statement 1:** Resistance of 50 W bulb is greater than that of 100 W.

Statement 2: Resistance of bulb is inversely proportional to rated power.

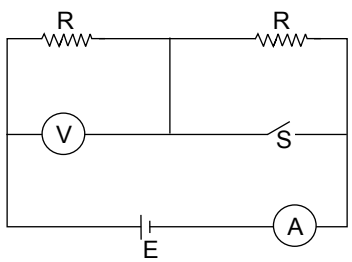
18. **Statement 1:** 40 W tube light give more light in comparison to 40 W bulb.

Statement 2: Light produced is same from same power.

MATCH THE COLUMN TYPE QUESTIONS

Each question contains statements given in two columns which have to be matched. Statements (A, B, C, D) in column I have to be matched with statements (p, q, r, s) in column II.

1. In the circuit shown, battery, ammeter and voltmeter are ideal and the switch S is initially as shown. What will be the changes in parameters as stated in left column if the switch S is opened? Possible changes are stated in right column.



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Column I	Column II
(a) Equivalent resistance across the battery	(p) Remains same
(b) Power dissipated by left resistance R	(q) Increases
(c) Voltmeter reading	(r) Decreases
(d) Ammeter reading	(s) Becomes zero

2. For a potentiometer circuit, match the column.

Column I	Column II
(a) Sensitivity	(p) increases with length of wire
(b) Accuracy	(q) decreases with length of wire
(c) Range	(r) increases with emf of primary cell
(d) Potential gradient	(s) maximum if internal resistance and rheostat resistance is zero.

3. Column II gives nature of temperature coefficient of resistance for materials written in column I.

Column I	Column II
(a) Metal	(p) Zero
(b) Insulator	(q) positive
(c) Semi-conductor	(r) negative
(d) Alloys	(s) unknown

4. A voltmeter and an ammeter are connected in series to an ideal cell of emf E. The voltmeter reading is V and the ammeter reading is I.

Column I	Column II
(a) Voltmeter resistance	(p) E – V
(b) Potential difference across ammeter	(q) V/I
(c) Voltmeter resistance plus ammeter resistance	(r) E/I
(d) Potential difference across voltmeter	(s) V

5. Column I gives physical quantities of a situation in which a current i passes through two rods I and II of equal length that are joined in series. The ratio of free electron density (n), resistivity (ρ) and cross-section area (A) of both are in ratio $n_1 : n_2 = 2 : 1$, $\rho_1:\rho_2 = 2 : 1$ and $A_1:A_2 = 1 : 2$ respectively. Column II gives corresponding results. Match the ratios in Column I with the values in Column II.

Column I

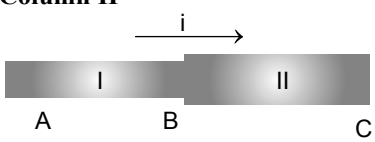
(a) $\dfrac{\text{Driff velocity of free electron in rod I}}{\text{Drift velocity of free electron in rod II}}$

(b) $\dfrac{\text{Electric field in rod I}}{\text{Electric field in rod II}}$

(c) $\dfrac{\text{Potential difference across rod I}}{\text{Potential difference across rod II}}$

(d) $\dfrac{\text{Average time taken by free elctron to move from } A \text{ to } B}{\text{Average time taken by free electron to move from } B \text{ to } C}$

Column II



(p) 0.5
(q) 1
(r) 2
(s) 4

6. Column II gives name of material used for device given in column I.

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	Column I		Column II
(a)	Resistance of resistance box	(p)	Tungsten
(b)	Fuse wire	(q)	manganin
(c)	Bulb	(r)	tin-leadalloy
(d)	Potentiometer wire	(s)	nichrome

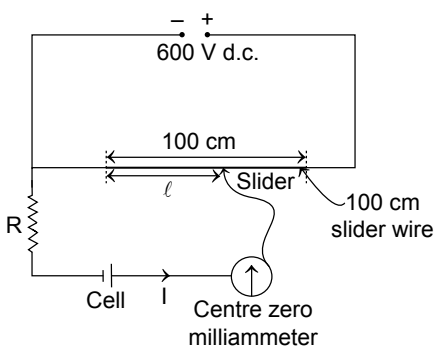
7. Column II gives order of resistivity for materials in column I.

	Column I		Column II
(a)	Semi-conductor	(p)	3×10^3 Ω-m
(b)	Conductor	(q)	10^{-8} Ω-m
(c)	Insulator	(r)	10^{16} Ω-m
(d)	Super conductor	(s)	1 Ω-m

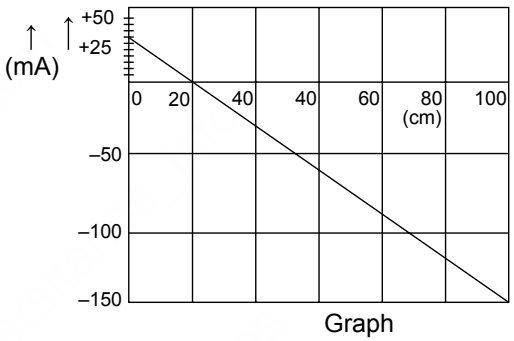
8. Match the column:

	Column I		Column II
(a)	Range and least amount of ammeter	(p)	Inverse relation
(b)	Least count and sensitivity of ammeter	(q)	Linear relation
(c)	Range and accuracy of ammeter	(r)	Quadratic relation
(d)	Range and multiplication factor of a voltmeter	(s)	Exponential relation

