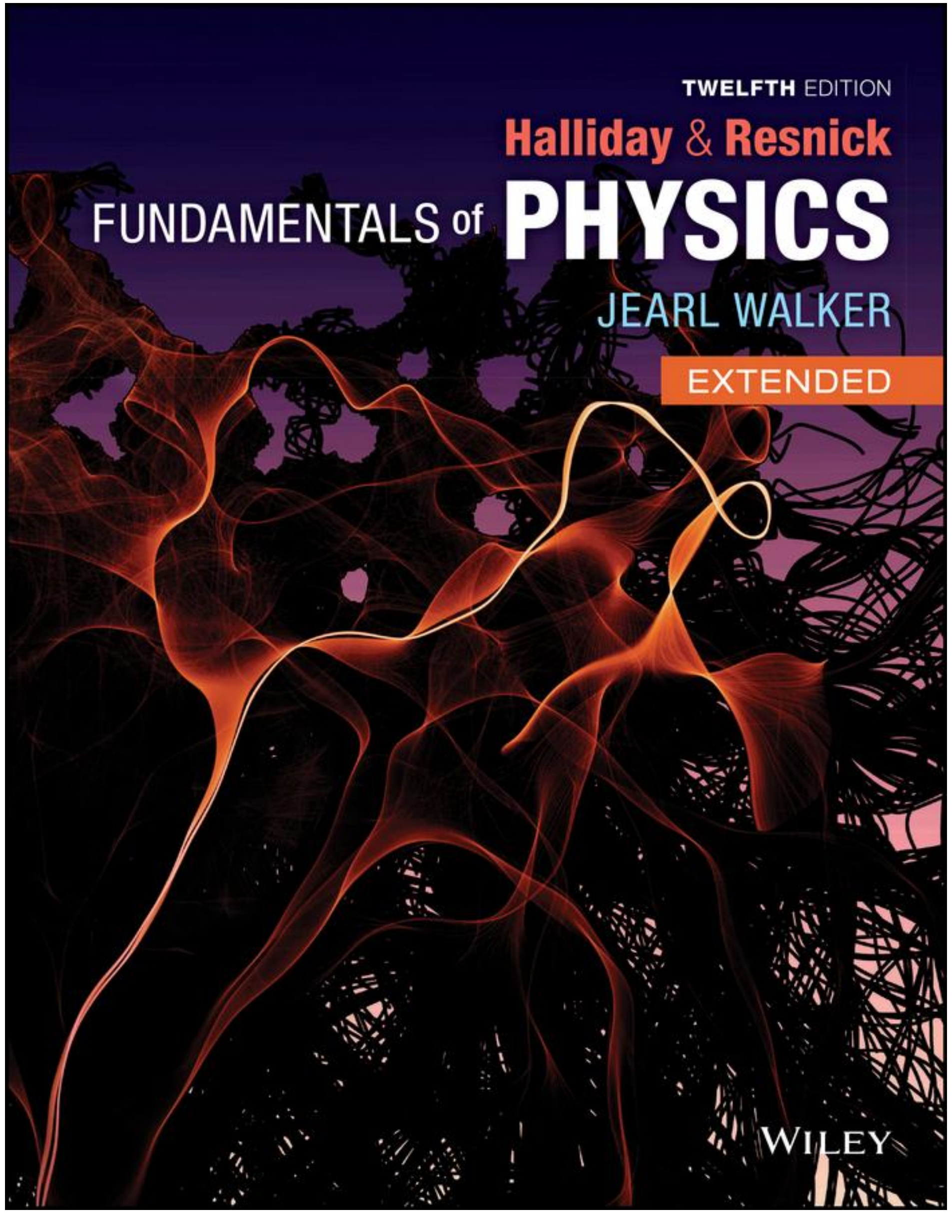


Fundamentals of Physics

Twelfth Edition

Halliday & Resnick

Jearl Walker

Chapter 21
Coulomb's Law

Units of Chapter 21

21.1 Coulomb's Law

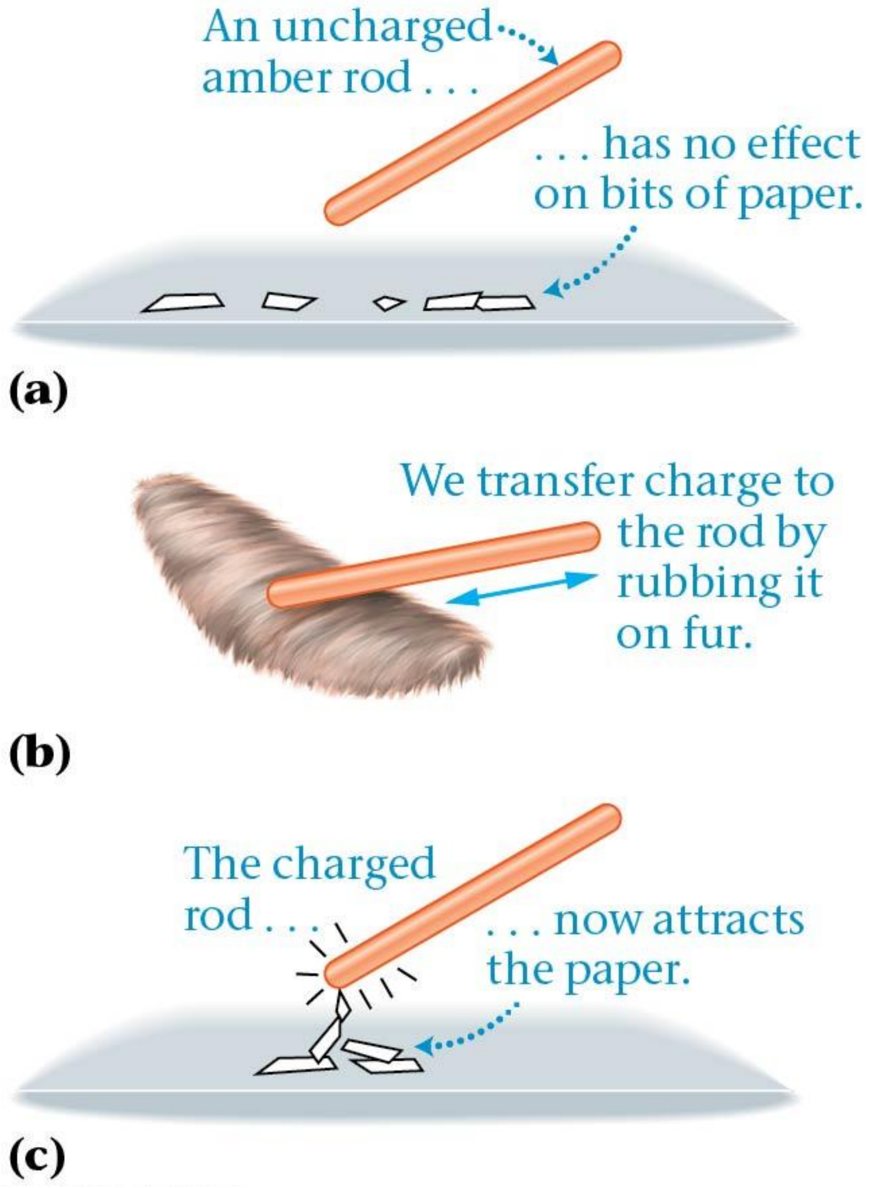
21.2 Charge is Quantized

21.3 Charge is Conserved

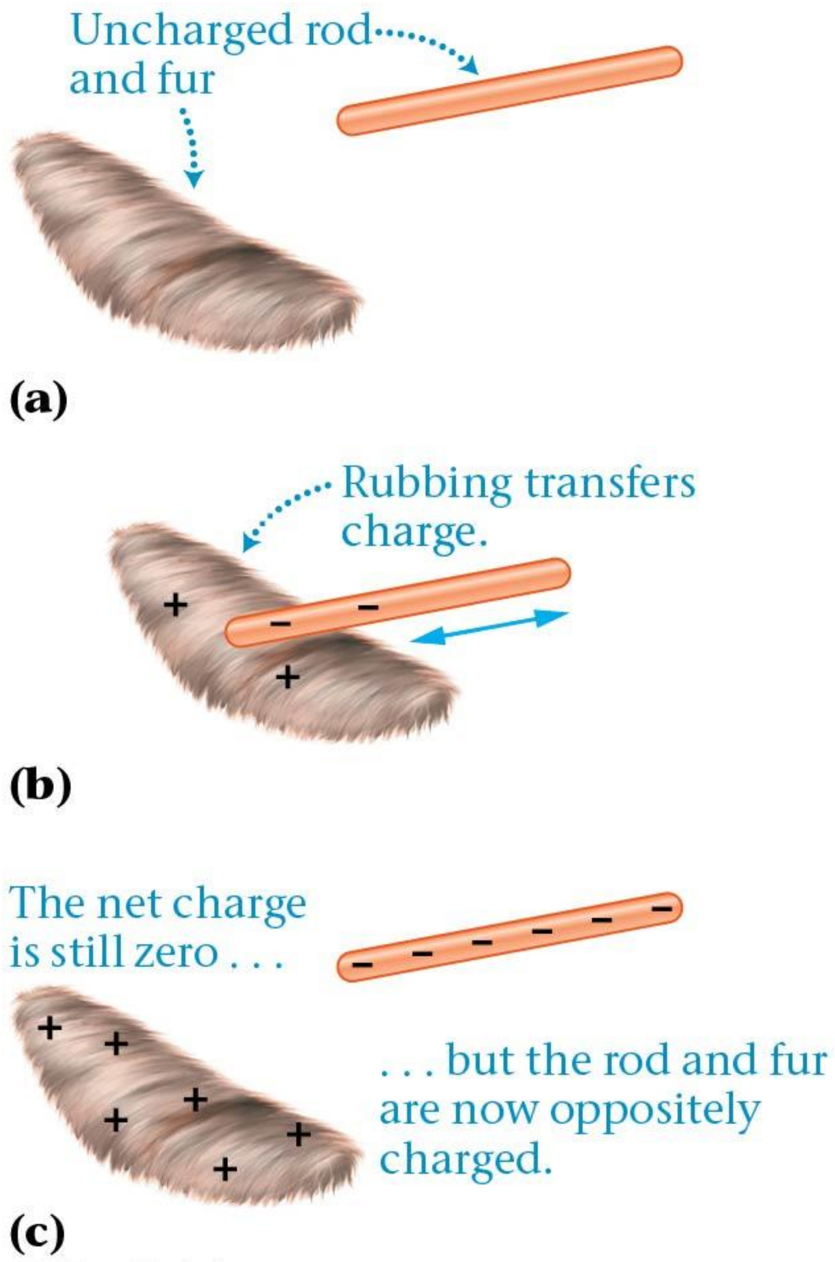
Section 21.1 Coulomb’s Law
Learning Objectives

