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NATIONAL TESTING AGENCY

Physics

Volume - 4

SIERRA INNOVATIONS

CONTENTS

ELECTROSTATICS

* A branch of physics that studies electric charges at rest.

Charge
- At rest → EF
- Constant velocity → EF + MF
- Accelerated motion → EF + MF + Emission of energy → In form of radiations → EMW

EF → Electric Field

mF → Magnetic Field

What is the charge?

* Charge is the property of the body by which it can show its electrical & magnetic effect.
* It is defined in terms of no. of electrons.

Charge → In terms of e^-.
- $n_e = n_p$ → Neutral
- $n_e > n_p$ → Excess of e^- → –ve charge → $M_{-ve} > M_{neutral}$
- $n_e < n_p$ → Deficiency of e^- → +ve charge → $M_{+ve} < M_{neutral}$

* Mass without charge can be possible for a body, but charge without mass is never possible.
* Mass depends on the frame of reference according to the theory of relativity, but charge is independent of frame of reference. That's why charge is called invariant.

$$M = \frac{M_0}{\sqrt{1-\frac{v^2}{v^2}}}$$

Charge does not follow this type of equation.

Electrostatic Force:

Coulomb's Law:

* Two charges 'q_1' and 'q_2' kept at distance 'r' in a medium exert a force 'F' on each other and the magnitude of the force is given as:

$$F = \frac{1}{4\pi\varepsilon}\frac{q_1 q_2}{r^2}$$ (In any medium)

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

where
ε = Absolute permitivity of medium
ε_0 = Aermittivity of free space
ε_r = Relative permittivity

F in air or vacuum

$$F = \frac{1}{4\pi E_0}\frac{q_1 q_2}{r^2} = \frac{K q_1 q_2}{r^2}$$

(K = electrostatic constant = 9×10^9 $N\text{-}m^2/C^2$)

Force (Vector)

- Mag.

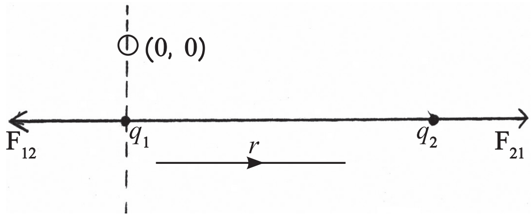
  $$F = \frac{K q_1 q_2}{r^2}$$

- Direction

  Always along the line joining the 2 charges.

$$\vec{F} = F\,\hat{F}$$

$\hat{F}$ ↓ Unit vector → direction



$$\vec{F}_{12} = \left(\frac{Kq_1q_2}{r^2}\right)(-\hat{r}) = -\frac{Kq_1q_2}{r^3}(\vec{r})$$

$$\vec{F}_{21} = \frac{Kq_1q_2}{r^2}(\hat{r}) = \frac{Kq_1q_2}{r^3}(\vec{r})$$

$$F \propto q_1q_1 \qquad F \propto \frac{1}{r^2}$$

$\Rightarrow$ $\boxed{F \propto \frac{q_1q_2}{r^2}}$

In CGS, $\boxed{K = 1}$

In SI $\boxed{K = \frac{1}{4\pi\varepsilon}}$

* According to Coulomb's law, force between 2 charges q_1 and q_2 kept at distance r is—
  1. $\propto$ to the product of the magnitude of the charges.
  2. Inversely $\propto$ to the square of the distance between them.
  3. For the direction, like charges repel & unlike charges attract.
  4. This force depends on the medium.

* q_1, q_2 → charge
  ↓
  Units → SI ⇒ C (Coulomb) → mc = 10^{-3} C
  → μc = 10^{-6} C
  → nc = 10^{-9} C
  → CGS ⇒ esu (Electrostatic unit)

