高二物理

1 電荷與電場

PowerPoint® Lectures for
University Physics, Thirteenth Edition
– Hugh D. Young and Roger A. Freedman

Lectures by Wayne Anderson *Revised by Sylveen H. Huang*

ELECTROMAGNETISM

21. Electric Charge and Electric Field

22. Gauss's Law

23. Electric Potential

24. Capacitance and Dielectrics

25. Current, Resistance, and Electromotive Force

26. Direct-Current Circuits

27. Magnetic Field and Magnetic Forces

ELECTROMAGNETISM

27. Magnetic Field and Magnetic Forces

28. Sources of Magnetic Field

29. Electromagnetic Induction

30. Inductance

31. Alternating Current

32. Electromagnetic Waves

OPTICS

33. The Nature and Propagation of Light

34. Geometric Optics and Optical Instruments

35. Interference

36. Diffraction

MODERN PHYSICS

37. Relativity
38. Photons: Light Waves Behaving as Particles
39. Particles Behaving as Waves
40. Quantum Mechanics
41. Atomic Structure
42. Molecules and Condensed Matter
43. Nuclear Physics
44. Particle Physics and Cosmology

Chapter 21

Electric Charge and Electric Field

PowerPoint® Lectures for
University Physics, Thirteenth Edition
– Hugh D. Young and Roger A. Freedman

Lectures by Wayne Anderson

Goals for Chapter 21

- To study electric charge and charge conservation
- To see how objects become charged
- To calculate the electric force between objects using Coulomb's law
- To learn the distinction between electric force and electric field
- To calculate the electric field due to many charges
- To visualize and interpret electric fields
- To calculate the properties of electric dipoles

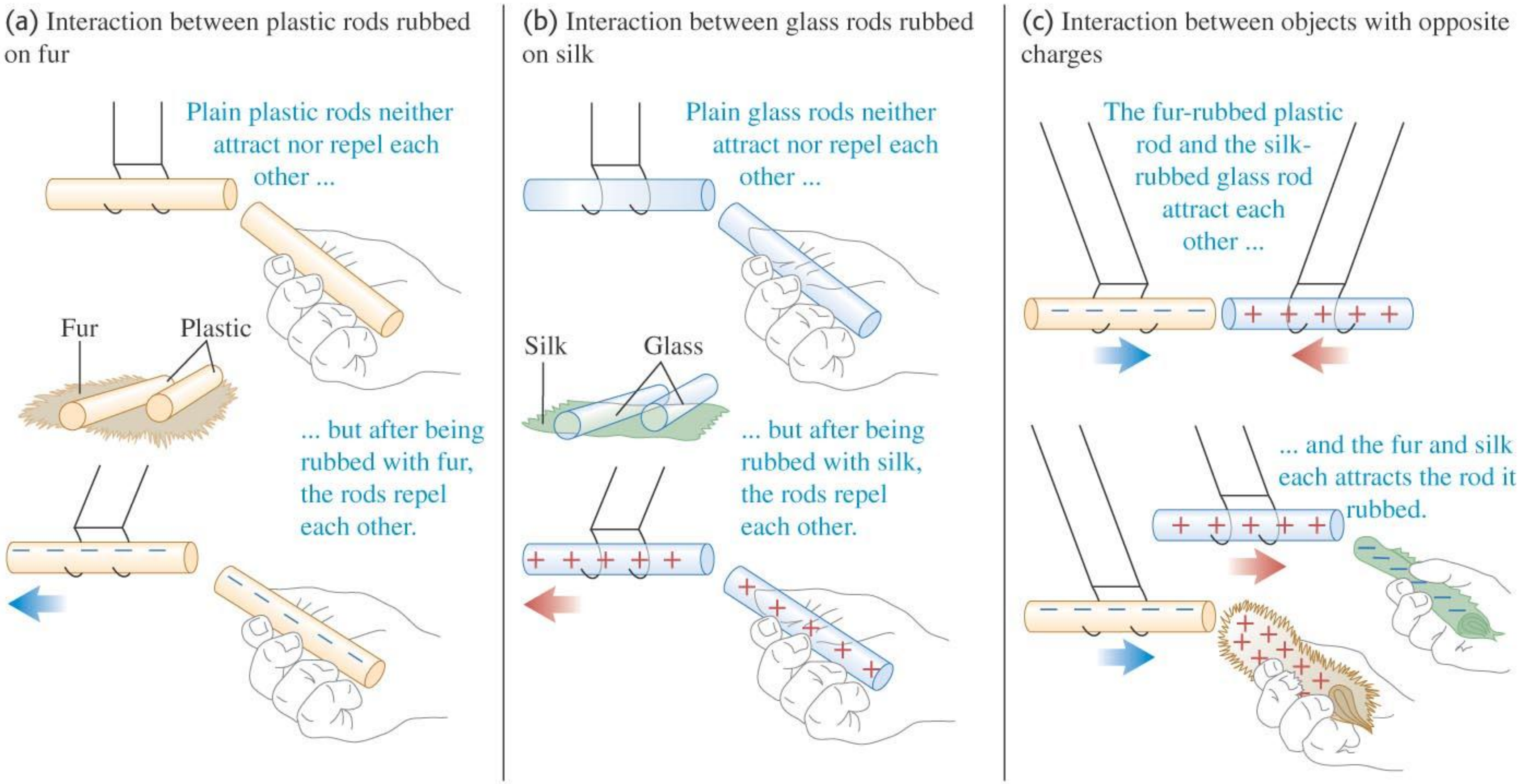
Introduction

- Water makes life possible as a solvent for biological molecules. What electrical properties allow it to do this?

- We now begin our study of *electromagnetism*, one of the four fundamental forces.
- We start with electric charge and look at electric fields.

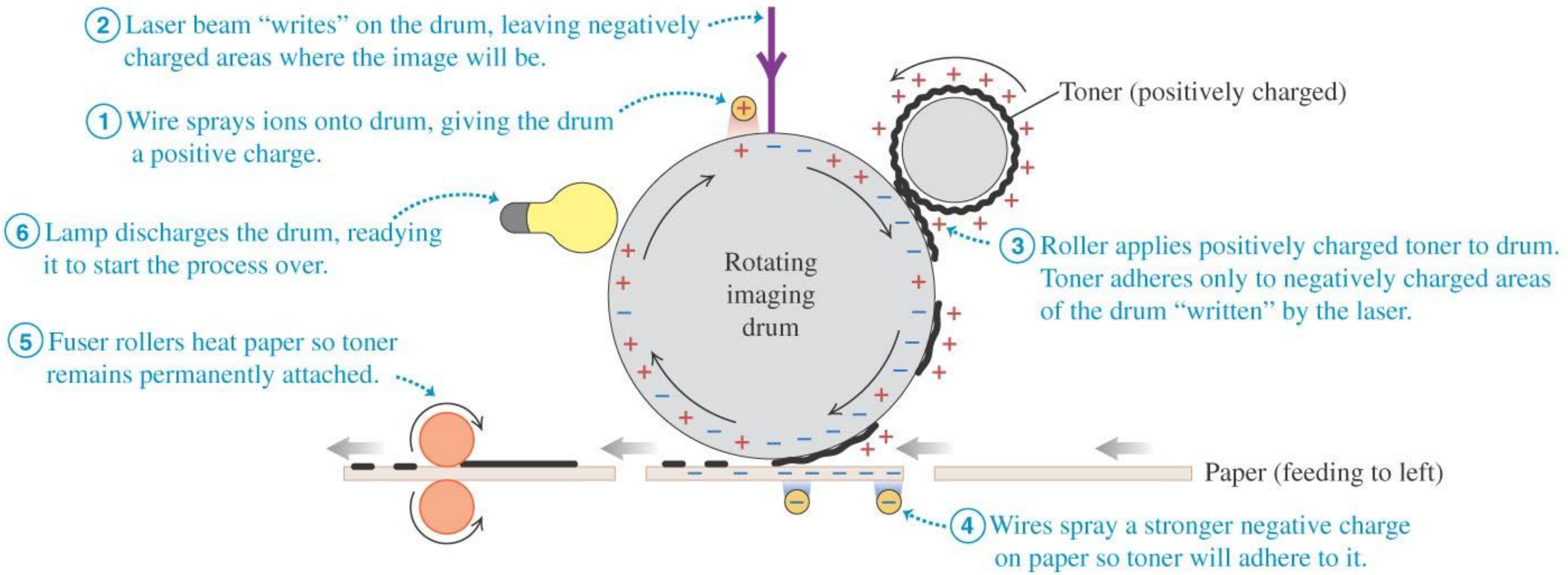
Electric charge

- Two positive or two negative charges repel each other. A positive charge and a negative charge attract each other.
- Figure 21.1 below shows some experiments in *electrostatics*.



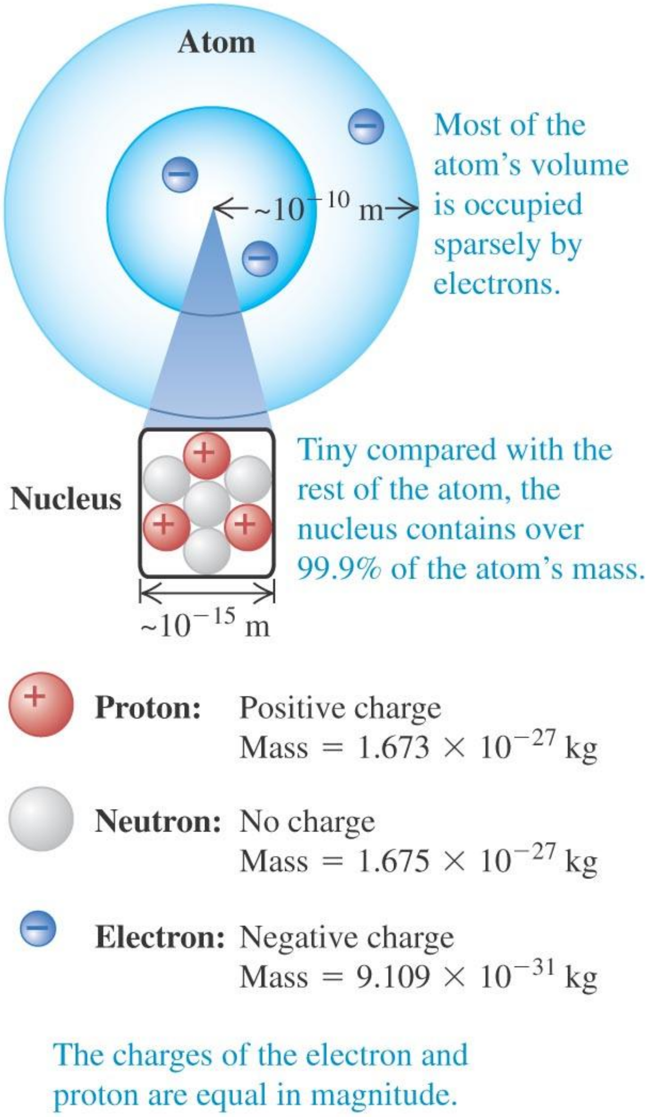
Laser printer

- A laser printer makes use of forces between charged bodies.



