UFUG 1504: Honors General Physics II

Chapter 21

Coulomb’s Law

Summary (1 of 2)

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.

Summary (2 of 2)

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.

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

Equation 21-4

The Elementary Charge $e = 1.602 \times 10^{-19}\,\text{C}.$

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

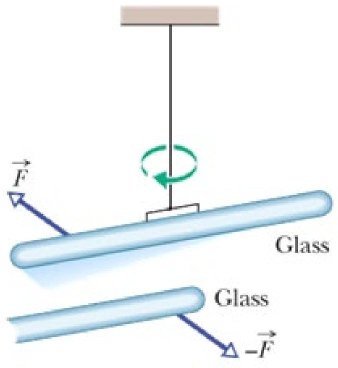
Equation 20-21

21-1 Coulomb's Law (6 of 16)

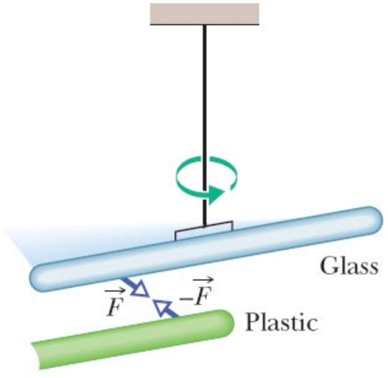
Magic?

(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.



(a)



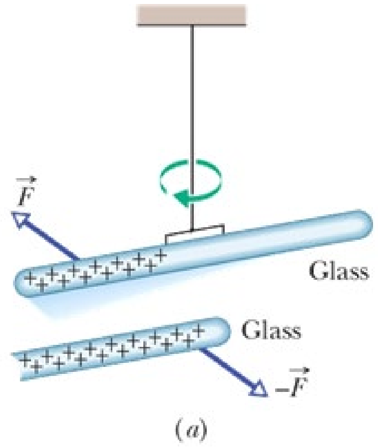
(b)

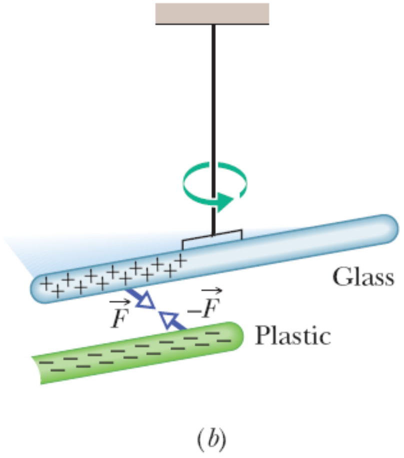
21-1 Coulomb's Law (7 of 16)

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.





21-1 Coulomb's Law (8 of 16)

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

21-1 Coulomb's Law (9 of 16)

Materials classified based on their ability to move charge

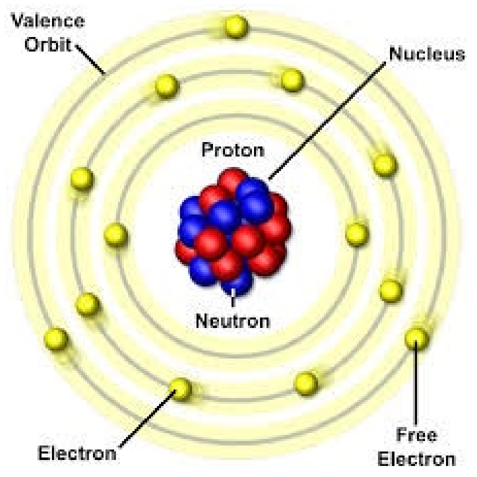
- **Conductors** are materials in which a significant number of electrons are free to move. Examples include metals.
- The charged particles in nonconductors (**insulators (绝缘体)**) are not free to move. Examples include rubber, plastic, glass.
- **Semiconductors** are materials that are intermediate 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 (9 of 16)

Opening questions:

What are the physical causes of conductors, insulators and semiconductors?

Classical explanation:



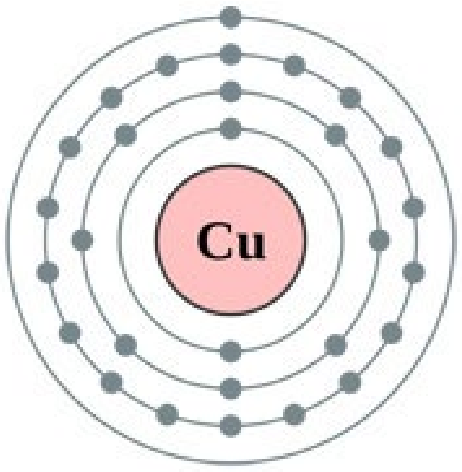
- **Charged Particles**. The properties of conductors and insulators are due to the structure and electrical nature of atoms. Atoms consist of positively charged protons (质子：+), negatively charged electrons (电子： -), and electrically neutral neutrons (中子:0). The protons and neutrons are packed tightly together in a central nucleus and do not move.

