

# Chapter 15

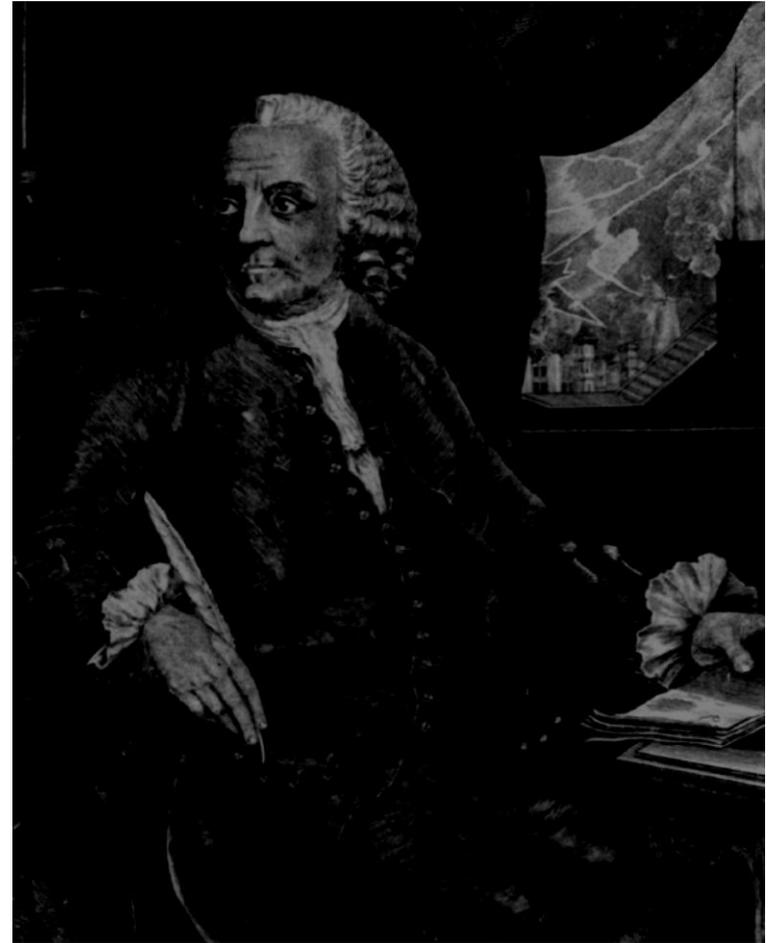
## Electric Forces and Electric Fields

# First Studies – 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

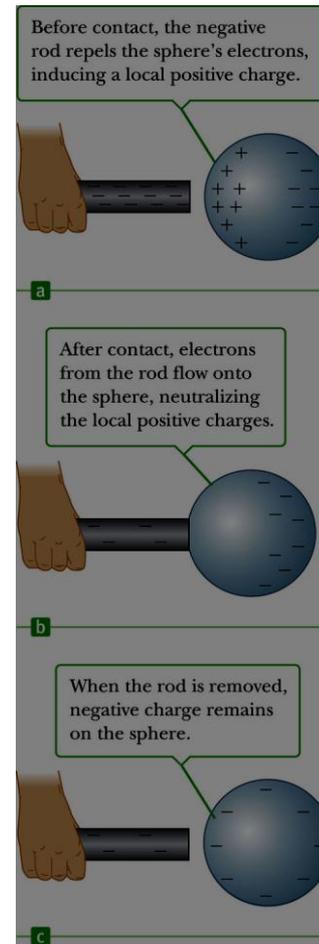
- Insulators are materials in which electric charges do not move freely.
  - Glass and rubber are examples of insulators.
  - When insulators are charged by rubbing, only the rubbed area becomes charged.
- There is no tendency for the charge to move into other regions of the material.

# Semiconductors

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

# Charging by Conduction

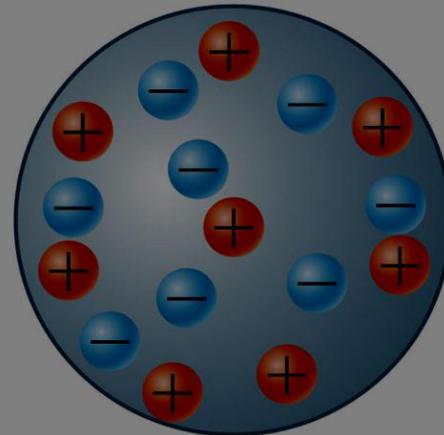
- A charged object (the rod) is placed in contact with another object (the sphere).
- Some electrons on the rod can move to the sphere.
- When the rod is removed, the sphere is left with a net negative charge.
- The object being charged is always left with a charge having the same sign as the object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



# 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.

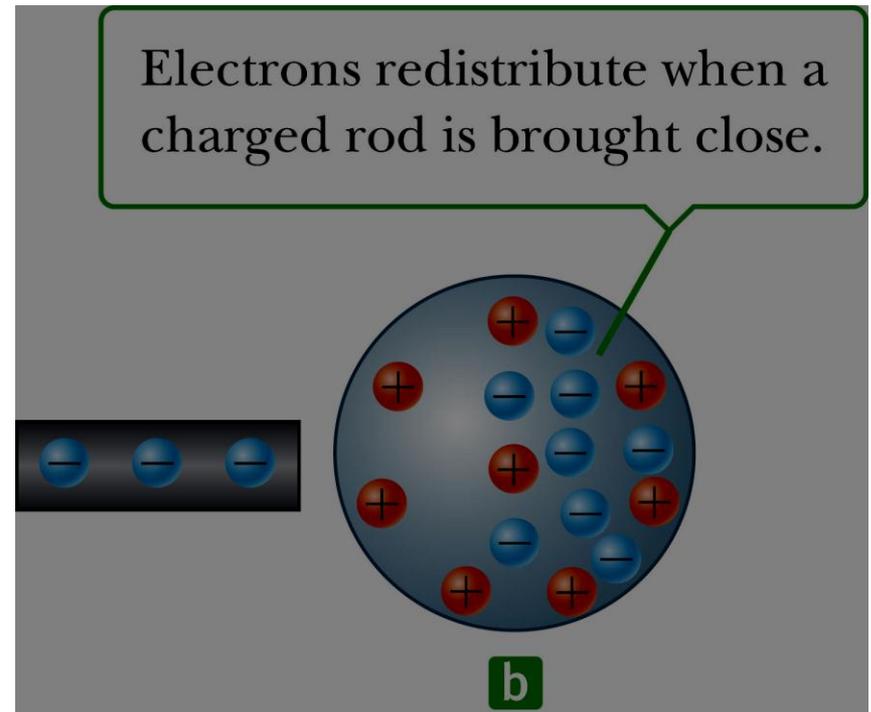
The neutral sphere has equal numbers of positive and negative charges.



a

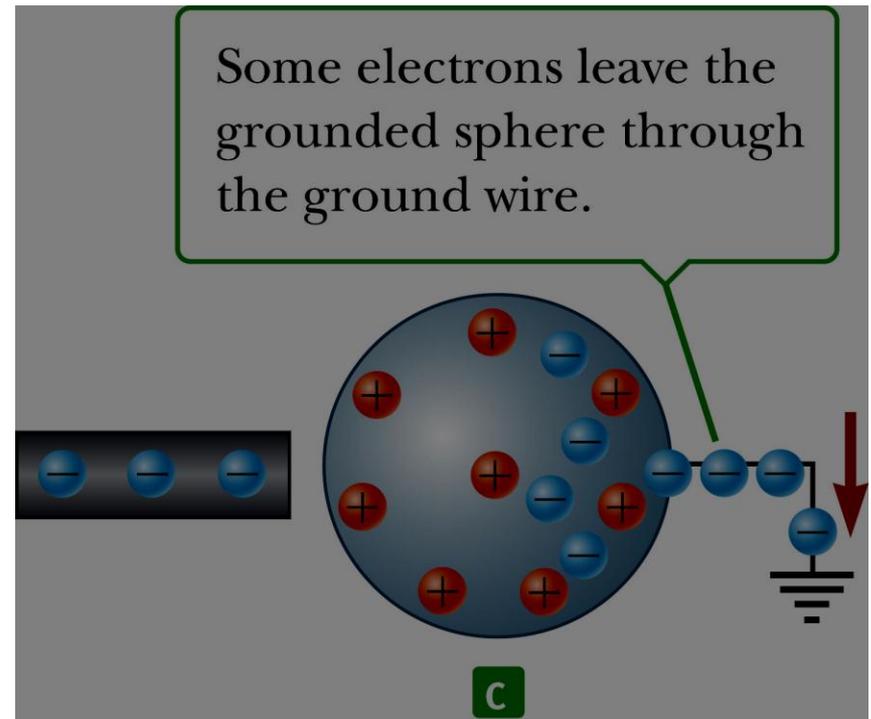
# Charging by Induction, 2

- 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.



