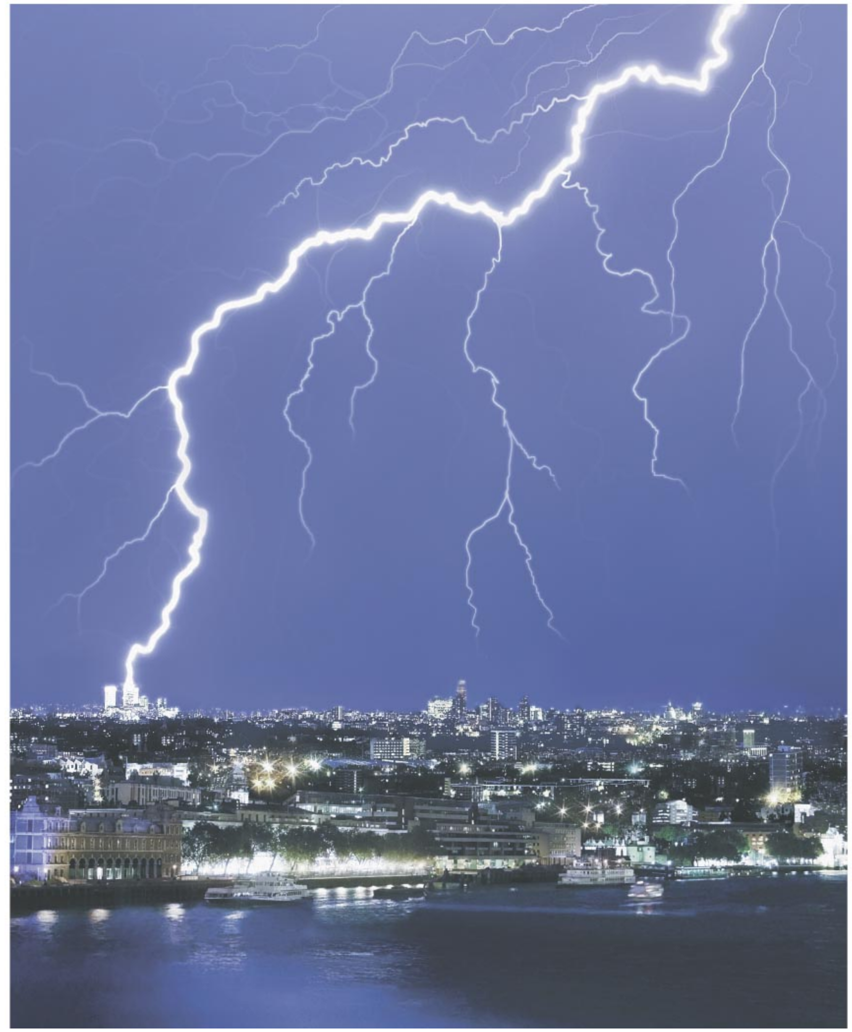
Chapter 26. Electric Charges and Forces

The electric force is one of the fundamental forces of nature. Controlled electricity is the cornerstone of our modern, technological society.



Chapter Goal: To develop a basic understanding of electric phenomena in terms of charges, forces, and fields.

Chapter 26. Electric Charges and Forces

Topics:

- Developing a Charge Model
- Charge
- Insulators and Conductors
- Coulomb's Law
- The Field Model

What is the SI unit of charge?

A. Coulomb
B. Faraday
C. Ampere
D. Ohm
E. Volt

What is the SI unit of charge?

✔ **A. Coulomb**
B. Faraday
C. Ampere
D. Ohm
E. Volt

A charge alters the space around it. What is this alteration of space called?

A. Charged plasma
B. Charge sphere
C. Electric ether
D. Electric field
E. Electrophoresys

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B. Charge sphere
C. Electric ether
✔ **D. Electric field**
E. Electrophoresys

If a negative charged rod is held near a neutral metal ball, the ball is attracted to the rod. This happens

A. because of magnetic effects.
B. because the ball tries to pull the rod’s electrons over to it.
C. because the rod polarizes the metal.
D. because the rod and the ball have opposite charges.

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The electric field of a charge is defined by the force on

A. an electron.
B. a proton.
C. a source charge.
D. a test charge.

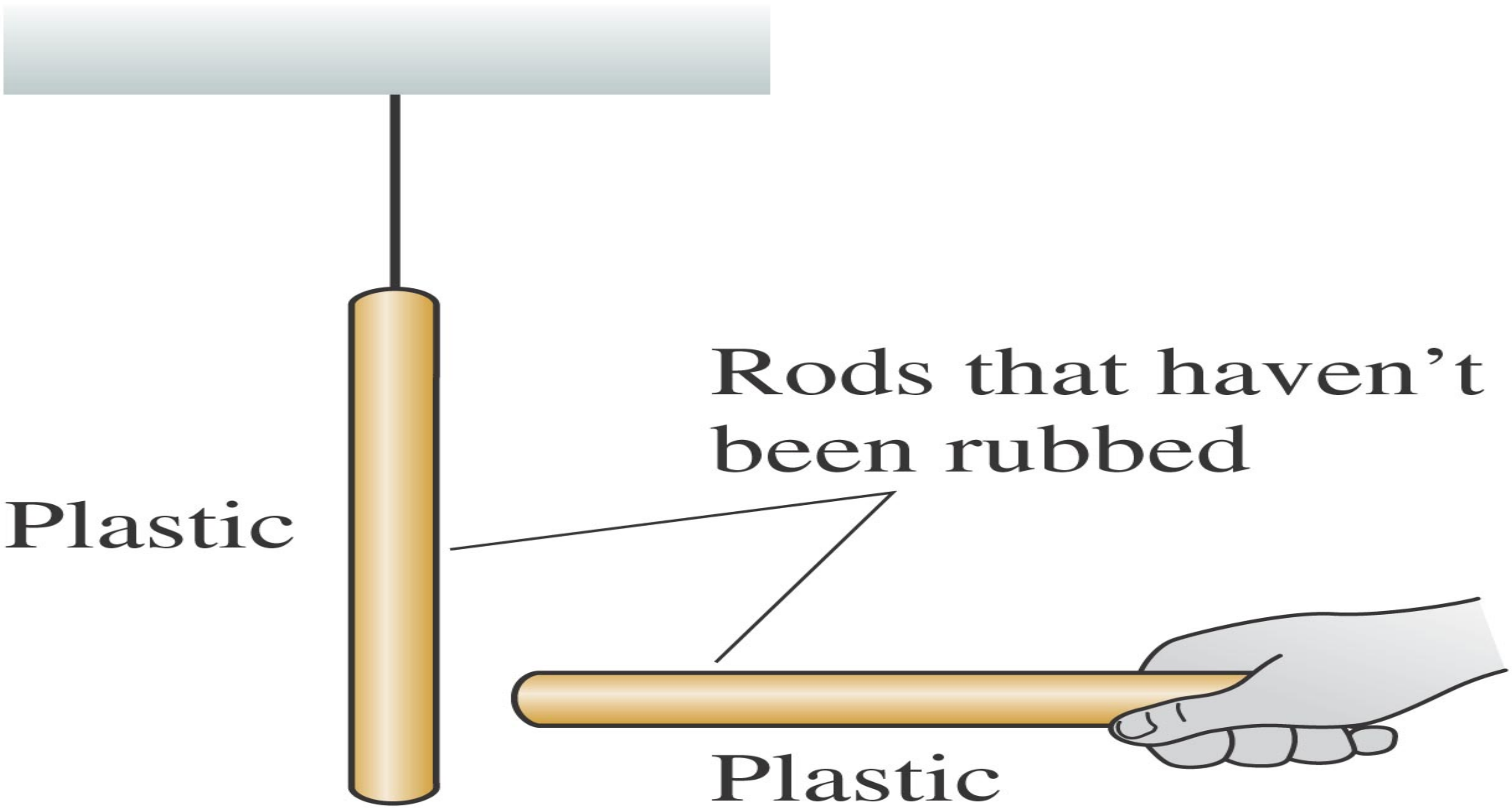
The electric field of a charge is defined by the force on

A. an electron.
B. a proton.
C. a source charge.
✔ **D. a test charge.**

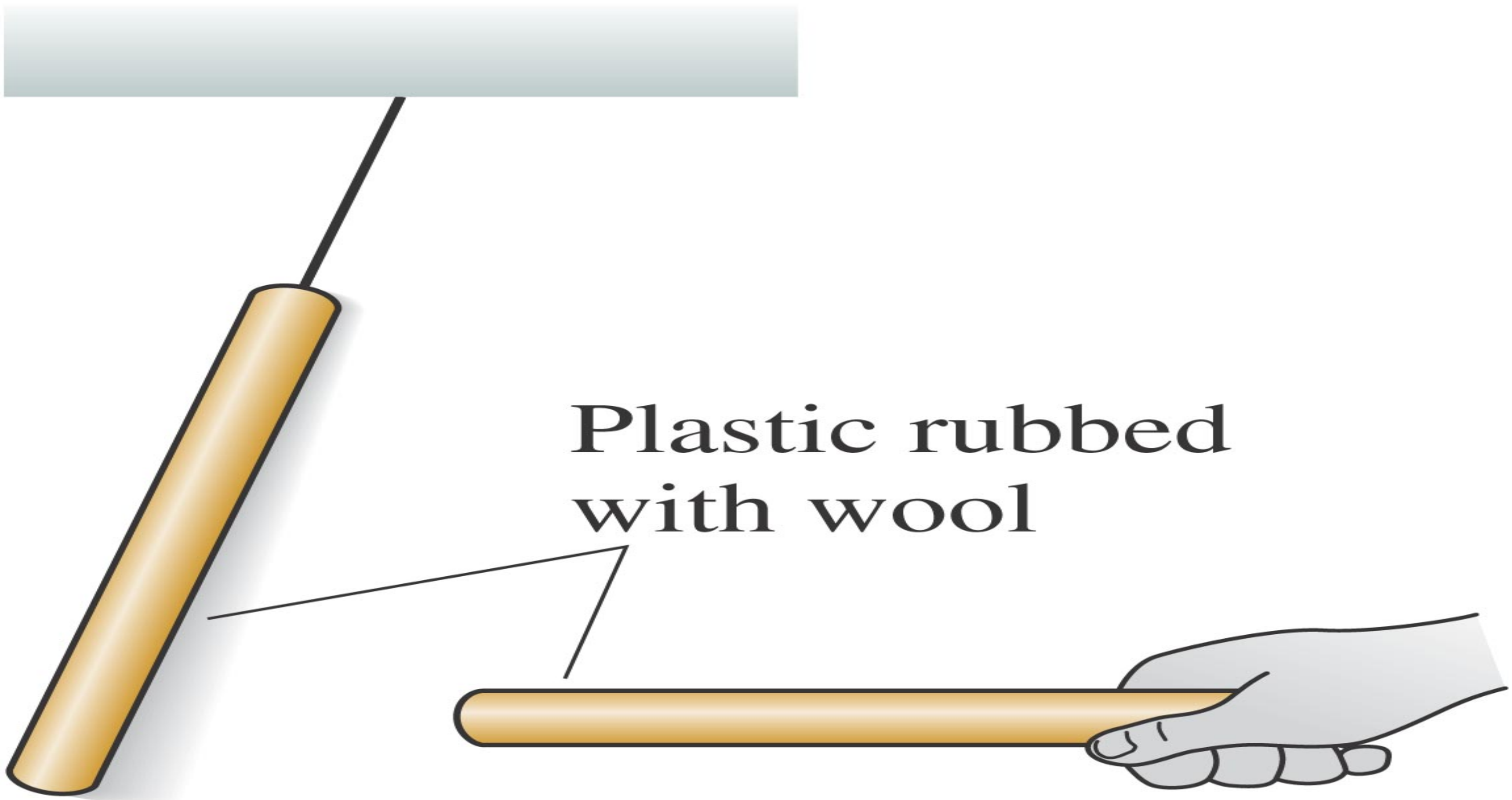
Learning Objectives

- To become familiar with basic electrical phenomena
- To learn the charge model and apply it to situations involving conductors and insulators
- To understand polarization and the attraction between neutral and charged objects
- To understand and use Coulomb’s law for point charges
- To recognize the principle of superposition for electrical forces
- To begin the process of understanding the field model and concept of a field
- To learn the electric field of a point charge