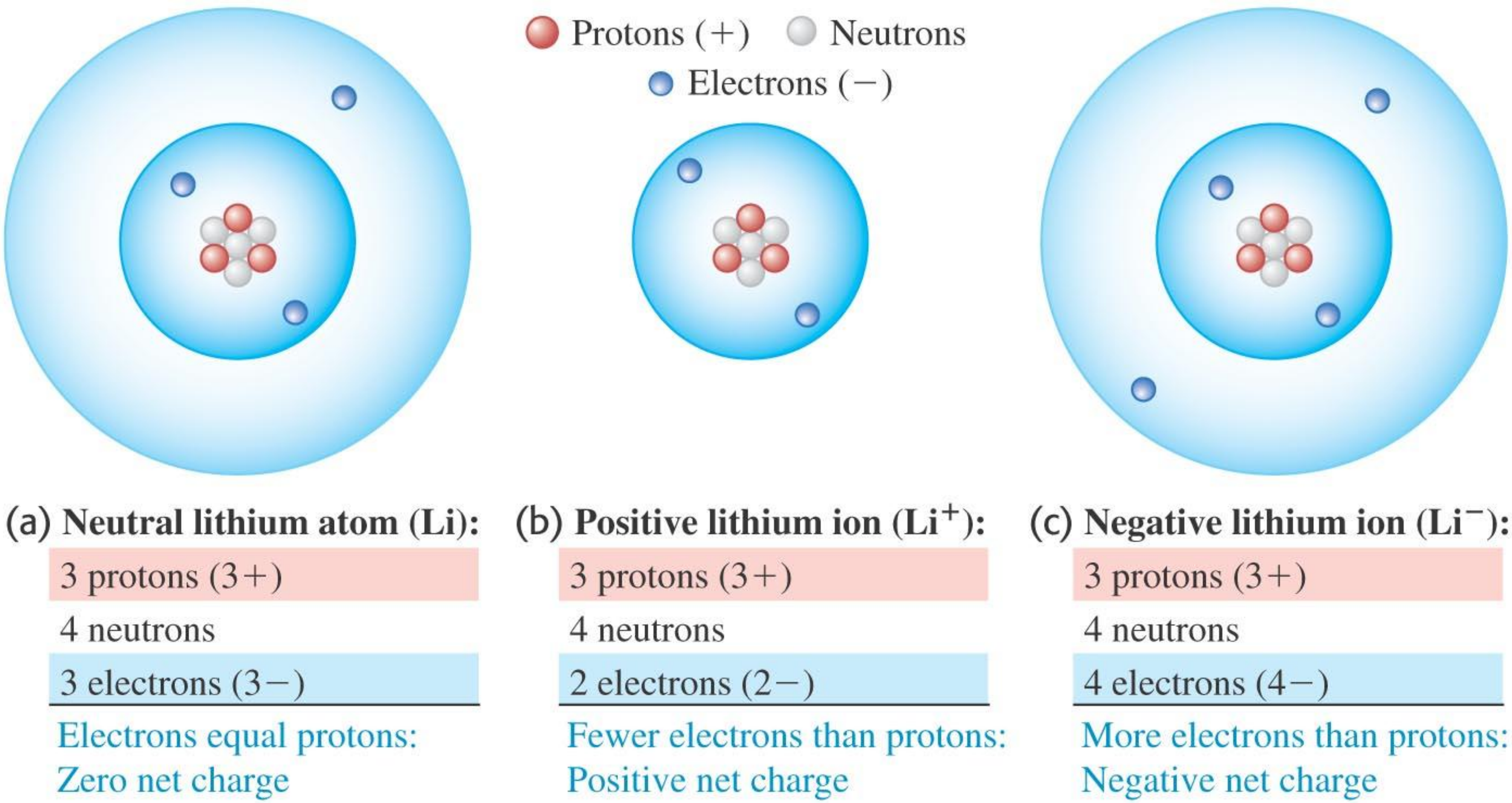
Electric charge and the structure of matter

- The particles of the atom are the negative *electron*, the positive *proton*, and the uncharged *neutron*.
- Protons and neutrons make up the tiny dense nucleus which is surrounded by electrons (see Figure 21.3 at the right).
- The electric attraction between protons and electrons holds the atom together.



Atoms and ions

- A neutral atom has the same number of protons as electrons.
- A *positive ion* is an atom with one or more electrons removed. A *negative ion* has gained one or more electrons.

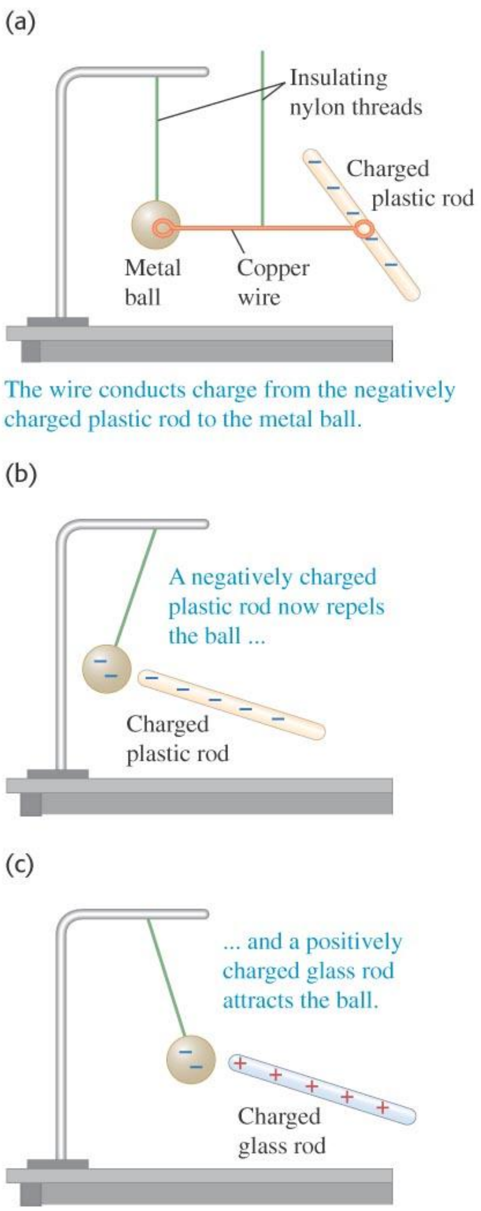


Conservation of charge

- The proton and electron have the same magnitude charge.
- The magnitude of charge of the electron or proton is a natural unit of charge. All observable charge is *quantized* in this unit.
- The universal *principle of charge conservation* states that the algebraic sum of all the electric charges in any closed system is constant.

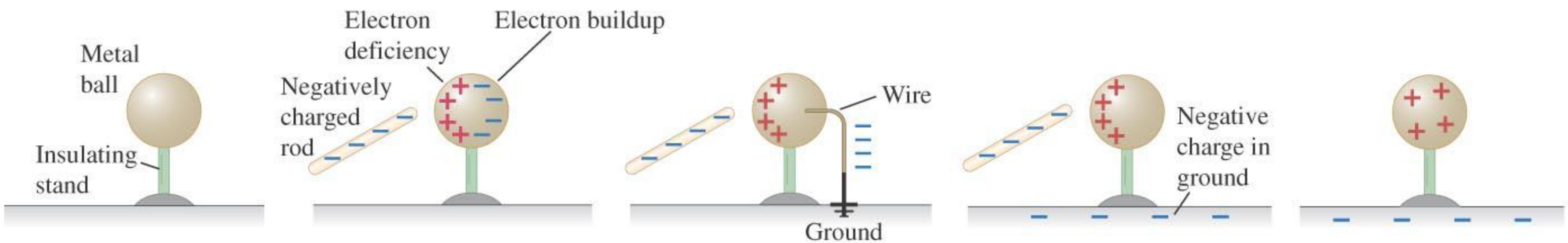
Conductors and insulators

- A *conductor* permits the easy movement of charge through it. An *insulator* does not.
- Most metals are good conductors, while most nonmetals are insulators. (See Figure 21.6 at the right.)
- *Semiconductors* are intermediate in their properties between good conductors and good insulators.



Charging by induction

- In Figure 21.7 below, the negative rod is able to charge the metal ball without losing any of its own charge. This process is called charging by *induction*.



(a) Uncharged metal ball

(b) Negative charge on rod repels electrons, creating zones of negative and positive **induced charge**.

(c) Wire lets electron build-up (induced negative charge) flow into ground.

(d) Wire removed; ball now has only an electron-deficient region of positive charge.

(e) Rod removed; electrons rearrange themselves, ball has overall electron deficiency (net positive charge).

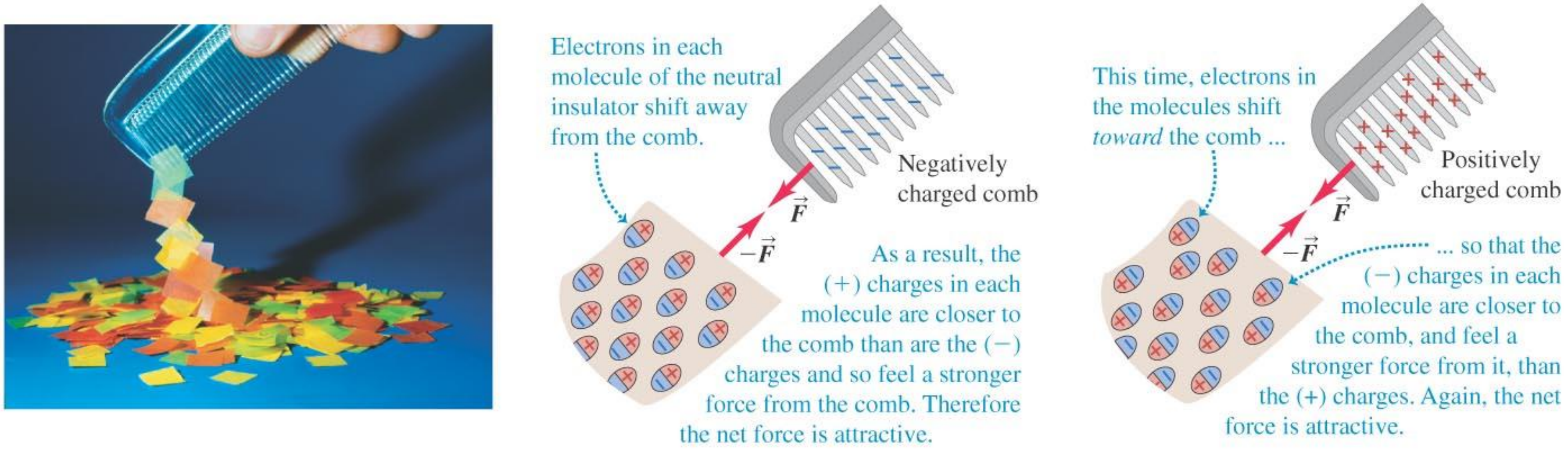
Electric forces on uncharged objects

- The charge within an insulator can shift slightly. As a result, two neutral objects can exert electric forces on each other, as shown in Figure 21.8 below.