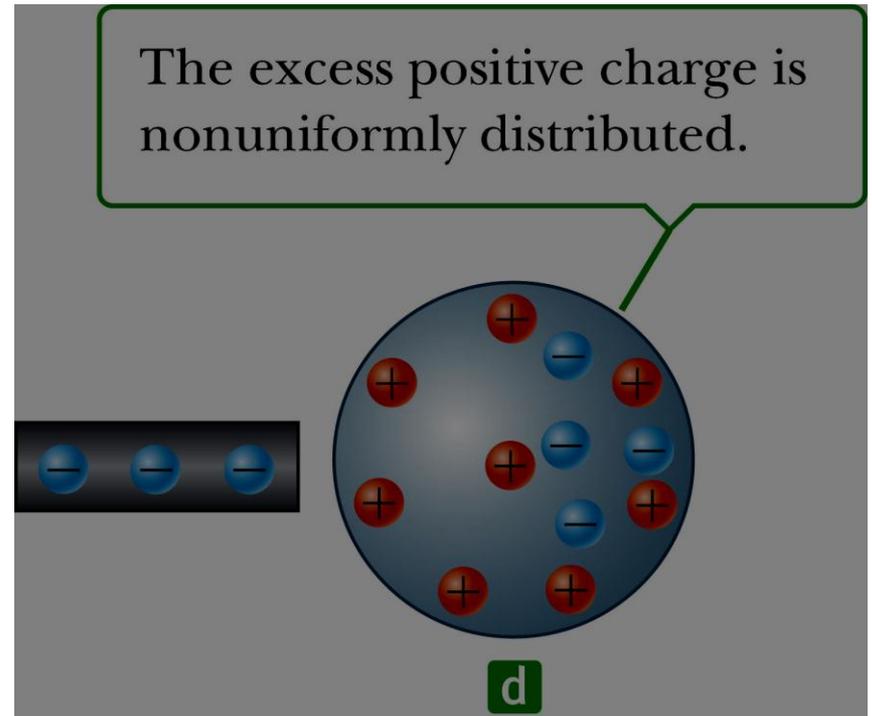
# Charging by Induction, 3

- 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



# Charging by Induction, 4

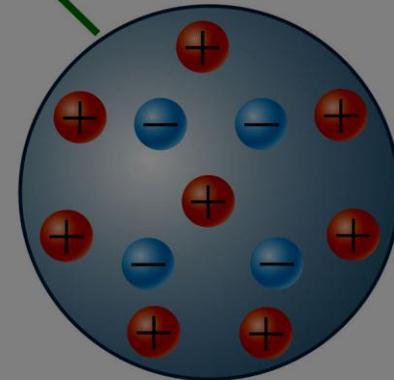
- The wire to ground is removed, the sphere is left with an excess of induced positive charge
- Initially, the positive charge on the sphere is nonuniformly distributed.



# Charging by Induction, Final

- Eventually, the excess positive charge becomes evenly distributed due to the repulsion between the positive charges.
- *Charging by induction requires no contact with the object inducing the charge.*

The remaining electrons redistribute uniformly, and there is a net uniform distribution of positive charge on the sphere's surface.



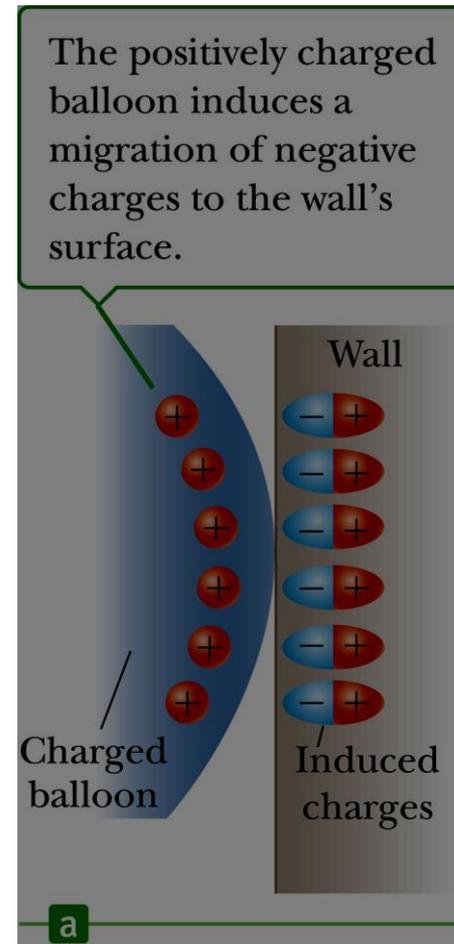
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# Polarization

- 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*.

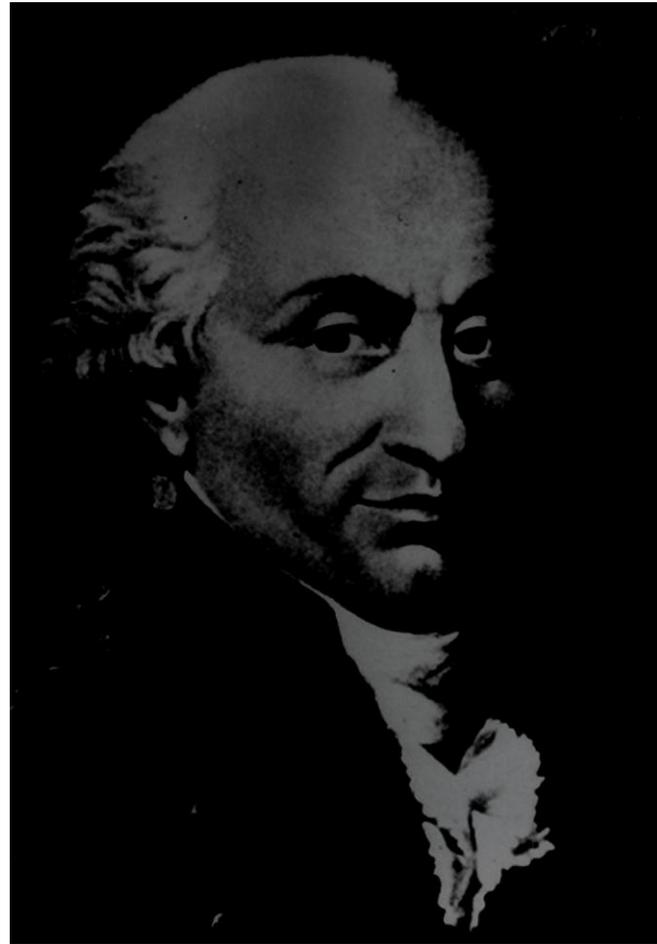
# Examples of Polarization

- 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.



# Charles Coulomb

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



# Coulomb's Law

- Coulomb shows that an electric 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  $\mu\text{C}$  range
  - Remember, Coulombs must be used in the equation
- Remember that force is a *vector* quantity
- Applies only to point charges and spherical distributions of charges
  - $r$  is the distance between the two centers of charge