1. Distinguish between being electrically neutral, negatively charged, and positively charged.
2. Distinguish between conductors, nonconductors (insulators), semiconductors, and superconductors.
3. Identify that Coulomb’s law applies only to (point-like) particles and objects that can be treated as particles.
4. If more than one force acts on a particle, find the net force by adding all the forces as vectors, not scalars.

- We are all made up of atoms, and every atom in the human body contains both positive and negative electric charges.
- The effects of electric charge were first observed as static electricity
- After being rubbed on a piece of fur, an amber rod acquires a charge and can attract small objects (Why?)



When an amber rod is rubbed with fur, some of the electrons on the atoms in the fur are transferred to the amber.



Remarks

1. The amber rod is not unique in its ability to ***become charged***. Other materials can behave in such way as well.

2. If ***glass is rubbed*** with a piece of ***silk***, it too can attract small objects (**the glass rod will become charged**)

3. They have noticed that, when suspending the ***amber and the glass*** rods they tend to ***get closer*** to each other, in other words, ***attract*** each other.

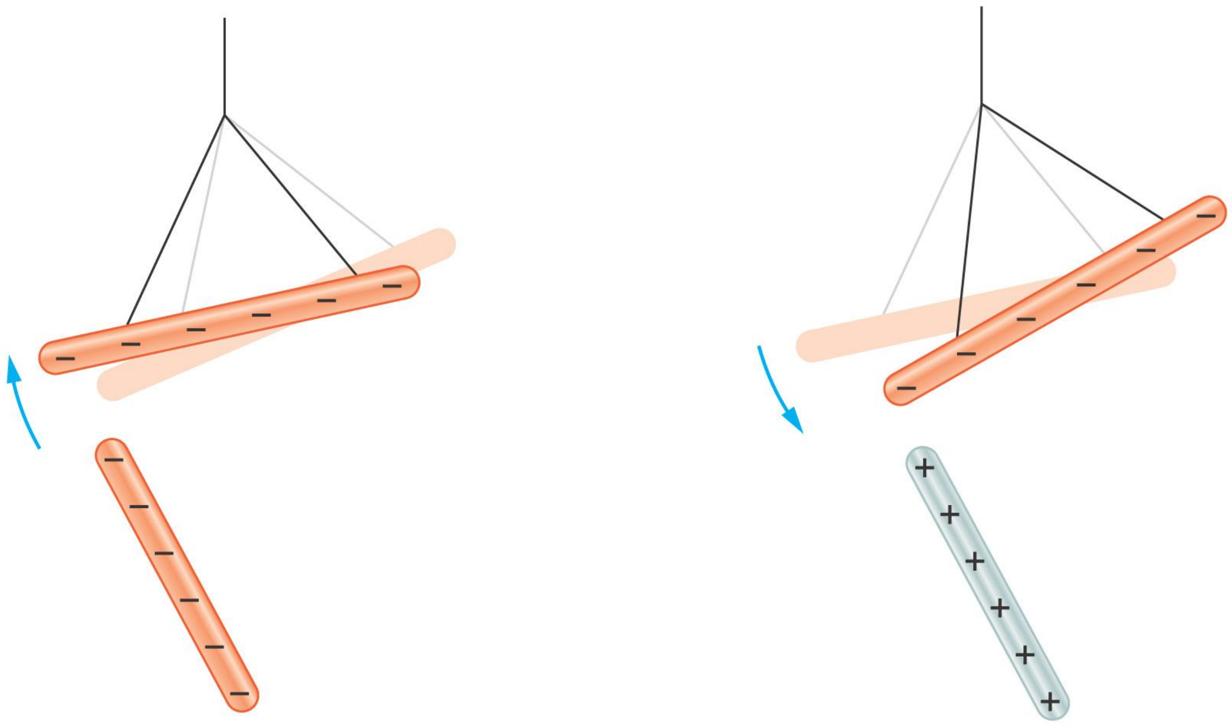
4. The above note implies that, the two rods (the glass and the amber) are both charged, still, ***they are not totally alike***.

General properties of charged objects

1. Two rods with opposite charges will attract each other. (**Fig. a**)

2. Two rods with the same charges will repel each other. (**Fig. b**)

Question: why the amber rod became negatively charged while the glass rod became positively charged?

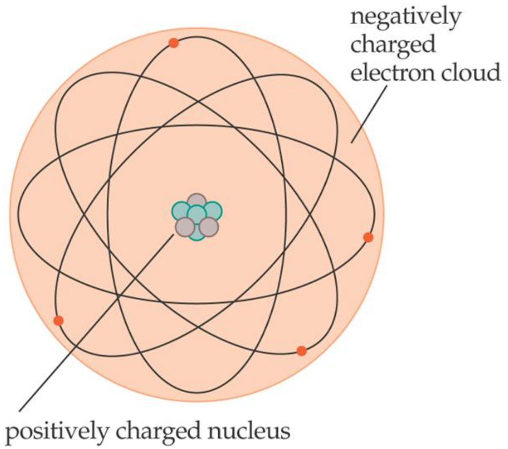

(a) (b)

3. All electrons have exactly the same charge, the charge of the electron is defined as: **$-e = -1.6 \times 10^{-19}$** Coulomb (C)

4. The charge of the proton (in the atomic nucleus) has the same magnitude but the opposite sign.

5. A more common unit of charge is the micro coulomb (μc) 1 μc = 10^{-6} C

6. The electrons in an atom are in a cloud surrounding the nucleus and can be separated from the atom with relative ease.



CHECKPOINT :

Is the mass of the amber rod after charging with fur:

a) Greater than its mass before charging

b) Less than its mass before charging

c) The same as its mass before charging

Answer: a)

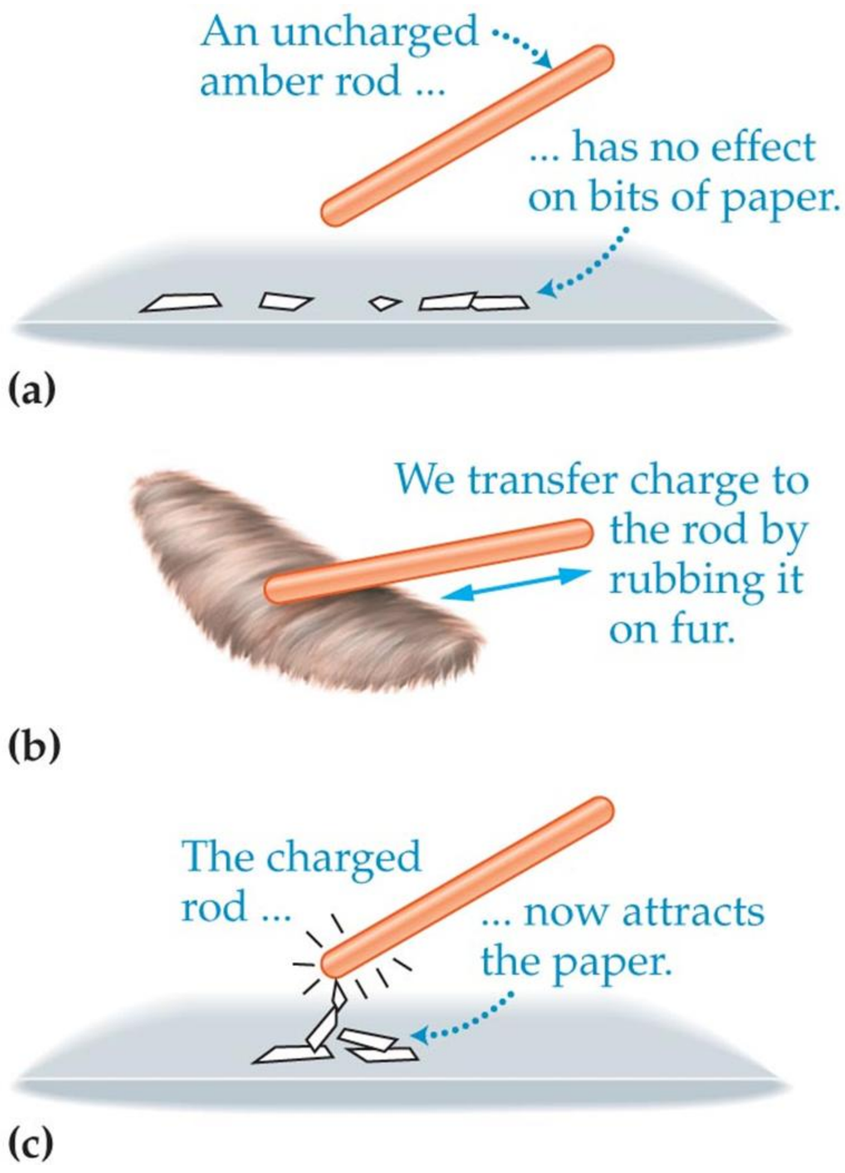
Note: the charged amber rod **has acquired electrons** from the fur, each electron has a small, but nonzero mass, and so, the mass of the amber rod increases ($m_e = 9.1 \times 10^{-31}$ kg)

