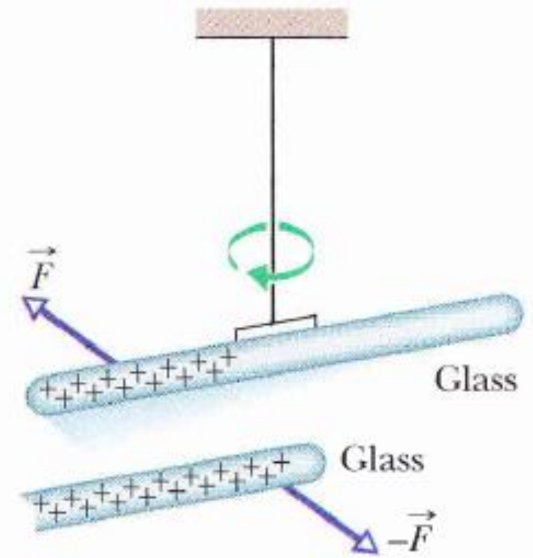
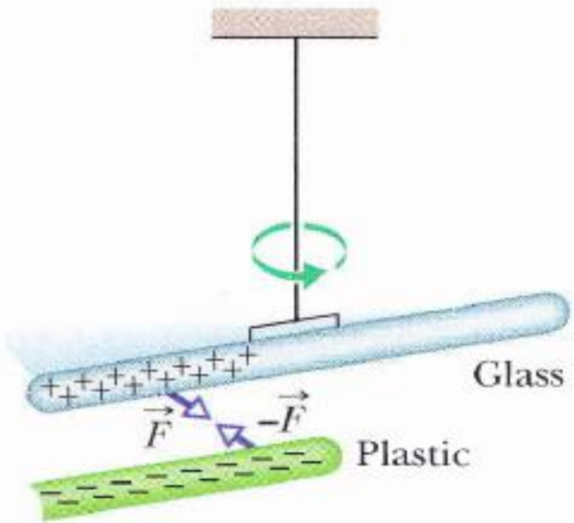
ELECTRIC CHARGE

- **Electric charge** is an **intrinsic property** of particles, such as electrons and protons.
- There are two types of charges: **positive** and **negatives**.
- **Electrons** have a **negative** charge.
- **Protons** have a **positive** charge.
- Charged particles can interact to create an **electrical force**.
- **Similar charges** produce a **repulsive force**, where each one repels the other.
- **Dissimilar charges** produce an **attractive force**, where each one attracts the other.

Glass + silk = + charge



(a)



(b)

Plastic+ fur = - charge

Charges with the same electrical sign repel each other, and charges with opposite electrical signs attract each other.

Conductors and Insulators

- Materials are classified into **four** categories in terms of their capability of conducting electricity.
- **Insulators**: materials that a significant amount of electrons are **not free** to move. examples include rubber plastic, glass, and chemically pure water.
- **Conductors**: materials that a significant amount of electrons are **free** to move (rather freely); examples include metals (such as copper in common lamp wire.
- **Semiconductors**: materials that sometimes behave like insulators and sometimes behave like conductors, intermediate between conductors and insulators. ; examples include silicon and germanium in computer chips
- **Superconductors**: materials that almost all electrons are free to move, perfect conductors(allowing charge to move without any hindrance).

QUANTIZATION OF CHARGE

- Th[…] the Coulomb (C) is the SI unit of charge.
- Any electric charge (q) is quantized, that means it depends on the number of electrons (n), according to

$$q = n\,e$$

- The electric current is the rate of change of the electric charge

$$i = \frac{dq}{dt}$$

Therefore , 1 Coulomb (C) = 1 Ampere (A). 1 second (s).