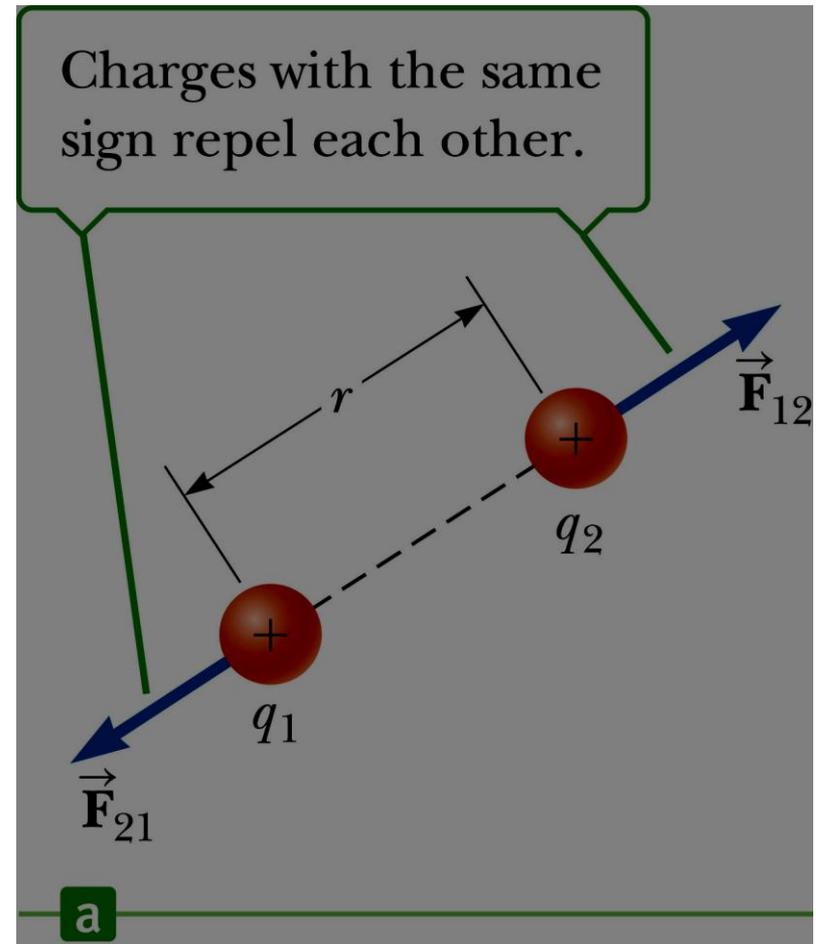
# Characteristics of Particles

**Table 15.1** Charge and Mass of the Electron, Proton, and Neutron

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

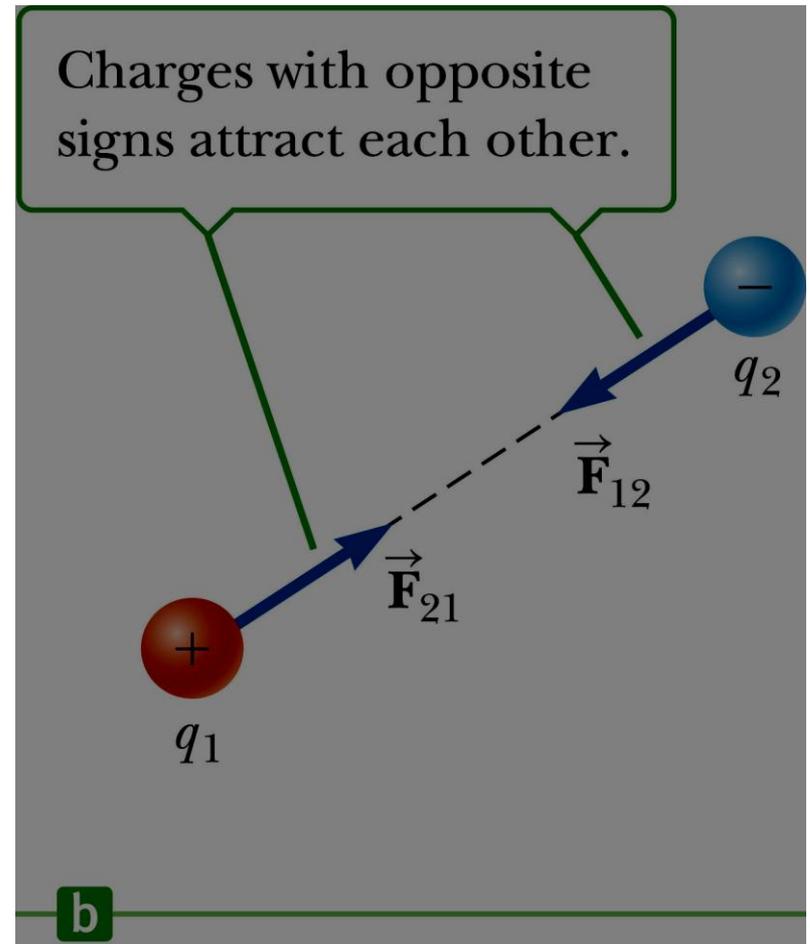
# Vector Nature of Electric Forces

- 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  $q_2$



# 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.

**PROBLEM** The electron and proton of a hydrogen atom are separated (on the average) by a distance of about  $5.3 \times 10^{-11}$  m. **(a)** Find the magnitudes of the electric force and the gravitational force that each particle exerts on the other, and the ratio of the electric force  $F_e$  to the gravitational force  $F_g$ .

$$F = k_c \frac{|q_1||q_2|}{r_{12}^2}, \quad k_e = 8.99 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2}$$

$$r_{12} = 5.3 \times 10^{-11} \text{ m}; \quad |q_1| = |q_2| = 1.6 \times 10^{-19} \text{ C}$$

$$F_e = \left( 8.99 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2} \right) \frac{(1.6 \times 10^{-19} \text{ C})^2}{(5.3 \times 10^{-11} \text{ m})^2}$$
$$= 8.2 \times 10^{-8} \text{ N.}$$

$$F_g = G \frac{m_1 m_2}{r_{12}^2} = \left( 6.67 \times 10^{-11} \frac{\text{Nm}^2}{\text{kg}^2} \right) \frac{(9.11 \times 10^{-31} \text{ kg}) \times (1.67 \times 10^{-27} \text{ kg})}{(5.3 \times 10^{-11} \text{ m})^2}$$
$$= 3.6 \times 10^{-47} \text{ N}$$

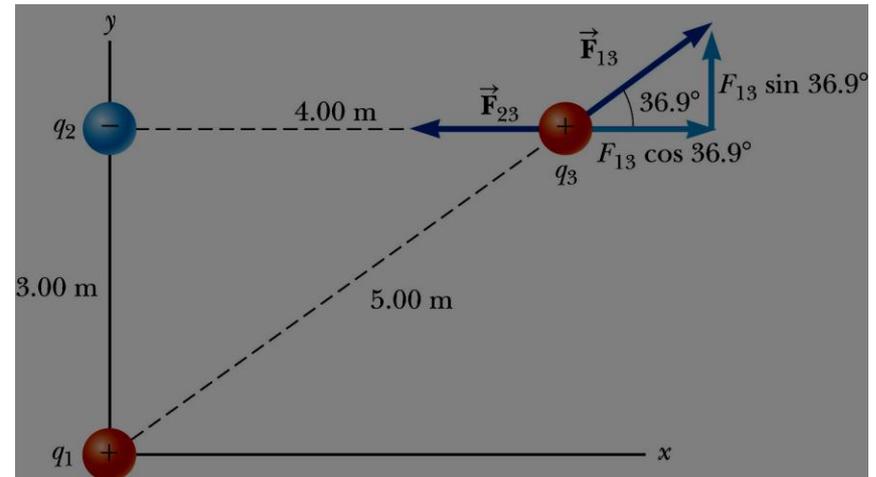
$$\therefore \frac{F_e}{F_g} = 2.3 \times 10^{39}!$$

