Chapter 21

Coulomb's Law

Lecture 1

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 → Modified by S.H. Seo

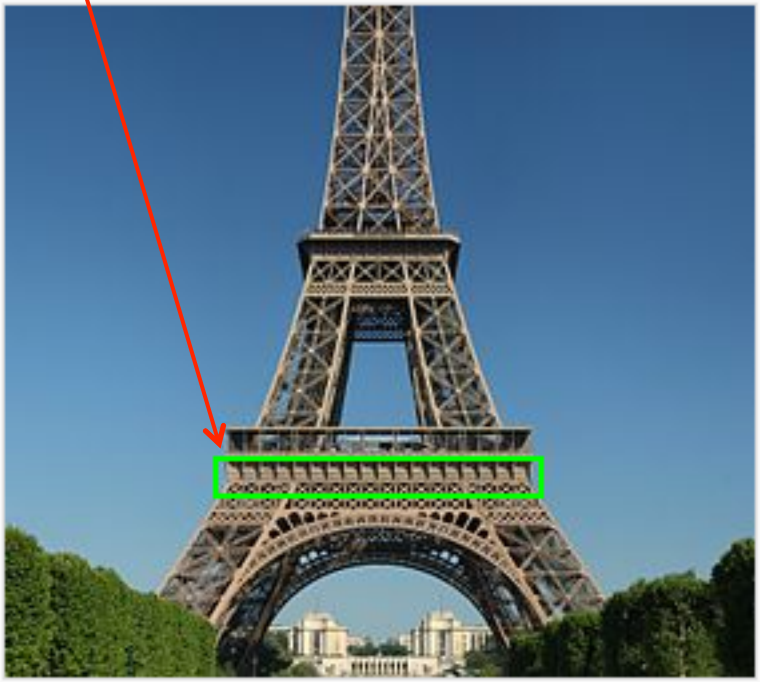
Charles-Augustin de Coulomb

Portrait by Hippolyte Lecomte

Born	14 June 1736 Angoulême, Angoumois, France
Died	23 August 1806 (aged 70) Paris, France
Nationality	French
Fields	Physics
Known for	Coulomb's law

List of the 72 names on the Eiffel Tower

On the Eiffel Tower, seventy-two names of French male scientists, engineers, and mathematicians are engraved in recognition of their contributions.



The location of the names on the tower

Adapted from Wikipedia

21-1 Coulomb's Law

Learning Objectives

21.01 Distinguish between being electrically neutral, negatively charged, and positively charged and identify excess charge.

21.02 Distinguish between conductors, nonconductors (insulators), semiconductors, and superconductors.

21.03 Describe the electrical properties of the particles in-side an atom.

21.04 Identify conduction electrons and explain their role in making a conducting object negatively or positively charged.

21.05 Identify what is meant by "electrically isolated" and by "grounding."

21.06 Explain how a charged object can set up induced charge in a second object.

21.07 Identify that charges with the same electrical sign repel each other and those with opposite electrical signs attract each other.

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21-1 Coulomb's Law

Learning Objectives (Contd.)

21.08 For either of the particles in a pair of charged particles, draw a free-body diagram, showing the electrostatic force (Coulomb force) on it and anchoring the tail of the force vector on that particle.

21.09 For either of the particles in a pair of charged particles, apply Coulomb's law to relate the magnitude of the electro- static force, the charge magnitudes of the particles, and the separation between the particles.

21.10 Identify that Coulomb's law applies only to (point-like) particles and objects that can be treated as particles.

21.11 If more than one force acts on a particle, find the net force by adding all the forces as vectors, not scalars.

21.12 Identify that a shell of uniform charge attracts or repels a charged particle that is outside the shell as if all the shell's charge were concentrated as a particle at the shell's center.

21-1 Coulomb's Law

Learning Objectives (Contd.)

21.13 Identify that if a charged particle is located inside a shell of uniform charge, there is no net electrostatic force on the particle from the shell.

21.14 Identify that if excess charge is put on a spherical conductor, it spreads out uniformly over the external surface area.

21.15 Identify that if two identical spherical conductors touch or are connected by conducting wire, any excess charge will be shared equally.

