Chapter 23

Electric Fields

Electricity and Magnetism, Some History

- Many applications
  - Macroscopic and microscopic
- Chinese
  - Documents suggest that magnetism was observed as early as 2000 BC
- Greeks
  - Electrical and magnetic phenomena as early as 700 BC
  - Experiments with amber and magnetite

Electricity and Magnetism, Some History, 2

- 1600
  - William Gilbert showed electrification effects were not confined to just amber
  - The electrification effects were a general phenomena
- 1785
  - Charles Coulomb confirmed inverse square law form for electric forces

Electricity and Magnetism, Some History, 3

- 1819
  - Hans Oersted found a compass needle deflected when near a wire carrying an electric current
- 1831
  - Michael Faraday and Joseph Henry showed that when a wire is moved near a magnet, an electric current is produced in the wire

Electricity and Magnetism, Some History, 4

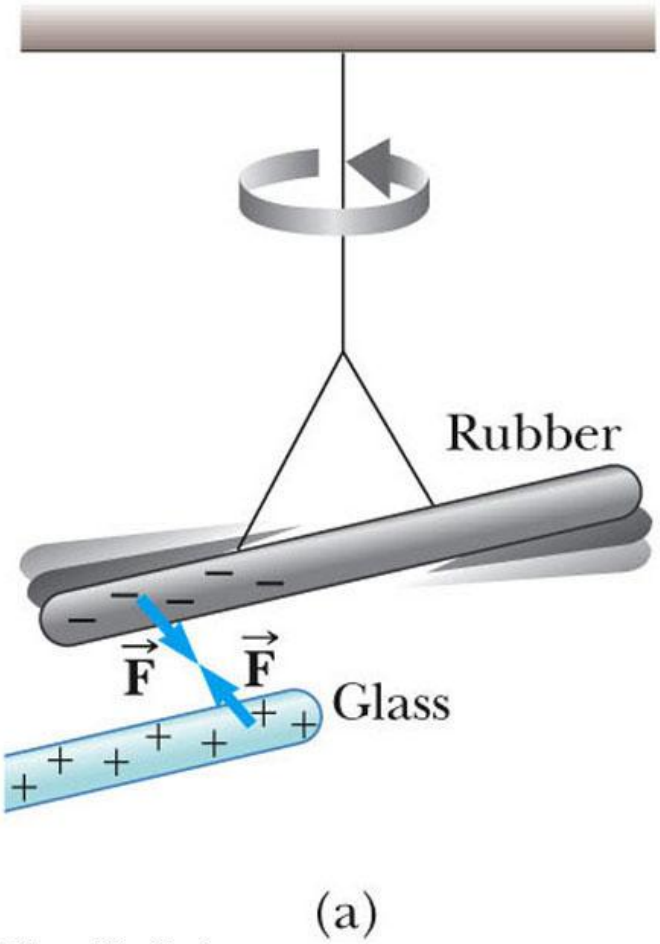
- 1873
  - James Clerk Maxwell used observations and other experimental facts as a basis for formulating the laws of electromagnetism
    - Unified electricity and magnetism
- 1888
  - Heinrich Hertz verified Maxwell’s predictions
  - He produced electromagnetic waves

Electric Charges

- There are two kinds of electric charges
  - Called 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 and charges with opposite signs attract one another

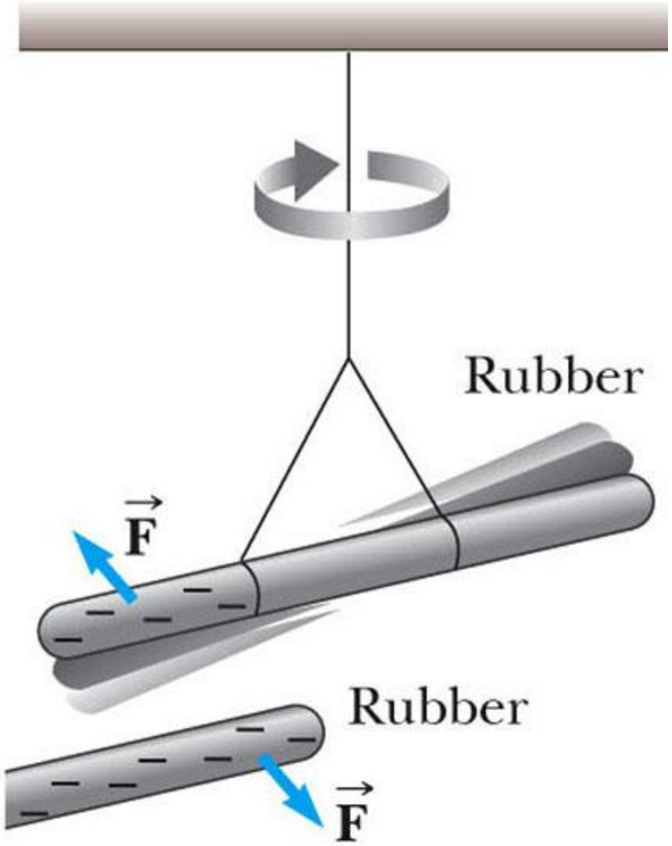
Electric Charges, 2

- The rubber rod is negatively charged
- The glass rod is positively charged
- The two rods will attract



Electric Charges, 3

- The rubber rod is negatively charged
- The second rubber rod is also negatively charged
- The two rods will repel



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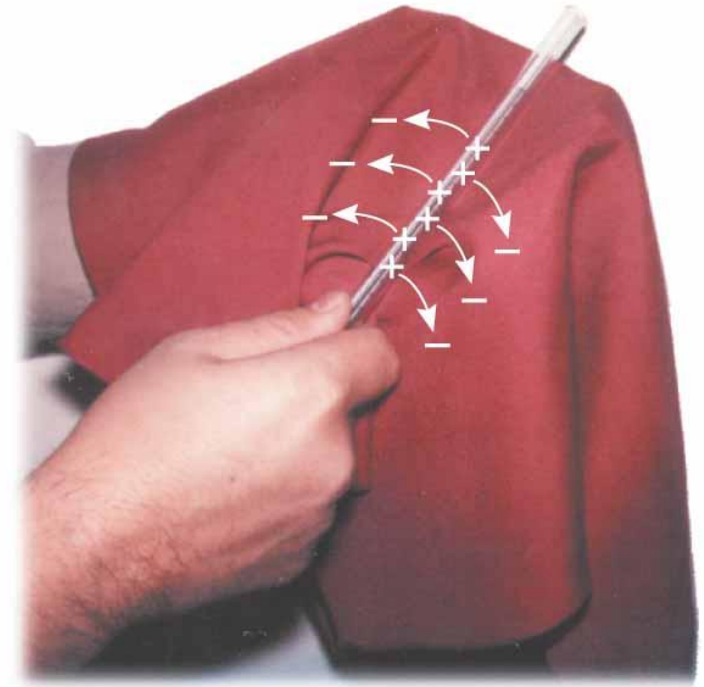
More About Electric Charges

- 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

Conservation of Electric Charges

- A glass rod is rubbed with silk
- Electrons are transferred from the glass to the silk
- Each electron adds a negative charge to the silk
- An equal positive charge is left on the rod



