

Coulomb's Law

The Fundamental Physics Course II

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We firstly study the electric forces then pay attention to the magnetic ones.

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- There are two types of electric charge as positive charge and negative charge.
- In most objects, there are about equal numbers of negatively charged particles and positively charged particles, and so the net charge is zero, the charge is said to be balanced, and the object is said to be electrically neutral (or just neutral for short).

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- In most objects, there are about equal numbers of negatively charged particles and positively charged particles, and so the net charge is zero, the charge is said to be balanced, and the object is said to be electrically neutral (or just neutral for short).
- Particles with the same sign of electrical charge repel each other, and particles with opposite signs attract each other.

We can classify materials generally according to the ability of charge to move through them.

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- **Superconductors** are materials that are perfect conductors, allowing charge to move without any hindrance.

- The properties of conductors and insulators are due to the structure and electrical nature of atoms.

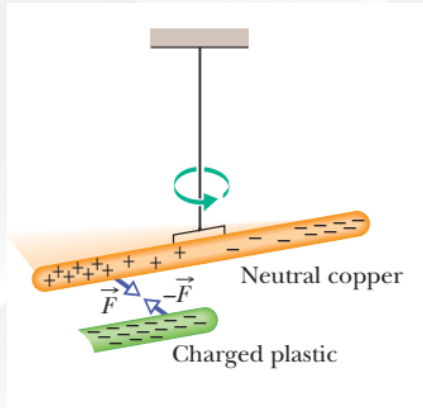
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- There are few free electrons in a nonconductor.

Induced charge means that some of positive and negative charges of an object have been separated due to the presence of a nearby charge.

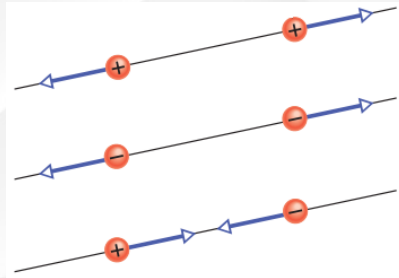


Note: Coulomb's Law works for only charged particles (and a few other things that can be treated as particles). For extended objects, with charge located in many different places, we need more powerful techniques.

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Note: Coulomb's Law works for only charged particles (and a few other things that can be treated as particles). For extended objects, with charge located in many different places, we need more powerful techniques.

- If two charged particles are brought near each other, they each exert an electrostatic force on the other.
- The direction of the force vectors depends on the signs of the charges.



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- The electrostatic force depends on the separation between the particles ($\propto \frac{1}{r^2}$)

So, the electrostatic force is calculated as

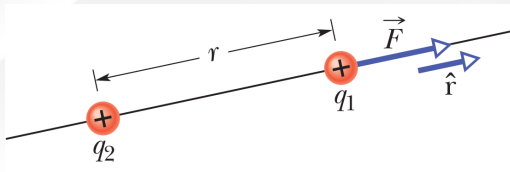
$$\vec{F} = k \frac{q_1 q_2}{r^2} \hat{r} \quad \text{Coulomb's Law}$$

where k is a positive constant called the *electrostatic constant* or the *Coulomb constant*

$$k = \frac{1}{4\pi\epsilon_0} = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2.$$

$$\epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2.$$

where ϵ_0 is called **permittivity constant**.



The SI unit of charge is the **coulomb**

$$1\text{C} = (1\text{A})(1\text{s}).$$

where A is the ampere which is the SI unit for electric current i

$$i = \frac{dq}{dt}, \quad \text{electric current.}$$

The electrostatic force obeys the principle of superposition. Suppose we have n charged particles near a chosen particle called particle 1; then the net force on particle 1 is given by the vector sum

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

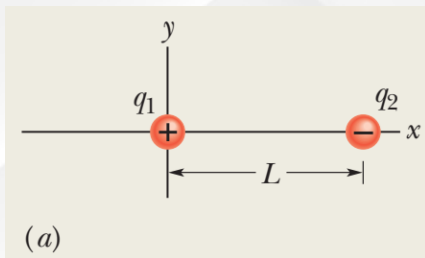
Shell theory 1.

