Chapter 23

Electric Fields

23.1 Properties of Electric Charges

23.3 Coulomb's Law

23.4 The Electric Field

23.6 Electric Field Lines

23.1 Properties of Electric Charges

Experiments

1-After running a comb through your hair on a dry day you will find that the comb attracts bits of paper.

2-Certain materials are rubbed together, such as glass rubbed with silk or rubber with fur, same effect will appear.

3-Another simple experiment is to rub an inflated balloon with wool. The balloon then adheres to a wall, often for hours.

Results

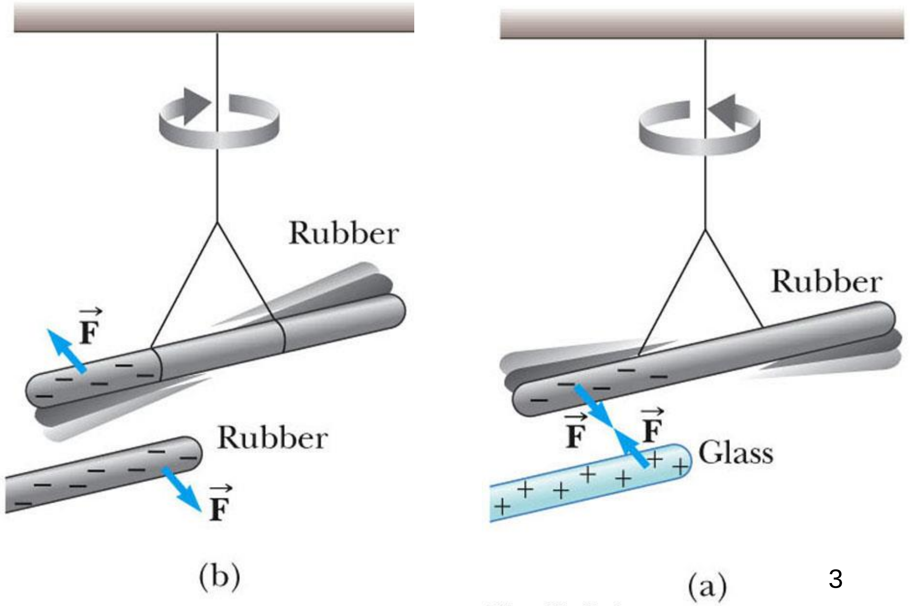
When materials behave in this way, they are said to be electrified, or to have become electrically charged.

Electric Charges

- There are two kinds of electric charges: positive and negative
  - Negative charges are the type possessed by electrons
  - Positive charges are the type possessed by protons

- Charges of the same sign repel one another

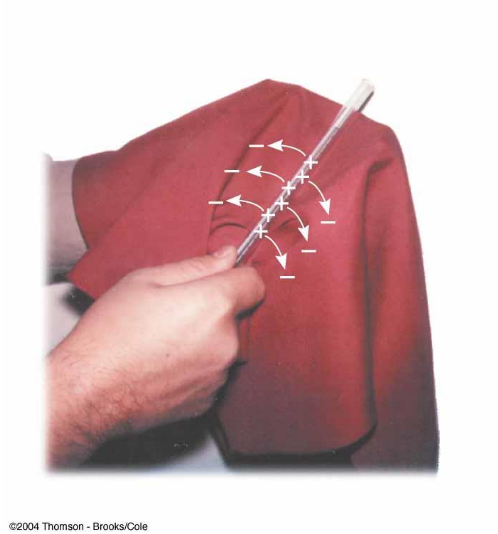
- charges with opposite signs attract one another



More About Electric Charges

1-Electric charge is always conserved in an isolated system

- For example, charge is not created in the process of rubbing two objects together.



- The electrification is due to a transfer of charge from one object to another.

More About Electric Charges

2-The electric charge, q, is said to be quantized

- q is the standard symbol used for charge as a variable
- Electric charge exists as discrete *"packets"*, $q = \pm Ne$
  - N is an integer
  - e is the fundamental unit of charge
  - $|e| = 1.6 \times 10^{-19}$ C
  - Electron: $q = -e$
  - Proton: $q = +e$

Conductors

- Electrical conductors are materials in which some of the electrons are free electrons
  - Free electrons are not bound to the atoms
  - These electrons can move relatively freely through the material.
  - Examples of good conductors include copper, aluminum and silver.
  - When a good conductor is charged in a small region, the charge readily distributes itself over the entire surface of the material.

Insulators

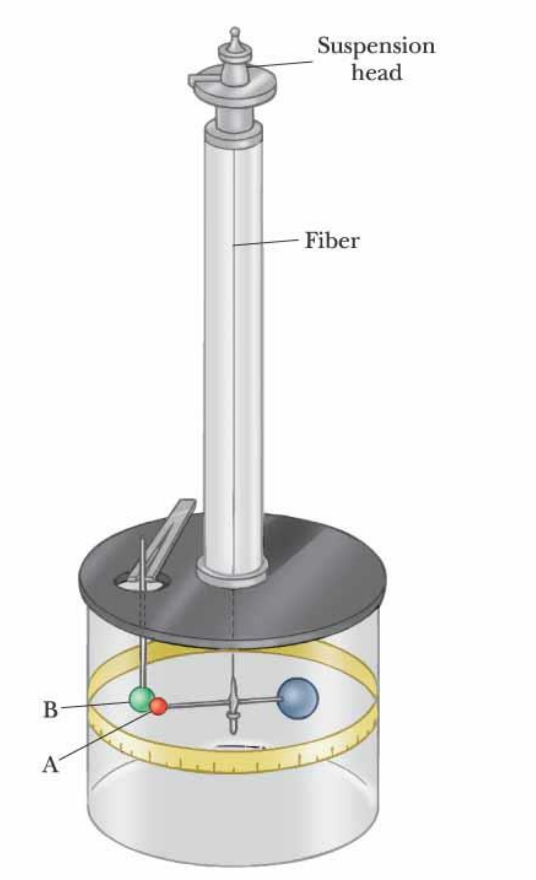
- Electrical insulators are materials in which all of the electrons are bound to atoms.
  - These electrons can not move relatively freely through the material.
  - Examples of good insulators include glass, rubber and wood.
  - When a good insulator is charged in a small region, the charge is unable to move to other regions of the material.