9. In the circuit shown below, the internal resistance of the cell is negligible. The distance of the slider from the left hand end of the slide wire is ℓ. The graph shows the variation with ℓ of the current I in the cell. Match the column:

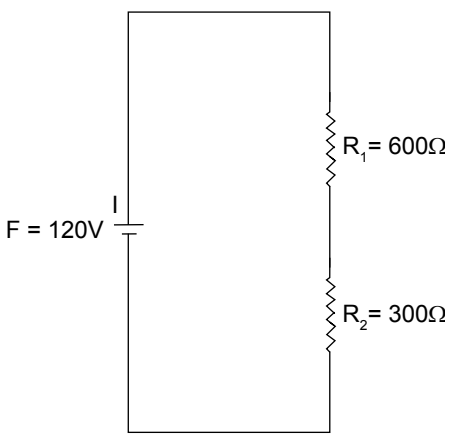


	Column I
(a)	The balance point is at length ℓ
(b)	E.M.F. of the cell
(c)	Value of the resistance R
(d)	Maximum emf that can be measured



	Column II
(p)	20 cm
(q)	1.20 V
(r)	30 ohm
(s)	6 V

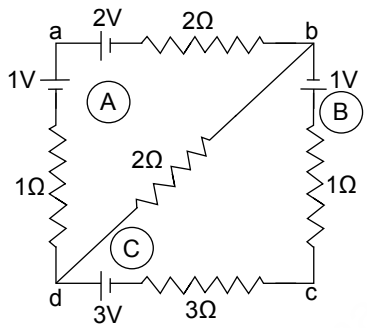
10. In the circuit, the battery is ideal. A voltmeter of resistance 600Ω is connected in turn across R_1 and R_2, giving readings V_1 and V_2 respectively.



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Column I	Column II
(a) V_1	(p) 30 volt
(b) V_2	(q) 60 volt
(c) Error in V_1 reading	(r) –20 volt
(d) Error in V_2 reading	(s) –10 volt

11. For the circuit shown in figure, match the columns:

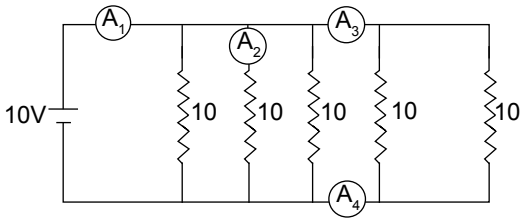


Column I		Column II
(a)	The current in *db*	(p) 1/13 amp
(b)	The PD across *db*	(q) 2/13 volt
(c)	The PD across the cell (*C*)	(r) 21/13 volt
(d)	The PD across the cell (*B*)	(s) 19/13 volt

12. Ammeter and voltmeter connected in the circuit are ideal. Then match the column.

Column I		Column II
(a)	Current passing through 3Ω resistance	(p) 6
(b)	Current passing through 10Ω resistance	(q) 2
(c)	Reading of ammeter	(r) 8
(d)	Reading of voltmeter	(s) 26

13. Column II gives reading of ideal ammeter A_1, A_2, A_3 and A_4 in ampere for the circuit shown.

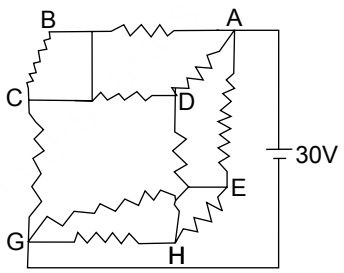


Column I	Column II
(a) A_1	(p) 2
(b) A_2	(q) 5
(c) A_3	(r) 1
(d) A_4	(s) 3

PASSAGE BASED QUESTIONS

PASSAGE–1

A resistor circuit is constructed such that twelve resistors are arranged to form a cube as shown in figure. Each resistor has a resistance of 2 Ohm.



The potential difference of 30 V is applied across two of the opposing points as shown.

1. The points having the same potential are
(A) *B, D, E* (B) *C, F, H* (C) *C, E*
(a) only (A) is correct
(b) (A), (B) and (C) are correct
(c) only (B) is correct
(d) both (A) and (B) are correct

2. If we replace resistors between *A* and *B* and resistors between *G* and *H* by resistors with wires of zero resistance, then the points having the same potential are
(A) *D, E, C, F* (B) *A, B*
(C) *G, H*

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(a) only (A) is correct
(b) only (B) is correct
(c) only (C) is correct
(d) (A), (B), (C) are correct

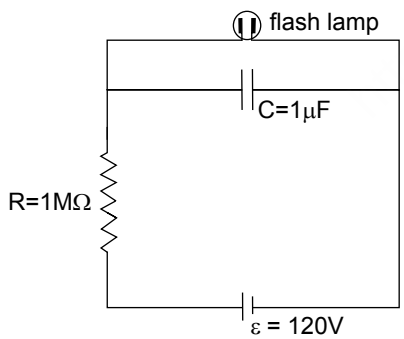
3. In the above question, the potential difference between the points *C* and *G* is
(a) 15 V (b) 10 V
(c) 20 V (d) 7.5 V

PASSAGE–2

A highway emergency flasher uses a 120 volt battery, a 1 MW resistor, a 1 mF capacitor, a neon flash lamp in the circuit shown in the figure. The flash lamp has a resistance more than 10^{10} W when the voltage across it is less than 110 V.