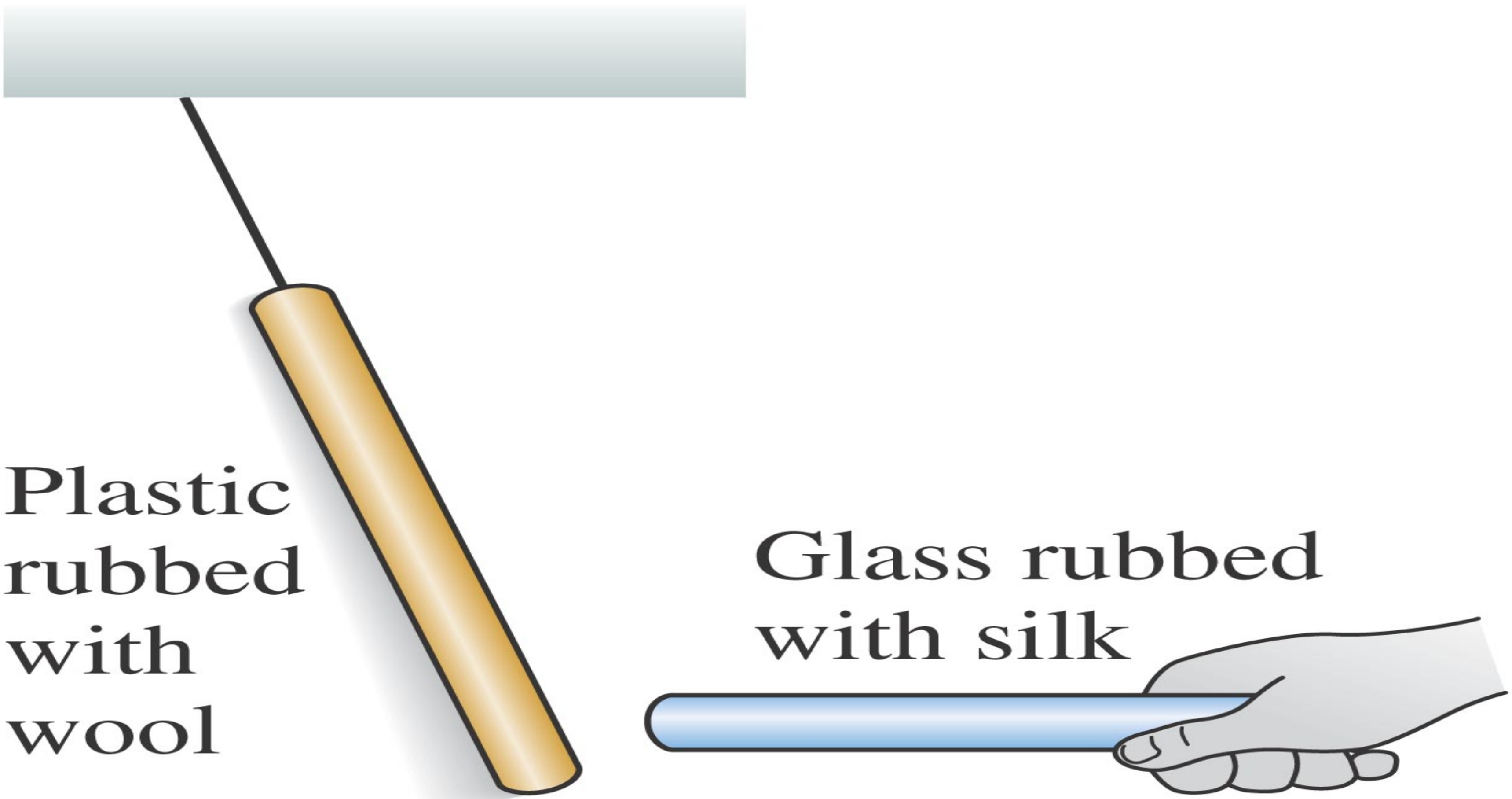
Experiment 1



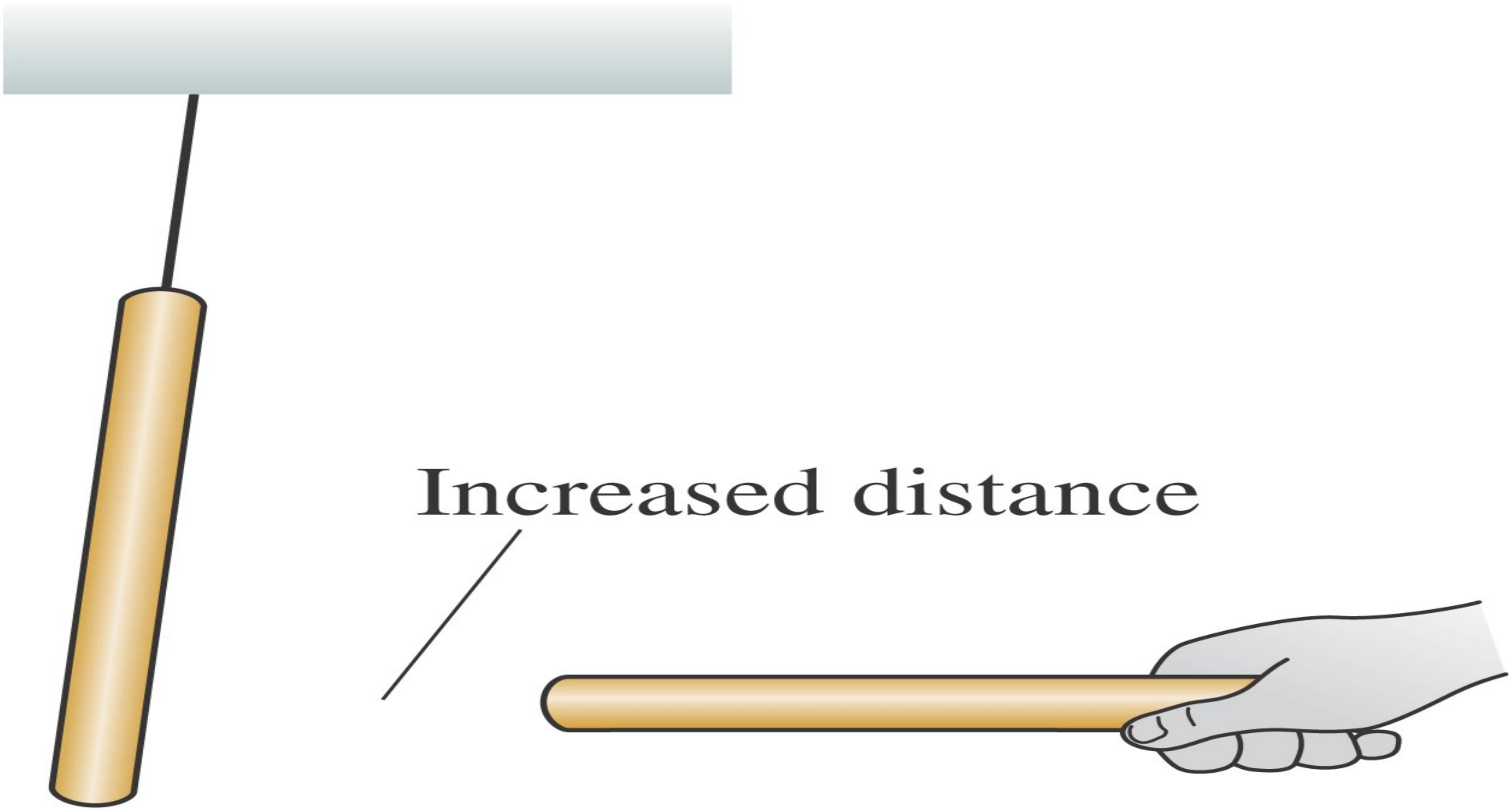
Experiment 2



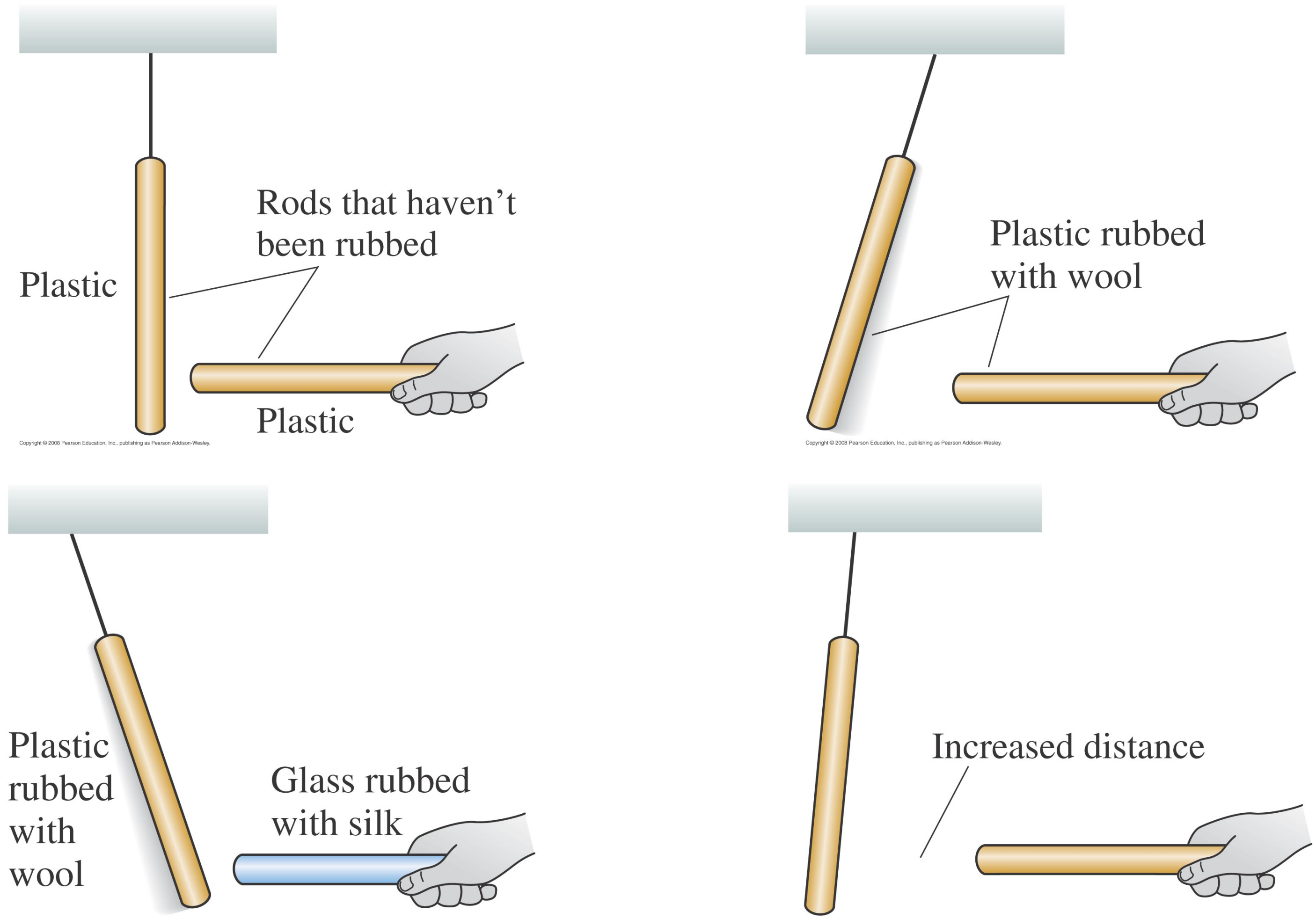
Experiment 3



Experiment 4

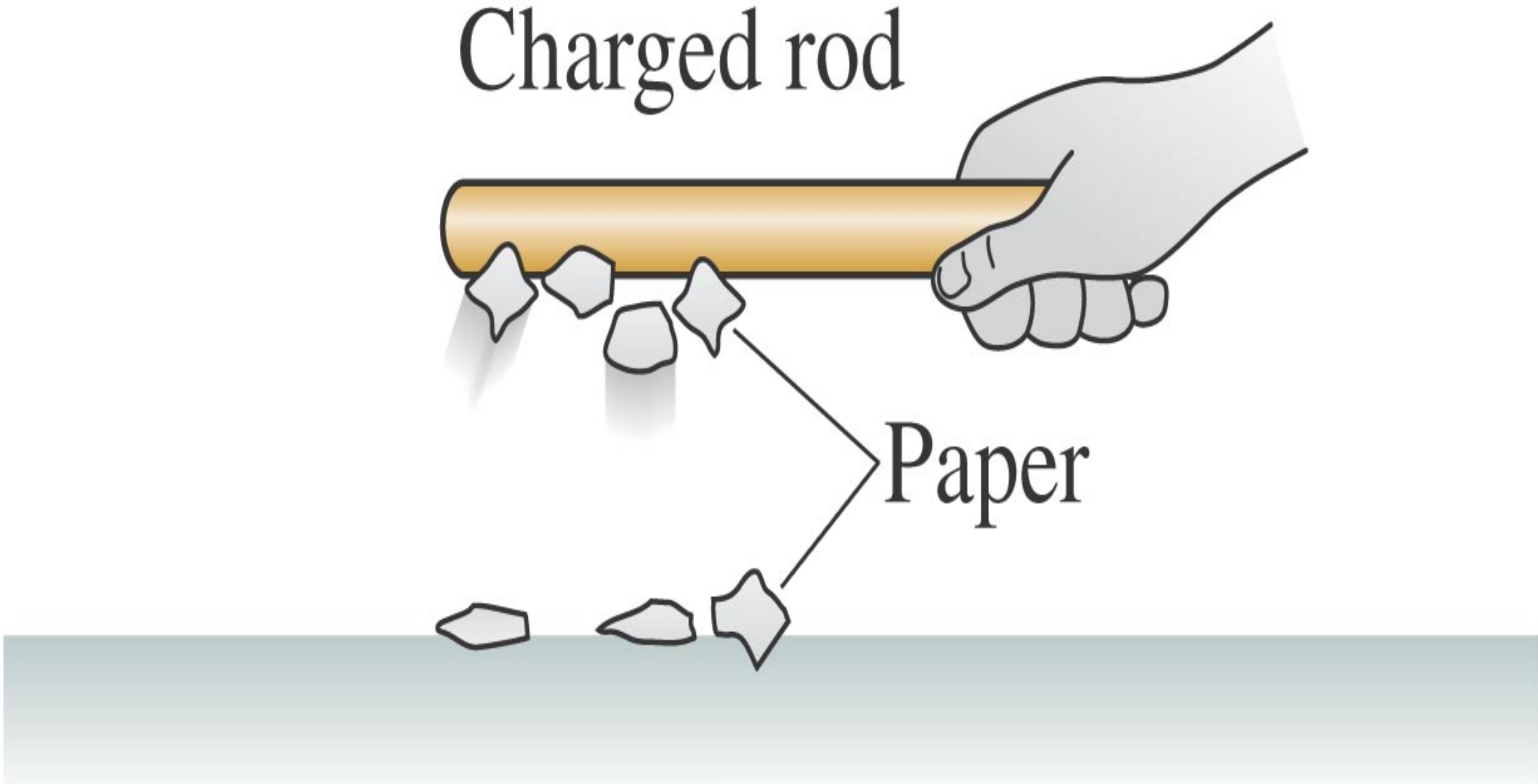


Recap 1-4

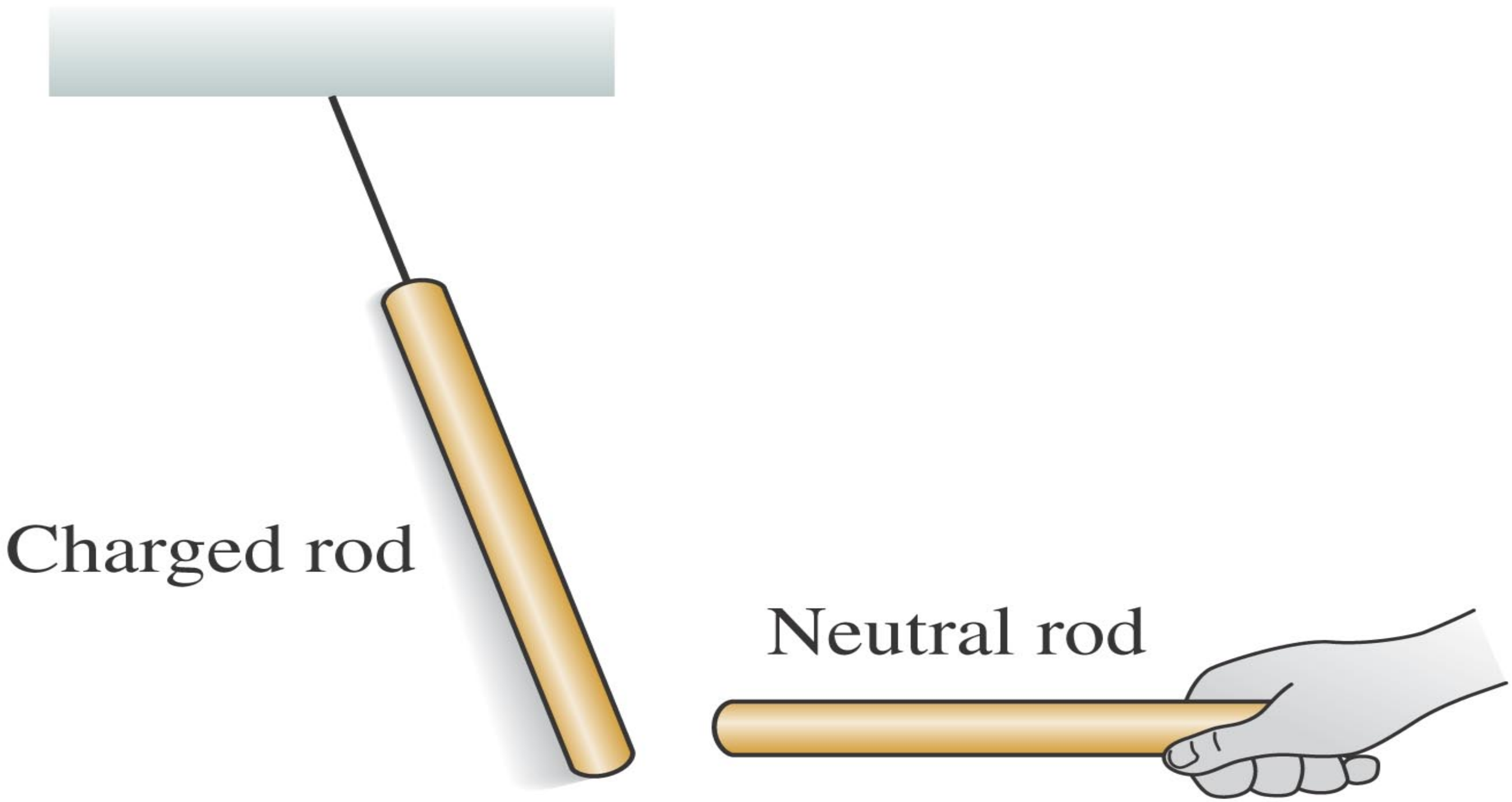


Rods that haven't been rubbed
Plastic
Plastic
Plastic rubbed with wool
Plastic rubbed with wool
Glass rubbed with silk
Increased distance

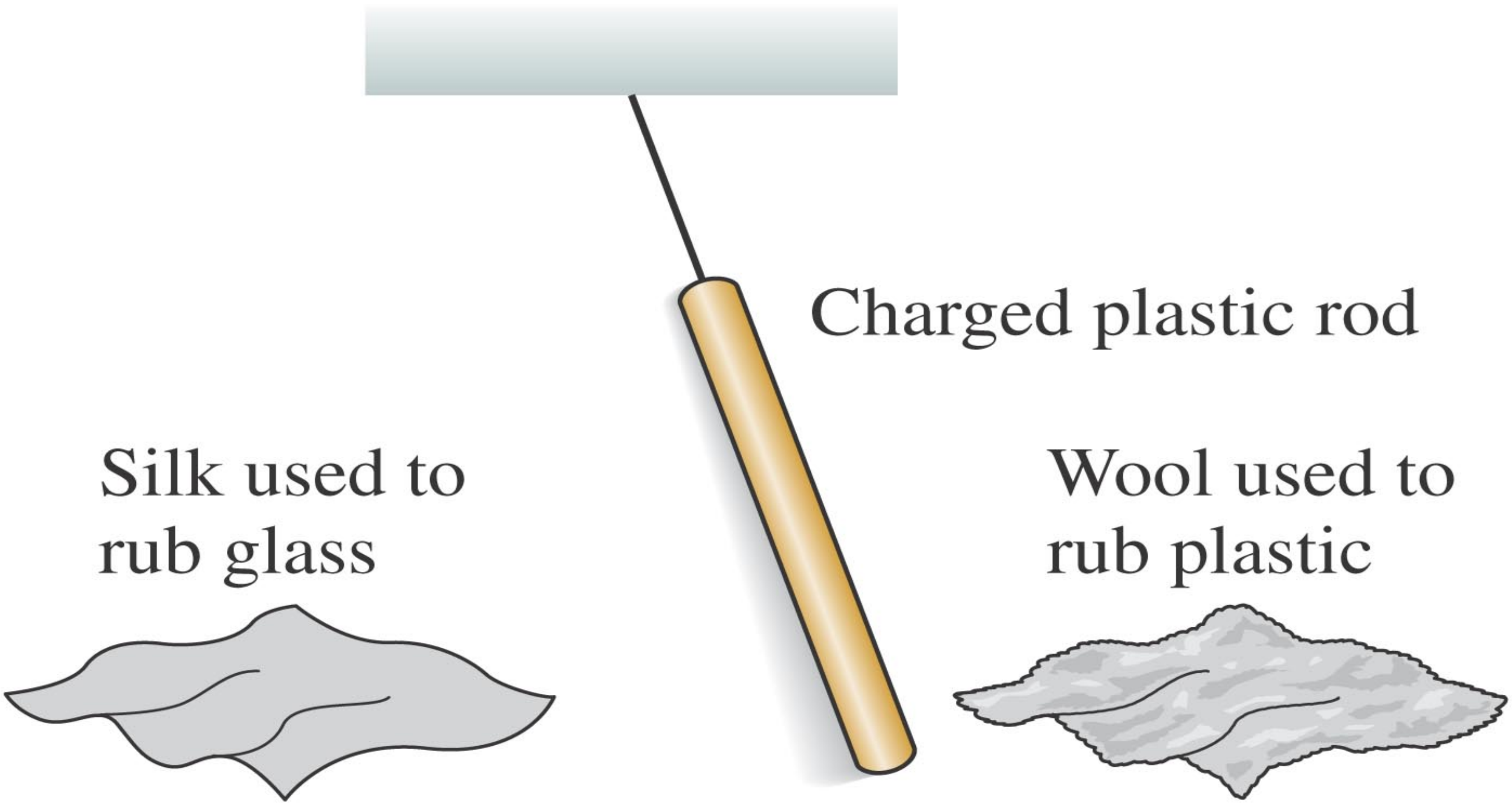
Experiment 5

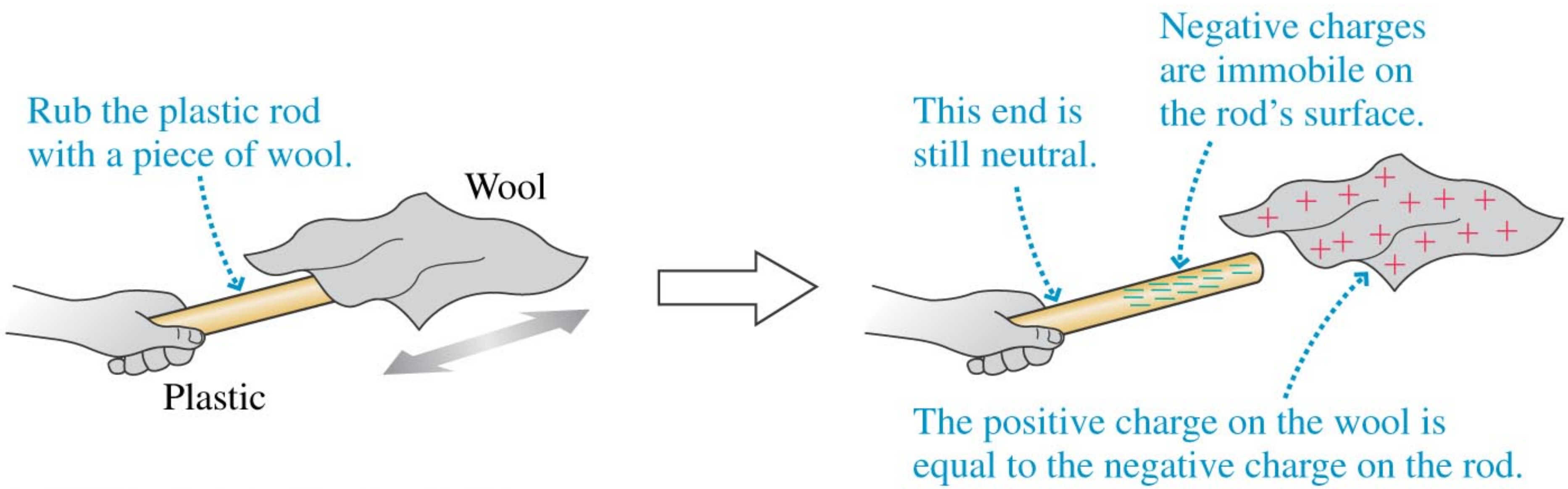


Experiment 6



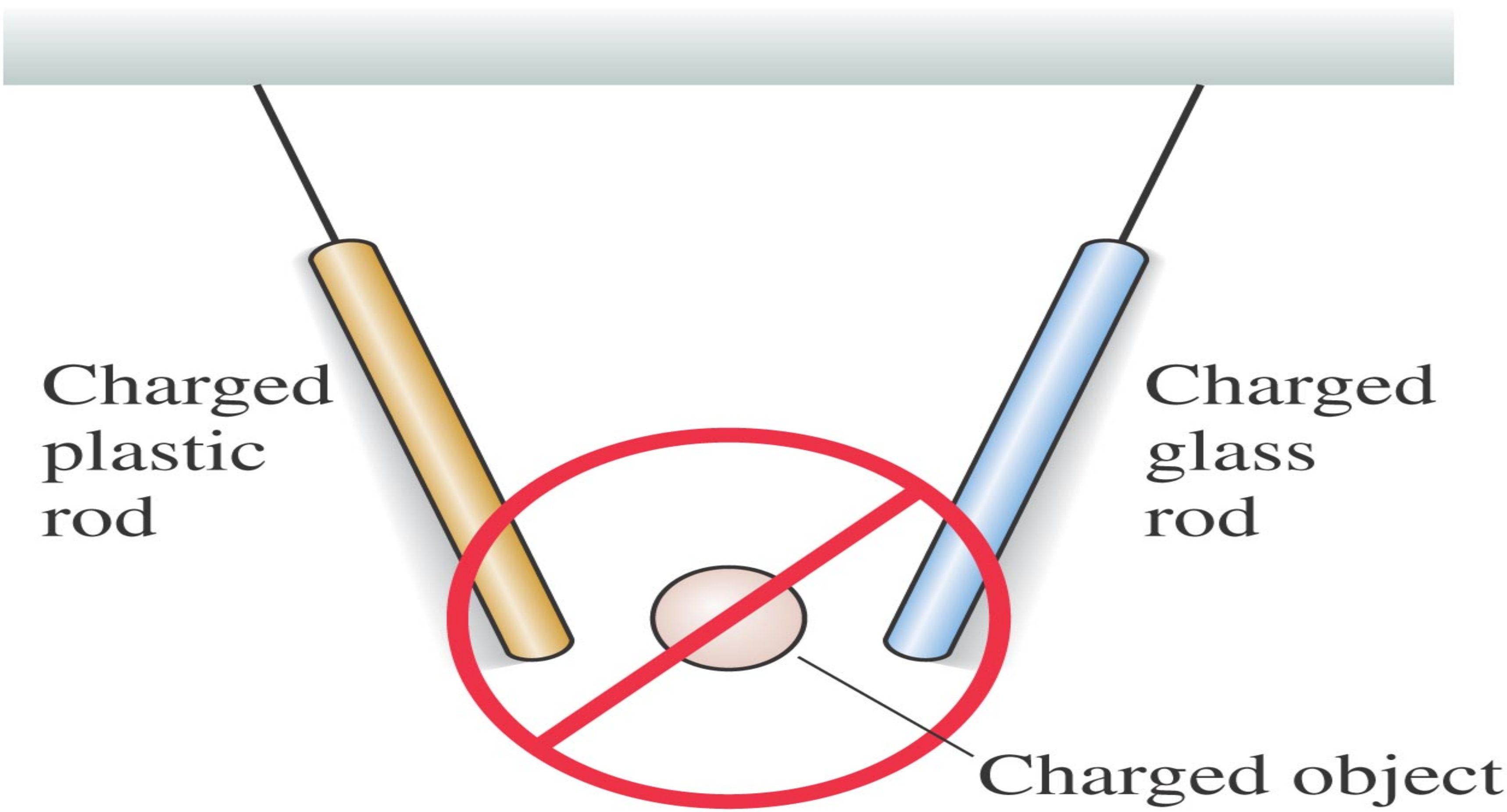
Experiment 7



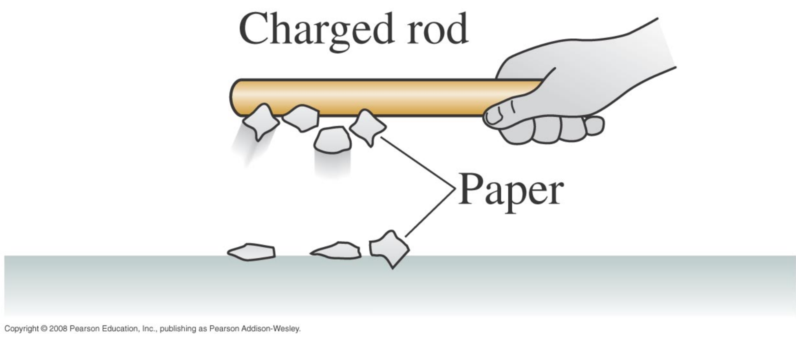


Rub the plastic rod
with a piece of wool.
Wool
Plastic
This end is
still neutral.
Negative charges
are immobile on
the rod's surface.
The positive charge on the wool is
equal to the negative charge on the rod.