Semiconductors

- The electrical properties of semiconductors are somewhere between those of insulators and conductors
- Examples of semiconductor materials include silicon and germanium.

23.3 Coulomb's Law

- Charles Coulomb measured the magnitudes of electric forces between two small charged spheres.
- He found the force depended on the charges and the distance between them.



Coulomb's experiment Results

The electric force between two stationary charged particles

- is inversely proportional to the square of the separation r between the particles and directed along the line joining them;
- is proportional to the product of the charges q_1 and q_2 on the two particles;
- is attractive if the charges are of opposite sign and repulsive if the charges have the same sign;
- is a conservative force.

Coulomb's Law, Equation

- The term point charge refers to a particle of zero size that carries an electric charge.
- The electrical behavior of electrons and protons is well described by modeling them as point charges.

Mathematically, $$F_e = k_e \frac{|q_1||q_2|}{r^2}$$

The SI unit of charge is the **coulomb** (C)

k_e is called the **Coulomb constant**

$k_e = 1/(4\pi\varepsilon_o) = 8.9876 \times 10^9\ \mathrm{N{\cdot}m^2/C^2}$

ε_o is the **permittivity of free space**

$\varepsilon_o = 8.8542 \times 10^{-12}\ \mathrm{C^2 / N{\cdot}m^2}$

Coulomb's Law, Notes

- Remember the charges need to be in coulombs

  e is the smallest unit of charge except *quarks*

  $$e = 1.6 \times 10^{-19}\ \mathrm{C}$$

  1 C needs 6.24×10^{18} electrons or protons

- Typical charges can be in the μC range

- Remember that force is a *vector* quantity

Particle Summary

TABLE 23.1

Charge and Mass of the Electron, Proton, and Neutron

Particle	Charge (C)	Mass (kg)
Electron (e)	$-1.602\,176\,5 \times 10^{-19}$	$9.109\,4 \times 10^{-31}$
Proton (p)	$+1.602\,176\,5 \times 10^{-19}$	$1.672\,62 \times 10^{-27}$
Neutron (n)	0	$1.674\,93 \times 10^{-27}$

$$F_e = k_e \frac{|q_1||q_2|}{r^2}$$

- Double one of the charges → force doubles
- Change sign of one of the charges→ force changes direction
- Change sign of *both* charges → force stays the same
- Double the distance between charges→force 4 times weaker
- Double both charges → force four times stronger

Coulomb's Law Examples

What is the force between two charges of 1 C separated by 1 meter?

Answer: 8.99×10^9 N,

Coulomb's Law Examples

What is the magnitude of the electric force of attraction between an iron nucleus (q=+26e) and its innermost electron if the distance between them is 1.5 x 10^{-12} m

The magnitude of the Coulomb force is

$$F_e = k_e \frac{|q_1|\,|q_2|}{r^2}$$

= (9.0 x 10^{9} N · m^2/C^2)(26)(1.60 x 10^{-19} C)(1.60 x 10^{-19} C)/(1.5x10^{-12} m$)^2$
= 2.7 x 10^{-3} N.

Coulomb's Law Examples

Part 1: The nucleus of a helium atom has two protons and two neutrons. the magnitude of the electric force between the two protons in the helium nucleus is 58 N. What if the distance is doubled; how will the force change?

Answer: 14.5 N

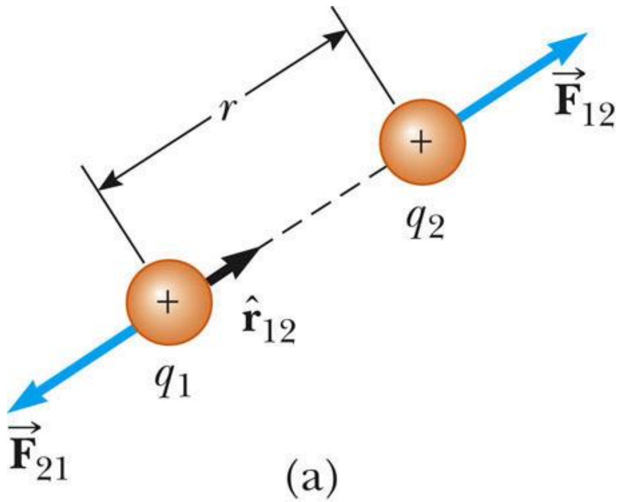
Inverse square law: If the distance is doubled then the force is reduced by a factor of 4.