21-1 Coulomb’s Law (9 of 16)

Opening questions:

What are the physical causes of conductors, insulators and semiconductors?

Classical explanation: Any limitation?



- When atoms of a conductor like copper come together to form the solid, some of their outermost electrons become free to wander about within the solid, leaving behind positively charged atoms (positive ions). We call the mobile electrons **conduction/free electrons**. There are few free electrons in a nonconductor.

21-1 Coulomb's Law (9 of 16)

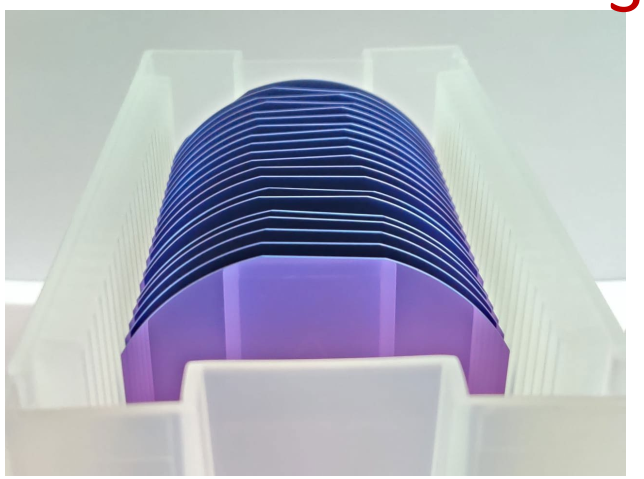
Opening questions:

What are the physical causes of conductors, insulators and semiconductors?

Classical explanation: outermost electrons are same

C

SiO_2

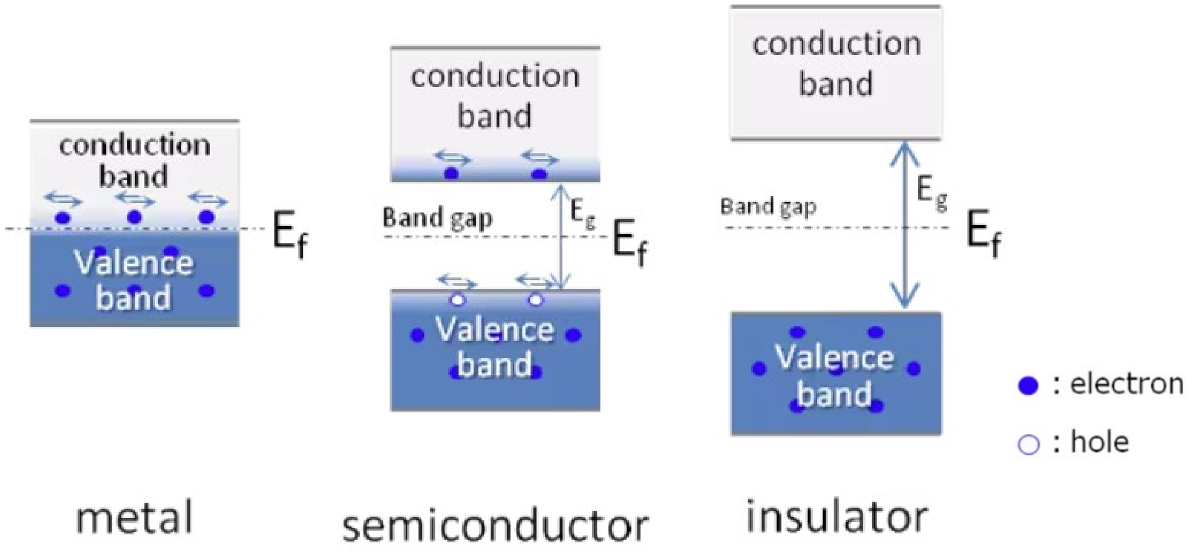


conductors **insulators** **semiconductors** **insulators**

21-1 Coulomb's Law (9 of 16)

Open questions:

What are the physical causes of conductors, insulators and semiconductors?