# The Superposition Principle

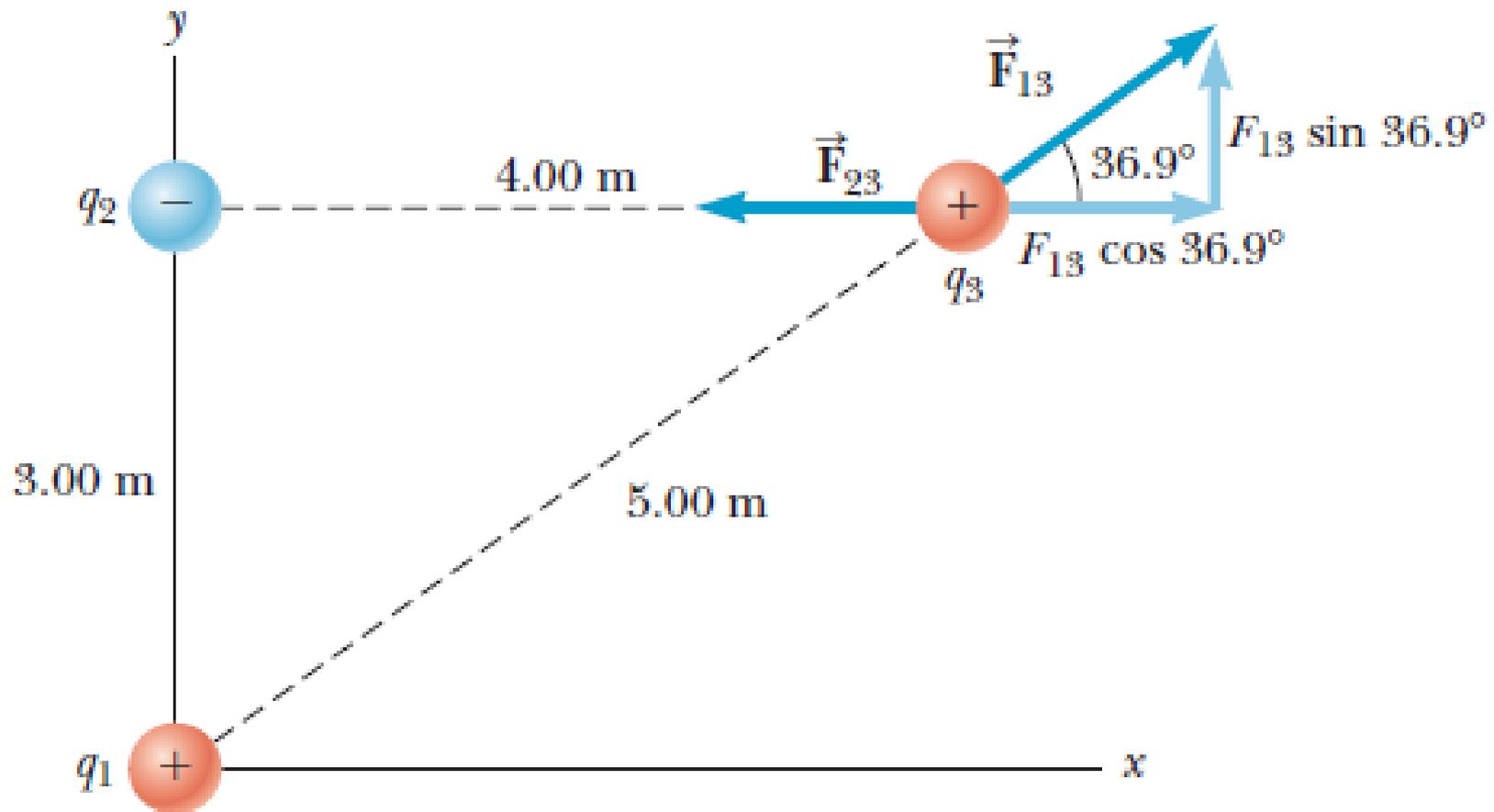
- The resultant force on any one charge equals the vector sum of the forces exerted by the other individual charges that are present.
  - Find the electrical forces between pairs of charges separately
  - Then add the vectors
- Remember to add the forces as *vectors*

# 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
- The *total force* exerted on  $q_3$  is the vector sum of  and



**PROBLEM** Consider three point charges at the corners of a triangle, as shown in Figure 15.8, where  $q_1 = 6.00 \times 10^{-9} \text{ C}$ ,  $q_2 = -2.00 \times 10^{-9} \text{ C}$ , and  $q_3 = 5.00 \times 10^{-9} \text{ C}$ . (a) Find the components of the force  $\vec{F}_{23}$  exerted by  $q_2$  on  $q_3$ . (b) Find the components of the force  $\vec{F}_{13}$  exerted by  $q_1$  on  $q_3$ . (c) Find the resultant force on  $q_3$ , in terms of components and also in terms of magnitude and direction.



$$F_{23} = k_e \frac{|q_2||q_3|}{r_{23}^2} = \left( 8.99 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2} \right) \frac{(2.00 \times 10^{-9} \text{C})(5.00 \times 10^{-9} \text{C})}{(4.00 \text{m})^2}$$

$$= 5.62 \times 10^{-9} \text{N}$$

$$F_{23x} = -5.62 \times 10^{-9} \text{N} ; F_{23y} = 0$$

$$F_{13} = \left( 8.99 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2} \right) \frac{(6.00 \times 10^{-9} \text{C})(5.00 \times 10^{-9} \text{C})}{(5.00 \text{m})^2}$$

$$= 1.08 \times 10^{-8} \text{N}$$

$$F_{13x} = F_{13} \cos \theta = (1.08 \times 10^{-8} \text{N}) \cos 36.9^\circ = 8.64 \times 10^{-9} \text{N}$$

$$F_{13y} = F_{13} \sin \theta = (1.08 \times 10^{-8} \text{N}) (\sin 36.9^\circ) = 6.48 \times 10^{-9} \text{N}$$

$$F_x = F_{23x} + F_{13x} = -5.62 \times 10^{-9} \text{N} + 8.64 \times 10^{-9} \text{N} = 3.02 \times 10^{-9} \text{N}$$

$$F_y = 0 + 6.48 \times 10^{-9} \text{ N} = 6.48 \times 10^{-9} \text{ N}$$

$$\begin{aligned} \therefore |\vec{F}| &= \sqrt{|F_x|^2 + |F_y|^2} = \sqrt{(3.01 \times 10^{-9} \text{ N})^2 + (6.48 \times 10^{-9} \text{ N})^2} \\ &= 7.15 \times 10^{-9} \text{ N} \end{aligned}$$

$$\theta = \tan^{-1} \frac{F_y}{F_x} = \tan^{-1} \frac{6.48 \times 10^{-9} \text{ N}}{3.02 \times 10^{-9} \text{ N}} = 65.0^\circ$$

## QUIZ 1

1. A suspended object  $A$  is attracted to a neutral wall. It's also attracted to a positively charged object  $B$ . Which of the following is true about object  $A$ ? (a) It is uncharged. (b) It has a negative charge. (c) It has a positive charge. (d) It may be either charged or uncharged.

2. Object  $A$  has a charge of  $12 \text{ mC}$ , and object  $B$  has a charge of  $16 \text{ mC}$ . Which statement is true?

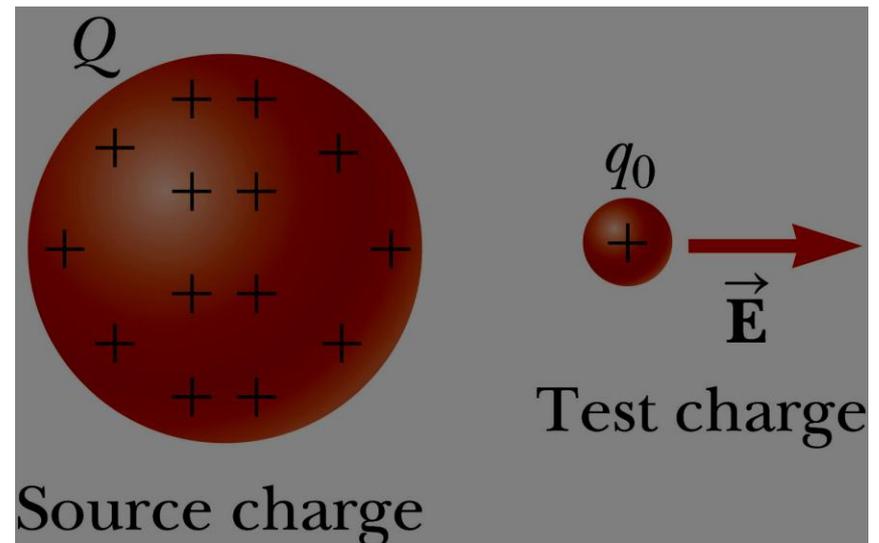
(a)  $\vec{F}_{AB} = -3\vec{F}_{BA}$ , (b)  $\vec{F}_{AB} = -\vec{F}_{BA}$   
(c)  $3\vec{F}_{AB} = -\vec{F}_{BA}$  (d)  $\vec{F}_{AB} = \vec{F}_{BA}$

# 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

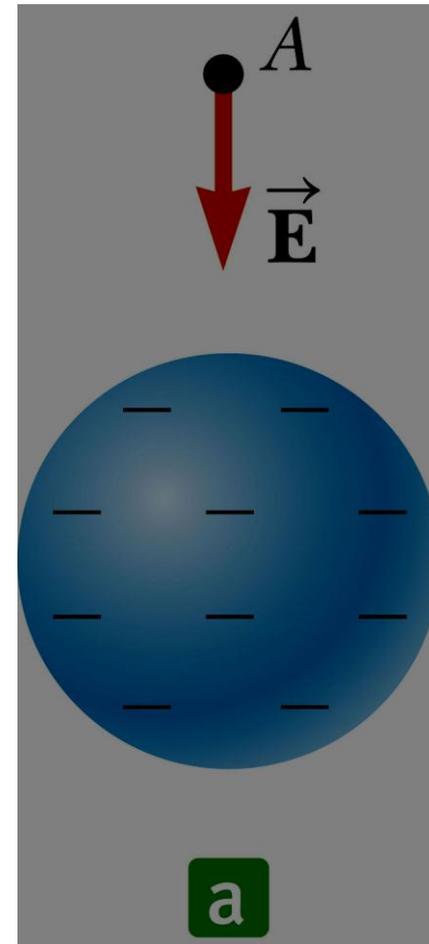
- Mathematically,

$$\vec{E} = \frac{\vec{F}}{q_o} = \frac{k_e Q}{r^2}$$

- SI unit: 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.

