Chapter 23

1

ELECTRIC FIELDS

1

Lecture 02

2

Electric Force
(Coulomb's Law)

2

Coulomb's Law

3

Charles coulomb measured the magnitudes of electric forces between two small charged spheres.

- The force is **inversely proportional** to the square of the separation (r) between the charges and directed along the line joining them.
- The force is **proportional** to the product of the charges, q_1 and q_2, on the two particles.

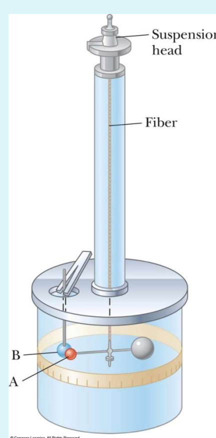
The electrical force between two stationary point charges is given by coulomb's law.

3

Coulomb's Law, cont.

4

- The term **Electrostatic** means that the charges are either stationary or moving only very slowly.
- Applies for only **point charges**.
  - The term point charge refers to a particle of **zero size** that carries an electric charge.



4

Coulomb's Law, cont.

5

- The force is **attractive** if the charges are of opposite sign.
- The force is **repulsive** if the charges are of like sign.
- The force is a **conservative** force.

5

Coulomb's Law, Equation

6

Mathematically,

$$F_e = k_e \frac{q_1 q_2}{r^2}$$

The SI unit of charge is the **Coulomb** (C).

k_e is called the Coulomb constant.

$$k_e = \frac{1}{4\pi\epsilon_\circ} \cong 9 \times 10^9 \; N.m^2/C^2$$

$\epsilon_\circ$ is the permittivity of free space.

$$\epsilon_\circ = 8.85 \times 10^{-12} \; C^2/N.m^2$$

6

Coulomb's Law, Notes

7

- Remember the charges need to be in Coulombs.
  - e is the smallest unit of charge.

$$e = 1.6 \times 10^{-19}\ C$$

  - So $1\ C$ needs 6.24×10^{18} electrons or protons
- Typical charges can be in the μC range.
- Remember that force is a **vector** quantity.

7

Particle Summary

8

- The electron and proton are identical in the magnitude of their charge, but very different in mass.
- The proton and the neutron are similar in mass, but very different in charge.

Particle	Charge (C)	Mass (kg)
Electron (e)	$-1.6021765 \times 10^{-19}$	9.1094×10^{-31}
Proton (p)	$+1.6021765 \times 10^{-19}$	1.67262×10^{-27}
Neutron (n)	0	1.67493×10^{-27}

8

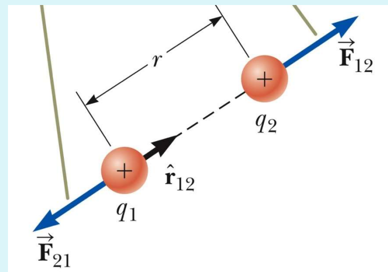
Vector Nature of Electric Forces

9

- In vector form,

$$\vec{F}_{12} = k_e \frac{q_1 q_2}{r^2} \hat{r}_{12}$$

- $\hat{r}_{12}$ is a unit vector directed from q_1 to q_2.
- The like charges produce a repulsive force between them.

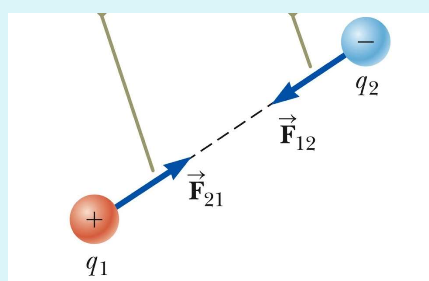


9

Vector Nature of Electrical Forces, 3

10

- Two point charges are separated by a distance *r*.
- The unlike charges produce an attractive force between them.



10

Vector Nature of Electrical Forces, cont.

11

- Electrical forces obey **Newton's Third Law**.
  - The force on q_1 is equal in magnitude and opposite in direction to the force on q_2

$$\vec{F}_{12} = -\vec{F}_{21}$$

- With like signs for the charges, the product $q_1 q_2$ is positive and the force is repulsive.
- With unlike signs for the charges, the product $q_1 q_2$ is negative and the force is attractive.