ELECTROSTATIC FORCE – COULOMB'S LAW

- The magnitude of the electrostatic force (attractive or repulsive) between two charged particles q_1 and q_2 separated by a distance r is determined by

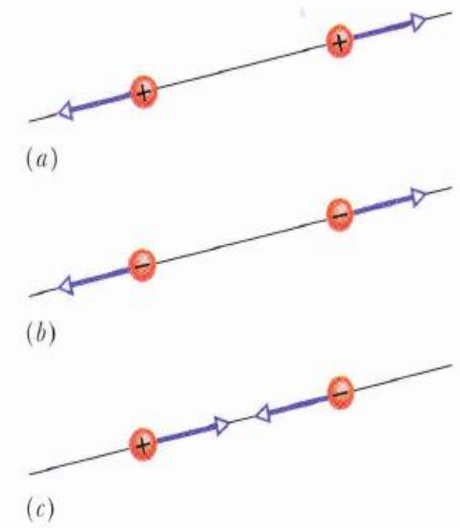
$$F = \frac{k|\,q_1||\,q_2|}{r^2}$$

where k is a constant equals to 9.0×10^9 N. m^2 / C^2, whi

$$k = \frac{1}{4\pi\varepsilon_0}$$

where ε_0 is known as the permittivity and equals to 8.8

The electric force is a vector quantity, therefore the resultant force on a superposition vector of all forces acting on i



$$\vec{F}_{1,\text{net}} = \vec{F}_{12} + \vec{F}_{13} + \vec{F}_{14} + \vec{F}_{15} + \cdots + \vec{F}_{1n},$$

Sample Problem 21-1 Build your skill

(a) Figure 21-9*a* shows two positively charged particles fixed in place on an x axis. The charges are $q_1 = 1.60 \times 10^{-19}$ C and $q_2 = 3.20 \times 10^{-19}$ C, and the particle separation is $R = 0.0200$ m. What are the magnitude and direction of the electrostatic force $\vec{F}_{12}$ on particle 1 from particle 2?

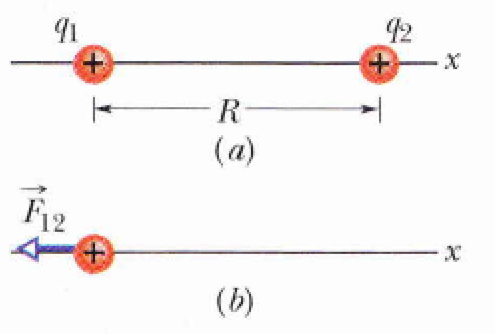


Figure 21-9a

Two particles: Using Eq. 21-4 with separation R substituted for r, we can write the magnitude F_{12} of this force as

$$\begin{aligned} F_{12} &= \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_2|}{R^2} \\ &= (8.99 \times 10^9\ \mathrm{N \cdot m^2/C^2}) \\ &\quad \times \frac{(1.60 \times 10^{-19}\ \mathrm{C})(3.20 \times 10^{-19}\ \mathrm{C})}{(0.0200\ \mathrm{m})^2} \\ &= 1.15 \times 10^{-24}\ \mathrm{N}. \end{aligned}$$

Thus, force $\vec{F}_{12}$ has the following magnitude and direction (relative to the positive direction of the x axis):

$$1.15 \times 10^{-24}\ \mathrm{N} \quad \text{and} \quad 180^\circ. \qquad \text{(Answer)}$$

We can also write $\vec{F}_{12}$ in unit-vector notation as

$$\vec{F}_{12} = -(1.15 \times 10^{-24}\ \mathrm{N})\hat{\mathrm{i}}. \qquad \text{(Answer)}$$

(b) Figure 21-9c is identical to Fig. 21-9a except that particle 3 now lies on the x axis between particles 1 and 2. Particle 3 has charge $q_3 = -3.20 \times 10^{-19}$ C and is at a distance $\frac{3}{4}R$ from particle 1. What is the net electrostatic force $\vec{F}_{1,\text{net}}$ on particle 1 due to particles 2 and 3?

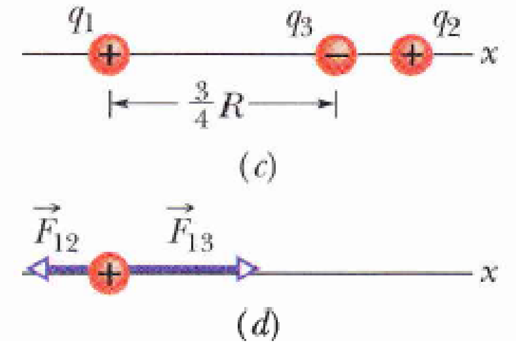


Figure 21-9c

Three particles: To find the magnitude of $\vec{F}_{13}$, we can rewrite Eq. 21-4 as

$$F_{13} = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_3|}{(\frac{3}{4}R)^2}$$
$$= (8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2) \times \frac{(1.60 \times 10^{-19}\text{ C})(3.20 \times 10^{-19}\text{ C})}{(\frac{3}{4})^2(0.0200\text{ m})^2}$$
$$= 2.05 \times 10^{-24}\text{ N}.$$