(a) A charged comb picking up uncharged pieces of plastic

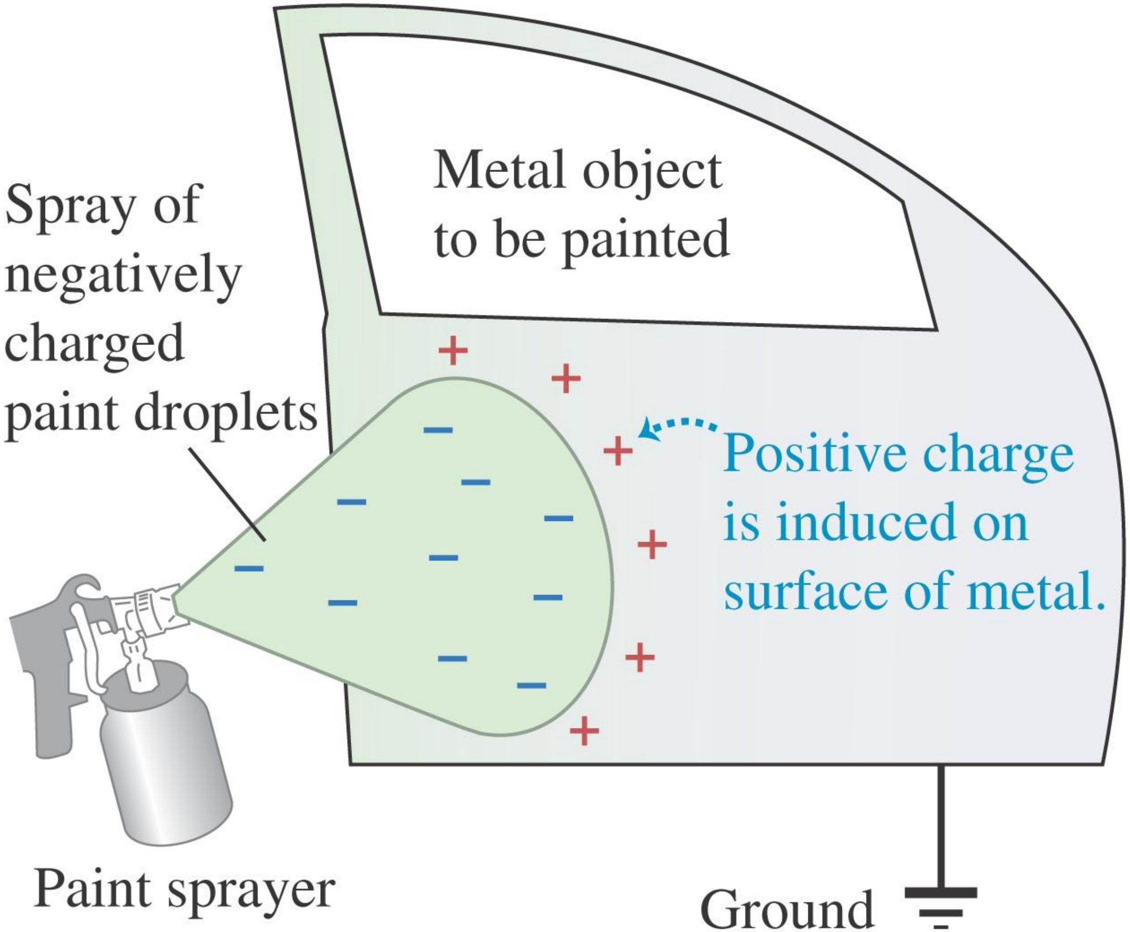
(b) How a negatively charged comb attracts an insulator

(c) How a positively charged comb attracts an insulator



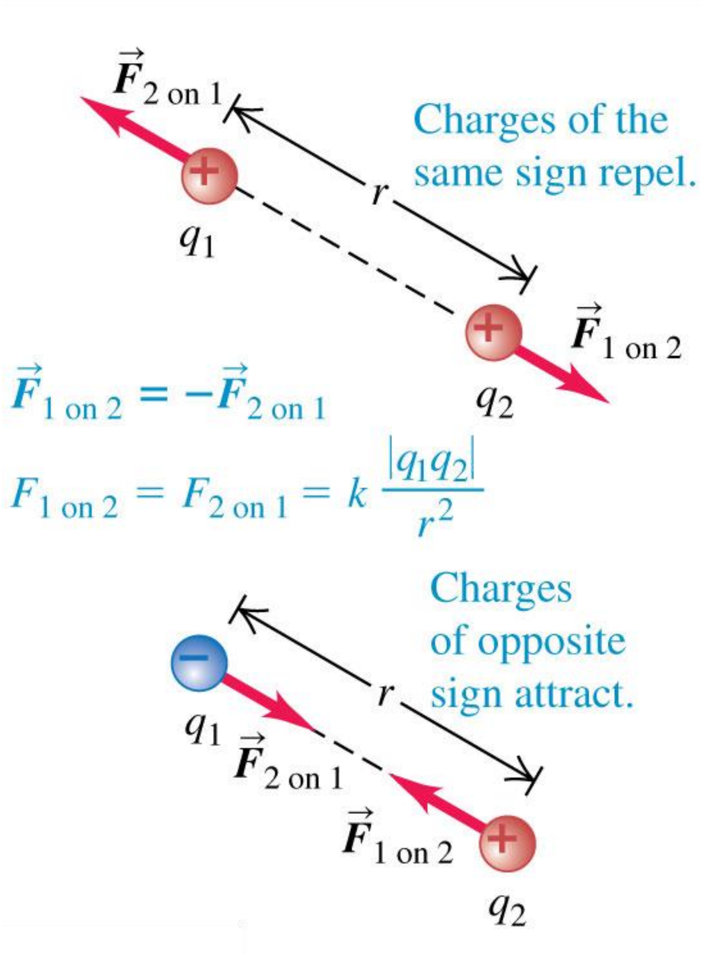
Electrostatic painting

- Induced positive charge on the metal object attracts the negatively charged paint droplets.



Coulomb’s law

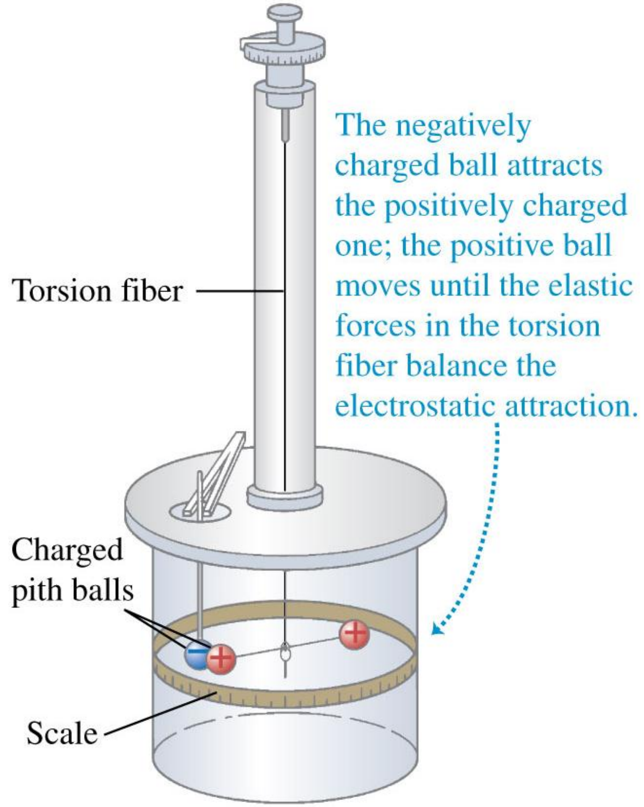
- *Coulomb’s Law*: The magnitude of the electric force between two point charges is directly proportional to the product of their charges and inversely proportional to the square of the distance between them. (See the figure at the right.)



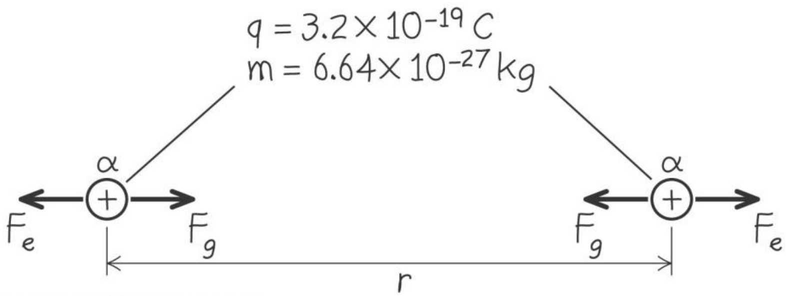
- Mathematically:
  $F = k|q_1q_2|/r^2 = (1/4\pi\varepsilon_0)|q_1q_2|/r^2$

Measuring the electric force between point charges

- The figure at the upper right illustrates how Coulomb used a torsion balance to measure the electric force between point charges.



- Example 21.1 compares the electric and gravitational forces. Follow it using Figure 21.11 at the lower right.



Ex.21.1 electric force vs. gravitational force

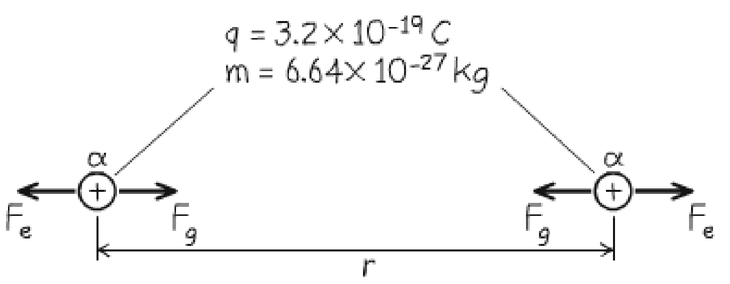
Example 21.1 **Electric force versus gravitational force**

An α particle (the nucleus of a helium atom) has mass $m = 6.64 \times 10^{-27}$ kg and charge $q = +2e = 3.2 \times 10^{-19}$ C. Compare the magnitude of the electric repulsion between two α ("alpha") particles with that of the gravitational attraction between them.

SOLUTION

IDENTIFY and SET UP: This problem involves Newton's law for the gravitational force F_g between particles (see Section 13.1) and Coulomb's law for the electric force F_e between point charges. To compare these forces, we make our target variable the ratio F_e/F_g. We use Eq. (21.2) for F_e and Eq. (13.1) for F_g.

