



Chapter 15

Electric Forces and Electric Fields

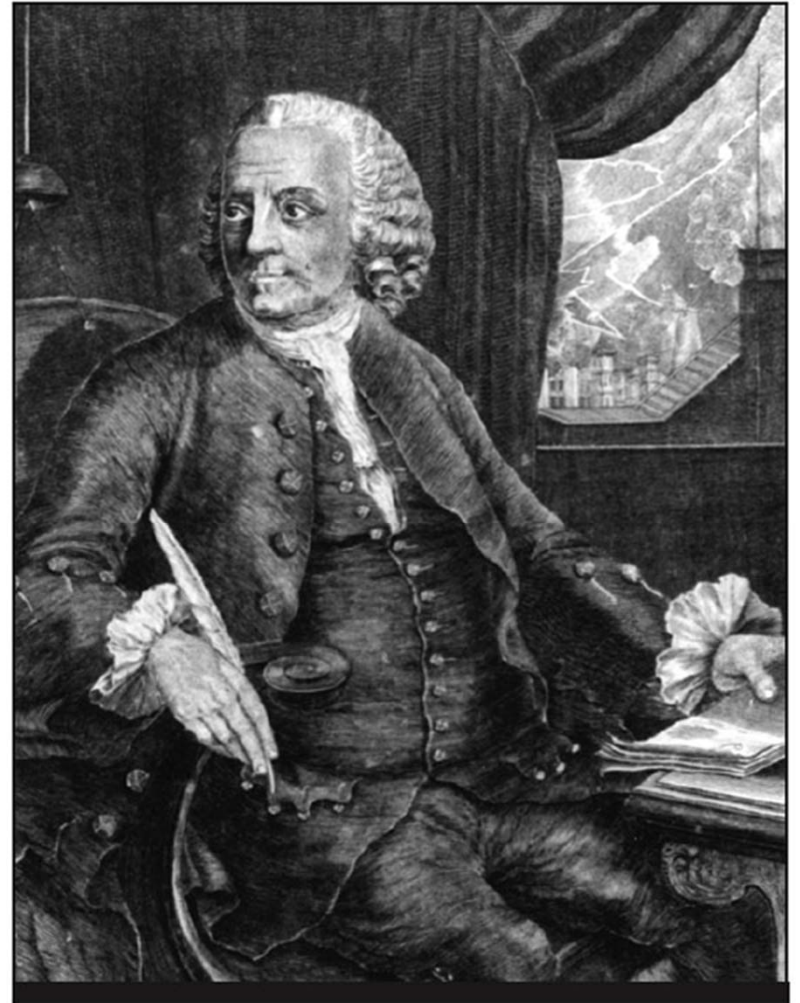


First Observations – Greeks

- Observed electric and magnetic phenomena as early as 700 BC
 - Found that amber, when rubbed, became electrified and attracted pieces of straw or feathers
 - Also discovered magnetic forces by observing magnetite attracting iron

Benjamin Franklin

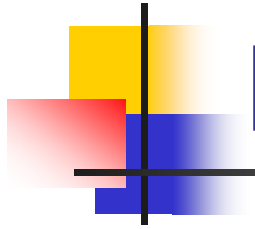
- 1706 – 1790
- Printer, author, founding father, inventor, diplomat
- Physical Scientist
 - 1740's work on electricity changed unrelated observations into coherent science





Properties of Electric Charges

- Two types of charges exist
 - They are called positive and negative
 - Named by Benjamin Franklin
- Like charges repel and unlike charges attract one another
- Nature's basic carrier of positive charge is the proton
 - Protons do not move from one material to another because they are held firmly in the nucleus



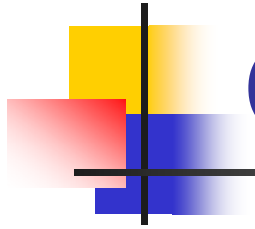
More Properties of Charge

- Nature's basic carrier of negative charge is the electron
 - Gaining or losing electrons is how an object becomes charged
- Electric charge is always conserved
 - Charge is not created, only exchanged
 - Objects become charged because negative charge is transferred from one object to another



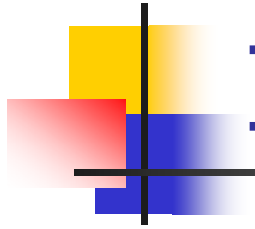
Properties of Charge, final

- Charge is quantized
 - All charge is a multiple of a fundamental unit of charge, symbolized by e
 - Quarks are the exception
 - Electrons have a charge of $-e$
 - Protons have a charge of $+e$
 - The SI unit of charge is the Coulomb (C)
 - $e = 1.6 \times 10^{-19} \text{ C}$



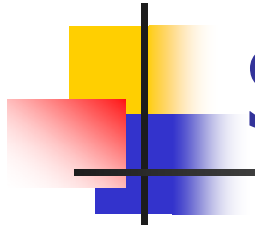
Conductors

- Conductors are materials in which the electric charges move freely in response to an electric force
 - Copper, aluminum and silver are good conductors
 - When a conductor is charged in a small region, the charge readily distributes itself over the entire surface of the material



Insulators

- Insulators are materials in which electric charges do not move freely
 - Glass and rubber are examples of insulators
 - When insulators are charged by rubbing, only the rubbed area becomes charged
 - There is no tendency for the charge to move into other regions of the material

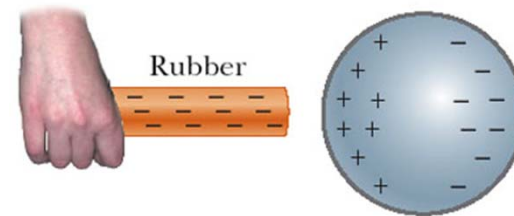


Semiconductors

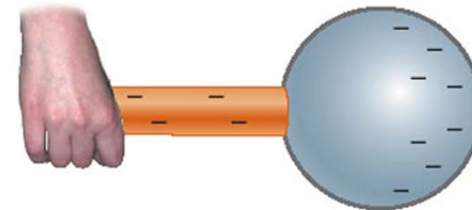
- The characteristics of semiconductors are between those of insulators and conductors
- Silicon and germanium are examples of semiconductors

Charging by Conduction

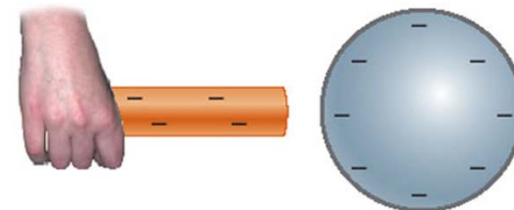
- A charged object (the rod) is placed in contact with another object (the sphere)
- Some electrons on the rod can move to the sphere
- When the rod is removed, the sphere is left with a charge
- The object being charged is always left with a charge having the same sign as the object doing the charging