Quantization of Electric Charges

- 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

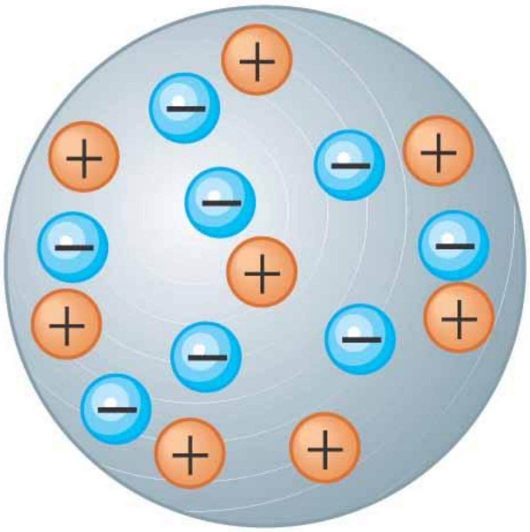
- Electrical insulators are materials in which all of the electrons are bound to atoms
  - These electrons can not move relatively freely through the material
  - Examples of good insulators include glass, rubber and wood
  - When a good insulator is charged in a small region, the charge is unable to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

Charging by Induction

- Charging by induction requires no contact with the object inducing the charge
- Assume we start with a neutral metallic sphere
  - The sphere has the same number of positive and negative charges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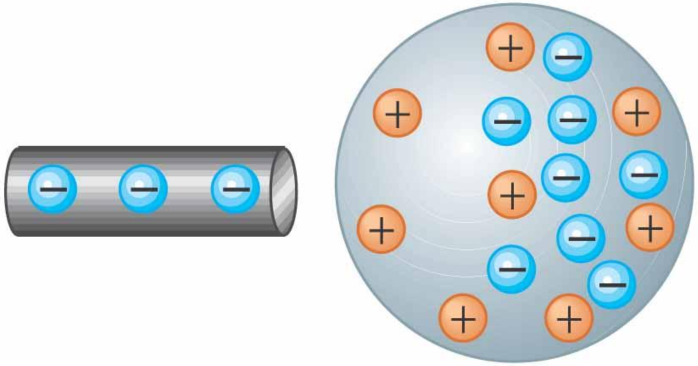
Charging by Induction, 2

- A charged rubber rod is placed near the sphere
  - It does **not** touch the sphere
- The electrons in the neutral sphere are redistributed



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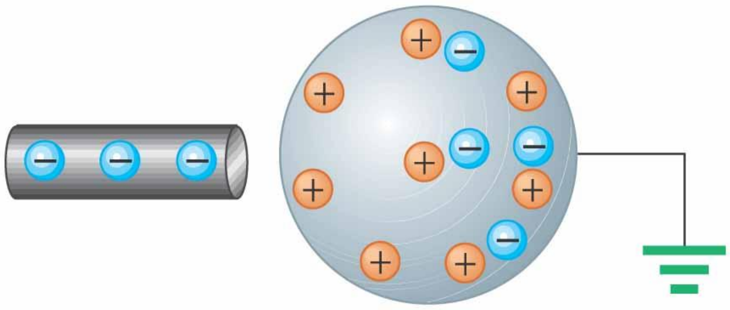
Charging by Induction, 3

- The sphere is grounded
- Some electrons can leave the sphere through the ground wire



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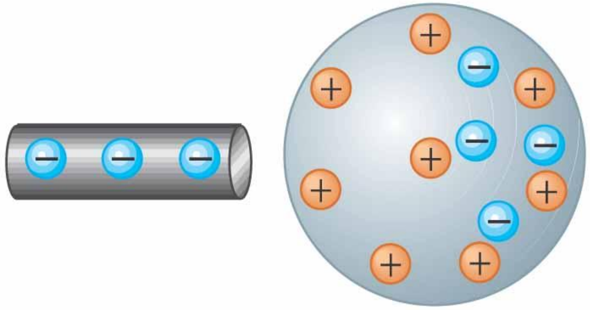
Charging by Induction, 4

- The ground wire is removed
- There will now be more positive charges
- The charges are not uniformly distributed
- The positive charge has been ***induced*** in the sphere



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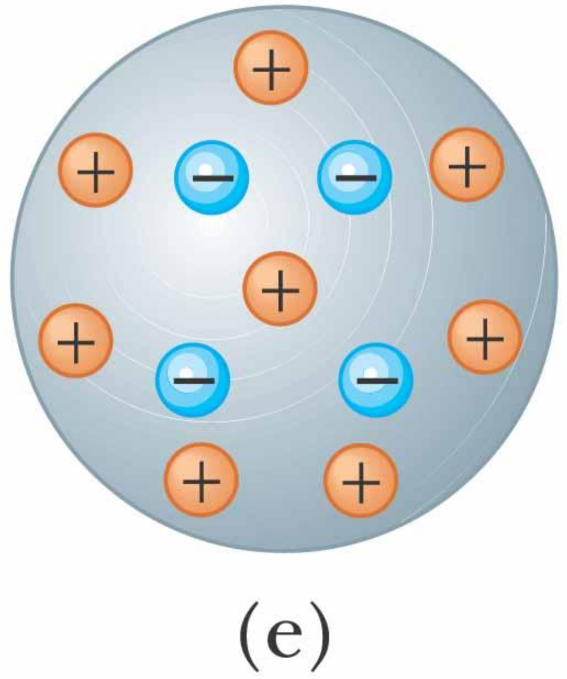
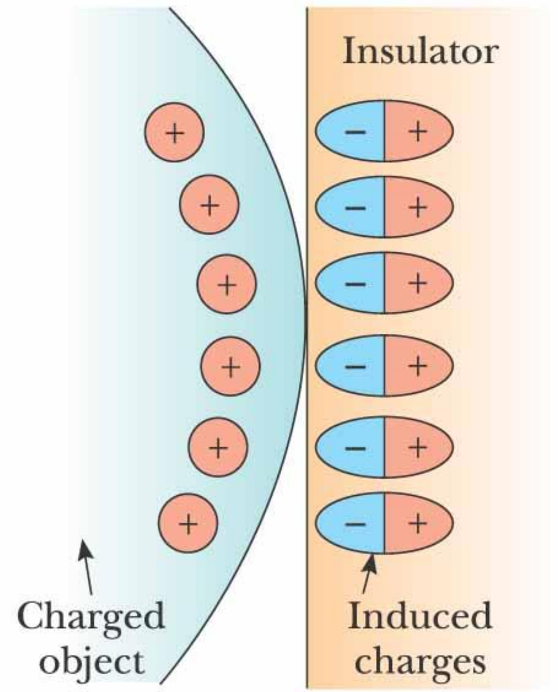
Charging by Induction, 5

- The rod is removed
- The electrons remaining on the sphere redistribute themselves
- There is still a net positive charge on the sphere
- The charge is now uniformly distributed



Charge Rearrangement in Insulators

- A process similar to induction can take place in insulators
- The charges within the molecules of the material are rearranged