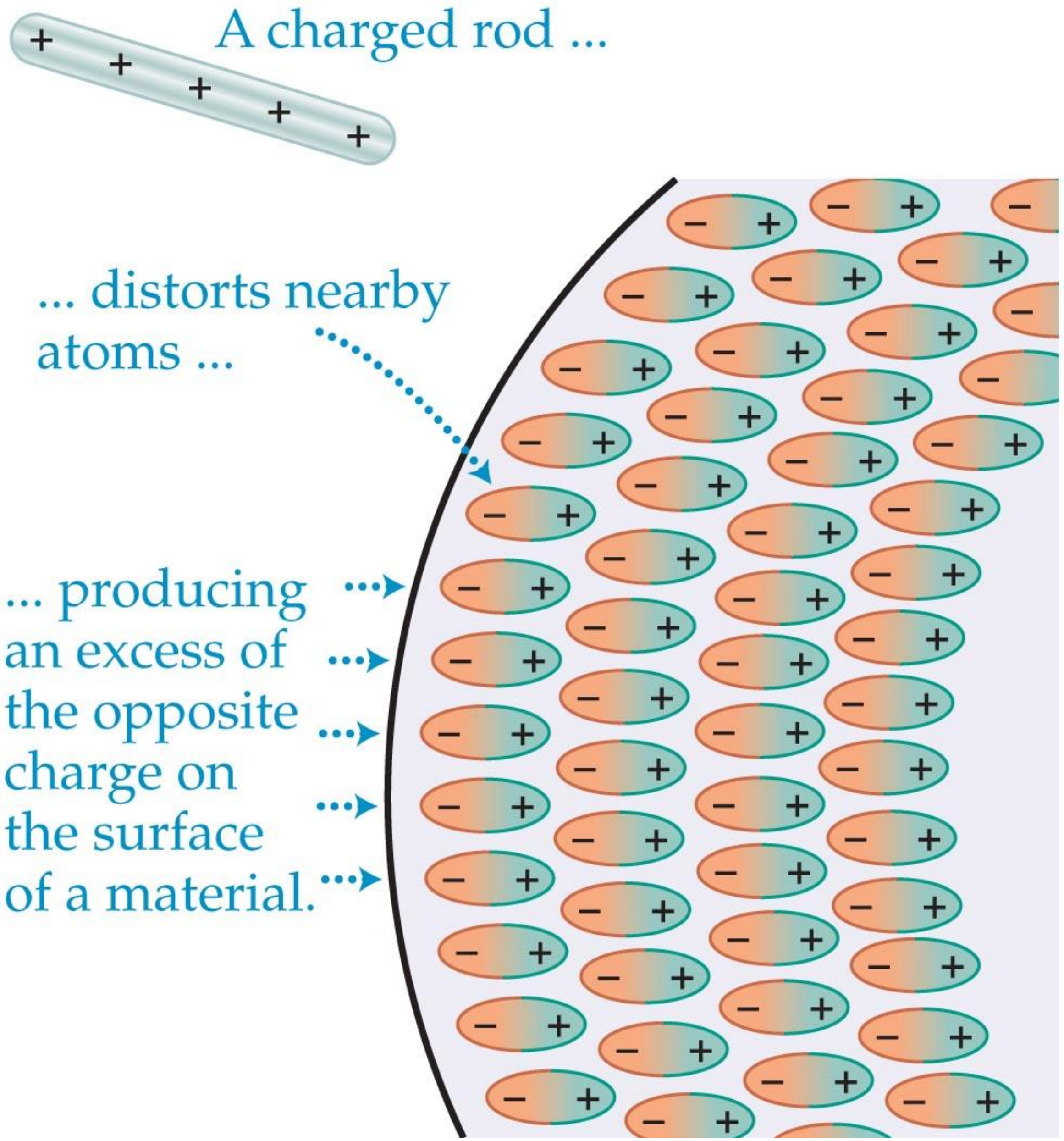
POLARIZATION (Induced Charge)

Question: Is it possible for a charged rod to attract small objects that have ***ZERO net charge***?

Answer: yes, just like when the amber rod attracted the small pieces of paper, and the glass rod attracts small objects.

And this mechanism is called ***POLARIZATION***.

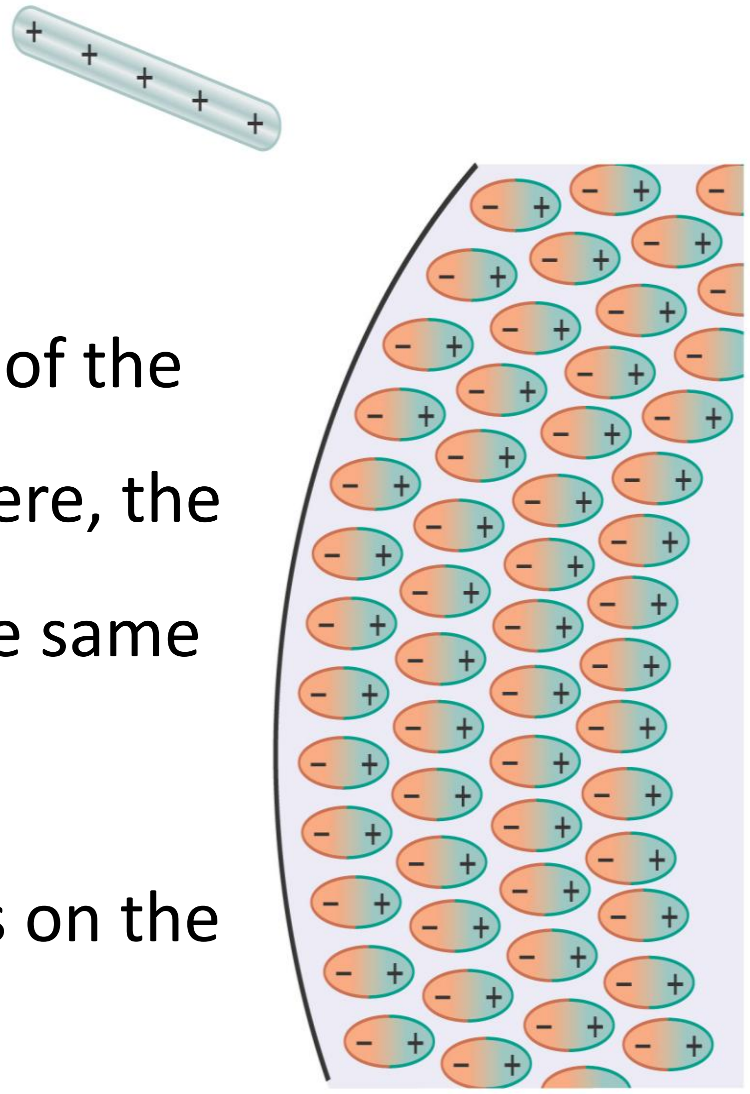



A charged rod ...
... distorts nearby atoms ...
... producing an excess of the opposite charge on the surface of a material.

Properties of polarized a material

1. The net charge on it is zero.

2. Due to the charged rod, the atoms near the surface of the polarized material will be distorted (will elongate), where, the opposite charge will rotate toward the surface, and the same charge will be repelled away from it.