21.16 Identify that a non-conducting object can have any given distribution of charge, including charge at interior points.

21.17 Identify current as the rate at which charge moves through a point.

21.18 For current through a point, apply the relationship between the current, a time interval, and the amount of charge that moves through the point in that time interval.

21-1 Coulomb's Law

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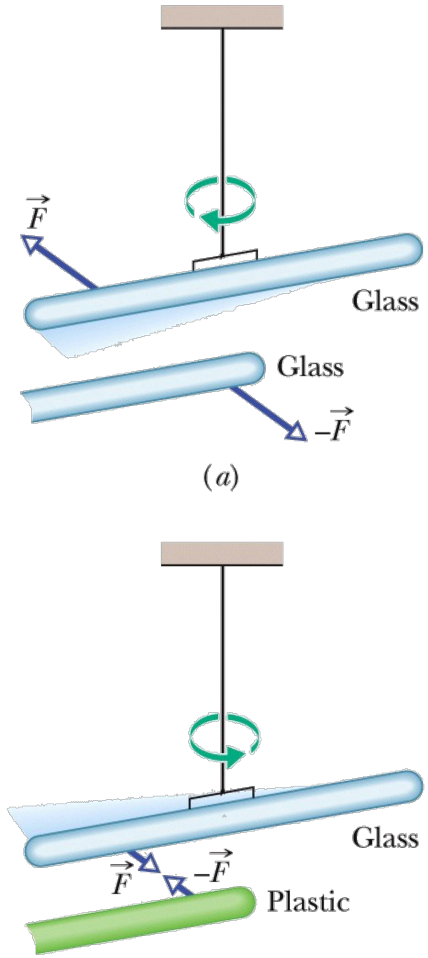
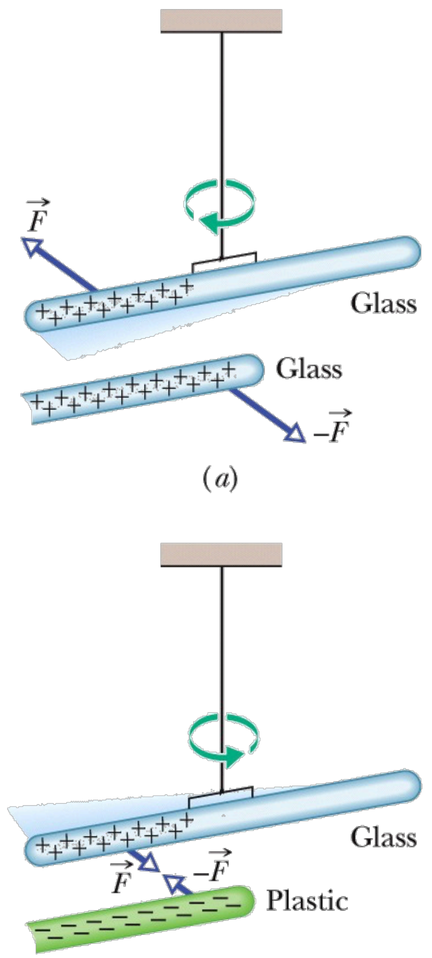
Magic?



(a) The two glass rods were each rubbed with a silk cloth and one was suspended by thread. When they are close to each other, they repel each other.

(b) The plastic rod was rubbed with fur. When brought close to the glass rod, the rods attract each other.