We can also write $\vec{F}_{13}$ in unit-vector notation:

$$\vec{F}_{13} = (2.05 \times 10^{-24}\text{ N})\hat{\text{i}}.$$

$$\vec{F}_{1,\text{net}} = \vec{F}_{12} + \vec{F}_{13}$$
$$= -(1.15 \times 10^{-24}\text{ N})\hat{\text{i}} + (2.05 \times 10^{-24}\text{ N})\hat{\text{i}}$$
$$= (9.00 \times 10^{-25}\text{ N})\hat{\text{i}}. \qquad \text{(Answer)}$$

Thus, $\vec{F}_{1,\text{net}}$ has the following magnitude and direction (relative to the positive direction of the x axis):

$$9.00 \times 10^{-25}\text{ N} \quad \text{and} \quad 0°. \qquad \text{(Answer)}$$

(c) Figure 21-9*e* is identical to Fig. 21-9*a* except that particle 4 is now included. It has charge $q_4 = -3.20 \times 10^{-19}$ C, is at a distance $\frac{3}{4}R$ from particle 1, and lies on a line that makes an angle $\theta = 60°$ with the x axis. What is the net electrostatic force $\vec{F}_{1,\text{net}}$ on particle 1 due to particles 2 and 4?

Summing components axis by axis. The sum of the x components gives us

$$\begin{aligned} F_{1,\text{net},x} &= F_{12,x} + F_{14,x} = F_{12} + F_{14}\cos 60° \\ &= -1.15 \times 10^{-24}\ \text{N} + (2.05 \times 10^{-24}\ \text{N})(\cos 60°) \\ &= -1.25 \times 10^{-25}\ \text{N}. \end{aligned}$$

The sum of the y components gives us

$$\begin{aligned} F_{1,\text{net},y} &= F_{12,y} + F_{14,y} = 0 + F_{14}\sin 60° \\ &= (2.05 \times 10^{-24}\ \text{N})(\sin 60°) \end{aligned}$$

The net force $\vec{F}_{1,\text{net}}$ has the magnitude

$$F_{1,\text{net}} = \sqrt{F_{1,\text{net},x}^2 + F_{1,\text{net},y}^2} = 1.78 \times 10^{-24}\ \text{N}. \quad \text{(Answer)}$$

To find the direction of $\vec{F}_{1,\text{net}}$, we take

$$\theta = \tan^{-1}\frac{F_{1,\text{net},y}}{F_{1,\text{net},x}} = -86.0°.$$

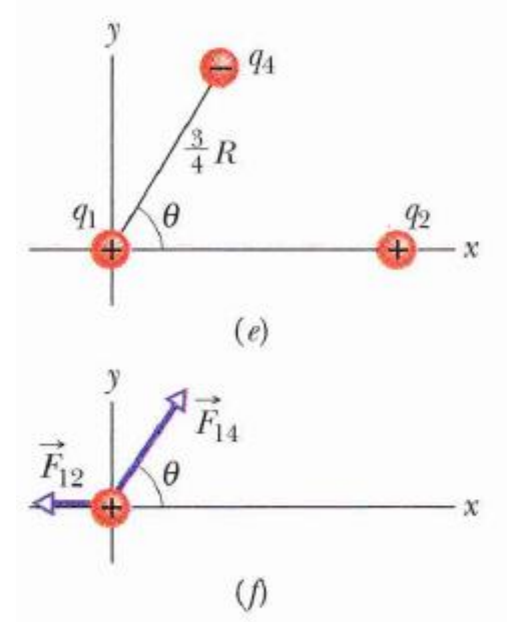


Figure 21-9e

Method 3. *Summing components axis by axis.* The sum of the x components gives us

$$\begin{aligned} F_{1,\text{net},x} &= F_{12,x} + F_{14,x} = F_{12} + F_{14}\cos 60^\circ \\ &= -1.15 \times 10^{-24}\ \text{N} + (2.05 \times 10^{-24}\ \text{N})(\cos 60^\circ) \\ &= -1.25 \times 10^{-25}\ \text{N}. \end{aligned}$$