3. As a result of step 2, a net opposite charge develops on the surface near the charged rod.

4. This net opposite charge is called: ***induced polarized charge***

Materials classified based on their ability to move charge

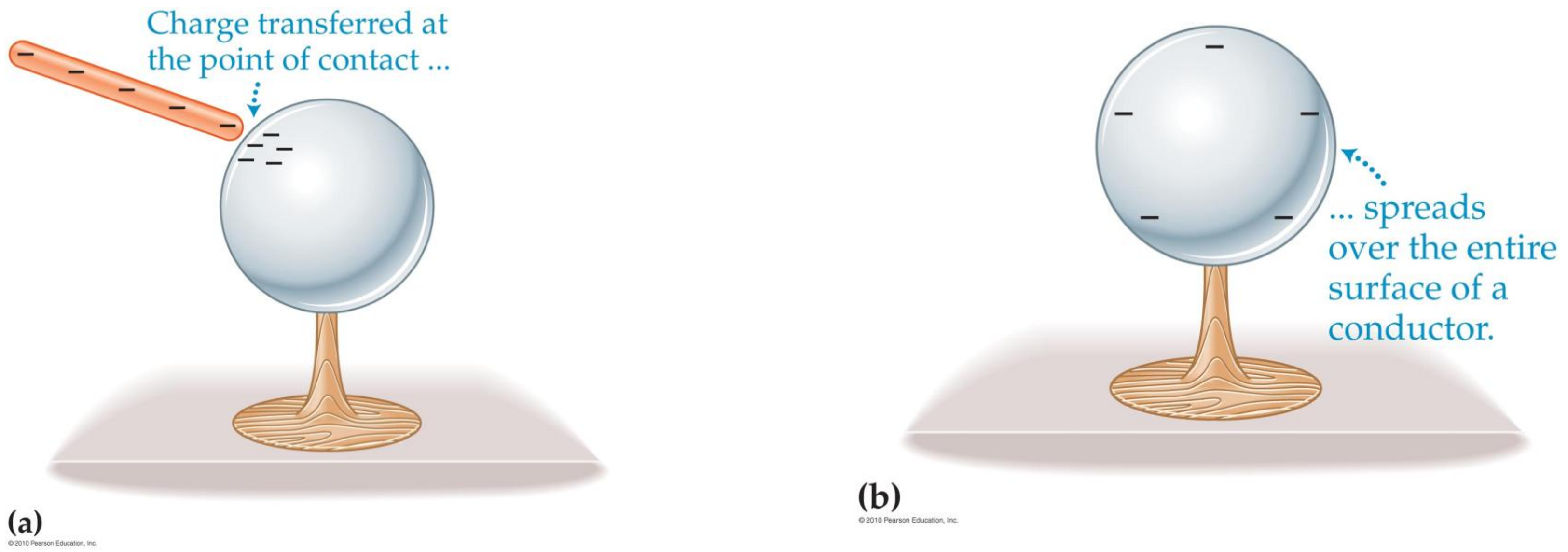
1. Insulators:

- Insulators are materials, in which charges are not free to move.
- Most insulators are nonmetallic substances.

Example: when rubbing the amber rod, the rubbed side becomes charged, whereas the other end remains neutral.

2. Conductors:

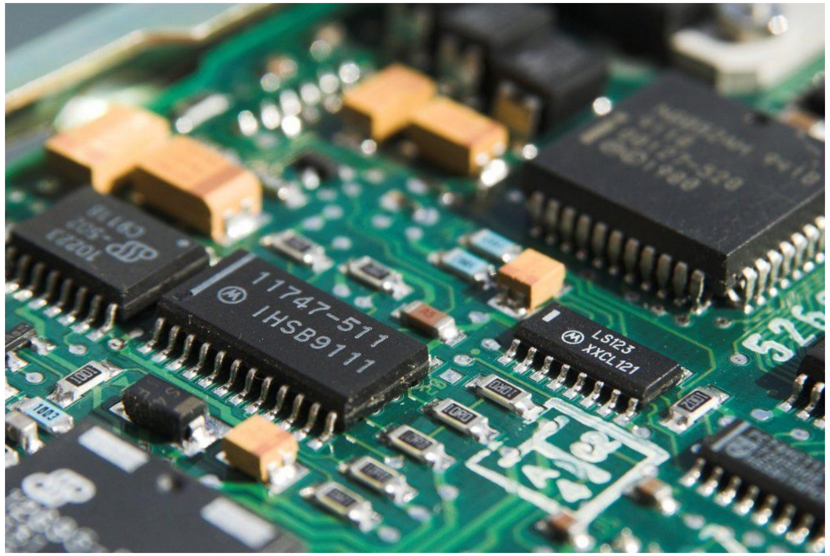
- Materials that allow the charges to move more freely. (look at the figure)
- Most conductors are metals.



- In the previous figure, an uncharged metal sphere is placed in an insulating base.
- A charged rod is brought into contact with the sphere.
- Some charges will be transferred to the sphere at point of contact.
- Since the metal is a good conductor of electricity, the charges will be evenly distributed **over the whole surface of the sphere**.

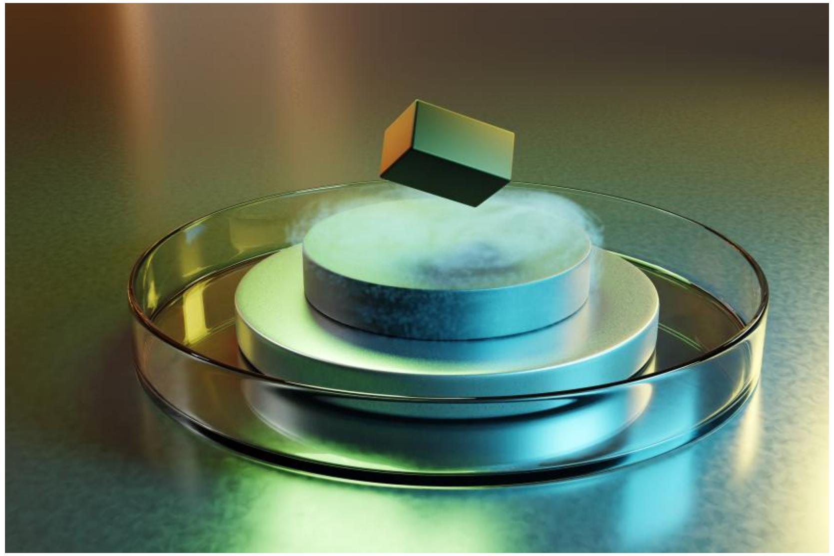
3. Semiconductors

➢ Materials that are intermediate between conductors and insulators; examples include silicon and germanium in computer chips.



4. Superconductors

➢ Materials that are perfect conductors, allowing charge to move without any hindrance



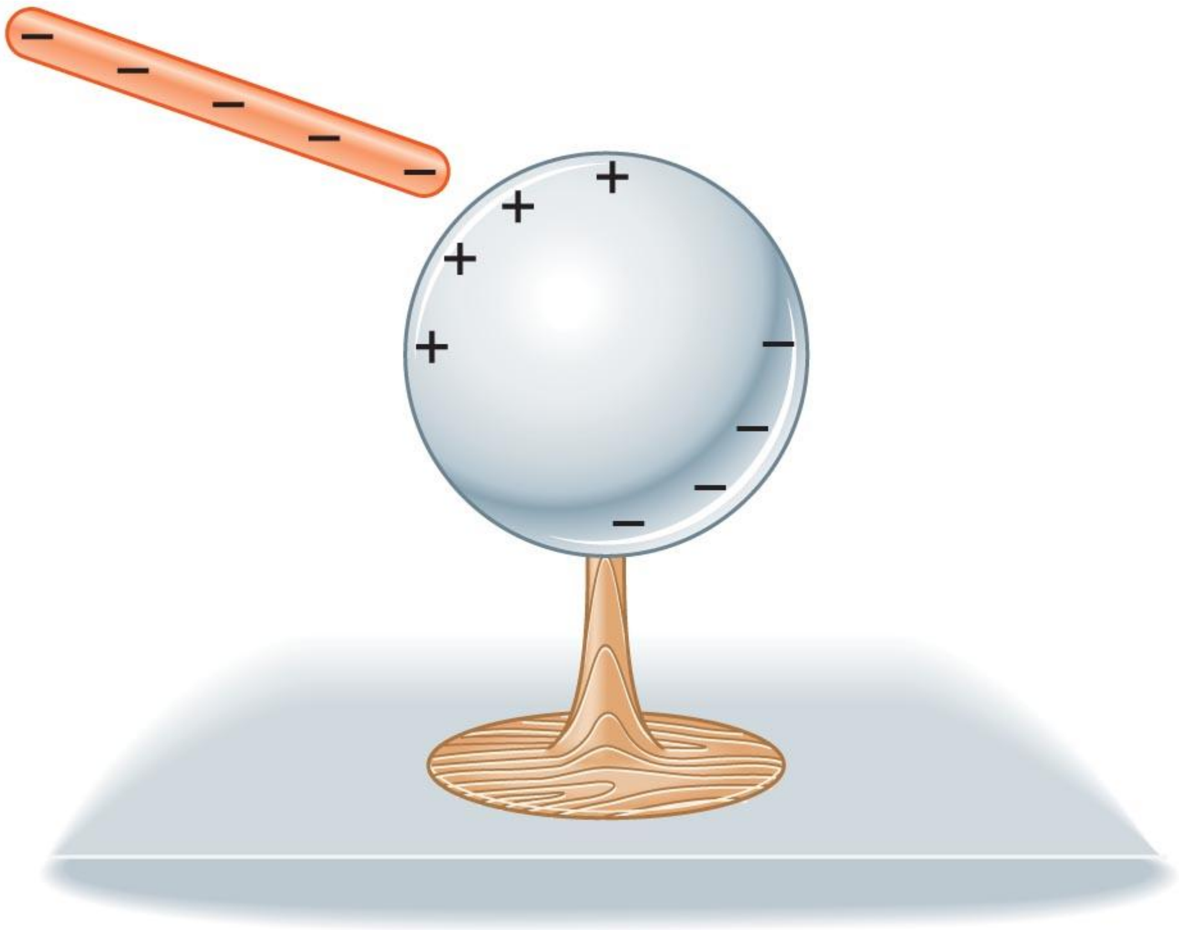
Charging By Induction

Charging by Induction is to charge an object without making direct physical contact