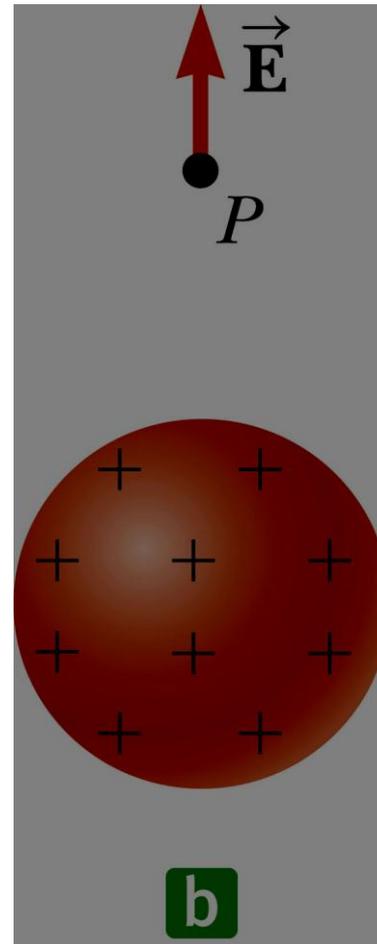
# Direction of Electric Field

- 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.

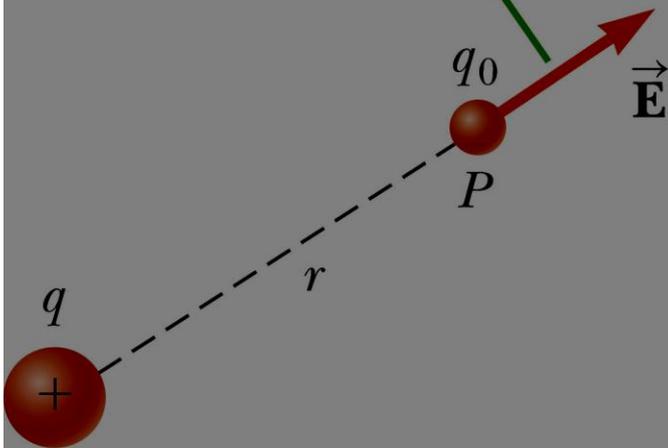


# More About a Test Charge and The Electric Field

- The test charge is required to be a small charge.
  - It can cause no rearrangement of the charges on the source charge.
  - Mathematically, the size of the test charge makes no difference.
- Using  $q_o = 1 \text{ C}$  is convenient
- The electric field exists whether or not there is a test charge present.

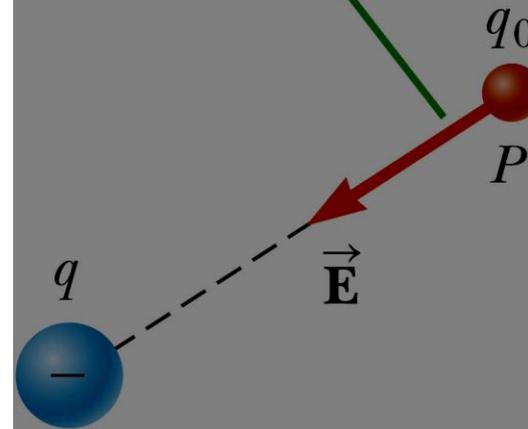
# Electric Field, Direction Summary

If  $q$  is positive, the electric field at  $P$  points radially outwards from  $q$ .



a

If  $q$  is negative, the electric field at  $P$  points radially inwards toward  $q$ .



b

# 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.

# 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.
- The direction is always along the line of the two charges.

- **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 trigonometry.

# 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

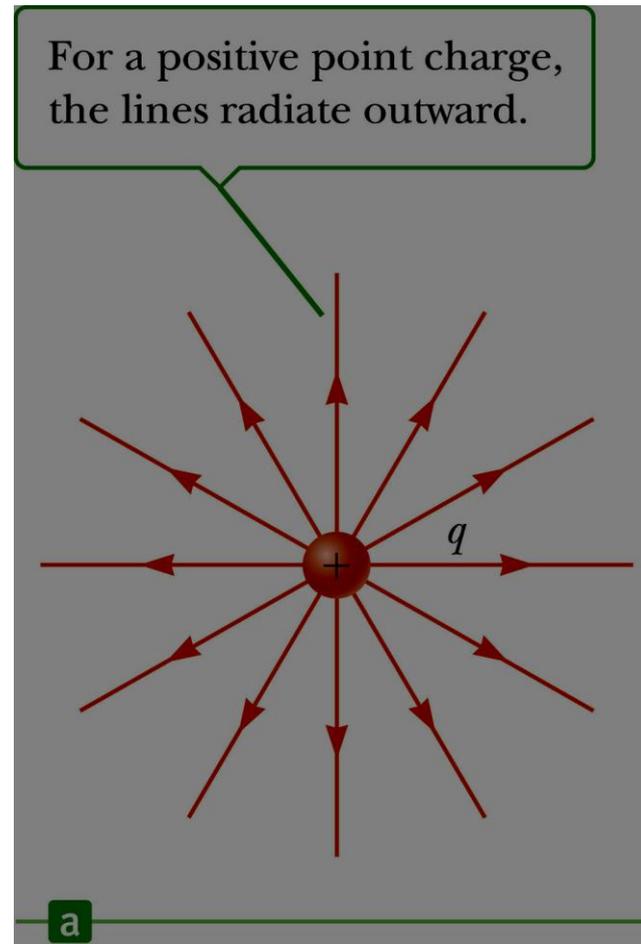
- A convenient aid for visualizing electric field patterns is to draw lines pointing in the direction of the field vector at any point.
- These lines are called **electric field lines** and were introduced by Michael Faraday.

# Electric Field Lines, Cont.

- The field lines are related to the field in the following manners:
  - The electric field vector,  $\vec{\mathbf{E}}$ , 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.

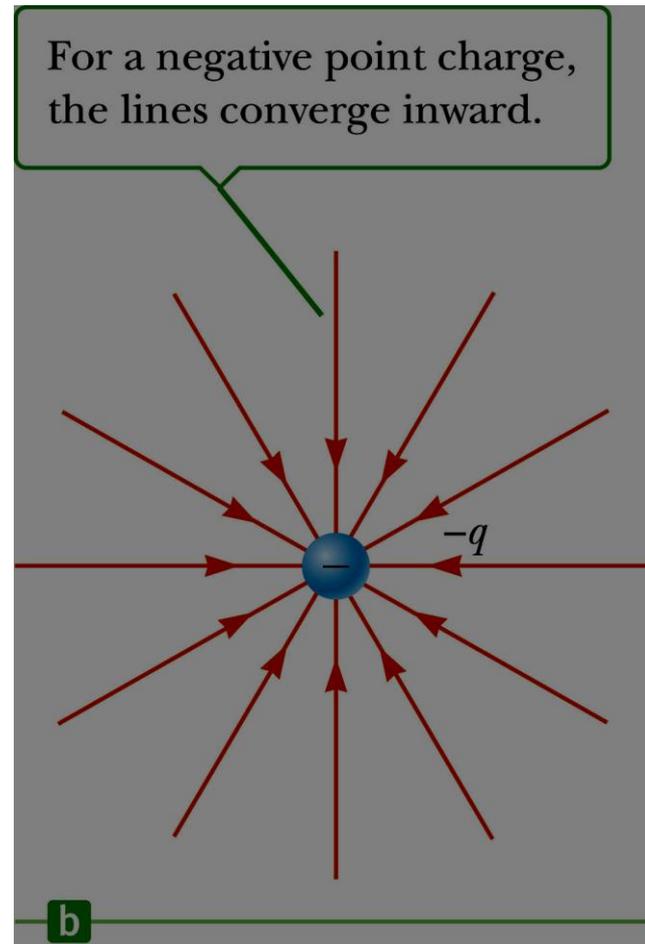
# Electric Field Line Patterns

- 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.