21-1 Coulomb's Law



Electric Charge

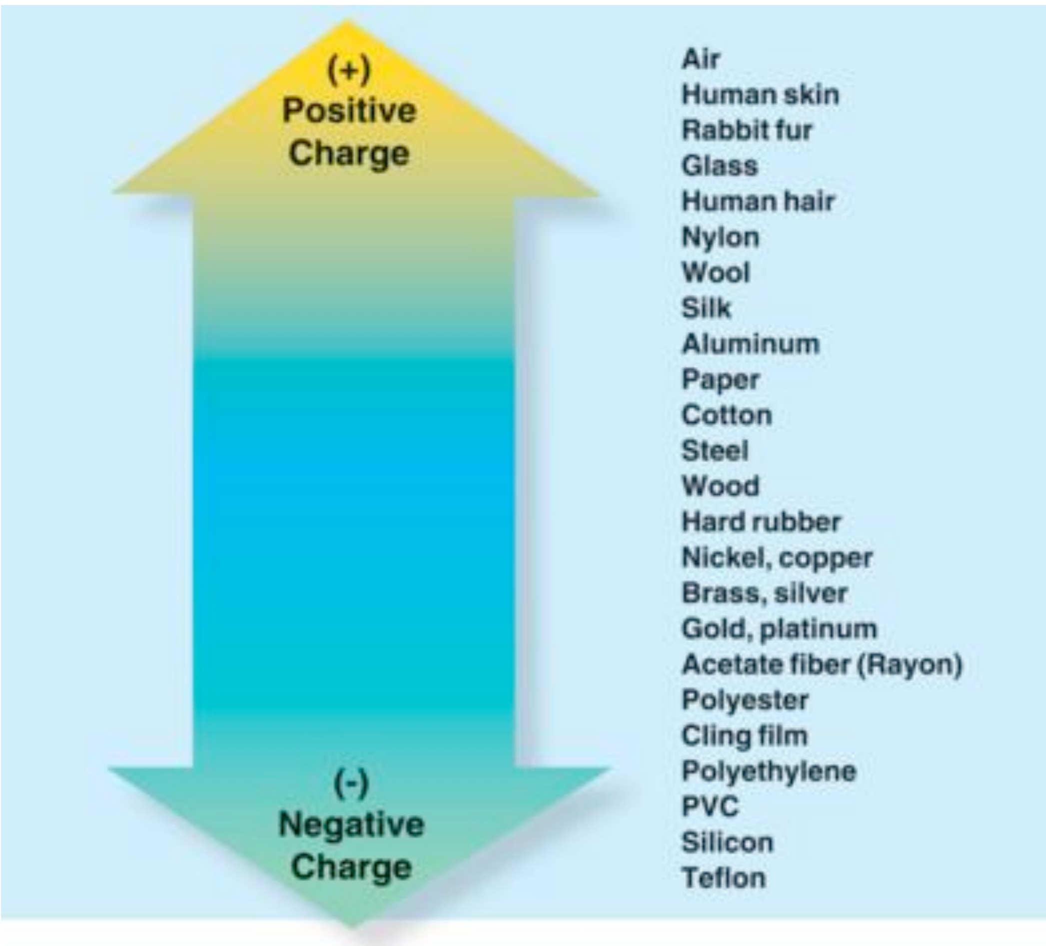
(a) Two charged rods of the same sign repel each other.

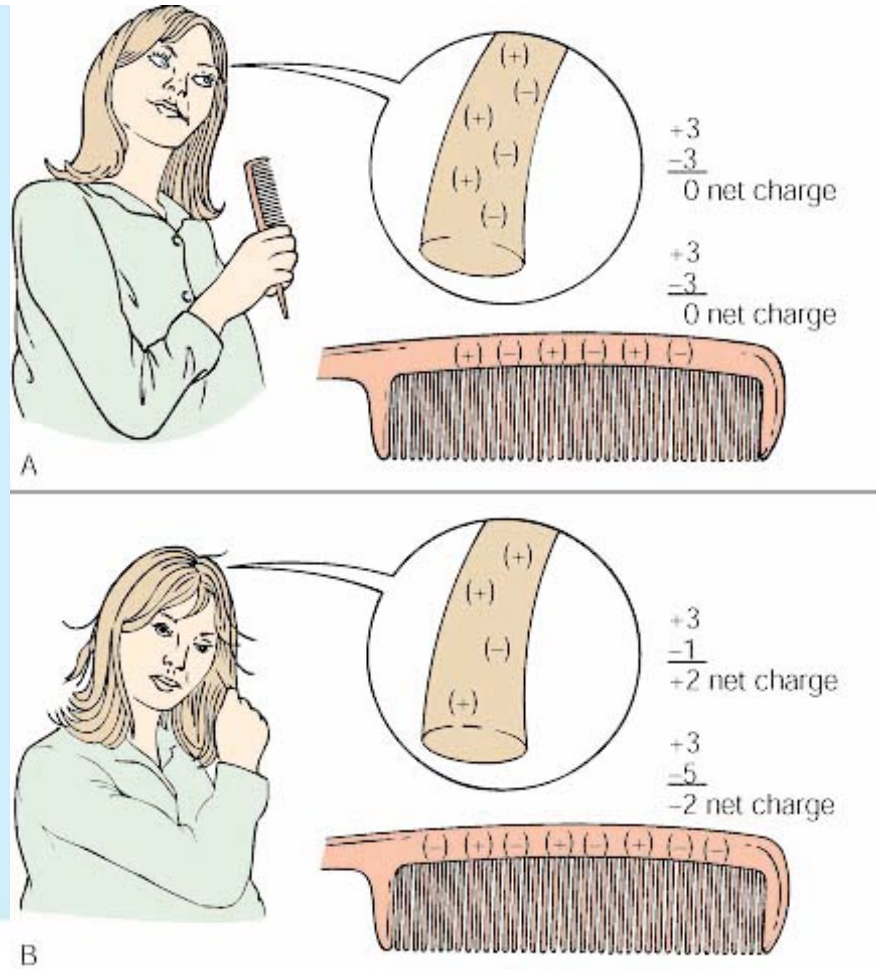
(b) Two charged rods of opposite signs attract each other. Plus signs indicate a positive net charge, and minus signs indicate a negative net charge.