(a) Before



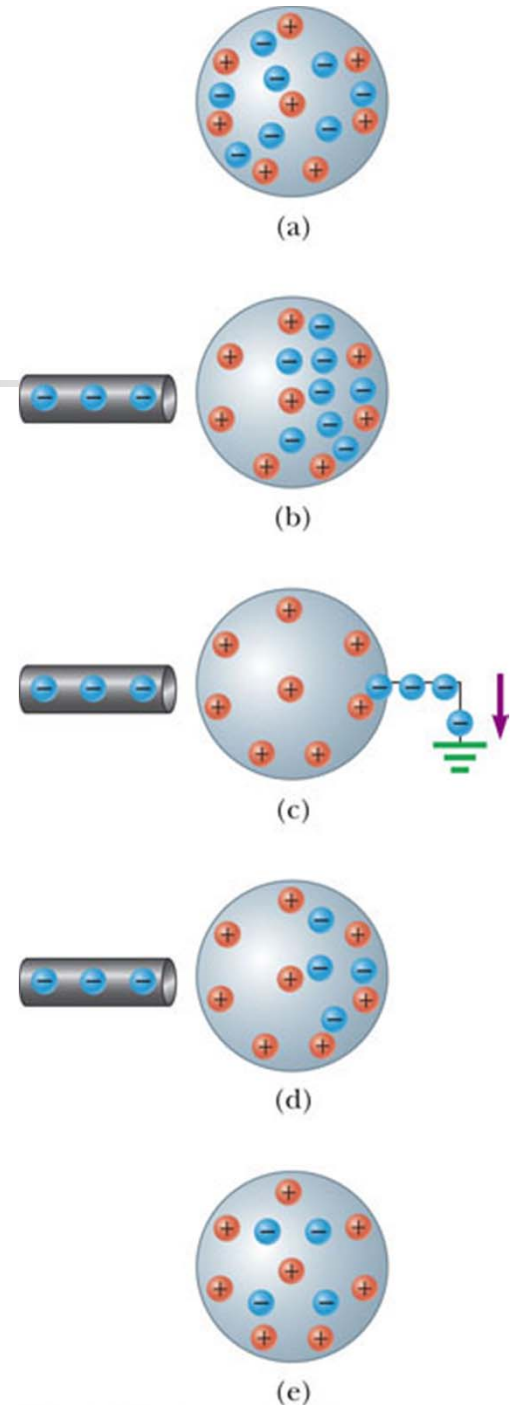
(b) Contact



(c) After breaking contact

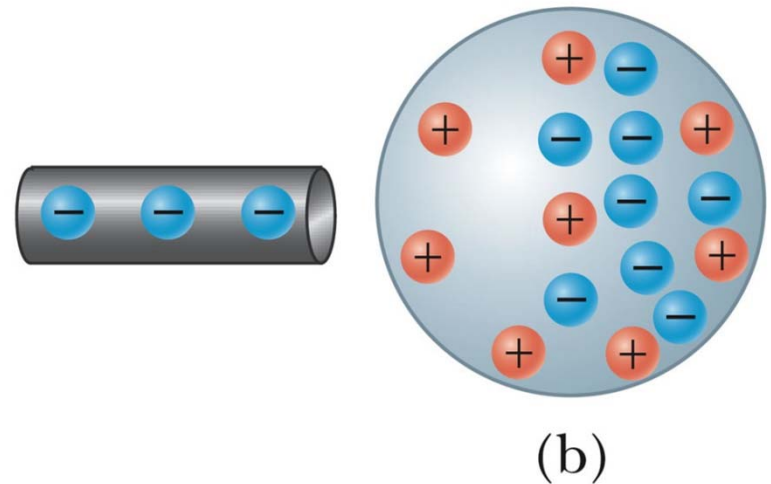
Charging by Induction

- When an object is connected to a conducting wire or pipe buried in the earth, it is said to be grounded
- A neutral sphere has equal number of electrons and protons



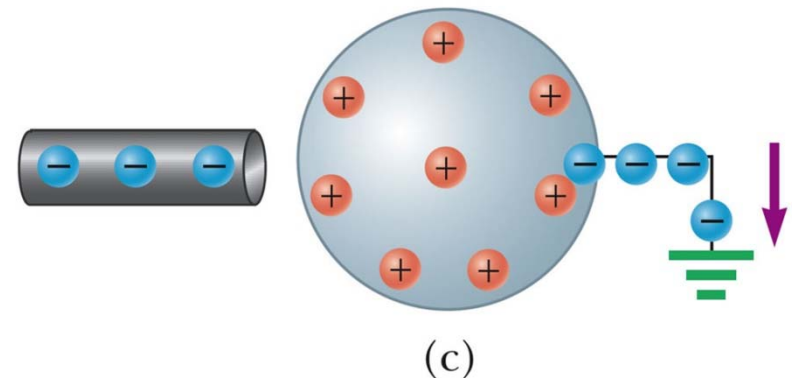
Charging by Induction, 2

- A negatively charged rubber rod is brought near an uncharged sphere
- The charges in the sphere are redistributed
 - Some of the electrons in the sphere are repelled from the electrons in the rod



Charging by Induction, 3

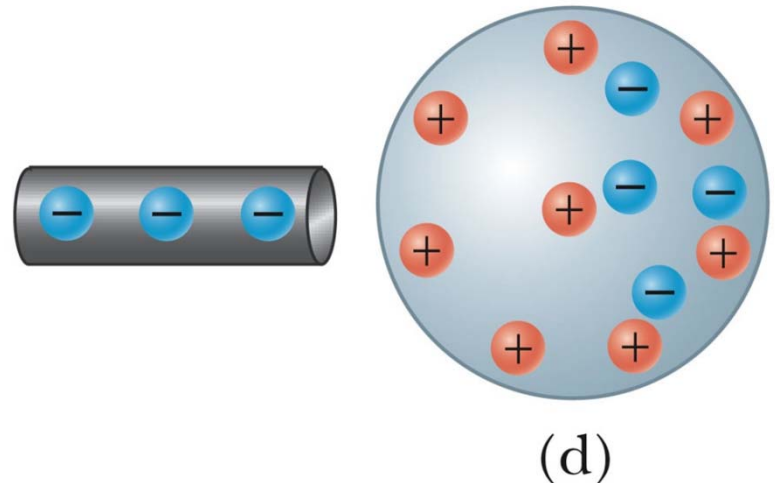
- The region of the sphere nearest the negatively charged rod has an excess of positive charge because of the migration of electrons away from this location
- A grounded conducting wire is connected to the sphere
 - Allows some of the electrons to move from the sphere to the ground



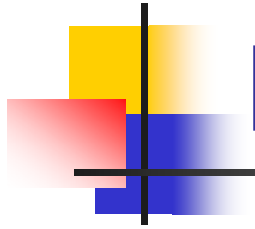
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Charging by Induction, final

- The wire to ground is removed, the sphere is left with an excess of induced positive charge
- The positive charge on the sphere is evenly distributed due to the repulsion between the positive charges
- *Charging by induction requires no contact with the object inducing the charge*



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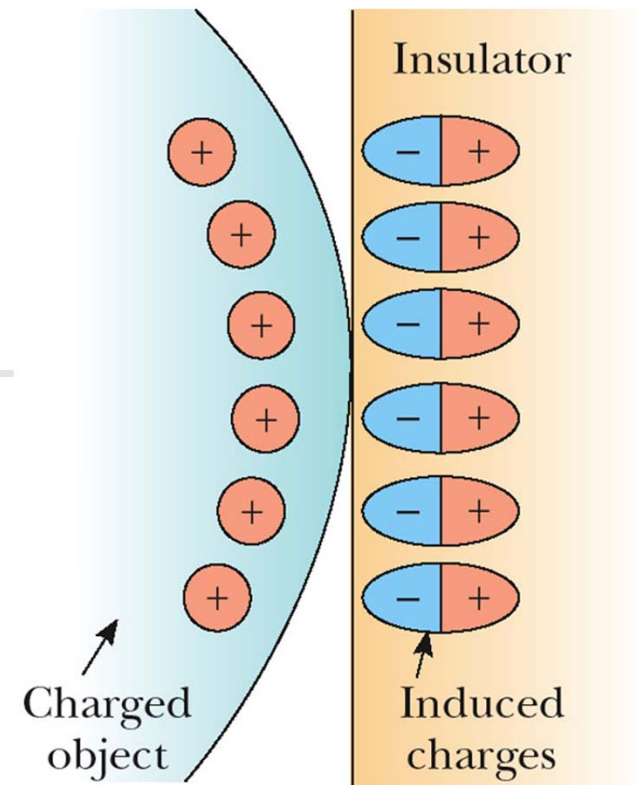


Polarization

- In most neutral atoms or molecules, the center of positive charge coincides with the center of negative charge
- In the presence of a charged object, these centers may separate slightly
 - This results in more positive charge on one side of the molecule than on the other side
- This realignment of charge on the surface of an insulator is known as *polarization*

Examples of Polarization

- The charged object (on the left) induces charge on the surface of the insulator
- A charged comb attracts bits of paper due to polarization of the paper



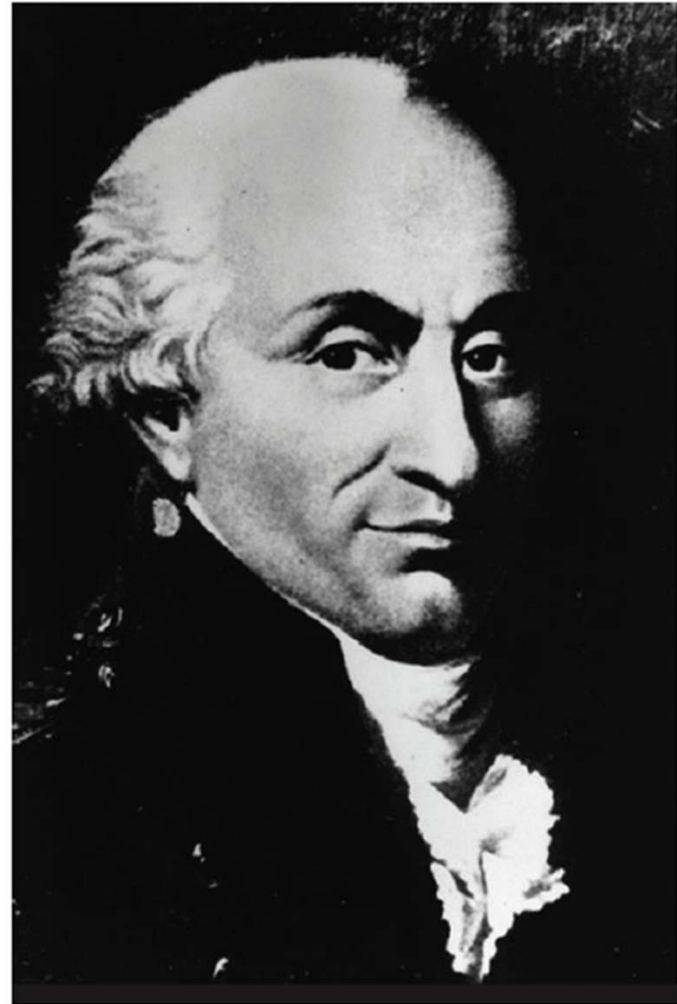
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Charles Coulomb

- 1736 – 1806
- Studied electrostatics and magnetism
- Investigated strengths of materials
 - Identified forces acting on beams





Coulomb's Law

- Coulomb shows that an electrical force has the following properties:
 - It is directed along the line joining the two particles and inversely proportional to the square of the separation distance, r , between them
 - It is proportional to the product of the magnitudes of the charges, $|q_1|$ and $|q_2|$ on the two particles
 - It is attractive if the charges are of opposite signs and repulsive if the charges have the same signs



Coulomb's Law, cont.