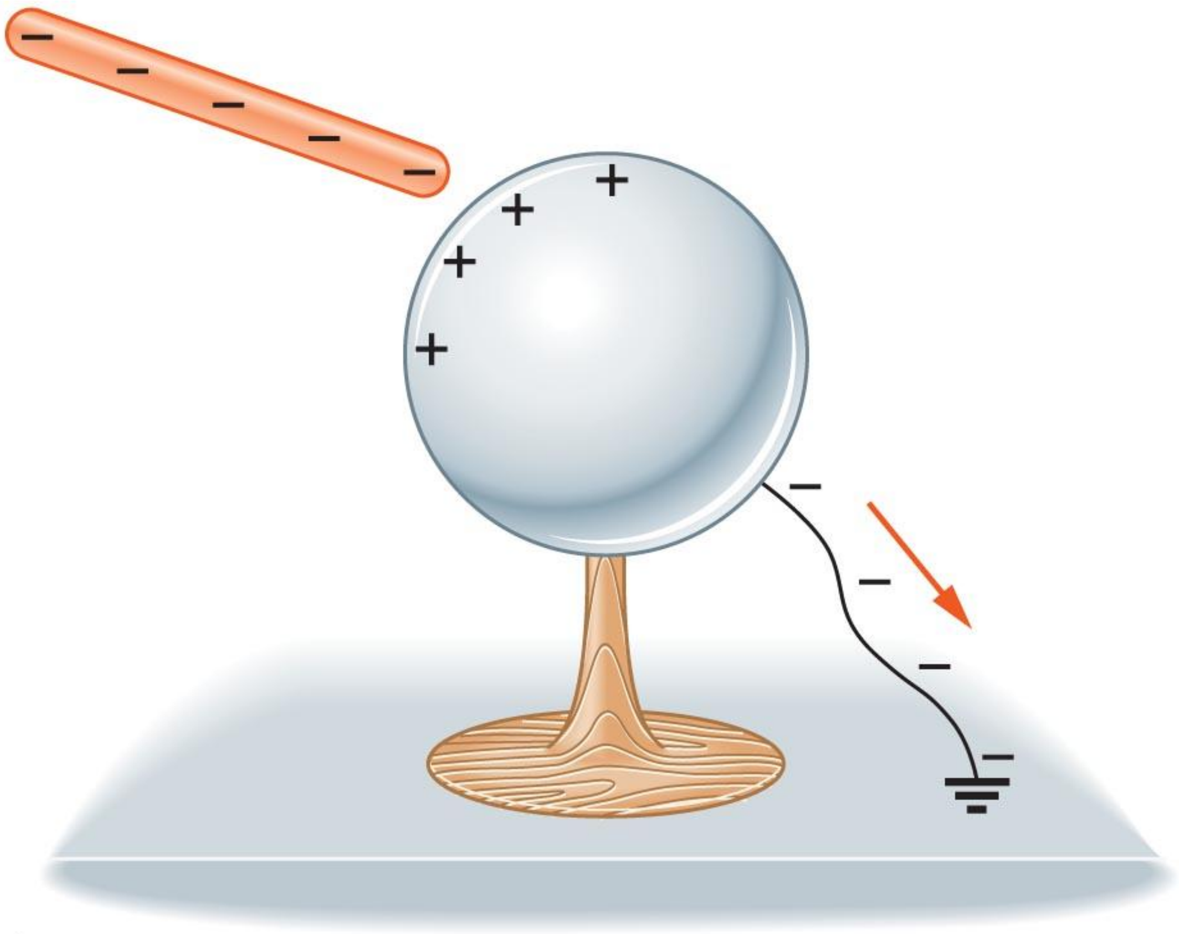
Question : Is it possible to charge a conductor by induction?

Answer: **YES**, a conductor can be charged by induction, if there is a way to ground it.

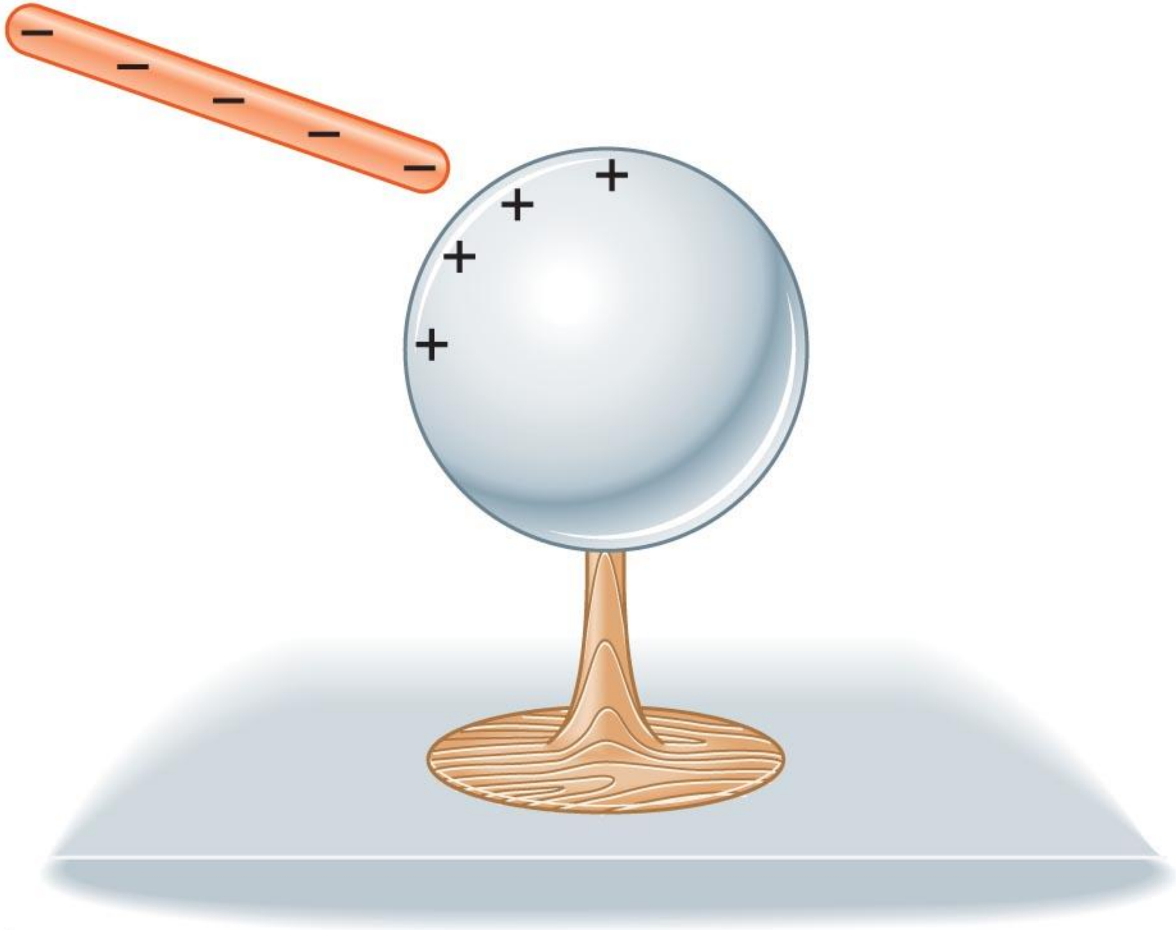
Note: When charging a conductor by induction, the final charge of the conductor will be opposite in sign to the charge of the charging rod



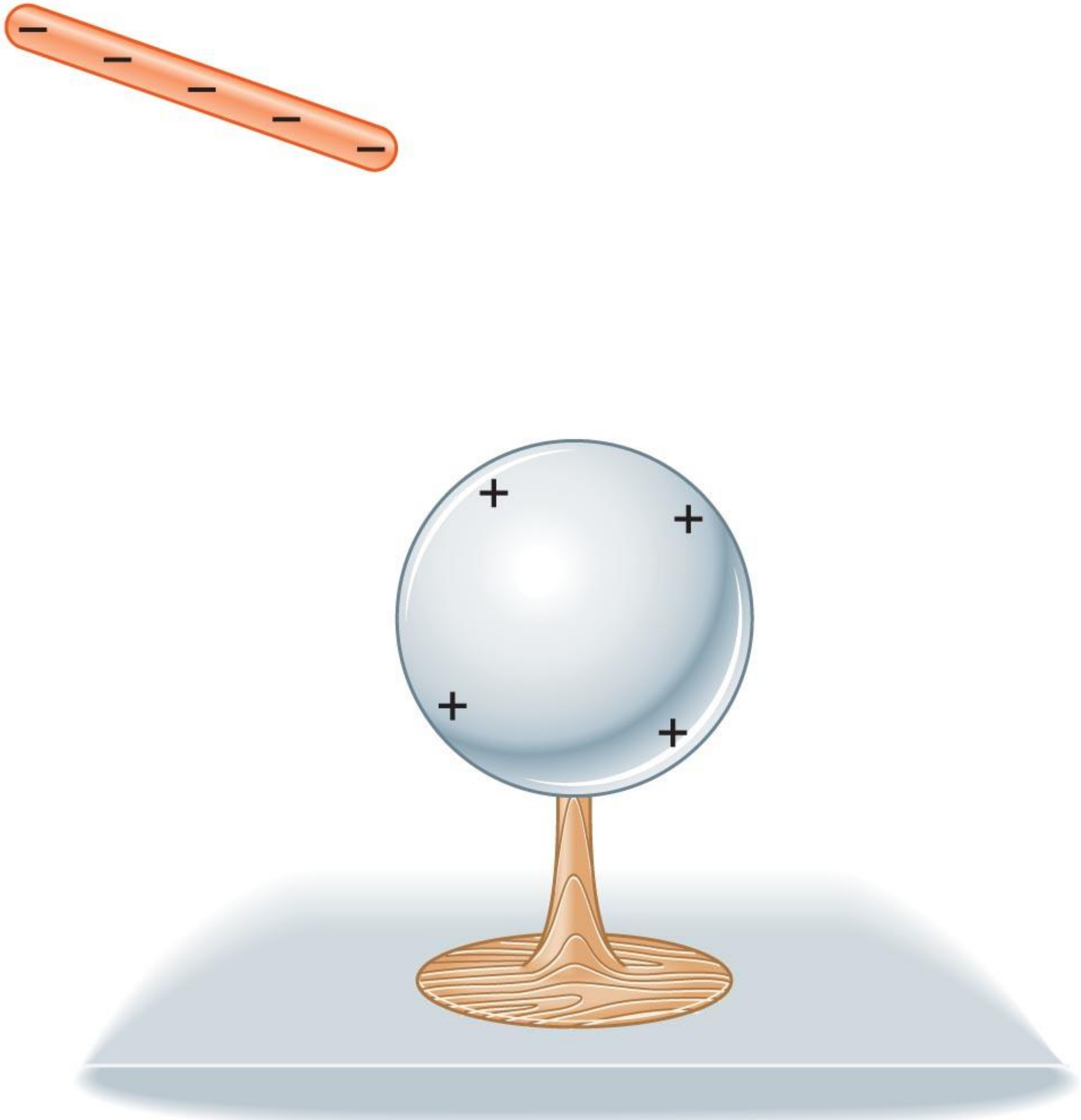
(a)