Above 110 V, the neon gas ionizes, the resistance of the lamp drops to 10 W, and the capacitor discharges completely. Until the capacitor voltage reaches the breakdown voltage V_b = 110 V, the large resistance of the flash lamp ensures that it draws a negligible current. The capacitor charges as if the lamp were absent. At V_b, however, the lamp resistance quickly becomes negligible, and the capacitor discharges through the lamp as if the battery and the series resistor were absent. The time between the flashes is the time for the capacitor to charge to V_b.

The flash duration is roughly the time for the capacitor to discharge through the lamp, or about the time constant of the capacitor-lamp circuit.



The flash energy is the stored energy in the capacitor at 110 volt.

4. The flash interval is found by solving for the time when the capacitor voltage is V_b = 110 V. ($V_b = \varepsilon(1 - e^{-t/CR})$, ln 12 = 2.5). The flash interval is
(a) 2 sec (b) 2/5 sec
(c) 5/2 sec (d) 1 sec

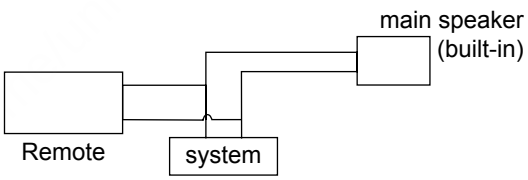
5. Time constant (τ_c) of the capacitor-lamp circuit is
(a) 20 μs (b) 15 μs
(c) 30 μs (d) 10 μs

6. Flash duration is
(a) 10 μs (b) 20 μs
(c) 30 μs (d) 5 μs

7. The energy in the flash is
(a) 6.1 mJ (b) 6.1 J
(c) 3 mJ (d) 12.2 mJ

PASSAGE–3

Most of the times we connect remote speakers to play music in another room along with the built-in speakers. These speakers are connected in parallel with the music system. At the instant represented in the picture, the a.c. voltage across the speakers is 6.00 V. The main speaker resistance is 8.00 Ω and the remote speaker has 4.00Ω resistance.



8. The equivalent resistance of the speakers is
(a) 12Ω (b) 4Ω
(c) 2.67Ω (d) 0.375Ω

9. The total current supplied by the music system is
(a) 2.25 *A* (b) 1 *A*
(c) 16 *A* (d) 1.5 *A*

10. The power dissipated in the speaker of 4.00 Ω resistance is
(a) 9 watts (b) 4.5 watts
(c) 13.5 watts (d) 0

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11. The total power delivered by the music system is

(a) 13.5 watts (b) 0

(c) 4.5 watts (d) 9 watts

PASSAGE–4

Potentiometer is an ideal voltmeter as voltmeter draws some current through the circuit while potentiometer needs no current to work. Potentiometer works on the principle of e.m.f. comparison. In working condition, a constant current flows through out the wire of potentiometer using standard cell of e.m.f.e_1. The wire of potentiometer is made of uniform material and cross sectional area and it has uniform resistance per unit length. The potential gradient, depends upon the current in the wire.

A potentiometer with a cell of e.m.f. 2 V and internal resistance 0.4Ω is used across the wire *AB*. A standard cadmium cell of e.m.f. 1.02 V gives a balance point at 66.3 cm length of wire. The standard cell is then replaced by a cell of unknown e.m.f.e and the balance point found similarly turns out to be 82.3 cm length of the wire. The length of potentiometer wire *AB* is 1 m.

12. The value of *e* is

(a) 1.26 V (b) 2.63 V

(c) 1.83 V (d) none

13. The reading of potentiometer if 4 V battery is used instead of *e*, is

(a) 88.3 cm

(b) 47.3 cm

(c) 95 cm

(d) can not be calculated

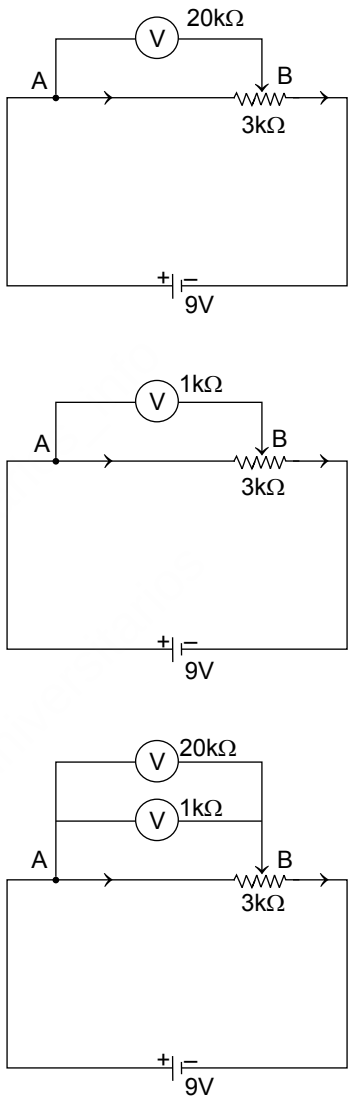
14. If the resistance is connected across the cell *e*, the balancing length will be

(a) increase (b) decrease

(c) remains same (d) None

SUBJECTIVE QUESTIONS

1. A battery of emf 9 V and negligible internal resistance is connected to a 3*k*Ω resistor. The potential drop across a part of the resistor (between points *A* and *B* in figure) is measured by (i) a 20*k*Ω voltmeter, (ii) a 1*k*Ω voltmeter. In (iii) both the voltmeters are connected across *AB*. In which case would you get the (1) highest, (2) lowest reading?