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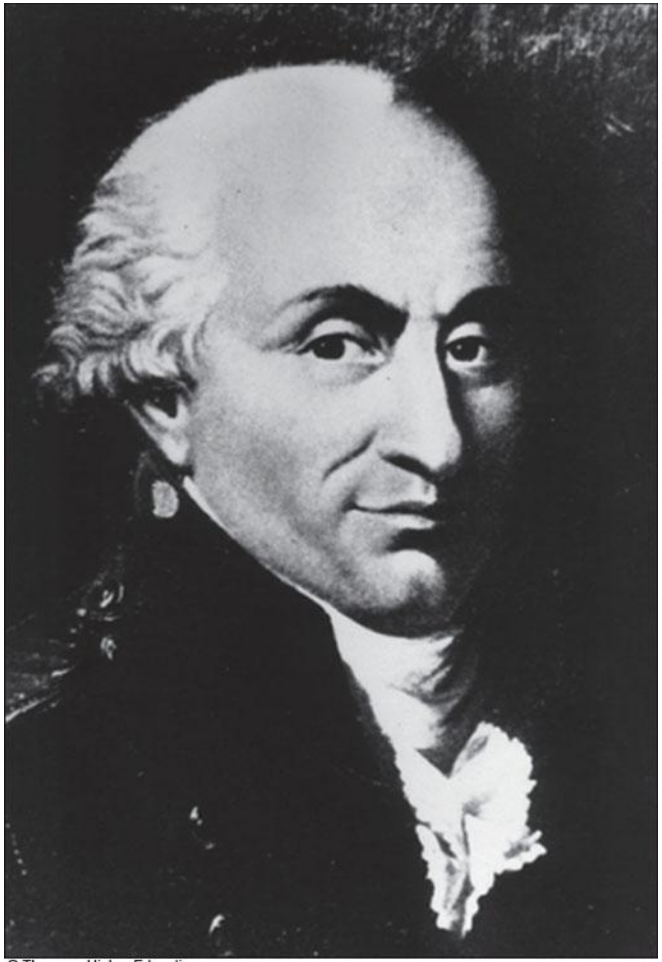
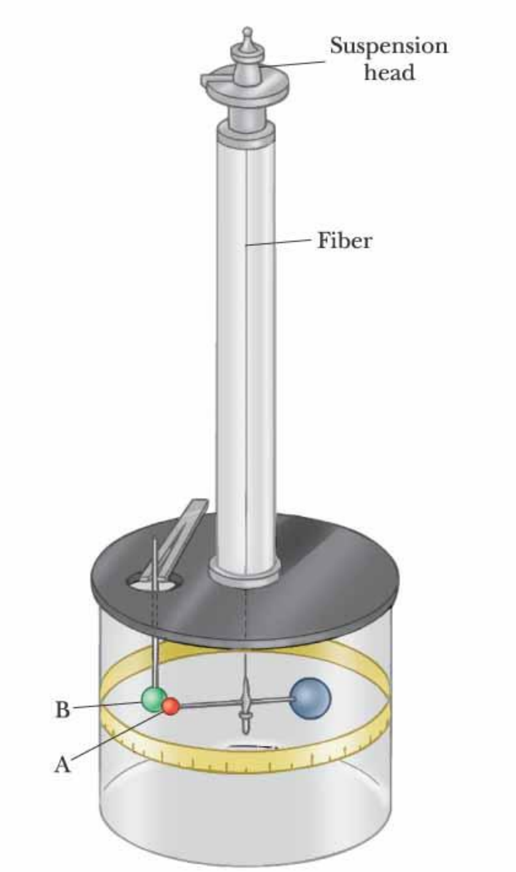
Charles Coulomb

- 1736 – 1806
- French physicist
- Major contributions were in areas of electrostatics and magnetism
- Also investigated in areas of
  - Strengths of materials
  - Structural mechanics
  - Ergonomics



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



Point Charge

- 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

Coulomb's Law, 2

- The electrical force between two stationary point charges is given by Coulomb's Law
- The force is inversely proportional to the square of the separation *r* between the charges and directed along the line joining them
- The force is proportional to the product of the charges, q_1 and q_2, on the two particles

Coulomb’s Law, 3

- The force is attractive if the charges are of opposite sign
- The force is repulsive if the charges are of like sign
- The force is a conservative force

Coulomb's Law, Equation

- 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**
  - $k_e = 8.9876 \times 10^9 \text{ N·m}^2/\text{C}^2 = 1/(4\pi e_o)$
  - e_o is the **permittivity of free space**
  - $e_o = 8.8542 \times 10^{-12} \text{ C}^2 / \text{N·m}^2$

Coulomb's Law, Notes

- Remember the charges need to be in coulombs
  - *e* is the smallest unit of charge
    - except quarks
  - $e = 1.6 \times 10^{-19}$ C
  - So 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

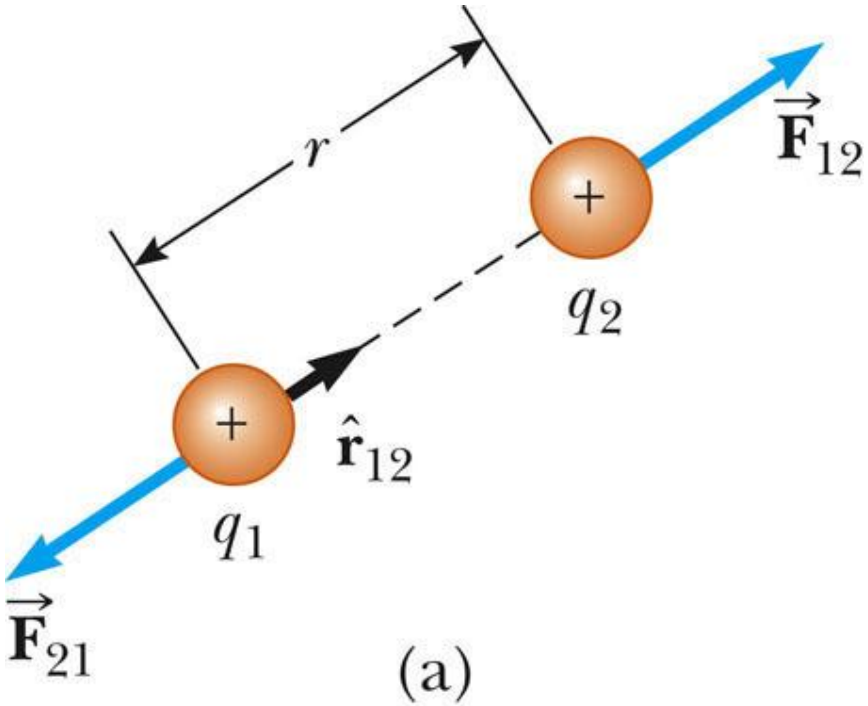
Particle	Charge (C)	Mass (kg)
Electron (e)	$-1.602\,176\,5 \times 10^{-19}$	$9.109\,4 \times 10^{-31}$
Proton (p)	$+1.602\,176\,5 \times 10^{-19}$	$1.672\,62 \times 10^{-27}$
Neutron (n)	0	$1.674\,93 \times 10^{-27}$

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
- Use the active figure to move the charges and observe the force



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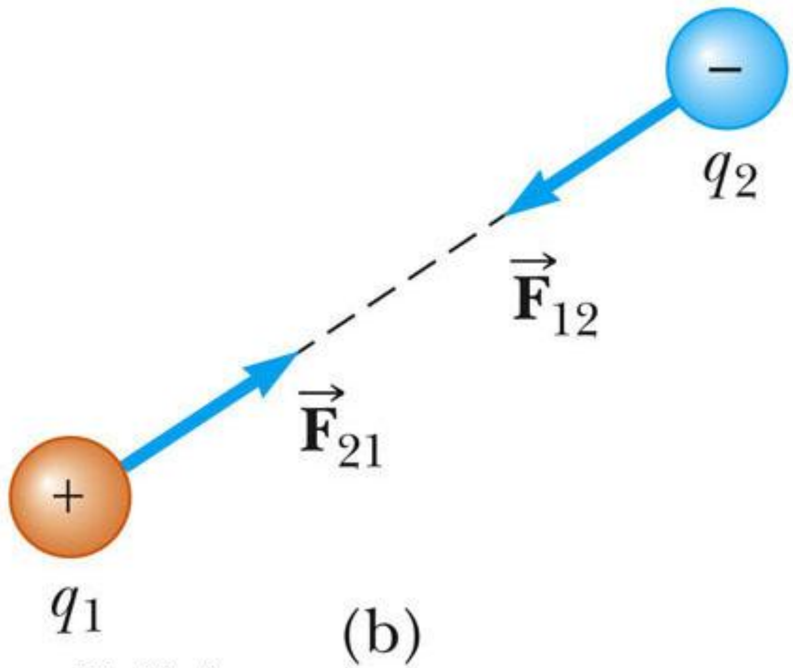
Vector Nature of Electrical Forces, 2