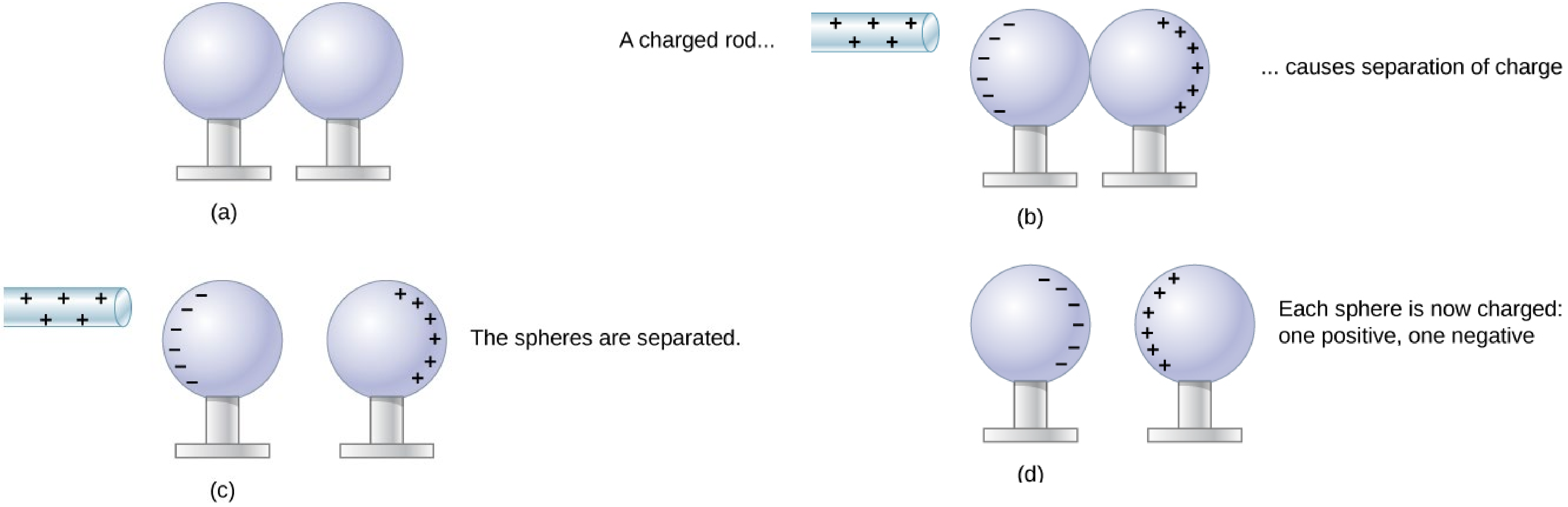
band theory

- Metals: Eg~0, has electrons can move freely
- Semiconductor: Eg< 5 eV, electrons to jump the gap easily from VB to CB with enough thermal energy, thus exhibit limited conductivity
- Insulator: Eg> 5 eV, few electrons can jump to CB. Therefore, current does not flow easily

If interested, study solid state physics

21-1 Coulomb's Law (11 of 16)

Induced Charge (感应电荷).



21-1 Coulomb's Law (12 of 16)

Coulomb's Law (important)

Coulomb's law describes the electrostatic force (静电力/库仑力)(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