Experiment 8



Recap 5-8


Charged rod
Paper
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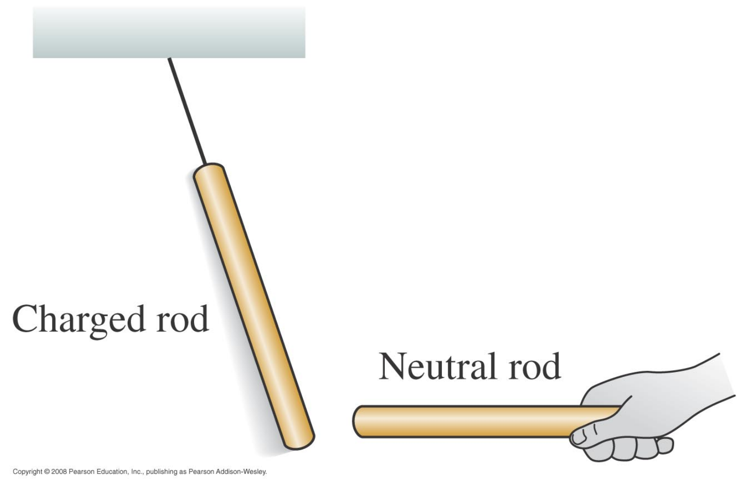
Charged rod
Neutral rod
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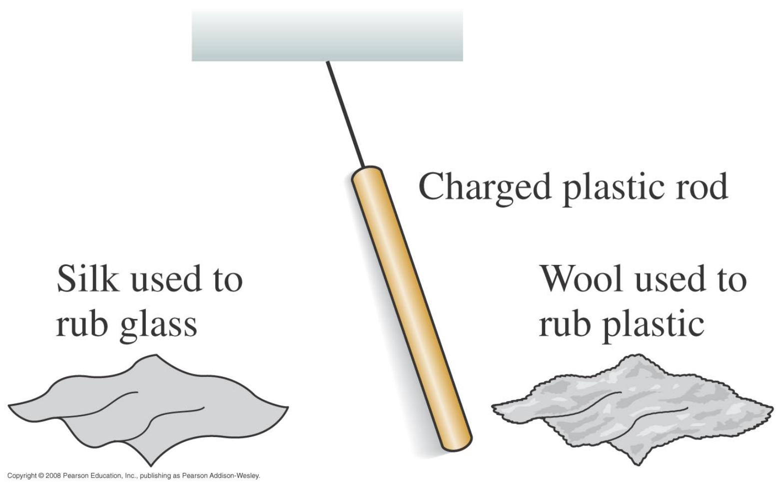
Charged plastic rod
Silk used to rub glass
Wool used to rub plastic
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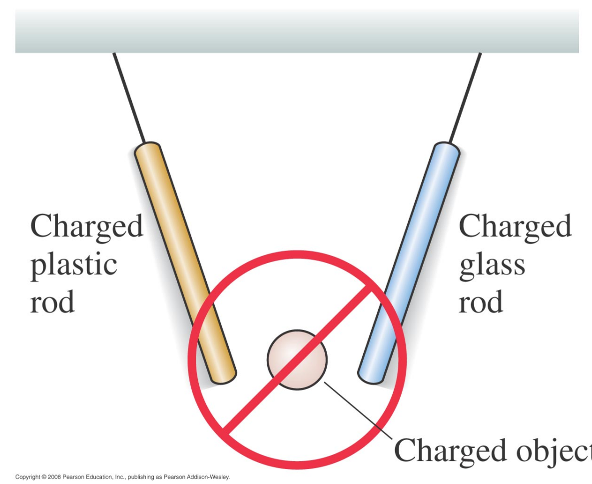
Charged plastic rod
Charged glass rod
Charged object
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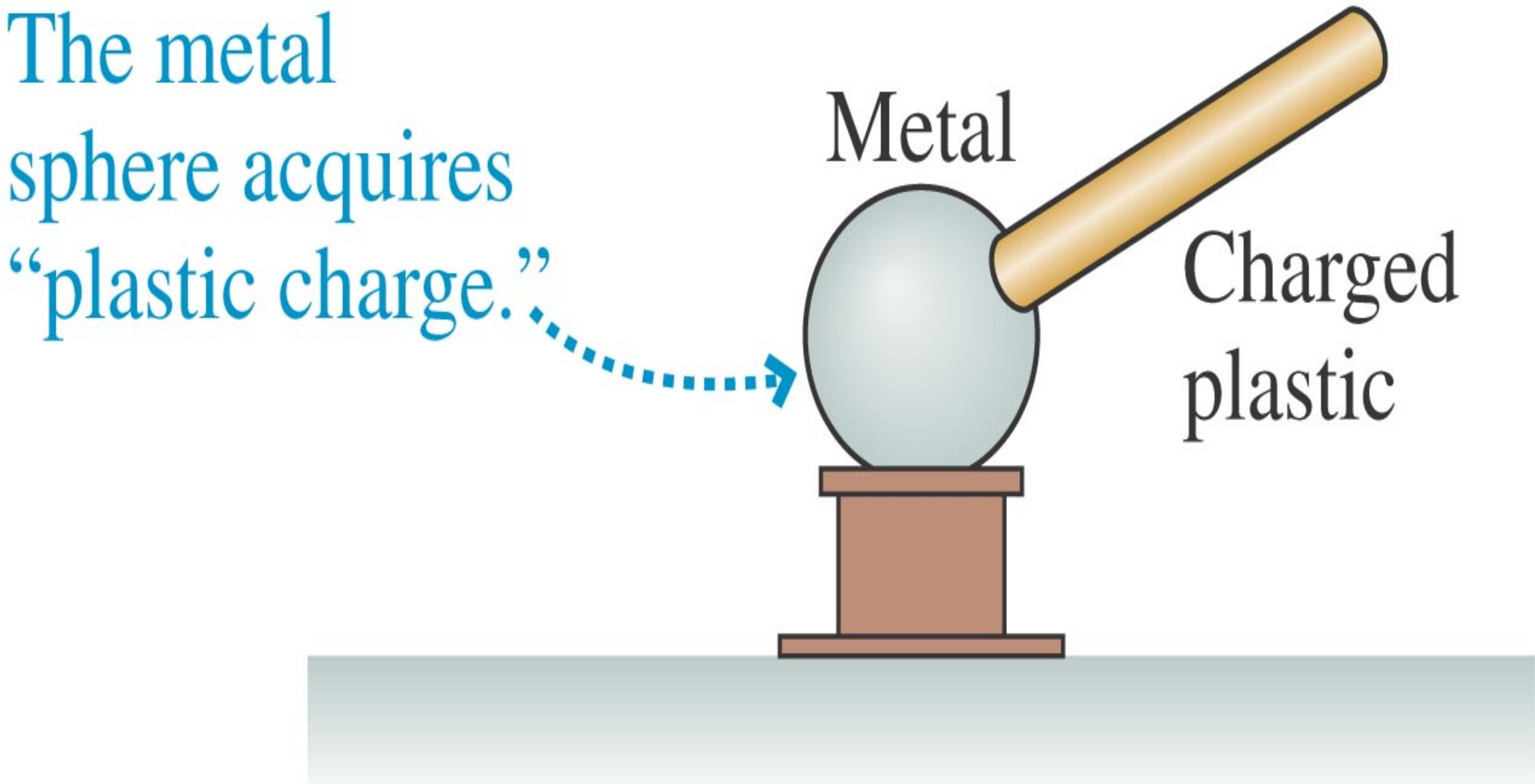
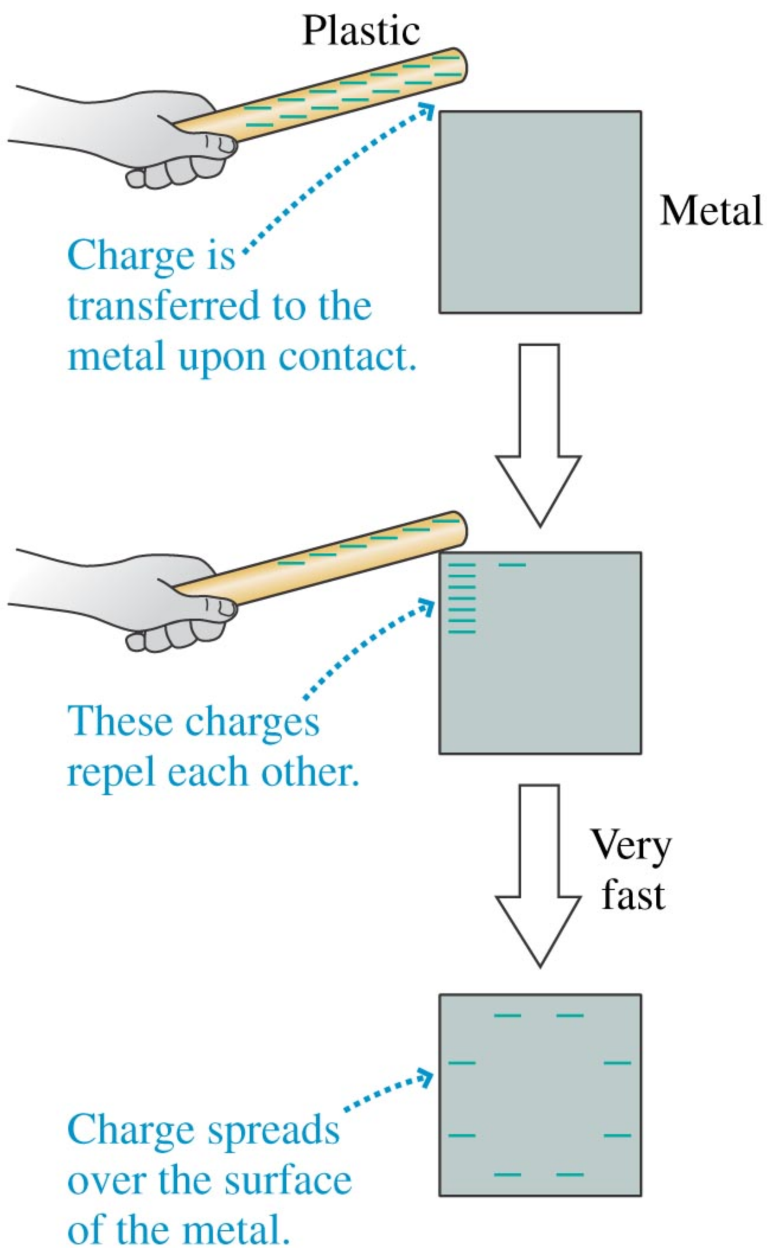
Charge Model, Part I

Charge model, part I The basic postulates of our model are:

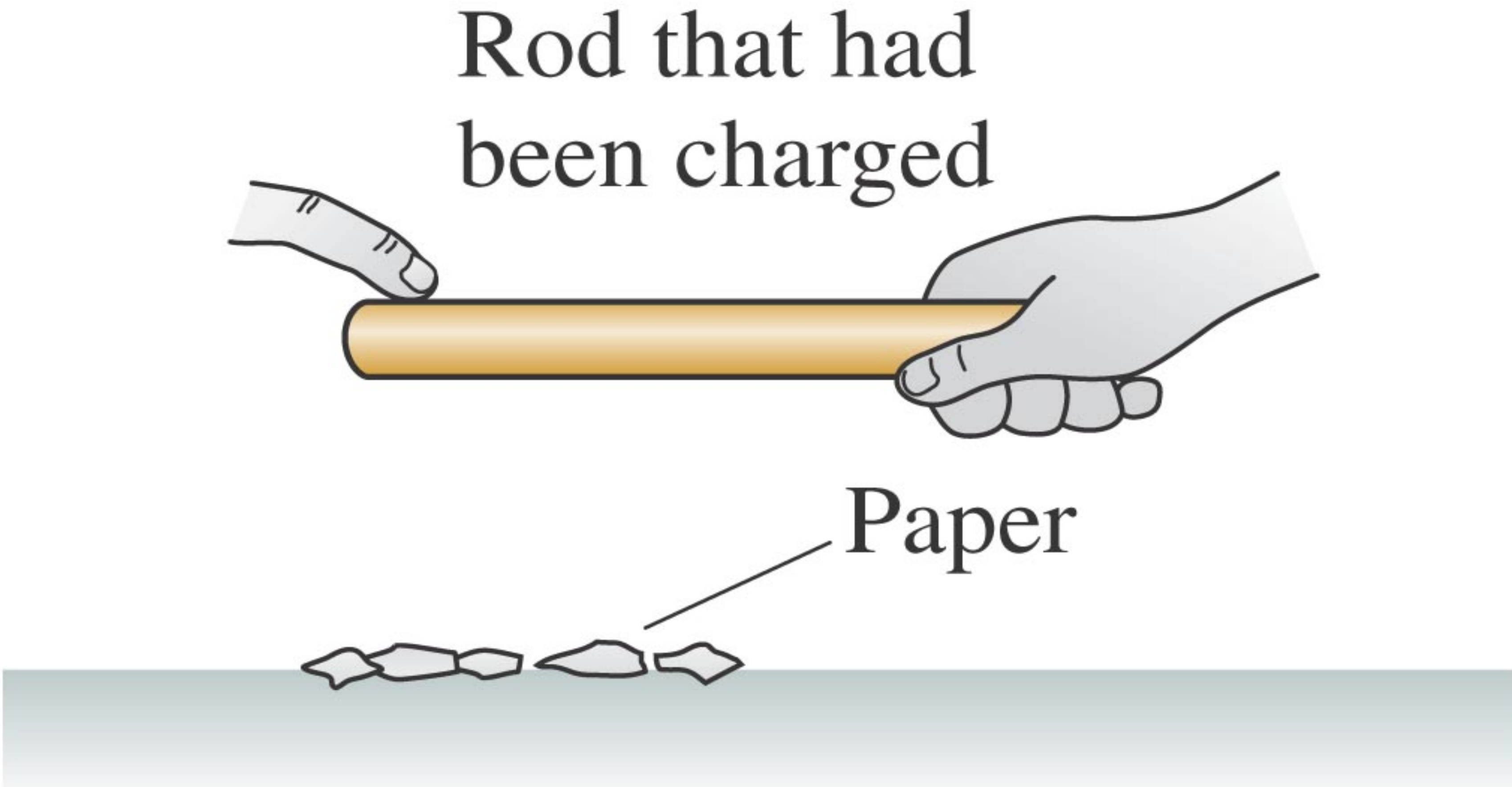
1. Frictional forces, such as rubbing, add something called **charge** to an object or remove it from the object. The process itself is called *charging*. More vigorous rubbing produces a larger quantity of charge.
2. There are two and only two kinds of charge. For now we will call these "plastic charge" and "glass charge." Other objects can sometimes be charged by rubbing, but the charge they receive is either "plastic charge" or "glass charge."
3. Two **like charges** (plastic/plastic or glass/glass) exert repulsive forces on each other. Two **opposite charges** (plastic/glass) attract each other.
4. The force between two charges is a long-range force. The size of the force increases as the quantity of charge increases and decreases as the distance between the charges increases.
5. *Neutral* objects have an *equal mixture* of both "plastic charge" and "glass charge." The rubbing process somehow manages to separate the two.

Experiment 9

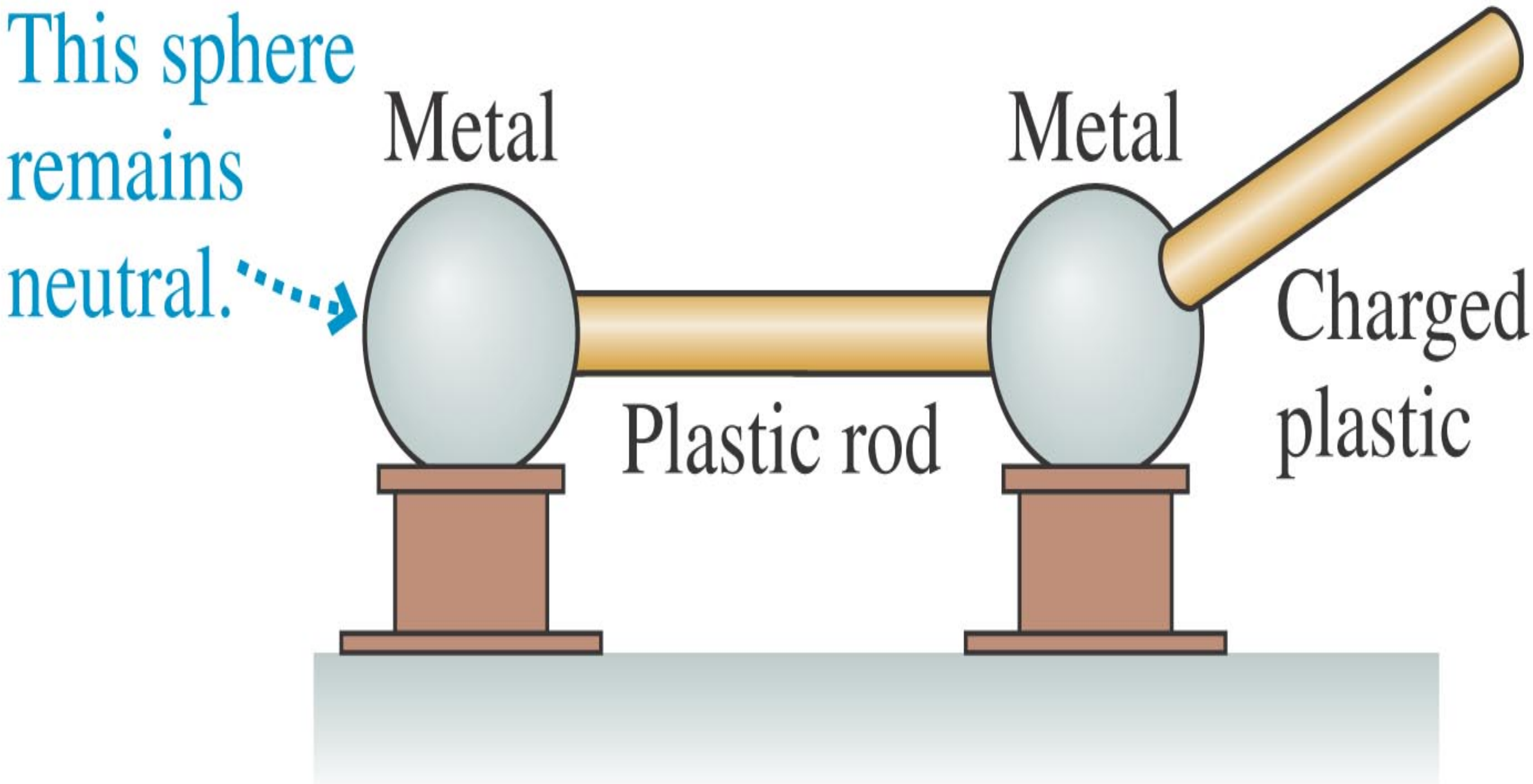



Plastic
Metal
Charge is transferred to the metal upon contact.
These charges repel each other.
Very fast
Charge spreads over the surface of the metal.