- 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
  - $\vec{\mathbf{F}}_{21} = -\vec{\mathbf{F}}_{12}$
- With like signs for the charges, the product q_1q_2 is positive and the force is repulsive

Vector Nature of Electrical Forces, 3

- 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
  - Use the active figure to investigate the force for different positions



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A Final Note about Directions

- The sign of the product of q_1q_2 gives the *relative* direction of the force between q_1 and q_2
- The *absolute* direction is determined by the actual location of the charges

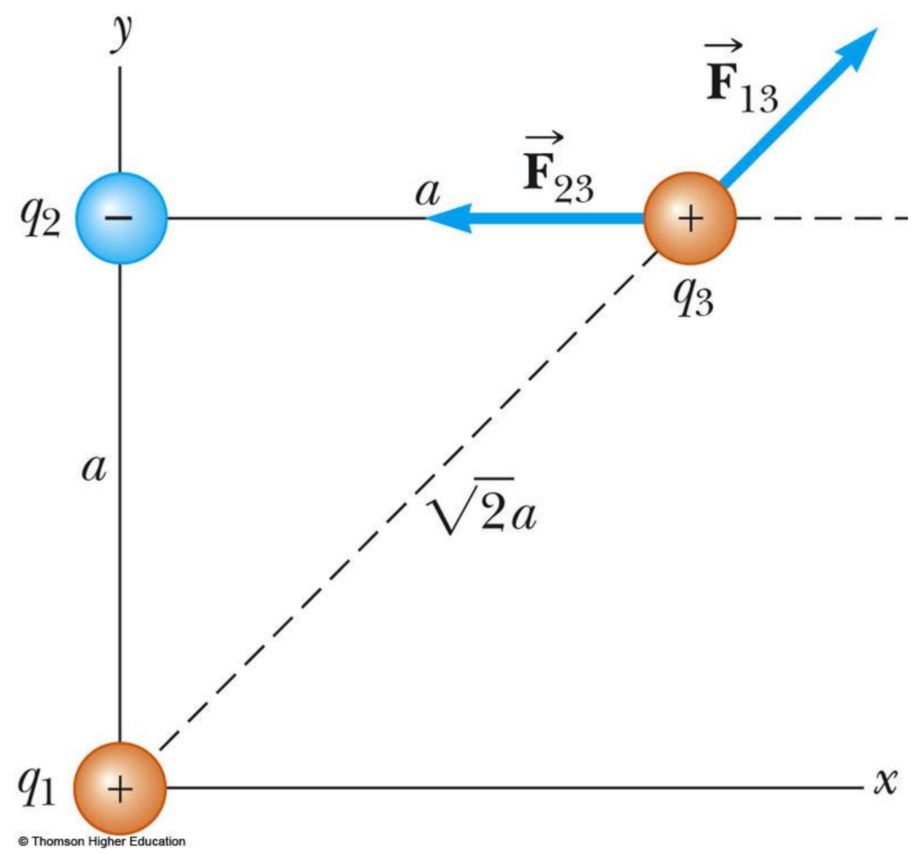
The Superposition Principle

- The resultant force on any one charge equals the vector sum of the forces exerted by the other individual charges that are present
  - Remember to add the forces *as vectors*
- The resultant force on q_1 is the vector sum of all the forces exerted on it by other charges:

$$\vec{\mathbf{F}}_1 = \vec{\mathbf{F}}_{21} + \vec{\mathbf{F}}_{31} + \vec{\mathbf{F}}_{41}$$

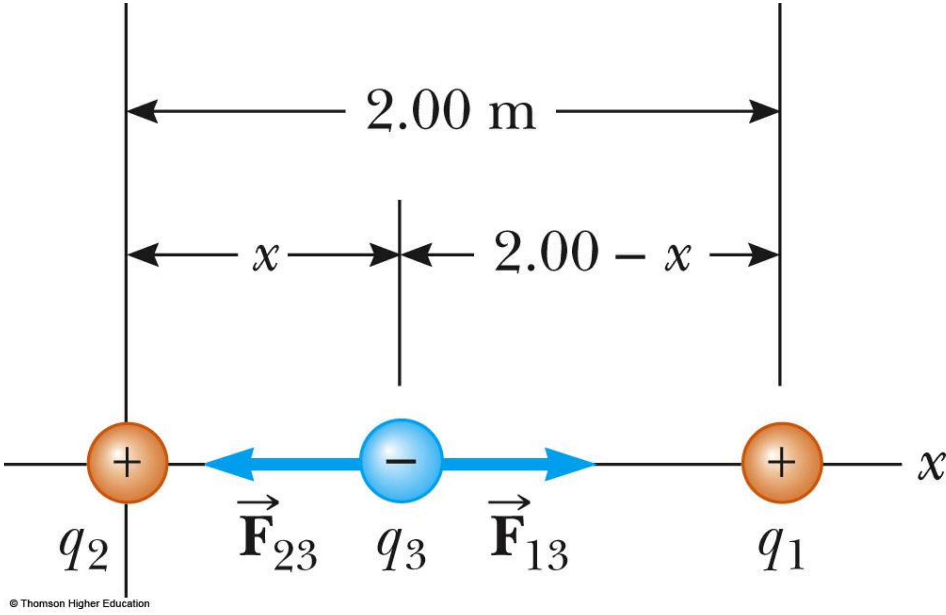
Superposition Principle, Example

- 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 $\vec{F}_{23}$



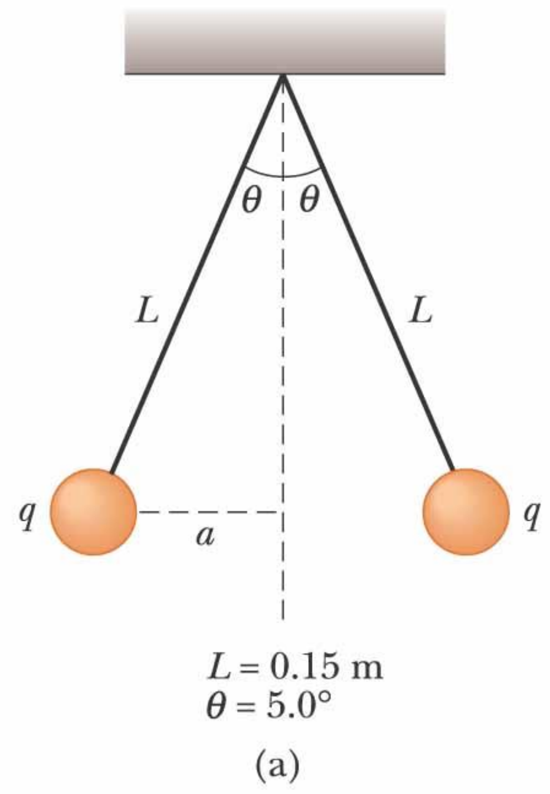
Zero Resultant Force, Example

- Where is the resultant force equal to zero?
  - The magnitudes of the individual forces will be equal
  - Directions will be opposite
- Will result in a quadratic
- Choose the root that gives the forces in opposite directions