Vector Nature of Electric Forces

- In vector form,

$$\vec{\mathbf{F}}_{12} = k_e \frac{q_1 q_2}{r^2} \hat{\mathbf{r}}_{12}$$

- $\hat{\mathbf{r}}_{12}$ is a unit vector directed from q_1 to q_2
- The like charges produce a repulsive force between them.
- **Electrical forces obey Newton's Third Law:** the force on q_1 is equal in magnitude and opposite in direction to the force on q_2



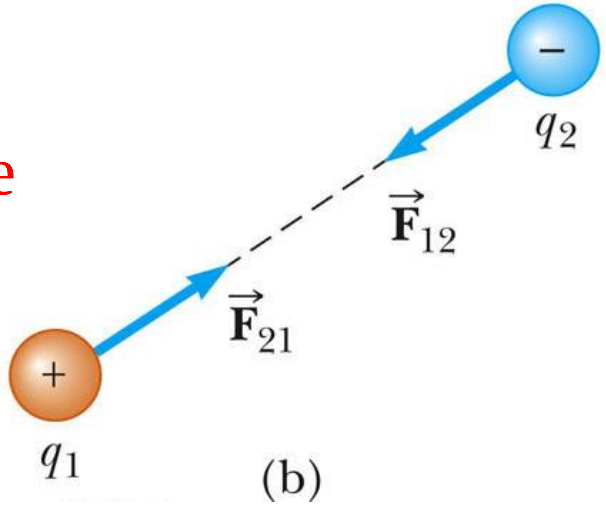
$$\vec{\mathbf{F}}_{21} = -\vec{\mathbf{F}}_{12}$$

Vector Nature of Electric Forces

- Two point charges are separated by a distance *r*

- The unlike charges produce an attractive force between them

- With unlike signs for the charges, the product q_1q_2 is negative and the force is attractive



Example 23.1 The Hydrogen Atom

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

Solution From Coulomb's law, we find that the magnitude of the electric force is

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

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

gravitational force is

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

$$= (6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2) \times \frac{(9.11 \times 10^{-31} \text{ kg})(1.67 \times 10^{-27} \text{ kg})}{(5.3 \times 10^{-11} \text{ m})^2}$$

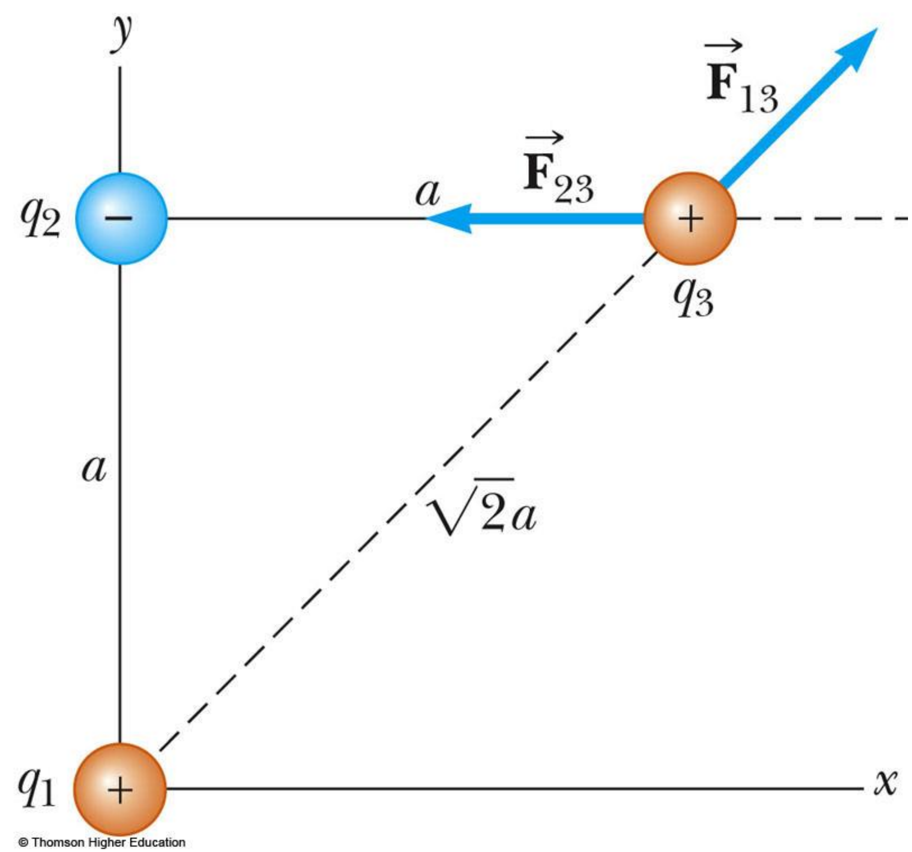
$$= \boxed{3.6 \times 10^{-47} \text{ N}}$$

q_1=e
q_2=-e
r=5.3x10^{-11} m
$F_{e=}$?
F_g=?

Example(23.2): Superposition Principle

- The force exerted by q_1 on q_3 is $\vec{F}_{13}$
- The force exerted by q_2 on q_3 is $\vec{F}_{23}$
- The *resultant force* exerted on q_3 is the vector sum of $\vec{F}_{13}$ and $\vec{F}_{23}$

$$\mathbf{F}_3 = \vec{F}_{23} + \vec{F}_{13}$$



Example 23.2 Find the Resultant Force

Consider three point charges located at the corners of a right triangle as shown in Figure 23.8, where $q_1 = q_3 = 5.0\ \mu C$, $q_2 = -2.0\ \mu C$, and $a = 0.10$ m. Find the resultant force exerted on q_3.