21.11 Our sketch for this problem.



EXECUTE: Figure 21.11 shows our sketch. From Eqs. (21.2) and (13.1),

$$F_e = \frac{1}{4\pi\epsilon_0}\frac{q^2}{r^2} \qquad F_g = G\frac{m^2}{r^2}$$

These are both inverse-square forces, so the r^2 factors cancel when we take the ratio:

$$\frac{F_e}{F_g} = \frac{1}{4\pi\epsilon_0 G}\frac{q^2}{m^2}$$

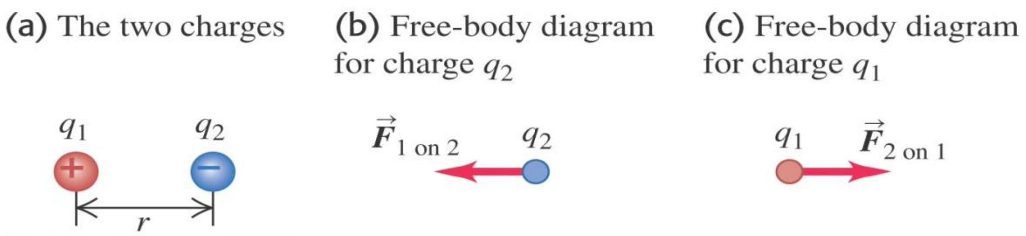
$$= \frac{9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2}{6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2}\frac{(3.2 \times 10^{-19}\ \text{C})^2}{(6.64 \times 10^{-27}\ \text{kg})^2}$$

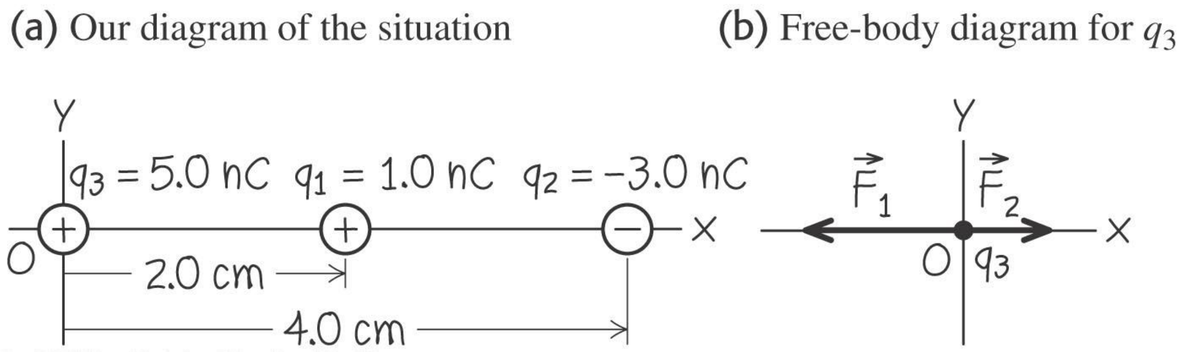
$$= 3.1 \times 10^{35}$$

EVALUATE: This astonishingly large number shows that the gravitational force in this situation is completely negligible in comparison to the electric force. This is always true for interactions of atomic and subnuclear particles. But within objects the size of a person or a planet, the positive and negative charges are nearly equal in magnitude, and the net electric force is usually much *smaller* than the gravitational force.

Force between charges along a line

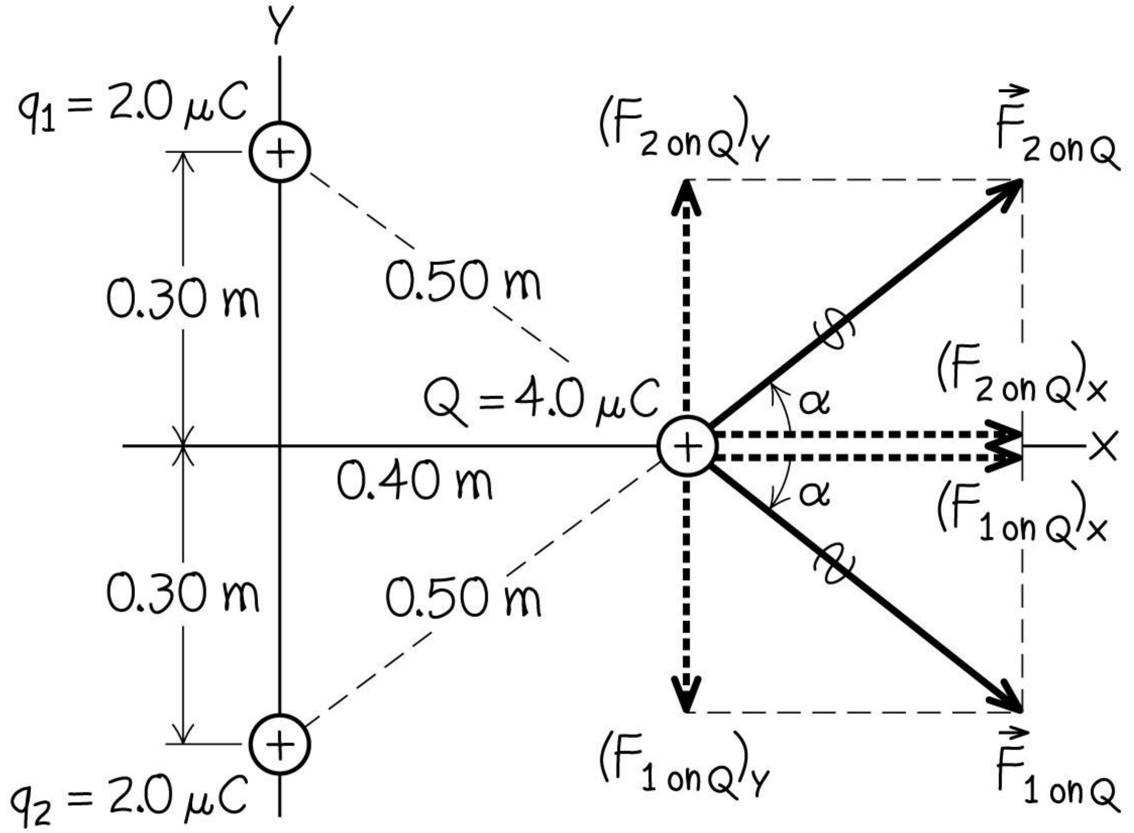
- Read Problem-Solving Strategy 21.1.
- Follow Example 21.2 for two charges, using Figure 21.12 at the right.
- Follow Example 21.3 for three charges, using Figure 21.13 below.





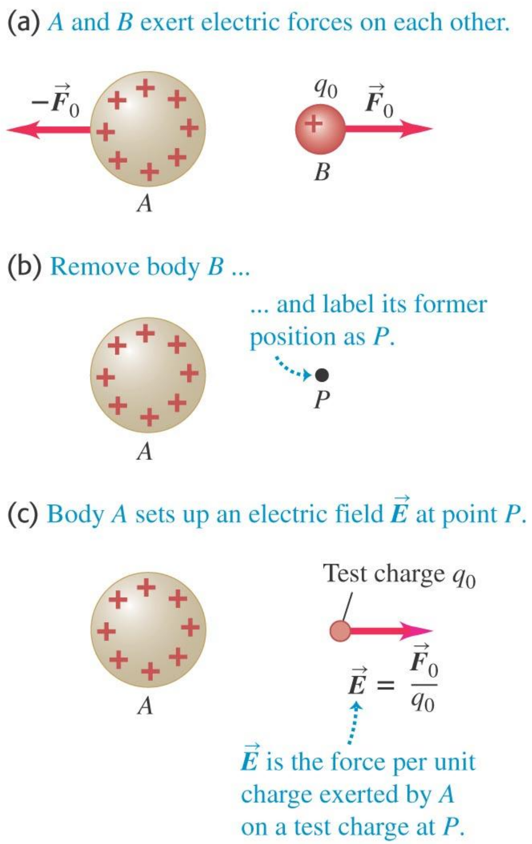
Vector addition of electric forces

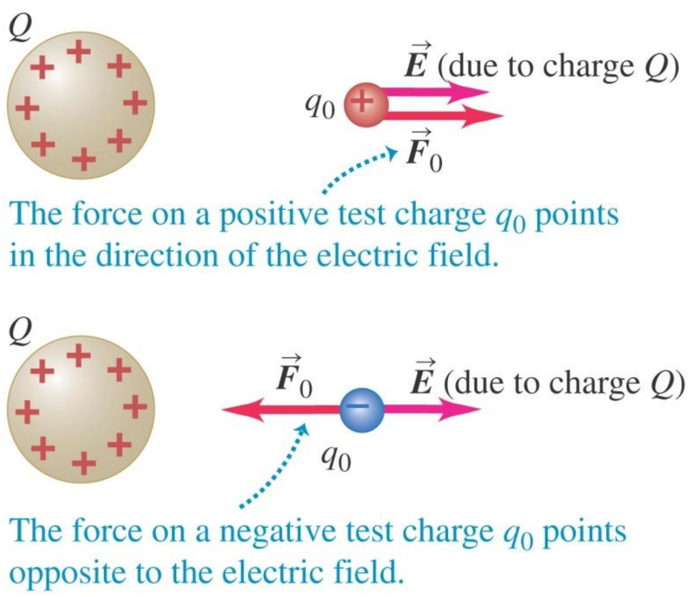
- Example 21.4 shows that we must use vector addition when adding electric forces. Follow this example using Figure 21.14 below.



Electric field

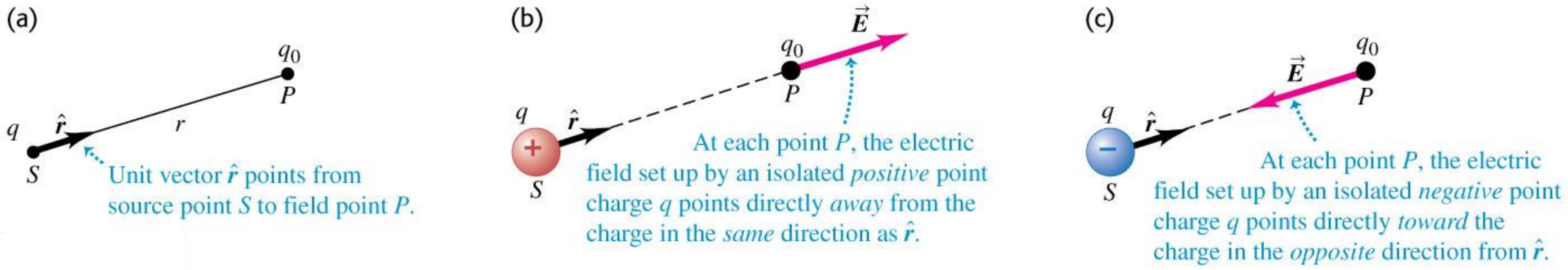
- A charged body produces an *electric field* in the space around it (see Figure 21.15 at the lower left).
- We use a small *test charge* q_0 to find out if an electric field is present (see Figure 21.16 at the lower right).