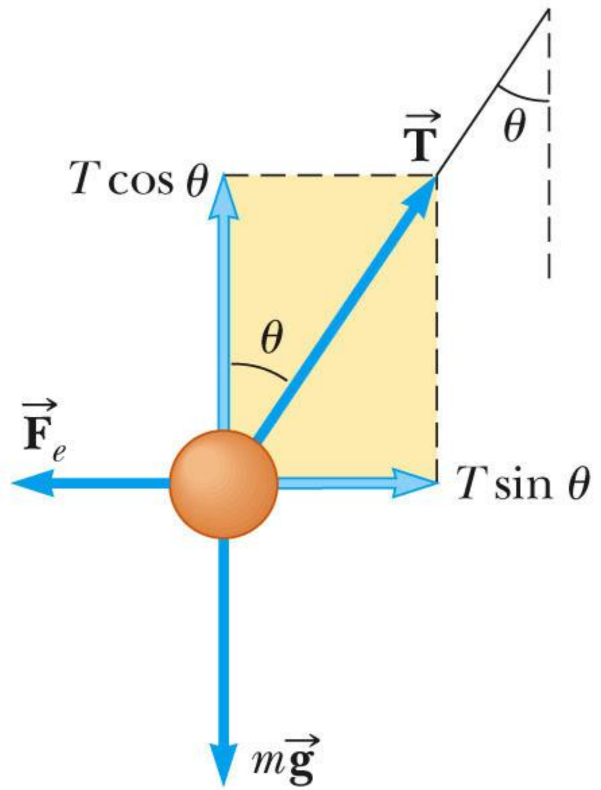
Electrical Force with Other Forces, Example

- The spheres are in equilibrium
- Since they are separated, they exert a repulsive force on each other
  - Charges are like charges
- Proceed as usual with equilibrium problems, noting one force is an electrical force



Electrical Force with Other Forces, Example cont.

- The free body diagram includes the components of the tension, the electrical force, and the weight
- Solve for |*q*|
- You cannot determine the sign of *q*, only that they both have same sign



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Electric Field – Introduction

- The electric force is a field force
- Field forces can act through space
  - The effect is produced even with no physical contact between objects
- Faraday developed the concept of a field in terms of electric fields

Electric Field – Definition

- 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

Electric Field – Definition, cont

- 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:

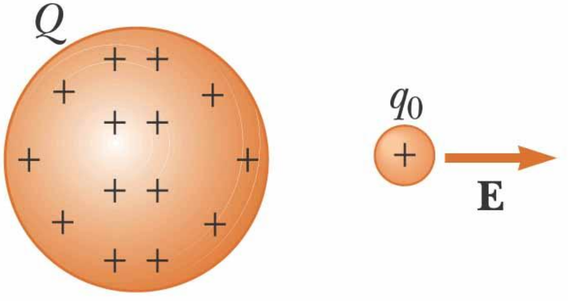
$$\vec{\mathbf{E}} \equiv \frac{\vec{\mathbf{F}}}{q_o}$$

Electric Field, Notes

- $\vec{\mathbf{E}}$ 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

Electric Field Notes, Final

- 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

- $\vec{\mathbf{F}}_e = q\vec{\mathbf{E}}$
  - This is valid for a point charge only
  - One of zero size
  - For larger objects, the field may vary over the size of the object
- If *q* is positive, the force and the field are in the same direction
- If *q* is negative, the force and the field are in opposite directions

Electric Field, Vector Form

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

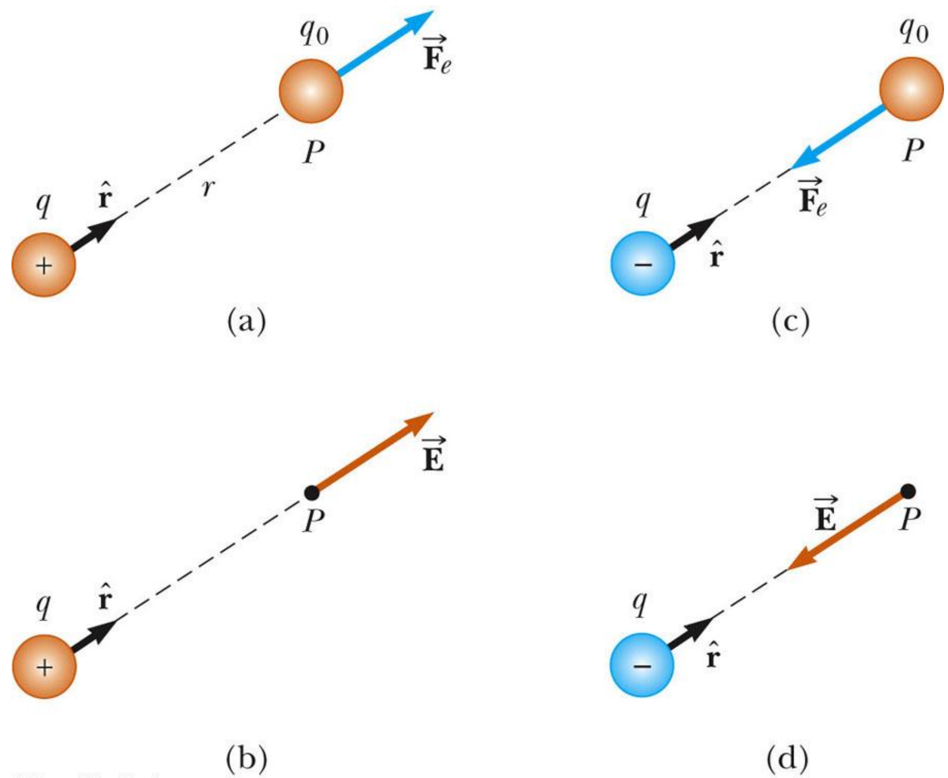
$$\vec{\mathbf{F}}_e = k_e \frac{qq_o}{r^2} \hat{\mathbf{r}}$$

- Then, the electric field will be

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

More About Electric Field Direction

- 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
- Use the active figure to change the position of point P and observe the electric field



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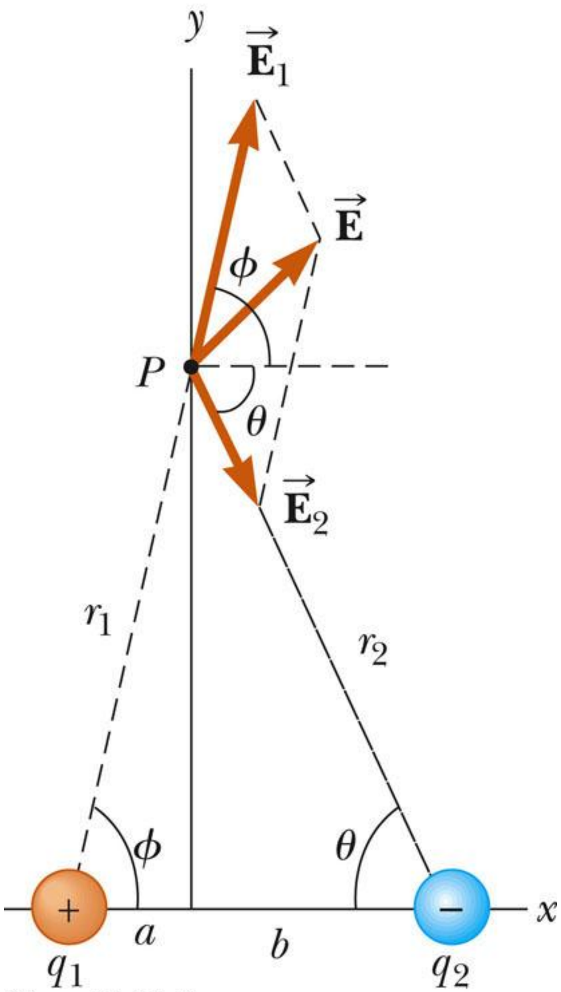
Superposition with Electric Fields