- Mathematically, $F = k_e \frac{|q_1| |q_2|}{r^2}$
- k_e is called the *Coulomb Constant*
 - $k_e = 8.987\ 5 \times 10^9\ \text{N m}^2/\text{C}^2$
- Typical charges can be in the μC range
 - Remember, Coulombs must be used in the equation
- Remember that force is a *vector* quantity
- Applies only to point charges



Characteristics of Particles

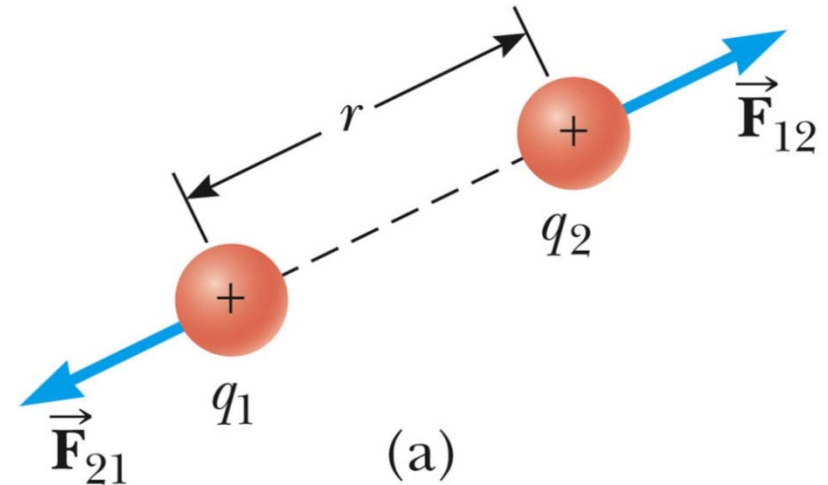
TABLE 15.1

Charge and Mass of the Electron, Proton, and Neutron

Particle	Charge (C)	Mass (kg)
Electron	-1.60×10^{-19}	9.11×10^{-31}
Proton	$+1.60 \times 10^{-19}$	1.67×10^{-27}
Neutron	0	1.67×10^{-27}

Vector Nature of Electric Forces

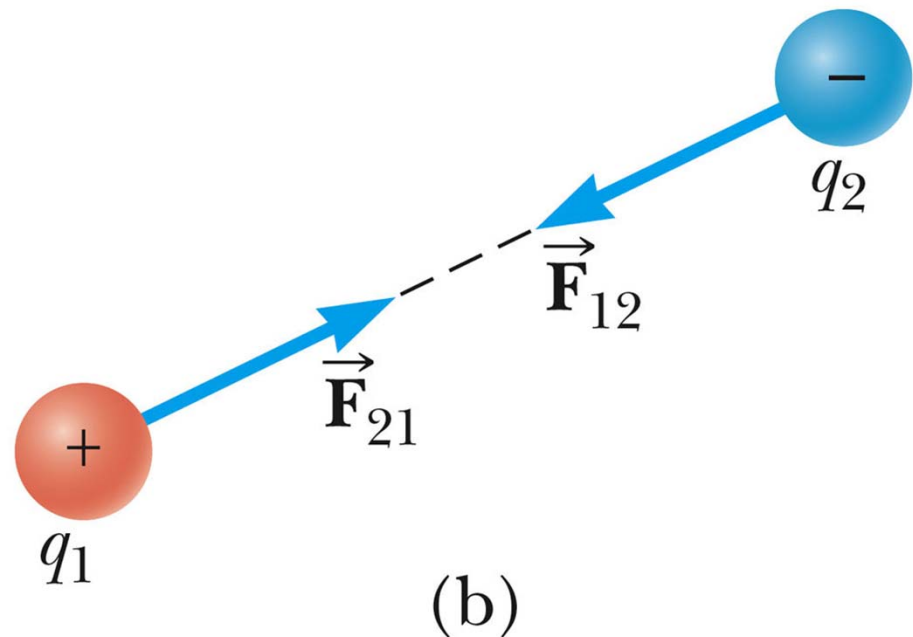
- Two point charges are separated by a distance r
- The like charges produce a repulsive force between them
- The force on q_1 is equal in magnitude and opposite in direction to the force on q_2



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Vector Nature of Forces, cont.

- Two point charges are separated by a distance r
- The unlike charges produce an attractive force between them
- The force on q_1 is equal in magnitude and opposite in direction to the force on q_2





Electrical Forces are Field Forces

- This is the second example of a field force
 - Gravity was the first
- Remember, with a field force, the force is exerted by one object on another object even though there is no physical contact between them
- There are some important similarities and differences between electrical and gravitational forces



Electrical Force Compared to Gravitational Force

- Both are inverse square laws
- The mathematical form of both laws is the same
 - Masses replaced by charges
 - G replaced by k_e
- Electrical forces can be either attractive or repulsive
- Gravitational forces are always attractive
- Electrostatic force is stronger than the gravitational force



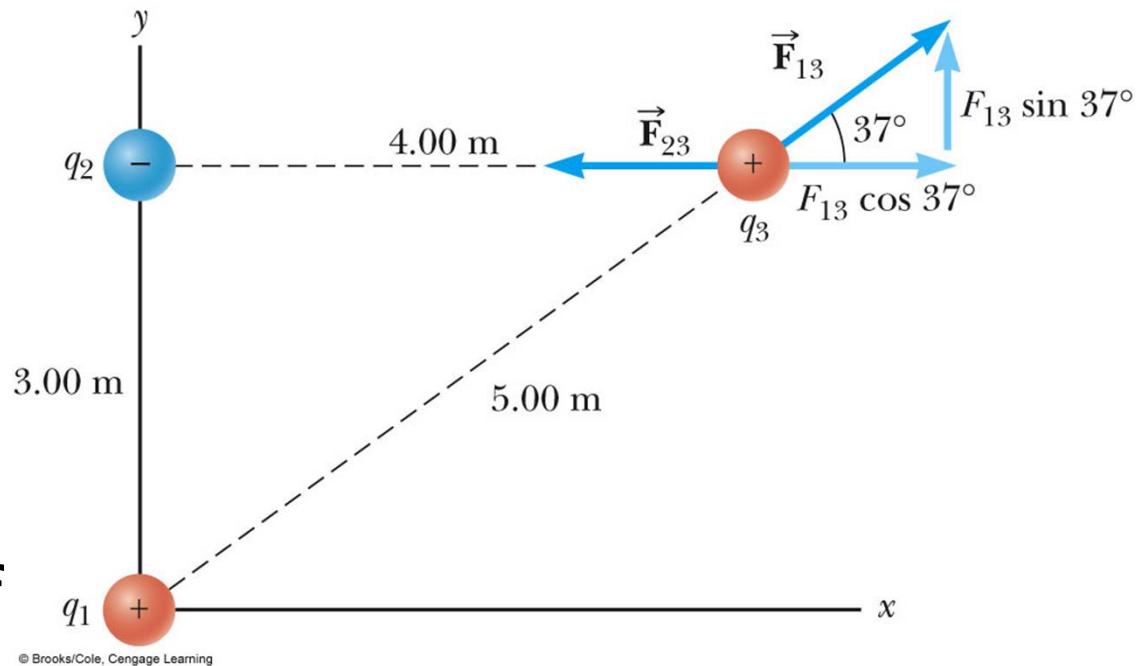
The Superposition Principle

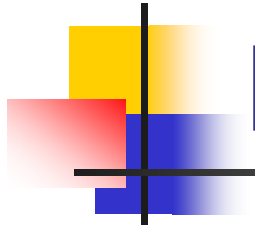
- The resultant force on any one charge equals the vector sum of the forces exerted by the other individual charges that are present
 - Find the electrical forces between pairs of charges separately
 - Then add the vectors
 - Remember to add the forces as *vectors*

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 *total force* exerted on q_3 is the vector sum of \vec{F}_{13} and \vec{F}_{23}