$\boxed{IC = 3 \times 10^9 \text{ esu}}$

* r = Distance between charges
  Unit → SI-m, CGS-cm 1 m = 100 cm

* Force
  Unit → SI-N, CGS-dyne 1 N = 10^5 dyne

* $K = \frac{Fr^2}{q_1q_2}$ $K = 9 \times 10^9 \frac{Nm^2}{c^2}$

Unit $\longrightarrow$ SI- $\frac{Nm^2}{c^2}$,

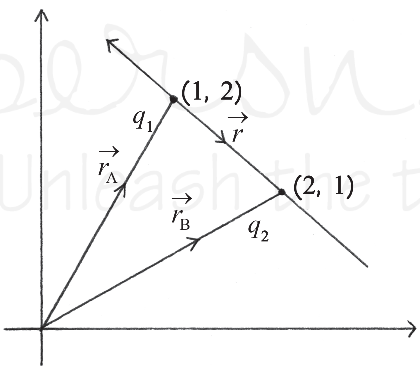
Dimensions- $\frac{[MLT^{-2}][L^2]}{[AT]^2} = [ML^3T^{-4}A^{-2}]$

* ε_0 $\qquad \varepsilon_0 = 8.85 \times 10^{-12} \frac{C^2}{Nm^2}$

Unit $\longrightarrow$ SI- $\frac{C^2}{Nm^2}$,

Dimensions- $[M^{-1}L^{-3}T^4A^2]$

Ques.:2 Charge particles located at the point (1, 2) & (2, 1). Find $\vec{F}_{12}$.



Solns.: $\vec{r}_A = \hat{i} + 2\hat{j}$ $\qquad \vec{r}_B = 2\hat{i} + \hat{j}$

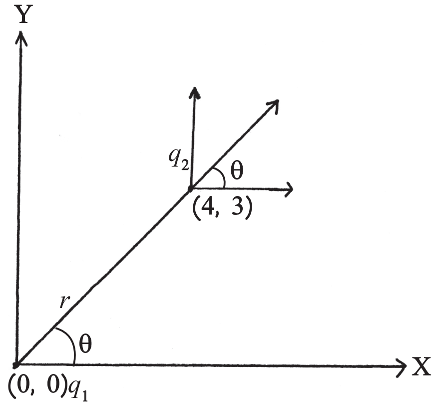
$$\vec{r}_A + \vec{r} = \vec{r}_B$$

$\Rightarrow$ $\vec{r} = (\hat{i} - \hat{j})$, $\hat{r} = \frac{\hat{i} - \hat{j}}{\sqrt{2}}$ = (South east)

$\vec{F}_{12} = \left(\frac{kq_1q_2}{r^2}\right)$ (North west) $= -\left(\frac{kq_1q_2}{r^2}\right)\hat{r}$

$|\vec{r}| = \sqrt{2}$

Ques.: All distances in cm, $q_1 = 2\mu C$, $q_2 = 10\ \mu C$. Find F on charge q_2.



Solns.:

$$F = \frac{9\times10^9\times2\times10^{-6}\times10\times10^{-6}}{(5\times10^{-2})^2}$$

$$= 9\times 8 = 72\ N$$

$$\tan\theta = \frac{3}{4}$$

$\Rightarrow$ $F = 72\ N,\ 37°$ w.r.t. horizontal

$$\boxed{F = 72\ N}$$

$$\vec{r} = 4\hat{i} + 3\hat{j}$$

$\Rightarrow$ $$\hat{r} = \frac{4\hat{i}+3\hat{j}}{5}$$

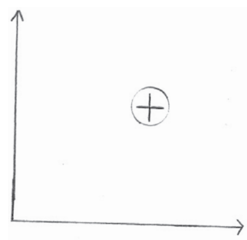
$$\boxed{\vec{F} = 72\left[\frac{4\hat{i}+3\hat{j}}{5}\right] N}$$

$$\vec{F} = 72\cos 37°\ \hat{i} + 72\sin 37°\ \hat{j}$$

$$\vec{F} = \frac{72}{5}[4\hat{i} + 3\hat{j}]\ N.$$

Superposition of Forces:

$\Rightarrow$ Resultant $\rightarrow$ Vector sum.

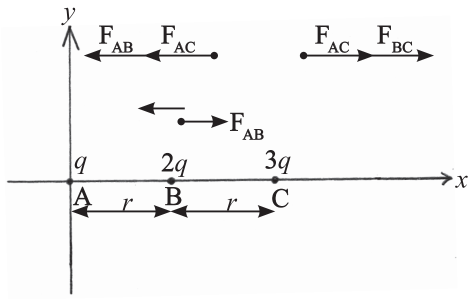


$$\vec{F}_{net} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \ldots$$

Superposition of forces means the resultant force on a particle is the vector sum of all the forces acting on it.