The sum of the y components gives us

$$\begin{aligned} F_{1,\text{net},y} &= F_{12,y} + F_{14,y} = 0 + F_{14}\sin 60^\circ \\ &= (2.05 \times 10^{-24}\ \text{N})(\sin 60^\circ) \\ &= 1.78 \times 10^{-24}\ \text{N}. \end{aligned}$$

The net force $\vec{F}_{1,\text{net}}$ has the magnitude

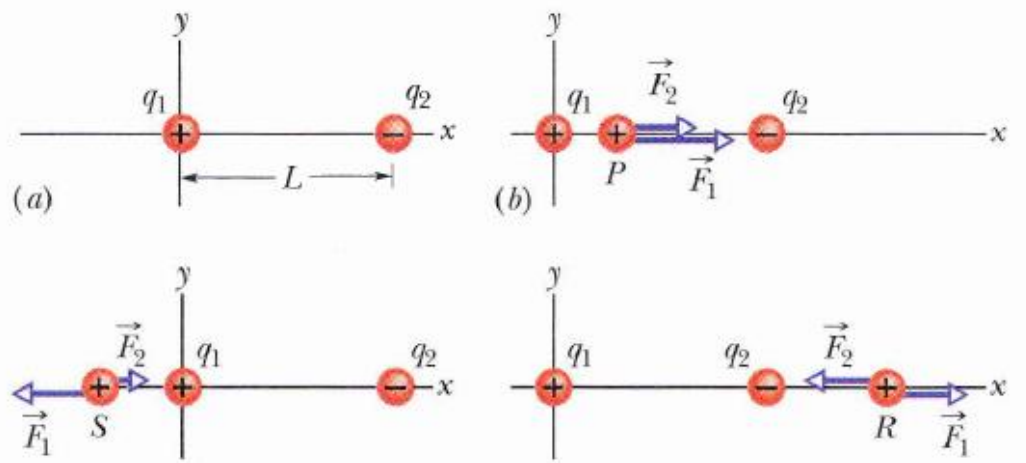
$$F_{1,\text{net}} = \sqrt{F_{1,\text{net},x}^2 + F_{1,\text{net},y}^2} = 1.78 \times 10^{-24}\ \text{N}. \quad \text{(Answer)}$$

To find the direction of $\vec{F}_{1,\text{net}}$, we take

$$\theta = \tan^{-1}\frac{F_{1,\text{net},y}}{F_{1,\text{net},x}} = -86.0^\circ.$$

Sample Problem 21-2

Figure 21-10*a* shows two particles fixed in place: a particle of charge $q_1 = +8q$ at the origin and a particle of charge $q_2 = -2q$ at $x = L$. At what point (other than infinitely far away) can a proton be placed so that it is in *equilibrium* (the net force on it is zero)? Is that equilibrium *stable* or *unstable*?



KEY IDEA If $\vec{F}_1$ is the force on the proton due to charge q_1 and $\vec{F}_2$ is the force on the proton due to charge q_2, then the point we seek is where $\vec{F}_1 + \vec{F}_2 = 0$. Thus,

$$\vec{F}_1 = -\vec{F}_2. \tag{21-8}$$

This tells us that at the point we seek, the forces acting on the proton due to the other two particles must be of equal magnitudes,

$$F_1 = F_2, \tag{21-9}$$

and that the forces must have opposite directions.

Calculations: With the aid of Eq. 21-4, we can now rewrite Eq. 21-9 (which says that the forces have equal magnitudes):

$$\frac{1}{4\pi\varepsilon_0}\frac{8qq_p}{x^2} = \frac{1}{4\pi\varepsilon_0}\frac{2qq_p}{(x-L)^2}. \qquad (21\text{-}10)$$

(Note that only the charge magnitudes appear in Eq. 21-10.) Rearranging Eq. 21-10 gives us

$$\left(\frac{x-L}{x}\right)^2 = \frac{1}{4}.$$

$$\frac{x-L}{x} = \frac{1}{2},$$

which gives us

$$x = 2L. \qquad \text{(Answer)}$$

Sample Problem 21-4

The nucleus in an iron atom has a radius of about 4.0×10^{-15} m and contains 26 protons.

(a) What is the magnitude of the repulsive electrostatic force between two of the protons that are separated by 4.0×10^{-15} m?