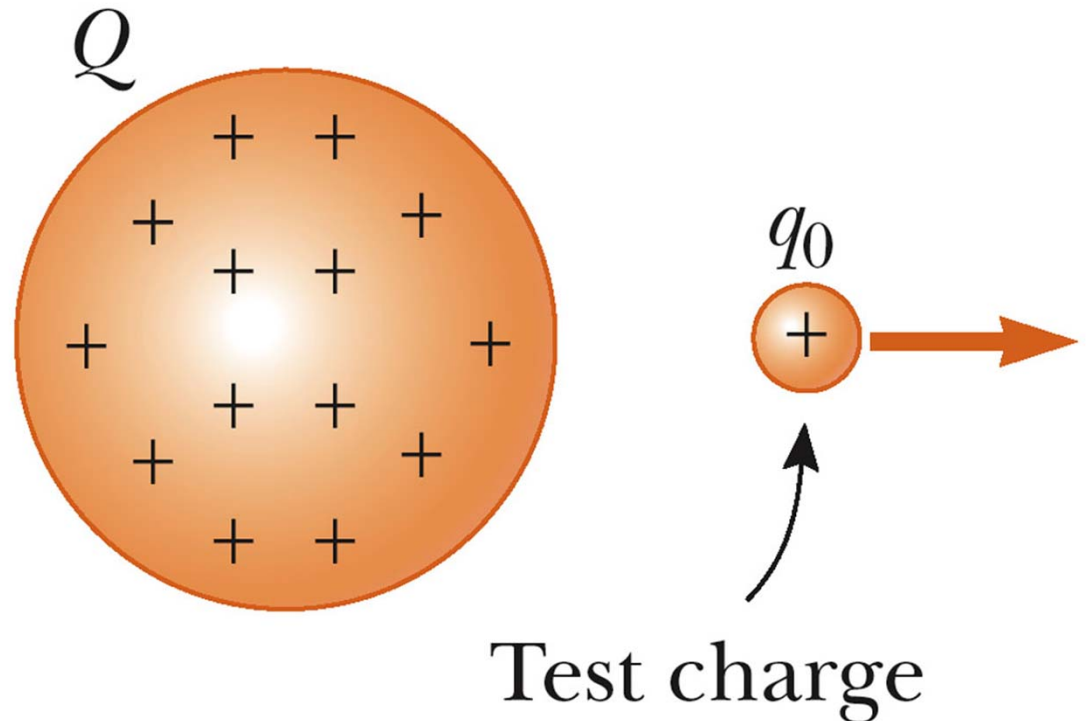


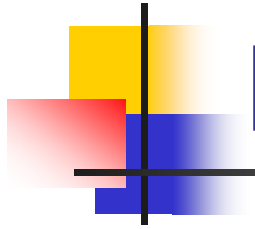
Electrical Field

- Faraday developed an approach to discussing fields
- An **electric field** is said to exist in the region of space around a charged object
 - When another charged object enters this electric field, the field exerts a *force* on the second charged object

Electric Field, cont.

- A charged particle, with charge Q , produces an electric field in the region of space around it
- A small *test charge*, q_0 , placed in the field, will experience a force



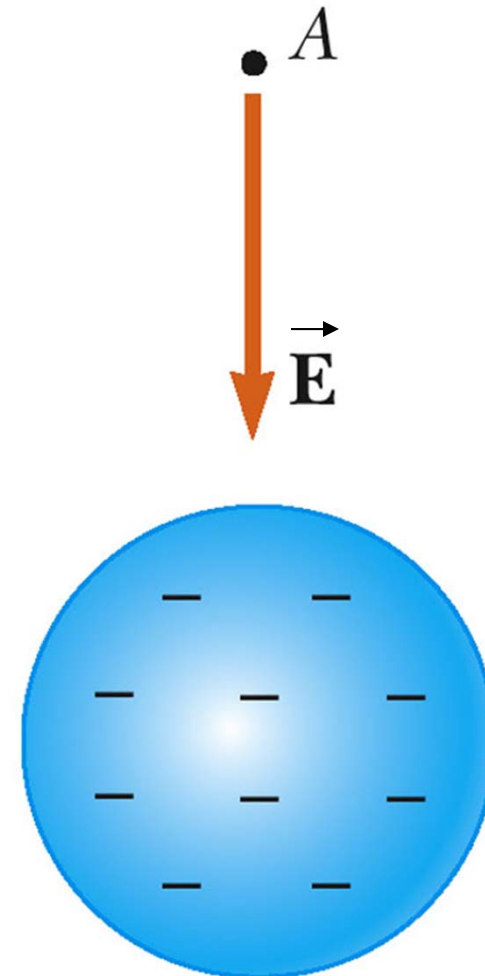


Electric Field

- Mathematically, $\vec{\mathbf{E}} = \frac{\vec{\mathbf{F}}}{q_o} = \frac{k_e Q}{r^2}$
- SI units are N / C
- Use this for the magnitude of the field
- The electric field is a vector quantity
- The direction of the field is defined to be the direction of the electric force that would be exerted on a small *positive* test charge placed at that point

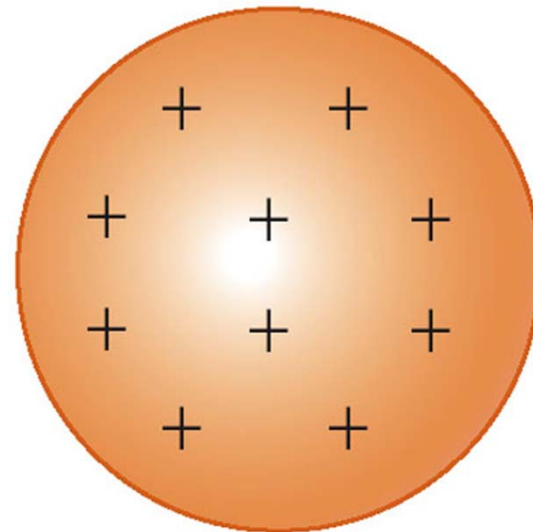
Direction of Electric Field

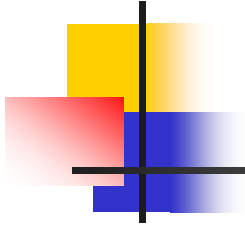
- The electric field produced by a negative charge is directed toward the charge
 - A positive test charge would be attracted to the negative source charge



Direction of Electric Field, cont

- The electric field produced by a positive charge is directed away from the charge
 - A positive test charge would be repelled from the positive source charge





- Find the magnitude of electric field at a distance of 8 cm from a 28 nC point charge.

Solution:

$$E = 8.99 \times 10^9 \text{ Nm}^2/\text{kg}^2 \cdot [28 \times 10^{-9} \text{ C} / (0.08 \text{ m})^2] =$$
$$39331 \text{ N/C}$$



Example

A small object of mass 5 g and charge -180 nC is suspended motionless above the ground when immersed in a uniform electric field perpendicular to the ground. What are the magnitude and direction of the electric field?



More About a Test Charge and The Electric Field

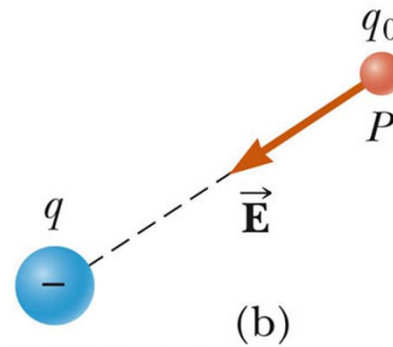
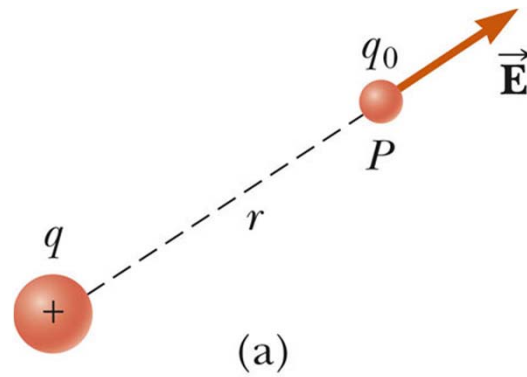
- The test charge is required to be a small charge
 - It can cause no rearrangement of the charges on the source charge
- The electric field exists whether or not there is a test charge present
- The Superposition Principle can be applied to the electric field if a group of charges is present

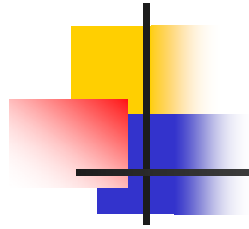


Electric Fields and Superposition Principle

- The superposition principle holds when calculating the electric field due to a group of charges
 - Find the fields due to the individual charges
 - Add them as vectors
 - Use symmetry whenever possible to simplify the problem

Electric Field, final





Problem Solving Strategy

- **Draw** a diagram of the charges in the problem
- **Identify** the charge of interest
 - You may want to circle it
- **Units** – Convert all units to SI
 - Need to be consistent with k_e



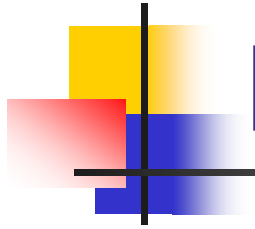
Problem Solving Strategy, cont

- **Apply Coulomb's Law**
 - For each charge, find the force on the charge of interest
 - Determine the direction of the force
- **Sum all the x- and y- components**
 - This gives the x- and y-components of the resultant force
- **Find the resultant force** by using the Pythagorean theorem and trig