2. The current in a conductor is 5 *A* when the voltage between the ends of the conductor is 12 V.

(i) What is the resistance of the conductor?

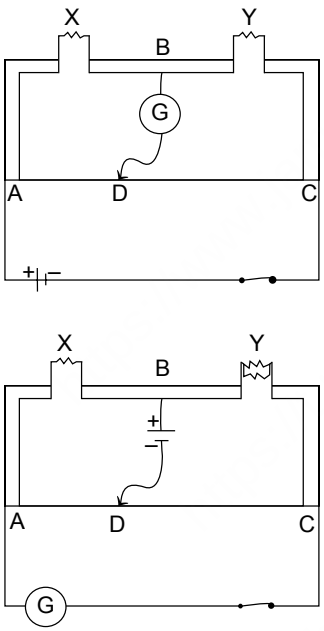
(ii) What will be the current in the same conductor if the voltage is increased to 42 V?

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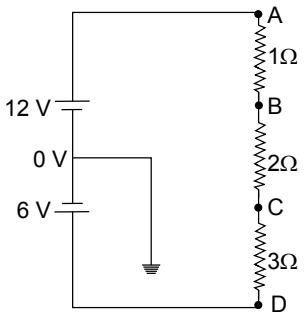
3. (a) In a metre bridge, (Figure) the balance point is found to be at 39.5 cm from the end A, when the resistor Y is of 12.5Ω. Determine the resistance of X. Why are the connections between resistors in a Wheatstone or metre bride made of thick copper strips?

(b) Determine the balance point of the bridge above if X and Y are interchanged.

(c) What happens if the galvanometer and cell are interchanged at the balance point of the bridge? Would the galvanometer show any current?



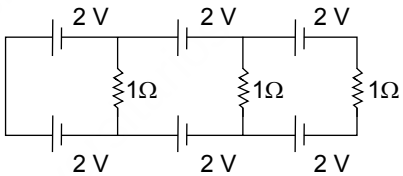
4. In the circuit shown what are the potentials at B, C and D?



5. A battery of emf 10 V and internal resistance 3Ω is connected to a resistor. If the current in the circuit is 0.5A, what is the resistance of the resistor? What is the terminal voltage of the battery when the circuit is closed?

6. A fuse made of lead wire has an area of cross-section 0.2 mm^2. On short circuiting, the current in the fuse wire reaches 30 amp. How long after the short circuiting will the fuse begin to melt? Specific heat capacity of lead = 134.3 J/kg-K.
Melting point of lead = 327ºC
Density of lead = 11340 kg/m^3
Resistivity of lead = 22 × 10^{-8} ohm-h
Initial temperature of the wire = 20ºC
Neglect heat loss.

7. Find the current in the three resistors shown in figure.

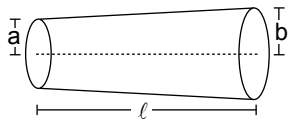


8. Flow of charge through a surface is given as: $Q = 4t^2 + 2t$ (for 0 to 10 sec.) (a) Find the current through the surface at t = 5sec. (b) Find the average current for (0 – 10 sec)

9. At the temperature 0ºC electric resistance of conductor 2 is η times that of conductor 1. Their temperature coefficients of resistance are equal to α_2 and α_1 respectively. Find the temperature coefficient of resistance of a circuit segment consisting of these two conductors when they are connected (a) in series (b) in parallel

10. Figure shows a conductor of length l having a circular cross-section. The radius of cross-section varies linearly from a to b. The resistivity of the material is ρ. Assuming that $b - a << l$, the resistance of the conductor is

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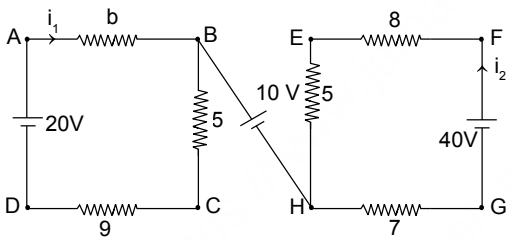


11. The region between two concentric conducting spheres of radii r_a and r_b is filled with a material of resistivity ρ.

(a) Show that the resistance between the spheres is given by, $R = \frac{\rho}{4\pi}\left(\frac{1}{r_a} - \frac{1}{r_b}\right)$

(b) Drive an expression for the current density as a function of radius, if the potential difference between the spheres is V_{ab}.

12. In the circuit shown,



(i) Find current i_1

(ii) Find current i_2

(iii) Find potential difference $(V_C - V_E)$

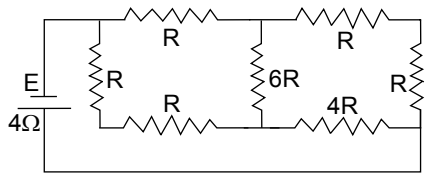
(iv) Find potential difference $(V_A - V_G)$

13. Six cells are connected (a) in series, (b) in parallel and (c) in 2 rows each containing 3 cells. The emf of each cell is 1.08 V and its internal resistance is 1 ohm. Calculate the currents that would flow through an external resistance of 5 ohm in the three cases.