(b)



(c)



(d)

Coulomb's Law

Coulomb's law gives the ***electrostatic force*** between two-point ***charges*** (***at rest***):

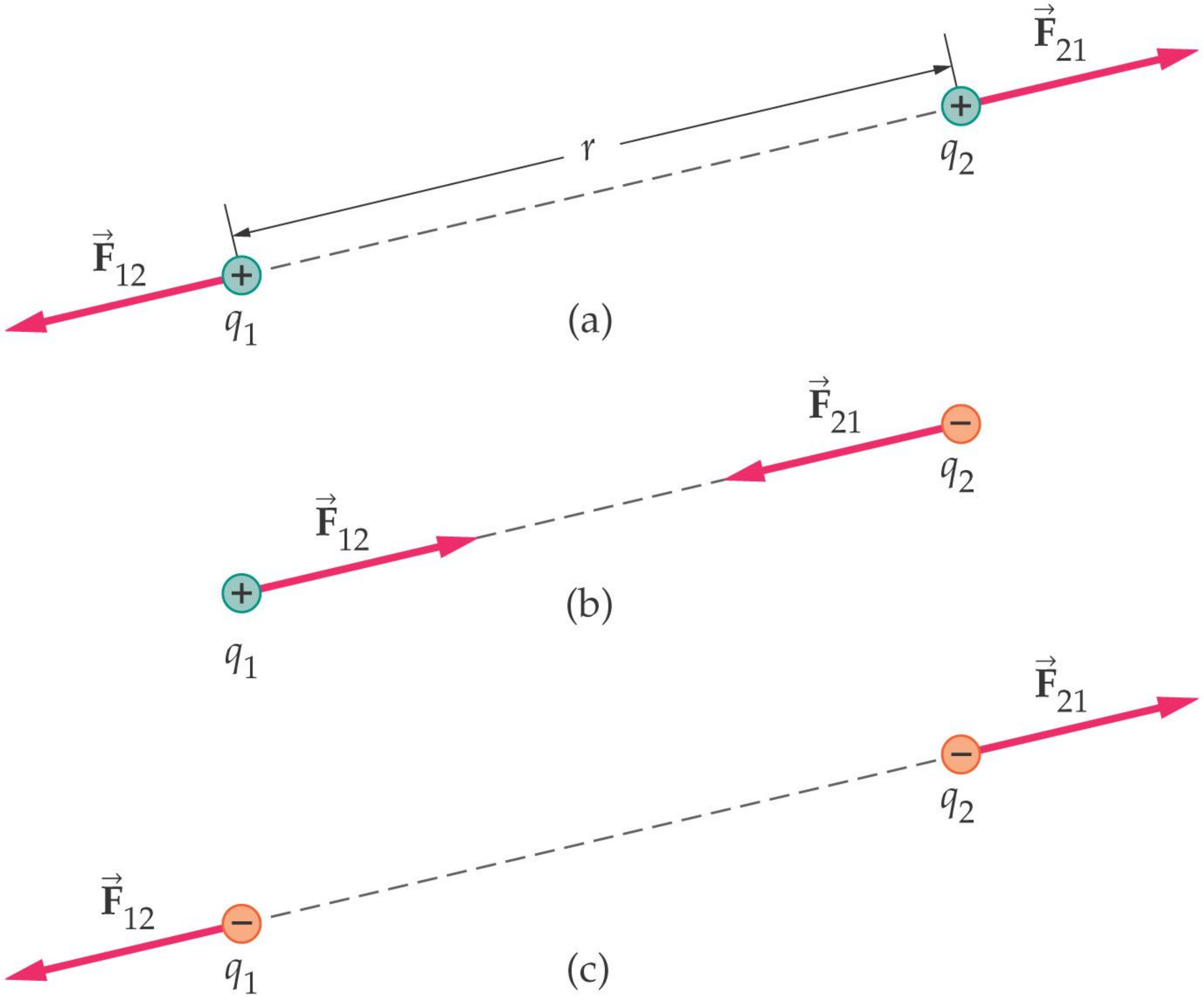
$$F = k\frac{|q_1||q_2|}{r^2}$$ (SI unit: Newton, N)

$$k = \frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9 \ \mathrm{N \cdot m^2/C^2}$$ (Coulomb's constant)

$$\varepsilon_0 = 8.85 \times 10^{-12} \ \mathrm{C^2/N \cdot m^2}$$ (permittivity constant)

- ✓ **F** is along the line connecting the charges
- ✓ **F** is attractive if the charges are opposite (Fig. b)
- ✓ **F** is repulsive if the charges are alike (Figs. a and c)

The forces on the two charges are action-reaction forces



Example 1

Two point-charges $q_1 = + 3.13 \times 10^{-6}$ C and $q_2 = - 4.47 \times 10^{-6}$ C, are separated by a distance of 25.5 cm.

1) Find the magnitude of the electrostatic force experienced by the positive charge

2) Is the magnitude of the force experienced by the negative charge greater than, less than, or the same as that experienced by the positive charge? Explain.

Mutiple Forces

- When a charge experiences forces due to two or more other charges, the net force on it is simply the vector sum of the forces taken individually.

- In other words, Coulomb's law helps us to calculate the force between several charges. We calculate the forces one at a time and ADD them **AS VECTORS**.

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

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.

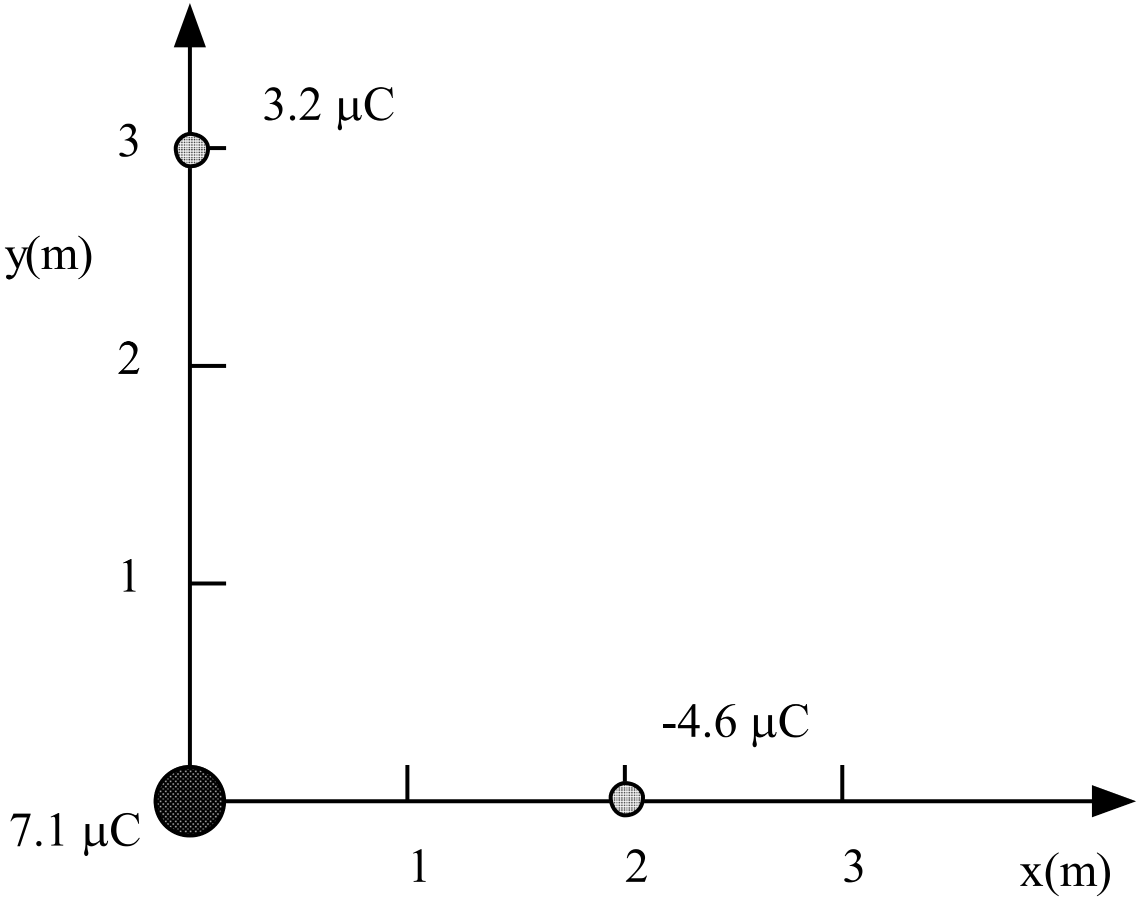
- **Shell theory 2.** A charged particle inside a shell with charge uniformly distributed on its surface has no net force acting on it due to the shell.