Ques.: Net force on (i)A, (ii)B, (iii)C.

Solns.: I.



$$F_{AB} = \frac{k(2q)(q)}{r^2} \quad (\longleftarrow)$$

$$F_{AC} = \frac{k(2q)(3q)}{(2r)^2} \quad (\longleftarrow)$$

$$F_{net} = \frac{2kq^2}{r^2} + \frac{\overset{3}{\cancel{6}}\, kq^2}{\underset{2}{\cancel{4}}\, r^2} \quad (\longleftarrow)$$

$$F_{net} \text{ on point A} = \frac{kq^2}{r^2}\left[2 + \frac{3}{2}\right] \frac{7}{2}\frac{kq^2}{r^2} (\longleftarrow)$$

II.

$$(\longrightarrow)\ F_{AB} = \frac{2kq^2}{r^2},\ F_{BC} = \frac{k(q)(3q)}{r^2} \quad (\longleftarrow)$$

$$F_{net} \text{ on point B} = \frac{-2kq^2}{r^2} + \frac{3kq^2}{r^2} = \frac{kq^2}{r^2} \quad (\longleftarrow)$$

III.

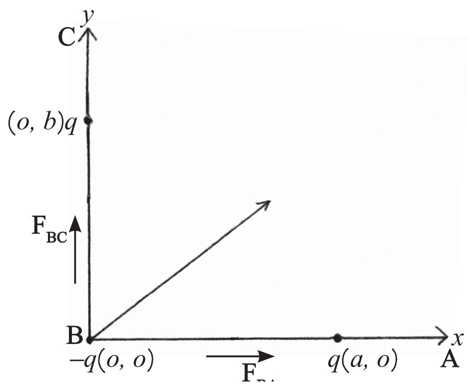
$$F_{AC} = \frac{3kq^2}{2r^2} \quad (\longrightarrow)$$

$$F_{BC} = \frac{3kq^2}{r^2} \quad (\longrightarrow)$$

$$F_{net} \text{ on point C} = \frac{3kq^2}{r^2} \times \frac{3}{2} = \frac{9kq^2}{2r^2} \quad (\longrightarrow)$$

Ques.: Find net force on $-q(0, 0)$?

Solns.:



$$\vec{F}_{BA} = \frac{-kq^2}{a^2}\hat{i}$$

$$\vec{F}_{BC} = \frac{-kq^2}{b^2}\hat{j}$$

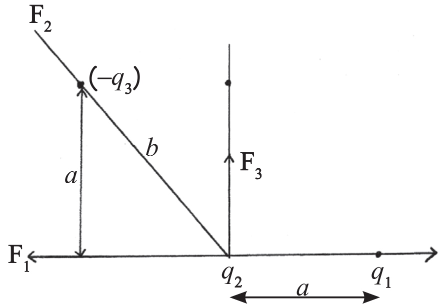
$$\boxed{\vec{F}_{net} = \frac{kq^2}{a^2}\hat{i} + \frac{kq^2}{b^2}\hat{j}}$$

$$\left|\vec{F}_{net}\right| = \sqrt{F_1^2 + F_2^2} = \frac{kq^2}{ab}\sqrt{a^2 + b^2}$$

Direction $\longrightarrow$ at an angle α to x-axis

$$\tan\alpha = \frac{F_2}{F_1} = \frac{a^2}{b^2}$$

Ques.: If the force acting on q_2 is along y-direction find the ratio of the charges q_1 & q_3?

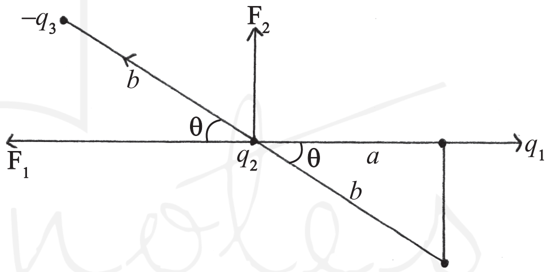


Solns.:

$$\vec{F}_3 = \frac{kq_2q_3}{b^2} \qquad \left(\vec{F}_1 = \frac{kq_1q_2}{a^2}\left(-\hat{i}\right)\right)$$