Problem Solving Strategy, Electric Fields

- Calculate Electric Fields of point charges
 - Use the equation to find the electric field due to the individual charges
 - The direction is given by the direction of the force on a positive test charge
 - The Superposition Principle can be applied if more than one charge is present



Electric Field Lines

- A convenient aid for visualizing electric field patterns is to draw lines pointing in the direction of the field vector at any point
- These are called **electric field lines** and were introduced by Michael Faraday

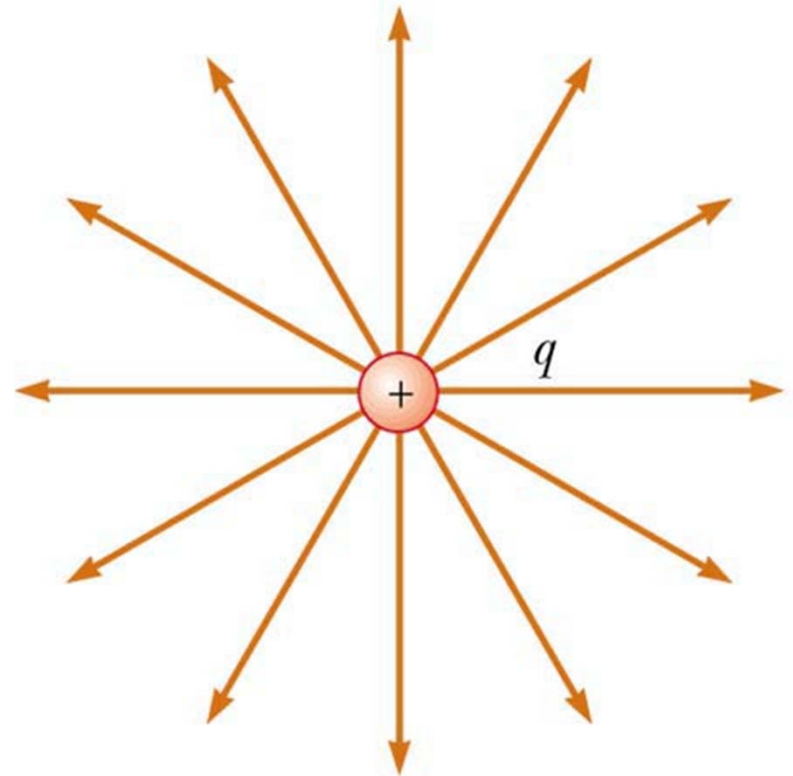


Electric Field Lines, cont.

- The field lines are related to the field in the following manners:
 - The electric field vector, \vec{E} , is tangent to the electric field lines at each point
 - The number of lines per unit area through a surface perpendicular to the lines is proportional to the strength of the electric field in a given region

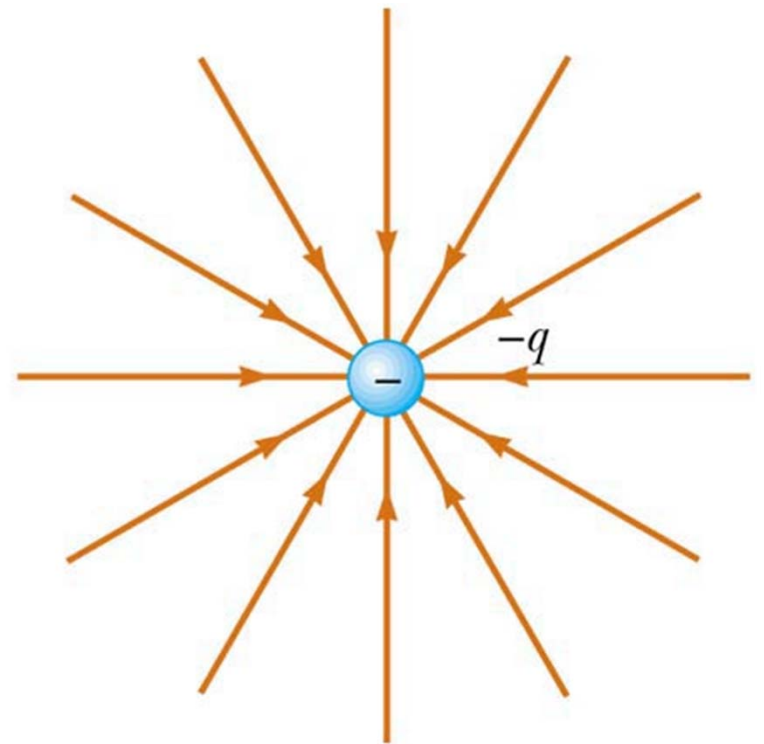
Electric Field Line Patterns

- Point charge
- The lines radiate equally in all directions
- For a positive source charge, the lines will radiate outward



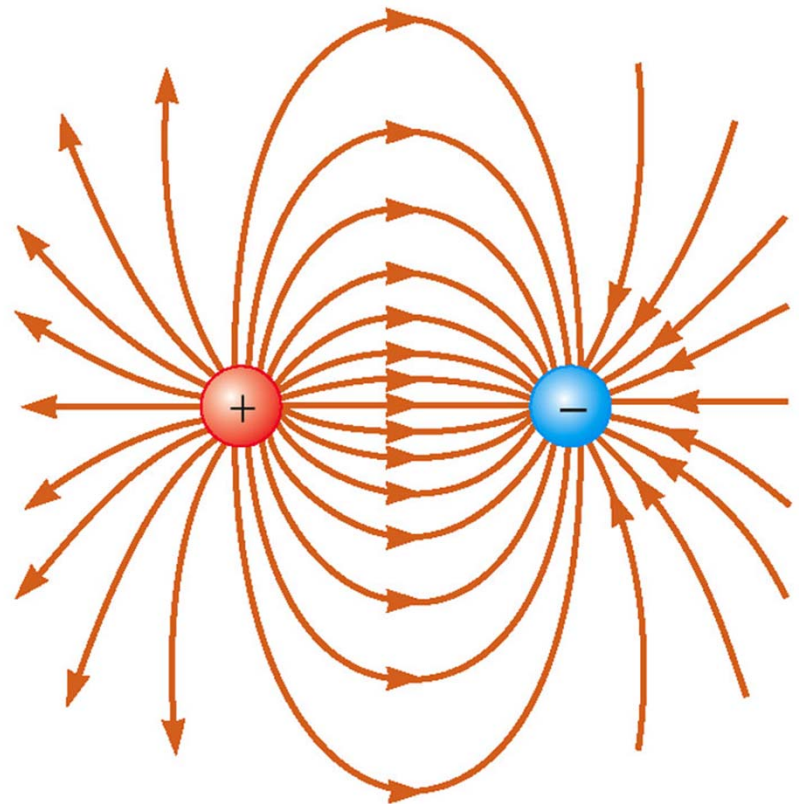
Electric Field Line Patterns

- For a negative source charge, the lines will point inward



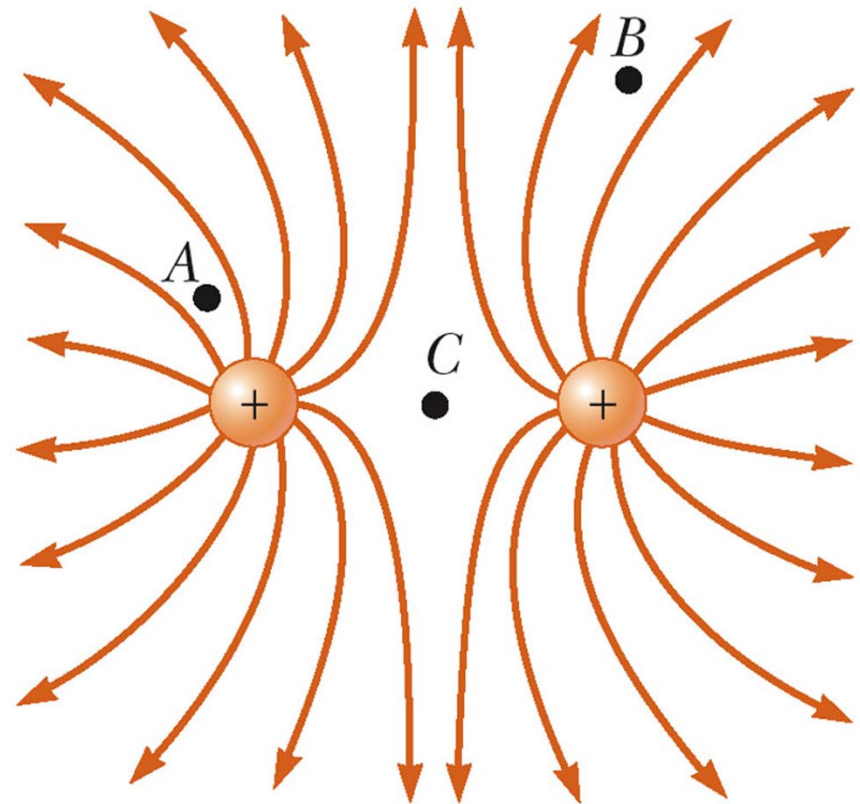
Electric Field Line Patterns

- An electric *dipole* consists of two equal and opposite charges
- The high density of lines between the charges indicates the strong electric field in this region