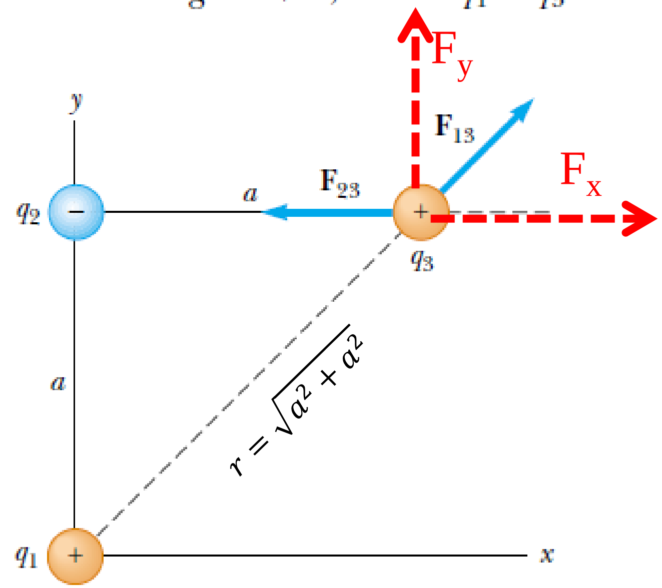


Figure 23.8 (Example 23.2) The force exerted by q_1 on q_3 is $\mathbf{F}_{13}$. The force exerted by q_2 on q_3 is $\mathbf{F}_{23}$. The resultant force $\mathbf{F}_3$ exerted on q_3 is the vector sum $\mathbf{F}_{13} + \mathbf{F}_{23}$.

Solution First, note the direction of the individual forces exerted by q_1 and q_2 on q_3. The force $\mathbf{F}_{23}$ exerted by q_2 on q_3 is attractive because q_2 and q_3 have opposite signs. The force $\mathbf{F}_{13}$ exerted by q_1 on q_3 is repulsive because both charges are positive.

The magnitude of $\mathbf{F}_{23}$ is

$$F_{23} = k_e \frac{|q_2||q_3|}{a^2}$$

$$= (8.99 \times 10^9\ \mathrm{N \cdot m^2/C^2}) \frac{(2.0 \times 10^{-6}\ \mathrm{C})(5.0 \times 10^{-6}\ \mathrm{C})}{(0.10\ \mathrm{m})^2}$$

$$= 9.0\ \mathrm{N}$$

In the coordinate system shown in Figure 23.8, the attractive force $\mathbf{F}_{23}$ is to the left (in the negative x direction).

$q_1=q_3=5\mu C$

$q_3=-2\mu C$

$r=2^{1/2}a$ m

$F_{3=}?$

The magnitude of the force $\mathbf{F}_{13}$ exerted by q_1 on q_3 is

$$F_{13} = k_e \frac{|q_1||q_3|}{(\sqrt{2}a)^2}$$

$$= (8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2) \frac{(5.0 \times 10^{-6} \text{ C})(5.0 \times 10^{-6} \text{ C})}{2(0.10 \text{ m})^2}$$

$$= 11 \text{ N}$$

The repulsive force $\mathbf{F}_{13}$ makes an angle of 45° with the x axis. Therefore, the x and y components of $\mathbf{F}_{13}$ are equal, with magnitude given by $F_{13} \cos 45° = 7.9$ N.

Combining $\mathbf{F}_{13}$ with $\mathbf{F}_{23}$ by the rules of vector addition, we arrive at the x and y components of the resultant force acting on q_3:

$$F_{3x} = F_{13x} + F_{23x} = 7.9 \text{ N} + (-9.0 \text{ N}) = -1.1 \text{ N}$$

$$F_{3y} = F_{13y} + F_{23y} = 7.9 \text{ N} + 0 = 7.9 \text{ N}$$

We can also express the resultant force acting on q_3 in unit-vector form as

$$\mathbf{F}_3 = \boxed{(-1.1\hat{\mathbf{i}} + 7.9\hat{\mathbf{j}}) \text{ N}}$$

What If? **What if the signs of all three charges were changed to the opposite signs? How would this affect the result for $\mathbf{F}_3$?**

Answer The charge q_3 would still be attracted toward q_2 and repelled from q_1 with forces of the same magnitude. Thus, the final result for $\mathbf{F}_3$ would be exactly the same.

$$F_x = F\cos\theta$$
$$F_y = F\sin\theta$$
$$\theta = 45^o$$

$$\Longrightarrow \quad F_x = F_y = 7.9 \text{ N}$$

Example 23.3 Where Is the Resultant Force Zero?

Interactive

Three point charges lie along the x axis as shown in Figure 23.9. The positive charge $q_1 = 15.0\ \mu\text{C}$ is at $x = 2.00$ m, the positive charge $q_2 = 6.00\ \mu\text{C}$ is at the origin, and the resultant force acting on q_3 is zero. What is the x coordinate of q_3?