Particles with the same sign of electrical charge repel each other, and particles with opposite signs attract each other.

Triboelectric Series

Triboelectricity: creating charges by **friction**





21-1 Coulomb's Law

Materials classified based on their ability to move charge

- **Conductors** are materials in which a significant number of electrons are free to move. Examples include metals.

- The charged particles in nonconductors (**insulators**) are not free to move. Examples include rubber, plastic, glass.

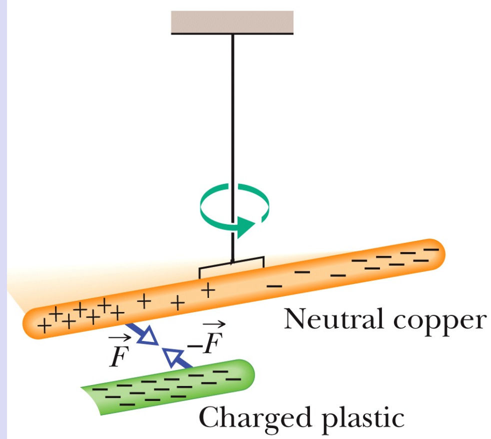
- **Semiconductors** are materials that are intermediate between conductors and insulators; examples include silicon and germanium in computer chips.

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

21-1 Coulomb's Law

- **Charged Particles.** The properties of conductors and insulators are due to the structure and electrical nature of atoms. Atoms consist of positively charged *protons*, negatively charged *electrons*, and electrically neutral *neutrons*. The protons and neutrons are packed tightly together in a central nucleus and do not move.
- When atoms of a conductor like copper come together to form the solid, some of their outermost—and so most loosely held—electrons become free to wander about within the solid, leaving behind positively charged atoms (positive ions). We call the mobile electrons **conduction electrons**. There are few (if any) free electrons in a nonconductor.

Induced Charge. A neutral copper rod is electrically isolated from its surroundings by being suspended on a non-conducting thread. Either end of the copper rod will be attracted by a charged rod. Here, conduction electrons in the copper rod are repelled to the far end of that rod by the negative charge on the plastic rod. Then that negative charge attracts the remaining positive charge on the near end of the copper rod, rotating the copper rod to bring that near end closer to the plastic rod.

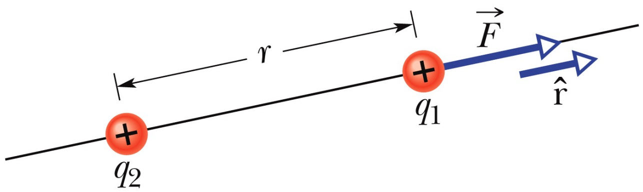


21-1 Coulomb's Law

Coulomb's Law

Coulomb's law describes the **electrostatic force** (or electric force) between two charged particles. If the particles have charges q_1 and q_2, are separated by distance r, and are at rest (or moving only slowly) relative to each other, then the magnitude of the force acting on each due to the other is given by

$$\boxed{F = \frac{1}{4\pi\varepsilon_0}\frac{|q_1|\,|q_2|}{r^2} \quad \text{(Coulomb's law),}}$$



The electrostatic force on particle 1 can be described in terms of a unit vector ***r*** along an axis through the two particles, radially away from particle 2.