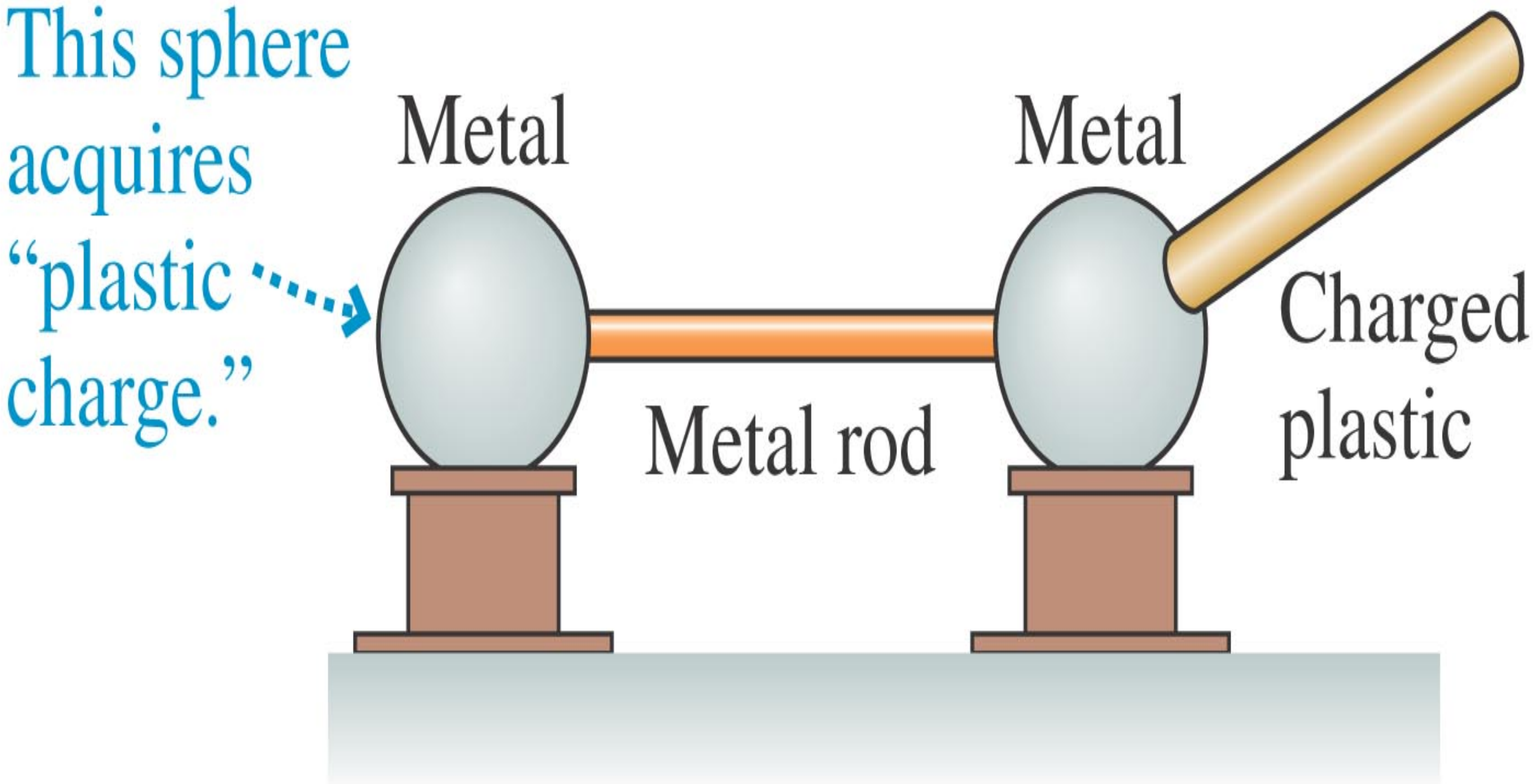
Experiment 10



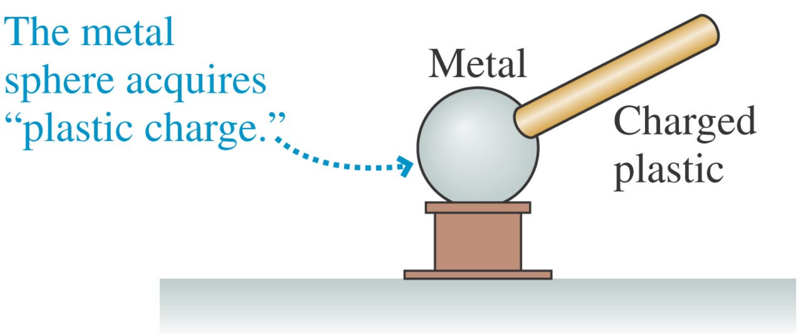
Experiment 11

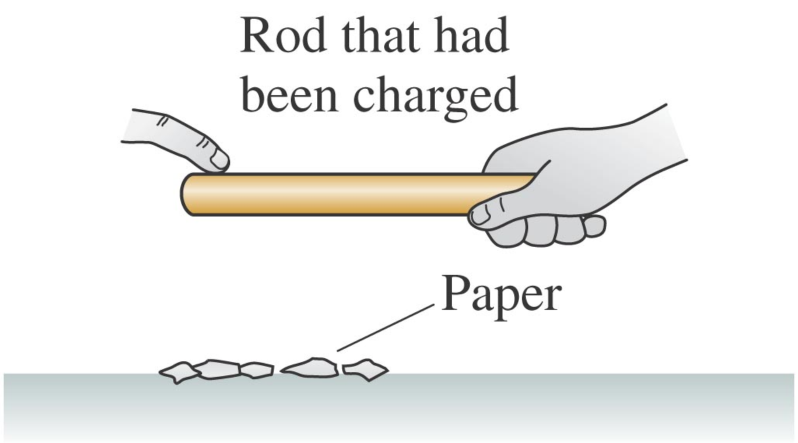


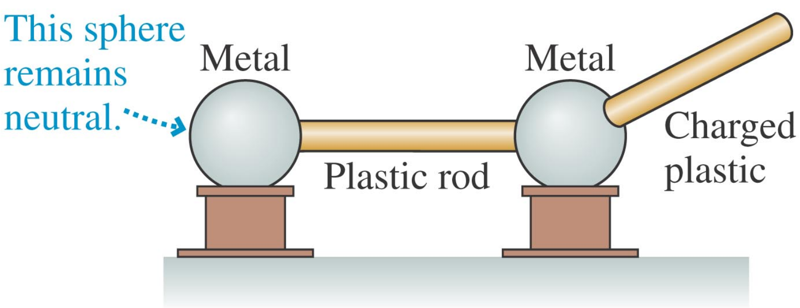
Experiment 12

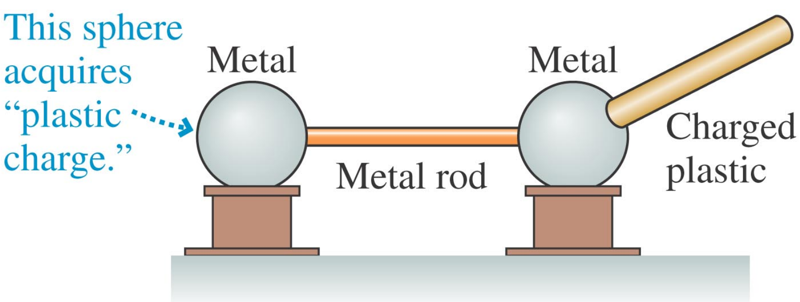


Recap 9-12


The metal
sphere acquires
“plastic charge.”
Metal
Charged
plastic


Rod that had
been charged
Paper


This sphere
remains
neutral.
Metal
Metal
Plastic rod
Charged
plastic


This sphere
acquires
“plastic
charge.”
Metal
Metal
Metal rod
Charged
plastic

Charge Model, Part II

6) There are two types of materials.

- Conductors are materials through or along which charge easily moves
- Insulators are materials on which charges remain in fixed place

7) Charges can be transferred from one object to another by contact

EXAMPLE 26.1 Transferring charge

EXAMPLE 26.1 Transferring charge

In Experiment 12, touching one metal sphere with a charged plastic rod caused a second metal sphere to become charged with the same type of charge as the rod. Use the postulates of the charge model to explain this.

EXAMPLE 26.1 Transferring charge

SOLVE We need the following ideas from the charge model:

1. Charge is transferred upon contact.
2. Metal is a conductor.
3. Like charges repel.

The plastic rod was charged by rubbing with wool. The charge doesn't move around on the rod, because it is an insulator, but some of the "plastic charge" is transferred to the metal upon contact. Once in the metal, which is a conductor, the charges are free to move around. Furthermore, because like charges repel, these plastic charges quickly move as far apart as they possibly can. Some move through the connecting metal rod to the second sphere. Consequently, the second sphere acquires "plastic charge."

To determine if an object has “glass charge,” you need to

A. see if the object attracts a charged plastic rod.
B. see if the object repels a charged glass rod.
C. Both A and B.
D. Either A or B.

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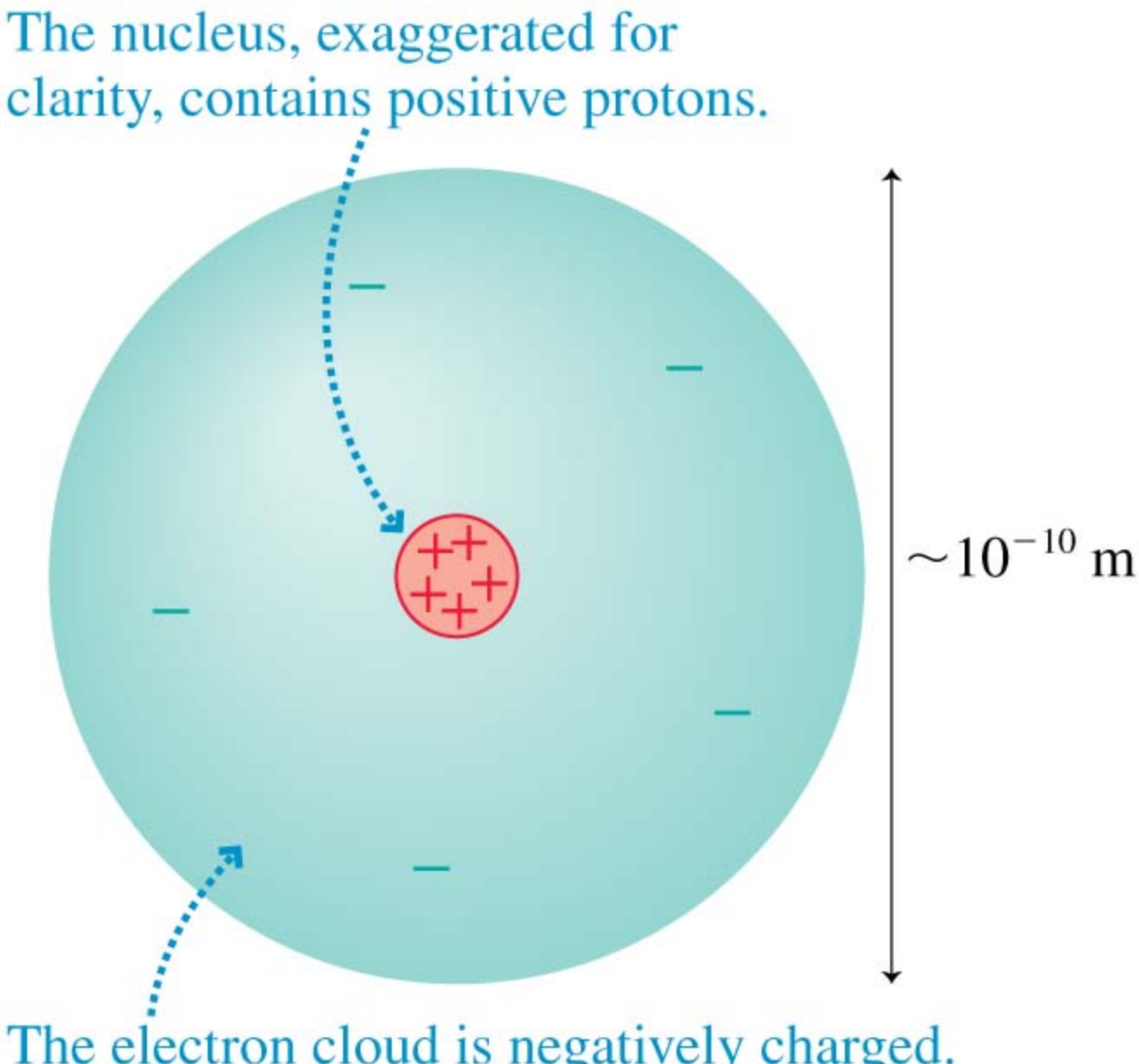
A. see if the object attracts a charged plastic rod.
✔ **B. see if the object repels a charged glass rod.**
C. Both A and B.
D. Either A or B.

FIGURE 26.1 An atom.



Atoms and Electricity

- An atom consists of a very small and dense *nucleus* surrounded by much less massive orbiting *electrons*.
- The nucleus is a composite structure consisting of *protons,* positively charged particles, and neutral *neutrons*.
- The atom is held together by the attractive electric force between the positive nucleus and the negative electrons.
- Electrons and protons have charges of opposite sign but *exactly* equal magnitude.
- This atomic-level unit of charge, called the **fundamental unit of charge,** is represented by the symbol *e*.

Charge quantization

TABLE 26.1 Protons and electrons

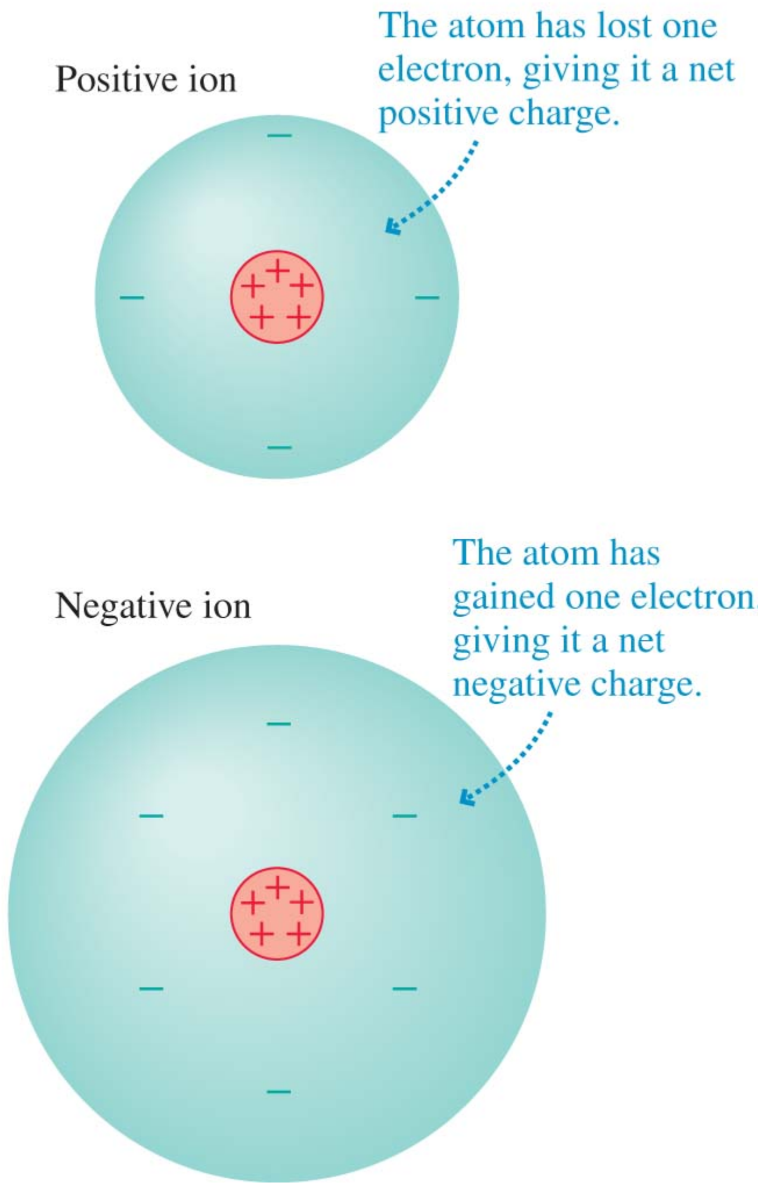
Particle	Mass (kg)	Charge
Proton	1.67×10^{-27}	$+e$
Electron	9.11×10^{-31}	$-e$

- A macroscopic object has net charge

$$q = N_p e - N_e e = (N_p - N_e)e$$

- Where N_p and N_e are the number of protons and electrons contained in the object.
- The process of removing an electron from the electron cloud of an atom is called **ionization.**
- An atom that is missing an electron is called a *positive ion*. Its *net* charge is $q = +e$.

FIGURE 26.2 Positive and negative ions.



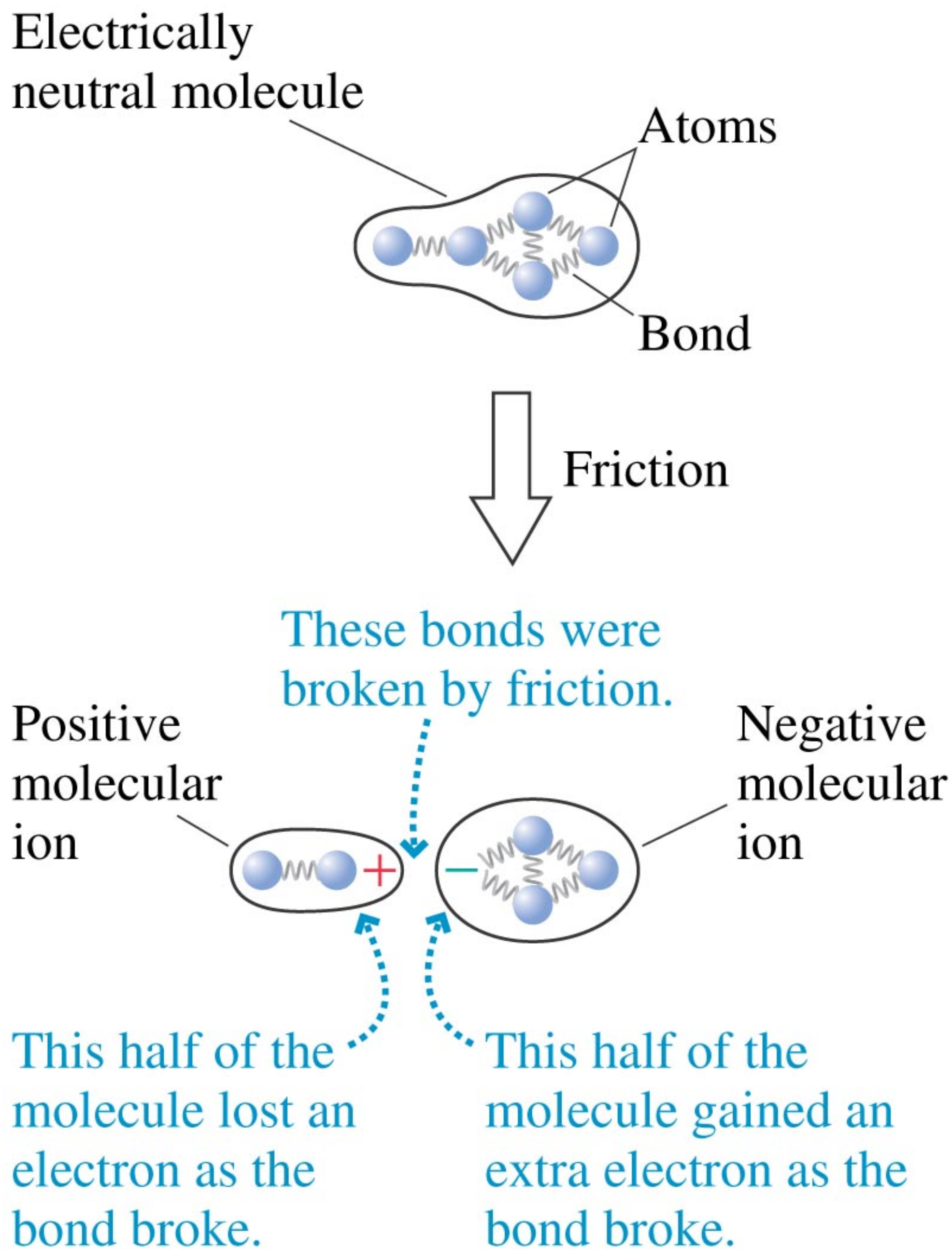
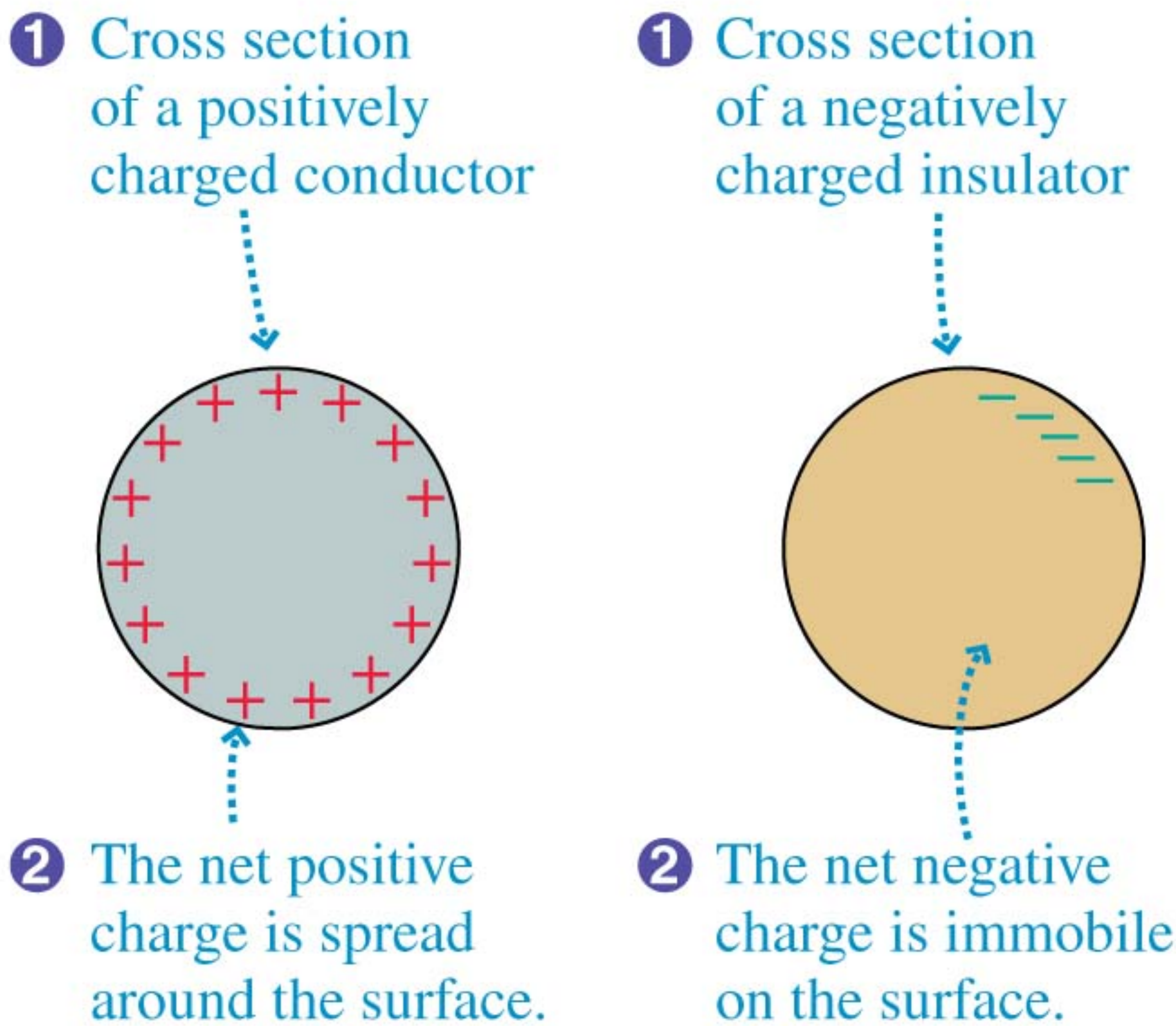

Electrically neutral molecule
Atoms
Bond
Friction
These bonds were broken by friction.
Positive molecular ion
Negative molecular ion
+
−
This half of the molecule lost an electron as the bond broke.
This half of the molecule gained an extra electron as the bond broke.