11

Multiple Charges

12

- The resultant force on any one charge equals the vector sum of the forces exerted by the other individual charges that are present.
  - Remember to add the forces **as vectors**.
- The resultant force on q_1 is the vector sum of all the forces exerted on it by other charges.
- For example, if four charges are present, the resultant force on one of these equals the vector sum of the forces exerted on it by each of the other charges.

$$\vec{F}_1 = \vec{F}_{21} + \vec{F}_{31} + \vec{F}_{41}$$

12

Prefixes and powers of ten

13

Power	Prefix	Abbreviation	Power	Prefix	Abbreviation
10^{-24}	yocto	y	10^{3}	kilo	k
10^{-21}	zepto	z	10^{6}	mega	M
10^{-18}	atto	a	10^{9}	giga	G
10^{-15}	femto	f	10^{12}	tera	T
10^{-12}	pico	p	10^{15}	peta	P
10^{-9}	nano	n	10^{18}	exa	E
10^{-6}	micro	μ	10^{21}	zetta	Z
10^{-3}	milli	m	10^{24}	yotta	Y
10^{-2}	centi	c			
10^{-1}	deci	d			

Mustafa Al-Zyout - Philadelphia University 10/5/2025

13

The Hydrogen Atom

Friday, 29 January, 2021 19:45

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.

R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.

J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.

H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.

H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.

The electron and proton of a hydrogen atom are separated by a distance of approximately $5.3 \times 10^{-11}\ m$. Find the magnitudes of the electric force and the gravitational force between the two particles.

$m_p = 1.67 \times 10^{-27}\ kg$

$m_e = 9.11 \times 10^{-31}\ kg$

$e = 1.6 \times 10^{-19}\ C$

$k_e = 9 \times 10^9\ N.m^2/C^2$

$G = 6.67 \times 10^{-11}\ N.m^2/kg^2$

SOLUTION

Use Coulomb's law to find the magnitude of the electric force:

$$F_e = k_e \frac{e^2}{r^2}$$

$$= (9 \times 10^9)\frac{(1.60 \times 10^{-19})^2}{(5.3 \times 10^{-11})^2}$$

$$= 8.2 \times 10^{-8} N$$

Use Newton's law of universal gravitation to find the magnitude of the gravitational force:

$$F_g = G\frac{m_e m_p}{r^2}$$

$$= (6.67 \times 10^{-11})\frac{(9.11 \times 10^{-31})(1.67 \times 10^{-27})}{(5.3 \times 10^{-11})^2}$$

$$= 3.6 \times 10^{-47} N$$

The ratio:

$$F_e/F_g \approx 2 \times 10^{39}.$$

Therefore, the gravitational force between charged atomic particles is negligible when compared with the electric force.

★ Find the Resultant Force

Friday, 29 January, 2021 19:49

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.

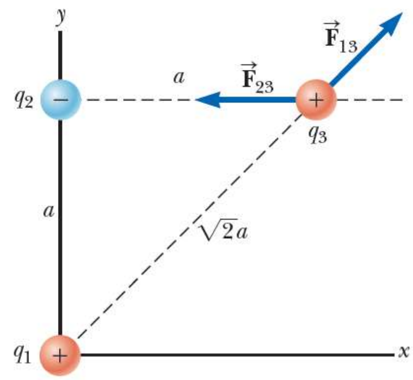
R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.

J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.

H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.

H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.

Consider three point charges located at the corners of a right triangle as shown, where $q_1 = q_3 = 5\,\mu C$, $q_2 = -2\,\mu C$ and $a = 0.1\,m$. Find the resultant force exerted on q_3 .



SOLUTION

The force $\vec{F}_{23}$ exerted by q_2 on q_3 is attractive because q_2 and q_3 have opposite signs. In the coordinate system shown, the attractive force $\vec{F}_{23}$ is to the left (in the negative x direction). The force $\vec{F}_{13}$ exerted by q_1 on q_3 is repulsive because both charges are positive. The repulsive force $\vec{F}_{13}$ makes an angle of $45°$ with the x axis.

Use Coulomb's law to find the magnitude of $\vec{F}_{23}$:

$$F_{23} = k_e \frac{q_2 q_3}{a^2} = (9 \times 10^9) \frac{(2.00 \times 10^{-6})(5.00 \times 10^{-6})}{(0.1)^2} = 9N$$

And the magnitude of the force $\vec{F}_{13}$:

$$F_{13} = k_e \frac{q_1 q_3}{\sqrt{2}a^2} = (9 \times 10^9) \frac{(5.00 \times 10^{-6})(5.00 \times 10^{-6})}{\left(\sqrt{2} \times 0.1\right)^2} = 11.25N$$