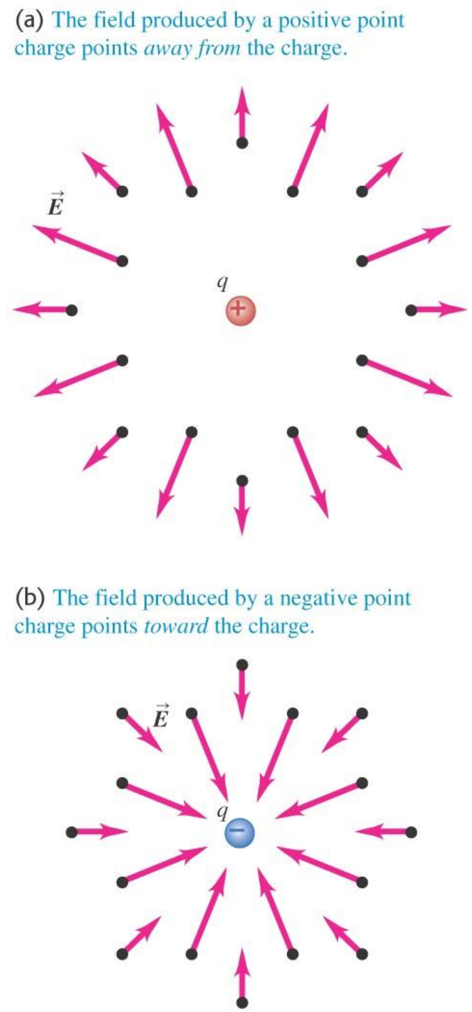
Definition of the electric field

- Follow the definition in the text of the electric field using Figure 21.17 below.



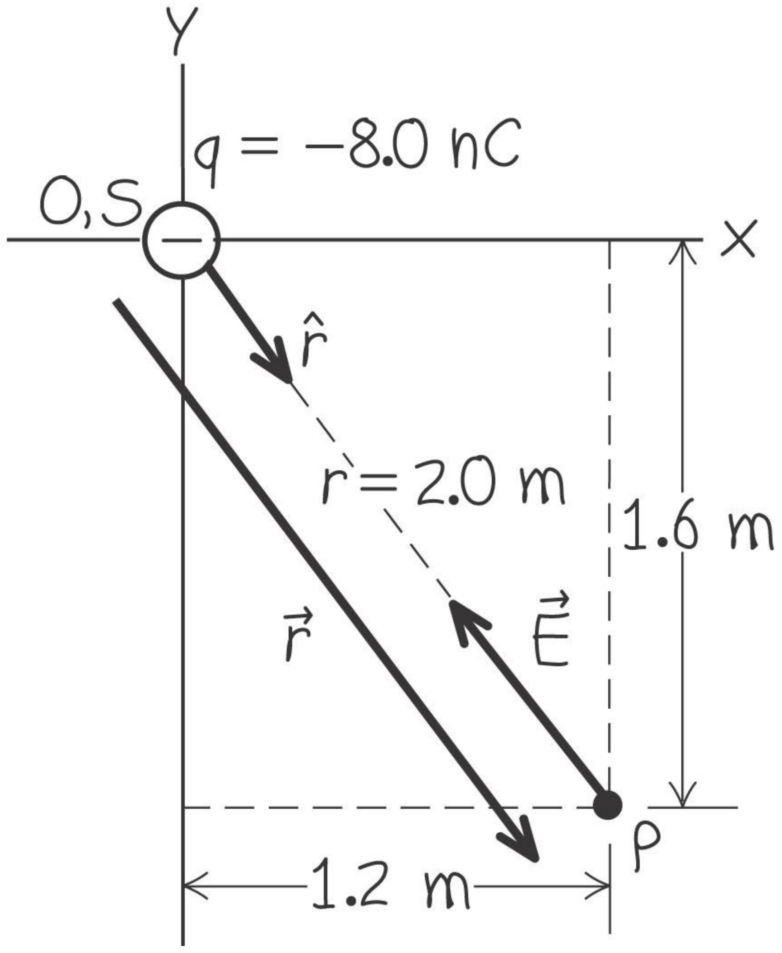
Electric field of a point charge

- Follow the discussion in the text of the electric field of a point charge, using Figure 21.18 at the right.
- Follow Example 21.5 to calculate the magnitude of the electric field of a single point charge.



Electric-field vector of a point charge

- Follow Example 21.6 to see the vector nature of the electric field. Use Figure 21.19 at the right.



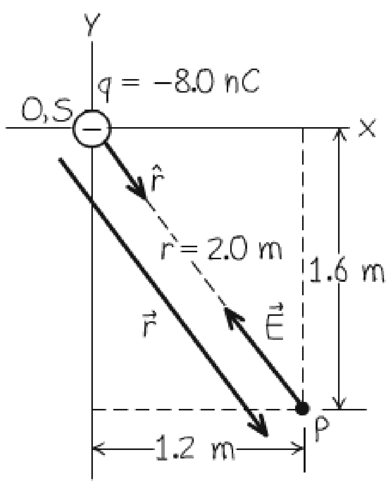
Example 21.6 Electric-field vector of a point charge

A point charge $q = -8.0\ \text{nC}$ is located at the origin. Find the electric-field vector at the field point $x = 1.2\ \text{m}$, $y = -1.6\ \text{m}$.

SOLUTION

IDENTIFY and SET UP: We must find the electric-field *vector* $\vec{E}$ due to a point charge. Figure 21.19 shows the situation. We use Eq. (21.7); to do this, we must find the distance r from the source point S (the position of the charge q, which in this example is at the origin O) to the field point P, and we must obtain an expression for the unit vector $\hat{r} = \vec{r}/r$ that points from S to P.

21.19 Our sketch for this problem.



EXECUTE: The distance from S to P is

$$r = \sqrt{x^2 + y^2} = \sqrt{(1.2\ \text{m})^2 + (-1.6\ \text{m})^2} = 2.0\ \text{m}$$

The unit vector $\hat{r}$ is then

$$\hat{r} = \frac{\vec{r}}{r} = \frac{x\hat{\imath} + y\hat{\jmath}}{r}$$

$$= \frac{(1.2\ \text{m})\hat{\imath} + (-1.6\ \text{m})\hat{\jmath}}{2.0\ \text{m}} = 0.60\hat{\imath} - 0.80\hat{\jmath}$$

Then, from Eq. (21.7),

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

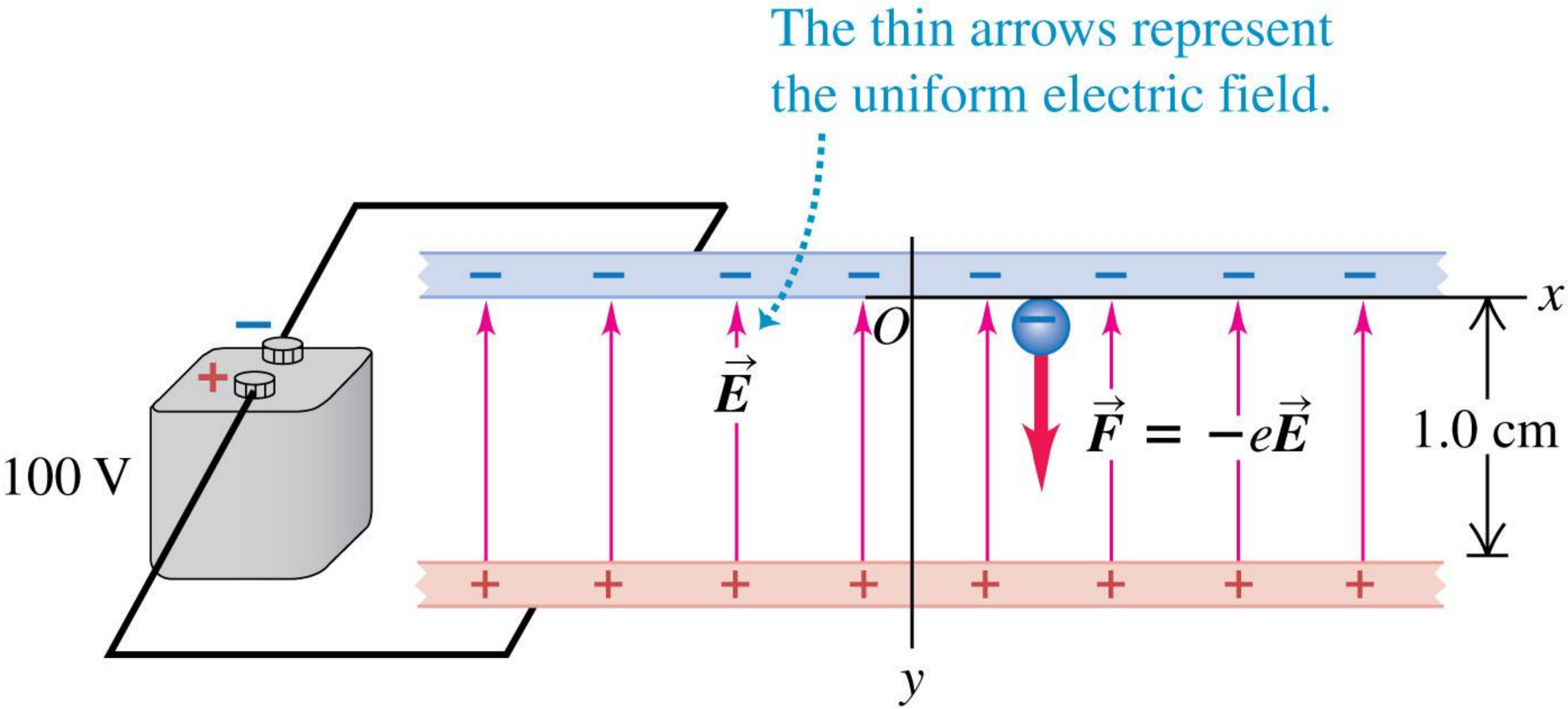
$$= (9.0 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)\frac{(-8.0 \times 10^{-9}\ \text{C})}{(2.0\ \text{m})^2}(0.60\hat{\imath} - 0.80\hat{\jmath})$$

$$= (-11\ \text{N/C})\hat{\imath} + (14\ \text{N/C})\hat{\jmath}$$

EVALUATE: Since q is negative, $\vec{E}$ points from the field point to the charge (the source point), in the direction opposite to $\hat{r}$ (compare Fig. 21.17c). We leave the calculation of the magnitude and direction of $\vec{E}$ to you (see Exercise 21.36).

Electron in a uniform field

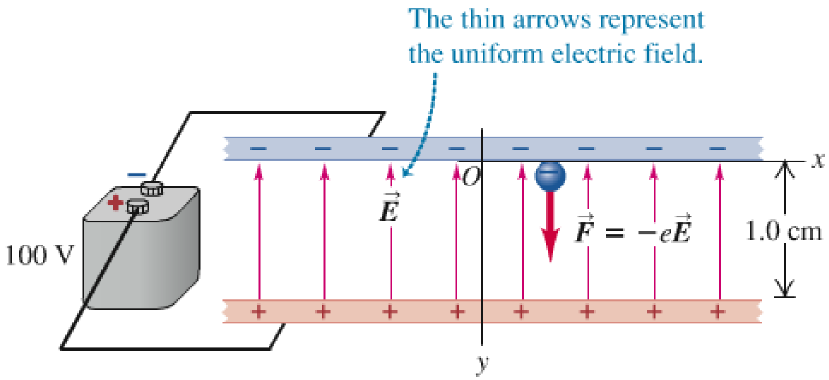
- Example 21.7 requires us to find the force on a charge that is in a known electric field. Follow this example using Figure 21.20 below.