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

Epsilon

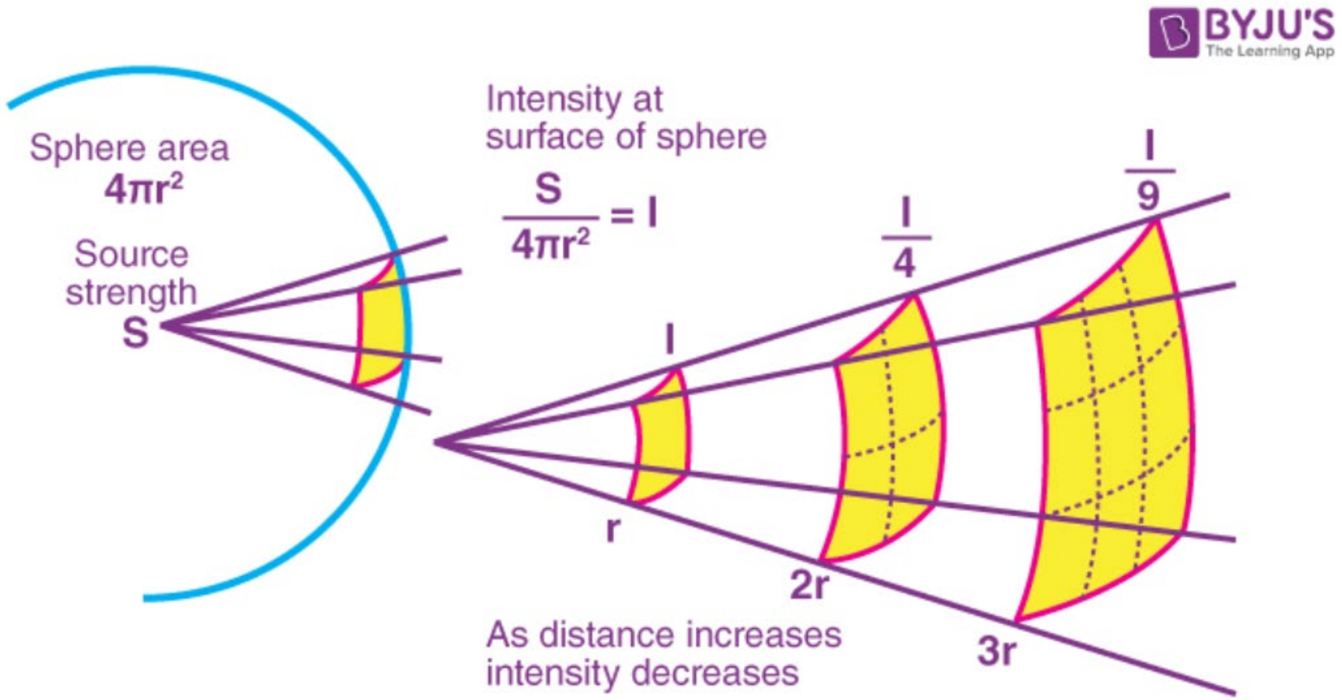
where $\varepsilon_0 = 8.85\times10^{-12}\ \mathrm{C^2/N^2\cdot m^2}$ is the permittivity constant (介电常数). The ratio $\frac{1}{4\pi\varepsilon_0}$ often replaced with the electrostatic constant (静电常数)(or Coulomb constant)

$k = 8.99\times10^{9}\ \mathrm{N\cdot m^2/C^2}$. Thus $k = \frac{1}{4\pi\varepsilon_0}$.

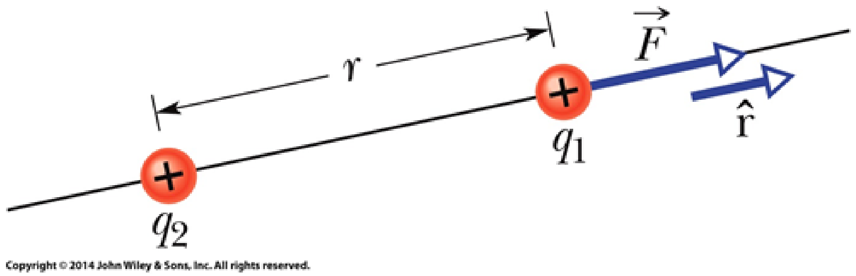
21-1 Coulomb's Law (12 of 16)

$$f = k\frac{|q_1||q_2|}{r^2} \quad \text{(Coulomb's law)}, \qquad F = G\frac{m_1 m_2}{r^2} \quad \text{(Newton's law of gravitation)}.$$

Open questions: Why are there so many inverse-square laws ($F \propto 1/R^2$)?



21-1 Coulomb's Law (13 of 16)

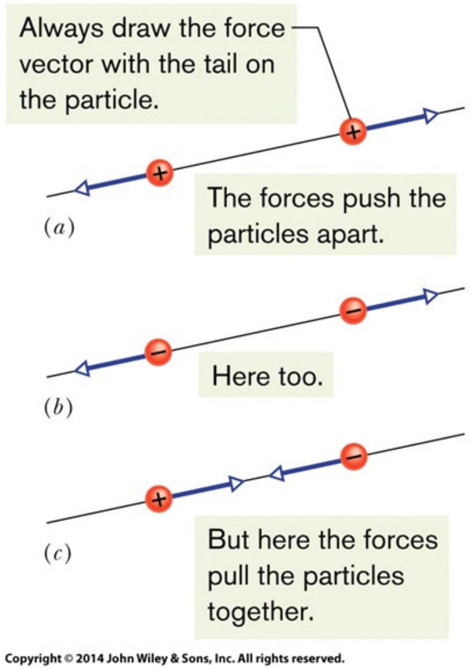


The electrostatic force on particle 1 can be described in terms of a unit vector r along an axis through the two particles, radially away from particle 2.

21-1 Coulomb's Law (14 of 16)

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.