Along x-direction $= 0 = F_1 + F_2 \cos\theta$

$$\cos\theta = -\frac{F_1}{F_2} = \frac{a}{b}$$



$$\frac{kq_1q_2}{a^2} + \frac{kq_2(-q_3)}{b^2}\left(\frac{a}{b}\right) = 0$$

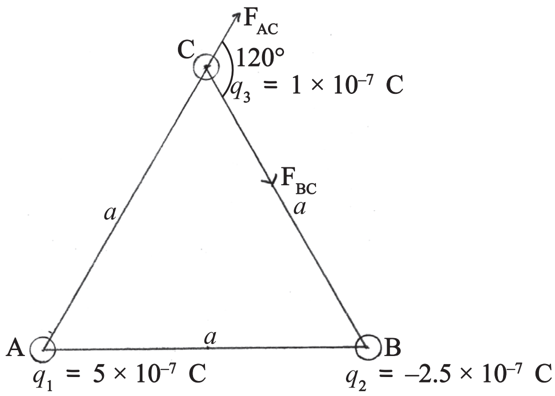
$$\frac{q_1}{a^2} = \frac{q_3 a}{b^3}$$

$$\Rightarrow \quad \frac{q_1}{a^3} = \frac{q_3}{b^3}$$

$$\Rightarrow \quad \frac{q_1}{q_3} = \frac{a^3}{b^3}$$

Ques.: Three charges of magnitude 5.0×10^{-7} C, -2.5×10^{-7} C and 1×10^{-7} C are fixed at the three corners A, B and C of an equilateral triangle of side 5 cm. Find the electric force on the charge at vertex C due to the rest two.

Solns.:



$$F_{AC} = \frac{9\times10^9 \times 5\times10^{-7} \times 1\times10^{-7}}{(0.05)^2} = 0.18 \text{ N}$$

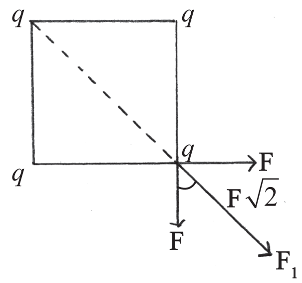
$$F_{BC} = \frac{9\times10^9 \times (-2.5\times10^{-7}) \times 1\times10^{-7}}{(0.05)^2} = -0.09 \text{ N}$$

$$\vec{F}_{net} = \vec{F}_{AC} + \vec{F}_{BC}$$

$$\left|\vec{F}_{net}\right| = \sqrt{F_{AC}^2 + F_{BC}^2 + 2(F_{AC})(F_{BC})\cdot\cos(120^\circ)}$$

$$= 0.156 \text{ N}$$

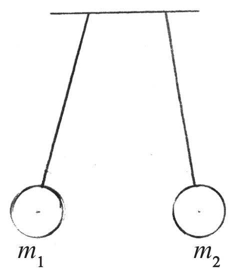
Ques.:



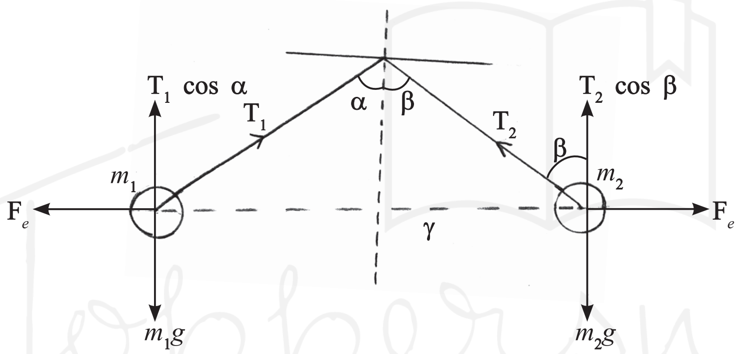
Solns.:

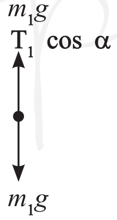
$$F_{net} = F_1 + F\sqrt{2}$$

Ques.: 2 balls of masses m_1 and m_2 & charges q_1 & q_2 are suspended from same point by 2 different threads. Find the relation between α & β.