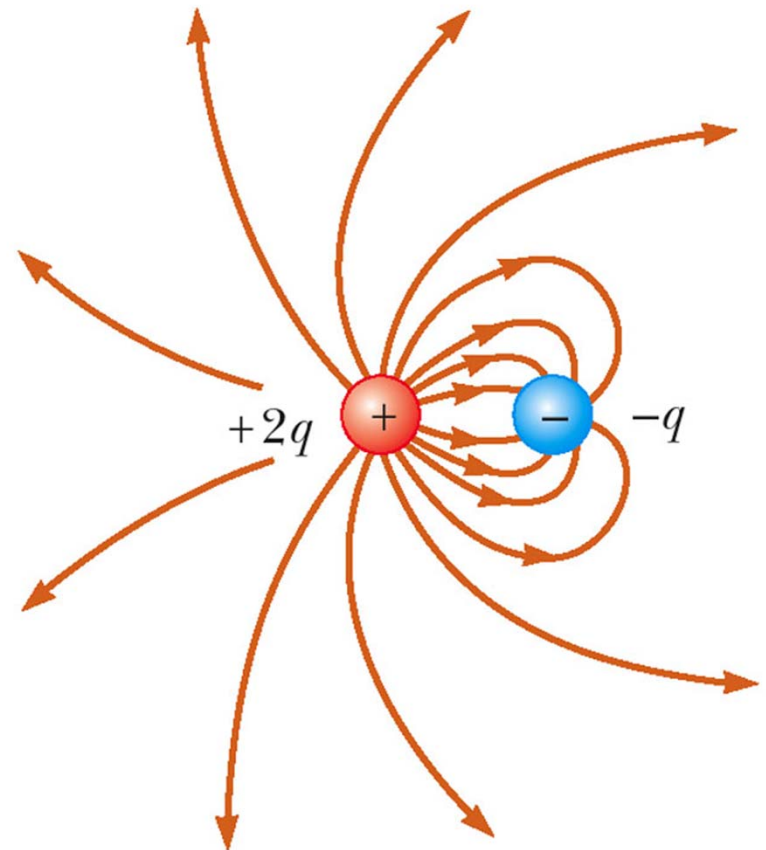
Electric Field Line Patterns

- Two equal but like point charges
- At a great distance from the charges, the field would be approximately that of a single charge of $2q$
- The bulging out of the field lines between the charges indicates the repulsion between the charges
- The low field lines between the charges indicates a weak field in this region



Electric Field Patterns

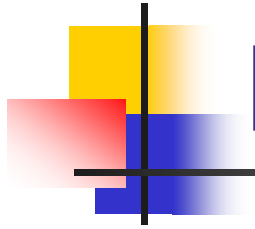
- Unequal and unlike charges
- Note that two lines leave the $+2q$ charge for each line that terminates on $-q$





Rules for Drawing Electric Field Lines

- The lines for a group of charges must begin on positive charges and end on negative charges
 - In the case of an excess of charge, some lines will begin or end infinitely far away
- The number of lines drawn leaving a positive charge or ending on a negative charge is proportional to the magnitude of the charge
- No two field lines can cross each other



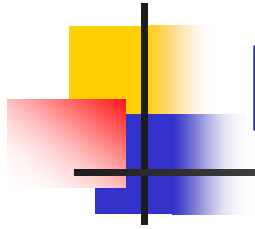
Electric Field Lines, final

- The electric field lines are *not* material objects
- They are used only as a pictorial representation of the electric field at various locations
- They generally do not represent the path of a charged particle released in the electric field



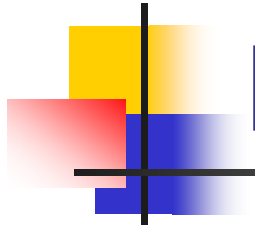
Conductors in Electrostatic Equilibrium

- When no net motion of charge occurs within a conductor, the conductor is said to be in **electrostatic equilibrium**
- An isolated conductor has the following properties:
 - The electric field is zero everywhere inside the conducting material
 - Any excess charge on an isolated conductor resides entirely on its surface



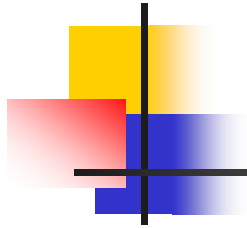
Properties, cont

- The electric field just outside a charged conductor is perpendicular to the conductor's surface
- On an irregularly shaped conductor, the charge accumulates at locations where the radius of curvature of the surface is smallest (that is, at sharp points)



Property 1

- The electric field is zero everywhere inside the conducting material
 - Consider if this were *not* true
 - If there were an electric field inside the conductor, the free charge there would move and there would be a flow of charge
 - If there were a movement of charge, the conductor would not be in equilibrium

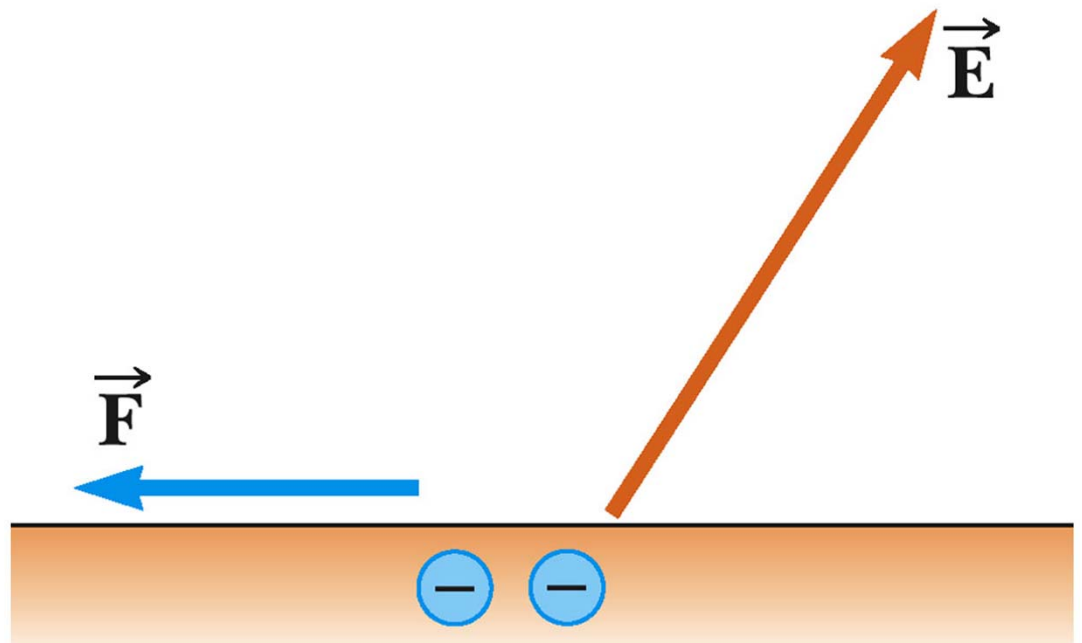


Property 2

- Any excess charge on an isolated conductor resides entirely on its surface
 - A direct result of the $1/r^2$ repulsion between like charges in Coulomb's Law
 - If some excess of charge could be placed inside the conductor, the repulsive forces would push them as far apart as possible, causing them to migrate to the surface

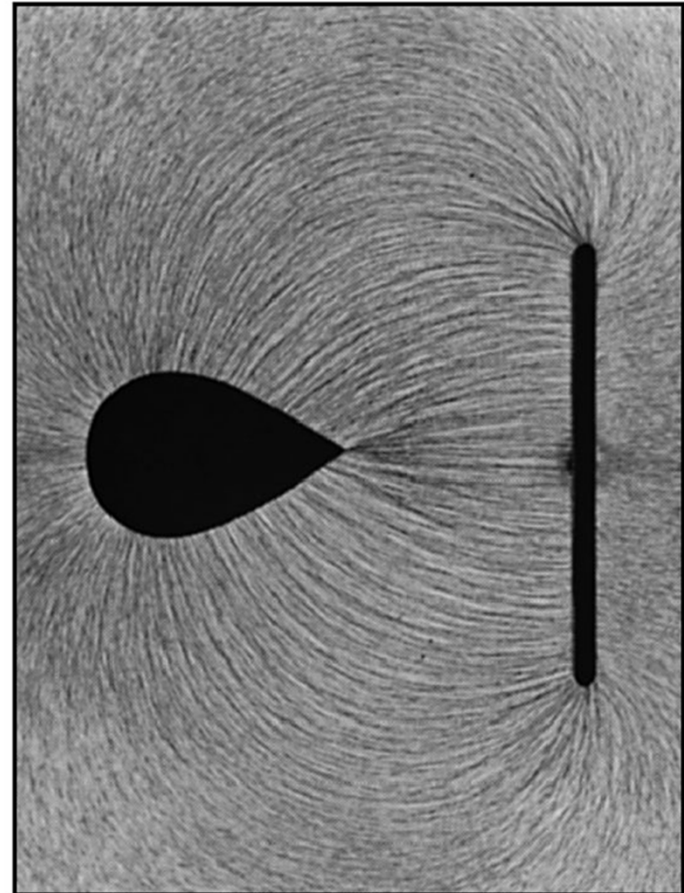
Property 3

- The electric field just outside a charged conductor is perpendicular to the conductor's surface
 - Consider what would happen if this was not true
 - The component along the surface would cause the charge to move
 - It would not be in equilibrium