Find the x and y components of the force $\vec{F}_{13}$:

$$F_{13x} = F_{13}\,cos\,4\,5.0° = 7.95N$$

$$F_{13y} = F_{13}\,sin\,4\,5.0° = 7.95N$$

Find the components of the resultant force acting on q_3:

$$F_{3x} = F_{13x} + F_{23x} = 7.95N + (-9N) = -1.05N$$

$$F_{3y} = F_{13y} + F_{23y} = 7.95N + 0 = 7.95N$$

Express the resultant force acting on q_3 in unit-vector form:

$$\vec{F}_3 = (-1.05\hat{\imath} + 7.95\hat{\jmath})N$$

We can use the Pythagorean theorem to find the magnitude of the resultant force F,

$$F = \sqrt{(-1.05)^2 + 7.95^2} = 8.02N$$

and we can use the figure to find its direction. Thus:

$$\varphi = \tan^{-1}\frac{7.95}{-1.05} = -82.5°$$

Since the sign of F_x is negative and the sign of F_y is positive, the resultant displacement lies in the second quadrant of the coordinate system. That is,

$$\theta = 180° - 82.5° = 97.5°$$

What if the signs of all three charges were changed to the opposite signs? How would that affect the result for $\vec{F}_3$?

Answer: The charge q_3 would still be attracted toward q_2 and repelled from q_1 with forces of the same magnitude. Therefore, the final result for $\vec{F}_3$ would be the same.

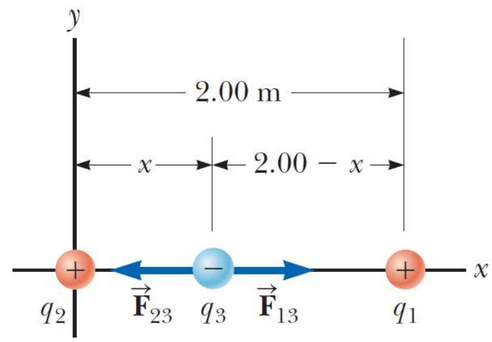
★ Where Is the Net Force Zero? 1

Friday, 29 January, 2021 19:49

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.

- [x] R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.
- [ ] J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.
- [ ] H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.
- [ ] H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.

Three point charges lie along the x axis as shown. The positive charge $q_1 = 15\,\mu C$ is at $x = 2\,m$, the positive charge $q_2 = 6\,\mu C$ is at the origin, and the net force acting on q_3 is zero. What is the x coordinate of q_3 ?



SOLUTION

Because q_3 is negative and q_1 and q_2 are positive, the forces $\vec{F}_{13}$ and $\vec{F}_{23}$ are both attractive. We model the point charge as a particle in equilibrium. Write an expression for the net force on charge q_3 when it is in equilibrium:

$$\vec{F}_3 = \vec{F}_{23} + \vec{F}_{13} = -k_e \frac{q_2 q_3}{x^2}\hat{\imath} + k_e \frac{q_1 q_3}{(2-x)^2}\hat{\imath} = 0$$

Move the second term to the right side of the equation and set the coefficients of the unit vector $\hat{\imath}$ equal:

$$k_e \frac{q_2 q_3}{x^2} = k_e \frac{q_1 q_3}{(2.00-x)^2}$$

Eliminate k_e and $|q_3|$ and rearrange the equation:

$$(2-x)^2|q_2| = x^2|q_1|$$

$$(4-4x+x^2)(6\times10^{-6}) = x^2(15\times10^{-6})$$

Reduce the quadratic equation to a simpler form:

$$3x^2 + 8x - 8 = 0$$

Solve the quadratic equation for the positive root: $x = 0.775m$

The second root to the quadratic equation is $x = -3.44m$. That is another location where the *magnitudes* of the forces on q_3 are equal, but both forces are in the same direction.

Distance is changed

Friday, 29 January, 2021 19:50

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.
R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.
J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.
H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.
H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.

A charged particle A exerts a force of $2.62\ \mu N$ to the right on charged particle B when the particles are $13.7\ mm$ apart. Particle B moves straight away from A to make the distance between them $17.7\ mm$. What vector force does it then exert on A?

Solution

In the first situation, the magnitude of the electrostatic force is:

$$F_{A\ on\ B,\,1} = k_e \frac{q_A q_B}{r_{AB,1}^2} \qquad (1)$$

In the second situation, since the charges are still the same, the magnitude of the electrostatic force is:

$$F_{B\ on\ A,\,2} = k_e \frac{q_A q_B}{r_{AB,2}^2} \qquad (2)$$

Dividing equation (2) by equation (1):

$$\frac{F_2}{F_1} = \frac{r_1^2}{r_2^2}$$

$$\Rightarrow\ F_2 = F_1 \frac{r_1^2}{r_2^2} = 2.62 \times 10^{-6} \times \frac{(13.7 \times 10^{-3})^2}{(17.7 \times 10^{-3})^2}$$

$$= 1.57 \times 10^{-6} N$$

Equilibrium-1

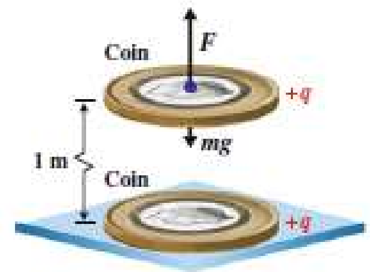
Friday, 29 January, 2021 19:50

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.