PREVIOUS YEARS' IIT-JEE QUESTIONS

1. A battery of internal resistance 4Ω is connected to the network of resistances as shown. In order that the maximum power can be delivered to the network, the value of R in Ω should be

[1995]



(a) 4/9 (b) 2

(c) 8/3 (d) 18

2. A steady current flows in a metallic conductor of nonuniform cross-section. The quantity/quantities constant along the length of the conductor is/are

[1997]

(a) current, electric field and drift speed

(b) drift speed only

(c) current and drift speed

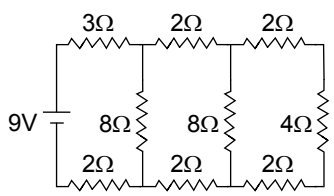
(d) current only

3. Find the emf (E) and internal resistance (r) of a single battery which is equivalent to a parallel combination of two batteries of emfs V_1 and V_2 internal resistances r_1 and r_2 respectively with their similar polarity connected to each other.

[1997]

4. In the circuit shown in the figure, the current through

[1998]



(a) the 3Ω resistor is 0.50 A

(b) the 3Ω resistor is 0.25 A

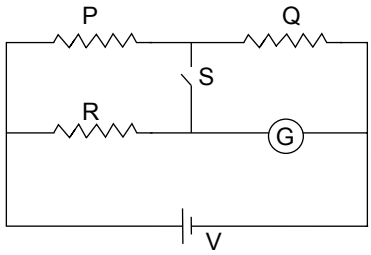
(c) 4Ω resistor is 0.50 A

(d) the 4Ω resistor is 0.25 A

5. In the circuit shown $P \neq R$, the reading of the galvanometer is same with switch S open or closed. Then

[1999]

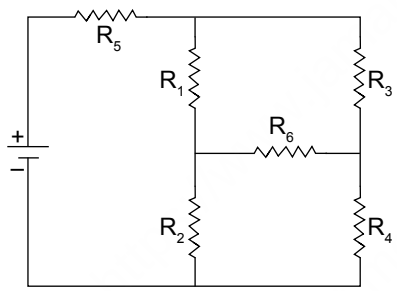
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(a) $I_R = I_G$ (b) $I_P = I_G$
(c) $I_Q = I_G$ (d) $I_Q = I_R$

6. In the given circuit, it is observed that the current I is independent of the value of the resistance R_6. Then the resistance values must satisfy

[2001]



(a) $R_1R_2R_5 = R_3R_4R_6$
(b) $\frac{1}{R_5}+\frac{1}{R_6}=\frac{1}{R_1+R_2}+\frac{1}{R_3+R_4}$
(c) $R_1R_4 = R_2R_3$
(d) $R_1R_3 = R_2R_4 = R_5R_6$

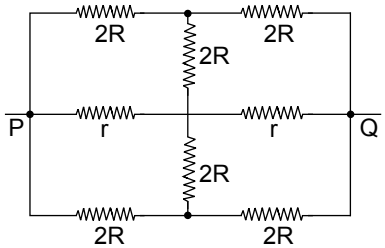
7. A wire of length L and 3 identical cells of negligible internal resistances are connected in series. Due to the current, the temperature of the wire is raised by ΔT in a time t. A number N of similar cells is now connected in series with a wire of the same material and cross-section but of length $2L$. The temperature of the wire is raised by the same amount ΔT in the same time t. The value of N is

[2001]

(a) 4 (b) 6
(c) 8 (d) 9

8. The effective resistance between the points P and Q of the electrical circuit shown in the figure is

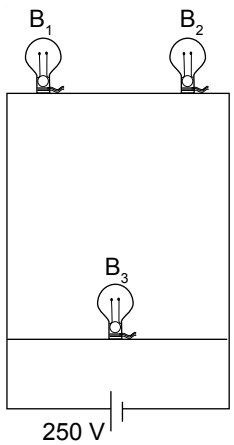
[2002]



(a) $2Rr/(R + r)$
(b) $8R(R + r)/(3R + r)$
(c) $2r + 4R$
(d) $5R/2 + 2r$

9. A 100 W bulb B_1, and two 60 W bulbs B_2 and B_3, are connected to a 250 V source, as shown in the figure. Now W_1, W_2 and W_3 are the output powers of the bulbs B_1, B_2 and B_3 respectively. Then

[2002]

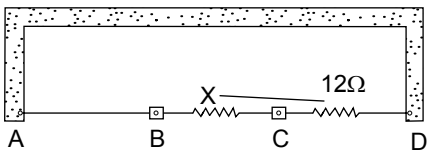


(a) $W_1 > W_2 = W_3$ (b) $W_1 > W_2 > W_3$
(c) $W_1 < W_2 = W_3$ (d) $W_1 < W_2 < W_3$

10. A thin uniform wire AB of length 1 m, an unknown resistance X and a resistance of 12Ω are connected by thick conducing strips, as shown in figure. A battery

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and a galvanometer (with a sliding jockey connected to it) are also available. Connections are to be made to measure the unknown resistance X using the principle of Wheatstone bridge. Answer the following question.



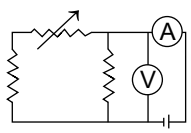
(a) Are there positive and negative terminals on the galvanometer?