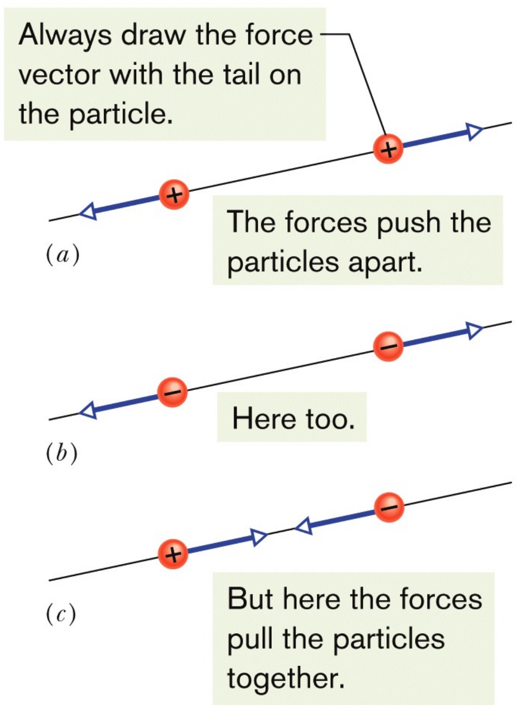
where $\boldsymbol{\varepsilon_0}$ = $8.85 \times 10^{-12}\ C^2/N.m^2$ is the **permittivity** constant. The ratio $1/4\pi\varepsilon_0$ is often replaced with the electrostatic constant (or Coulomb constant) $k=8.99\times10^9\ N.m^2/C^2$. Thus k = $1/4\pi\varepsilon_0$.

21-1 Coulomb's Law

Coulomb's Law

- The electrostatic force vector acting on a charged particle due to a second charged particle is either directly toward the second particle (opposite signs of charge) or directly away from it (same sign of charge).

- If multiple electrostatic forces act on a particle, the net force is the vector sum (not scalar sum) of the individual forces.



Two charged particles repel each other if they have the same sign of charge, either (a) both positive or (b) both negative. (c) They attract each other if they have opposite signs of charge.

Electric Force vs Gravity

Electrostatics	Gravity
Force: $F_e = \frac{kq_1q_2}{r^2}$	Force: $F_g = \frac{Gm_1m_2}{r^2}$
Field Strength: $E = \frac{F_e}{q}$	Field Strength: $g = \frac{F_g}{m}$
Field Strength: $E = \frac{kq}{r^2}$	Field Strength: $g = \frac{Gm}{r^2}$
Electrostatic Constant: $k = 8.99 * 10^9 \frac{N \bullet m^2}{C^2}$	Gravitational Constant: $G = 6.67 * 10^{-11} \frac{N \bullet m^2}{kg^2}$
Charge Units: Coulombs	Mass Units: kilograms

$$\frac{F_{gravity}}{F_{electric}}(Hydrogen) = 10^{-39}$$

$$= 0.00000000000000000000000000000000000001$$

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Example 23.1 The Hydrogen Atom

The electron and proton of a hydrogen atom are separated (on the average) by a distance of approximately 5.3×10^{-11} m. Find the magnitudes of the electric force and the gravitational force between the two particles.

Solution From Coulomb's law, we find that the attractive electric force has the magnitude

$$F_e = k_e \frac{|e|^2}{r^2} = \left(8.99 \times 10^9 \frac{\mathrm{N \cdot m^2}}{\mathrm{C^2}}\right) \frac{(1.60 \times 10^{-19}\ \mathrm{C})^2}{(5.3 \times 10^{-11}\ \mathrm{m})^2}$$

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

Using Newton's law of gravitation and Table 23.1 for the particle masses, we find that the gravitational force has the magnitude

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

$$= \left(6.7 \times 10^{-11} \frac{\mathrm{N \cdot m^2}}{\mathrm{kg^2}}\right)$$

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

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

The ratio $F_e/F_g \approx 2 \times 10^{39}$. Thus, the gravitational force between charged atomic particles is negligible when compared with the electric force. Note the similarity of form of Newton's law of gravitation and Coulomb's law of electric forces. Other than magnitude, what is a fundamental difference between the two forces?