Example 2

A charge q_1 = - 5.4 μC is at the origin and a charge q_2 = -2.2 μC is set on the x axis at a distance x = 1 m. Find the net force acting on a charge q_3 = +1.6 μC located at a distance x= 0.75 m. (Ans. 0.507-0.138 = 0.369 N)

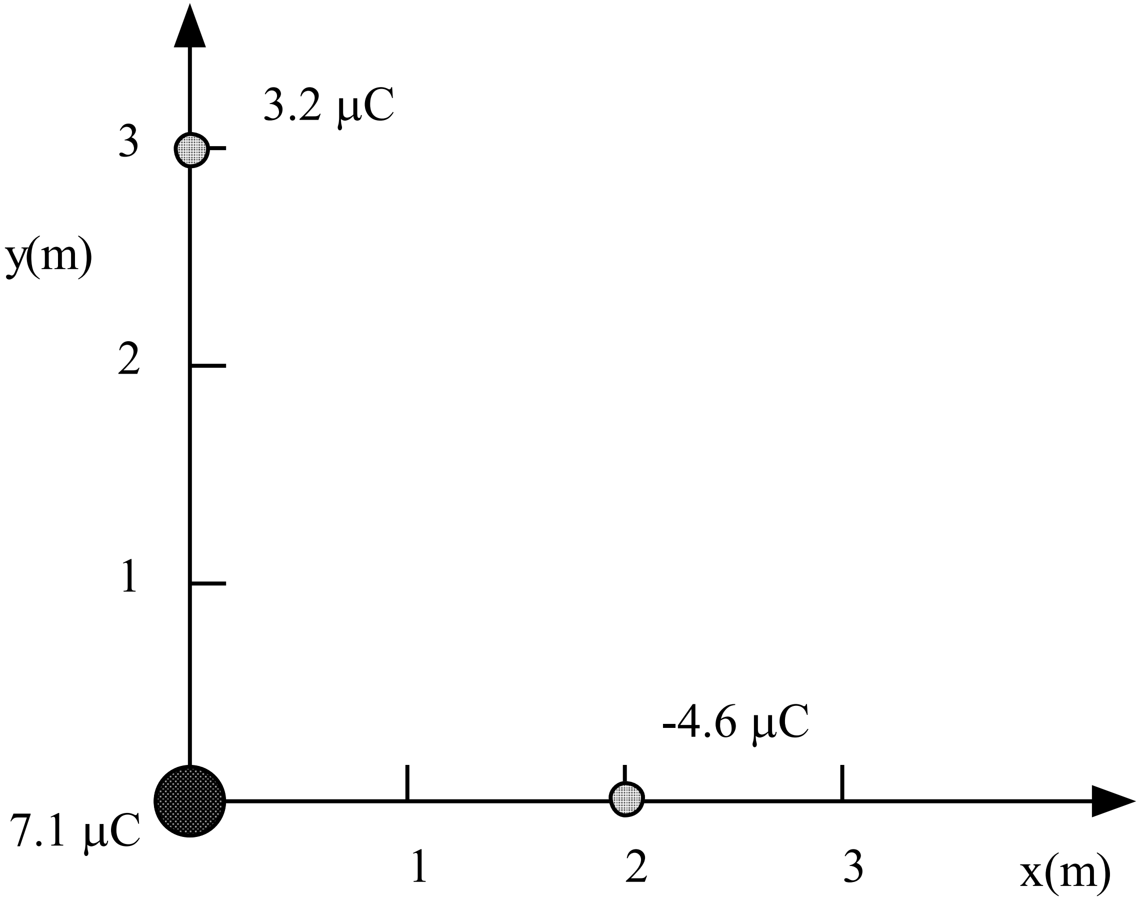
Example 3

In the figure below, find the magnitude and direction of the net force on the charge located at the origin

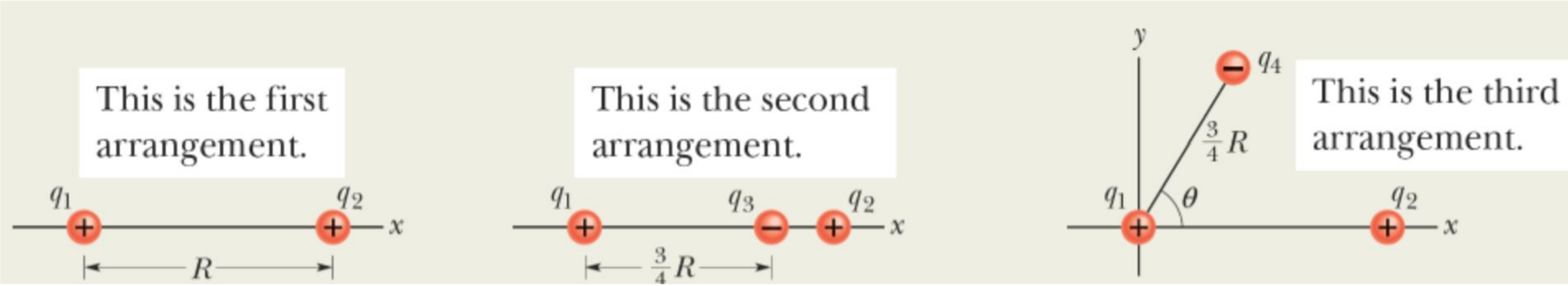


Example 4

In the figure below, find the magnitude and direction of the net force on the charge located at the y=3m



Extra Home Practice 1



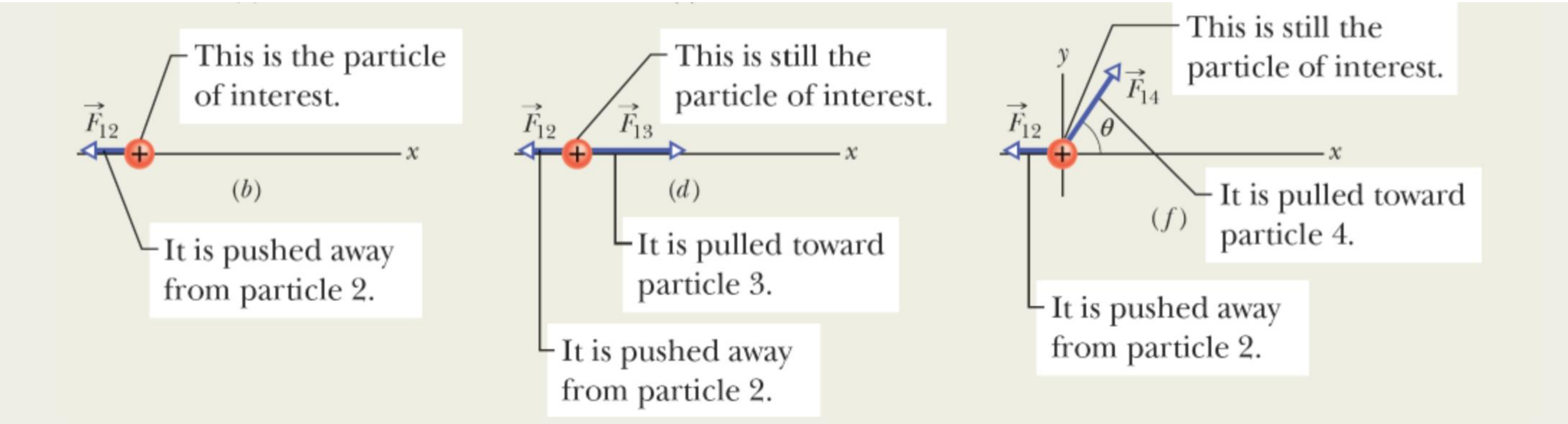
Calculate the net force on q_1 in each of the shown arrangements.