Example 21.7 Electron in a uniform field

When the terminals of a battery are connected to two parallel conducting plates with a small gap between them, the resulting charges on the plates produce a nearly uniform electric field $\vec{E}$ between the plates. (In the next section we'll see why this is.) If the plates are 1.0 cm apart and are connected to a 100-volt battery as shown in Fig. 21.20, the field is vertically upward and has magnitude $E = 1.00 \times 10^4$ N/C. (a) If an electron (charge $-e = -1.60 \times 10^{-9}$ C, mass $m = 9.11 \times 10^{-31}$ kg) is released from rest at the upper plate, what is its acceleration? (b) What speed and kinetic energy does it acquire while traveling 1.0 cm to the lower plate? (c) How long does it take to travel this distance?

21.20 A uniform electric field between two parallel conducting plates connected to a 100-volt battery. (The separation of the plates is exaggerated in this figure relative to the dimensions of the plates.)



SOLUTION

IDENTIFY and SET UP: This example involves the relationship between electric field and electric force. It also involves the relationship between force and acceleration, the definition of kinetic energy, and the kinematic relationships among acceleration, distance, velocity, and time. Figure 21.20 shows our coordinate system. We are given the electric field, so we use Eq. (21.4) to find the force on the electron and Newton's second law to find its acceleration. Because the field is uniform, the force is constant and we can use the constant-acceleration formulas from Chapter 2 to find the electron's velocity and travel time. We find the kinetic energy using $K = \frac{1}{2}mv^2$.

Example 21.7

EXECUTE: (a) Although $\vec{E}$ is upward (in the $+y$-direction), $\vec{F}$ is downward (because the electron's charge is negative) and so F_y is negative. Because F_y is constant, the electron's acceleration is constant:

$$a_y = \frac{F_y}{m} = \frac{-eE}{m} = \frac{(-1.60 \times 10^{-19}\ \text{C})(1.00 \times 10^4\ \text{N/C})}{9.11 \times 10^{-31}\ \text{kg}}$$
$$= -1.76 \times 10^{15}\ \text{m/s}^2$$

(b) The electron starts from rest, so its motion is in the y-direction only (the direction of the acceleration). We can find the electron's speed at any position y using the constant-acceleration Eq. (2.13), $v_y{}^2 = v_{0y}{}^2 + 2a_y(y - y_0)$. We have $v_{0y} = 0$ and $y_0 = 0$, so at $y = -1.0$ cm $= -1.0 \times 10^{-2}$ m we have

$$|v_y| = \sqrt{2a_y y} = \sqrt{2(-1.76 \times 10^{15}\ \text{m/s}^2)(-1.0 \times 10^{-2}\ \text{m})}$$
$$= 5.9 \times 10^6\ \text{m/s}$$

The velocity is downward, so $v_y = -5.9 \times 10^6$ m/s. The electron's kinetic energy is

$$K = \tfrac{1}{2}mv^2 = \tfrac{1}{2}(9.11 \times 10^{-31}\ \text{kg})(5.9 \times 10^6\ \text{m/s})^2$$
$$= 1.6 \times 10^{-17}\ \text{J}$$

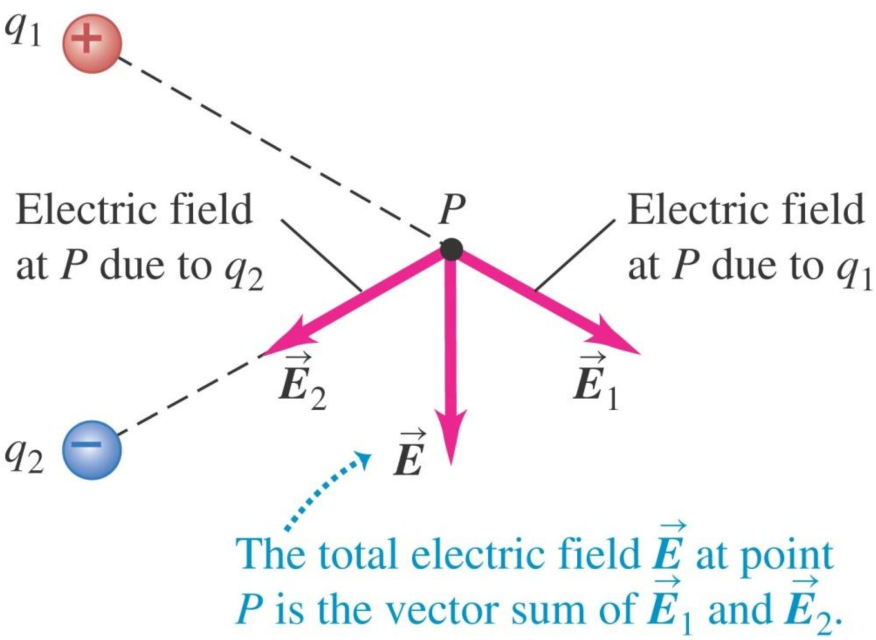
(c) From Eq. (2.8) for constant acceleration, $v_y = v_{0y} + a_y t$,

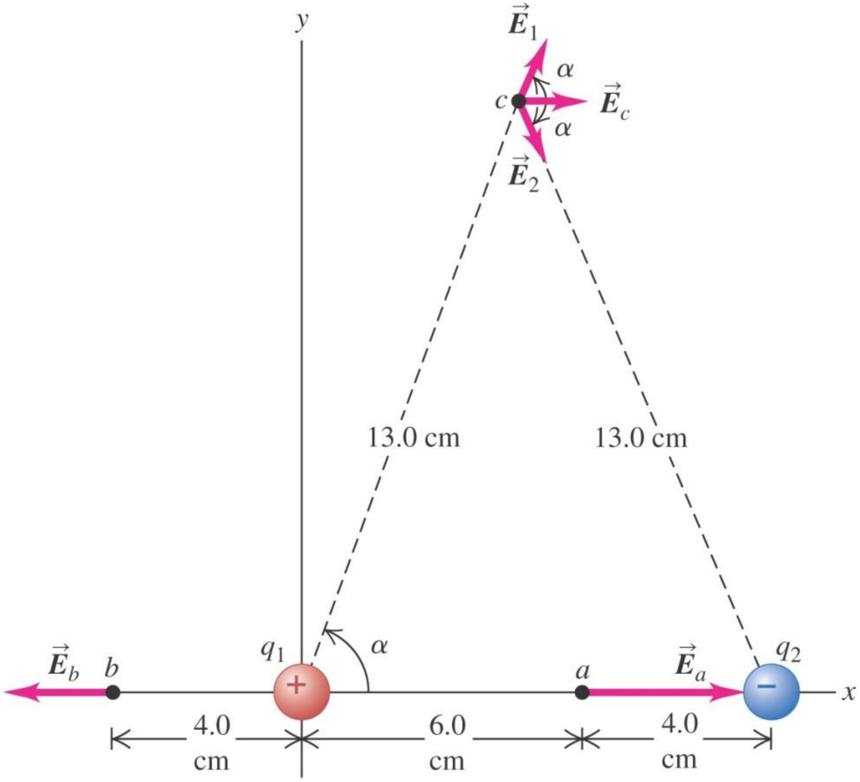
$$t = \frac{v_y - v_{0y}}{a_y} = \frac{(-5.9 \times 10^6\ \text{m/s}) - (0\ \text{m/s})}{-1.76 \times 10^{15}\ \text{m/s}^2}$$
$$= 3.4 \times 10^{-9}\ \text{s}$$

EVALUATE: Our results show that in problems concerning subatomic particles such as electrons, many quantities—including acceleration, speed, kinetic energy, and time—will have *very* different values from those typical of everyday objects such as baseballs and automobiles.

Superposition of electric fields

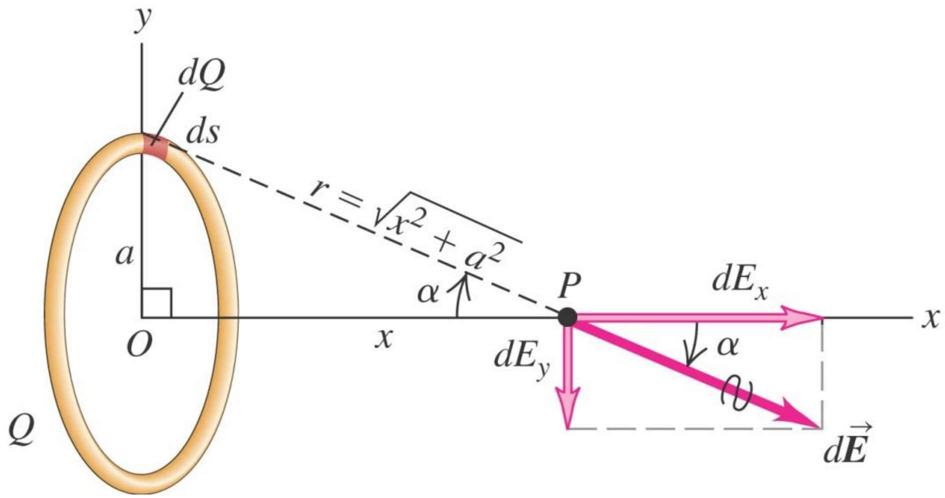
- The total electric field at a point is the vector sum of the fields due to all the charges present. (See Figure 21.21 below right.)
- Review Problem-Solving Strategy 21.2.
- Follow Example 21.8 for an electric dipole. Use Figure 21.22 below.