21-1 Coulomb's Law (15 of 16)

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

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

Shell Theories: There are two shell theories for electrostatic force

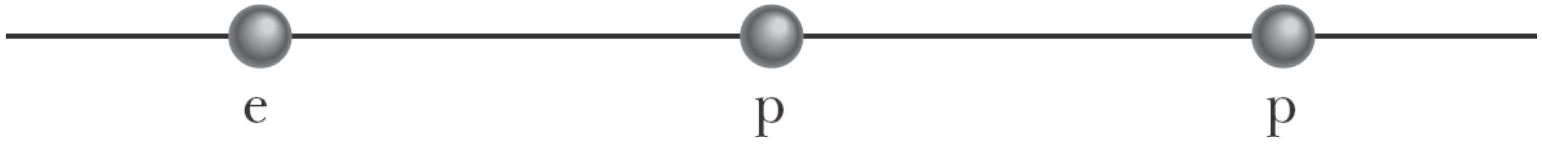
Shell theory 1. A charged particle outside a shell with charge uniformly distributed on its surface is attracted or repelled as if the shell's charge were concentrated as a particle at its center.

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.

21-1 Coulomb’s Law (16 of 16)

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?



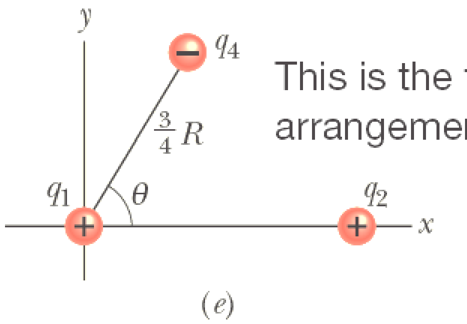
Answer:

(a) left towards the electron

(b) left away from the other proton

(c) left

21-1 Coulomb's Law (16 of 16)

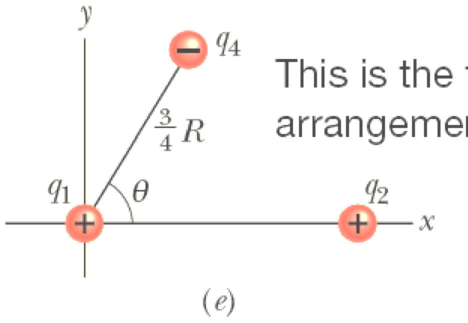


This is the third arrangement.

(c) Figure 21-7*e* is identical to Fig. 21-7*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?

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.

21-1 Coulomb's Law (16 of 16)



(e)

This is the third arrangement.

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

$$F_{14} = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_4|}{(\frac{3}{4}R)^2}$$
$$= (8.99 \times 10^9\ \mathrm{N \cdot m^2/C^2})$$
$$\times \frac{(1.60 \times 10^{-19}\ \mathrm{C})(3.20 \times 10^{-19}\ \mathrm{C})}{(\frac{3}{4})^2(0.0200\ \mathrm{m})^2}$$
$$= 2.05 \times 10^{-24}\ \mathrm{N}.$$

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

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

$$F_{1,\mathrm{net}} = \sqrt{F^2_{1,\mathrm{net},x} + F^2_{1,\mathrm{net},y}} = 1.78 \times 10^{-24}\ \mathrm{N}.$$

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

21-2 Charge is Quantized (1 of 4)

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.

21-2 Charge is Quantized (2 of 4)

- Electric charge is quantized (量化的) (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

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

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

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

21-2 Charge is Quantized (3 of 4)

Table 21-1 The Charges of Three Particles

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

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, $3.57e$.

21-2 Charge is Quantized (4 of 4)

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 (1 of 3)

Learning Objectives

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

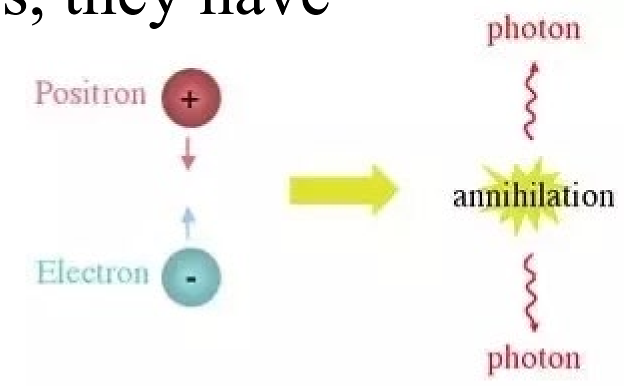
21.22 Identify an annihilation process of particles and a pair production of particles.