- 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

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

Superposition Example

- Find the electric field due to q_1, $\vec{\mathbf{E}}_1$
- Find the electric field due to q_2, $\vec{\mathbf{E}}_2$
- $\vec{\mathbf{E}} = \vec{\mathbf{E}}_1 + \vec{\mathbf{E}}_2$
  - Remember, the fields add as vectors
  - The direction of the individual fields is the direction of the force on a positive test charge

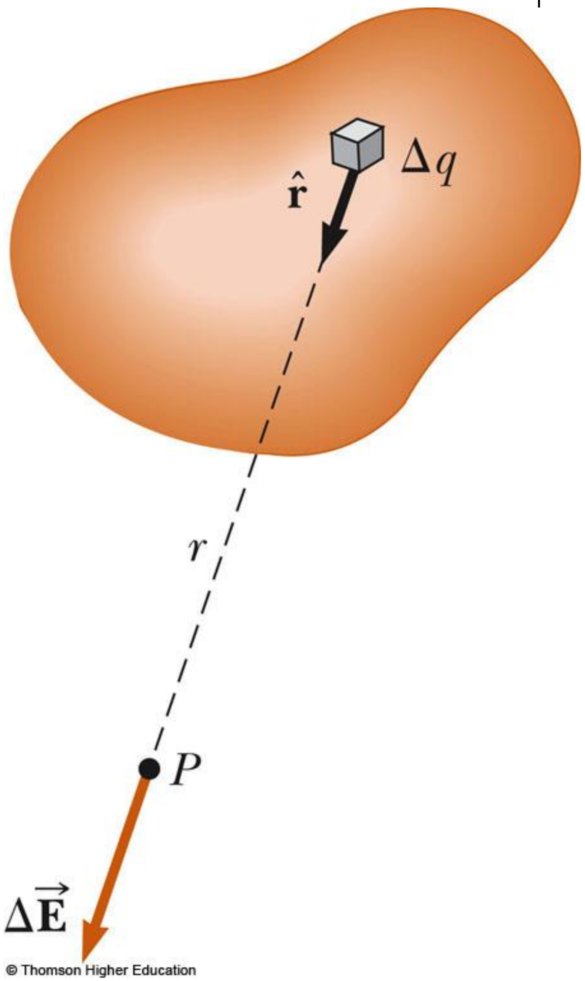


Electric Field – Continuous Charge Distribution

- The distances between charges in a group of charges may be much smaller than the distance between the group and a point of interest
- In this situation, the system of charges can be modeled as continuous
- The system of closely spaced charges is equivalent to a total charge that is continuously distributed along some line, over some surface, or throughout some volume

Electric Field – Continuous Charge Distribution, cont

- Procedure:
  - Divide the charge distribution into small elements, each of which contains Δq
  - Calculate the electric field due to one of these elements at point *P*
  - Evaluate the total field by summing the contributions of all the charge elements



Electric Field – Continuous Charge Distribution, equations

- For the individual charge elements

$$\Delta \vec{\mathbf{E}} = k_e \frac{\Delta q}{r^2} \hat{\mathbf{r}}$$

- Because the charge distribution is continuous

$$\vec{\mathbf{E}} = k_e \lim_{\Delta q_i \to 0} \sum_i \frac{\Delta q_i}{r_i^2} \hat{\mathbf{r}}_i = k_e \int \frac{dq}{r^2} \hat{\mathbf{r}}$$

Charge Densities

- **Volume charge density**: when a charge is distributed evenly throughout a volume
  - $\rho \equiv Q / V$ with units C/m^3
- **Surface charge density**: when a charge is distributed evenly over a surface area
  - $\sigma \equiv Q / A$ with units C/m^2
- **Linear charge density**: when a charge is distributed along a line
  - $\lambda \equiv Q / \ell$ with units C/m

Amount of Charge in a Small Volume

- If the charge is nonuniformly distributed over a volume, surface, or line, the amount of charge, dq, is given by
  - For the volume: $dq = \rho \, dV$
  - For the surface: $dq = \sigma \, dA$
  - For the length element: $dq = \lambda \, d\ell$

Problem-Solving Strategy

- *Conceptualize*
  - Establish a mental representation of the problem
  - Image the electric field produced by the charges or charge distribution
- *Categorize*
  - Individual charge?
  - Group of individual charges?
  - Continuous distribution of charges?

Problem-Solving Strategy, cont

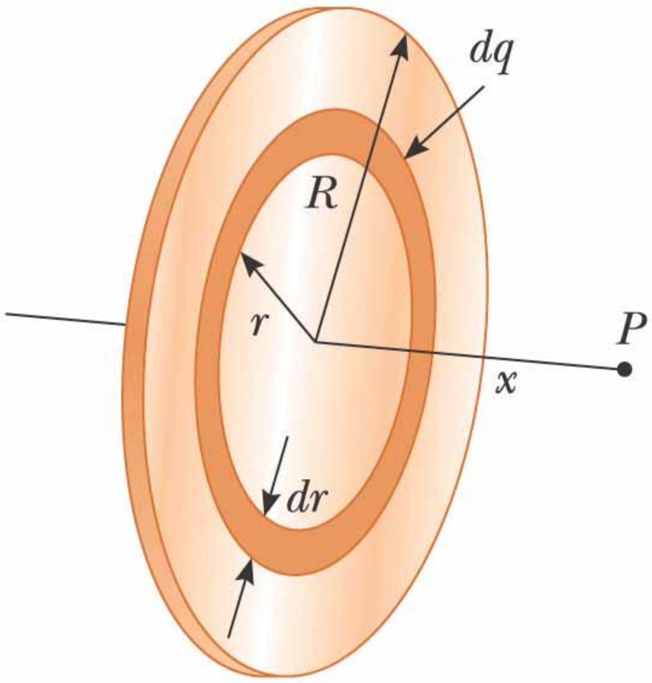
- *Analyze*
  - **Units**: when using the Coulomb constant, k_e, the charges must be in C and the distances in m
  - **Analyzing a group of individual charges**:
    - Use the superposition principle, find the fields due to the individual charges at the point of interest and then add them as vectors to find the resultant field
    - Be careful with the manipulation of vector quantities
  - **Analyzing a continuous charge distribution:**
    - The vector sums for evaluating the total electric field at some point must be replaced with vector integrals
    - Divide the charge distribution into infinitesimal pieces, calculate the vector sum by integrating over the entire charge distribution