- R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.
- J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.
- H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.
- H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.

Two identical copper coins of mass $m = 2.5\ g$ contain about $N = 2 \times 10^{22}\ atoms$ each. A number of electrons n are removed from each coin to acquire a net positive charge q. Assume that when we place one of the coins on a table and the second above the first, the second coin stays at rest in air at a distance of $1m$.

- Find the value of q that keeps the two coins in that configuration.
- Find the number of removed electrons n from each coin.



Solution:

(a)The upper coin is in equilibrium due to its weight and the electrostatic repulsion between the two charged coins. Therefore:

$$\sum \vec{F} = 0$$

$$F_e = mg$$

$$\frac{k_e q_1 q_2}{r^2} = mg$$

$$\frac{9 \times 10^9 \times q^2}{1^2} = 2 \cdot 5 \times 10^{-3} \times 9.8$$

$$q = \sqrt{\frac{1^2 \times 2 \cdot 5 \times 10^{-3} \times 9.8}{9 \times 10^9}} = 1 \cdot 65 \times 10^{-6} C$$

This small charge leads to a measurable force between large bodies.

(b) From the fundamental charge (e) and the total charge q on each coin, we can find the number of removed electrons n as follows:

$$Q = Ne$$
$$\Rightarrow +1.65 \times 10^{-6} = N \times 1.6 \times 10^{-19}$$

$$\Rightarrow N \approx 1 \times 10^{13}$$

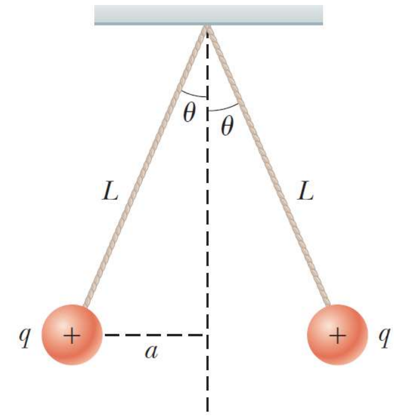
★ Equilibrium-2 (Electroscope)

Friday, 29 January, 2021 19:50

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.

- R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.
- J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.
- H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.
- H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.

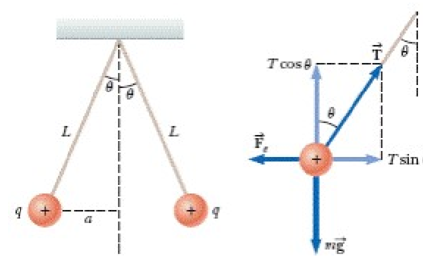
Two identical small charged spheres, each having a mass of $3 \times 10^{-2}\ kg$ hang in equilibrium as shown. The length (L) of each string is 0.150 m, and the angle $\theta = 5^{\circ}$. Find the magnitude of the charge on each sphere.



SOLUTION

The two spheres exert repulsive forces on each other. If they are held close to each other and released, they move outward from the center and settle into the configuration shown.

The key phrase "in equilibrium" helps us model each sphere as a particle in equilibrium.



The force diagram for the left-hand sphere is shown, the sphere is in equilibrium under the application of the force $\vec{T}$ from the string, the electric force $\vec{F_e}$ from the other sphere, and the gravitational force $m\vec{g}$.

Write Newton's second law for the left-hand sphere in component form:

$$(1) \sum F_x = T\sin\theta - F_e = 0 \ \Rightarrow\ T\sin\theta = F_e$$

$$(2) \sum F_y = T\sin\theta - mg = 0 \ \Rightarrow\ T\cos\theta = mg$$

Divide Equation (1) by Equation (2) to find F_e:

$$\tan\theta = \frac{F_e}{mg} \ \Rightarrow\ F_e = mg\tan\theta$$

Use the geometry of the right triangle in the Figure to find a relationship between $a, L,$ and θ:

$$\sin\theta = \frac{a}{L} \ \Rightarrow\ a = L\sin\theta$$

Solve Coulomb's law for the charge $|q|$on each sphere:

$$q = \sqrt{\frac{F_e r^2}{k_e}} = \sqrt{\frac{F_e (2a)^2}{k_e}} = \sqrt{\frac{mg\tan\theta\,(2L\sin\theta)^2}{k_e}}$$

Substitute numerical values:

$$q = \sqrt{\frac{(3.00 \times 10^{-2})(9.80)(\tan 5\,°)[(2)(0.150)(\sin 5\,°)]^2}{9 \times 10^9}}$$

$$q = 4.42 \times 10^{-8} C$$

The situation is the same whether both spheres are positively charged or negatively charged.