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

21-3 Charge is Conserved (2 of 3)

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

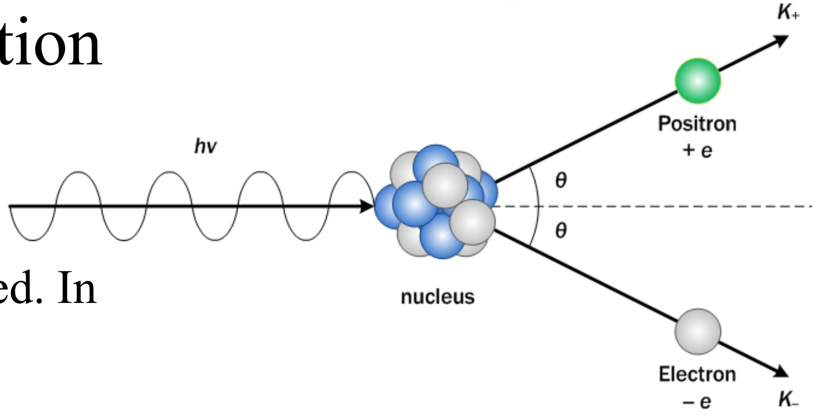
If two charged particles undergo an annihilation process, they have equal and opposite signs of charge.



$$e^- + e^+ \rightarrow \gamma + \gamma$$

Annihilation process (湮灭), transforming into two *gamma rays*

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

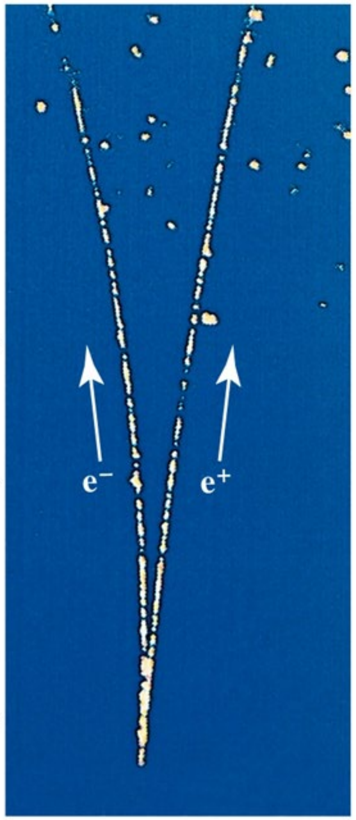


$$\gamma \rightarrow e^- + e^+$$

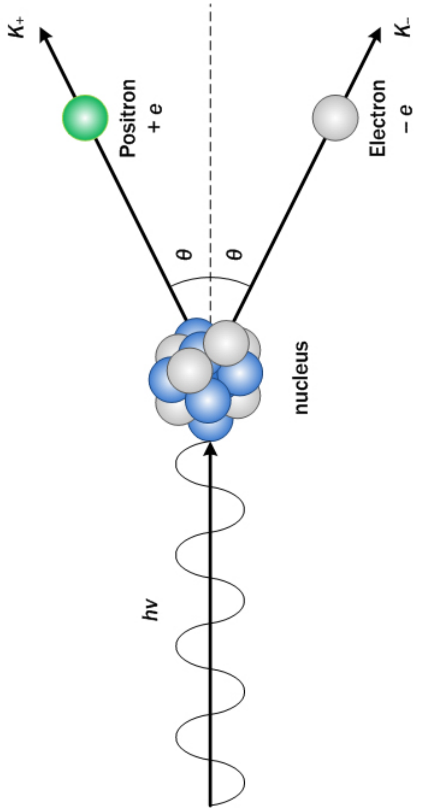
In *pair production (成对产生)*, the converse of annihilation, charge is also conserved. In this process a gamma ray transforms into an electron and a positron:

21-3 Charge is Conserved (3 of 3)

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.



Courtesy Lawrence Berkeley Laboratory



Summary (1 of 2)

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.

Summary (2 of 2)

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.

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

Equation 21-4

The Elementary Charge $e = 1.602\times10^{-19}\,\mathrm{C}.$

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

Equation 20-21

In-class quiz (2 of 2)

10 In Fig. 21-19, a central particle of charge $-2q$ is surrounded by a square array of charged particles, separated by either distance d or $d/2$ along the perimeter of the square. What are the magnitude and direction of the net electrostatic force on the central particle due to the other particles? (*Hint:* Con-