Problem Solving Hints, final

- *Analyze, cont.*
  - **Symmetry:**
    - Take advantage of any symmetry to simplify calculations
- *Finalize*
  - Check to see if the electric field expression is consistent with your mental representation
  - Check to see if the solution reflects any symmetry present
  - Image varying parameters to see if the mathematical result changes in a reasonable way

Example – Charged Disk

- The ring has a radius *R* and a uniform charge density *σ*
- Choose *dq* as a ring of radius *r*
- The ring has a surface area 2*πr dr*

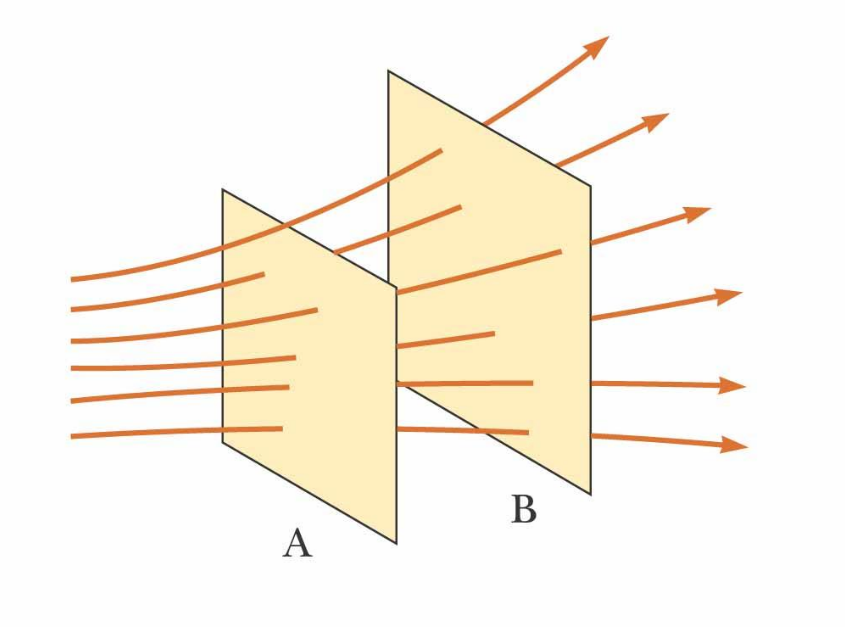


Electric Field Lines

- 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

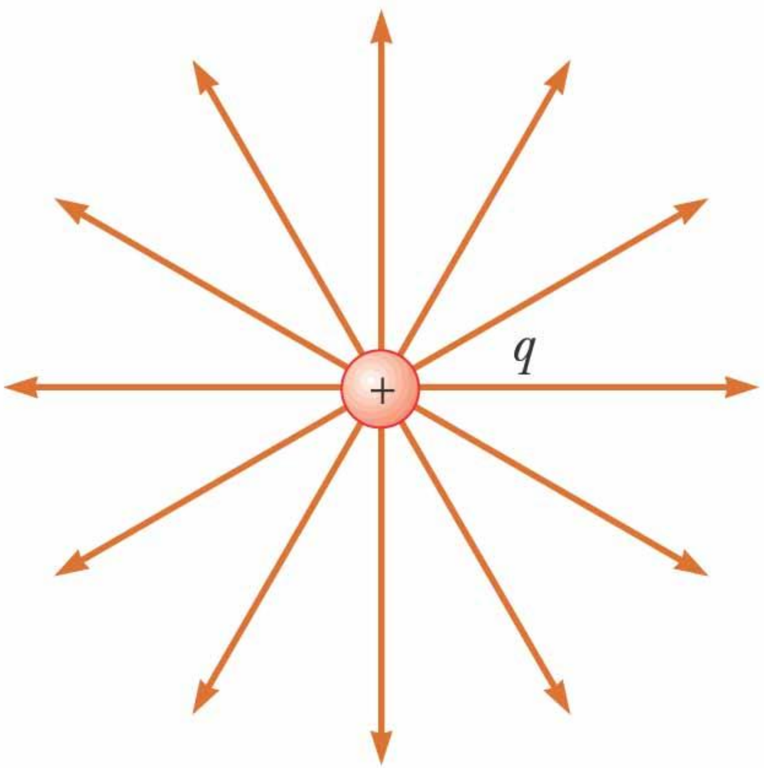
Electric Field Lines, General

- 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



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



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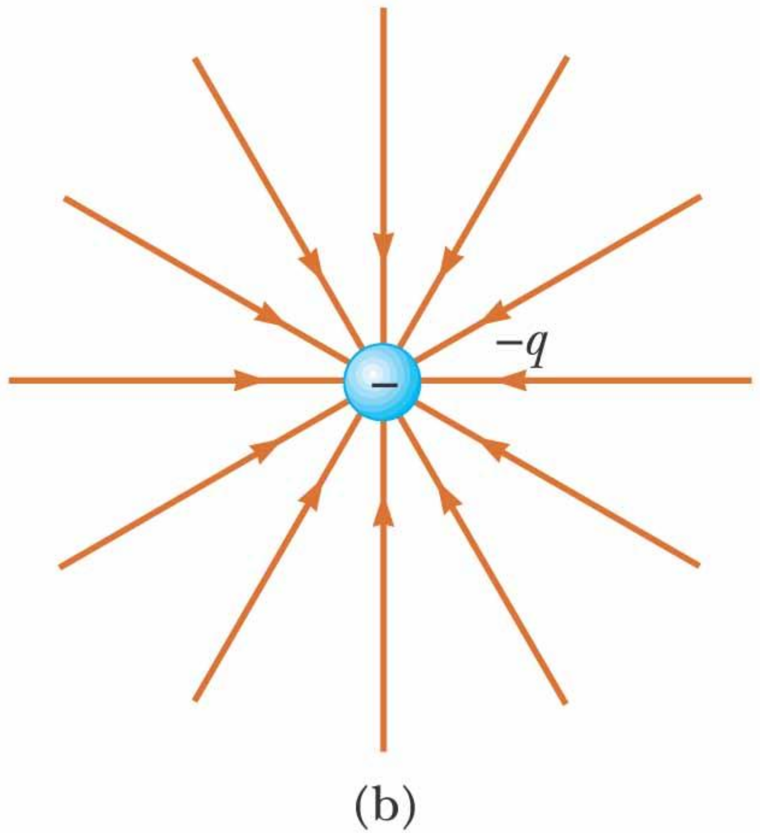
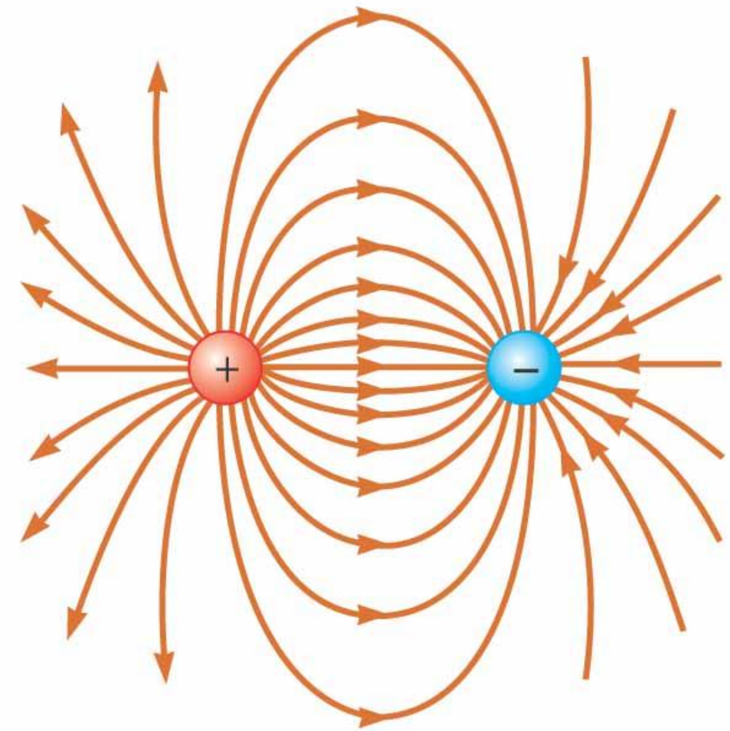
Electric Field Lines, Negative Point Charge