FIGURE 26.4 Charge diagrams.



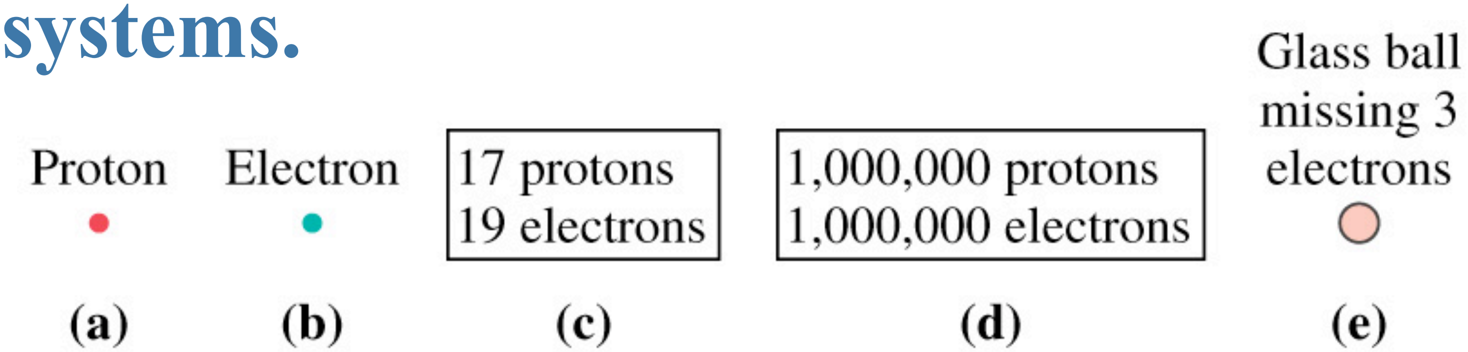
Tactics: Drawing charge diagrams

TACTICS BOX 26.1 **Drawing charge diagrams**

1. Draw a simplified two-dimensional cross section of the object.
2. Draw *surface* charges *very close* to the object's boundary.
3. Draw *interior* charges uniformly within the interior of the object.
4. Show only the *net* charge. A neutral object should show *no* charges, not a lot of plusses and minuses.
5. Conserve charge from one diagram to the next if you use a series of diagrams to explain a process.

Exercises 10–13

Rank in order, from most positive to most negative, the charges q_a to q_e of these five systems.



A. $q_a = q_b > q_e > q_c > q_d$

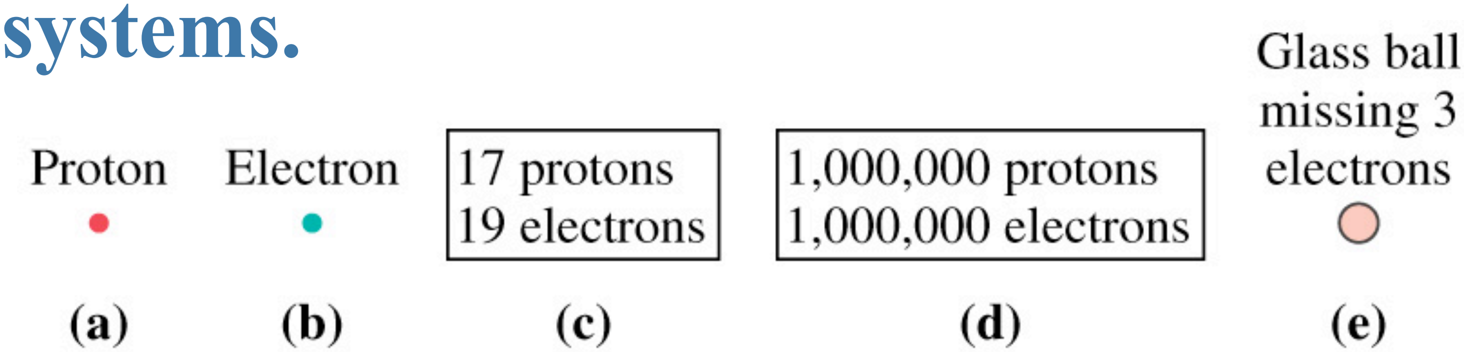
B. $q_a > q_e > q_d > q_c > q_b$

C. $q_e > q_a > q_d > q_b > q_c$

D. $q_d > q_c > q_e > q_a = q_b$

E. $q_d > q_c > q_e > q_a > q_b$

Rank in order, from most positive to most negative, the charges q_a to q_e of these five systems.



A. $q_a = q_b > q_e > q_c > q_d$

B. $q_a > q_e > q_d > q_c > q_b$

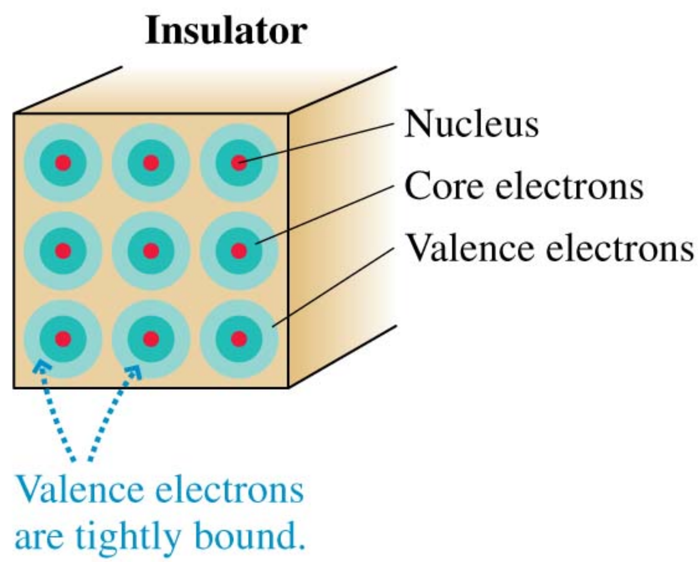
C. $\mathbf{q_e > q_a > q_d > q_b > q_c}$

D. $q_d > q_c > q_e > q_a = q_b$

E. $q_d > q_c > q_e > q_a > q_b$

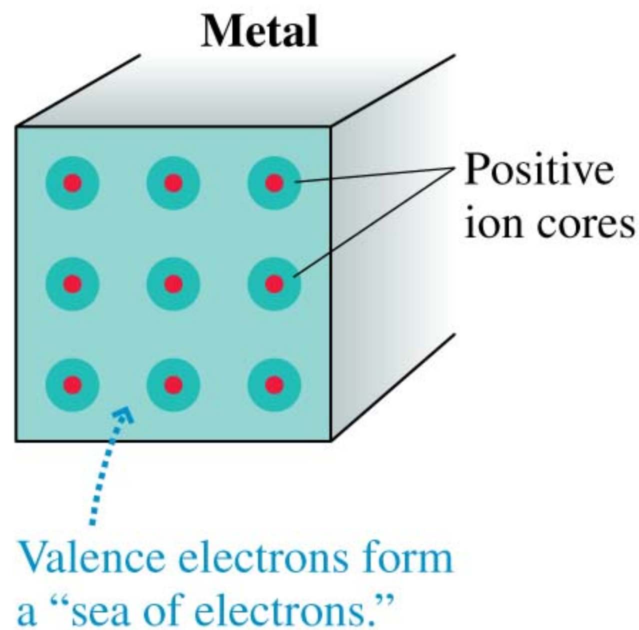
Insulators

- The electrons in the insulator are all tightly bound to the positive nuclei and not free to move around.
- Charging an insulator by friction leaves patches of molecular ions on the surface, but these patches are immobile.



Conductors

- In metals, the outer atomic electrons are only weakly bound to the nuclei.
- These outer electrons become detached from their parent nuclei and are free to wander about through the entire solid.
- The solid *as a whole* remains electrically neutral, but the electrons are now like a negatively charged liquid permeating an array of positively charged **ion cores.**



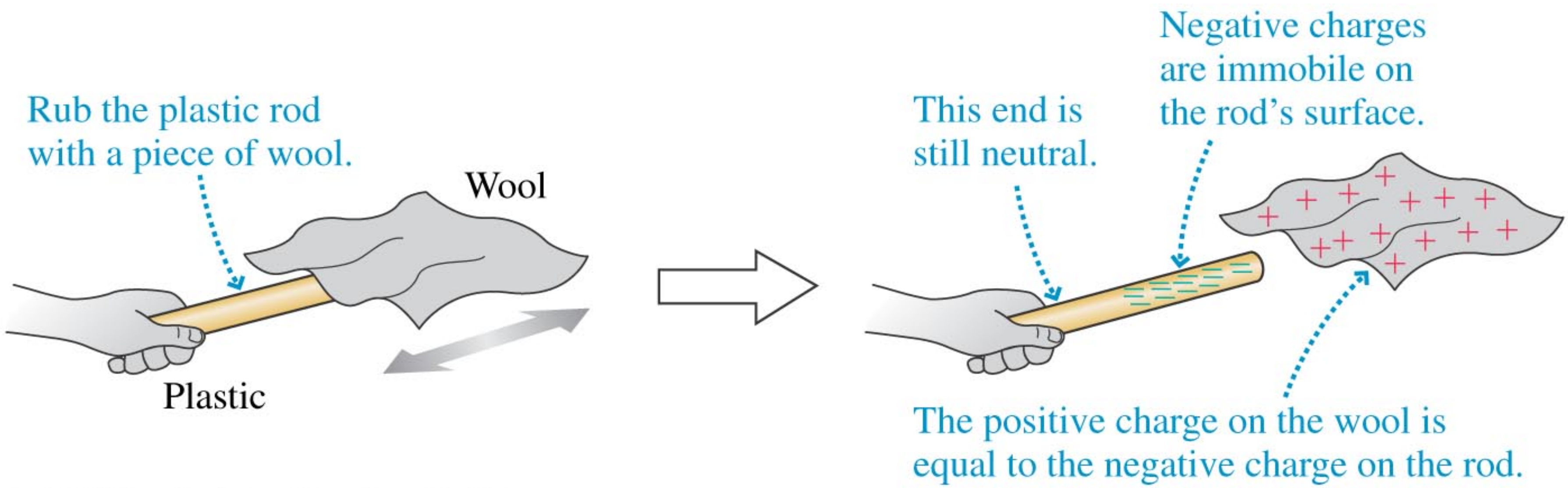

Rub the plastic rod
with a piece of wool.
Wool
Plastic
This end is
still neutral.
Negative charges
are immobile on
the rod's surface.
The positive charge on the wool is
equal to the negative charge on the rod.

FIGURE 26.7 A conductor is charged by contact with a charged plastic rod.

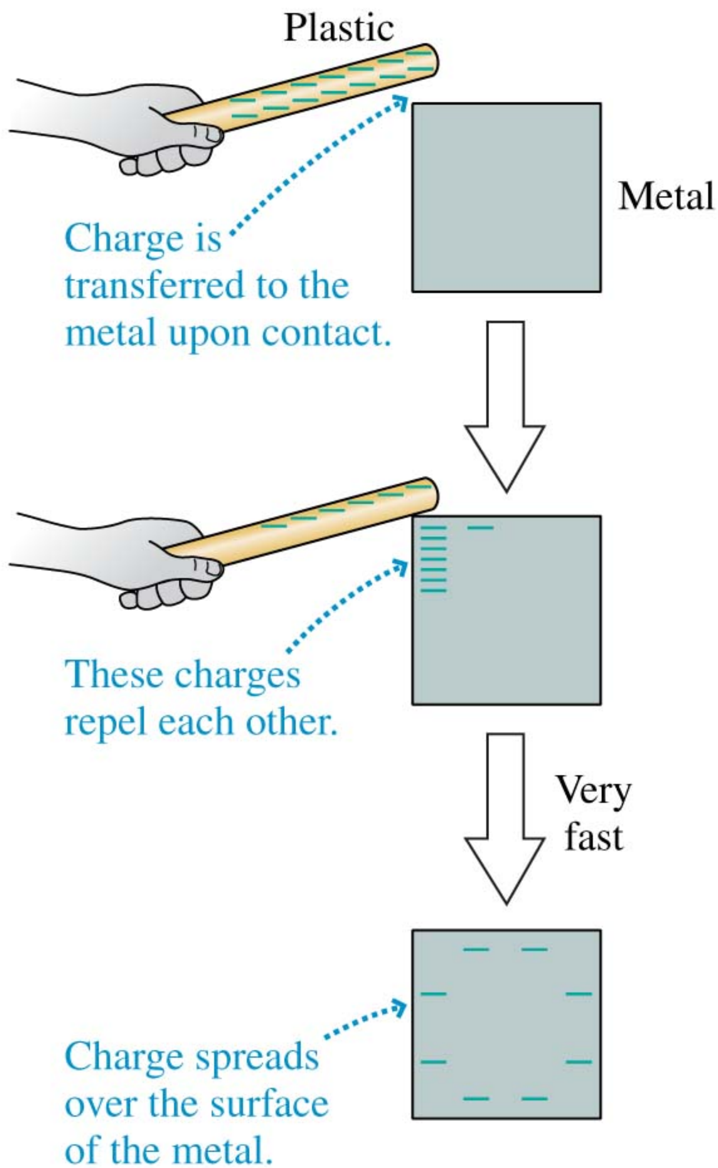
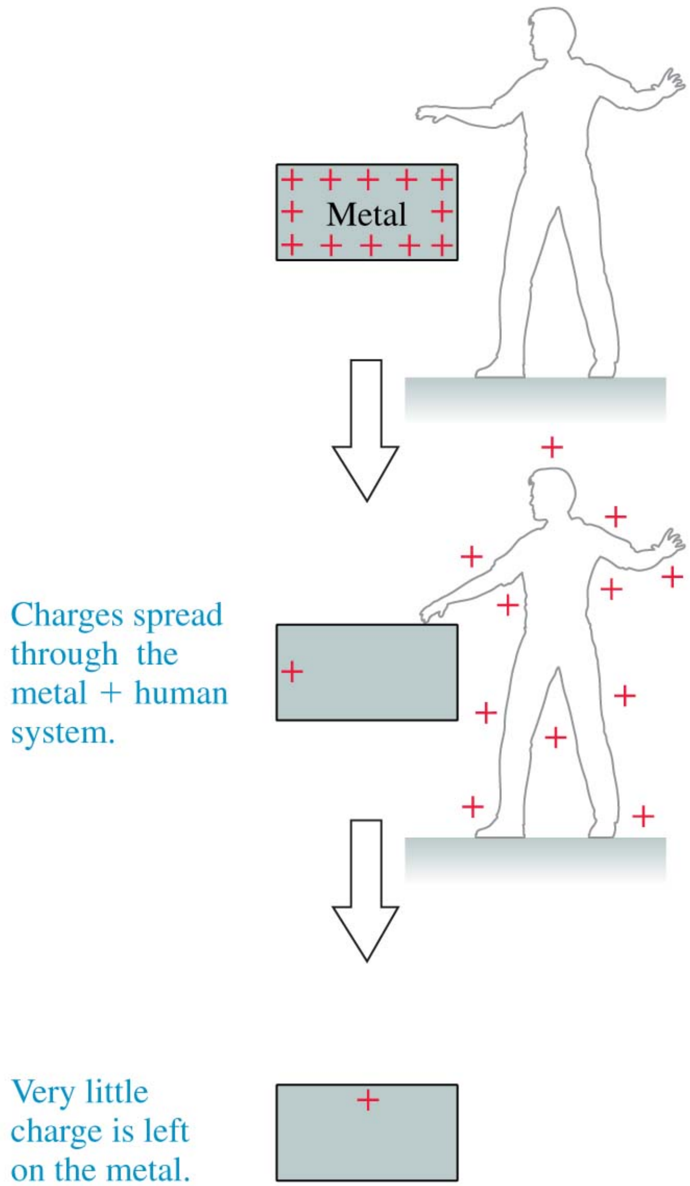


FIGURE 26.10 Touching a charged metal discharges it.



Charge Polarization

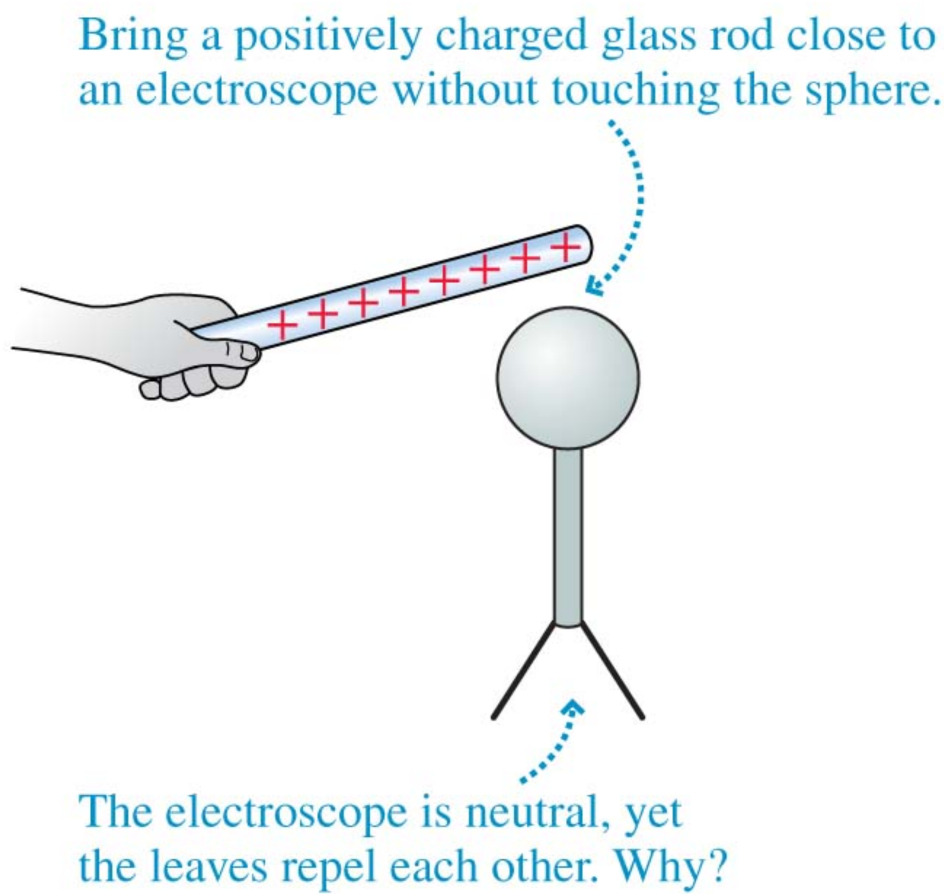
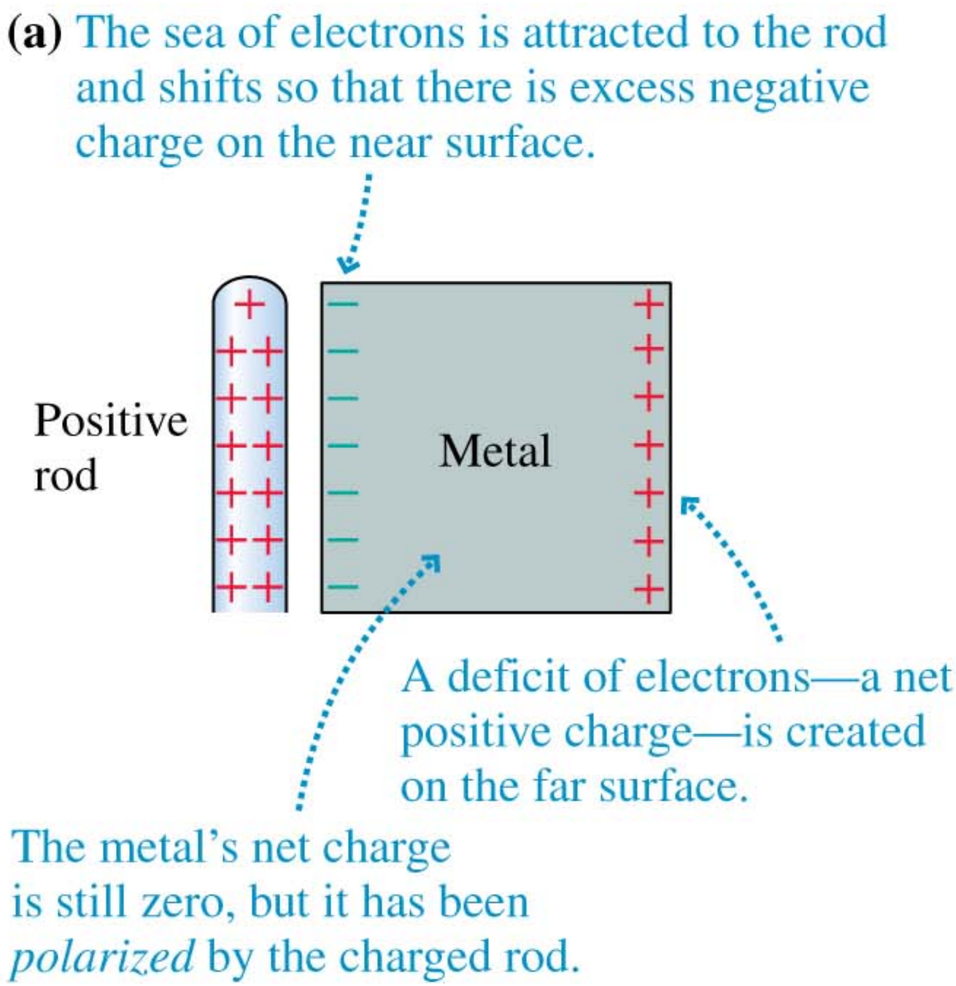


FIGURE 26.11 A charged rod held close to an electroscope causes the leaves to repel each other.