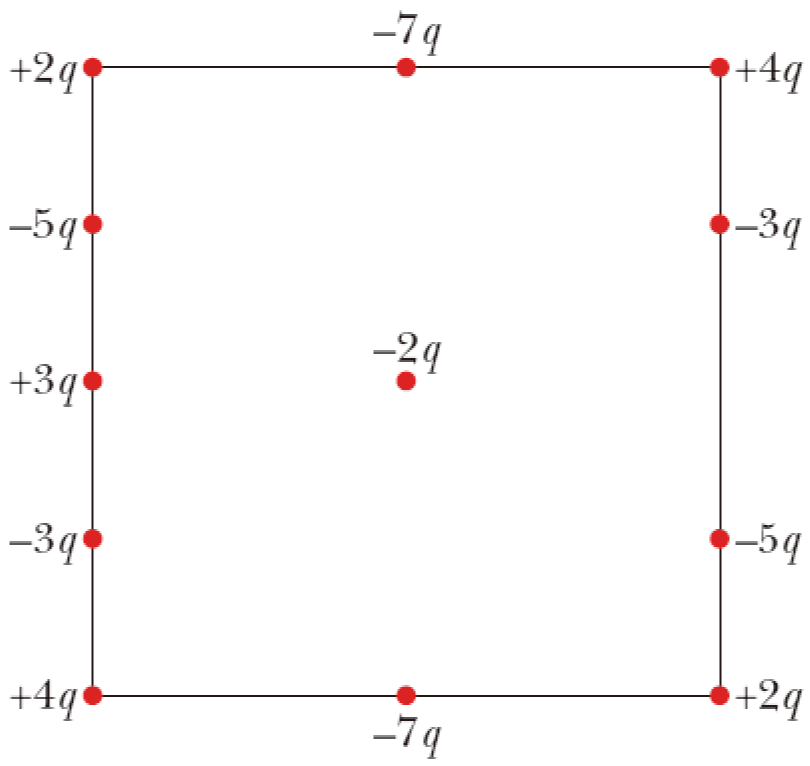


Figure 21-19 Question 10.

In-class quiz (2 of 2)

••17 In Fig. 21-28*a*, particles 1 and 2 have charge 20.0 μC each and are held at separation distance $d = 1.50$ m. (a) What is the magnitude of the electrostatic force on particle 1 due to particle 2? In Fig. 21-28*b*, particle 3 of charge 20.0 μC is positioned so as to complete an equilateral triangle. (b) What is the magnitude of the net electrostatic force on particle 1 due to particles 2 and 3?

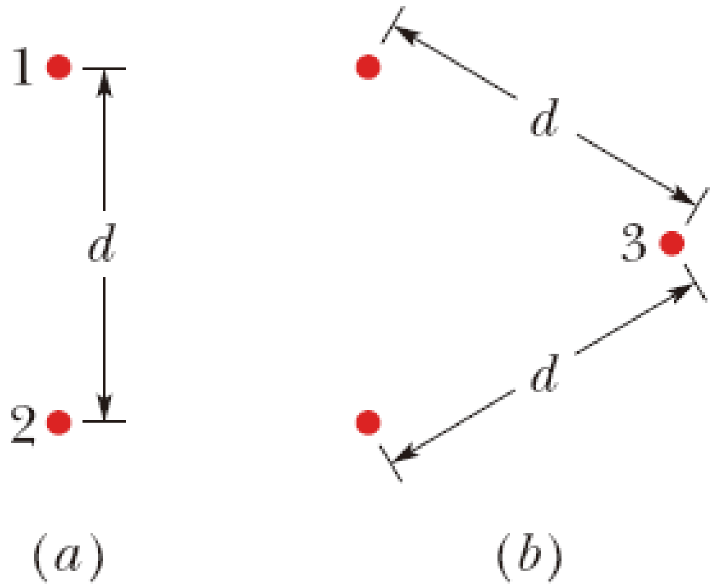
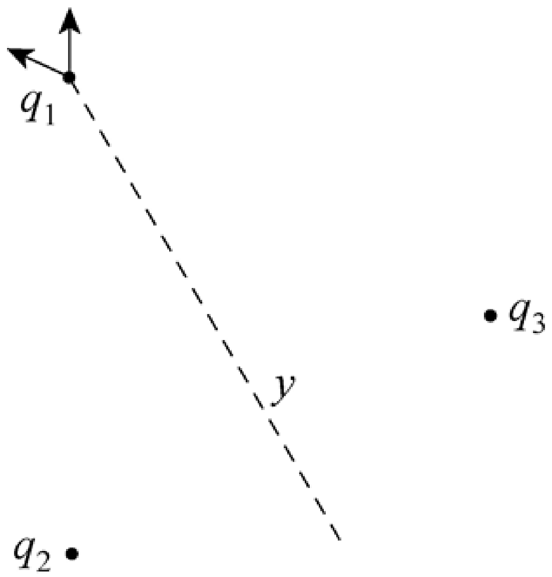


Figure 21-28 Problem 17.