Solution Because q_3 is negative and q_1 and q_2 are positive, the forces $\mathbf{F}_{13}$ and $\mathbf{F}_{23}$ are both attractive, as indicated in Figure 23.9. From Coulomb's law, $\mathbf{F}_{13}$ and $\mathbf{F}_{23}$ have magnitudes

$$F_{13} = k_e \frac{|q_1||q_3|}{(2.00 - x)^2} \qquad F_{23} = k_e \frac{|q_2||q_3|}{x^2}$$

For the resultant force on q_3 to be zero, $\mathbf{F}_{23}$ must be equal in magnitude and opposite in direction to $\mathbf{F}_{13}$. Setting the magnitudes of the two forces equal, we have

$$k_e \frac{|q_2||q_3|}{x^2} = k_e \frac{|q_1||q_3|}{(2.00 - x)^2}$$

Noting that k_e and $|q_3|$ are common to both sides and so can be dropped, we solve for x and find that

$$(2.00 - x)^2 |q_2| = x^2 |q_1|$$

$$(4.00 - 4.00x + x^2)(6.00 \times 10^{-6}\ \text{C}) = x^2(15.0 \times 10^{-6}\ \text{C})$$

This can be reduced to the following quadratic equation:

$$3.00x^2 + 8.00x - 8.00 = 0$$

Solving this quadratic equation for x, we find that the positive root is $x = $ 0.775 m. There is also a second root, $x = -3.44$ m. This is another location at which the magnitudes of the forces on q_3 are equal, but both forces are in the same direction at this location.

What If? Suppose charge q_3 is constrained to move only along the x axis. From its initial position at $x = 0.775$ m, it is pulled a very small distance along the x axis. When released, will it return to equilibrium or be pulled further from equilibrium? That is, is the equilibrium stable or unstable?

Answer If the charge is moved to the right, $\mathbf{F}_{13}$ becomes larger and $\mathbf{F}_{23}$ becomes smaller. This results in a net force to the right, in the same direction as the displacement. Thus, the equilibrium is *unstable.*

Note that if the charge is constrained to stay at a *fixed* x coordinate but allowed to move up and down in Figure 23.9, the equilibrium is stable. In this case, if the charge is pulled upward (or downward) and released, it will move back toward the equilibrium position and undergo oscillation.

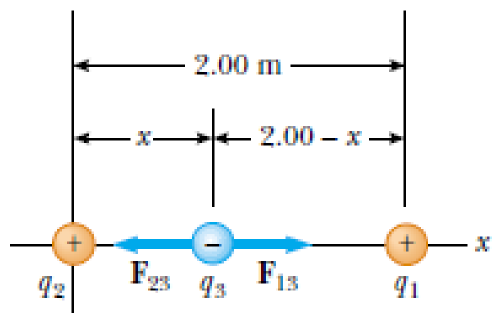


Figure 23.9 (Example 23.3) Three point charges are placed along the x axis. If the resultant force acting on q_3 is zero, then the force $\mathbf{F}_{13}$ exerted by q_1 on q_3 must be equal in magnitude and opposite in direction to the force $\mathbf{F}_{23}$ exerted by q_2 on q_3.

23.4 The Electric Field

- The electric force is a field force.

- Field forces can act through space producing effect even with no physical contact between interacting objects.

- An electric field is said to exist in the region of space around a charged object. This charged object is the source charge.

- When another charged object, the test charge, enters this electric field, an electric force acts on it.

23.4 The Electric Field

- The electric field is defined as the electric force on the test charge per unit charge

- The electric field vector, $\vec{\mathbf{E}}$, at a point in space is defined as the electric force $\vec{\mathbf{F}}$ acting on a positive test charge, q_o, placed at that point divided by the test charge:

$$\vec{\mathbf{E}} \equiv \frac{\vec{\mathbf{F}}}{q_o}$$

23.4 The Electric Field

- $\vec{E}$ is the field produced by some charge or charge distribution, separate from the test charge.

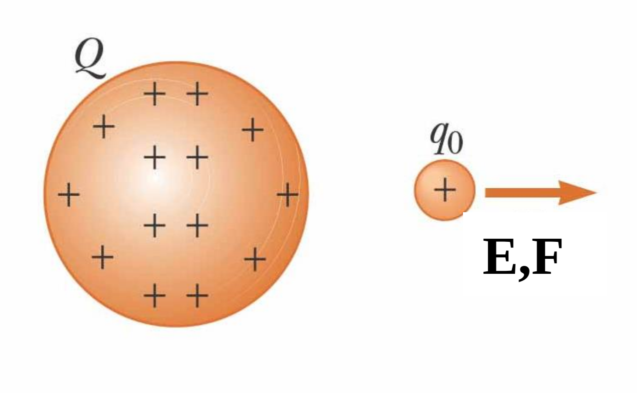
- The existence of an electric field is a property of the source charge →the presence of the test charge is not necessary for the field to exist.

- The test charge serves as a detector of the field.

23.4 The Electric Field

- The direction of $\vec{E}$ is that of the force on a positive test charge

- The SI units of $\vec{E}$ are N/C
- We can also say that an electric field exists at a point if a test charge at that point experiences an electric force



Relationship Between F and E

- $$\overrightarrow{F_e} = q\vec{E}$$

  This is valid for a point charge only. For larger objects, the field may vary over the size of the object. **SEE (Page 717)**