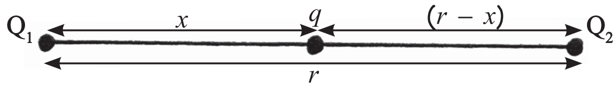
Solns.:





$$\alpha = \beta \Rightarrow m_1 = m_2$$
$$\alpha < \beta \Rightarrow m_1 > m_2$$
$$\alpha > \beta \Rightarrow m_1 < m_2$$

Ques.: Where to place q so that net force on it becomes 0?



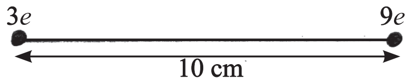
Solns.: $\Rightarrow$ $$\frac{kqQ_1}{x^2} = \frac{kqQ_2}{(r-x)^2}$$

$\Rightarrow$ $$\frac{Q_1}{x^2} = \frac{Q_2}{(r-x)^2}$$

$\Rightarrow$ $$\left(\frac{r-x}{x}\right)^2 = \frac{Q_2}{Q_1}$$

$\Rightarrow$ $$\boxed{x = \frac{r}{1+\sqrt{\frac{Q_2}{Q_1}}} = \frac{r\sqrt{Q_1}}{\sqrt{Q_1}+\sqrt{Q_2}}}$$

Ques.: Determine the location at which a small q charge is placed so that net force on it becomes equal to 0.

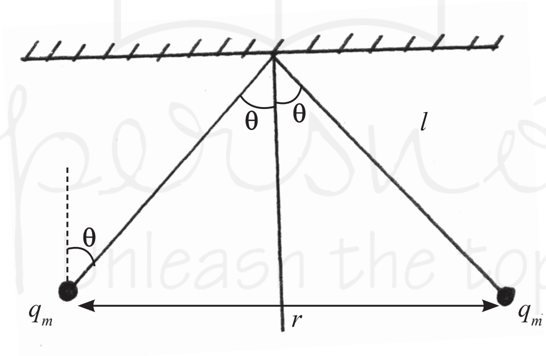


Solns.: $\Rightarrow$

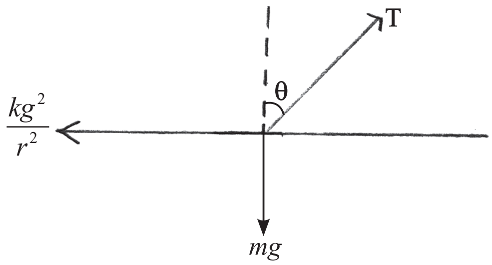
$$\text{from } 3e,\ x = \frac{10\,\text{cm}}{1+\sqrt{\frac{9e}{3e}}} = \frac{10}{\sqrt{3}+1}\ \text{cm}$$

$$\text{from } 9e,\ y = \frac{10}{1+\sqrt{\frac{3e}{9e}}} = \frac{10\sqrt{3}}{\sqrt{3}+1}\ \text{cm}$$

Ques.: q = same, m = same, in equilibrium both the particles are at a distance 'r'. Find the $\angle$ made by the string joined with one of the particle with the vertical?



Solns.:



$$T\cos\theta = mg$$

$$T\sin\theta = \frac{kq^2}{r^2}$$

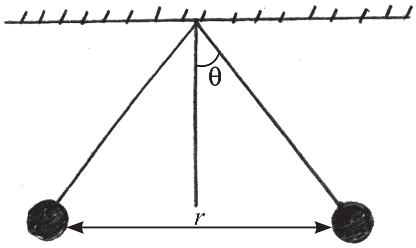
$$\boxed{\tan\theta = \frac{kq^2}{r^2 mg}}$$

$\Rightarrow$

$$\boxed{\theta = \tan^{-1}\left(\frac{kq^2}{r^2 mg}\right)}$$

$$T = \sqrt{(mg)^2 + \left(\frac{kg^2}{r^2}\right)^2}$$

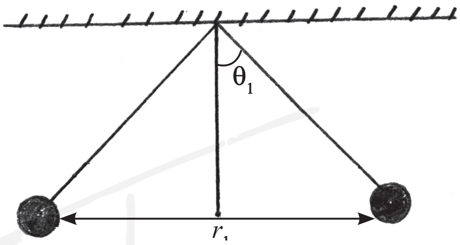
Ques.: 'r' is eq^m distance between particles. If height of the string is halved, what will be new eq^m distance r_1 ?