Example 21.9 Field of a ring of charge

- On the ring axis



$$dE = \frac{1}{4\pi\epsilon_0}\frac{dQ}{x^2 + a^2}$$

$$dE_x = dE\cos\alpha = \frac{1}{4\pi\epsilon_0}\frac{dQ}{x^2 + a^2}\frac{x}{\sqrt{x^2 + a^2}}$$

$$= \frac{1}{4\pi\epsilon_0}\frac{\lambda x}{(x^2 + a^2)^{3/2}}ds$$

Example 21.9 Field of a ring of charge

$$E_x = \int dE_x = \frac{1}{4\pi\epsilon_0}\frac{\lambda x}{(x^2 + a^2)^{3/2}}\int_0^{2\pi a} ds$$

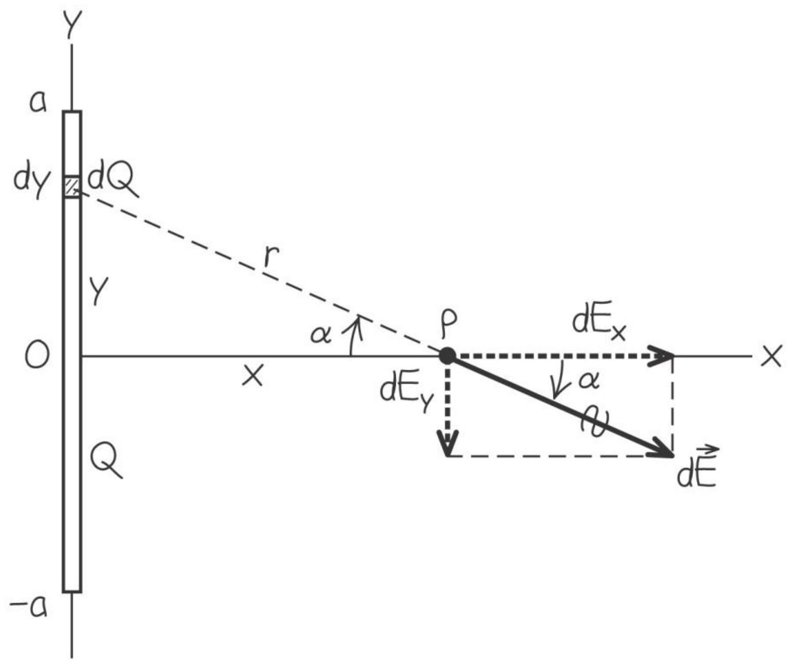
$$= \frac{1}{4\pi\epsilon_0}\frac{\lambda x}{(x^2 + a^2)^{3/2}}(2\pi a)$$

$$\vec{E} = E_x\hat{\imath} = \frac{1}{4\pi\epsilon_0}\frac{Qx}{(x^2 + a^2)^{3/2}}\hat{\imath}$$

- For x >> a

$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{Q}{x^2}\hat{\imath}$$

Example 21.10 Field of a charged line segment



$$dE = \frac{1}{4\pi\epsilon_0}\frac{dQ}{r^2} = \frac{1}{4\pi\epsilon_0}\frac{Q}{2a}\frac{dy}{(x^2+y^2)}$$

$$dE_x = \frac{1}{4\pi\epsilon_0}\frac{Q}{2a}\frac{x\,dy}{(x^2+y^2)^{3/2}}$$

$$dE_y = \frac{1}{4\pi\epsilon_0}\frac{Q}{2a}\frac{y\,dy}{(x^2+y^2)^{3/2}}$$

$$E_x = \frac{1}{4\pi\epsilon_0}\frac{Q}{2a}\int_{-a}^{+a}\frac{x\,dy}{(x^2+y^2)^{3/2}} = \frac{Q}{4\pi\epsilon_0}\frac{1}{x\sqrt{x^2+a^2}}$$

$$E_y = \frac{1}{4\pi\epsilon_0}\frac{Q}{2a}\int_{-a}^{+a}\frac{y\,dy}{(x^2+y^2)^{3/2}} = 0$$

$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{Q}{x\sqrt{x^2+a^2}}\hat{\imath}$$

Field of a charged line segment

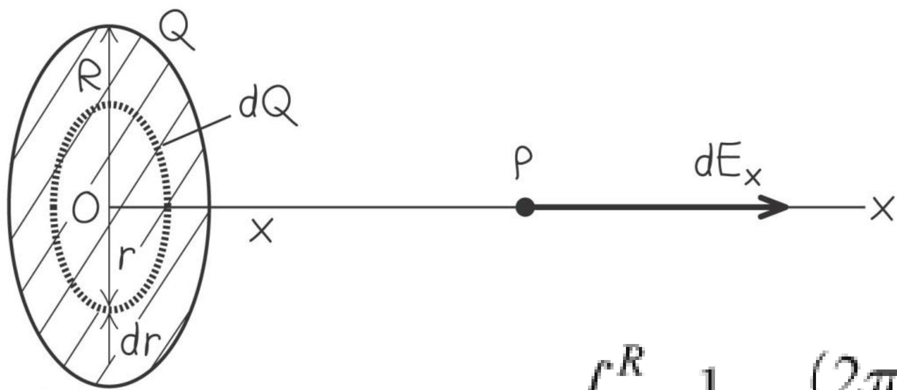
- For x >> a

$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{Q}{x\sqrt{x^2 + a^2}}\hat{\imath} \quad \rightarrow \quad \vec{E} = \frac{1}{4\pi\epsilon_0}\frac{Q}{x^2}\hat{\imath}$$

- For very long segment (a >> x)

$$\vec{E} = \frac{1}{2\pi\epsilon_0}\frac{\lambda}{x\sqrt{(x^2/a^2) + 1}}\hat{\imath} \quad \rightarrow \quad \vec{E} = \frac{\lambda}{2\pi\epsilon_0 x}\hat{\imath}$$

Example 21.11 Field of a uniformly charged disk



$$dQ = \sigma\, dA = 2\pi\sigma r\, dr.$$

$$dE_x = \frac{1}{4\pi\epsilon_0} \frac{2\pi\sigma r x\, dr}{(x^2 + r^2)^{3/2}}$$

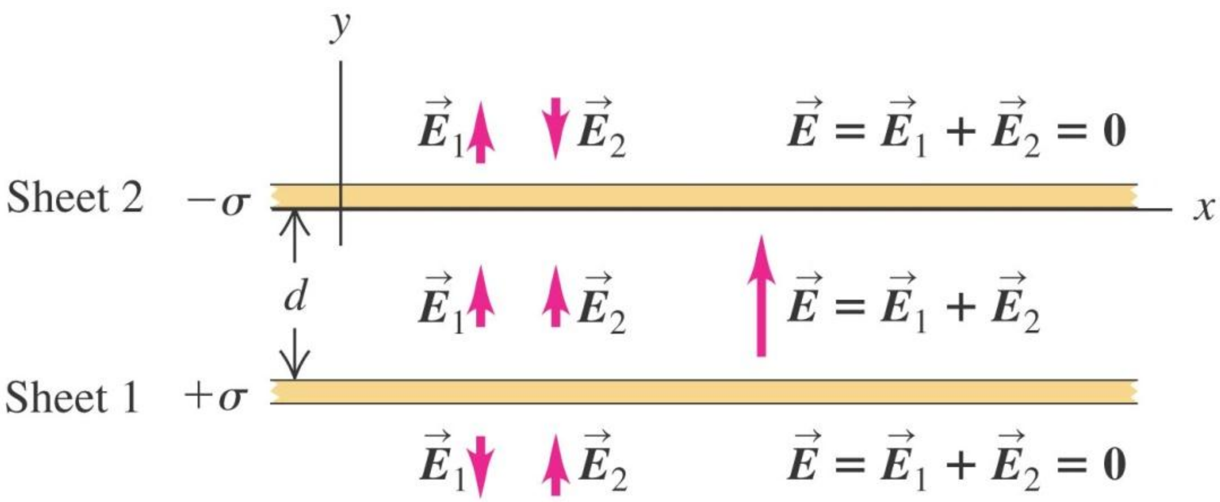
$$E_x = \int_0^R \frac{1}{4\pi\epsilon_0} \frac{(2\pi\sigma r\, dr)x}{(x^2 + r^2)^{3/2}} = \frac{\sigma x}{4\epsilon_0} \int_0^R \frac{2r\, dr}{(x^2 + r^2)^{3/2}}$$

$$E_x = \frac{\sigma x}{2\epsilon_0}\left[-\frac{1}{\sqrt{x^2 + R^2}} + \frac{1}{x} \right]$$

$$= \frac{\sigma}{2\epsilon_0}\left[1 - \frac{1}{\sqrt{(R^2/x^2) + 1}} \right]$$

- For R >> a $\quad E = \dfrac{\sigma}{2\epsilon_0}$

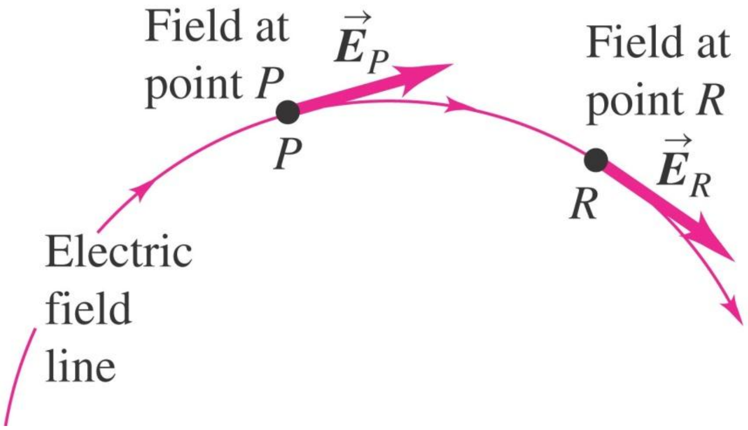
Example 21.12 Field of two oppositely charged infinite sheets



$$E_1 = E_2 = \frac{\sigma}{2\epsilon_0} \qquad \vec{E} = \vec{E}_1 + \vec{E}_2 = \begin{cases} \mathbf{0} & \text{above the upper sheet} \\ \dfrac{\sigma}{\epsilon_0}\hat{j} & \text{between the sheets} \\ \mathbf{0} & \text{below the lower sheet} \end{cases}$$

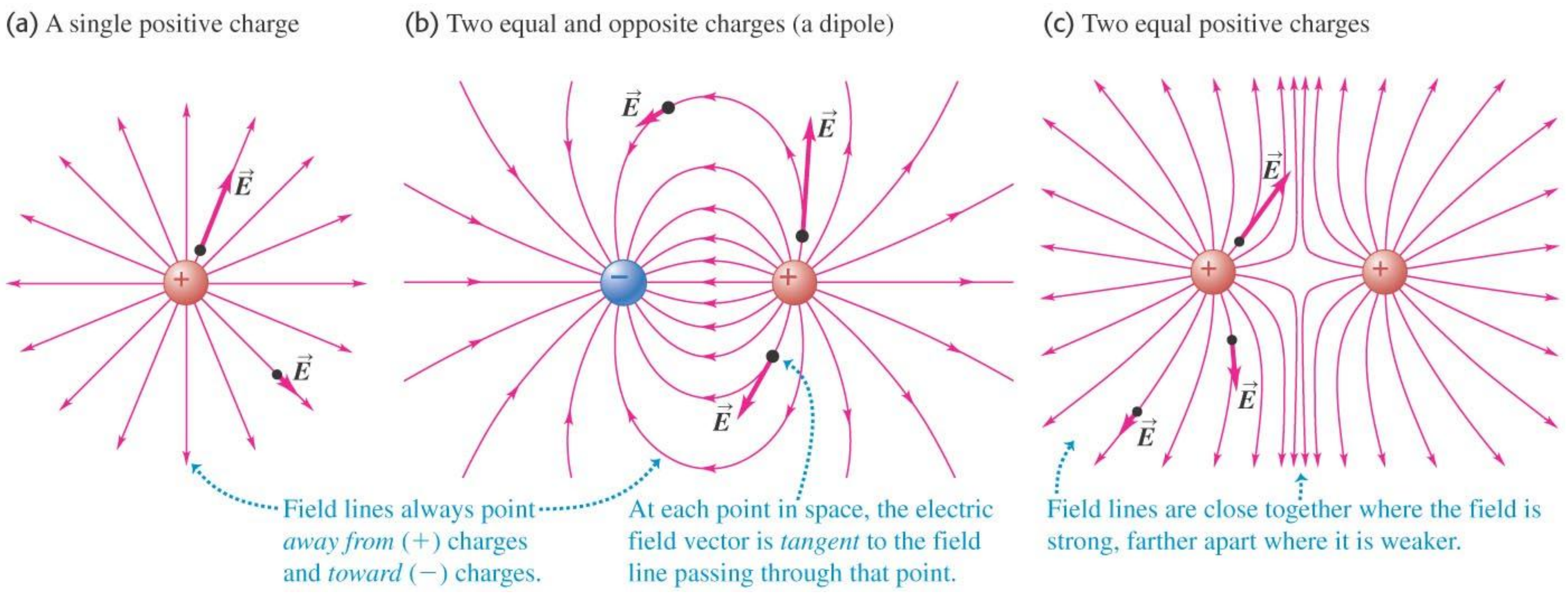
Electric field lines

- An *electric field line* is an imaginary line or curve whose tangent at any point is the direction of the electric field vector at that point. (See Figure 21.27 below.)