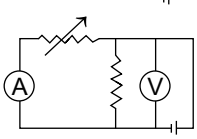
(b) Copy the figure in your answer book and show the battery and the galvanometer (with jockey) connected at appropriate points.

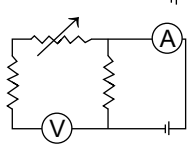
(c) After appropriate connections are made, it is found that no deflection takes place in the galvanometer when the sliding jockey touches the wire at a distance of 60 cm from A. Obtain the value of resistance X.

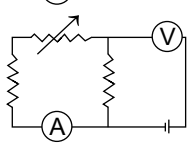
11. Express which of the following set-up can be used to verify Ohm's law?

[2003]

(a)


(b)


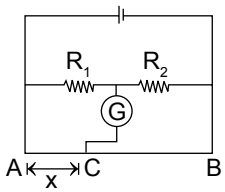
(c)


(d)


12. In the given circuit, no current is passing through the galvanometer.

If the cross-sectional diameter of AB is doubled then for null point of galvanometer the value of AC would

[2003]

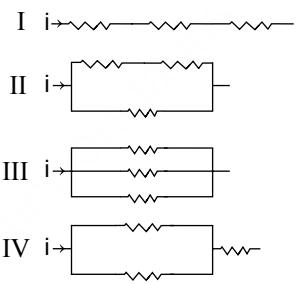


(a) x (b) $x/2$

(c) $2x$ (d) none

13. The three resistance of equal value are arranged in the different combinations shown below. Arrange them in increasing order of power dissipation.

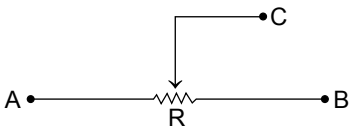
[2003]



(a) III < II < IV < I (b) II < III < IV < I

(c) I < IV < III < II (d) I < III < II < IV

14. How a battery is to be connected so that shown rheostat will behave like a potential divider?

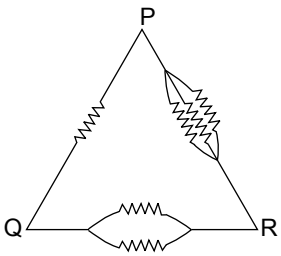


Also indicate the points about which output can be taken.

[2003]

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15. Six equal resistances are connected between points P, Q and R as shown in the figure.



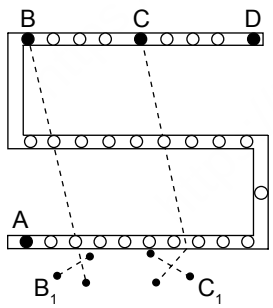
Then the net resistance will be maximum between

[2004]

(a) P and Q (b) Q and R
(c) P and R (d) any two points

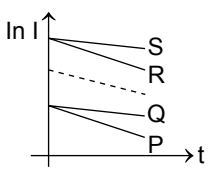
16. For the post office box arrangement to determine the value of unknown resistance, the unknown resistance should be connected between

[2004]



(a) B and C (b) C and D
(c) A and D (d) B_1 and C_1

17. In an RC circuit while charging, the graph of ln I versus time is as shown by the dotted line in the adjoining diagram where I is the current.



When the value of the resistance is doubled, which of the solid curves best represents the variation of ln I versus time?

[2004]

(a) P (b) Q
(c) R (d) S

18. Draw the circuit for experimental verification of Ohm's law using a source of variable D.C. voltage, a main resistance of 100Ω, two galvanometers and two resistances of values $10^6\Omega$ and $10^{-3}\Omega$ respectively. Clearly show the positions of the voltmeter and the ammeter.

[2004]

19. A moving coil galvanometer of resistance 100Ω is used as an ammeter using a resistance 0.1Ω. The maximum deflection current in the galvanometer is 100 μA. Find the minimum current in the circuit so that the ammeter shows maximum deflection.

[2005]

(a) 100.1 mA (b) 1000.1 mA
(c) 10.01 mA (d) 1.01 mA

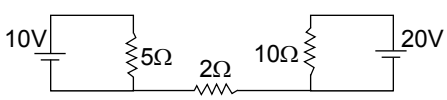
20. An ideal gas is filled in a closed rigid and thermally insulated container. A coil of 100Ω resistor carrying current 1 A for 5 minutes supplies heat to the gas. The change in internal energy of the gas is

[2005]

(a) 10 kJ (b) 30 kJ
(c) 20 kJ (d) 0 kJ

21. Find the value of current through 2Ω resistance for the given circuit.

[2005]



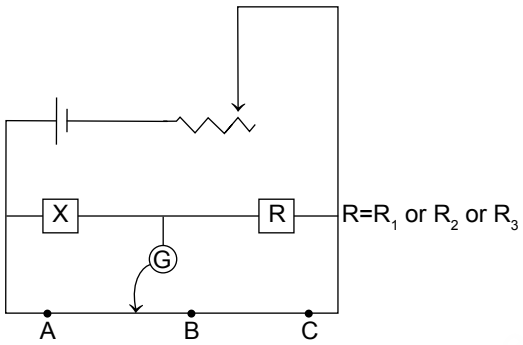
(a) 5A (b) 2A
(c) zero (d) 4A

22. An unknown resistance X is to be determined using resistances R_1, R_2 or R_3. Their

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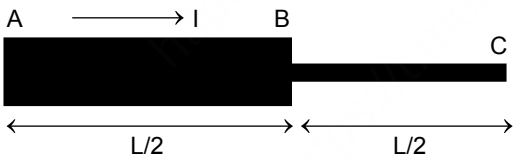
corresponding null points are *A*, *B* and *C*. Find which of the above will give the most accurate reading and why?