Solns.:

$$\tan\theta = \frac{kq^2}{r^2 mg}$$

$$\Rightarrow \quad r = \sqrt{\frac{kq^2}{mg,}}$$



$$\tan\theta = \frac{r/2}{h}$$

$$\frac{kq^2}{r^2 mg} = \frac{r}{2h}$$

$$r^3 = \frac{2hkq^2}{mg} \quad \ldots(1)$$

$$\tan\theta_1 = \frac{kq^2}{r_1^2 mg}$$

$$\tan\theta_1 = \frac{r_1/2}{h/2} = \frac{r_1}{h} = \frac{kq^2}{r_1^2 \cdot mg}$$

$$r_1^3 = \frac{hkq^2}{mg} \quad \ldots(2)$$

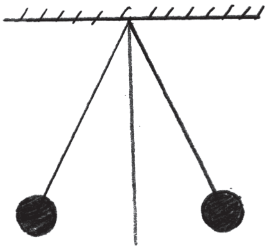
From eq^n (1) & (2)

$$\Rightarrow \quad r^3 = 2r_1^3$$

$$\Rightarrow \quad r_1^3 = \frac{r^3}{2}$$

$$\Rightarrow \quad \boxed{r_1 = \frac{r}{2^{1/3}}}$$

Ques.: If the system is taken into a gravity free satellite, then find the tension in the string:

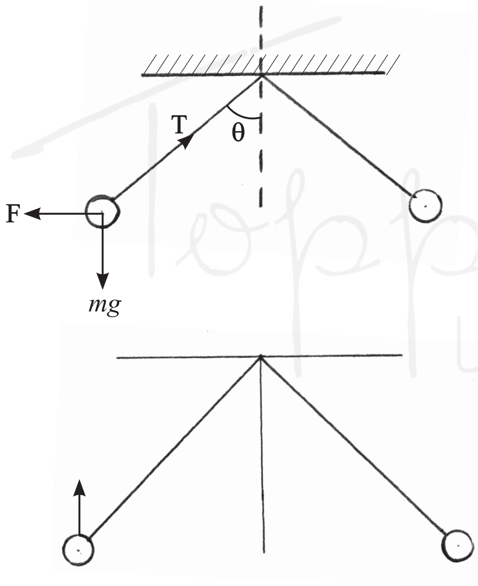


Solns.:

$$T = \frac{kq^2}{(2l)^2} = \frac{kq^2}{4l^2}$$

Ques.: 2 identical charged spheres are suspended by 2 strings of equal length. Each string makes an angle θ with the vertical. When suspended in a liquid of density $0.8\ \text{g/cm}^3$, the angle remains the same. What is the dielectric constant of the liquid, $d_s = 1.6$ g/ce.

Solns.:



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

$$mg' = \text{app. weight} = mg - B$$

$$B = V\int g = V_S d_L g$$

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

$$\frac{F}{mg} = \frac{F'}{mg'}$$

$$\boxed{\begin{aligned} mg' &= mg - B \\ mg' &= V_S d_s g - V_s d_L g \\ &= V_s(d_s - d_L)g \end{aligned}}$$

We know,

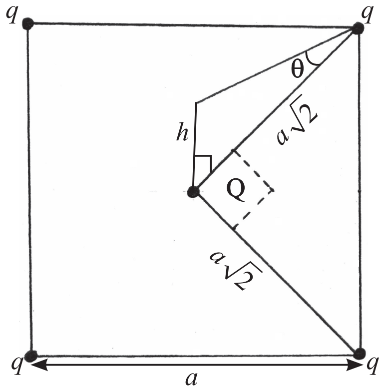
$$F = \frac{1}{4\pi\varepsilon_0\varepsilon_r}\frac{q_1q_2}{r^2}$$

$$F' = \frac{F}{\varepsilon_r}$$

$$\Rightarrow \qquad \frac{F}{V_s d_s g} = \frac{F}{\varepsilon_r (V_s)(d_s - d_L)g}$$

$$\boxed{\varepsilon_r = \frac{d_s}{d_S - d_L} = 2}$$

Ques.: 4 identical particles are kept at the vertices of a square 5^{th} particle of charge Q is placed at a height 'h' from the centre of the square. Find the net force on it, if the side of the square is 'a'?