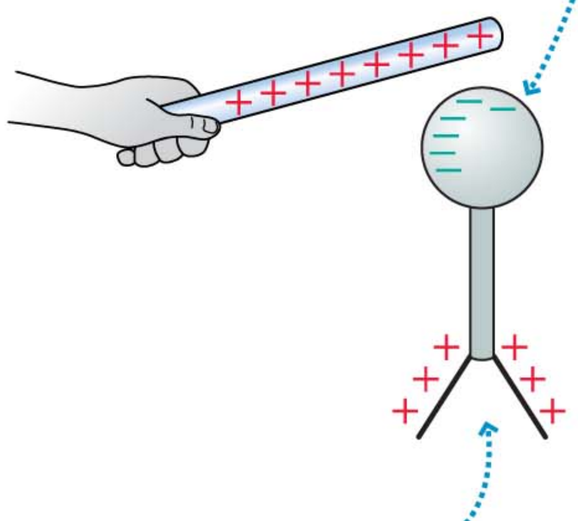
Charge Polarization

FIGURE 26.12 A charged rod polarizes a metal.



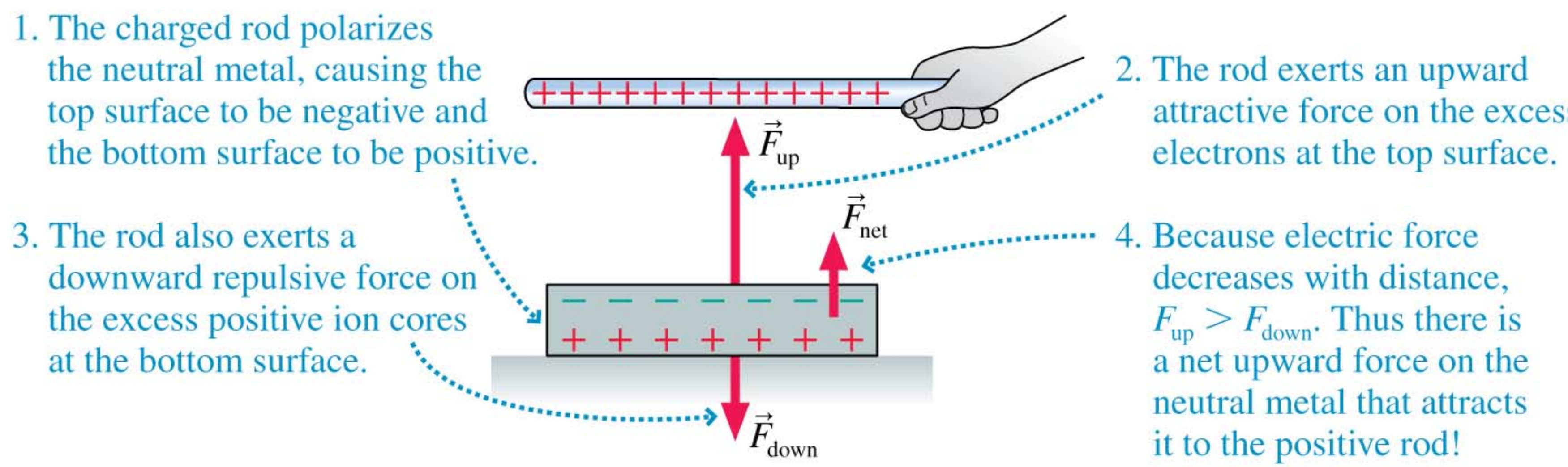
Charge Polarization

FIGURE 26.12 A charged rod polarizes a metal.



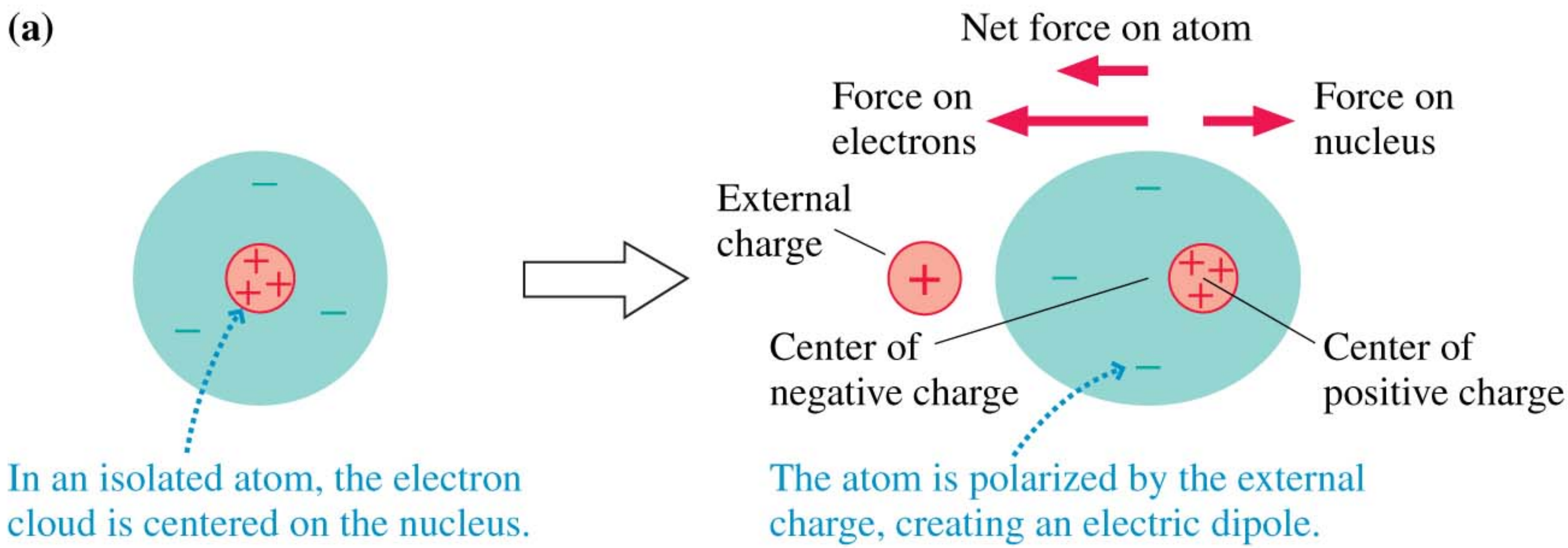
Polarization Force

FIGURE 26.13 The polarization force on a neutral piece of metal is due to the slight charge separation.



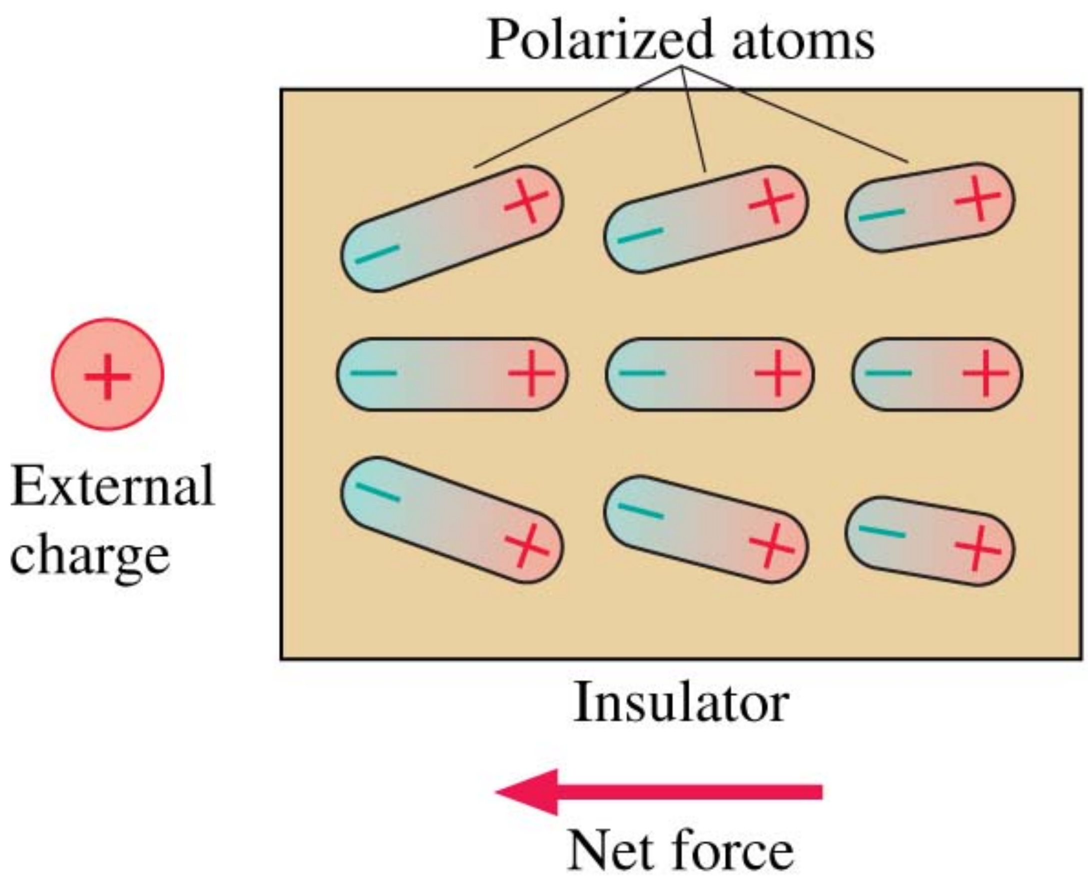
The Electric Dipole

FIGURE 26.14 A neutral atom is polarized by an external charge, forming an *electric dipole.*



The Electric Dipole

FIGURE 26.15 The atoms in an insulator are polarized by an external charge.



An electroscope is positively charged by *touching* it with a positive glass rod. The electroscope leaves spread apart and the glass rod is removed. Then a negatively charged plastic rod is brought close to the top of the electroscope, but it doesn't touch. What happens to the leaves?

A. The leaves get closer together.
B. The leaves spread further apart.
C. The leaves don't move.
D. One leaf moves higher, the other lower.

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✔ **A. The leaves get closer together.**
B. The leaves spread further apart.
C. The leaves don't move.
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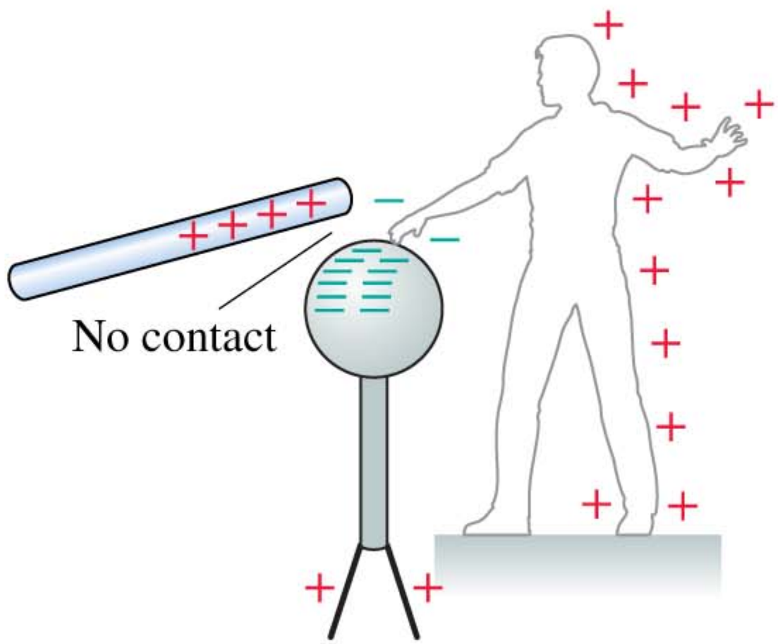
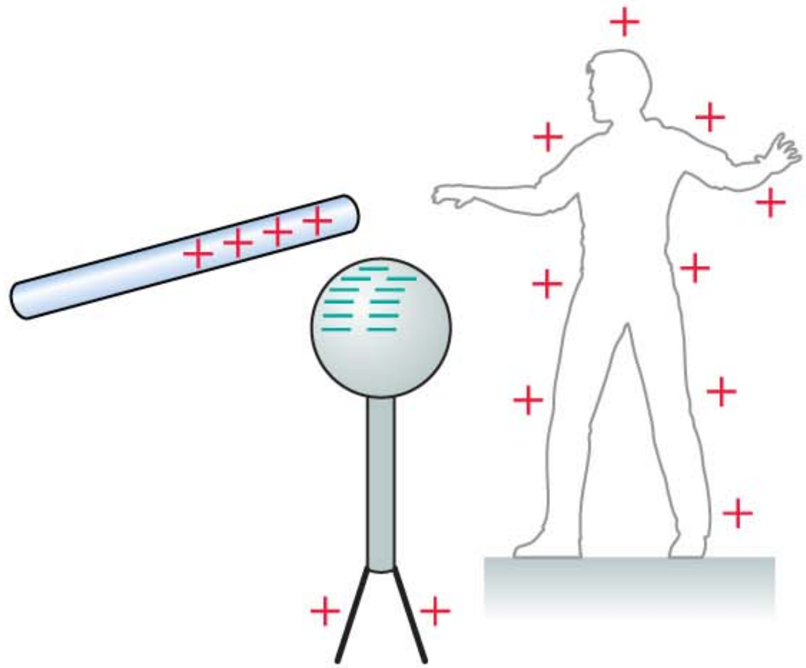
Charging by Induction, Step 1



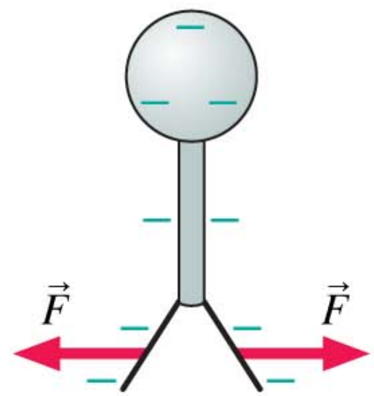
1. The charged rod polarizes the electroscope + person conductor. The leaves repel slightly due to polarization, but overall the electrosc has an excess of electrons and the pe has a deficit of electrons.

Charging by Induction, Step 2



2. The negative charge on the electroscope is isolated when contact is broken.

Charging by Induction, Step 3



3. When the rod is removed, the leaves first collapse as the polarization vanishes, then repel as the excess negative charge spreads out. The electroscope has been *negatively* charged.

Coulomb's law:

1. If two charged particles having charges q_1 and q_2 are a distance r apart, the particles exert forces on each other of magnitude

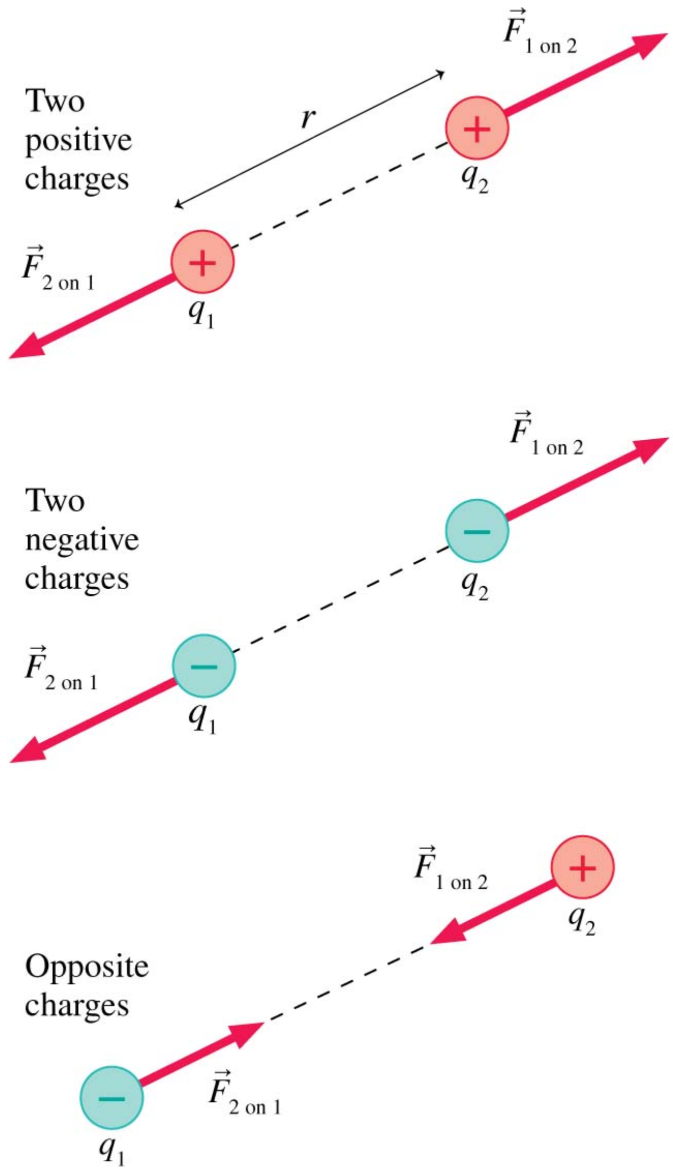
$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2} \qquad (26.2)$$

where K is called the **electrostatic constant.** These forces are an action/reaction pair, equal in magnitude and opposite in direction.

2. The forces are directed along the line joining the two particles. The forces are *repulsive* for two like charges and *attractive* for two opposite charges.

In SI units $K = 8.99 \times 10^9$ N m^2/C^2.

FIGURE 26.17 Attractive and repulsive forces between charges.



- Coulomb’s law is a force law

- Coulomb’s law applies only to point charges

- Strictly speaking - Coulomb’s law applies only to electrostatics. Good approximation if relative speed between charges is less then the speed of light

- Electric Forces can be superimposed
  – If multiple charges 1,2,3,… present the net force on charge j due to all other charges is

$$\vec{F}_{net} = \vec{F}_{1j} + \vec{F}_{2j} + \vec{F}_{3j} + \ldots$$

PROBLEM-SOLVING STRATEGY 26.1 Electrostatic forces and Coulomb's law

MP

MODEL Identify point charges or objects that can be modeled as point charges.

VISUALIZE Use a *pictorial representation* to establish a coordinate system, show the positions of the charges, show the force vectors on the charges, define distances and angles, and identify what the problem is trying to find. This is the process of translating words to symbols.

SOLVE The mathematical representation is based on Coulomb's law:

$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$

- Show the directions of the forces—repulsive for like charges, attractive for opposite charges—on the pictorial representation.
- When possible, do graphical vector addition on the pictorial representation. While not exact, it tells you the type of answer you should expect.
- Write each force vector in terms of its x- and y-components, then add the components to find the net force. Use the pictorial representation to determine which components are positive and which are negative.

ASSESS Check that your result has the correct units, is reasonable, and answers the question.

The sum of two forces

- Two +10 nC charged particles are 2.0 cm apart on the x-axis. What is the net force on a +1 nC charge midway between them? What is the net force if the charged particle on the right is replaced by a -10 nC charge

The sum of two forces

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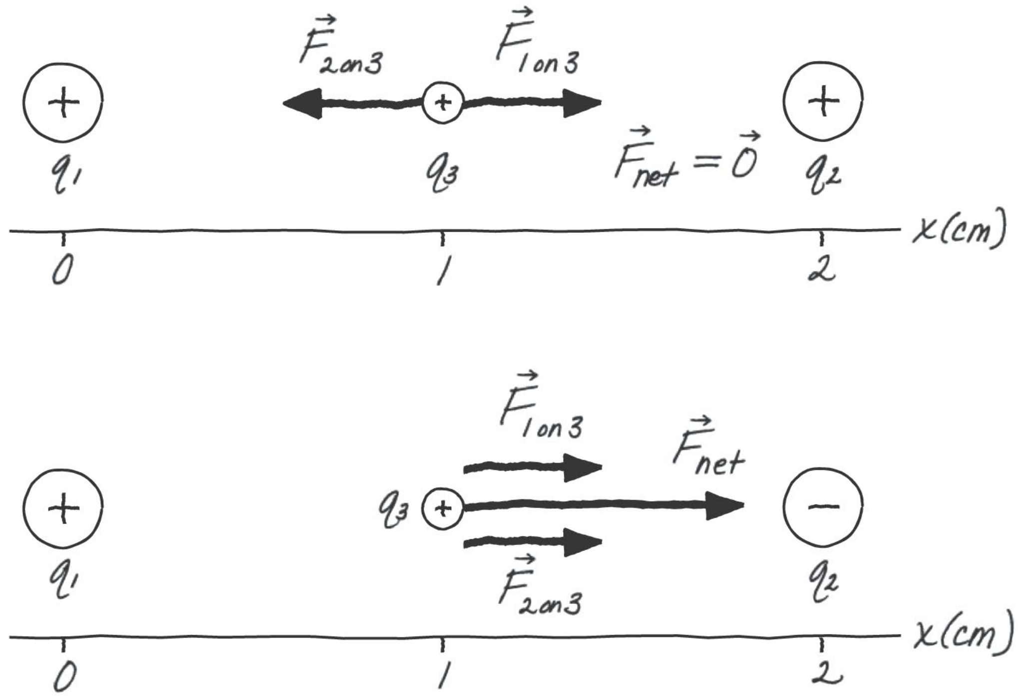

The point of zero force

- Two positively charged particles q_1 and $q_2=3q_1$ are 10.0 cm apart. Where could a third charge q_3 be placed so as to experience no net force?