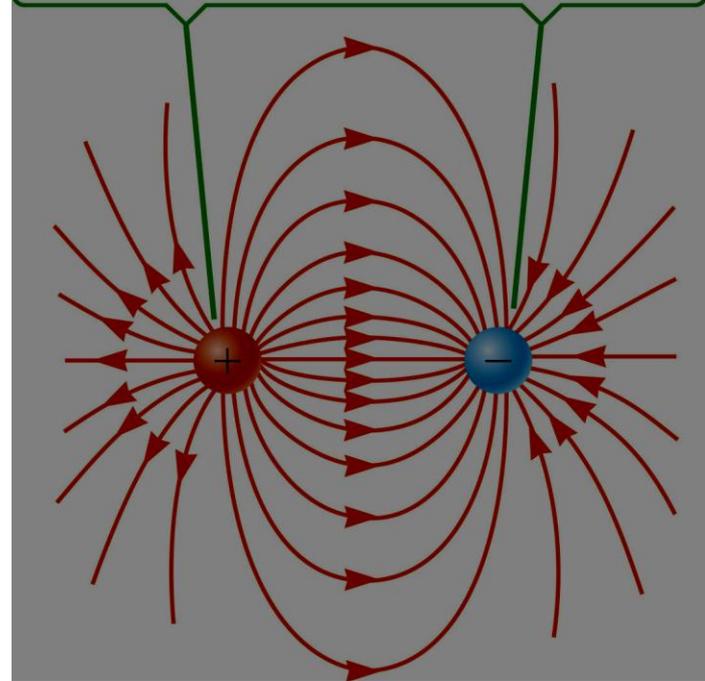
# Rules for Drawing Electric Field Lines

- 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 Line Patterns

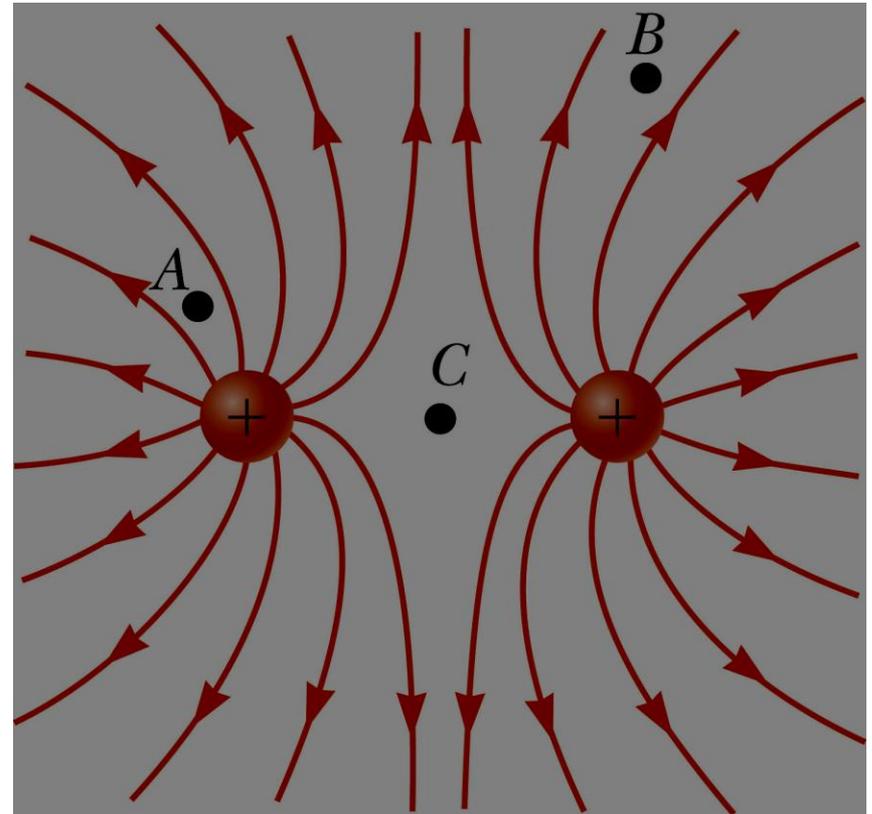
- An electric *dipole* consists of two equal and opposite charges.
- The high density of lines between the charges indicates the strong electric field in this region.

The number of field lines leaving the positive charge equals the number terminating at the negative charge.



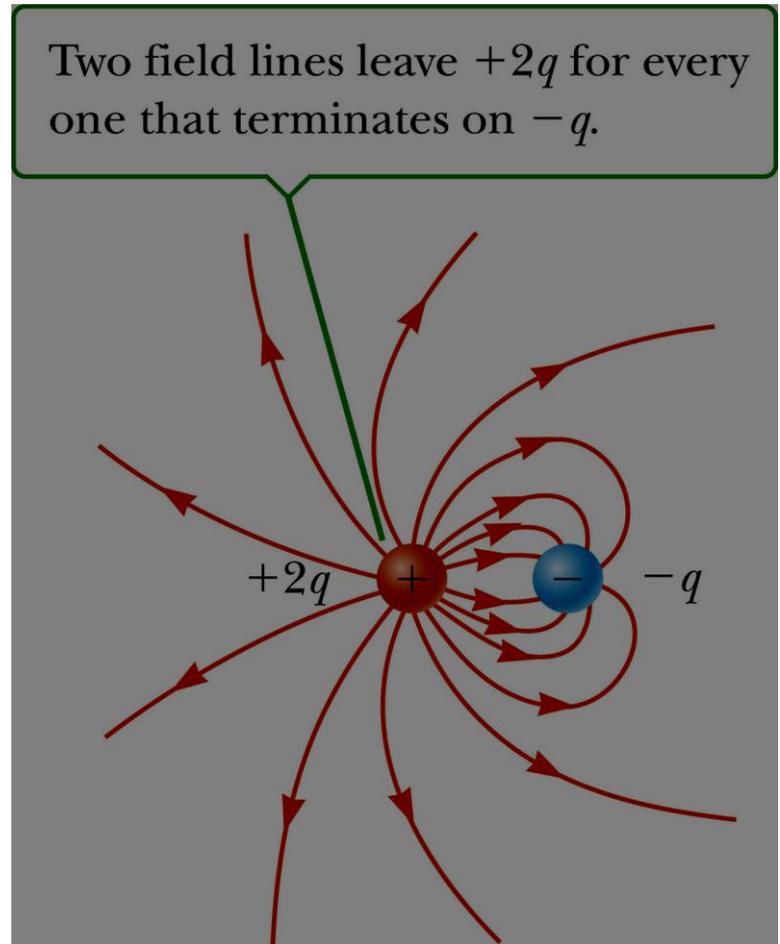
# Electric Field Line Patterns

- 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  $-q$
- At a great distance from the charges, the field would be equivalent to that of a single charge  $+q$



# 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

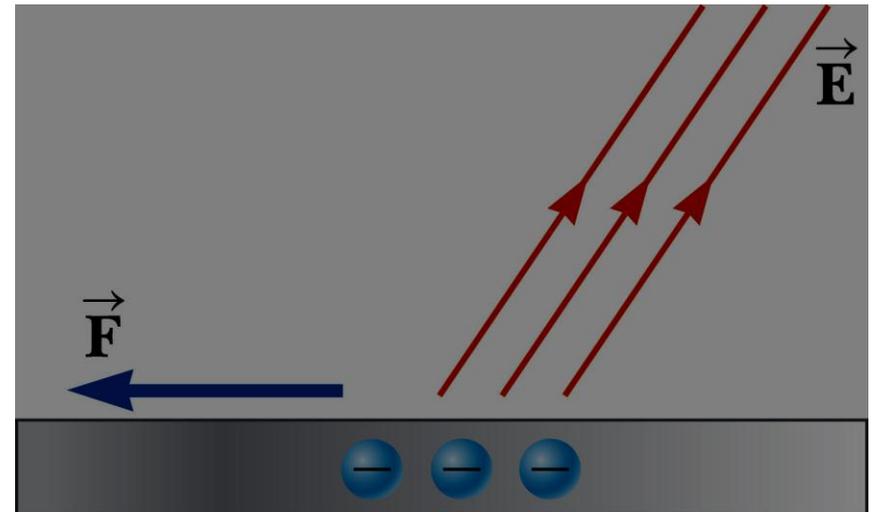
- The electric field is zero everywhere inside the conducting material.
  - Consider if this were *not* true
- If there were an electric field inside the conductor, the free charge there would move and there would be a flow of charge.
- If there were a movement of charge, the conductor would not be in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