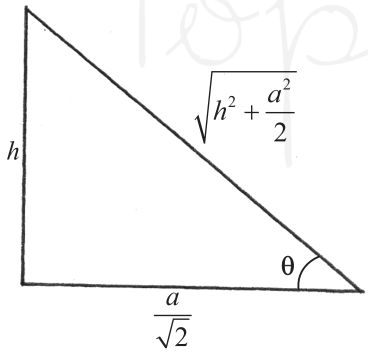


Solns.: ⇒

$$r^2 = \frac{a^2}{2} + h^2$$

⇒

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



$$\tan\theta = \frac{h\sqrt{2}}{a} = \frac{\sqrt{2}h}{a} = \frac{h\sqrt{2}}{a}$$

$$F_{net} = 4F\sin\theta$$

[Horizontal camponent cancel, vertical component add]

$$F_{net} = \frac{4 \times kqQ}{\left(\frac{a^2}{2} + h^2\right)} \times \frac{h}{\left(\sqrt{\frac{a^2}{2} + h^2}\right)} = \frac{4hkqQ}{\left(\frac{a^2}{2} + h^2\right)^{3/2}}$$

$$\left(\because \sin\theta = \frac{h}{\sqrt{\frac{a^2}{2} + h^2}}\right)$$

For equilibrium,

$$4F\sin\theta = mg$$

$$m = \frac{4F\sin\theta}{g} = \frac{4kQqh}{\left(h^2 + \frac{a^2}{2}\right)^{3/2} g}$$

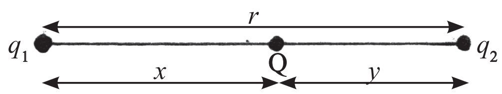
For the Equilibrium of System:

1. Position of charge.
2. Nature & magnitude of the charge.

1. Position of Charge:

Ques.: Find the position of the charge Q for which, system will be equilibrium?

$$\frac{kq_1Q}{x^2} = \frac{kQq_2}{y^2}$$



Solns.:

$$\frac{x}{y} = \sqrt{\frac{q_1}{q_2}}$$

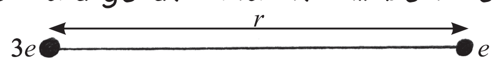
$\Rightarrow$

$$\boxed{x + y = r}$$

$$x = \frac{r}{1+\sqrt{\frac{q_2}{q_1}}} = \frac{r\sqrt{q_1}}{\sqrt{q_1}+\sqrt{q_2}} \quad \text{(from } q_1\text{)}$$

$$y = \frac{r}{1+\sqrt{\frac{q_1}{q_2}}} = \frac{r\sqrt{q_2}}{\sqrt{q_1}+\sqrt{q_2}} \quad \text{(from } q_2\text{)}$$

Ques.: Find the position of the 3rd charge at which it will be in equilibrium.



Solns.: $\Rightarrow$

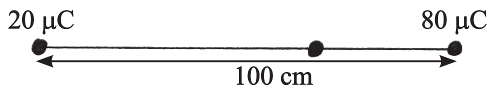
$$x = \frac{r}{1+\sqrt{3}}$$

$$y = \frac{r}{1+\frac{1}{\sqrt{3}}}$$

$$= \frac{r\sqrt{3}}{\sqrt{3}+1}$$

Ques.: Find the distance from 20 μC so that net force on the particle kept at the point will be equal to 0.

Solns.:



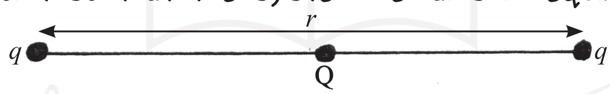
$$x = \frac{r}{1+\sqrt{\frac{q_2}{q_1}}} = \frac{r}{1+\sqrt{\frac{80}{20}}} = \frac{r}{3}$$

$$x = \frac{100}{3} = 33 \text{ cm}$$

2. Nature and Magnitude of Charge:

To calculate-Magnitude of the charge so that system will be in equilibrium.
We must apply net force = 0, on any other charge in the system.