Given:

$q_1 = 1.6 \times 10^{-19}$C $\;\; q_2 = 3.2 \times 10^{-19}$C $\;\; q_3 = q_4 = -3.2 \times 10^{-19}$C,

$R = 2$ cm

Answer to Home Practice 1:



Answer to first arrangement

1.15×10^{-24} N and 180°. (Answer)

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

Answer to second arrangement

$$\vec{F}_{1,\ \text{net}} = \vec{F}_{12} + \vec{F}_{13}$$

$$= -(1.15 \times 10^{-24}\ \text{N})\hat{\text{i}} + (2.05 \times 10^{-24}\ \text{N})\hat{\text{i}}$$

$$= (9.00 \times 10^{-25}\ \text{N})\hat{\text{i}}. \quad \text{(Answer)}$$

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

9.00×10^{-25} N and 0°. (Answer)

Answer to third arrangement

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

The sum of the y components gives us

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

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

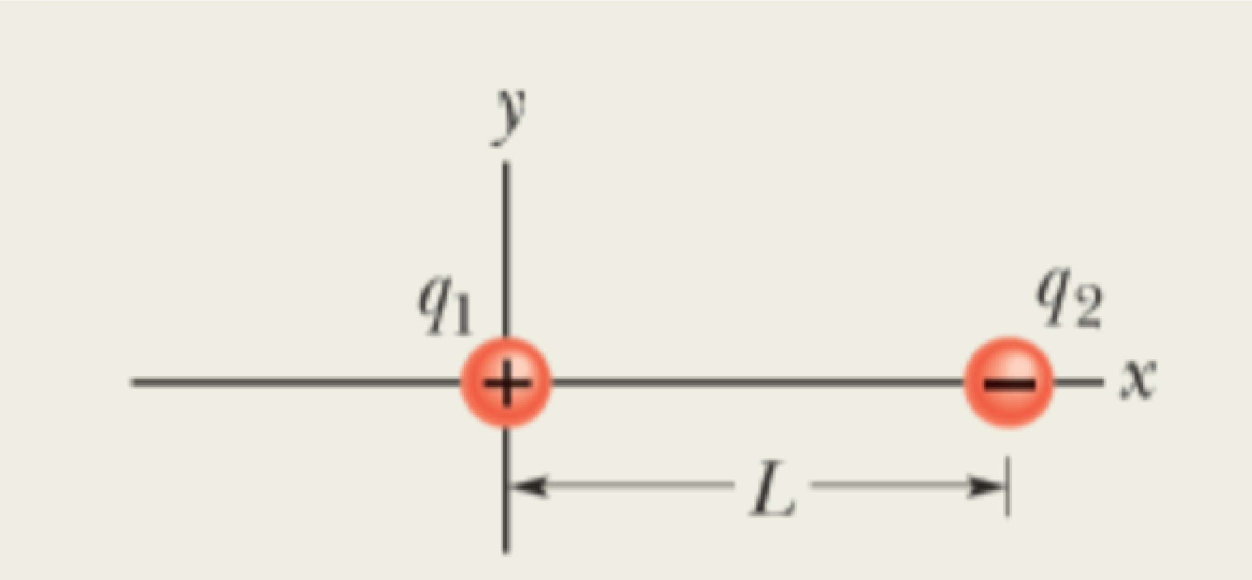
$$F_{1,\text{net}} = \sqrt{F_{1,\text{net},x}^2 + F_{1,\text{net},y}^2} = 1.78 \times 10^{-24}\ \ \text{N.} \quad \text{(Answer)}$$

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

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

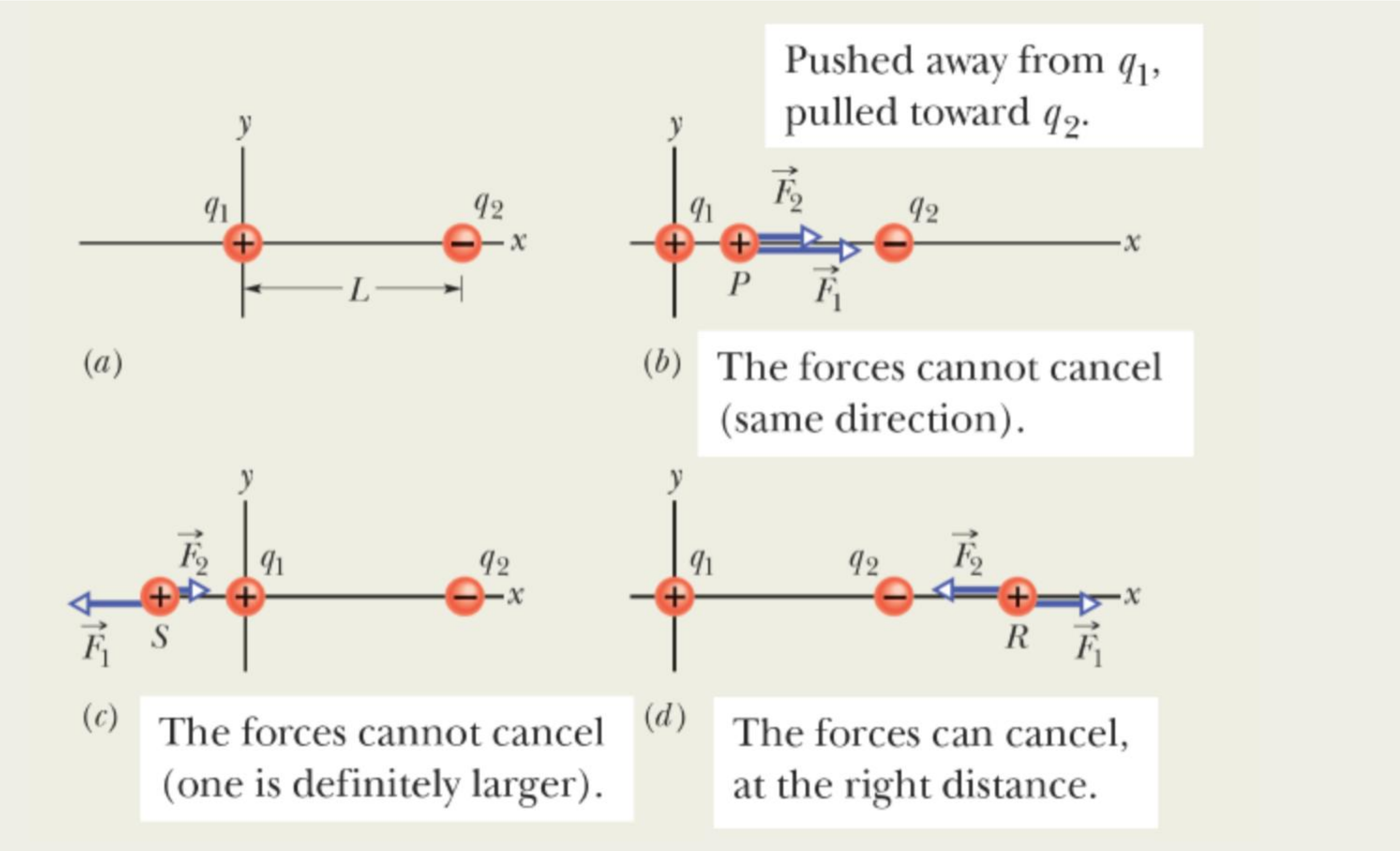
Extra Home Practice 2

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)? $q_1=+8q$ and $q_2=-2q$



Answer to Home Practice 2:

Three possible locations P, S, and R for a proton. At each location, F_1 is the force on the proton from q_1 and F_2 is the force on the proton from q_2.



Section 21.2 Charge is Quantized

Learning Objectives

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

- The charge of a particle or object must be a positive or negative integer times the elementary charge.
- Electric charge is **quantized** (restricted to certain values). It is possible, for example, to find a particle that has no charge at all or a charge of +10*e* or -6*e* , but not a particle with a charge of, say, 3.57*e*.
- 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

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

Charge for Three Particles and Their Antiparticles

Particle	Symbol	Charge	Antiparticle	Symbol	Charge
Electron	e or e^-	$-e$	Positron	e^+	$+e$
Proton	p	$+e$	Antiproton	$\bar{p}$	$-e$
Neutron	n	0	Antineutron	$\bar{n}$	0

Example:

Initially, sphere *A* has a charge of −50*e* and sphere *B* has a charge of +20*e*.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: −15*e*

Section 21.3 Charge is Conserved

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

If you rub a glass rod with silk, a positive charge appears on the rod. Measurement shows that a negative charge of equal magnitude appears on the silk. This suggests that rubbing does not create charge but only transfers it from one body to another, upsetting the electrical neutrality of each body during the process.

- If two charged particles undergo an annihilation process, they have equal and opposite signs of charge.(A **gamma ray** $\boldsymbol{\Upsilon}$ is a high-energy form of **electromagnetic radiation** (a photon) that has **no mass and no electric charge**.)

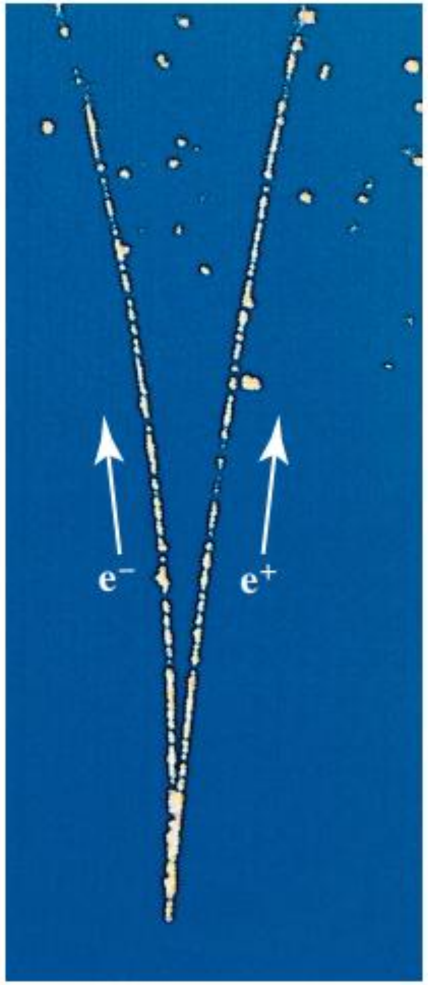
$$e^- + e^+ \rightarrow \gamma + \gamma$$

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

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

Experimental Evidence of Particle Charge Conservation

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 of Lawrence Berkeley Laboratory