In-class quiz (2 of 2)

17. (a) Equation 21-1 gives

$$F_{12} = k\frac{q_1 q_2}{d^2} = \left(8.99\times10^9\,\mathrm{N\cdot m^2/C^2}\right)\frac{\left(20.0\times10^{-6}\,\mathrm{C}\right)^2}{\left(1.50\,\mathrm{m}\right)^2} = 1.60\ \mathrm{N}.$$

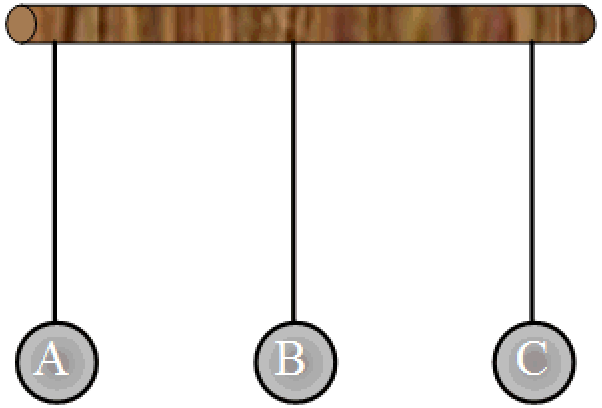


(b) On the right, a force diagram is shown as well as our choice of y axis (the dashed line).

The y axis is meant to bisect the line between q_2 and q_3 in order to make use of the symmetry in the problem (equilateral triangle of side length d, equal-magnitude charges $q_1 = q_2 = q_3 = q$). We see that the resultant force is along this symmetry axis, and we obtain

$$\left|F_y\right| = 2\left(k\frac{q^2}{d^2}\right)\cos 30° = 2\left(8.99\times10^9\,\mathrm{N\cdot m^2/C^2}\right)\frac{\left(20.0\times10^{-6}\,\mathrm{C}\right)^2}{\left(1.50\,\mathrm{m}\right)^2}\cos 30° = 2.77\ \mathrm{N}.$$

21.3.5. Three insulating balls are hung from a wooden rod using thread. The three balls are then individually charged via induction. Subsequently, balls A and B are observed to attract each other, while ball C is repelled by ball B. Which one of the following statements concerning this situation is correct?



a) A and B are charged with charges of opposite signs; and C is charged with charge that has the same sign as B.

b) A and B are charged with charges of the same sign; and C is electrically neutral.

c) A is electrically neutral; and C is charged with charge that has the same sign as B.

d) B is electrically neutral; and C is charged with charge that has the same sign as A.

21.3.5. Three insulating balls are hung from a wooden rod using thread. The three balls are then individually charged via induction. Subsequently, balls A and B are observed to attract each other, while ball C is repelled by ball B. Which one of the following statements concerning this situation is correct?

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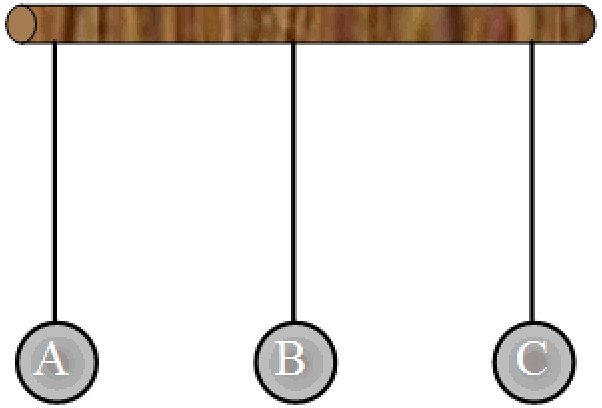

b) A and B are charged with charges of the same sign; and C is electrically neutral.

c) A is electrically neutral; and C is charged with charge that has the same sign as B.

d) B is electrically neutral; and C is charged with charge that has the same sign as A.

21.5.2. Can an object carry a charge of 2.0×10^{-19} C?

a) Yes, if the object is a conductor.

b) Yes, if the object has electrons or protons.

c) Yes, if the object is an insulator.

d) No, because objects do not have charge.

e) No, because charge is quantized.

21.5.2. Can an object carry a charge of 2.0×10^{-19} C?

a) Yes, if the object is a conductor.

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

b) Yes, if the object has electrons or protons.

c) Yes, if the object is an insulator.

d) No, because objects do not have charge.

e) No, because charge is quantized.


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