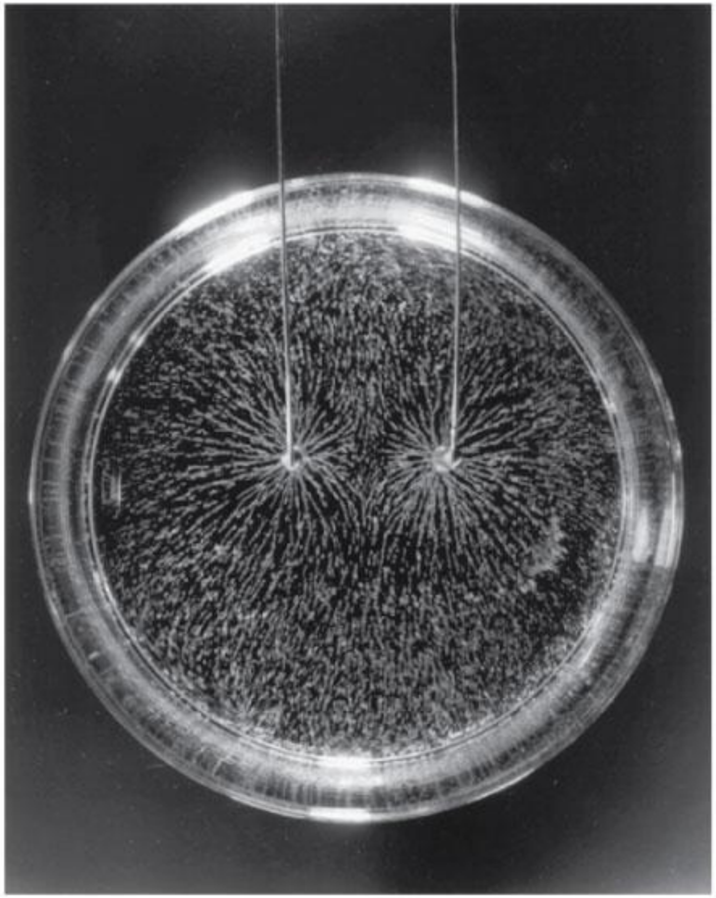
Electric field lines of point charges

- Figure 21.28 below shows the electric field lines of a single point charge and for two charges of opposite sign and of equal sign.



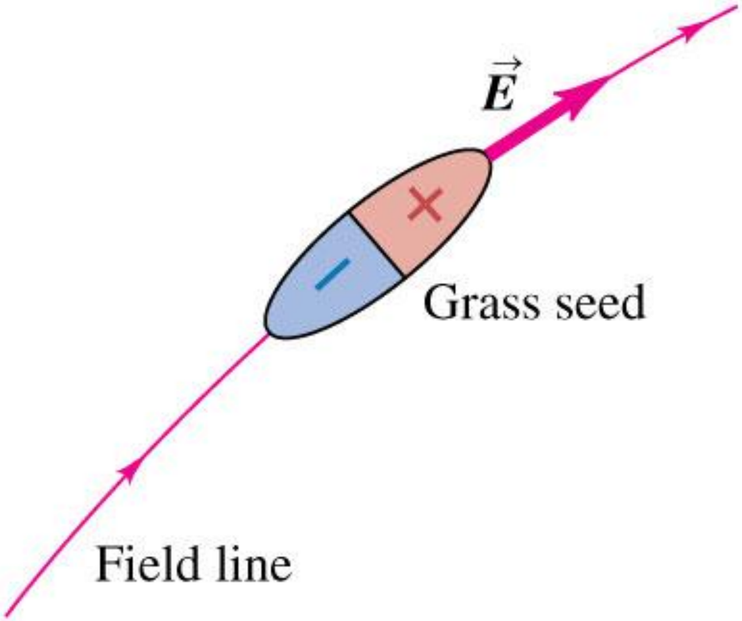
Visualizing electric field

(a)



© 2012 Pearson Education, Inc.

(b)

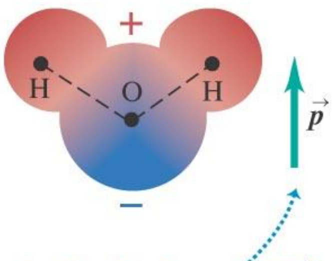


© 2012 Pearson Education, Inc.

Electric dipoles

- An *electric dipole* is a pair of point charges having equal but opposite sign and separated by a distance.
- Figure 21.30 at the right illustrates the water molecule, which forms an electric dipole.

(a) A water molecule, showing positive charge as red and negative charge as blue

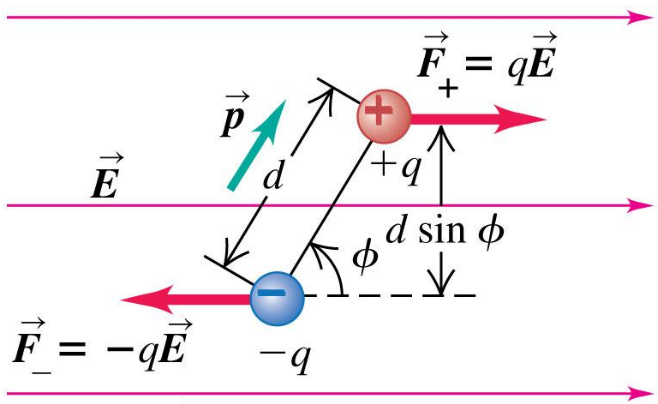


The electric dipole moment $\vec{p}$ is directed from the negative end to the positive end of the molecule.

(b) Various substances dissolved in water

Force and torque on a dipole

- Figure 21.31 below left shows the force on a dipole in an electric field.



$$\tau = (qE)(d \sin \phi)$$

$$p = qd$$

electric dipole moment

$$\vec{\tau} = \vec{p} \times \vec{E}$$ (torque on an electric dipole, in vector form)

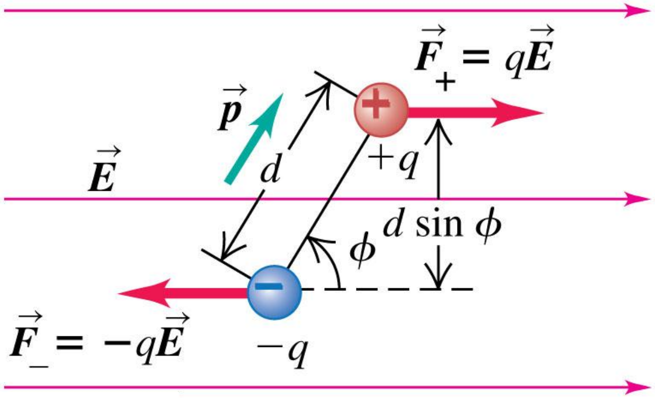
Potential of a dipole

$$dW = \tau\, d\phi = -pE\sin\phi\, d\phi \qquad W = U_1 - U_2.$$

$$W = \int_{\phi_1}^{\phi_2} (-pE\sin\phi)\, d\phi \qquad U(\phi) = -pE\cos\phi$$

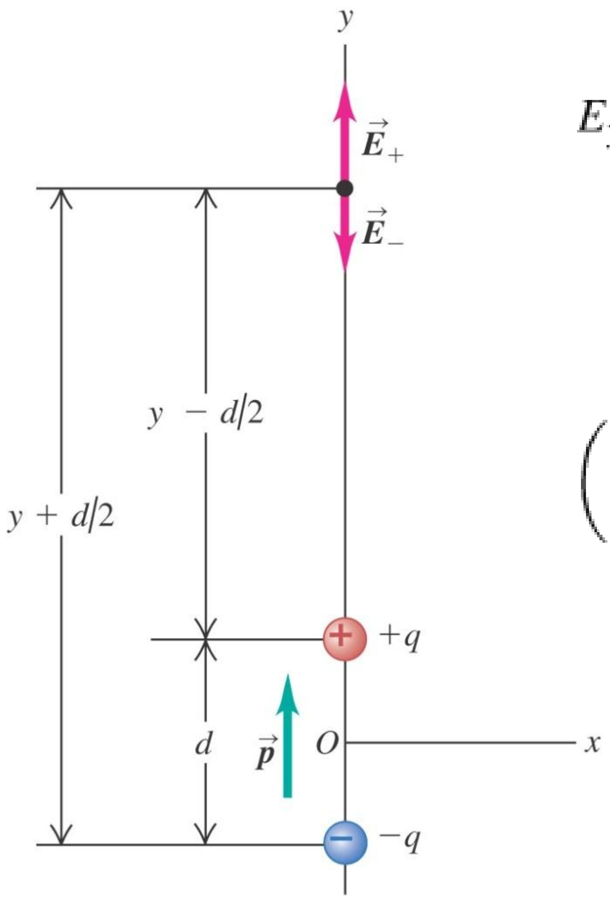
$$= pE\cos\phi_2 - pE\cos\phi_1$$

$U = -\vec{p} \cdot \vec{E}$ (potential energy for a dipole in an electric field)



Electric field of a dipole

- Follow Example 21.14 using Figure 21.33.



$$E_y = \frac{q}{4\pi\epsilon_0}\left[\frac{1}{(y-d/2)^2} - \frac{1}{(y+d/2)^2}\right]$$

$$= \frac{q}{4\pi\epsilon_0 y^2}\left[\left(1-\frac{d}{2y}\right)^{-2} - \left(1+\frac{d}{2y}\right)^{-2}\right]$$

$$\left(1-\frac{d}{2y}\right)^{-2} \cong 1 + \frac{d}{y} \quad \text{and} \quad \left(1+\frac{d}{2y}\right)^{-2} \cong 1 - \frac{d}{y}$$

$$E_y \cong \frac{q}{4\pi\epsilon_0 y^2}\left[1 + \frac{d}{y} - \left(1 - \frac{d}{y}\right)\right] = \frac{qd}{2\pi\epsilon_0 y^3} = \frac{p}{2\pi\epsilon_0 y^3}$$