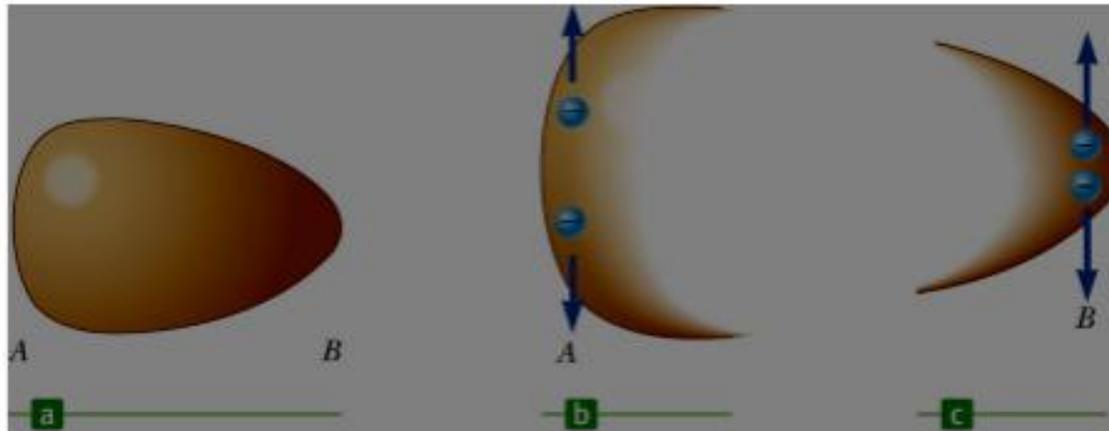
- The electric field just outside a charged conductor is perpendicular to the conductor's surface.
  - Consider what would happen if this was not true.
  - The component along the surface would cause the charge to move.
  - It would not be in equilibrium.



# 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.

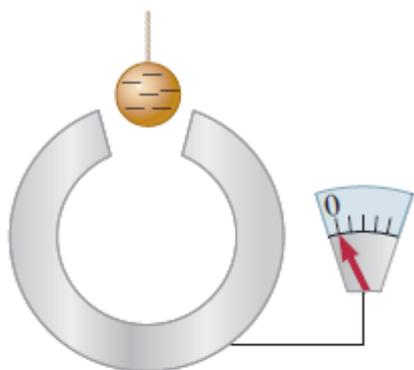


- Any excess charge moves to its surface.
- The charges move apart until an equilibrium is achieved.
- The amount of charge per unit area is ~~greater~~ <sup>smaller</sup> at the flat end.
- The forces from the charges at the sharp end produce a larger resultant force away from the surface.

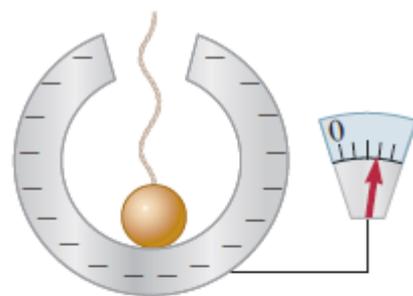
# An Experiment to Verify Properties of Charges

- Faraday's Ice-Pail Experiment

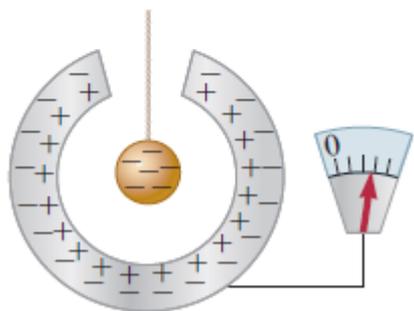
- Concluded a charged object suspended inside a metal container causes a rearrangement of charge on the container in such a manner that the sign of the charge on the inside surface of the container is opposite the sign of the charge on the suspended object



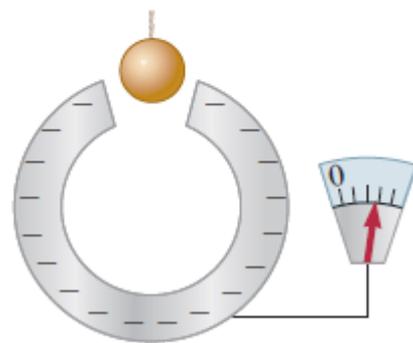
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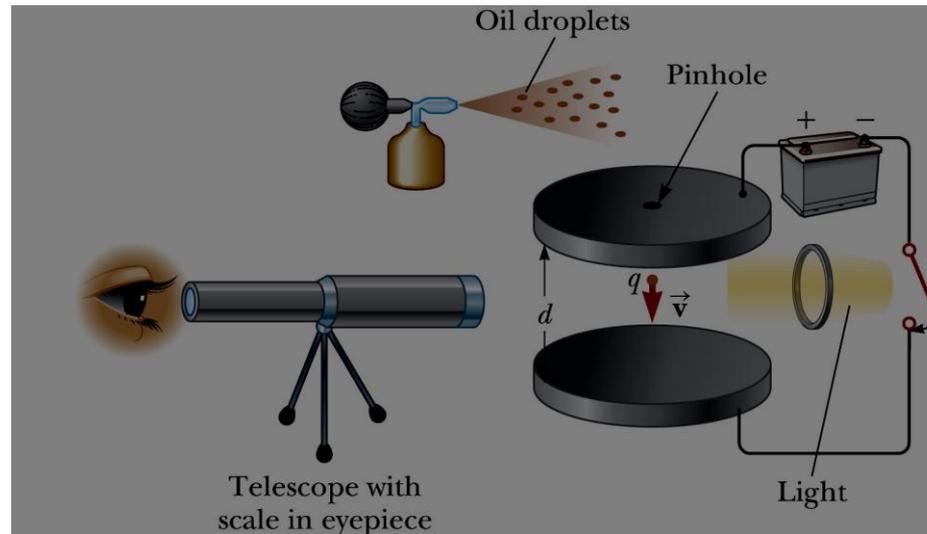


b



d

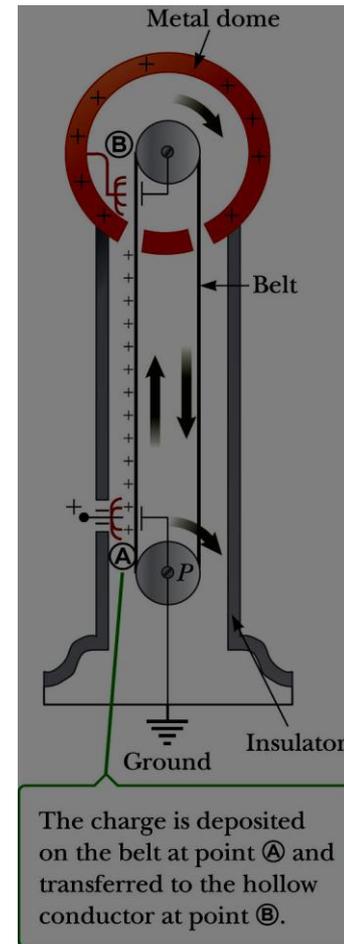
# Millikan Oil-Drop Experiment



- Measured the elementary charge,  $e$
  - Found every charge had an integral multiple of  $e$
- $$-q = n e$$