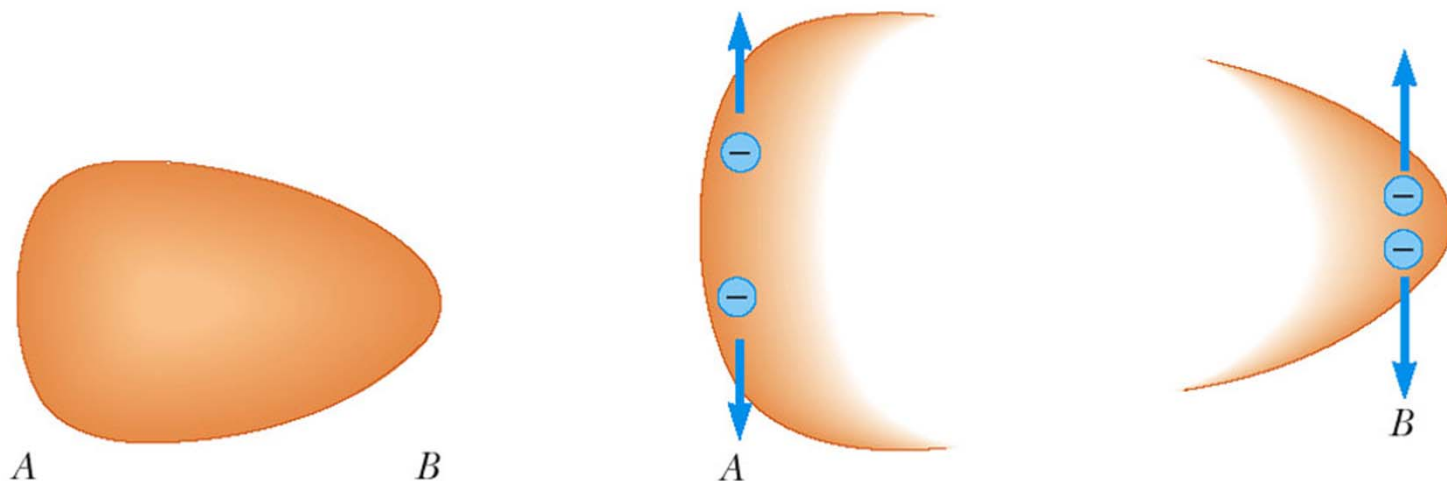


Property 4

- On an irregularly shaped conductor, the charge accumulates at locations where the radius of curvature of the surface is smallest (that is, at sharp points)



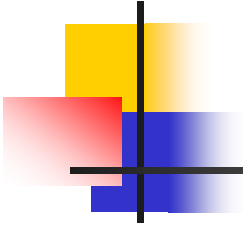
Property 4, cont.



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- Any excess charge moves to its surface
- The charges move apart until an equilibrium is achieved
- The amount of charge per unit area is greater at the flat end
- The forces from the charges at the sharp end produce a larger resultant force away from the surface
- Why a lightning rod works

Example 4



An electron with a speed of 5×10^6 m/s enters a uniform electric field $E = 1000$ N/C pointed in the same direction. a. How long will it take for the electron to come to stop? b. How far will it travel during this time?

$$q_e = 1.6 \times 10^{-19} \text{ C} \quad m_e = 9.11 \times 10^{-31} \text{ kg}$$

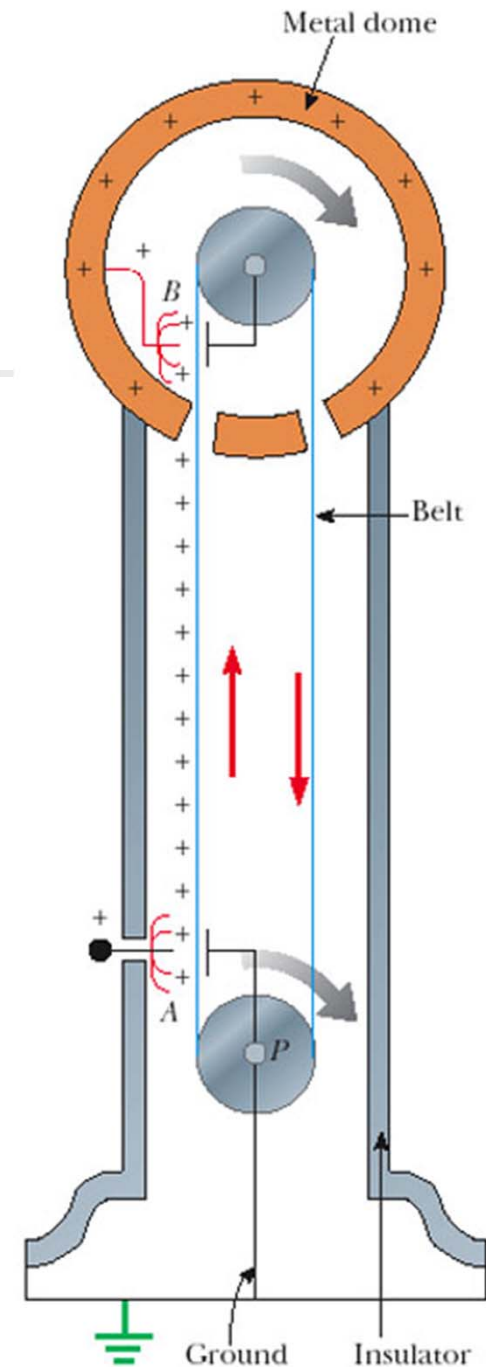


Experiments to Verify Properties of Charges

- Faraday's Ice-Pail Experiment
 - Concluded a charged object suspended inside a metal container causes a rearrangement of charge on the container in such a manner that the sign of the charge on the inside surface of the container is opposite the sign of the charge on the suspended object
- Millikan Oil-Drop Experiment
 - Measured the elementary charge, e
 - Found every charge had an integral multiple of e
 - $q = n e$

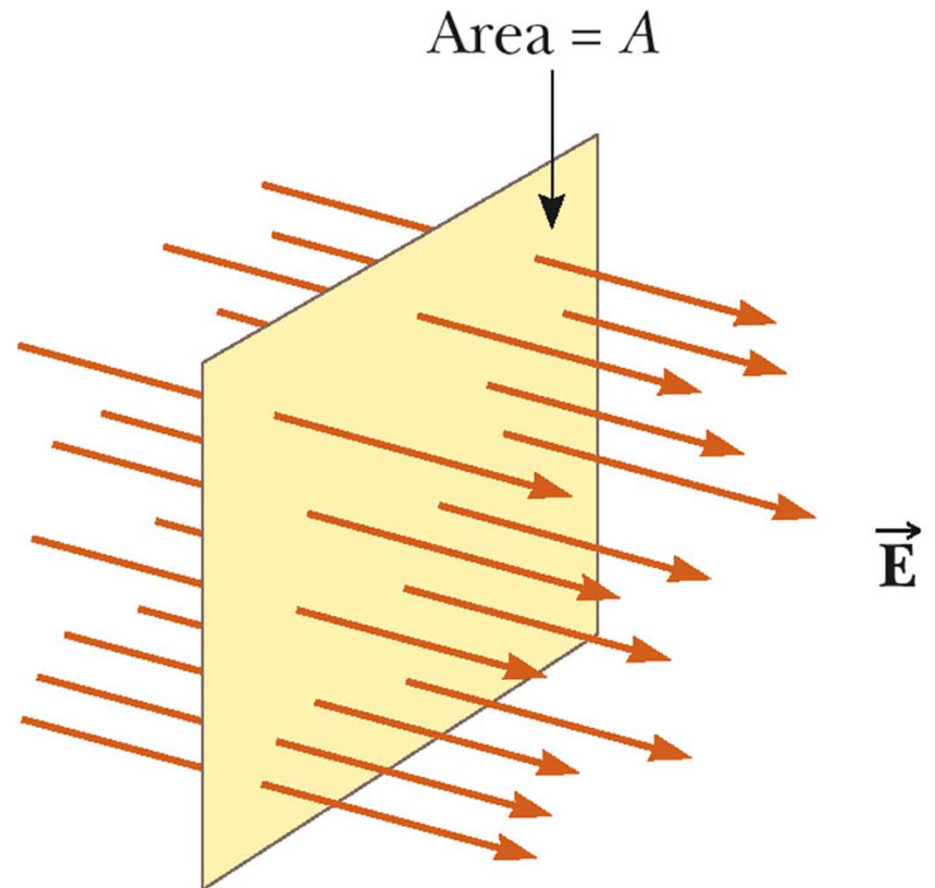
Van de Graaff Generator

- An electrostatic generator designed and built by Robert J. Van de Graaff in 1929
- Charge is transferred to the dome by means of a rotating belt
- Eventually an electrostatic discharge takes place



Electric Flux

- Field lines penetrating an area A perpendicular to the field
- The product of EA is the flux, Φ
- In general:
 - $\Phi_E = E A \cos \theta$





Electric Flux, cont.