21-1 Coulomb's Law

Multiple Forces: If multiple electrostatic forces act on a particle, the net force is the vector sum (not scalar sum) of the individual forces.

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

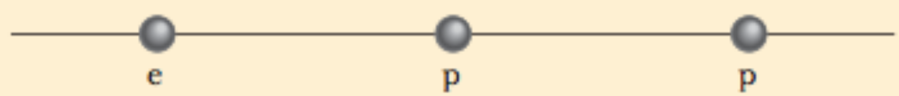
Shell Theories: There are two shell theories for electrostatic force

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.

Checkpoint 2

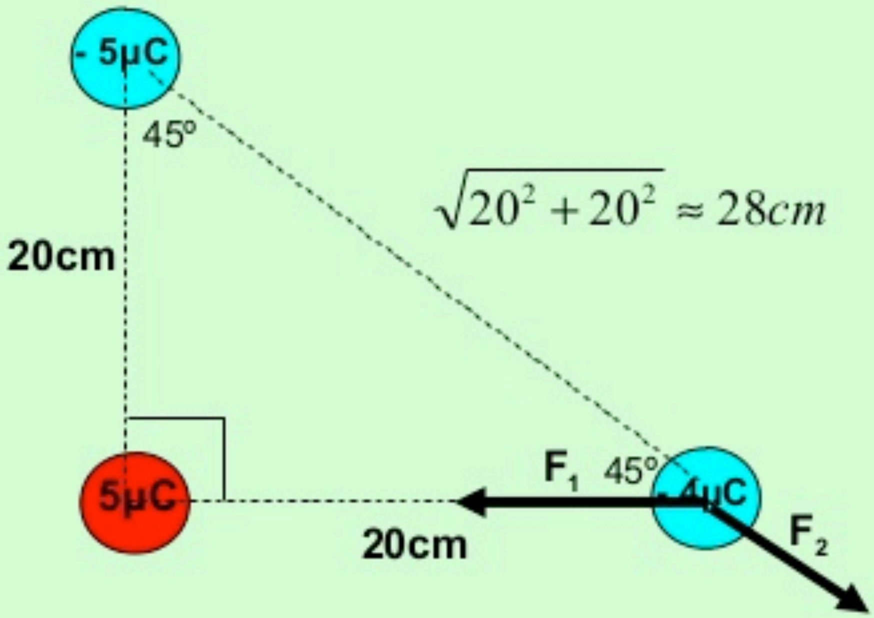
The figure shows two protons (symbol p) and one electron (symbol e) on an axis. On the central proton, what is the direction of (a) the force due to the electron, (b) the force due to the other proton, and (c) the net force?



Answer: (a) left towards the electron
(b) left away from the other proton
(c) left

Example 3

Three charged objects are placed as shown. Find the net force on the object with the charge of -4µC.



$$\sqrt{20^2+20^2} \approx 28cm$$

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

$$F_1 = 9\times10^9 \frac{(5\times10^{-6})(4\times10^{-6})}{(0.20)^2} = 4.5N$$

$$F_2 = 9\times10^9 \frac{(5\times10^{-6})(4\times10^{-6})}{(0.28)^2} = 2.30N$$

F_1 and F_2 must be added together as vectors.

21-2 Charge is Quantized

Learning Objectives

21.19 Identify the elementary charge.

21.20 Identify that the charge of a particle or object must be a positive or negative integer times the elementary charge.

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21-2 Charge is Quantized

- Electric charge is quantized (restricted to certain values).