Calculation: Table 21-1 tells us that the charge of a proton is $+e$. Thus, Eq. 21-4 gives us

$$
\begin{aligned}
F &= \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2} \\
&= \frac{(8.99 \times 10^{9}\ \mathrm{N \cdot m^2/C^2})(1.602 \times 10^{-19}\ \mathrm{C})^2}{(4.0 \times 10^{-15}\ \mathrm{m})^2} \\
&= 14\ \mathrm{N}. \qquad \text{(Answer)}
\end{aligned}
$$

(b) What is the magnitude of the gravitational force between those same two protons?

$$
\begin{aligned}
F &= G\frac{m_p^2}{r^2} \\
&= \frac{(6.67 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2})(1.67 \times 10^{-27}\ \mathrm{kg})^2}{(4.0 \times 10^{-15}\ \mathrm{m})^2} \\
&= 1.2 \times 10^{-35}\ \mathrm{N}. \qquad \text{(Answer)}
\end{aligned}
$$

Worked Exercises

1. How many electrons would be removed from a metal to have a charge of 4.8 μC?

Solution

We know that the electric charge is quantized and defined by the equation

$$q = n\, e$$

$$n = \frac{q}{e} = \frac{4.8 \times 10^{-6}}{1.6 \times 10^{-19}} = 3.0 \times 10^{13} \text{ electrons}$$

Worked Exercises

2. 5×10^{20} electrons pass between two points in 4 s, calculate the current.

Solution

We know that the current is the rate of change of charge, therefore

$$i = \frac{dq}{dt} = \frac{q}{t}$$

But the charge is

$$q = n\,e$$

$$i = \frac{ne}{t} = \frac{5\times10^{20}\times1.6\times10^{-19}}{4} = 20 \text{ A}$$

WORKED EXERCISES

3. Two charges 4 μC and - 3 μC are separated by 2 cm. Calculate the force between them ?

Solution

Since the signs of the charges are different, they produce an attractive force. The magnitude of this force is

$$F = \frac{k|\,q_1||\,q_2|}{r^2}$$

$$F = \frac{9 \times 10^9 \times 4 \times 10^{-6} \times 3 \times 10^{-6}}{0.02^2} = 270 \text{ N}$$

WORKED EXERCISES

4. Calculate the distance between two point charges 2.4 μC and – 1.8 μC for the electrostatic force to be of magnitude 10.8 N?

Solution

The magnitude of the electrostatic force is given by

$$F = \frac{k|\,q_1||\,q_2|}{r^2} \qquad \rightarrow \qquad r = \sqrt{\frac{k|\,q_1||\,q_2|}{F}}$$

$$r = \sqrt{\frac{k|\,q_1||\,q_2|}{F}} = \sqrt{\frac{9 \times 10^9 \times 2.4 \times 10^{-6} \times 1.8 \times 10^{-6}}{10.8}} = 0.06\,m = 6\,cm$$

WORKED EXERCISES

5. A point charge 2.0 μC is placed at a distance 4 cm form another point charge q. If the attractive force between them is 56.25 N, find q.

Solution

The magnitude of the electrostatic force is given by

$$F = \frac{k|\,q_1||\,q_2|}{r^2} \quad \rightarrow \quad q_2 = \frac{F\,r^2}{k\,q_1}$$

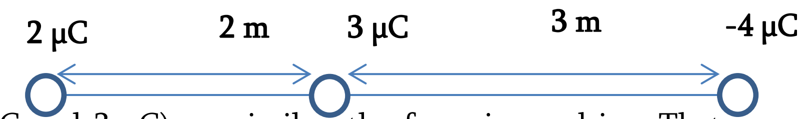
$$q_2 = \frac{56.25 \times 0.04^2}{9\times10^9\times2.0\times10^{-6}} = 5.0 \times 10^{-6}\mathrm{C} = 5\mu C$$

Since the force is ATTRACTIVE, the signs of the charges are DIFFERENT. Therefore the unknown charge is negative **-5.0 μC .**

WORKED EXERCISES

6. Three point charges 2.0, 3.0, and -4.0 μC are located as shown in the figure. Find the magnitude of the force acting on the 2 μC charge due to the others .