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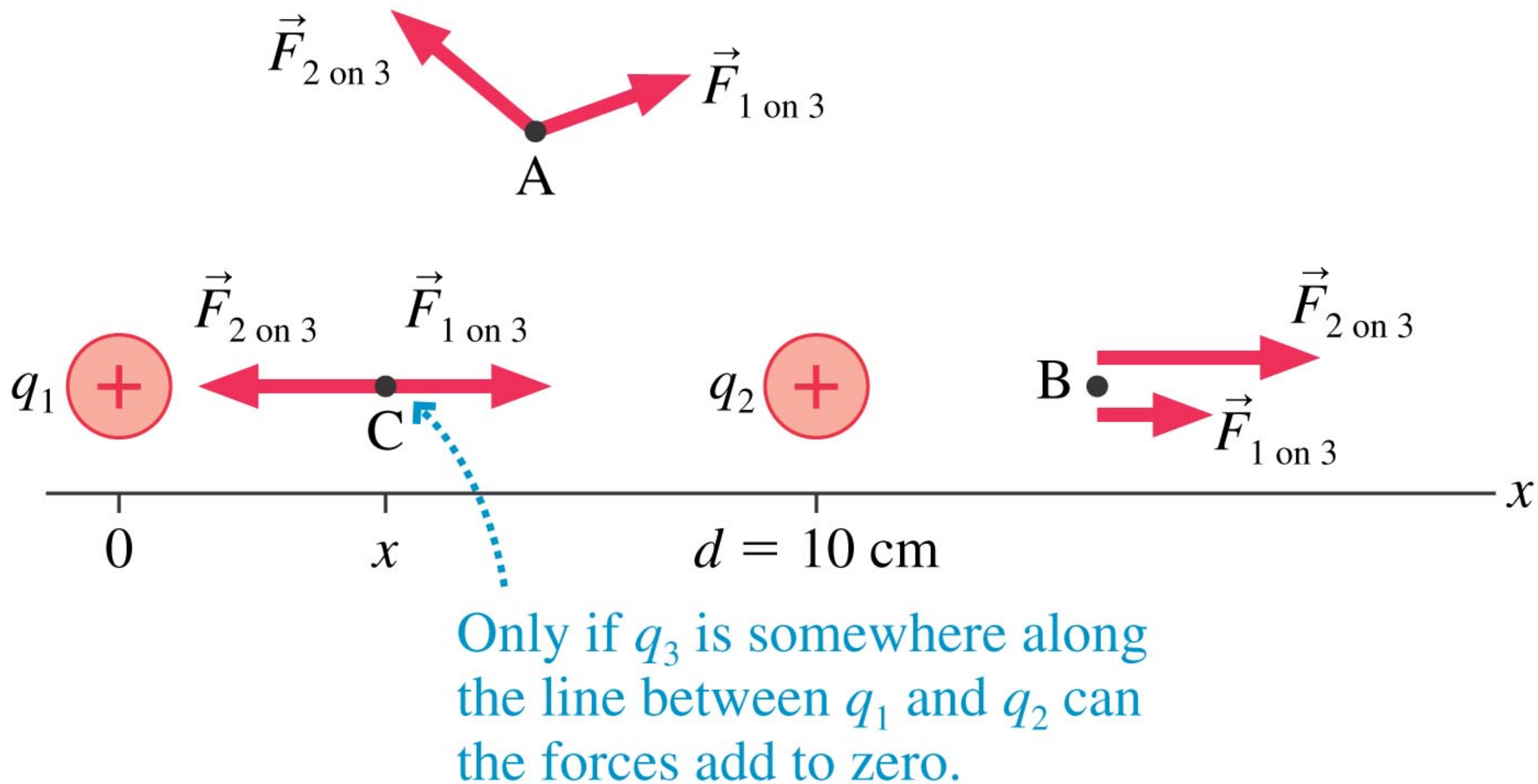

Three Charges

- Three charged particle with q_1 = -50 nC, q_2 = +50 nc and q_3 = 30 nC are placed on the corners of a 5.0 cm by 10.0 cm rectangle as shown. What is the net force on charge q_3?

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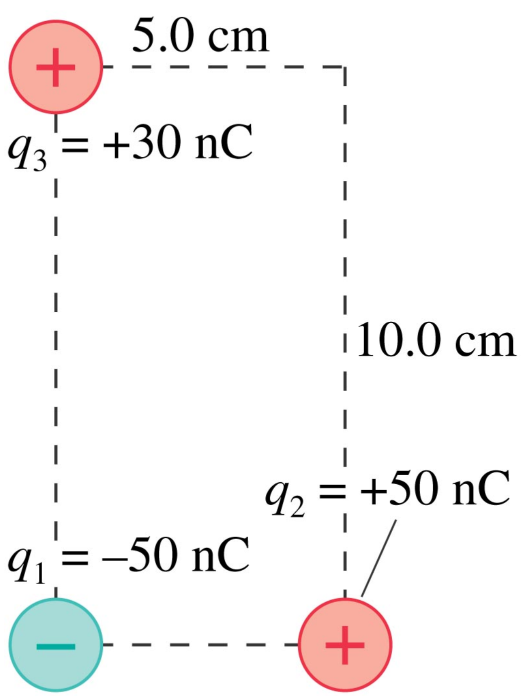

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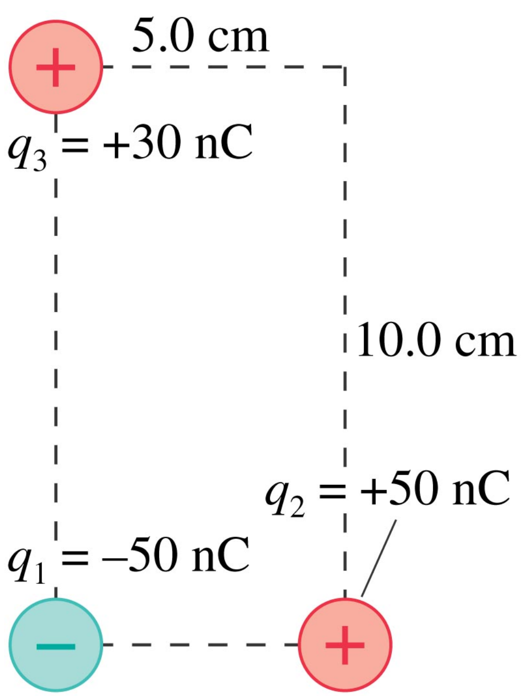
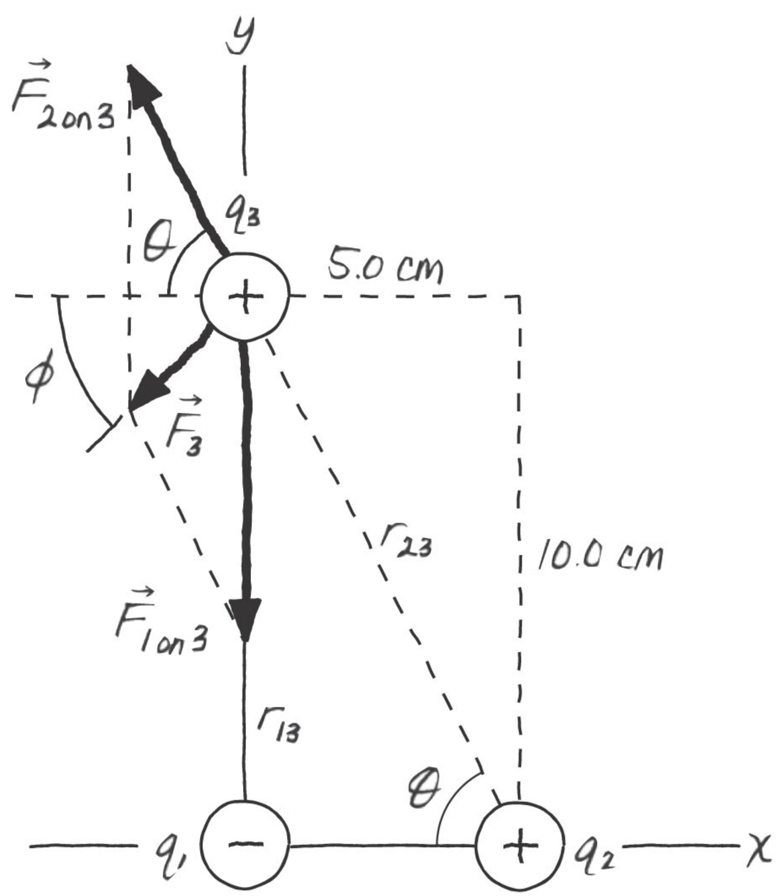




EXAMPLE 26.6 Lifting a glass bead

QUESTION:

EXAMPLE 26.6 Lifting a glass bead

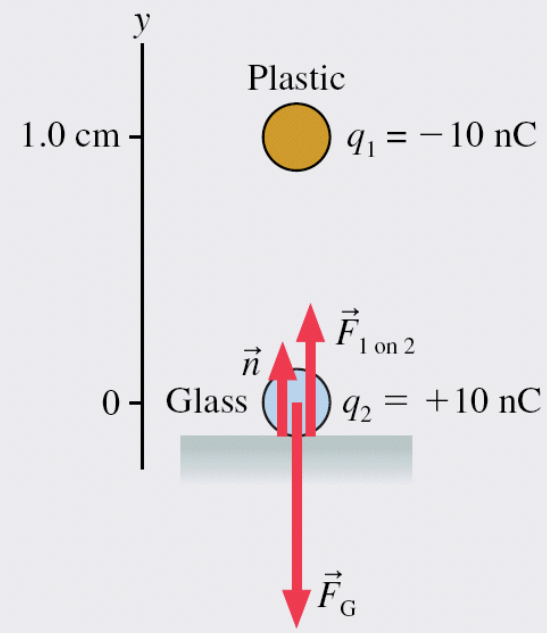
A small plastic sphere charged to −10 nC is held 1.0 cm above a small glass bead at rest on a table. The bead has a mass of 15 mg and a charge of +10 nC. Will the glass bead "leap up" to the plastic sphere?

MODEL Model the plastic sphere and glass bead as point charges.

EXAMPLE 26.6 Lifting a glass bead

VISUALIZE **FIGURE 26.22** establishes a y-axis, identifies the plastic sphere as q_1 and the glass bead as q_2, and shows a free-body diagram.

FIGURE 26.22 A pictorial representation of the charges and forces.



EXAMPLE 26.6 Lifting a glass bead

SOLVE If $F_{1\text{ on }2}$ is less than the gravitational force $F_G = m_{\text{bead}}g$, then the bead will remain at rest on the table with $\vec{F}_{1\text{ on }2} + \vec{F}_G + \vec{n} = \vec{0}$. But if $F_{1\text{ on }2}$ is greater than $m_{\text{bead}}g$, the glass bead will accelerate upward from the table. Using the values provided,

$$F_{1\text{ on }2} = \frac{K|q_1||q_2|}{r^2} = 9.0 \times 10^{-3}\text{ N}$$

$$F_G = m_{\text{bead}}g = 1.5 \times 10^{-4}\text{ N}$$

$F_{1\text{ on }2}$ exceeds $m_{\text{bead}}g$ by a factor of 60, so the glass bead will leap upward.

EXAMPLE 26.6 Lifting a glass bead

ASSESS The values used in this example are realistic for spheres ≈ 2 mm in diameter. In general, as in this example, electric forces are *significantly* larger than gravitational forces. Consequently, we can neglect gravity when working electric-force problems unless the particles are fairly massive.

Charges A and B exert repulsive forces on each other. $q_A = 4q_B$. Which statement is true?

A. $F_{\text{A on B}} > F_{\text{B on A}}$

B. $F_{\text{A on B}} < F_{\text{B on A}}$

C. $F_{\text{A on B}} = F_{\text{B on A}}$

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✔ **C. $F_{\text{A on B}} = F_{\text{B on A}}$**

The Electric Field

We begin our investigation of electric fields by postulating a **field model** that describes how charges interact:

1. Some charges, which we will call the **source charges,** alter the space around them by creating an *electric field.*
2. A separate charge *in* the electric field experiences a force exerted *by the field.*

Suppose probe charge q experiences an electric force $F_{\text{on } q}$ due to other charges.

$$\vec{E}(x, y, z) \equiv \frac{F_{\text{on } q} \text{ at } (x, y, z)}{q}$$

The units of the electric field are N/C. The magnitude E of the electric field is called the **electric field strength.**

The Electric Field of a Point Charge

The electric field at distance *r* from a point charge *q* is

$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}\hat{r} \qquad \text{(electric field of a point charge)}$$

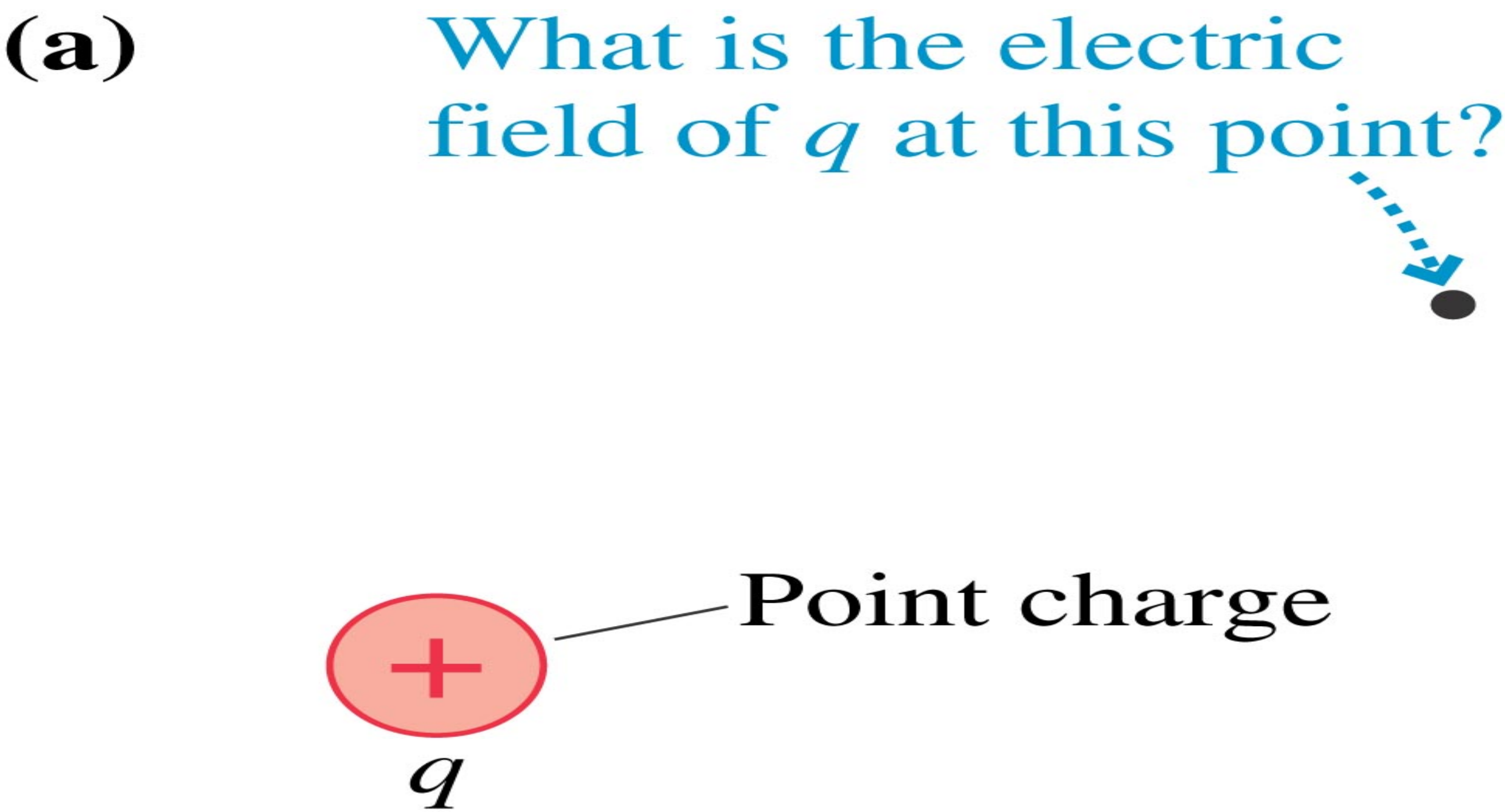
where the unit vector for *r* points away from the charge to the point at which we want to know the field.
This unit vector expresses the idea "away from *q*".

Concept of (Electric) Field

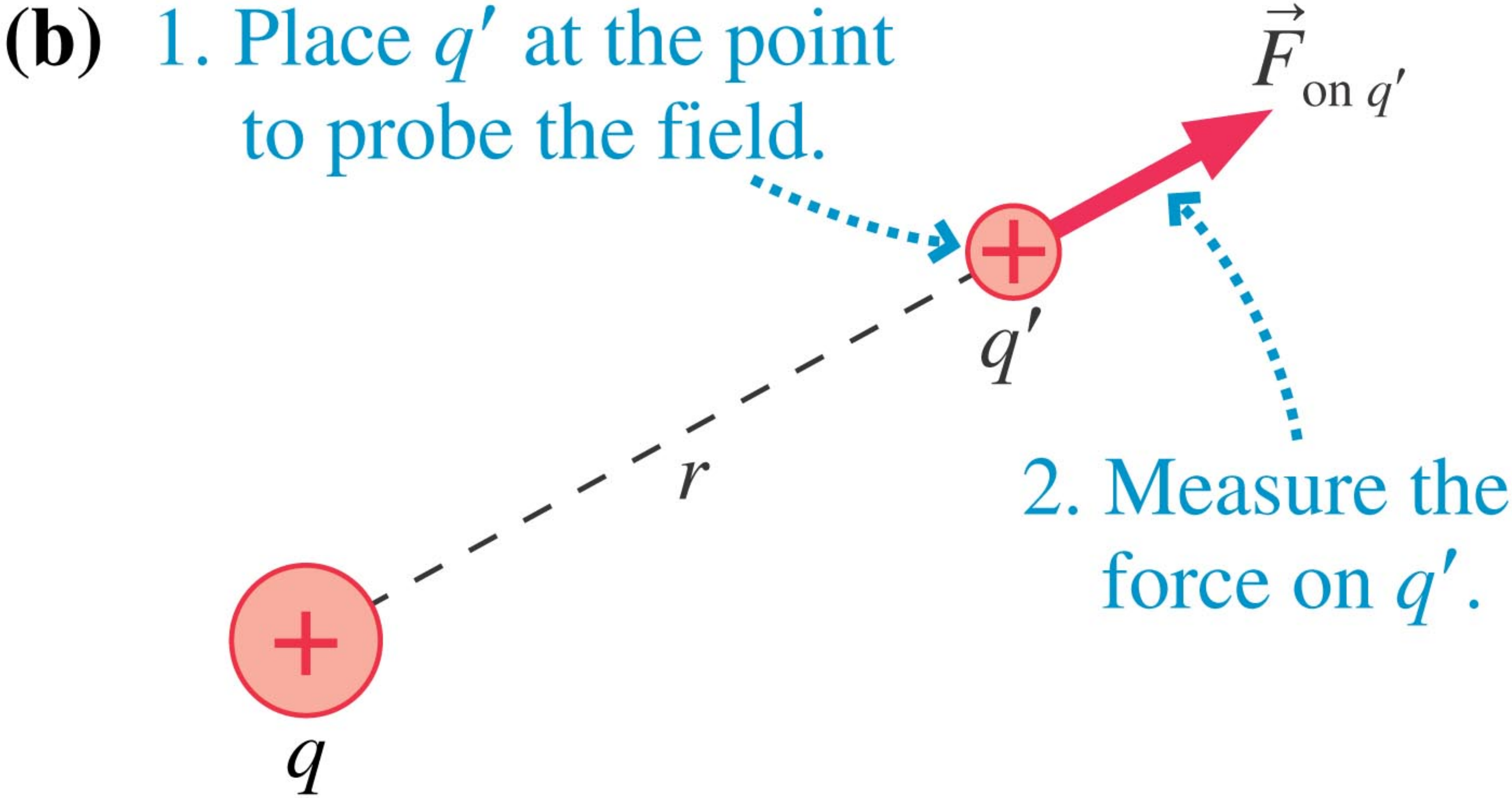
- The electric field concept is introduced as a way to explain how two charges interact without touching.