- The charge of a particle can be written as ne, where *n* is a positive or negative integer and *e* is the elementary charge. Any positive or negative charge *q* that can be detected can be written as

$$\boxed{q = ne, \qquad n = \pm 1, \pm 2, \pm 3, \ldots,}$$

in which *e*, the elementary charge, has the approximate value

$$\boxed{e = 1.602 \times 10^{-19}\ \mathrm{C}.}$$

Table 21-1 The Charges of Three Particles

Particle	Symbol	Charge
Electron	e or e^-	$-e$
Proton	p	$+e$
Neutron	n	0

21-2 Charge is Quantized

When a physical quantity such as charge can have only discrete values rather than any value, we say that the quantity is **quantized**. It is possible, for example, to find a particle that has no charge at all or a charge of $+10e$ or $-6e$, but not a particle with a charge of, say, $3.57e$.

Checkpoint 4

Initially, sphere A has a charge of $-50e$ and sphere B has a charge of $+20e$. The spheres are made of conducting material and are identical in size. If the spheres then touch, what is the resulting charge on sphere A?

Answer: $-15e$

21-3 Charge is Conserved

Learning Objectives

21.21 Identify that in any isolated physical process, the net charge cannot change (the net charge is always conserved).

21.22 Identify an annihilation process of particles and a pair production of particles.

21.23 Identify mass number and atomic number in terms of the number of protons, neutrons, and electrons.

21-3 Charge is Conserved

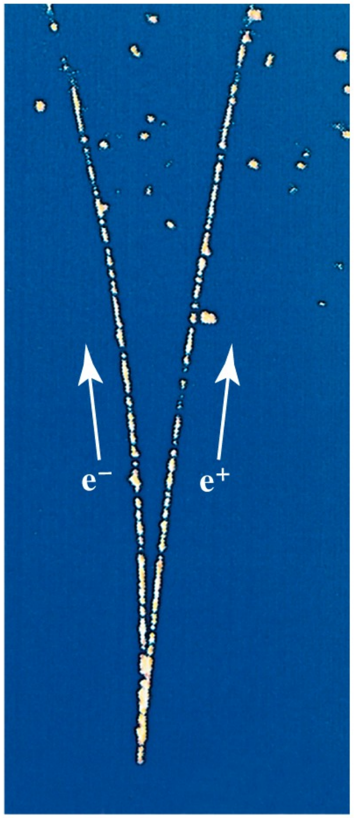
The net electric charge of any isolated system is always conserved.

If two charged particles undergo an annihilation process, they have equal and opposite signs of charge.

$$\boxed{e^- + e^+ \rightarrow \gamma + \gamma}$$

If two charged particles appear as a result of a pair production process, they have equal and opposite signs of charge.

$$\boxed{\gamma \rightarrow e^- + e^+}$$



Courtesy Lawrence Berkeley Laboratory

A photograph of trails of bubbles left in a bubble chamber by an electron and a positron. The pair of particles was produced by a gamma ray that entered the chamber directly from the bottom. Being electrically neutral, the gamma ray did not generate a telltale trail of bubbles along its path, as the electron and positron did.

21 Summary

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Electric Charge

- The strength of a particle's electrical interaction with objects around it depends on its electric charge, which can be either positive or negative.

Conductors and Insulators

- Conductors are materials in which a significant number of electrons are free to move. The charged particles in nonconductors (insulators) are not free to move.

Conservation of Charge

- The net electric charge of any isolated system is always conserved.

Coulomb's Law

- The magnitude of the electrical force between two charged particles is proportional to the product of their charges and inversely proportional to the square of their separation distance.

$$\boxed{F = \frac{1}{4\pi\varepsilon_0}\frac{|q_1|\,|q_2|}{r^2}}$$

Eq. 21-4

The Elementary Charge

- Electric charge is quantized (restricted to certain values).
- *e* is the elementary charge

$$\boxed{e = 1.602 \times 10^{-19}\ \text{C.}}$$

Eq. 21-12

21.3.8. Glass is a very good electrical insulator. How is then possible that a glass rod can be charged by rubbing it with cloth?

a) When the rod is rubbed, it becomes an electrical conductor.

b) Although the rod is an insulator, any excess charge will slowly be conducted away.

c) When the rod is rubbed, the part of the rod that is in contact with the cloth becomes electrically conductive.

d) Because the rod is an insulator, the charge that is transferred to the surface of the rod has difficulty moving.

e) None of the above answers are correct.

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