Ques.: 2 identical charges are kept at distance 'r'. Find the nature & magnitude of the 3rd charge placed at midpoint so that the system remains in equilibrium.



Solns.:

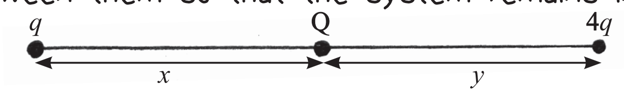
$$\frac{kqQ}{(r/2)^2} + \frac{kqq}{r^2} = 0$$

$$\frac{4kQq}{r^2} + \frac{kqq}{r^2} = 0$$

$$\Rightarrow \quad \frac{kq}{r^2}[4Q + q] = 0$$

$$\boxed{Q = \frac{-q}{4}}$$

Ques.: Two charges q and $4q$ are kept at distance r. Find the nature and magnitude of the 3rd charge placed between them so that the system remains in equilibrium.



Solns.: $\Rightarrow$

$$x = \frac{r}{1+2} = \frac{r}{3}$$

$$y = \frac{2r}{3}$$

$$\frac{kq(4q)}{r^2} + \frac{k(4q)(Q)\times 9}{(2r)^2} = 0$$

$$\frac{kq}{r^2}\left(4q+\frac{\cancel{4}Q\times 9}{\cancel{4}}\right) = 0$$

$\Rightarrow$ $$4q + 9Q = 0$$

$$\boxed{Q = \frac{-4}{9}q}$$

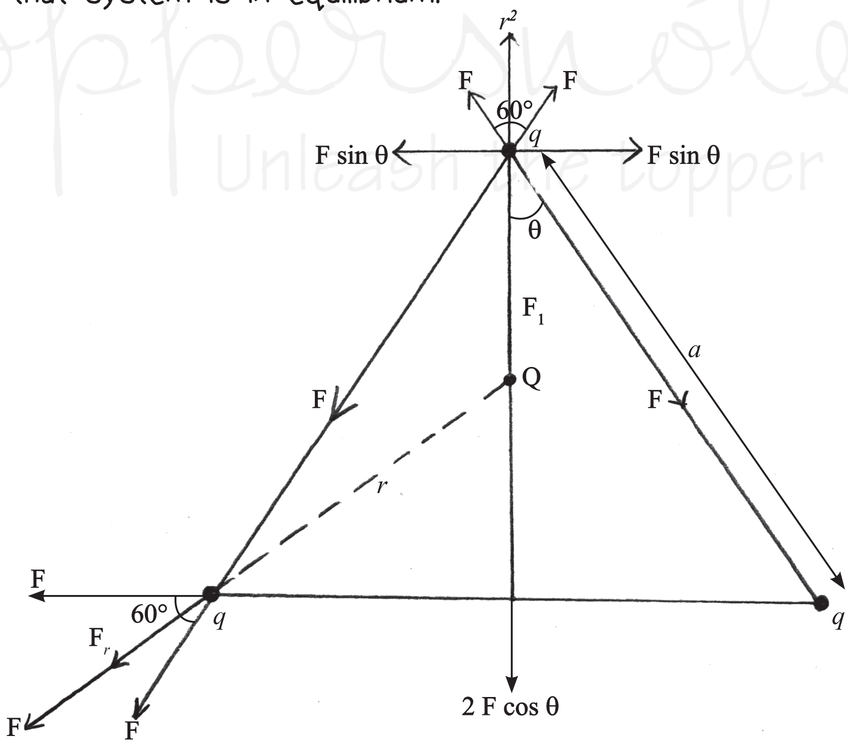
$$\frac{kqQ}{\left(\frac{r}{3}\right)^2} + \frac{kq(4q)}{r^2} = 0$$

$\Rightarrow$ $$\frac{9kq(4q)}{r^2} + \frac{4kqq}{r^2} = 0$$

$$\frac{kq}{r^2}[9Q + 4q] = 0$$

$\Rightarrow$ $$\boxed{Q = -\frac{-4q}{9}}$$

Ques.: Magnitude, so that system is in equilibrium.



Solns.: $$r = \frac{a}{\sqrt{3}}$$

$$F_R = \sqrt{F^2 + F^2 + 2F^2\cos 60^\circ}$$

$$= \sqrt{3F^2} = F\sqrt{3}$$