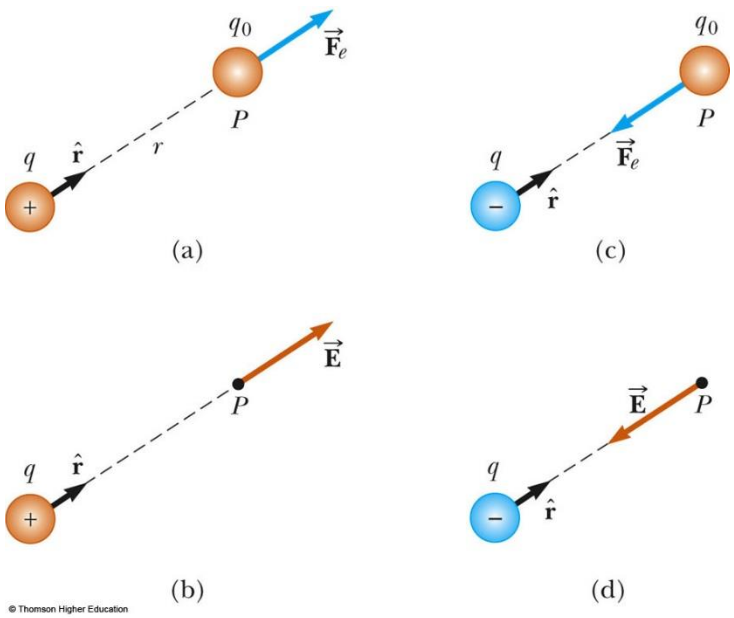
- If source charge, *q*, is positive, the force and the field are in the same direction.

- If source charge, *q*, is negative, the force and the field are in opposite directions.

Relationship Between F and E

- a) q is positive, the force is directed away from q.
- b) The direction of the field is also away from the positive source charge.

- c) q is negative, the force is directed toward q.
- d) The field is also toward the negative source charge.



Electric Field, Vector Form

- Remember Coulomb's law, between the source, q, and test, q_o, charges, can be expressed as:

$$\vec{\mathbf{F}}_e = k_e \frac{q q_o}{r^2} \hat{\mathbf{r}}$$

- Then, the electric field will be:

$$\vec{\mathbf{E}} = \frac{\vec{\mathbf{F}}_e}{q_o} = k_e \frac{q}{r^2} \hat{\mathbf{r}}$$

Superposition with Electric Fields

- At any point *P*, the total electric field due to a group of source charges equals the vector sum of the electric fields of all the charges.

$$\vec{\mathbf{E}} = k_e \sum_i \frac{q_i}{r_i^{\,2}} \hat{\mathbf{r}}_i$$

Example 23.5 Electric Field Due to Two Charges

A charge $q_1 = 7.0\ \mu C$ is located at the origin, and a second charge $q_2 = -5.0\ \mu C$ is located on the x axis, 0.30 m from the origin (Fig. 23.14). Find the electric field at the point P, which has coordinates (0, 0.40) m.

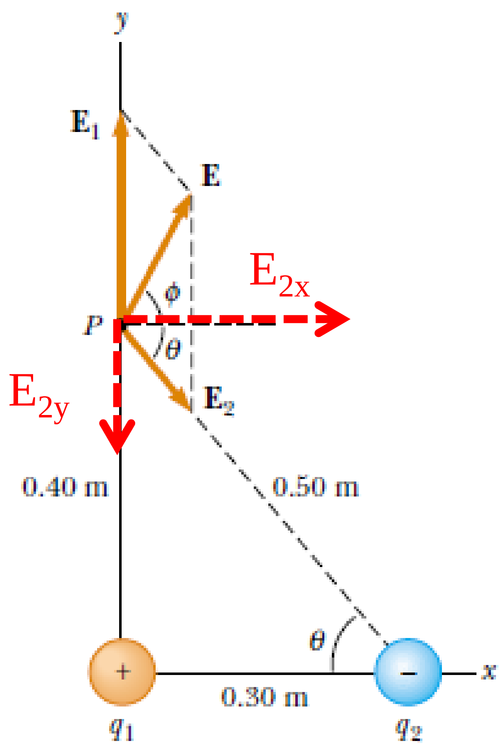


Figure 23.14 (Example 23.5) The total electric field $\mathbf{E}$ at P equals the vector sum $\mathbf{E}_1 + \mathbf{E}_2$, where $\mathbf{E}_1$ is the field due to the positive charge q_1 and $\mathbf{E}_2$ is the field due to the negative charge q_2.

Solution First, let us find the magnitude of the electric field at P due to each charge. The fields $\mathbf{E}_1$ due to the 7.0-μC charge and $\mathbf{E}_2$ due to the -5.0-μC charge are shown in Figure 23.14. Their magnitudes are

$$E_1 = k_e \frac{|q_1|}{{r_1}^2} = (8.99 \times 10^9\ \mathrm{N \cdot m^2/C^2}) \frac{(7.0 \times 10^{-6}\ \mathrm{C})}{(0.40\ \mathrm{m})^2}$$
$$= 3.9 \times 10^5\ \mathrm{N/C}$$

$$E_2 = k_e \frac{|q_2|}{{r_2}^2} = (8.99 \times 10^9\ \mathrm{N \cdot m^2/C^2}) \frac{(5.0 \times 10^{-6}\ \mathrm{C})}{(0.50\ \mathrm{m})^2}$$
$$= 1.8 \times 10^5\ \mathrm{N/C}$$

The vector $\mathbf{E}_1$ has only a y component. The vector $\mathbf{E}_2$ has an x component given by $E_2 \cos\theta = \frac{3}{5}E_2$ and a negative y component given by $-E_2 \sin\theta = -\frac{4}{5}E_2$. Hence, we can express the vectors as

$$\mathbf{E}_1 = 3.9 \times 10^5 \hat{\mathbf{j}}\ \mathrm{N/C}$$
$$\mathbf{E}_2 = (1.1 \times 10^5 \hat{\mathbf{i}} - 1.4 \times 10^5 \hat{\mathbf{j}})\ \mathrm{N/C}$$