[2005]



23. Two wires *AB* and *BC*, each of length *L*/2 are made of the same material. The radius of wire *AB* is 2*r* and of wire *BC* is *r*. The current I flows through the composite wire (figure). Choose the correct of the following:

[2006]



(a) Potential difference across *BC* is twice that across *B*

(b) Potential dissipated in *BC* is four times the power dissipated in *AB*

(c) Current densities in *AB* and *BC* are equal

(d) Electric field in *AB* and *BC* are equal.

24. A resistance of 2Ω is connected across one gap of a meter-bridge (the length of the wire is 100 cm.) and an unknown resistance, greater 2Ω, is connected across the other gap. When these resistances are interchanged, the balance point shifts by 20 cm. Neglecting end corrections, the unknown resistance is

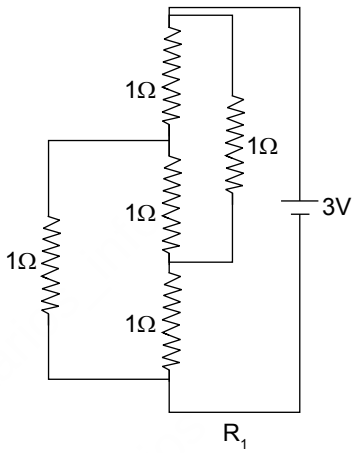
[2007]

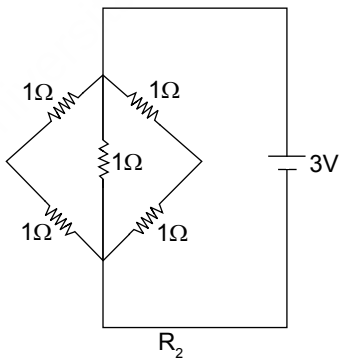
(a) 3Ω (b) 4Ω

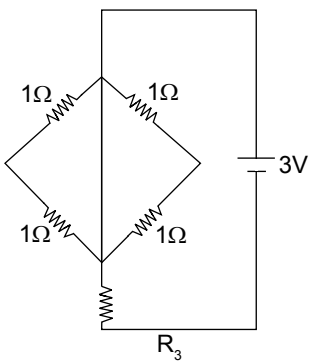
(c) 5Ω (d) 6Ω

25. Figure shows three resistor configurations R_1, R_2 and R_3 connected to 3 V battery. If the power dissipated by the configuration R_1, R_2 and R_3 is P_1, P_2 and P_3, respectively, then

[2008]







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(a) $P_1 > P_2 > P_3$ (b) $P_1 > P_3 > P_2$
(c) $P_2 > P_1 > P_3$ (d) $P_3 > P_2 > P_1$

26. **STATEMENT-1:** In a meter bridge experiment, null point for an unknown resistance is measured. Now, the unknown resistance is put inside an enclosure maintained at a higher temperature. The null point can be obtained at the same point as before by decreasing the value of the standard resistance.
STATEMENT-2: Resistance of a metal increases with increase in temperature.
[2008]

(a) STATEMENT-1 is True, STATEMENT-2 is True; STATEMENT-2 is a correct explanation for STATEMENT-1
(b) STATEMENT-1 is True, STATEMENT-2 is True; STATEMENT-2 is NOT a correct explanation for STATEMENT-1
(c) STATEMENT-1 is True, STATEMENT-2 is False
(d) STATEMENT-1 is False, STATEMENT-2 is True
[2008]

ANSWERS

ONLY ONE OPTION IS CORRECT

1. (a)	**2.** (d)	**3.** (b)	**4.** (a)	**5.** (d)	**6.** (c)	**7.** (b)	**8.** (a)
9. (a)	**10.** (d)	**11.** (c)	**12.** (c)	**13.** (b)	**14.** (d)	**15.** (b)	**16.** (b)
17. (b)	**18.** (a)	**19.** (b)	**20.** (a)	**21.** (a)	**22.** (d)	**23.** (d)	**24.** (d)
25. (c)	**26.** (b)	**27.** (d)	**28.** (d)	**29.** (d)	**30.** (a)	**31.** (b)	**32.** (d)
33. (c)	**34.** (a)	**35.** (b)	**36.** (c)	**37.** (d)	**38.** (b)	**39.** (c)	**40.** (a)
41. (d)	**42.** (a)	**43.** (d)	**44.** (d)	**45.** (b)	**46.** (c)	**47.** (b)	**48.** (d)
49. (c)	**50.** (b)	**51.** (c)	**52.** (d)	**53.** (d)	**54.** (c)	**55.** (a)	**56.** (b)
57. (a)	**58.** (a)	**59.** (d)	**60.** (a)	**61.** (b)	**62.** (c)	**63.** (a)	**64.** (d)
65. (a)	**66.** (b)	**67.** (d)	**68.** (c)	**69.** (b)	**70.** (a)	**71.** (c)	