A charged particle outside a shell with charge uniformly distributed on its surface is attracted or repelled as if the shell's charge were concentrated as a particle at its center.

Shell theory 2.

A charged particle inside a shell with charge uniformly distributed on its surface has no net force acting on it due to the shell.

Figure 21-8a 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? (That is, if the proton is displaced, do the forces drive it back to the point of equilibrium or drive it farther away?)



Solution:

Equilibrium means $\sum \vec{F} = 0$. In our example we have $\sum F_x = 0$. Then we have

$$\begin{aligned}\frac{1}{4\pi\epsilon_0} \frac{8qq_p}{x^2} &= \frac{1}{4\pi\epsilon_0} \frac{2qq_p}{(x-L)^2}, \\ \left(\frac{x-L}{x}\right)^2 &= \frac{1}{4} \\ \Rightarrow \frac{x-L}{x} &= \pm \frac{1}{2} \\ x &= \pm 2L.\end{aligned}$$

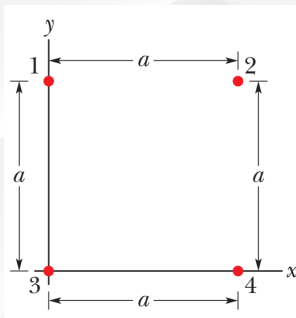
Since the repulsive force in the left side is much more than the attractive one then only $x = 2L$ is acceptable.

- Charge is Quantized. $q = ne$ where $e \approx 1.602 \times 10^{-19} C$ with $n = \pm 1, \pm 2, \pm 3, \dots$.

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- Charge is conserved. For instance alpha decay, pair production and $\dots$.

In Fig. 21-25, four particles form a square. The charges are $q_1 = q_4 = Q$ and $q_2 = q_3 = q$

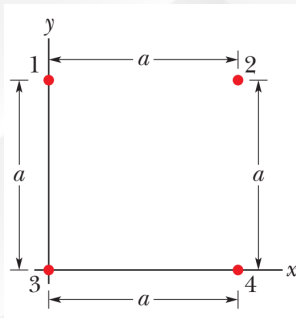
- What is Q/q if the net electrostatic force on particles 1 and 4 is zero?



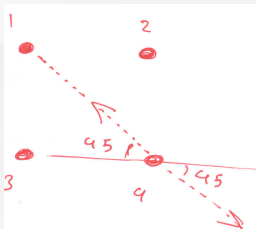
Further example 1

In Fig. 21-25, four particles form a square. The charges are $q_1 = q_4 = Q$ and $q_2 = q_3 = q$

- What is Q/q if the net electrostatic force on particles 1 and 4 is zero?
- Is there any value of q that makes the net electrostatic force on each of the four particles zero? Explain.



Solution:



(a) we assume $Q > 0$ and $q < 0$

$$F_{1x} = \frac{1}{4\pi\epsilon_0} \left(-\frac{QQ}{(\sqrt{2}a)^2} \cos 45^\circ + \frac{|q|Q}{a^2} \right) = \frac{Q|q|}{4\pi\epsilon_0 a^2} \left(-\frac{Q/|q|}{2\sqrt{2}} + 1 \right),$$

$$F_{1x} = 0 \Rightarrow -\frac{Q/|q|}{2\sqrt{2} + 1} = 0,$$

$$Q/|q| = 2\sqrt{2} \text{ or } Q/q = -2\sqrt{2} = -2.83.$$

Solution:

(b) Suppose we have an equilibrium situation. It means $\sum \vec{F} = 0$. Thus for example we have $F_{2y} = 0$

$$\begin{aligned} F_{2y} &= \frac{1}{4\pi\epsilon_0} \left(-\frac{|q|^2}{(\sqrt{2}a)^2} \sin 45^\circ - \frac{|q|Q}{a^2} \right) \\ &= \frac{|q|^2}{4\pi\epsilon_0 a^2} \left(-\frac{1}{2\sqrt{2}} + \frac{Q}{|q|} \right) = 0, \\ \Rightarrow Q/|q| &= \frac{1}{2\sqrt{2}} \quad \ast \end{aligned}$$

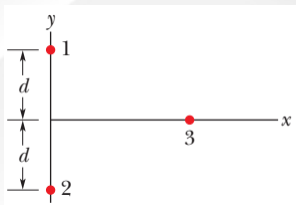
The result is inconsistent with that obtained in part (a).