The resultant field $\mathbf{E}$ at P is the superposition of $\mathbf{E}_1$ and $\mathbf{E}_2$:

$$\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2 = (1.1 \times 10^5 \hat{\mathbf{i}} + 2.5 \times 10^5 \hat{\mathbf{j}})\ \mathrm{N/C}$$

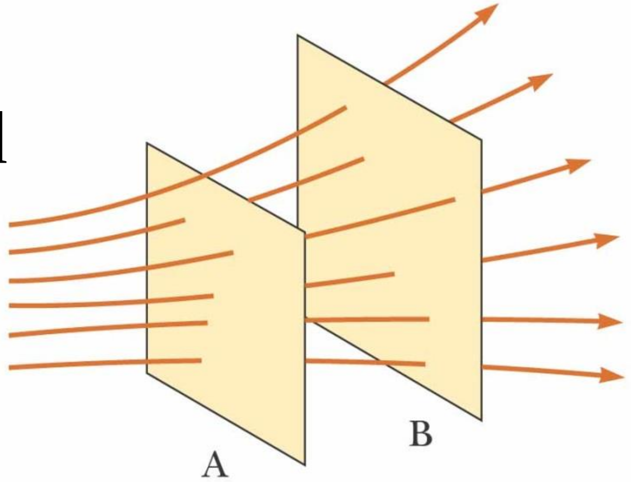
From this result, we find that $\mathbf{E}$ makes an angle ϕ of 66° with the positive x axis and has a magnitude of 2.7×10^5 N/C.

23.6 Electric Field Lines

- Field lines give us a means of representing the electric field pictorially.
- The electric field vector $\vec{\mathbf{E}}$ is tangent to the electric field line at each point.
- The line has a direction that is the same as that of the electric field vector.
- The number of lines per unit area through a surface perpendicular to the lines is proportional to the magnitude of the electric field in that region.

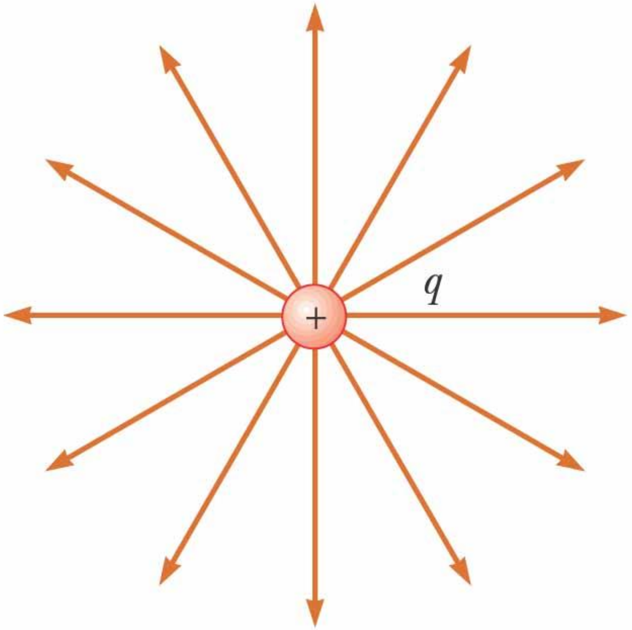
23.6 Electric Field Lines

- The density of lines through surface A is greater than through surface B.
- The magnitude of the electric field is greater on surface A than B.
- The lines at different locations point in different directions.
- This indicates the field is nonuniform.



23.6 Electric Field Lines Positive Point Charge

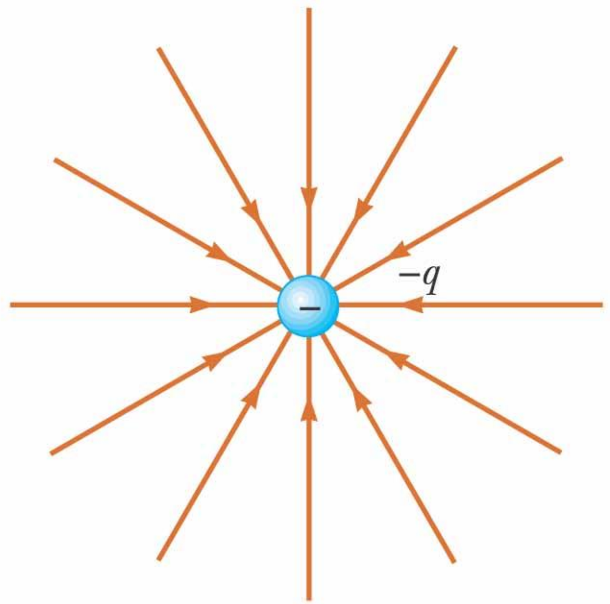
- The field lines radiate outward in all directions.
- In three dimensions, the distribution is spherical.
- The lines are directed away from the source charge.
- A positive test charge would be repelled away from the positive source charge.