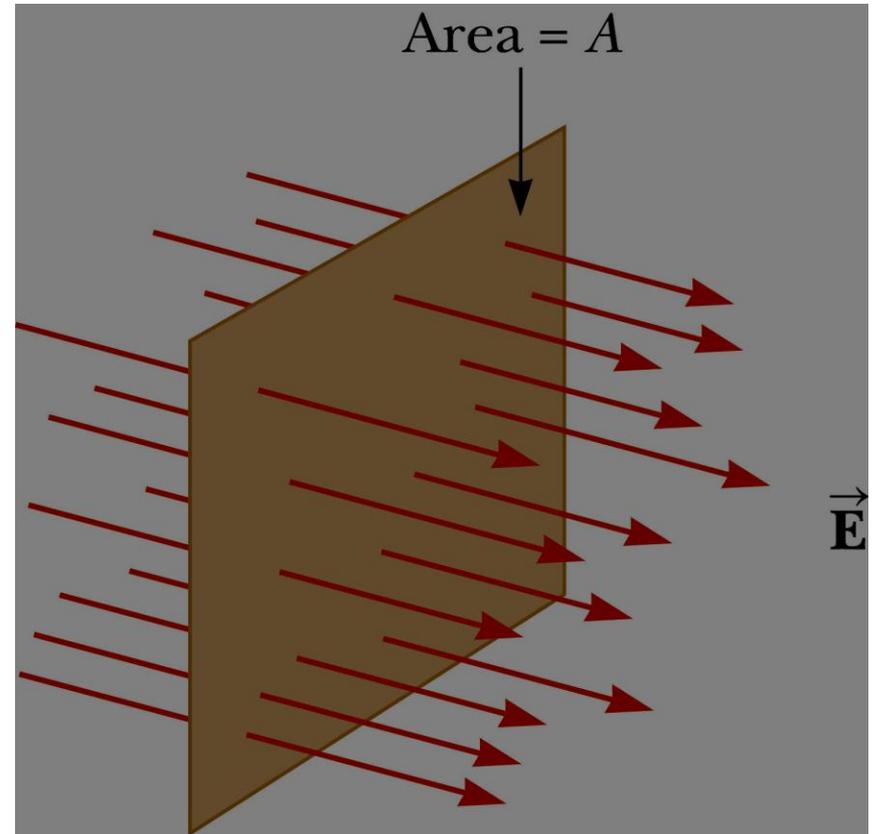
# Van de Graaff Generator

- 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

- Electric flux is a measure of how much the electric field vectors penetrate through a given surface.
- Field lines penetrating an area  $A$  perpendicular to the field
- The product of  $EA$  is the flux,  $\Phi$
- 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  $\theta$  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.

- SI unit:  $\text{N} \cdot \text{m}^2 / \text{C}$

# Gauss' Law

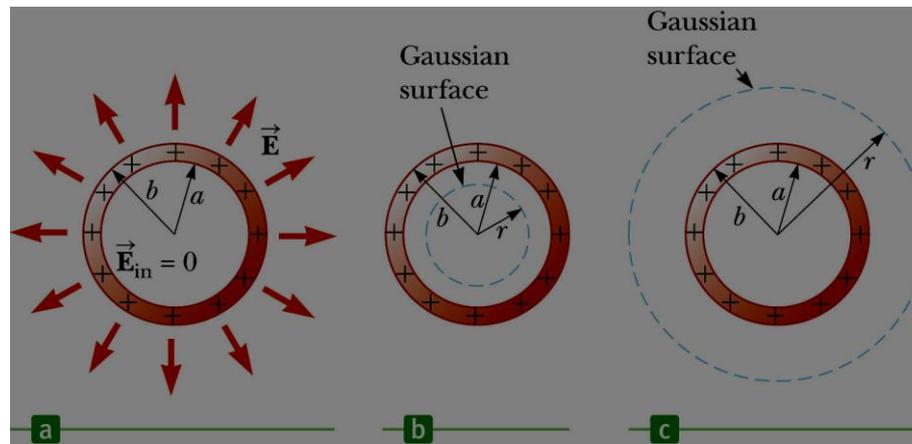
•Gauss' Law states that the electric flux through any closed surface is equal to the net charge  $Q$  inside the surface divided by  $\epsilon_0$

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

– $\epsilon_0$  is the *permittivity of free space* and equals  $8.85 \times 10^{-12} \text{ C}^2/\text{Nm}^2$

–The area in  $\Phi$  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



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

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

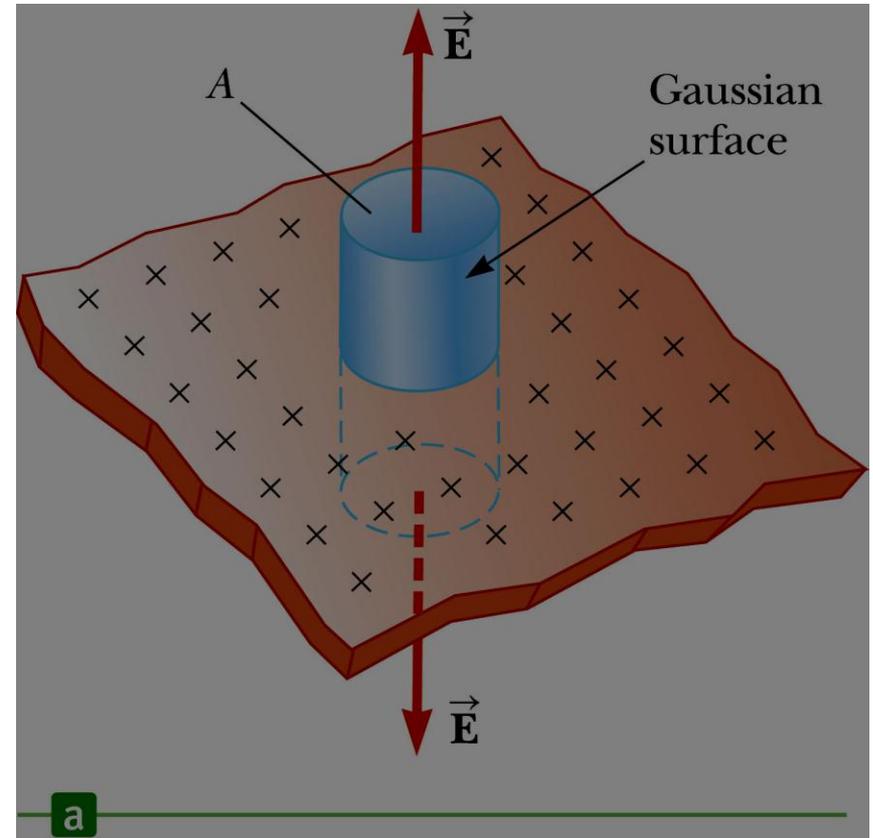
- The electric field inside the shell is zero.

# 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  $Q = \sigma A$

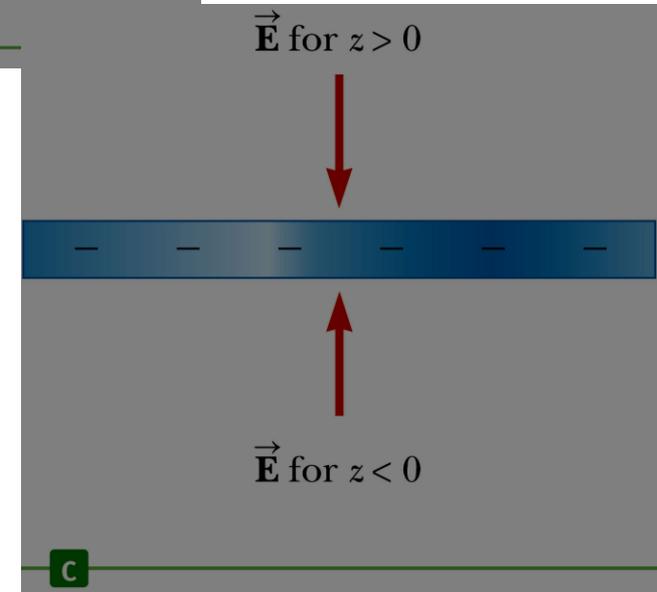
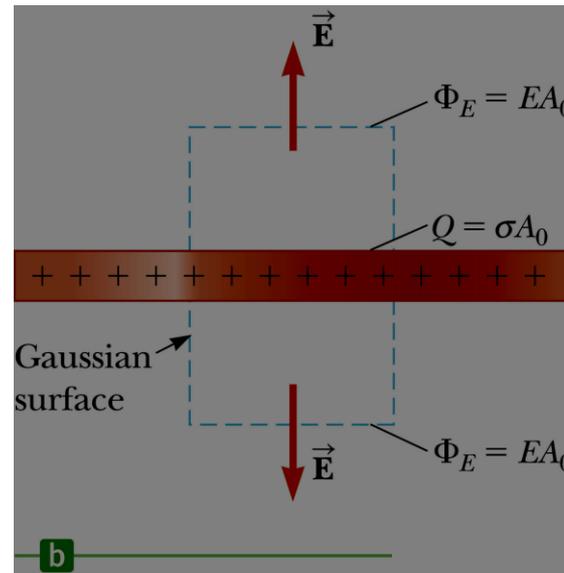
$$E = \frac{\sigma}{2\epsilon_0}$$

- 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.