Further example 2

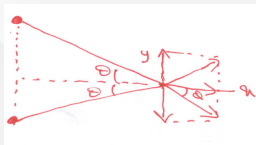
In Fig. 21-32, particles 1 and 2 of charge $q_1 = q_2 = +3.20 \times 10^{-19} \text{ C}$ are on a y axis at distance $d = 17.0 \text{ cm}$ from the origin. Particle 3 of charge $q_3 = +6.40 \times 10^{-19} \text{ C}$ moved gradually along the x axis from $x = 0$ to $x = +5.0 \text{ m}$. At what values of x will the magnitude of the electrostatic force on the third particle from the other two particles be

(a) minimum and (b) maximum?

What are the (c) minimum and (d) maximum magnitudes?



Solution:

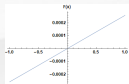


(a)

$$F_{\text{net}} = 2F \cos \theta = \frac{1}{4\pi\epsilon_0} \frac{2(2e)(4e)}{x^2 + d^2} \frac{x}{\sqrt{x^2 + d^2}},$$

$$= \frac{1}{4\pi\epsilon_0} \frac{4e^2 x}{(x^2 + d^2)^{3/2}}$$

where $\cos \theta = \frac{x}{\sqrt{x^2 + d^2}}$. $x_{\text{min}} = 0$ because



(b) Finding an extreme leads to

$$F'(x) = 0 \Rightarrow \frac{4e^2 (d^2 - 2x^2)}{\pi \varepsilon_0 (d^2 + x^2)^{5/2}} = 0$$
$$x = \pm \frac{d}{\sqrt{2}}.$$

The plus sign gives the maximum value.

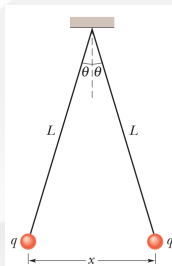
(c) $F(x = 0) = 0$

(d) $F(x = d/\sqrt{2}) = 4.916487832744266 \times 10^{-26}$

In Fig. 21-39, two tiny conducting balls of identical mass m and identical charge q hang from nonconducting threads of length L . Assume that u is so small that $\tan u$ can be replaced by its approximate equal, $\sin u$. (a) Show that

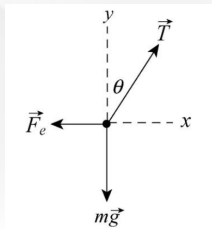
$$x = \left(\frac{q^2 L}{2\pi\epsilon_0 m g} \right)^{1/3}$$

gives the equilibrium separation x of the balls. (b) If $x = 5.0$ cm and $m = 10g$, and $L = 120$ cm, what is $|q|$?



Solution.

(a)



$$\left. \begin{aligned} -F_e + T \sin \theta &= 0 \\ -mg + T \cos \theta &= 0 \end{aligned} \right\} \Rightarrow mg \tan \theta - F_e = 0.$$

$$\tan \theta = \frac{x/2}{\sqrt{L^2 - (x/2)^2}} \approx \frac{x}{2L} + O(x^2)$$

$$\Rightarrow \frac{mgx}{2L} \approx \frac{1}{4\pi\epsilon_0} \frac{q^2}{x^2}$$
$$\Rightarrow x = \left(\frac{q^2 L}{2\pi\epsilon_0 mg} \right)^{1/3}$$

(b) Solving the q in terms of x leads to

$$q = \pm \sqrt{\frac{mgx^3}{2kL}} = \pm \sqrt{\frac{(0.010\text{kg})(9.8\text{m/s}^2)(0.050\text{m})^3}{2(8.99 \times 10^9 \text{Nm}^2/\text{C}^2)(1.2\text{m})}}$$
$$|q| = 2.38277 \times 10^{-8} \text{ C}.$$