(a)

23.6 Electric Field Lines Negative Point Charge

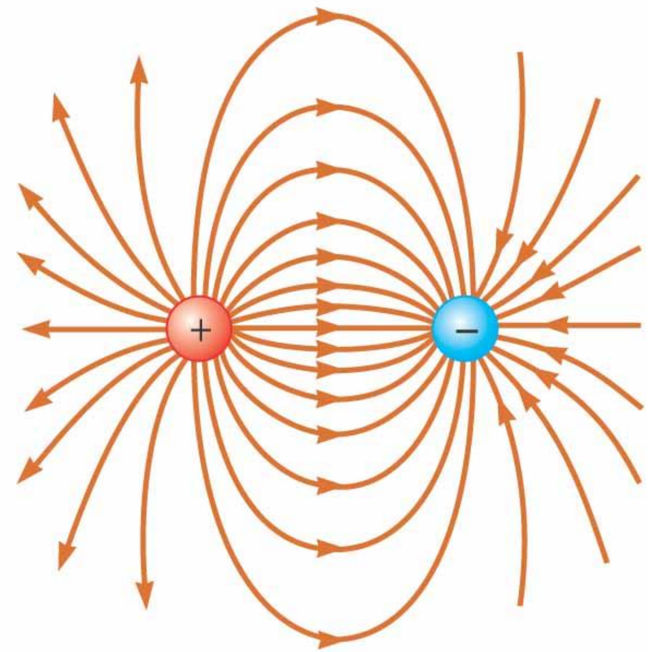
- The field lines radiate inward in all directions.
- In three dimensions, the distribution is spherical.
- The lines are directed toward the source charge.
- A positive test charge would be attracted toward the negative source charge.



(b)

23.6 Electric Field Lines Dipole

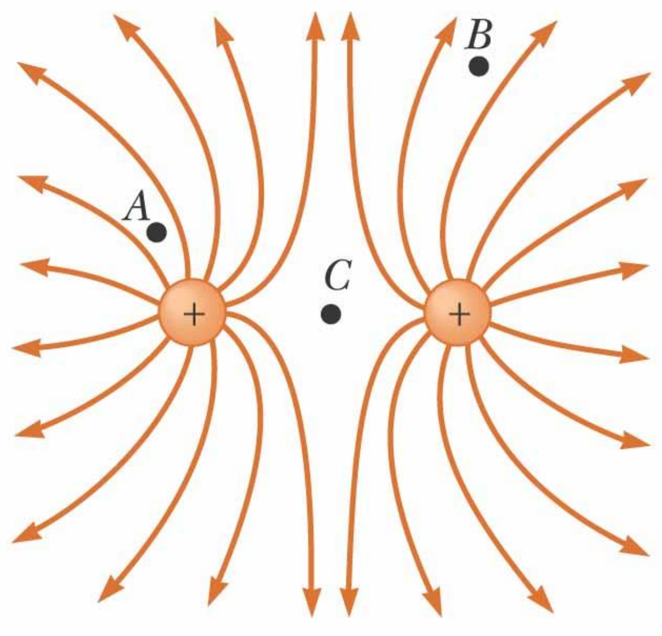
- The charges are equal and opposite.
- The number of field lines leaving the positive charge equals the number of lines terminating on the negative charge.



(a)

23.6 Electric Field Lines
Like Charges

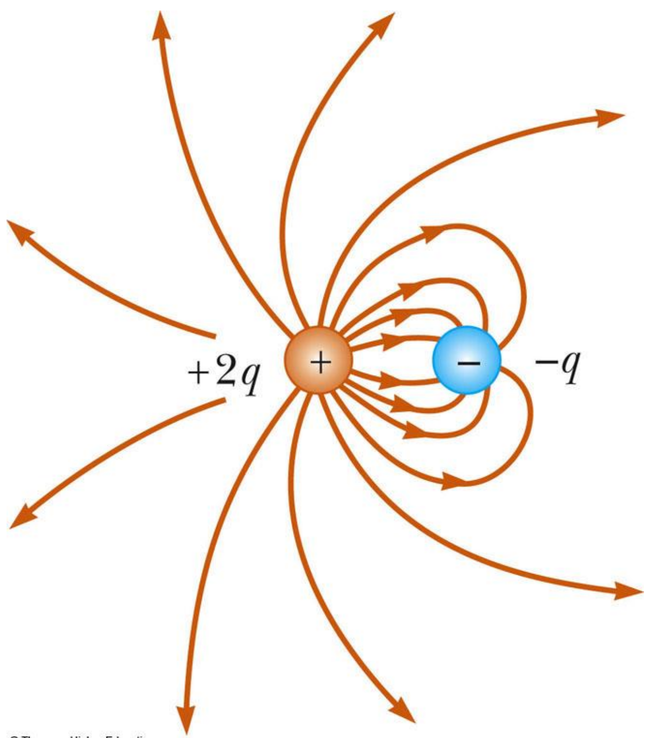
- The charges are equal and positive
- The same number of lines leave each charge since they are equal in magnitude
- At a great distance, the field is approximately equal to that of a single charge of $2q$



(a)

23.6 Electric Field Lines Unequal Charges

- The positive charge is twice the magnitude of the negative charge
- Two lines leave the positive charge for each line that terminates on the negative charge
- At a great distance, the field would be approximately the same as that due to a single charge of $+q$



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23.6 Electric Field Lines
Rules for Drawing

- The lines must <u>begin</u> on a <u>positive</u> charge and <u>terminate</u> on a <u>negative</u> charge. In the case of an <u>excess</u> of one type of charge, some lines will begin or end <u>infinitely</u> far away.
- The <u>number</u> of lines drawn leaving a positive charge or approaching a negative charge is <u>proportional</u> to the <u>magnitude</u> of the charge.
- <u>No</u> two field <u>lines</u> can cross.
- Remember field lines are <u>not</u> material objects, they are a pictorial <u>representation</u> used to qualitatively describe the electric field.

HW

Serway 6th edition page 730

Problems: 4,5,7,9,11,13,15,19,21 and Example 23.4 (page 714)

Due time: Mon, 24/11/1434 H