- There are two aspects to this idea
  - The source charges alter the space around them. This is called the electric field
  - Test charges in the field experience a force from the field

Electric Field (E)



Electric Field (E)



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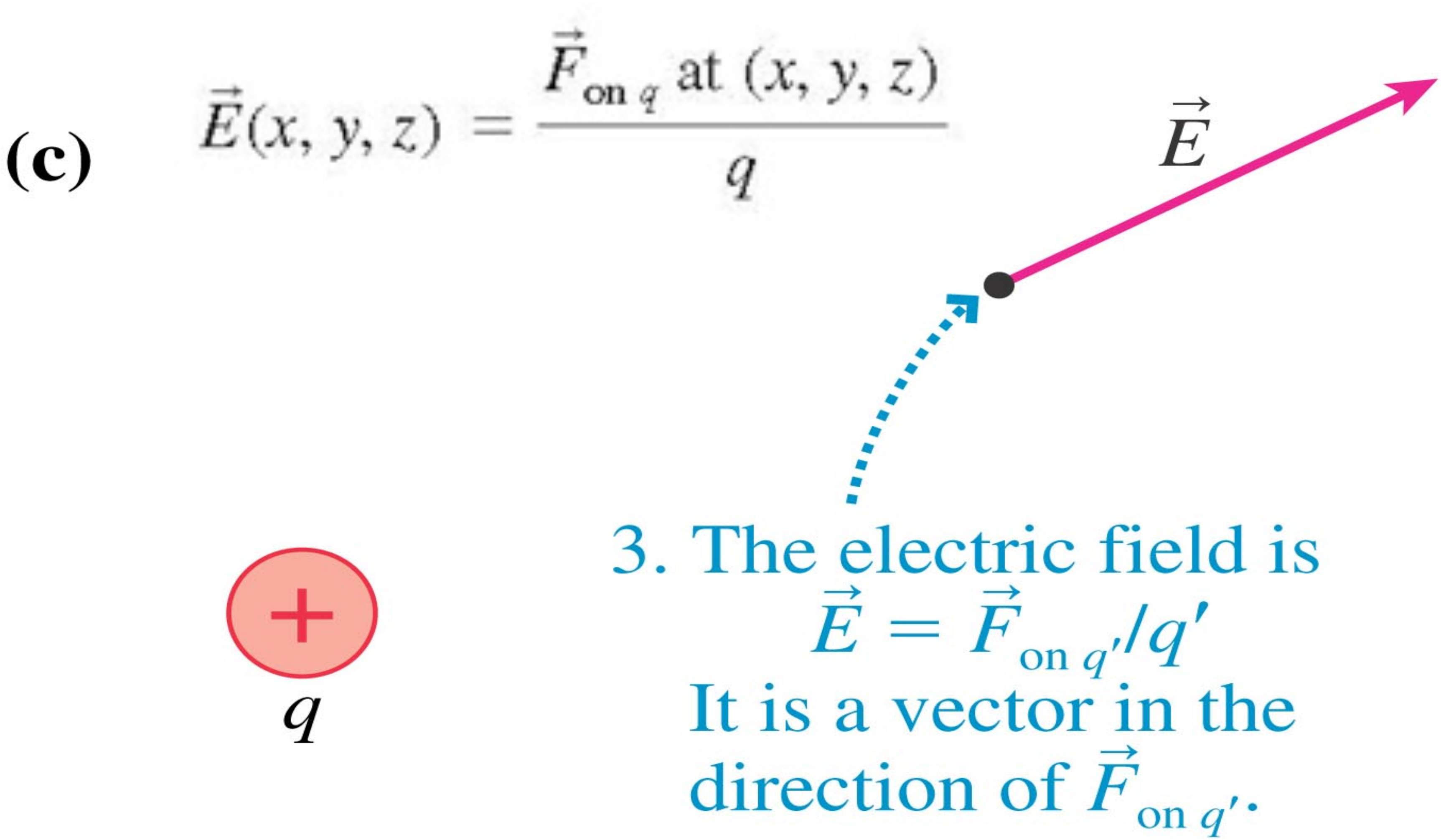
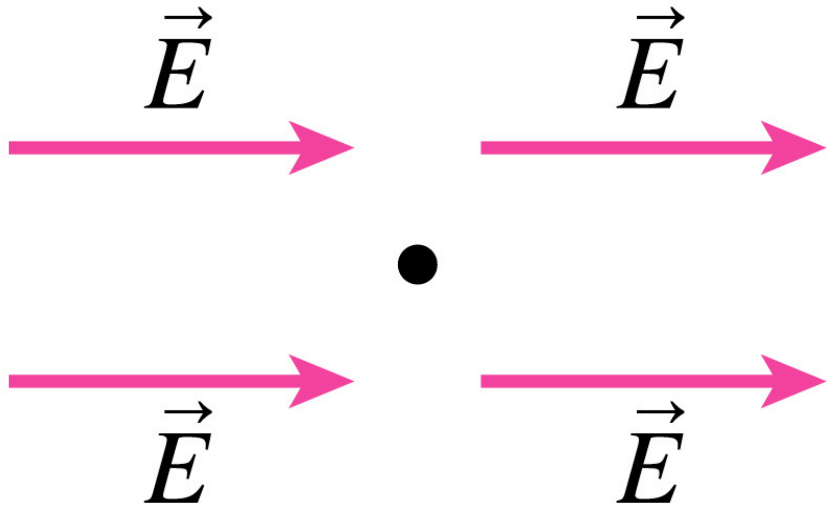


An electron is placed at the position marked by the dot. The force on the electron is



A. to the right.
B. to the left.
C. zero.
D. There's not enough information to tell.

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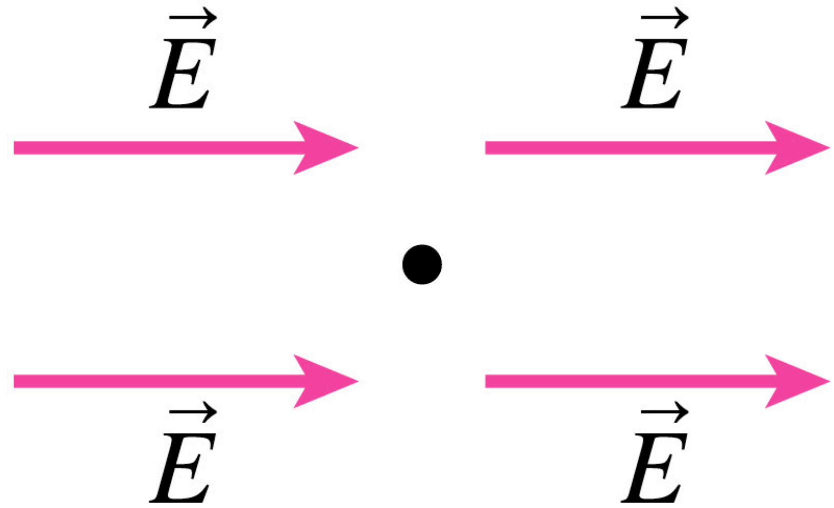


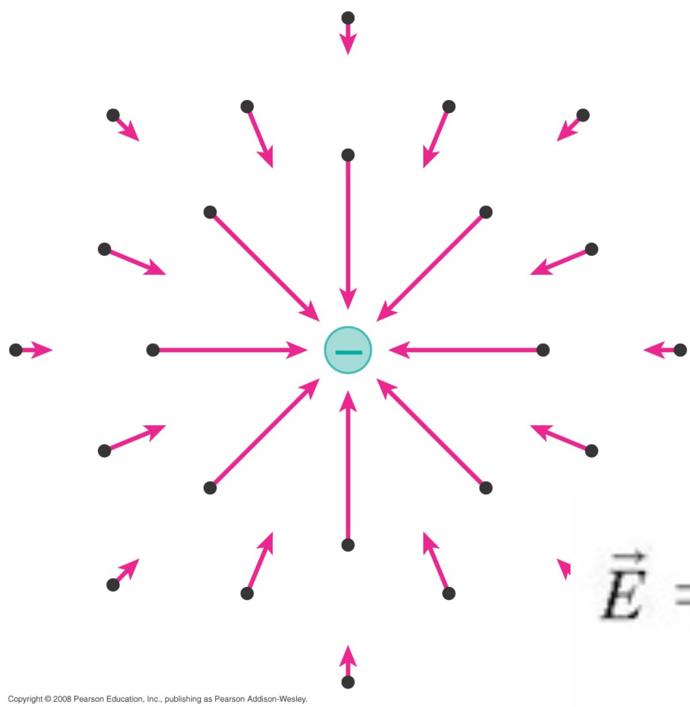
A. to the right.

✔ **B. to the left.**

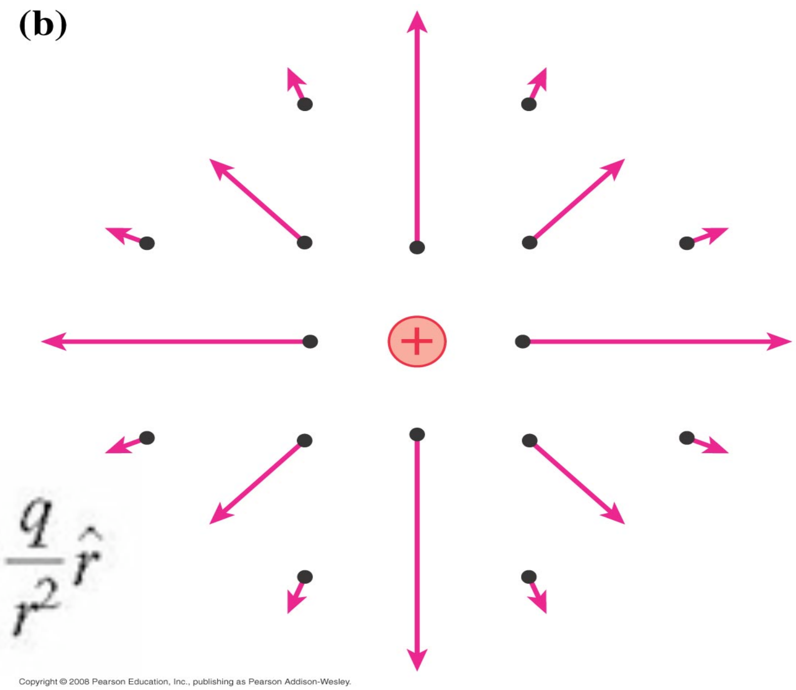
C. zero.

D. There's not enough information to tell.

Electric Field of Negative Point Charge



Electric Field of Positive Point Charge



$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}\hat{r}$$

Important points

- The electric field exists at all points in space (even though the diagrams may only show a few illustrative vectors
- The electric field is present whether the test charge is there or not. The test charge measures the electric field is does not create it
- The field at each point in space is a vector. It causes a test charge to experience a force in a particular direction

Calculating the Electric Field

- A 1.0 nC charged particle is located at the origin. Points 1,2 and 3 have (x,y) coordinates (1 cm, 0 cm), (0 cm, 1cm) and (1 cm, 1cm), respectively. Determine the electric field **E** at these points, then show the vectors on an electric field diagram

Calculating the Electric Field

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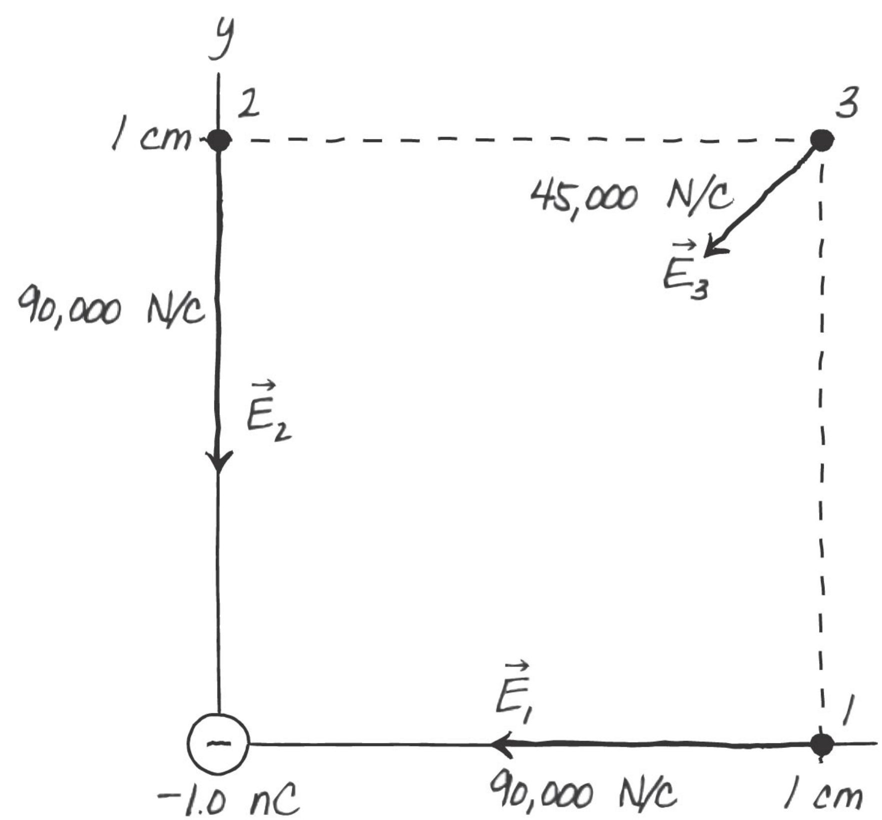


EXAMPLE 26.8 The electric field of a proton

QUESTIONS:

EXAMPLE 26.8 The electric field of a proton

The electron in a hydrogen atom orbits the proton at a radius of 0.053 nm.

a. What is the proton's electric field strength at the position of the electron?
b. What is the magnitude of the electric force on the electron?

EXAMPLE 26.8 The electric field of a proton

SOLVE a. The proton's charge is $q = e$. Its electric field strength at the distance of the electron is

$$E = \frac{1}{4\pi\epsilon_0}\frac{e}{r^2} = \frac{1}{4\pi\epsilon_0}\frac{1.6 \times 10^{-19}\ \text{C}}{(5.3 \times 10^{-11}\ \text{m})^2}$$

$$= 5.1 \times 10^{11}\ \text{N/C}$$

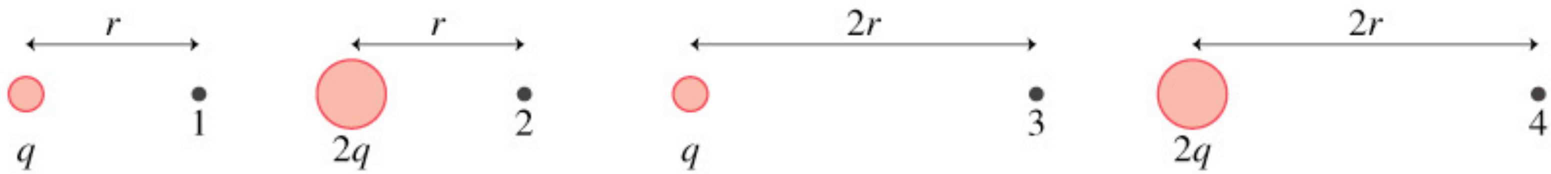
Notice how large this field is in comparison to the field of Example 26.7.

EXAMPLE 26.8 The electric field of a proton

b. We could use Coulomb's law to find the force on the electron, but the whole point of knowing the electric field is that we can use it directly to find the force on a charge in the field. The magnitude of the force on the electron is

$$
\begin{aligned}
F_{\text{on elec}} &= |q_e| E_{\text{of proton}} \\
&= (1.60 \times 10^{-19}\ \text{C})(5.1 \times 10^{11}\ \text{N/C}) \\
&= 8.2 \times 10^{-8}\ \text{N}
\end{aligned}
$$

Rank in order, from largest to smallest, the electric field strengths E_1 to E_4 at points 1 to 4.



A. $E_2 > E_4 > E_1 > E_3$
B. $E_1 = E_2 > E_3 = E_4$
C. $E_2 > E_1 = E_4 > E_3$
D. $E_2 > E_1 > E_4 > E_3$
E. $E_1 > E_2 > E_3 > E_4$

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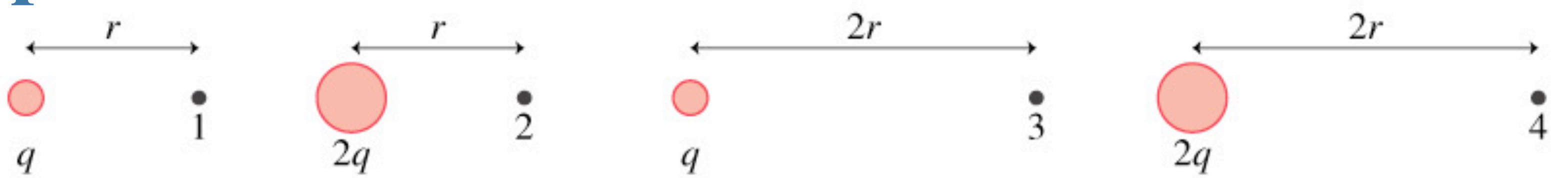


A. $E_2 > E_4 > E_1 > E_3$

B. $E_1 = E_2 > E_3 = E_4$

C. $E_2 > E_1 = E_4 > E_3$

✔ **D. $E_2 > E_1 > E_4 > E_3$**

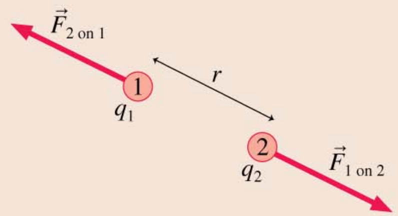
E. $E_1 > E_2 > E_3 > E_4$

General Principles

Coulomb's Law

The forces between two charged particles q_1 and q_2 separated by distance r are

$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$



These forces are an action/reaction pair directed along the line joining the particles.

- The forces are repulsive for two like charges, attractive for two opposite charges.
- The net force on a charge is the sum of the forces from all other charges.
- The unit of charge is the coulomb (C).
- The electrostatic constant is $K = 9.0 \times 10^9\ \text{N m}^2/\text{C}^2$.

Important Concepts

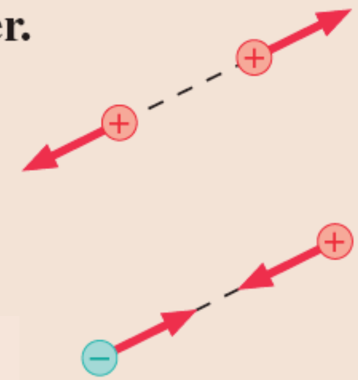
The Charge Model

There are two kinds of charge, positive and negative.

- Fundamental charges are protons and electrons, with charge $\pm e$ where $e = 1.60 \times 10^{-19}$ C.
- Objects are charged by adding or removing electrons.
- The amount of charge is $q = (N_p - N_e)e$.
- An object with an equal number of protons and electrons is **neutral,** meaning no *net* charge.

Charged objects exert electric forces on each other.

- Like charges repel, opposite charges attract.
- The force increases as the charge increases.
- The force decreases as the distance increases.



Important Concepts

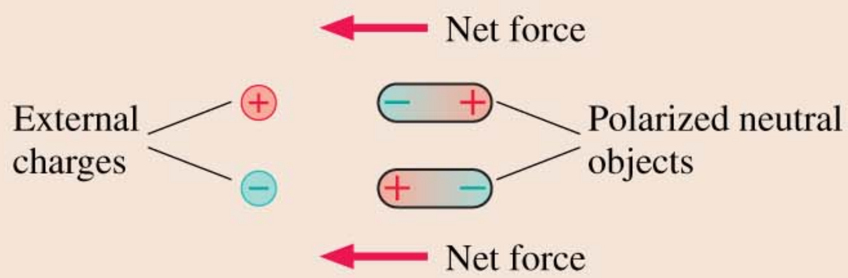
The Charge Model

There are two types of material, insulators and conductors.

- Charge remains fixed in or on an insulator.
- Charge moves easily through or along conductors.
- Charge is transferred by contact between objects.

Charged objects attract neutral objects.

- Charge polarizes metal by shifting the electron sea.
- Charge polarizes atoms, creating electric dipoles.
- The polarization force is always an attractive force.

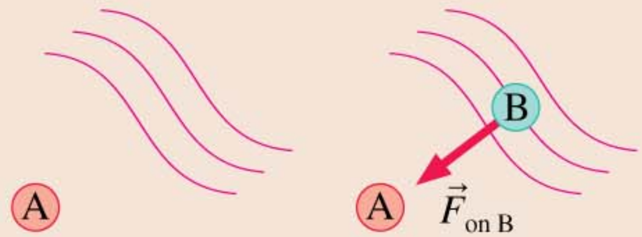


Important Concepts

The Field Model

Charges interact with each other via the electric field $\vec{E}$.

- Charge A alters the space around it by creating an electric field.



- The field is the agent that exerts a force. The force on charge q_B is $\vec{F}_{\text{on B}} = q_B\vec{E}$.

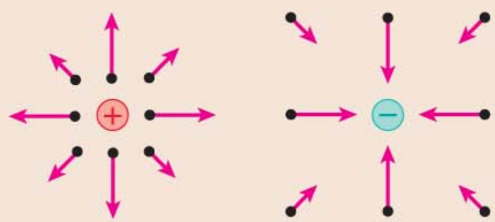
An electric field is identified and measured in terms of the force on a **probe charge** q:

$$\vec{E} = \vec{F}_{\text{on } q}/q$$

Important Concepts

The Field Model

- The electric field exists at all points in space.
- An electric field vector shows the field only at one point, the point at the tail of the vector.



The electric field of a **point charge** is

$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}\hat{r}$$