- The field lines radiate inward in all directions
- The lines are directed toward the source charge
  - A positive test charge would be attracted toward the negative source charge



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



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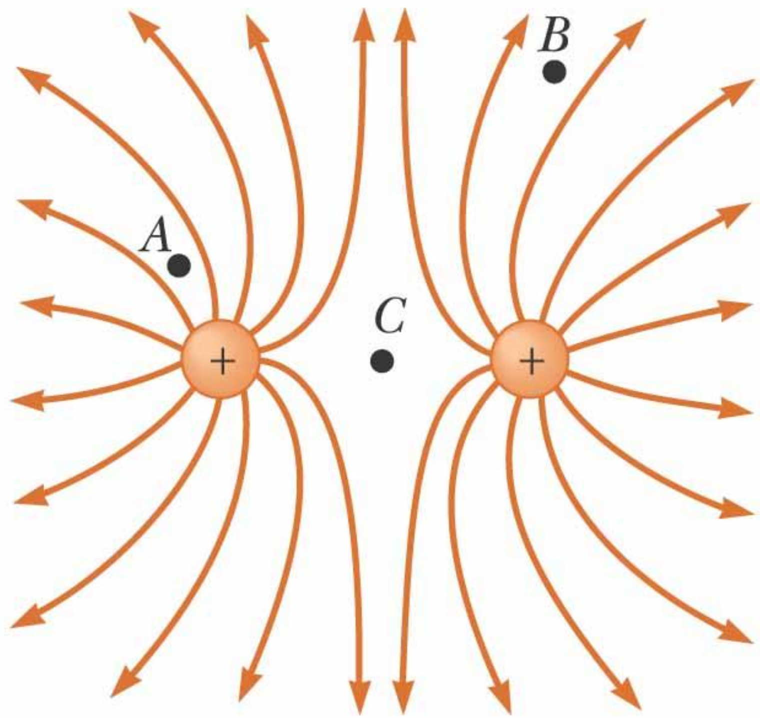
Electric Field Lines – Like Charges

- 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 2*q*



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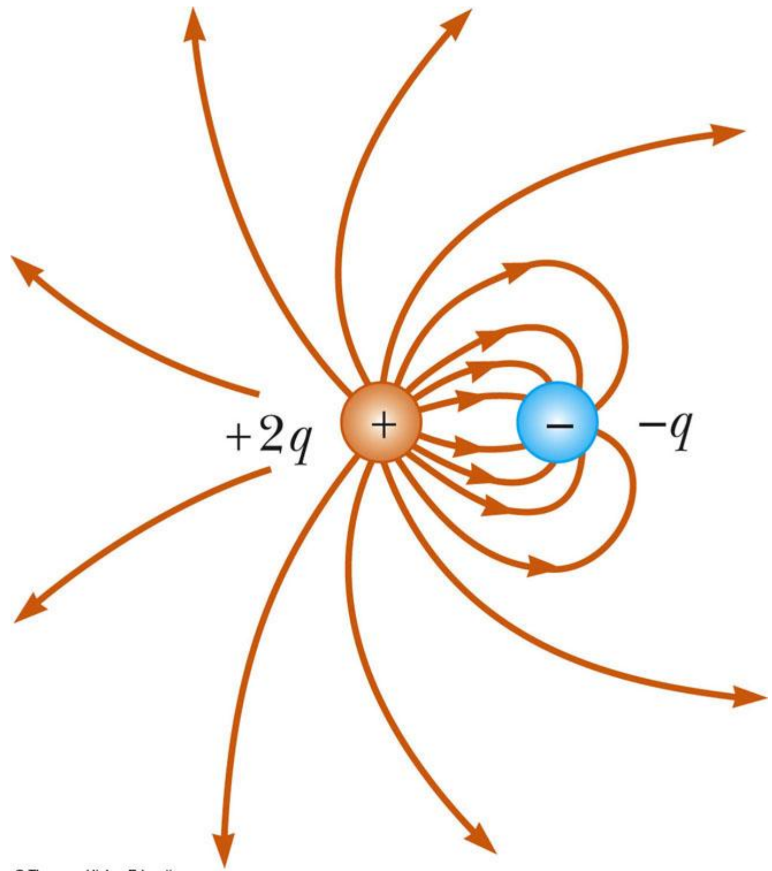
Electric Field Lines, Unequal Charges

- 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 $+q$
- Use the active figure to vary the charges and positions and observe the resulting electric field



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Electric Field Lines – Rules for Drawing

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

Motion of Charged Particles

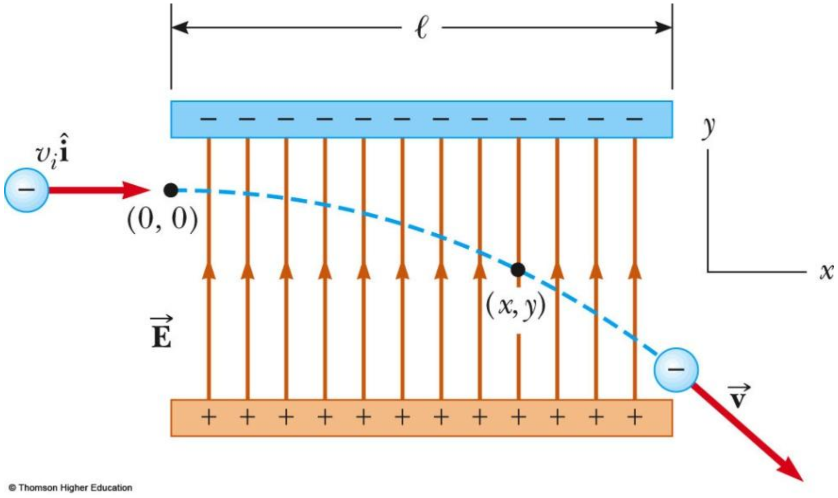
- When a charged particle is placed in an electric field, it experiences an electrical force
- If this is the only force on the particle, it must be the net force
- The net force will cause the particle to accelerate according to Newton's second law

Motion of Particles, cont

- $\vec{\mathbf{F}}_e = q\vec{\mathbf{E}} = m\vec{\mathbf{a}}$
- If $\vec{\mathbf{E}}$ is uniform, then the acceleration is constant
- If the particle has a positive charge, its acceleration is in the direction of the field
- If the particle has a negative charge, its acceleration is in the direction opposite the electric field
- Since the acceleration is constant, the kinematic equations can be used

Electron in a Uniform Field, Example

- The electron is projected horizontally into a uniform electric field
- The electron undergoes a downward acceleration
  - It is negative, so the acceleration is opposite the direction of the field
- Its motion is parabolic while between the plates



Use the active figure to vary the field and the characteristics of the particle.

PLAY ACTIVE FIGURE