Solution



Since the signs of charges (2 μC and 3 μC) are similar, the force is repulsive. That means the force will be to left and its magnitude is

$$F_{12} = \frac{9 \times 10^{9} \times 2 \times 10^{-6} \times 3 \times 10^{-6}}{2^{2}} = 0.0135 \text{ N}$$

WORKED EXERCISES

Since the signs of charges (2 μC and -4 μC) are dissimilar, the force is attractive. That means the force will be to right and its magnitude is

$$F_{13} = \frac{9 \times 10^{9} \times 2 \times 10^{-6} \times 4 \times 10^{-6}}{5^{2}} = 0.00288 \text{ N}$$

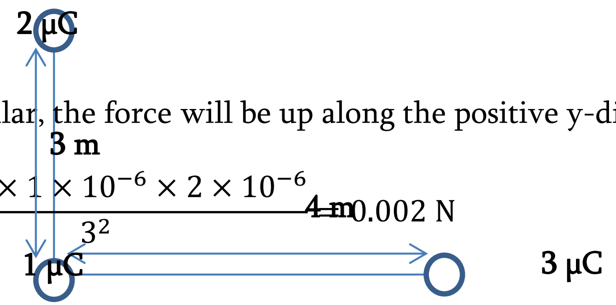
Therefore the magnitude of the force on the 2 μC particle due to the other charged particles is

$$F = |F_{12} - F_{13}| = |0.0135 - 0.00288| = 0.01062 \text{ N}$$

WORKED EXERCISES

7. Three point charges 1.0, 2.0, and 3.0 μC are arranged as shown in the figure. Find the magnitude of the force acting on the 2 μC charge due to the others .

Solution



Since the signs of charges (1 μC and 2 μC) are similar, the force will be up along the positive y-direction with magnitude of

$$F_{12} = \frac{9 \times 10^{9} \times 1 \times 10^{-6} \times 2 \times 10^{-6}}{3^{2}} = 0.002\ \mathrm{N}$$

WORKED EXERCISES

Since the signs of charges (2 μC and 3 μC) are also similar, the force will have two components (one along x and other along y axes)

$$F_{13x} = \frac{9 \times 10^9 \times 2 \times 10^{-6} \times 3 \times 10^{-6}}{5^2} \cdot \frac{4}{5} = 0.00173\ \text{N}$$

$$F_{13y} = \frac{9 \times 10^9 \times 2 \times 10^{-6} \times 3 \times 10^{-6}}{5^2} \cdot \frac{3}{5} = 0.0013\ \text{N}$$

Therefore the magnitude of the force on the 2 μC particle due to the other charged particles is

$$F_x = 0.00173\ N$$

$$F_y = 0.002 + 0.0013 = 0.0033\ N$$

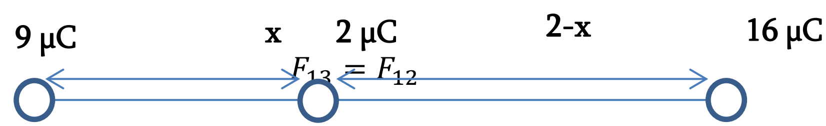
$$F = \sqrt{F_x^2 + F_y^2} = 0.00372\ N$$

WORKED EXERCISES

8. Two charges 9.0 and 16.0 μC are separated by a distance of 2 m. Where should a third charge 2 μC be placed for a net force on it zero?

Solution

As the charges are of same sign, the third charge must be placed between them and close to the smaller charge in order to have a zero net force.



$$\frac{9 \times 10^{9} \times 2 \times 10^{-6} \times 9 \times 10^{-6}}{x^{2}} = \frac{9 \times 10^{9} \times 2 \times 10^{-6} \times 16 \times 10^{-6}}{(2-x)^{2}}$$

Worked Exercises

$$\frac{9}{x^2} = \frac{16}{(2-x)^2}$$

Taking the square root of the above, we get

$$\frac{3}{x} = \frac{4}{2-x}$$

This leads to

$$x = \frac{6}{7} = 0.86\ m$$

WORKED EXERCISES

9. Four identical charges (2 μC) are located at the vertices of a square of side 5 cm. Calculate the magnitude of the electric force on a 5 μC located at the center of the square.

Solution

The electric forces on the 5 μC due to the other charges have the same magnitude. Each charge along the diagonal will experience equal and opposite force on the 5 μC charge, therefore, the resultant force is zero.