- $\Phi_E = E A \cos \theta$
 - The perpendicular to the area A is at an angle θ to the field
 - When the area is constructed such that a closed surface is formed, use the convention that flux lines passing into the interior of the volume are negative and those passing out of the interior of the volume are positive



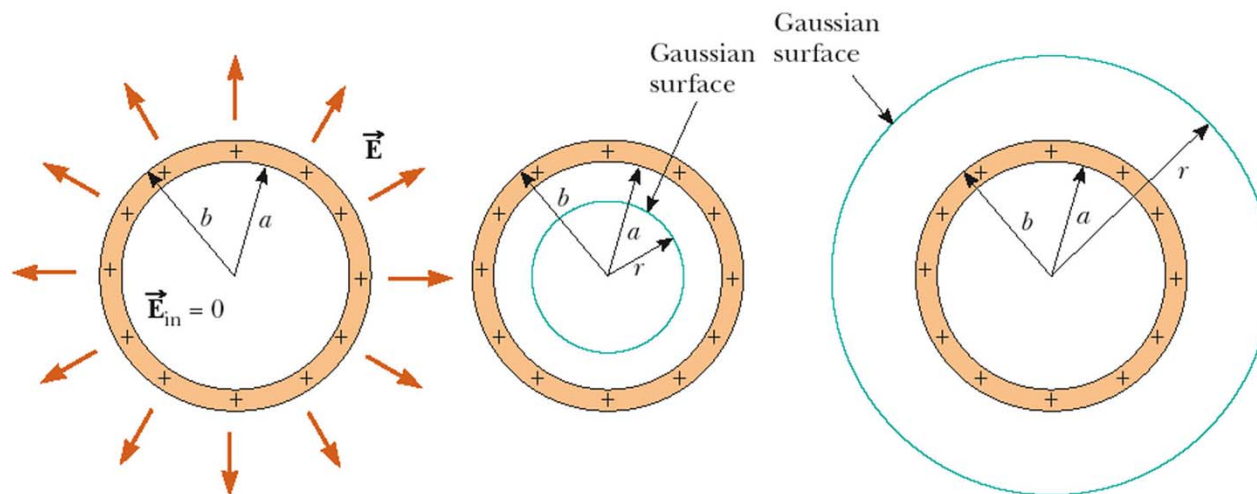
Gauss' Law

- Gauss' Law states that the electric flux through any closed surface is equal to the net charge Q inside the surface divided by ϵ_0

$$\Phi_E = \frac{Q_{inside}}{\epsilon_0}$$

- ϵ_0 is the *permittivity of free space* and equals $8.85 \times 10^{-12} \text{ C}^2/\text{Nm}^2$
- The area in Φ is an imaginary surface, a Gaussian surface, it does not have to coincide with the surface of a physical object

Electric Field of a Charged Thin Spherical Shell



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- The calculation of the field outside the shell is identical to that of a point charge

$$E = \frac{Q}{4\pi r^2 \epsilon_0} = k_e \frac{Q}{r^2}$$

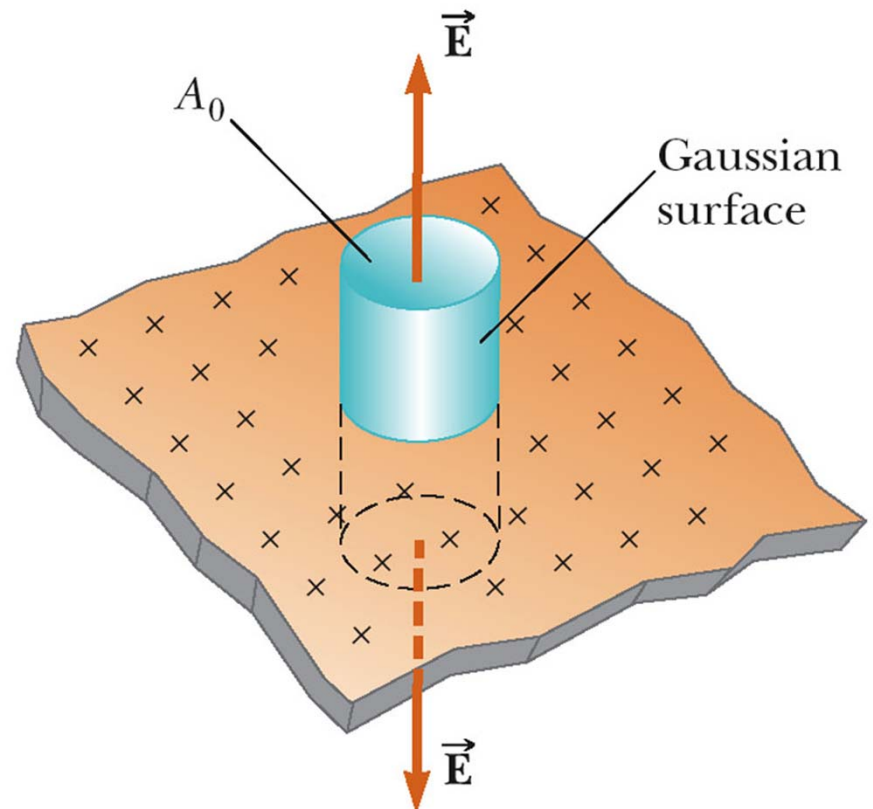
- The electric field inside the shell is zero

Electric Field of a Nonconducting Plane Sheet of Charge

- Use a cylindrical Gaussian surface
- The flux through the ends is EA , there is no field through the curved part of the surface
- The total charge is $Q = \sigma A$

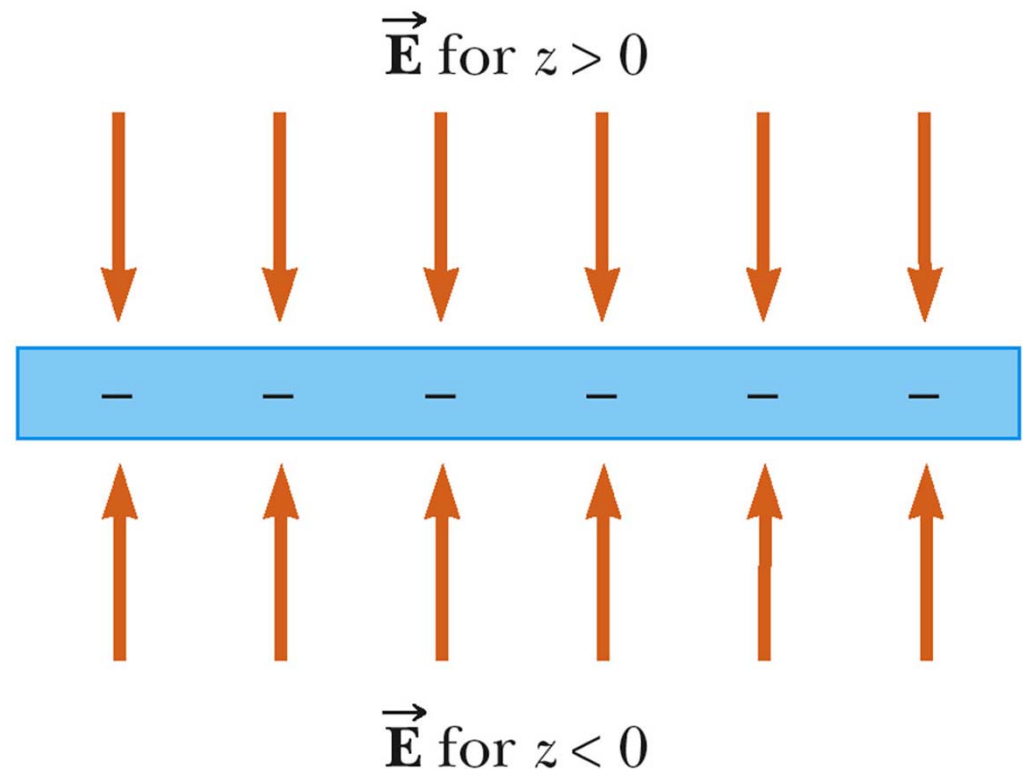
$$E = \frac{\sigma}{2\epsilon_0}$$

- Note, the field is uniform



Electric Field of a Nonconducting Plane Sheet of Charge, cont.

- The field must be perpendicular to the sheet
- The field is directed either toward or away from the sheet



Parallel Plate Capacitor

- The device consists of plates of positive and negative charge
- The total electric field between the plates is given by

$$E = \frac{\sigma}{\epsilon_0}$$

- The field outside the plates is zero