ONE OR MORE THAN ONE CHOICE MAY BE CORRECT

1. (a, c, d)	**2.** (a, b, c)	**3.** (a, b)	**4.** (a, b, c, d)	**5.** (b, c)	**6.** (a, c)	**7.** (a, b, c)	**8.** (a, c)
9. (a, d)	**10.** (b, c)	**11.** (a, b, c)	**12.** (b, c)	**13.** (a, b, c, d)	**14.** (a, c)	**15.** (a, b, c, d)	

ASSERTION AND REASON QUESTIONS

1. (b)	**2.** (c)	**3.** (d)	**4.** (b)	**5.** (c)	**6.** (c)	**7.** (c)	**8.** (a)
9. (b)	**10.** (d)	**11.** (d)	**12.** (c)	**13.** (d)	**14.** (c)	**15.** (a)	**16.** (a)
17. (a)	**18.** (c)						

MATCH THE COLUMN TYPE QUESTIONS

1. (a) → q, (b) → r, (c) → r, (d) → r
2. (a) → q, (b) → p, (c) → r, s (d) → r, s
3. (a) → q, (b) → t, (c) → r, (d) → p
4. (a) → q, (b) → p, (c) → r, (d) → s
5. (a) → q, (b) → s, (c) → s, (d) → q
6. (a) → q, (b) → r, (c) → p, (d) → q
7. (a) → q, (b) → r, (c) → p, (d) → q
8. (a) → q, (b) → p, (c) → q, (d) → p

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9. (a) → p, (b) → q, (c) → r, (d) → s
10. (a) → q, (b) → p, (c) → r, (d) → s
11. (a) → p, (b) → q, (c) → r, (d) → s
12. (a) → p, (b) → q, (c) → r, (d) → s
13. (a) → q, (b) → r, (c) → r, (d) → p

PASSAGE BASED QUESTIONS

1. (d) **2.** (c) **3.** (a) **4.** (c) **5.** (d) **6.** (c) **7.** (a) **8.** (c)
9. (a) **10.** (a) **11.** (a) **12.** (a) **13.** (d) **14.** (c)

HINTS AND EXPLANATIONS

SUBJECTIVE QUESTIONS

1. The 20KΩ voltmeter gives the highest reading; the last case (both the voltmeters across *AB*) gives the lowest reading.

2. (i) Given that I = 5*A*; *V* = 12 V; *R* =?

$$R = \frac{V}{I} = \frac{12V}{5A} = 2.4\Omega$$

(ii) It the voltage applied becomes 42 V

$$I = \frac{V}{R} = \frac{42V}{2.4ohm} = 17.5A$$

3. (a) $X = 8.2\Omega$ to minimise resistance of the connection which are not accounted for in the bridge formula.
(b) 60.5 cm From *A*, (c) The galvanometer will show no current.

4. 11 Volt, 9 Volt, 6 Volt

5. 17Ω, 8.5 V

6. If *L* be the length of the wire, its resistance

$$R\frac{\rho L}{A} = \frac{(22\times10^{-8})L}{(0.2\times10^{-6})m^2}$$

Heat produced in the wire in one second = $I^2R = (30)^2$ RJ
Heat required to raise the temperature of the wire to 327ºC

$Q = ms\Delta T = (LAd)(134.4)(307)$J

The required to melt the wire

$$= \frac{Q}{I^2R} = \frac{LAd\times134.4\times307}{I\times\rho L}\times A$$

$$= \frac{A^2d}{I^2\rho} \times 134.4 \times 307 = 0.0945 \text{ s}$$

7. 0 Amp

8. (a) Instantaneous current

$$I = \frac{dQ}{dt} = \frac{d}{dt}(4t^2 + 2t) = 8t + 2$$

at $t = 5$ sec; I = 8 × 5 + 2 = 42 Amp

(b) Average current

$$I = \frac{\Delta Q}{\Delta t} = \frac{Q}{t} = \frac{4\times(10)^2 + 2\times10}{10}$$

$$= \frac{420}{10} = 42\ Amp.$$

9. (a) $\alpha = (\alpha_1 + \eta\alpha_2)/(1 + \eta)$; (b) $\alpha \approx (\alpha_2 + \eta\alpha_1)/(1 + \eta)$

10. $\rho\ell/\pi ab$

11. (b) $J = \frac{V}{\rho r^2}\left(\frac{r_b r_a}{r_b - r_a}\right)$

12. (i) 1*A* (ii) 2*A* (iii) –5 V (iv) 30 V

13. (a) The cells in series.
Given that ε = 1.08 V, *n* = 6, *r* = 1 ohm,
R = 5 ohm

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The total emf = $n\varepsilon = 6 \times 1.08$ V
The total internal resistance
$nr = 6 \times 1 = 6$ ohm
The current in the circuit

$$I_s = \frac{n\varepsilon}{R+nr} = \frac{6\times1.08}{5+6} = 0.589\ A$$

(b) The cells in parallel,
Here $\varepsilon = 1.08$ v, $m = 6$, $r = 1$ ohm, $R = 5$ ohm

$$I_p = \frac{m\varepsilon}{mR+r} = \frac{6\times1.08}{6\times5+1} = \frac{6.48}{31} = 0.209\ A$$

(c) The cells in multiple are with $n=3$, $m=2$

$$I = \frac{mn\varepsilon}{mR+nr}$$

$$= \frac{6\times1.08}{(2\times5)+(3\times1)} = \frac{6.48}{13} = 0.498\ A$$

PREVIOUS YEARS' IIT-JEE QUESTIONS

1. (b)

2. (d)

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